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SUMMARY OF SEVERAL HYDRAULIC TESTS IN SUPPORT OF THE LIGHT WATER BREEDER REACTOR DESIGN

(LWBR Development Program)

MAY 1979

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BETTIS ATOMIC POWER LABORATORY
WEST MIFFLIN, PENNSYLVANIA

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**SUMMARY OF SEVERAL HYDRAULIC TESTS
IN SUPPORT OF THE LIGHT WATER BREEDER
REACTOR DESIGN
(LWR Development Program)**

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FOREWORD

The Shippingport Atomic Power Station located in Shippingport, Pennsylvania was the first large-scale, central-station nuclear power plant in the United States and the first plant of such size in the world operated solely to produce electric power. This program was started in 1953 to confirm the practical application of nuclear power for large-scale electric power generation. It has provided much of the technology being used for design and operation of the commercial, central-station nuclear power plants now in use.

Subsequent to development and successful operation of the Pressurized Water Reactor in the DOE-owned reactor plant at the Shippingport Atomic Power Station, the Atomic Energy Commission in 1965 undertook a research and development program to design and build a Light Water Breeder Reactor core for operation in the Shippingport Station.

The objective of the Light Water Breeder Reactor (LWBR) program has been to develop a technology that would significantly improve the utilization of the nation's nuclear fuel resources employing the well-established water reactor technology. To achieve this objective, work has been directed toward analysis, design, component tests, and fabrication of a water-cooled, thorium oxide fuel cycle breeder reactor for installation and operation at the Shippingport Station. The LWBR core started operation in the Shippingport Station in the Fall of 1977 and is expected to be operated for about 3 to 4 years. At the end of this period, the core will be removed and the spent fuel shipped to the Naval Reactors Expended Core Facility for a detailed examination to verify core performance including an evaluation of breeding characteristics.

In 1976, with fabrication of the Shippingport LWBR core nearing completion, the Energy Research and Development Administration established the Advanced Water Breeder Applications (AWBA) program to develop and disseminate technical information which would assist U. S. industry in evaluating the LWBR concept for commercial-scale applications. The program will explore some of the problems that would be faced by industry in adapting technology confirmed in the LWBR program. Information to be developed includes concepts for commercial-scale prebreeder cores which would produce uranium-233 for light water breeder cores while producing electric power, improvements for breeder cores based on the technology developed to fabricate and operate the Shippingport LWBR core, and other information and technology to aid in evaluating commercial-scale application of the LWBR concept.

FOREWORD (Cont)

All three development programs (Pressurized Water Reactor, Light Water Breeder Reactor, and Advanced Water Breeder Applications) have been administered by the Division of Naval Reactors with the goal of developing practical improvements in the utilization of nuclear fuel resources for generation of electrical energy using water-cooled nuclear reactors.

Technical information developed under the Shippingport, LWBR, and AWBA programs has been and will continue to be published in technical memoranda, one of which is this present report.

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As part of the Light Water Breeder Reactor development program, hydraulic tests of reactor components were performed. This report presents the results of several of those tests performed for components which are somewhat unique in their application to a pressurized water reactor design. The components tested include; triplate orifices used for flow distribution purposes, multi-venturi type flowmeters, tight lattice triangular pitch rod support grids, fuel rod end support plates, and the balance piston which is a major component of the movable fuel balancing system. Test results include component pressure loss coefficients, flowmeter coefficients and fuel rod region pressure drop characteristics. These test results plus additional hydraulic tests performed during the development program were used in the design and analysis of the Light Water Breeder Reactor.

SUMMARY OF SEVERAL HYDRAULIC TESTS IN SUPPORT
OF THE LIGHT WATER BREEDER REACTOR DESIGN
(LWBR Development Program)

K. D. McWilliams
J. R. Turner

I. INTRODUCTION

The Light Water Breeder Reactor (LWBR) Program is developing the technology to breed fissile material in a light water reactor in order to use nuclear fuel significantly more efficiently in light water thermal reactors. To achieve this objective, technology is being developed through the design and fabrication of a breeder reactor core that has been installed in the existing Department of Energy (DOE) owned pressurized water reactor plant at Shippingport, Pennsylvania. The LWBR design and the fabrication of the reactor core were accomplished by the Bettis Atomic Power Laboratory under the technical direction of the Division of Naval Reactors, DOE. The operation of the LWBR core in the Shippingport Atomic Power Station is expected to confirm that breeding of fissile material can be achieved in a pressurized light water reactor using a thorium (ThO_2)

and thorium/uranium ($\text{ThO}_2\text{-UO}_2$) binary fuel system. This core represents the first large scale fabrication of a thorium base binary fuel of high density and the first use of uranium-233 fabricated into ceramic fuel in a power reactor.

The development of the Light Water Breeder Reactor (LWBR) design resulted in several unique hydraulic design problems in addition to the conventional hydraulic concerns in the design of a pressurized water reactor (PWR). These unique features were largely a result of the overall objective to demonstrate breeding in a light water environment. This report presents the results of some of the more important hydraulic tests conducted to confirm that the unique design features are adequate. Reference 1 gives an overall view of the Light Water Breeder Reactor Design.

Figure 1 shows a cross section of the LWBR core in the Shippingport PWR vessel. The four basic rodded regions: seed, standard blanket, power flattened blanket, and reflector are designated. The seed-blanket arrangement makes it possible to utilize movable fuel for reactivity control. This eliminates the need for poison rods which degrade neutron economy and reduce the breeding potential. The power flattened blanket region is a region having a low metal to water ratio and surrounds the seed-blanket configuration. The low metal to water ratio in the power flattened blanket region increases the power on the outer periphery of the seed-blanket region because of the moderating effect of the water. This results in flattening of the overall core power distribution. The reflector region, which surrounds the other three regions, reduces neutron leakage from the core. The seed and blanket regions contain both fissile fuel in the form of UO_2 bearing ThO_2 pellets and fertile fuel in the form of ThO_2 pellets. Only fertile fuel in the form of ThO_2 pellets is contained in the reflector region.

The different metal to water ratios and fissile fuel loadings contained in each region results in variations in the region average power densities. In addition, the hydraulic resistances of each region are different. Therefore, to balance each region's individual power capability and thus maximize core power capability, the coolant is apportioned to the various regions by orificing. The seed region is unorificed. The standard blanket and power flattened blanket regions are orificed as a single region with hydraulic coupling between the two types of blankets. The reflector region requires the maximum amount of orificing (minimum flow) since it produces the least amount of power. These three hydraulic regions are isolated from one another using Zircaloy shells around each reflector module and inside each blanket module. To minimize pressure loads on the Zircaloy shells, triplate orifices are installed at both the inlet and outlet of each orificed module. The use of three orifice plates in series reduces the coolant velocities in the orifice relative to a single plate orifice design. An example of the orifice arrangement is shown in Figure 2 for a Type I blanket module. Section II discusses the various flow tests which were performed to characterize the orifice pressure loss as a function of orifice plate hole diameters.

To verify that adequate flow is being provided to the various regions of the core, special venturi type flowmeters were designed and incorporated in the entrance regions to all of the seed and blanket modules. Each flowmeter contains a number of venturis in parallel. The pressure taps for each venturi are manifolded such that one flowmeter pressure drop signal is obtained. Hydraulic testing of these flowmeters was performed to determine the meter flow coefficient and pressure loss characteristics. These tests are discussed in Section III.

To maximize breeding, the seed and standard blanket regions have been designed with high metal to water ratios. This was partly achieved by placing fuel rods as close together as practical. The resulting design placed rods on a triangular pitch with approximately 0.060 inches between rods. This design resulted in the need for a special support grid design with the potential for large pressure losses. Hydraulic tests, as discussed in Section IV, were performed to determine the pressure loss characteristics of several types of grid designs.

In addition to being supported by grids, one end of each fuel rods is attached to a baseplate. One baseplate is located at both the top and bottom of each module with approximately one-half of the fuel rods in each module attached to the baseplate at the bottom of the module and the other half to the baseplate at the top. The fuel rod support system is illustrated in Figure 3 for a Type III blanket module. Coolant flow passes through the baseplates by means of holes which are spaced between the attached rods. The ends of the fuel rods which are attached to the opposite baseplate are located in line with these holes. The pressure loss of the baseplate is dependent on the gap between the plates and the rod ends. Section V discusses the hydraulic testing which was performed to determine the sensitivity of the baseplate pressure loss coefficient to the proximity of the rod free end.

As was previously mentioned, the LWBR core employs a movable fuel system to maximize neutron economy and enhance the breeding potential. A hydraulic balance system is used to provide a downward force on the movable fuel which counteracts the upward hydraulic force caused by axial flow of coolant through the movable fuel region. Inlet plenum pressure is supplied to the top of a balance piston which is attached to the movable fuel as illustrated in Figure 4.

This hydraulic balance system results in a net downward force on the movable fuel of a magnitude approximately equal to the movable fuel assembly weight. Hydraulic testing of the balance piston is discussed in Section VI. The overall system performance, such as scram characteristics, buffing performance, net force, etc. of the LWBR movable fuel hydraulic balance system is presented in Reference 2.

II. ORIFICE TESTS

The orifices used in the LWBR core consist of three plates attached in series. Each of the three plates is multiholed with the flow holes on a triangular pitch. The flow holes in the center plate are staggered with respect to the flow holes in the upstream and downstream plates. The resulting effect of this orifice arrangement is a large pressure loss coefficient with reasonably low coolant velocities. The low coolant velocities are desirable to avoid potential orifice erosion problems and possibly detrimental effects (such as structural or instrumentation vibration) downstream of the orifice.

Many of the potential hydraulic variables in the orifice tests were fixed. Mechanical concerns established the thickness and spacing of the orifice plates, the orifice hole pitch was set equal to the fuel rod pitch, and the fuel module shapes fixed the overall shape of the orifices. Thus, only the flow hole size was varied in testing. However, the data obtained provide a significant number of points in the potential design space of triplate orifices.

A. Description of Test Assemblies

Three basic triplate orifice arrangements were tested: an infinite array configuration, a full scale representation of the combined standard blanket and power flattened blanket orifice, and a full scale representation of the reflector module orifice. These tests are designated RET-9 Phase I, II and III, respectively. In each test, orifices were tested with the three plates having the same hole diameters and with the three plates having hole diameter variations from plate to plate.

1. Infinite Array Orifices (RET-9 Phase I)

Infinite array orifices consisted of three circular, multiholed orifice plates. The plates were representative of either the blanket or reflector region orifices with respect to plate thickness, spacing, and flow hole pitch. All of the orifice configurations were clamped between the flanges of standard 6-inch pipe sections to form the test section as illustrated in Figure 5. Four sets of pressure taps were set in the 6-inch pipe. The taps were set 90 degrees apart and approximately 6 inches upstream and downstream of the orifice plates. The orifice pressure drop was measured with differential pressure cells.

Parts 1, 2 and 3 of the infinite array tests had the same hole diameter from plate to plate and within each plate (see Table 1). The hole diameter, used for all holes in each three-plate orifice, was changed for each of the test runs of Parts 1, 2 and 3. These orifices were representative of the LWBR blanket and reflector triplate orifices.

The second series of infinite array tests (Parts 4 and 5) investigated the pressure loss effects of varying the hole diameter from plate to plate. Part 4 and 5 test plates were representative of the blanket region orifice plates. This second series of tests was performed in two parts: one in which the diameter used for all 69 holes in the upstream plate was varied with respect to the diameter used for all holes in both the center and downstream plate; and one in which the diameter used for all 69 holes in the center plate was varied with respect to the diameter used for all holes in both the upstream and downstream plate. Table 2 summarizes these tests.

2. Full Scale Blanket Orifices (RET-9 Phase II)

The RET-9 Phase II series of tests was a full scale representation of an orifice used in the LWBR Type III blanket modules which contain both standard blanket and power flattened blanket rodded regions as shown in Figure 1.

The two regions contain rods on a 0.631-inch triangular pitch; however, the rods in the power flattened region are 0.526 inch in diameter while those in the standard blanket region are 0.571 inch in diameter. Since both of these core regions are in direct hydraulic communication and have different rod diameters, the coolant velocities are different in these regions. To avoid potentially large flow redistributions at the fuel region inlet and outlet, different orifice flow hole diameters between the standard and power flattened portions of the triplate orifice were required.

Figure 6 is a sketch of the orifice test vessel cross-section just above the triplate orifice. The middle region, labeled guide tube, represents the region containing the movable fuel and therefore received no flow in these orifice tests. Figure 6 also illustrates the boundary between the standard and power flattened blanket regions. Figure 7 shows the internal components of the orifice test section which include the triplate orifice and the entrance and exit pieces. The entrance and exit pieces represent the guide tube which houses the movable seed fuel assembly. The components shown in Figure 7 were inserted in a hexagonal housing designated as the upper and lower hex barrels in Figure 8. In some of the test runs, divider plates were used to separate the orifice exit flow of the standard region from that of the power flattened region.

Pressure drop measurements of the triplate orifice were obtained by differential pressure cells connected to six sets of pressure taps (three per region) located approximately 4 inches upstream and downstream of the triplate orifice. In addition, six velocity probes were placed approximately 5 inches downstream of the triplate orifices to measure the flow split. The flow split is the ratio of flow in the standard blanket region to the flow in the power-flattened blanket region.

The full scale blanket orifice test was run in two parts. Part 1 employed orifice plates having the same diameter in all holes from plate to plate as described in Table 3. The second part investigated the effects of plate to plate flow hole diameter variations as described in Table 4.

3. Full Scale Reflector Orifices (RET-9 Phase III)

The orifices in the RET-9 Phase III tests were full scale representations of the Type V Reflector inlet triplate orifice which is illustrated in Figure 9. Figure 10 shows a portion of the test section which includes an inlet insert and the bottom orifice plate of the triplate set. The inlet insert simulates the core reflector inlet geometry. Figure 11 shows the assembled inlet insert, the triplate orifice, and a trapezoidal shaped outlet insert to simulate the exit region of the orifice. This entire assembly was inserted in a hexagonal barrel. Static pressure taps were located approximately 1/2 inch upstream and 5 inches downstream of the reflector triplate orifice on three sides of the test vessel. Pressure drops across the orifice were monitored with differential pressure transducers.

The plates of each triplate orifice were 0.375 inch thick and were fastened together with a 0.625-inch space between plates. The flow holes of each plate were located on a 0.902-inch triangular pitch and the average number of holes per plate was 128. Table 5 summarizes the orifice hole configurations tested.

B. Orifice Test Procedure

All of the test sections described above were tested individually by connecting them to a cold water loop. The loop contained a variable speed centrifugal pump and a loop flow orifice. The water temperature was varied from approximately 80°F to 150°F. The loop flow rate was varied up to the maximum permitted by test section allowable pressure. Pressure drop measurements across the triplate orifices were made for various flow rates. In the

case of the full scale blanket triplate orifice (RET-9 Phase II) velocity measurements were also taken at each of the flow rates. In addition, loop temperature and loop orifice pressure drops were recorded. Flow visualization studies were performed for the full scale blanket and reflector orifice tests.

C. Data Reduction

The flow and orifice pressure drop data are used to calculate the pressure loss coefficient of the triplate orifice as follows:

$$K = \frac{\rho A^2 \Delta P}{2.236 w^2} \quad \text{Eq. 1}$$

where:

K = pressure loss coefficient (unitless)

ρ = water density (lb/ft³)

A = average flow area per plate of triplate (in²)

ΔP = triplate orifice pressure drop (psi)

w = orifice flow rate (lb/sec)

The average flow area per plate of the triplate orifice is calculated as follows:

$$A = \frac{N \pi d^2}{4} \quad \text{Eq. 2}$$

where:

N = average number of flow holes per plate

d = average flow hole diameter (inch)

$$= \sqrt{\frac{n_1 d_1^2 + n_2 d_2^2 + n_3 d_3^2}{n_1 + n_2 + n_3}}$$

d_1, d_2, d_3 = hole diameters (inch) of the three plates having
 n_1, n_2 and n_3 holes.

The average Reynolds number in the triplate is determined using the following equation.

$$Re = 5.5 \times 10^4 \left(\frac{w}{Nd\mu} \right)$$

Eq. 3

where:

Re = average orifice Reynolds number

μ = water viscosity (lbs/ft-hr)

The above equations were used to reduce the data from all of the orifice tests. In the case of the full scale blanket orifice test (RET-9 Phase II Part 1), three loss coefficients were calculated for each orifice. An overall pressure loss coefficient (K) was calculated using Equation 1 where A is the average flow area per plate of the triplate and w is the total orifice flow. Two additional loss coefficients were calculated, one for the standard region and one for the power flattened region. Each was calculated using Equation 1 with the average flow area and flow rate for the region of concern. The flow rate in the standard or power flattened region was determined from the velocity measurements taken in these tests using the following expression:

$$w = \left(\frac{A_T \rho}{62.16} \right) \sqrt{h}$$

Eq. 4

where:

w = flow rate in standard or power flattened region (lb/sec)

A_T = total flow area at the exit of the standard or power flattened region (inch²)

h = standard or power flattened region velocity head (inch)

For all of the tests, the loss coefficient was plotted as a function of area ratio. The area ratio was defined as the ratio of the average flow area per plate to the flow area just upstream of the orifice. In the case of the full scale blanket orifice test (RET-9 Phase II, Part 1) the area ratio was also calculated for both the standard and power flattened regions and

correlated with the individual region loss coefficient. In this case, the ratio is the average flow area of the standard or power flattened region divided by the upstream flow area of the individual region.

D. Orifice Test Results

For purposes of correlating the test data, the orifices were divided into two classes: those with plate to plate hole diameter variations of less than 10 percent, and those with variations of greater than 10 percent. For the first class, it was found possible to relate the orifice K to area ratio only. For the second class of orifices, the relationship between K and area ratio was found to be dependent on the relative differences in hole diameter from plate to plate and on which plate had varying hole diameters.

1. Plate to Plate Hole Diameter Variations Less than 10 Percent

The test runs having plate to plate hole diameter variations of less than 10 percent are tabulated below.

Test Runs Having Less than 10 Percent Plate to Plate Hole Diameter Variation

<u>RET-9 Test Designation</u>		<u>Run Numbers</u>
Phase I	Part 1	1 through 9
	Part 2	1 through 9
	Part 3	1 through 9
	Part 4	1A, 2B, 3C, 4D, 5E, 6F
	Part 5	1G, 2H, 3H, 3I
Phase II	Part 1	1 through 7
	Part 2	1 through 8
Phase III	-	1, 6

The results of these tests show that the loss coefficient is essentially independent of Reynolds' number. Typical examples of the variation are shown in Figure 12.

The pressure loss coefficients for these tests were found to vary with area ratio as shown in Figure 13 which contains the data for all of the runs tabulated above. As can be seen from the figure, the values for the loss coefficient rise at the low area ratio, level off, and then decrease at the higher area ratios. The curves rise at the lower area ratios because of the effect of decreased L/d ratio where L is the thickness of the orifice plate and d is the diameter of the flow hole. Thick plate orifice data (Reference 3) indicate an increasing pressure loss coefficient as L/d decreases below approximately 2.0.

The decrease in loss coefficient at the higher area ratios is because the flow holes of the center plate overlap with the flow holes of the other two plates of the triplate orifice. The overlapping of flow holes has a tendency to straighten the flow path through the orifice thereby decreasing the turning losses. Hence, the resulting decrease in loss coefficient with increases in area ratio.

The differences between the infinite array loss coefficients (RET-9 Phase I) and the full scale test loss coefficients (RET-9 Phase II and III) are believed to be a result of the cross-sectional geometric differences between the two types of tests. The infinite array tests were performed using circular plates in a pipe which yielded a circular orifice entrance and exit region cross section. As described in Section II.A.2 and 3, the entrance and exit region cross sections for the full scale tests were representative of the regions in the actual LWER core design.

Flow visualization studies of the full scale triplate orifice tests indicated the presence of vortices and random turbulence at the exit of the orifices. In the infinite array tests, the cross-sectional area is circular and does not induce any discontinuities which could cause similar flow patterns. Although these vortices in the full scale tests did not affect the static pressure drop readings, they do cause additional pressure losses which increase the triplate pressure loss coefficient (K). This is consistent with the results presented in Figure 13 which show a higher K for the full scale orifices than for the infinite array orifices. The full scale blanket test combined standard and power flattened regions with different hole diameters. This results in different hydraulic resistance between the two regions of the orifice which most likely induces cross flow within the orifice. Cross flow further increases the pressure loss coefficient relative to the infinite array orifices which have uniform hydraulic resistance.

When comparing the reflector infinite array and full scale tests at the same area ratio, the full scale test has a larger hole diameter. This results in a smaller L/d and therefore a higher pressure loss coefficient than in the infinite array test.

The reflector triplate orifice models have higher pressure loss coefficients than the blanket design models. This is as expected because the flow hole pitch in the reflector orifice (0.902 inch) is greater than the pitch in the blanket orifice (0.631 inch). The larger flow hole pitch of the reflector orifice results in greater turning losses and thus a higher K .

Figure 14 presents the three pressure loss coefficients described in Section II.C for RET-9 Phase II Part 1. As can be seen from the figure, the total loss coefficient and the individual region loss coefficients correlate well with the flow area ratio.

2. Plate to Plate Hole Diameter Variations Greater Than 10 Percent

The following table provides a listing of the test runs which fall into this second class of orifices.

Test Runs Having Greater Than 10 Percent Plate to Plate Hole Diameter Variation

<u>RET-9 Test Designation</u>		<u>Run Numbers</u>
Phase I	Part 4	All runs except 1A, 2B, 3C, 4D, 5E, 6F (see Table 2)
Phase I	Part 5	All runs except 1G, 2H, 3H, 3I (see Table 2)
Phase III		2 through 5

Figure 15 shows the variation in the pressure loss coefficient versus Reynolds number for typical runs in the Phase I Part 4 test series. The pressure loss coefficients in these figures, and all other loss coefficients discussed in this section, were calculated using a constant average flow area per plate of 10 square inches rather than the actual average flow area per plate. Using a constant flow area to calculate the loss coefficient clearly illustrates the variation in triplate orifice hydraulic resistance for each orifice tested. Hydraulic resistance is defined as the loss coefficient divided by the square of the flow area. The Reynolds numbers shown in Figure 15 are the average Reynolds numbers in the triplate orifice and are calculated using the average flow hole diameter of the triplate.

As can be seen from Figure 15 and Table 2, the pressure loss coefficient tends to vary more with respect to Reynolds number as the hole diameter difference between the upstream plate and the two downstream plates increases. This variation of pressure loss coefficient with respect to Reynolds number decreases as the flow hole diameter of the upstream and two downstream plates become more nearly the same.

Figures 16 and 17 present all of the loss coefficients for the runs identified in Table 2 and Table 5 plotted as a function of area ratio. These runs include all tests which have greater than 10 percent plate to plate hole diameter variation. The K's were based on a Reynolds number of approximately 1.0×10^5 . Each of the curves in Figures 16 and 17 show the same general sensitivity to flow area ratio. As the area ratio increases the hydraulic resistance of the orifices decreases and tends to approach an asymptotic value. However, it is also seen that area ratio is not the only correlating parameter since one value of area ratio yields several different values of hydraulic resistance. These different values result from (a) differences in the relative size of hole diameters from plate to plate, and (b) differences in which plate had varying hole diameters. The effect of item (a) can be generalized to say that for orifices having the same area ratio, the hydraulic resistance of the orifices increases as the difference in hole diameter from plate to plate increases. Item (b) can be demonstrated by comparing runs 5B and 4G of Table 2. Both orifices have the same area ratio and the same variation in plate to plate hole diameters; however, the loss coefficient (based on an area of 10 in.²) for run 5B is 6.9 versus 6.1 for run 4G.

Figure 18 is a plot of pressure loss coefficient (K) versus flow hole diameter of the orifice plate with the varying flow hole size. These curves illustrate that starting with all plates of the same hole diameter increasing the flow hole size of all three plates decreases the orifice hydraulic resistance at the fastest rate; increasing the flow hole size of the two downstream plates decreases the resistance the next fastest; while increasing the flow hole size of the center plates decreases the resistance at the slowest rate.

In summary, the triplate orifice pressure loss coefficients were found to be more sensitive to Reynolds number as the difference in hole diameter

among the three plates increases. In addition, the orifice hydraulic resistance (K/A^2) decreases with increasing average flow area ratio (due to both a reduction in K and an increase in A) and increases as the hole diameter difference from plate to plate increases for a constant average flow area ratio. Also for orifices having the same average flow area ratio and the same variation in plate to plate hole diameters, the hydraulic resistance was found to depend on how the hole diameters were distributed from plate to plate.

These tests provided basic information used in the design of the LWBR core orifice plates. Once the required core flow distribution (Reference 4) was established the hydraulic loss data presented herein was used in establishing the orifice hole diameters.

III. FLOWMETER TESTS

The LWBR flow venturi meters contain a number of individual venturis in parallel. The static pressures of the venturis are manifolded to provide an average static pressure measurement. This particular design provides an adequate coolant velocity increase for measurement purposes while at the same time provides a low overall pressure loss coefficient and uniform flow distribution. Due to the uniqueness of these flowmeter designs, flow tests were performed for a seed flowmeter and a Type III blanket flowmeter to determine the flow coefficients and pressure loss characteristics. The tests simulated the flowmeter inlet and exit configurations as they exist in the LWBR core. The core flowmeters are illustrated in Figure 19.

A. Description of Test Assembly

The seed flowmeter test model, designated RET-10 Phase I, consisted of a simulated reactor vessel inlet baffle plate, prototypic seed strainer plate, prototypic seed flowmeter, and a simulated guide tube extension. A schematic of the test model is shown in Figure 20. The simulated inlet baffle plate was 2.5 inches thick and contained nineteen 1.81-inch diameter flow holes located

on a 2.7-inch triangular pitch. The prototypic strainer plate, as shown in Figure 21, was 0.38 inch thick and contained 914 0.250-inch diameter flow holes located on a 0.33-inch triangular pitch. The prototypic seed flowmeter, shown in Figure 22, contained seven venturis, each having a throat diameter of 1.82 inches. The simulated guide tube, which provides a path for the movable fuel in the core, is shown in Figure 23. This tube was 14.7 inches long with an internal across flats dimension of 10.2 inches.

The five pressure tap elevations shown in Figure 20 were instrumented with differential pressure cells. Elevations 1, 4 and 5 each had three manifolded pressure taps. Elevation 2 had 12 manifolded pressure taps while elevation 3, which was located at the throat of the venturis, had seven manifolded pressure taps.

The blanket flowmeter test model, designated RET-10 Phase II, is shown in Figure 24. This test included a simulated bottom plate extension, a full scale Type III module blanket flowmeter, a simulated bottom plate, and a simulated blanket guide tube. The simulated bottom plate was 3.12 inches thick and contained 34 holes, each having a diameter of 1.37 inches. These holes lined up with the individual venturis in the flowmeter. The flowmeter consisted of 34 venturis with 1.024-inch nominal throat diameters. The blanket flowmeter and the simulated bottom plate are shown in Figures 25 and 26.

The blanket flowmeter test instrumentation consisted of six upstream and six downstream pressure taps, and two pressure taps sensing pressure from manifolds internal to the flowmeter. These two manifold taps were prototypic and yielded the pressure drop used for determining the meter coefficient. The manifolded pressures are obtained from 23 inlet flowmeter pressure taps and from the 24 throat pressure taps for those venturis located around the outer periphery of the flowmeter.

B. Flowmeter Test Procedure

The seed and blanket flowmeter test sections were individually flow tested by connecting them to a hot water and a cold water loop, respectively. The flow rate through the seed flowmeter test model was varied from approximately 100 to 400 lbs. mass/sec. for loop water temperatures of approximately 100, 350, and 520°F. Water temperature, pressure drop across the seed flowmeter, and pressure drop across a calibrated loop flow orifice were recorded for each flow rate. The flow rate through the blanket flowmeter was varied from approximately 80 to 500 lbs. mass/sec. while monitoring the loop temperature and model and loop flow orifice pressure drops. The water temperature varied from approximately 70°F to 100°F.

C. Data Reduction

The test data were used to determine the component pressure loss coefficients and the flowmeter flow coefficients. For the seed test, the pressure loss coefficient was determined for both the seed strainer plate and the flowmeter. In the blanket test, a pressure loss coefficient was determined for the flowmeter and the bottom plate. The loss coefficients were calculated using the following equation:

$$K = \frac{\rho A^2 \Delta P}{2.236 w^2} \quad \text{Eq. 4}$$

where:

K = pressure loss coefficient (unitless)

ρ = water density (lb/ft³)

A = venturi throat flow area (in.²)

= 18.2 (seed test)

= 28.0 (blanket test)

ΔP = component pressure drop (psi)

w = total mass flow rate through the flowmeter (lb/sec.)

The meter coefficient was calculated from the following expression

$$C = 1.495 \frac{w}{A} \left(\frac{1}{\sqrt{\rho \Delta P_{FM}}} \right) \quad \text{Eq. 5}$$

where :

C = the meter flow coefficient (unitless)

w, ρ , A defined above

ΔP_{FM} = static pressure drop from flowmeter entrance to the
throat of the venturi (psi)

The meter coefficient was determined as a function of the meter Reynolds number defined as follows

$$Re = 5.5(10^4) \frac{w}{nD\mu} \quad \text{Eq. 6}$$

where :

n = number of venturis in flowmeter

= 7 (seed test)

= 34 (blanket test)

D = venturi throat diameter (in.)

= 1.82 (seed test)

= 1.024 (blanket test)

μ = water viscosity (lb/ft-hr)

D. Flowmeter Test Results

1. Seed Test

Figure 27 shows the seed flowmeter and strainer plate pressure loss coefficient versus Reynolds number. The loss coefficient was calculated using the pressure drop P_1 to P_5 as designated in Figure 20. It is noted that the flowmeter pressure drop recovers approximately 20 percent in the guide tube extension region. This is demonstrated by the fact that the flowmeter and strainer plate pressure loss coefficient obtained using pressure P_4 (see

Figure 20) is approximately 20 percent greater than the loss coefficient obtained using pressure P_5 as is shown on Figures 28 and 27, respectively.

Figure 29 shows the seed flowmeter flow coefficient (C) for all test operating temperatures as a function of Reynolds number. The seed flowmeter flow coefficient, which represents a measure of the ratio of the actual weight rate of flow to the theoretical weight rate of flow, increased with Reynolds number but is always less than 1. The non-recoverable static pressure differential (P_1-P_5) across the seed flowmeter was on the order of 20 percent of the flowmeter signal pressure differential (P_2-P_3). The permanent pressure loss across a typical venturi flowmeter is normally expected (Reference 5) to be between 10 and 20 percent of the signal pressure differential.

2. Blanket Test

Figure 30 presents the overall pressure loss coefficient for the blanket flowmeter and simulated bottom plate as a function of the throat Reynolds number. Figure 31 presents the resulting flowmeter flow coefficient versus Reynolds number.

Another LWBR hydraulic test containing a blanket flowmeter showed that an audible noise was generated by the flowmeter. The noise resulted from the downstream edge configuration of the throat pressure taps in conjunction with the Helmholtz type resonator system of the manifolded pressure taps. The downstream edge of the throat pressure taps were chamfered eliminating the noise. The chamfer was 0.03 inch by 45 degrees for the 0.09-inch pressure tap holes. Calibration tests were subsequently rerun using the RET-10 Phase II model and demonstrated that the modified pressure tap has an indiscernible effect on the flowmeter flow coefficients shown in Figure 31.

In summary, testing demonstrated that multi-venturis in parallel can be used to accurately measure flow rates while maintaining a low non-recoverable pressure loss. These test results were used in establishing calibration curves for the LWBR in-core flowmeters.

IV. GRID AND FUEL ROD HYDRAULIC RESISTANCE TESTS

Two basic grid designs considered during the LWBR development program are discussed herein. Various grids of each design were hydraulically tested during the program. These tests provided an experimental basis for the establishment of the hydraulic loss coefficients used in thermal and hydraulic analyses. In addition to providing experimental grid loss coefficients, these tests also provided data useful in qualifying the rodded region friction factor model.

A. Description of Test Assembly

Three basic grid tests with the following geometrical conditions are discussed in this section:

<u>Grid Test Designation</u>	<u>No. of Cells in Grid</u>	<u>Cell Pitch (triangular), inch</u>	<u>Rod Diameter, inch</u>
RET-11 Phase I	798	0.325	0.255
RET-11 Phase III	619	0.369	0.305
RET-11 Phase II	187/446	0.631	0.571/0.526

The Phase III and II grids were representative of the LWBR seed and blanket regions respectively. The Phase I grid represented one of the earlier seed region design concepts.

1. RET-11 Phase I

Each of the ten grids used in this test was composed of two sets of straps, one at both the bottom and top of the grid, held together by vertical tie bars as shown in Figures 32 and 33. Figure 33 is a picture of the Phase I grid with part of the total number of rods inserted in the grid. The 798 cells in each grid were located on a 0.325 nominal triangular pitch. The 0.255-inch diameter rods were held by means of a spring and four fixed dimples at each grid level. The grid geometrical characteristics are summarized in Table 6.

Figure 34 shows the assembled RET-11 Phase I rod bundle inside a hexagonal support shell. The rodded assembly was approximately 10 feet long and contained 10 grids on an axial spacing ranging from 10.75 to 12.80 inches. The grids were held in place by six support posts which were attached to the hexagonal support shell. Approximately half of the 117-inch long rods were secured at their top end by a top baseplate while the other half were attached at their bottom end by a bottom plateplate.

The support shell had an across flats outside dimension of 9.620 inches. The assembly, shown in Figure 34, was inserted inside an acrylic hexagonal pressure vessel whose across flat inside dimension was 9.815 inches. These two components formed an annular gap of approximately 0.0975 inch around the grid-fuel rod assembly. The support shell had twelve 1.0-inch diameter holes located between any two grid levels and between the last downstream grid level and the top baseplate. These holes minimize the pressure differential across the shell. Figure 35 shows the entire test assembly and associated instrumentation setup. Forty of the rods were instrumented to measure the pressure drop across the grids and along the rods.

2. RET-11 Phase III

Two of the three grids used in this phase of testing were representative of the LWBR core seed grids. All three of the grids were made of half-hex elements which were held together by brazed pinned joints. These half-hex elements and the grid assembly are illustrated in Figures 36 and 37. When assembled, each grid cell locates and supports a 0.305-inch diameter fuel rod by means of a spring constraining the rod onto four fixed dimples. Three half-hex grids were tested and are designated as grids No. A, No. 1 and No. 10.

Grid No. A was developmental and was composed of non-prototypic half-hex elements having a material thickness of 0.012 inch. Many of its as-manufactured dimensions were non-prototypic. The most noteworthy non-prototypic

characteristics were the large across-flats dimension and several non-uniform cells. Furthermore, there was some braze crudding in the pin joints between the individual half-hex elements. "Braze crudding" refers to an overflow of braze from the half-hex pinned joints. The braze covers the surface of the grid and increases the piece thickness, decreases the flow area and potentially increases the surface roughness.

In order for the oversized grid No. A to be installed in the test section, approximately 0.040 inch of the vessel internal wall material at the bottom end of the test section had to be removed.

Grid No. 1 had a grid material thickness of 0.014 inch. Some braze crudding was present but was not considered to be significant. Grid No. 10 had a grid material thickness of 0.014 inch. The across-flats dimension showed little variation but was somewhat undersize. The geometrical characteristics for each grid are summarized in Table 6.

The RET-11 Phase III seed grid test assembly is shown in Figure 38. The test section vessel was a hexagonal tube approximately three feet long with an inside across flats dimension of 9.438 inches. The test assembly contained two grids which were held in place by six support posts. The support posts were attached to the vessel wall. The rods were secured at their ends by the top and bottom baseplates.

Two assemblies were tested. In assembly No. 1, grid No. A and grid No. 1 were located in the lower and upper test positions respectively with the axial spacing between grids being 16.7 inches. Assembly No. 2 was tested with grid No. 1 in the lower position and grid No. 10 in the upper position. The spacing between grids was also 16.7 inches.

Static pressure taps were located axially approximately every inch along each of three-hex sides of the test vessel. Pressure drop across the grids and along the length of the rods were monitored with differential pressure cells.

3. RET-11 - Phase II

The grids used in this test were representative of the LWBR Type III blanket region. The Type III blanket region is comprised of 187 0.571-inch diameter rods and 446 0.526-inch diameter rods. All rods are contained in an open hydraulic triangular pitch matrix of 0.631 inches. These grids were constructed from half-hex components, as shown in Figure 39, in essentially the same manner as the half-hex seed grids. Each cell had one spring and two fixed dimples all located in the same axial plane.

Two Type III blanket grids were used for this test program. These grids, designated Nos. 3001 and 3002, are described in Table 6.

The test model consisted of two grids, 633 solid stainless simulated fuel rods, grid support posts, upper and lower base- and cover plates, various flow dividers and separators (that modeled the LWBR inlet/exit flow geometry), the inner boundary blanket guide tube, and an outer hex flow boundary. A schematic of the test model is shown in Figure 40. The model pressure vessel was constructed of fiberglass while the baseplates, cover plates, and flow separators were constructed from acrylic material. Vessel dimensions are tabulated in Table 6. Photographs of several of the test model components are shown in Figures 41 through 43.

Two assemblies of the model were tested. In assembly No. 1, grid No. 3001 was in the bottom location while grid No. 3002 was in the top location. In assembly No. 2, the grids were reversed. This second assembly was run to confirm inlet and exit effects detected in the first test and to check data consistency with the RET-11 Phase III seed grid flow test.

Static pressure taps were located axially at seventeen locations along the test section. At each axial station, eight taps were located azimuthally around the vessel. Pressure drops were monitored with differential pressure

cells. A picture of the grid test assembly and the entire test assembly is shown in Figures 44 and 45, respectively.

B. Rod and Grid Test Procedure

The test assemblies were connected to water circulating loops. Water temperatures of approximately 75°F to 150°F were monitored and maintained. Loop flow was obtained with a centrifugal pump with test assembly flow rates varied by means of a butterfly valve and variations in pump speed. The test assembly flow rates were measured by means of calibrated loop orifices.

C. Data Reduction

The friction loss data for the rods in areas without grids were reduced to friction factors using equation (1).

$$f = \frac{144 \Delta P_f}{W^2} \frac{2g \rho A^2}{L_f} \frac{D_H}{L_f} \quad \text{Eq. 1}$$

where:

f = Friction factor (unitless)

ΔP_f = Rodded region pressure drop (psi)

$g = 32.17 \text{ ft/sec}^2$

ρ = Water Density (lb/ft³)

A = Total rodded region flow area (ft²)

D_H = Rodded region hydraulic diameter (ft)

L_f = Distance between ΔP_f taps (ft)

W = flowrate (lb/sec). In RET 11 - Phase II and III, the flow rate

used for determining rod friction and grid pressure loss coefficients was the measured loop flow rate. Whereas in RET-11 Phase I, the flow rate was the difference between the measured loop flow and the analytically determined flow rate through the annulus formed by the shell and the pressure vessel.

The grid loss coefficient was determined with equation 2.

$$K_G = \frac{144 \Delta P_G}{W^2} - \frac{2g \rho A^2}{D_H} - \frac{f L_G}{D_H} \quad \text{Eq. 2}$$

where:

K_G = grid loss coefficient

ΔP_G = pressure drop across the grid including a length (L_G) of the rodged region (psi)

L_G = distance between pressure taps (ft)

The grid loss coefficient (K_G) does not include any rod friction loss and is based on the total rodged region (non-gridded) flow area. The Reynolds number for the rodged region was calculated via equation 3.

$$N_{RE} = \frac{3600 W}{\mu} \frac{D_H}{A} \quad \text{Eq. 3}$$

where:

N_{RE} = rodged region Reynolds number

μ = liquid viscosity (lb/ft-hr)

3600 = conversion factor (sec/hr)

D. Rod and Grid Test Results

1. Rodded Region Friction Factor

Figures 46 through 50 present the rodged region friction factors as a function of Reynolds number for the three phases of the RET-11 test. Also shown on the figures are the Moody friction factor curves and the Moody friction curves times 1.1. The Moody curves are based on relative surface roughnesses of 0.0002, 0.00044, and 0.00027 for Phases I, III and II respectively.

In all tests, the data generally fall above the Moody curve. At the higher Reynolds numbers, the rodged region friction factor data are nearly bounded by the Moody curve and 1.1 times the Moody curve. These trends are consistent with other published data concerning friction factors in rod

bundles, such as that summarized in Reference 6. At the low Reynolds number, there is somewhat more scatter of the data and less agreement with the 10 percent spread on the Moody friction factor than at the high Reynolds numbers. This region of low Reynolds number corresponds to low pressure differentials across the rods where the instrumentation is least accurate resulting in more scatter in the data. It is also noted that in Phase I the friction factor data (see Figure 46) were reduced using a measured total flow rate analytically adjusted for the annulus flow rate. This was necessary because the annulus flow (approximately 15 percent of total flow) bypassed the test section but was measured in the loop flow.

2. Grid Loss Coefficients

a. RET-11 Phase I

Grid loss coefficients are shown for three of the ten grid levels in Figures 51, 52 and 53. The strap-and-tie bar design exhibits rising loss coefficient with an increasing Reynolds number. The loss coefficient attains a constant value at a relatively-low Reynolds number of 2.5×10^4 . This is unlike the half-hex design loss coefficients discussed below. The reason for these characteristics is believed to be that the form losses are more predominant than friction for the Phase I test grid design. As shown in Figure 33, there is very little grid material located over the middle 80 percent of the grid length. This would tend to maximize the form losses and minimize friction losses. That is, the grid design had, in effect, two inlet and exit losses per grid versus only one of each for the half-hex grid. The average grid loss coefficient for the ten grids is 2.34 at a Reynolds number of 4×10^4 .

b. RET-11 Phase III

The grid pressure drop-flow data are presented as hydraulic loss coefficients in Figures 54 through 57 as a function of the rodded region Reynolds number. The entrance-grid loss coefficients, shown on Figures 54 and 56, are slightly smaller than those located in the fully developed flow regions shown on Figures 55 and 57. This phenomenon is explicitly demonstrated by Grid No. 1 which was inserted at each of the two positions. The lower loss coefficient for the entrance grid is likely the result of the larger grid boundary flow area caused by removing part of the vessel surface to accommodate the No. A Grid. However, the undeveloped flow region upstream of the entrance grid can also impact on the measured loss coefficient. The entrance effect is exhibited by both Grid No. A and Grid No. 1 which indicates it is not a strong function of the quality of grid construction.

The data show in each case that the grid loss coefficient has a Reynolds number dependency which becomes less significant at the higher Reynolds numbers ($>7 \times 10^4$). Based on the nominal grid surface roughness of 20 μ in. and the gridded region Reynolds number, the grid friction loss is still decreasing because the region of complete turbulence has not been attained. Inspection data for surface roughness were taken for clean and braze-covered regions in typical grid sections. The surface roughness for the braze-covered regions varied from 44 to 135 μ in. with an average value of 77 μ in. The clean regions of the grid had surface finishes ranging from 10 to 40 μ in. with an average value of 20 μ in.

c. RET-11 Phase II

Figures 58 through 61 show the measured grid pressure loss coefficients versus Reynolds number for both grid assemblies. The results were that both grids, when located at the same axial elevation, had the same pressure

loss coefficient, indicating that differences in grid construction between No. 3001 and No. 3002 did not produce measurable hydraulic differences. For each test assembly, the grid in the lower test location showed a loss coefficient approximately 10 percent higher than the grid in the top location presumably due to entrance effects.

In conclusion, grid hydraulic testing showed that all grids of a given type have nearly the same pressure drop characteristics independent of local differences in geometry with the possible exception of the upstream grid which is influenced by entrance effects. Testing also showed that the grid design influences the pressure loss coefficient magnitude as well as the pressure loss coefficient dependency with Reynold Number. Measured rod friction data generally exceed the Moody friction curves. These data were used in the qualification of the rodded region friction model. The grid loss coefficient data were used to predict the core hydraulic characteristics.

V. EFFECT OF ROD FREE END PROXIMITY ON BASEPLATE PRESSURE/LOSS COEFFICIENT

A hydraulic test was performed to determine the sensitivity of the baseplate pressure loss coefficient to the proximity of the free end of the fuel rod. The basic test configuration of the baseplates and 0.255-inch diameter fuel rods is illustrated in Figure 62. Four of the test section rods were top mounted while the other six were bottom mounted. The baseplate flow hole diameter was 0.260 inch and was located either directly upstream or downstream of the rod free end depending on the type of rod mounting. Maximum misalignment between the rod free end and the flow hole in the baseplate was 0.030 inch. The length of the test bundle was approximately 45 inches.

Top mounted rod free ends were used as the variable in changing the clearance (designated by δ in Figure 62) with the baseplate flow holes. Baseplate pressure drop was recorded while the flow rate through the test section was

varied. The test was conducted at ambient temperature and approximately 60 psia conditions. The three clearances which were tested were 0.6, 0.2 and 0.075 inch with the two largest clearances resulting in nearly the same pressure drop across the baseplate. However, the pressure drop through the baseplate increased as the clearance was changed from 0.2 to 0.075 inch. These results are shown on Figure 63. Thus for a 0.255-inch diameter fuel rod, a minimum clearance of approximately 0.2 inch is required to maintain a constant pressure loss coefficient. Since this minimum clearance is approximately the same magnitude as the rod diameter, it was concluded that a conservative approach would be to maintain an equivalent rod diameter clearance between the rod free end and the baseplate at all times in reactor life.

VI. PISTON LABYRINTH SEAL TESTS

The piston serves a two-fold purpose of (1) providing a downward hydraulic force on the movable fuel assembly for scrambling, and (2) providing for the slowing down of the scrambled movable fuel assembly to achieve the desired impact velocity. Both purposes, which are described in detail in Reference 2, are functions of the piston pressure loss coefficients.

The piston, Figure 64, consists of (1) a 10-inch diameter balance (upper) piston, and (2) a 5-inch diameter (lower) buffer piston. Figure 65 shows schematically three characteristic elevations of the piston. The first sketch shows the piston disengaged from both the upper and lower buffer cylinders. The second sketch shows the balance piston partially engaged with the upper buffer cylinder, and the buffer piston disengaged from the lower buffer cylinder. The third sketch shows both the balance and buffer pistons fully engaged in their respective buffer cylinders. These three configurations represent the positions where the nominal, maximum and minimum downward hydraulic forces occur on the movable fuel assembly. The variation of downward hydraulic force with piston

elevation is related to changes in engagement of the piston with the buffer cylinders. Additional details relating to the hydraulic forces as a function of piston elevation are provided in Reference 2.

Two basic flow tests were performed to determine the pressure loss coefficients of the piston at these three characteristic elevations. The two tests are designated RET 15 Phase I and Phase II. Phase I determined the sensitivity of the pressure loss coefficient to (1) the radial clearance between the piston and its annular mating components consisting of the compression sleeve and buffer cylinders, and (2) the land to pitch ratio of the balance piston labyrinth. Phase II testing determined the sensitivity of the pressure loss coefficient to the eccentricity of a prototypic piston with respect to its annular mating component.

Phase I and II test data enable definition of a design minimum and maximum pressure loss coefficient for the three characteristic elevations. These coefficients account for manufacturing and assembly tolerance on radial clearance and eccentricity. The range of piston hydraulic resistances and their effect on movable fuel assembly scram characteristics are described in Reference 2.

A. Description of Test Assembly

1. RET-15 Phase I

Figure 66 shows a schematic of the Phase I test model. The model was fabricated such that the balance piston and buffer piston were individual components, either of which could be easily removed from the assembly. Therefore, tests could be run either on the balance piston or buffer piston as individual components or with both components combined as shown in Figure 66. An upper and lower alignment block was used to maintain the pistons in the center of the flow housing. These blocks were unique to the test and were designed

(subsequently confirmed by testing) to have a negligible hydraulic resistance so as not to influence the piston resistance.

The assembly shown in Figure 67 consisted of the pistons, alignment blocks and shafts. The assembly could be vertically moved over a 16-inch travel. The lowest position corresponded to characteristic elevation No. 3, identified in Figure 65, wherein the bottom surface of the balance piston rested on the top surface of the lower buffer cylinder. The highest position, wherein the bottom surface of the balance piston was 16 inches above the top surface of the lower buffer cylinder, corresponds to characteristic elevation No. 1 identified in Figure 65.

Tables 7 and 8 along with Figures 68 and 69 summarize the range of physical dimensions tested.

2. RET-15 Phase II

Figure 70 shows a schematic of the RET-15 Phase II test model. The model consisted of a prototype piston, and a simulated compression sleeve, upper buffer cylinder and lower buffer cylinder. Pertinent component dimensions and pressure tap locations are shown on Figure 71.

a. Piston and Supporting Assembly

Figure 64 shows the piston (made of Type 348 corrosion resistant steel) used in testing which contained an average as-built balance piston diameter of 10.012 inches and an average as-built buffer piston diameter of 4.800 inches. The balance piston overall length was 13.50 inches. Eleven inches of this length contained labyrinth lands and grooves being nominally 0.250 and 0.375 inches wide respectively. Upper and lower rubbing pads were contained on the remaining length. The balance piston labyrinth land edge radius of curvature was between 0.002 and 0.003 inch. As shown on Figure 64, the buffer piston had a smooth, 5.35-inch long, cylindrical surface.

A simulated LWR seed support shaft and tie rod was used to support the piston. The free ends of the two shafts were each located in a support sleeve which in turn were radially supported by three adjusting screws spaced 120 degrees apart. These screws were used to adjust the piston to compression sleeve radial clearance and were unique to the test.

b. Compression Sleeve and Upper Buffer Cylinder

The average as-built inside diameter of the compression sleeve and upper buffer cylinder was 10.075 and 10.056 inches respectively. The compression sleeve was approximately 35.5 inches long, 12 inches of which comprised the upper buffer cylinder. Figure 72 shows an internal view of the compression sleeve in which the upper buffer cylinder is in the foremost region of the figure. This component was fabricated from 304 CRES.

c. Lower Buffer Cylinder

The lower buffer cylinder shown in Figure 73 was fabricated from 304 corrosion resistant steel and had an average labyrinth land internal diameter of 4.864 inches and an overall length of 5.50 inches. The labyrinth land and groove width were nominally 0.225 and 0.375 inch respectively with a labyrinth edge radius of curvature between 0.001 and 0.003 inch. The groove depth was 0.25 inch.

B. Piston Test Procedure

1. Phase I

A given piston configuration would be assembled and lowered into the sleeve. Test variables were piston, geometry, loop flow rate and vertical position of the piston in the compression sleeve. A typical test series consisted of taking two data sets at each of approximately five flow rates for as many vertical positions as were physically interesting for that particular piston arrangement.

This test was conducted in a low temperature, low pressure facility. Two orifice meters, set in accordance with ASME standards, were used to measure flow in the loop. Flow was regulated by means of a valve located upstream of the test section.

2. Phase II

Table 9 summarizes the piston elevation and radial location for each of the six configurations which were tested. Due to manufacturing tolerances and the radial positioning technique, it was not always feasible nor practical to position the balance piston exactly concentric or completely eccentric. Eccentricity measurements were taken both before and after flow testing to insure that the piston was not displaced during the test. Eccentricity was measured using a depth gage positioned through the compression sleeve pressure taps. If a significant difference was noted, the test was repeated. For each test configuration, the flow rate past the piston was varied for loop water temperatures of approximately 100, 200, 350 and 500°F. The flow rate was measured using a 1.626-inch orifice located upstream of the test section.

C. Data Reduction

Hydraulic pressure loss coefficients (K) and resistances (R) were calculated using Equations (1) and (2) respectively.

$$K = \frac{\rho g A_f^2 \Delta P}{72 w^2} \quad \text{Eq. (1)}$$

$$R = \frac{144K}{2 \rho g A_f^2} \quad \text{Eq. (2)}$$

Reynolds numbers (Re) were calculated using Equation (3).

$$Re = \frac{17.28 \times 10^4 w}{\mu w_p} \quad \text{Eq. (3)}$$

where:

ρ = density (lb/ft³)

g = 32.2 (ft/sec²)

A_f^2 = annular gap flow area (in.²)

ΔP = pressure differential (psi)

w = mass flow rate (lbs/sec)

μ = viscosity (lb/ft-hr)

W_p = wetted perimeter (inches)

D. Piston Pressure Loss Coefficient Results

1. Phase I

Figure 74 shows a typical plot of balance piston hydraulic resistance versus Reynolds number based on the annular gap (radial clearance) flow area of the piston. From this plot it can be seen that typical Phase I Reynolds numbers were on the order of 5,000 to 30,000, and that the data cannot be adequately represented by a straight line. This non-linear data is due to the increased friction component of the hydraulic resistance at low Reynolds number. All data was therefore plotted in a manner similar to Figure 74 and extrapolated to $Re = 30,000$. All resistances contained in this section correspond to a gap Reynolds number of 30,000.

Figure 75 shows the effect of the radial clearance and labyrinth land to pitch ratio (L/P) on balance piston hydraulic resistance. This is the resistance across the balance piston only when the piston is located 16 inches above the top surface of the lower buffer cylinder. The plot in Figure 75 shows the expected result that the hydraulic resistance is primarily dependent on $1/A_f^2$. The effect of L/P ratio on resistance is sufficient to shift the curves slightly. It can be seen that for the range of radial clearances tested, the resistance generally increases with decreasing L/P , indicating that a larger labyrinth cell (and shorter land length) generates more hydraulic loss.

Figure 76 shows the experimentally determined hydraulic resistance versus radial clearance for the buffer piston in the zero-inch position. The balance piston was not part of the test assembly. Radial clearance was the only parameter varied for the buffer piston study.

Figure 77 shows the hydraulic resistance of both pistons over the full 16 inches of travel. This sequence of tests confirmed the linear relationship between the resistance and percent of piston displacement into the buffer zone. These results also confirm that the hydraulic resistances are additive for the pistons tested together.

2. Phase II

Figures 78 through 83 show the balance and buffer piston pressure loss coefficients as a function of Reynolds number for each of the six test configurations outlined in Table 9. The loss coefficient nomenclature is in terms of the pressure tap designation identified in Figure 71. For example, K_{14} represents the loss coefficient obtained using the pressure drop from pressure tap P_1 to P_4 . The hydraulic resistance of the buffer piston in test configurations 1, 2, 4 and 5 was too small to be measured since the buffer piston was not engaged in the lower buffer cylinder.

Table 10 shows a comparison, based on a mean statistical log-log regression analysis of the data obtained for the higher temperature runs, of concentric and eccentric balance and buffer piston pressure loss coefficients. The concentric pressure loss coefficients were higher than the corresponding eccentric pressure loss coefficients. The relatively small pressure loss coefficient differences between Tests 2 and 5 as compared to Tests 1 and 4 and Tests 3 and 6 are a result of the balance piston not being as eccentric in Test 5 (see Table 9).

In summary, balance piston hydraulic testing enables defining the effects of radial clearance, land to pitch ratio, eccentricity and elevation, on the pressure loss coefficients. These pressure loss coefficients were in turn used to determine the LWBR movable fuel assembly scram characteristics as summarized in Reference 2.

VII. SUMMARY

Hydraulic tests of special triplate orifices were used to define the orifice hydraulic resistance as a function of plate hole size for various fixed geometric characteristics. The fixed geometric characteristics included plate thickness, plate-to-plate spacing, and boundary configuration. The orifice resistance was found to:

1. Decrease with increasing area ratio*
2. Increase with increasing difference in hole diameter from plate to plate for a fixed area ratio*
3. Depend on how the variable hole diameters were distributed from plate to plate.

Hydraulic tests also demonstrated that multi-venturi flowmeters could be used to accurately measure flow and at the same time have a low overall non-recoverable pressure loss. Both the meter coefficient and the hydraulic resistance were determined for flowmeters representative of those used in LWBR.

Tests of full size LWBR modules were used to define rodded region friction factors and support grid hydraulic resistances. The rodded region friction factors were found to be greater than those predicted from the Moody curves. The grid pressure loss coefficients were determined for three types of grid

*Area ratio was defined as the ratio of the average flow area per plate to the flow area just upstream of the orifice.

designs. The grid design was found to affect the dependency of the grid pressure loss coefficient on the Reynolds number. In addition, it was found that for a given grid design the pressure loss coefficient was independent of local geometric differences and was influenced by entrance region effects.

The pressure loss coefficient of LWBR type baseplates was determined as a function of proximity to the rod free end. For baseplates having hole diameters approximately equal to the rod diameter, the baseplate loss coefficient is independent of the rod proximity for clearances greater than the rod diameter. At smaller clearances, the baseplate loss coefficient increases.

Tests of the LWBR balance piston design determined the balance piston hydraulic resistance as a function of (1) piston to cylinder radial clearance, (2) eccentricity, (3) labyrinth land to pitch ratio, and (4) piston elevation. These data were used in determining the steady state and transient operating characteristics of the LWBR movable fuel.

VIII. ACKNOWLEDGEMENT

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5 TABLE 1. INFINITE ARRAY TRIPLATE ORIFICE TESTS (RET-9 PHASE I)
(All three plates in each orifice have the same diameter for all holes)

<u>Test Orifice Description</u>	<u>Test Designation</u>	<u>No. of Holes Per Plate</u>	<u>Hole Diameters* (in.)</u>	<u>Hole Pitch- Triangular (in.)</u>	<u>Plate Thickness (in.)</u>			<u>Spacing Between Plates (in.)</u>
					<u>Bottom Plate</u>	<u>Middle Plate</u>	<u>Top Plate</u>	
Representative of blanket orifices	Part 1 (run numbers 1-9)	69	0.201, 0.228, 0.250, 0.272, 0.302, 0.323, 0.341, 0.377, 0.404	0.631	0.375	0.375	0.375	0.505
Representative of Reflector Orifices	Part 2 (run numbers 1-9)	36	0.201, 0.228, 0.250, 0.272, 0.302, 0.323, 0.341, 0.377, 0.404	0.902	0.375	0.375	0.375	0.625
Representative of Reflector Orifices	Part 3 (run numbers 1-9)	36	0.201, 0.228, 0.250, 0.272, 0.302, 0.323, 0.341, 0.377, 0.404	0.902	0.375	0.375	0.500	0.625

*Only one diameter was used for all holes in the three orifice plates in each run. Each of the nine runs used a different hole diameter. The nine hole diameters (one for each run) used in Parts 1, 2 and 3 of the RET-9 PHASE I test are listed in this column.

TABLE 2. INFINITE ARRAY TRIPLATE ORIFICE TESTS (RET-9 PHASE I)*
(Hole diameter variations from plate to plate)

Part 4 of Phase I - run numbers for each flow hole combination (1A through 6F)

Run Numbers	Upstream Plate Flow Hole Diameter (inch)	(Center and Downstream Plate Flow Hole Diameter (inch))					
		<u>0.297</u>	<u>0.345</u>	<u>0.392</u>	<u>0.453</u>	<u>0.501</u>	<u>0.563</u>
1A to 1F	0.297	1A	1B	1C	1D	1E	1F
2A to 2F	0.345	2A	2B	2C	2D	2E	2F
3A to 3F	0.392	3A	3B	3C	3D	3E	3F
4A to 4F	0.453	4A	4B	4C	4D	4E	4F
5A to 5F	0.501	5A	5B	5C	5D	5E	5F
6A to 6F	0.563	6A	6B	6C	6D	6E	6F

Part 5 of Phase I - run numbers for each flow hole combination

Run Numbers	Center Plate Flow Hole Diameter (inch)	Upstream and Downstream Plate Flow Hole Diameter (inch)		
		<u>0.345</u>	<u>0.376</u>	<u>0.440</u>
1H	0.297	--	1H	--
1G,2H,1I	0.345	1G	2H	1I
2G,3H,2I	0.392	2G	3H	2I
4H,3I	0.440	--	4H	3I
3G,5H	0.453	3G	5H	--
4G,6H,4J	0.501	4G	6H	4I
7H,5I	0.563	--	7H	5I

*Each plate of all orifices contained 69 flow holes arranged on a 0.631 inch triangular pitch.
The plates were 0.375 inch thick and spaced 0.5 inch apart.

TABLE 3. FULL SCALE BLANKET TRIPLATE ORIFICE TESTS (RET-9 PHASE II, PART 1)*
(All three plates have the same flow hole diameter)

Run No. /	Average No. of Holes per Plate		Flow Hole Size (inch)	
	Std.	PFB	Std.	PFB
1	125.7	352.7	0.214	0.214
2	125.7	352.7	0.271	0.271
3	125.7	352.7	0.271	0.294
4	125.7	352.7	0.271	0.315
5	125.7	352.7	0.311	0.352
6	125.7	352.7	0.343	0.380
7	125.7	352.7	0.378	0.419

*All plates in this series were 0.375 inch thick and spaced 0.505 inch apart.
The flow holes in both the standard and power flattened regions were placed
on a 0.631 inch triangular pitch.

/Each run was made with and without flow dividers.

Std. = Standard blanket and PFB = Power flattened blanket

TABLE 4. FULL SCALE BLANKET TRIPLATE ORIFICE TESTS (RET-9 PHASE II, PART 2)*
(Hole diameter variations from plate to plate)

	Run Number							
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>
<u>Average Number of Holes Per Plate for the Triplate Assembly</u>								
Standard Region	122.0	122.0	122.0	122.0	122.0	122.0	122.0	122.0
PFB Region	350.3	350.3	350.0	350.3	350.3	350.3	350.3	350.3
Combined Region	472.3	472.3	472.3	472.3	472.3	472.3	472.3	472.3
<u>Hole Diameters (Inch)</u>								
Standard Region								
1. Bottom Plate	0.378	0.378	0.388	0.388	0.388	0.388	0.388	0.420
2. Middle Plate	0.378	0.378	0.378	0.389	0.395	0.395	0.419	0.419
3. Top Plate	0.378	0.378	0.378	0.388	0.394	0.394	0.420	0.420
4. Average Plate	0.378	0.378	0.381	0.388	0.392	0.392	0.403	0.419
PFB Region								
1. Bottom Plate	0.419	0.438	0.438	0.438	0.438	0.438	0.438	0.438
2. Middle Plate	0.419	0.419	0.422	0.422	0.422	0.437	0.437	0.437
3. Top Plate	0.419	0.438	0.438	0.438	0.438	0.438	0.438	0.438
4. Average Plate	0.419	0.432	0.432	0.432	0.432	0.438	0.438	0.438
Combined Average	0.409	0.418	0.419	0.421	0.423	0.425	0.429	0.434
<u>Area Ratio</u>								
Standard Region	0.293	0.293	0.300	0.310	0.317	0.316	0.334	0.362
PFB Region	0.393	0.417	0.419	0.419	0.419	0.430	0.430	0.430
Combined Regions	0.366	0.382	0.386	0.389	0.392	0.397	0.403	0.411

*All plates in this series were 0.375 inch thick spaced 0.505 inch apart. The flow holes in both the standard and power flattened regions were placed on a 0.631 inch triangular pitch.

Defined as the average flow area of all three plates divided by the upstream flow area.

PFB = Power Flattening Blanket

TABLE 5. FULL SCALE REFLECTOR TRIPLATE ORIFICE TESTS (RET-9 PHASE III)*

<u>Run No.</u>	<u>Bottom Orifice Plate Hole Size (inch)</u>	<u>Middle Orifice Plate Hole Size (inch)</u>	<u>Top Orifice Plate Hole Size (inch)</u>	<u>Average Triplate Flow Area (A_F)(inch²)</u>
1	0.150	0.150	0.150	2.26
2	0.210	0.150	0.150	2.99
3	0.246	0.150	0.150	3.53
4	0.246	0.1775	0.1775	4.08
5	0.246	0.2025	0.2025	4.71
6	0.246	0.246	0.246	6.09

*All plates in this series were 0.375 inch thick spaced 0.625 inch apart. The flow holes of each plate were located on a 0.902 inch triangular pitch and the average number of holes per plate was 128.

TABLE 6. GRID AND ROD BUNDLE CHARACTERISTICS FOR GRID TESTS (RET-11)

Test Phase	I	III			II	
Type Grid	Seed Strap & Tie Bar	Seed Half Hex			Blanket Half Hex	
Fuel Rod OD (inch)	0.255	0.305			0.571/0.526	
Fuel Rod Roughness (micro-inch)	40	85			80	
Number of Fuel Rods	798	619			187/446	
Rod Length (inch)	117	~ 26			29	
Cell Pitch (inch)	0.325	0.369			0.631	
Grid Number	1 thru 10	<u>A</u>	<u>1</u>	<u>10</u>	<u>3001</u>	<u>3002</u>
Grid Height (inch)	1.5	1.4	1.6	1.6	1.6	1.6
Grid Material Thickness (inch)	0.015	0.012	0.014	0.014	0.014	0.014
Grid Across Flats						
Outside (inches)	9.386	9.452	9.382	9.339	19.230	19.219
Inside (inches)	NA	NA	NA	NA	10.189	10.192
Vessel Across Flats (inches)	9.439 ¹	9.438			10.182	19.425*
Rodded Region Flow Area (inches) ²	37.74	30.77			86.77	
Hydraulic Diameter (inch)	0.203	0.196			0.294	
Range of Distance Between Grids (inches)	10.75 to 12.80	16.70			11.50 to 19.65	

*Blanket grid has an annular hexagonal geometry, inside and outside across flat dimensions respectively.

¹Support shell inside dimension

NA = Not Applicable

TABLE 7. RANGE OF PISTON AND CYLINDER DIMENSIONS TESTED*

	<u>Balance Piston</u>	<u>Buffer Cylinder</u>
D_s = Compression Sleeve Inside Diameter		
Over Bottom 12 inches (inches)	10.072	N/A
Height Greater than 12 inches (inches)	10.074	N/A
P = Pitch of Labyrinth (inches)	0.625	0.600
Z = Number of Labyrinth Cells	17	8
R = Edge Radius of Labyrinth Cells (inches)	0.005	0.005
D_G = Groove Diameter of Labyrinth (inches)	9.500	5.360
S = Groove Length (inches)	0.325 - 0.480	0.375
δ = Radial Clearance Between Mating Components (inches)	0.018 - 0.070	0.015 - 0.030
D = Diameter of Piston (inches)	9.969 - 10.039	4.803 - 4.824

*See Figures 68 and 69 for illustration of nomenclature.

TABLE 8. PISTON CONFIGURATIONS TESTED

A. Balance Piston Located 16 Inches Above the Top Surface of the Lower Buffer Cylinder (Buffer piston not included in test assembly)

<u>Balance Piston Designation</u>	<u>D* (in.)</u>	<u>δ* (in.)</u>	<u>L/P†</u>	<u>D_G* (in.)</u>
1	10.038	0.018	0.40	9.500
2	10.039	0.017	0.48	9.500
3	10.039	0.017	0.23	9.500
5	10.005	0.034	0.40	9.500
1-1	10.026	0.024	0.40	9.500
2-1	10.028	0.023	0.48	9.500
3-1	10.026	0.024	0.23	9.500
1-2	10.017	0.028	0.40	9.500
2-2	10.017	0.028	0.48	9.500
3-2	10.016	0.029	0.23	9.500
1-3	9.989	0.042	0.40	9.500
2-3	9.988	0.043	0.48	9.500
3-3	9.988	0.043	0.23	9.500
1-4	9.969	0.052	0.40	9.500
3-4	9.968	0.053	0.23	9.500
1-5	9.933	0.070	0.40	9.500
3-5	9.933	0.070	0.23	9.500
10	9.993	0.040	0.40	9.500
11	10.034	0.020	0.40	9.500
10-1	9.977	0.048	0.40	9.500
11-1	10.025	0.024	0.40	9.500
6	9.991	0.0415	0.40	9.829
7	9.991	0.041	0.40	9.664
7-1	9.991	0.041	0.40	9.337

B. Top Surface of Buffer Piston Flush with Top Surface of Lower Buffer Cylinder (Balance piston not included in test assembly)

<u>Buffer Piston Designation</u>	<u>D* (in.)</u>	<u>δ* (in.)</u>	<u>L/P†</u>	<u>D_G* (in.)</u>
1	4.803	0.030	0.37	5.360
2	4.834	0.015	0.37	5.360
3	4.824	0.020	0.37	5.360
4	4.813	0.025	0.37	5.360

C. Balance and Buffer Piston Assembly Where Elevation was Varied

<u>Balance Piston Designation†</u>	<u>Buffer Piston Designation†</u>
3-4	1
1-4	4
10-1	1

*See Table 7 for explanation of abbreviation.

†Labyrinth land to pitch ratio (unitless).

‡See A and B above for dimensions.

TABLE 9. SUMMARY OF RADIAL CLEARANCE BETWEEN PISTON AND COMPRESSION SLEEVE

Test Configuration Number	Distance from Bottom of Balance Piston to Buffer Stop Surface (inches)	Balance Piston Labyrinth - Compression Sleeve Radial Clearance at 3 Azimuthal Locations		
		$\theta = 0^\circ$ (inch)	$\theta = 120^\circ$ (inch)	$\theta = 240^\circ$ (inch)
1	13.5	0.030	0.029	0.030
2	5.4	0.030	0.032	0.029
3	0.0	0.023	0.021	0.023
4	13.5	0.040	0.042	0.007
5	5.4	0.036	0.037	0.017
6	0.0	0.029	0.032	0.005

TABLE 10. COMPARISON OF CONCENTRIC AND ECCENTRIC PISTON PRESSURE LOSS COEFFICIENTS*

<u>Reynolds Number</u>	<u>Concentric</u>	<u>Eccentric</u>	<u>Concentric</u> <u>Eccentric</u> x 100%
	K_{1-4}	K_{1-4}	
	<u>Test 1</u>	<u>Test 4</u>	<u>Percent</u>
30 x 10 ³	13.6	12.3	110
60 x 10 ³	13.5	12.3	110
90 x 10 ³	13.5	12.3	110
	<u>Test 2</u>	<u>Test 5</u>	<u>Percent</u>
30 x 10 ³	22.2	21.6	103
60 x 10 ³	21.9	20.7	106
90 x 10 ³	21.7	20.2	108
	<u>Test 3</u>	<u>Test 6</u>	<u>Percent</u>
30 x 10 ³	12.35	9.8	126
60 x 10 ³	11.2	9.35	120
90 x 10 ³	10.6	9.1	116.5
	K_{4-5}	K_{4-5}	
	<u>Test 3</u>	<u>Test 6</u>	<u>Percent</u>
30 x 10 ³	5.25	4.7	111
60 x 10 ³	5.1	4.65	110
90 x 10 ³	5.0	4.6	108

K_{1-4} and K_{4-5} correspond to pressure tap locations identified on Figure 71.

*Based on a mean statistical log-log regression analysis of the data obtained from the higher temperature runs of concentric and eccentric balance and buffer piston pressure loss coefficients.

Module Types

Description

I	Seed surrounded by Standard Blanket
II,III	Seed surrounded by Standard and Power Flattened Blanket. Regions II and III differ due to overall boundary dimensions.
IV,V	Reflector regions. Regions IV and V differ due to overall boundary dimensions.

FIGURE 1 - CROSS SECTION OF THE LWBR CORE WITH MODULE IDENTIFICATION

BLANKET SUPPORT
TUBE (304 CRES)

TOP ORIFICE
PLATES (304 CRES)

TOP BASE PLATE
BOLT
(INCONEL X)

TOP BASE
PLATE
(INCONEL)

BLANKET
SUPT. POST
(ZIRCALOY)

GUIDE TUBE
(ZIRCALOY)

TOP SEAL
BLOCK
(304 CRES)

TOP COVER
PLATE
(INCONEL)

TOP MNTD.
FUEL RODS

BLANKET
GRID

BOTTOM BASE
PLATE
(INCONEL)

STUB TUBE
(304 CRES)

GUIDE TUBE
EXTENSION
(304 CRES)

BOTTOM
COVER PLATE
(INCONEL)

BOTTOM
ORIFICE
PLATES
(304 CRES)

FIGURE 2 - LWBR TYPE I BLANKET MODULE

FIGURE 3 - LWBR TYPE III BLANKET MODULE

FIGURE 4-LWBR BYPASS INLET FLOW (BIF) BALANCE SYSTEM

FIGURE 5 – SKETCH OF THE RET-9 PHASE I TEST SECTION

FIGURE 6 - RET-9 PHASE II TEST VESSEL-CROSS SECTION
ABOVE TRIPLATE ORIFICE

FIGURE 7 - RET-9 PHASE II TRIPLATE ORIFICE

FIGURE 8 - RET-9 PHASE II TEST ASSEMBLY

FIGURE 9 - TYPE V REFLECTOR ASSEMBLY

FIGURE 10. - RET-9 PHASE III REFLECTOR INLET INSERT AND BOTTOM ORIFICE PLATE

FIGURE 11 - RET-9 PHASE III INLET AND OUTLET INSERTS

FIGURE 12- INFINITE ARRAY TRIPLATE ORIFICE PRESSURE LOSS COEFFICIENTS VS REYNOLDS NUMBER
(RET-9 PHASE I PART 4 DATA, ALL 3 PLATES HAVE THE SAME HOLE DIAMETER)

FIGURE 13- TRIPLATE ORIFICE PRESSURE LOSS COEFFICIENT* VS AREA RATIO
(TRIPLATES HAVING LESS THAN 10% PLATE TO PLATE HOLE DIAMETER VARIATION)

FIGURE 14 - RET-9 PHASE II PART I TRIPLATE LOSS COEFFICIENT
VS AREA RATIO

FIGURE 15- INFINITE ARRAY TRIPLATE ORIFICE PRESSURE LOSS COEFFICIENT VS REYNOLDS NUMBER
 (RET-9 PHASE I PART 4 DATA, TRIPLATES HAVING GREATER THAN
 10% PLATE TO PLATE HOLE DIAMETER VARIATIONS)

FIGURE 16- PRESSURE LOSS COEFFICIENT VS AREA RATIO
(RET-9 TEST PHASE I & II)

FIGURE 17-PRESSURE LOSS COEFFICIENT VERSUS
AREA RATIO (RET-9 PHASE I PART 5)

FIGURE 18 - PRESSURE LOSS COEFFICIENT VERSUS FLOW HOLE DIAMETER

FIGURE 19- LWBR BOTTOM PLATE DETAILS

NUMBER IN PARENTHESIS REPRESENTS THE
NUMBER OF MANIFOLDED PRESSURE TAPS

FIGURE 20-SCHEMATIC OF THE SEED FLOWMETER
TEST SECTION (RET-10 PHASE I)

Neg. No. 48774-3

FIGURE 21 - RET-10 SEED FLOWMETER STRAINER PLATE

Neg. No. 48774-2

FIGURE 22 - RET-10 SEED FLOWMETER

FIGURE 23 - RET-10 PHASE I GUIDE TUBE EXTENSION

FIGURE 24 - RET-10 BLANKET FLOWMETER TEST ASSEMBLY

FIGURE 25 - RET-10 PHASE II TEST SECTION DETAILS

FIGURE 26 - RET-10 BLANKET FLOWMETER DETAILS

FIGURE 27 - SEED FLOWMETER AND STRAINER PLATE
PRESSURE LOSS COEFFICIENT

FIGURE 28 - SEED FLOWMETER AND STRAINER PLATE
PRESSURE LOSS COEFFICIENT

FIGURE 29-SEED FLOWMETER FLOW COEFFICIENT

FIGURE 30-BLANKET FLOWMETER AND BOTTOM
PLATE PRESSURE LOSS COEFFICIENT

FIGURE 31 - BLANKET FLOWMETER FLOW COEFFICIENT
VS REYNOLDS NUMBER

**FIGURE 32-RET-II PHASE I
GRID ASSEMBLY**

FIGURE 33 - RET-11 PHASE I TEST - GRID ASSEMBLY

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FIGURE 34 - RET-11 PHASE I ROD BUNDLE ASSEMBLY INSIDE HEXAGONAL SUPPORT SHELL

FIGURE 35 - RET-11 PHASE I TEST ASSEMBLY

FIGURE 36-ILLUSTRATION OF RET-II
 PHASE III HALF-HEX GRID ELEMENT

FIGURE 37 - ILLUSTRATION OF RET-II PHASE III
GRID ASSEMBLY

FIGURE 38 - RET-11 PHASE III TEST ASSEMBLY

PLAN VIEW
OF
COMPLETE GRID

FIGURE 39 - ILLUSTRATION OF RET-II PHASE II
GRID ASSEMBLY

FIGURE 40 -RET-II, PHASE II GRID FLOW
TEST MODEL SCHEMATIC

FIGURE 41 - RET-11 PHASE II TEST VESSEL

FIGURE 42 - RET-11 PHASE II BOTTOM BASEPLATE

FIGURE 43 - RET-11 PHASE II INLET FLOW SEPARATOR AND BOTTOM COVER PLATE

FIGURE 44 - RET-11 PHASE II GRID ASSEMBLY

FIGURE 45 - RET-11 PHASE-II TEST ASSEMBLY

FIGURE 46 - RET II PHASE I RODDED REGION FRICTION FACTOR
VS REYNOLDS NUMBER

FIGURE 47-RET-II PHASE III RODDED REGION FRICTION FACTOR VS REYNOLDS NUMBER USING GRIDS NO. A AND NO.1 (ASSEMBLY NO.1)

FIGURE 48 - RET-II PHASE III RODDED REGION
FRICTION FACTOR VS REYNOLDS NUMBER USING
GRIDS NO. 1 AND NO. 10 (ASSEMBLY NO. 2)

FIGURE 49 -RET-II PHASE II RODDED REGION FRICTION
 FACTOR VS REYNOLDS NUMBER
 (ASSEMBLY NO. I)

FIGURE 50-RET-II PHASE II RODDED REGION FRICTION
FACTOR VS REYNOLDS NUMBER
(ASSEMBLY NO. 2)

FIGURE 51 -RET II PHASE I GRID LOSS COEFFICIENT
VS REYNOLDS NUMBER

FIGURE 52 - RET-II PHASE I GRID LOSS COEFFICIENT
VS REYNOLDS NUMBER

FIGURE 53 - RET II PHASE I GRID LOSS COEFFICIENT
VS REYNOLDS NUMBER

FIGURE 54-RET-II PHASE III GRID LOSS COEFFICIENT VS REYNOLDS NUMBER FOR GRID NO. A IN THE LOWER POSITION

FIGURE 55 -RET-II PHASE III GRID LOSS COEFFICIENT VS REYNOLDS NUMBER FOR GRID NO. 1 IN THE UPPER POSITION

FIGURE 56-RET-II PHASE III GRID LOSS COEFFICIENT VS
REYNOLDS NUMBER FOR GRID NO. I IN THE LOWER POSITION

FIGURE 57-RET-II PHASE III GRID LOSS COEFFICIENT VS
REYNOLDS NUMBER FOR GRID NO. 10 IN THE UPPER POSITION

FIGURE 58-RET-II PHASE II BLANKET GRID FLOW TEST

FIGURE 59-RET-II PHASE II BLANKET GRID FLOW TEST

FIGURE 60-RET-II PHASE II BLANKET GRID FLOW TEST

FIGURE 61 -RET-II PHASE II BLANKET GRID FLOW TEST

FIGURE 62 - ILLUSTRATION OF LWBR FUEL ROD BASE PLATE SUPPORT SYSTEM

FIGURE 63 - BASE PLATE PRESSURE LOSS COEFFICIENT
FOR VARIOUS CLEARANCES BETWEEN THE ROD
FREE END AND THE BASE PLATE

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FIGURE 64 - RET-15 PHASE II PISTON

FIGURE 65 - CHARACTERISTIC ELEVATIONS OF THE LWBR PISTON

FIGURE 66 - RET-15, PHASE I MODEL SCHEMATIC

- P = PITCH OF LABYRINTH
- L = LAND LENGTH
- S = GROOVE LENGTH
- δ = RADIAL CLEARANCE
- D = BALANCE PISTON DIAMETER
- D_s = COMPRESSION SLEEVE INSIDE DIAMETER
- D_g = GROOVE DIAMETER OF LABYRINTH
- R = EDGE RADIUS OF CELLS
- Z = NUMBER OF LABYRINTH CELLS IN ENTIRE LABYRINTH SEAL

FIGURE 68—BALANCE PISTON LABYRINTH
NOMENCLATURE

P = PITCH OF LABYRINTH
 L = LAND LENGTH
 S = GROOVE LENGTH
 δ = RADIAL CLEARANCE
 D = BUFFER PISTON DIAMETER
 D_s = BUFFER SEAL DIAMETER
 D_g = GROOVE DIAMETER OF LABYRINTH
 R = EDGE RADIUS OF CELLS
 Z = NUMBER OF CELLS IN ENTIRE LABYRINTH SEAL

FIGURE 69-BUFFER PISTON LABYRINTH
 NOMENCLATURE

FIGURE 70 - RET-15 PHASE II MODEL SCHEMATIC

FIGURE 71 - RET-15 PHASE II PRESSURE TAP LOCATIONS

FIGURE 72 - INTERNAL VIEW OF RET-15 PHASE II UPPER
BUFFER CYLINDER AND COMPRESSION SLEEVE

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FIGURE 73 - RET-15 PHASE II LOWER BUFFER CYLINDER

FIGURE 74 - RET-15 PHASE I BIF SYSTEM LABYRINTH SEAL FLOW TEST

FIGURE 75 - RET-15 PHASE I LABYRINTH SEAL FLOW TEST

FIGURE 76 - RET-15 PHASE I LABYRINTH SEAL FLOW TEST

FIGURE 77-RET-15 PHASE I LABYRINTH SEAL FLOW TEST

FIGURE 78 - BALANCE PISTON PRESSURE LOSS COEFFICIENT

FIGURE 79-BALANCE PISTON PRESSURE LOSS COEFFICIENT

FIGURE 80-BALANCE PISTON PRESSURE LOSS COEFFICIENT

FIGURE 81 - BALANCE PISTON PRESSURE LOSS COEFFICIENT

FIGURE 82- BALANCE PISTON PRESSURE LOSS COEFFICIENT

FIGURE 83 - BALANCE PISTON PRESSURE LOSS COEFFICIENT