**ANNULAR INLET
FFTF HYDRAULIC FEATURE MODEL**

FEBRUARY 1969

**AEC RESEARCH &
DEVELOPMENT REPORT**

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

3 3679 00061 2236

BNWL-952
UC-38, Engineering
and Equipment

ANNULAR INLET
FFTF HYDRAULIC FEATURE MODEL

By

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Mechanical Engineering Department
Physics and Engineering Division

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FEB 20 '69

January 1969

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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

ABSTRACT

The FFTF annular inlet concept is an arrangement for introducing reactor coolant through the annular zone formed between the reactor vessel and the reactor core vessel. This concept eliminates the need for piping to the supply plenum and provides a zone for inlet coolant mixing. This reactor concept was studied using a one-tenth scale model with four equally spaced inlet pipes located tangentially to the reactor axis. The model was designed using Euler number equality and constructed of clear plastic to permit visual observation of the flowing water modeling fluid. The testing was performed to evaluate the mixing characteristics of the water and to reveal any unsuspected hydraulic behavior. Motion picture analysis at flow rates from 10 - 100% with both balanced and unbalanced conditions was the main analysis tool employed.

The direct impingement of the coolant stream against the reactor vessel wall proved to be an undesirable condition. To improve this condition, 90° inlet nozzle diffusers were installed. The formation of vortices within the inlet zone during each test were accompanied by vertical bands of alternate high and low coolant velocity in the annular zone. The high velocity zones were at 45° to the inlets, the low zones directly below the inlets. The vortices did not occur during one test in which the inlet diffusers were rotated 30° from vertical. Instead, pressure drops through the vessel were noted to increase over values obtained from tests at the same flow rates with the diffusers positioned vertically.

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ANNULAR INLET
FFTF HYDRAULIC FEATURE MODEL

P. M. Jackson

INTRODUCTION

Battelle Memorial Institute, Pacific Northwest Laboratory, Richland, Washington, has been assigned the project management responsibility for the Fast Flux Test Facility (FFTF) and the performance of portions of the associated development program. One of the overall objectives of this development work is to resolve uncertainties of flow distributions, thermal gradients, gas entrainment, and other abnormalities in the FFTF reactor vessel by a program of flow testing with controlled temperature water as a substitute for the liquid sodium reactor coolant. This work is being performed in conjunction with the Hydraulic Core Mockup facility. The initial phase of this program is to provide qualitative information on selected major problem areas, or on various alternate conceptual reactor features.

This document reports the initial evaluation of the hydraulic characteristics of the annular inlet reactor vessel concept. The annular inlet concept is an arrangement for introducing reactor coolant through the annular zone formed between the main reactor vessel and the reactor core vessel. This concept eliminates the use of piping to the supply plenum and provides a zone where coolant from the several reactor loops can mix to provide a coolant of more uniform temperature to the reactor fuel ducts. These reactor coolant loops, each of which contain pumps and heat exchangers, could supply coolant to the reactor at other than optimum conditions in the event of a pump, heat exchanger, or piping failure. The resulting thermal gradients produced in the annular zone could result in excessive thermal stresses in the vessel and core components and lead to failures

of these components. This test series was performed to supply information to aid in evaluating this possible problem and to reveal any unsuspected hydraulic behavior.

SUMMARY AND CONCLUSION

The first phase testing of the Annular Inlet Concept was conducted with a one-tenth size model of the reactor and water used as the modeling fluid. The testing program indicated several problem areas concerning the annular inlet concept. These include (1) impact of inlet stream against the reactor vessel, (2) velocity variations within the annulus of about a two to one ratio, and (3) the formation of vortices within the distribution chamber surrounding the inlet plenum.

The goal of this test program was to study the momentum interchange effects. The test output was based on the use of visual methods only. Motion picture analysis provided most of the information on the flow characterization. A major concern was the threat to the integrity of the annular inlet reactor presented by malfunctioning of the cooling or pumping components of an individual coolant flow loop. This condition could produce a situation resulting in the supply of hotter, cooler, or less volume of coolant to the reactor. A hotter or cooler coolant stream, dependent upon the temperature transient, could produce thermal stresses within the vessel walls. The most seriously affected zone would be at the point of the coolant stream impact with the reactor vessel. The model tests demonstrated the impact effect quite clearly with the horizontal velocity component at this zone exceeding the vertical component by about three times.

Deflectors were positioned on each inlet to direct the water stream 90° downward, thus eliminating the direct impingement. This addition did not significantly affect the water mixing within the annulus and had no effect on the vortices (these are explained in more detail later). Tests conducted both with and without the deflectors produced alternate vertical zones of high and low velocity water flow (2 to 1 ratio) within the annulus. The low velocity zones were oriented

immediately below the inlets, and the high velocity zones at 45° to them. A test conducted with all four inlet diffusers rotated 30° clockwise provided a uniform water velocity within the annular zone and the first and only test completely without vortices. Vortex formations within the model lower dome were evident from the start. The addition of such modifications as a restrictor plate, skirt, melt down plates, flow straighteners, and flow deflectors did not effect the size, number, or relative strength of the vortices. Four vortices formed in each test were oriented 90° apart, or at 45° to the inlet openings. Each vortex was comprised of a cone about 10 in. in diameter. Adjacent vortices rotated in opposite directions. The positions of the vortices, while relatively stable, would break and reform with irregularity. The apex of each vortex would move alternatively between about two adjacent openings through the ring surrounding the fuel duct inlet region.

The core of a vortex is a region of reduced pressure in which entrained gasses tend to accumulate and come out of solution. Upon the collapse of a vortex, these gasses are swept into the inlet plenum region. Vortex formation in the reactor will cause an imbalance in the flow distribution within the inlet plenum, thus restricting coolant supply to certain fuel ducts and with the movement between two adjacent openings, the flow distribution to the affected fuel ducts would change with time. This condition, because of the essentially air saturated water source, was noted to be more pronounced in the model than would be expected in a reactor system.

It was not until the flow deflectors were rotated 30° that a test was conducted without vortex formation. This test yielded a significantly higher differential pressure between the vessel inlet streams and the fuel duct inlet region than was noted in any previous test with the deflectors oriented vertically, or not installed. The pressure drop in this instance was increased

by approximately a factor of four. Respective values in the model were 4 psi and 1 psi, with similar pressure drop increases expected under full scale, sodium-conditions.

The model design, based upon the Euler number ratio and pressure drop ratio both equal to one, resulted in a velocity ratio of 0.93 and a Reynolds number ratio of 0.038 (model to prototype). It was not possible to model Reynolds number equality. The Reynolds number in the annular region of the model was distorted about 1 to 26, as compared to a full scale sodium system (4.2×10^4 to 1.1×10^6). However, the Reynolds number in the model is within the turbulent region and it is believed that model flow will adequately characterize the momentum interchange effects expected in the prototype.

The fluid mechanics of vortices is very complex and no comprehensive theory concerning this phenomena is available.⁽¹⁾ However, it is reasonable to expect that vortexing problems would be evidenced in a reactor vessel built from a design similar to the modeled arrangement. It should be noted that only limited efforts were taken to eliminate the vortex formation in this feature model. Vortices are a potential problem in any hydraulic system. Further studies will be conducted in the test program scheduled for the one-third scale piped inlet model and the half scale reactor model.

1. H. J. Bomelburge. An Evaluation of the Applicability of the Water Model Testing to Liquid Metal Engineering Problems, LMEC, 68-4. February 1968.

DISCUSSION

TEST APPARATUS

The one-tenth size annular inlet model was based upon the concept shown in Drawing SK-3-12574 (Figure 1). Four equally spaced inlets enter at 90° to the vessel axis. Each is fitted with an orifice for flow measurement and a valve for flow control (Figures 2 and 3). The model was connected to an existing pumping facility capable of providing water flow to 400 gpm at ambient temperature. The one-tenth size model is geometrically similar to the reactor concept. This scale resulted from equating the Euler number and the pressure drop of the model to that of the reactor concept. This similitude produces a theoretical model to prototype velocity ratio of about 0.93. The Reynolds number ratio is 0.038 (1 to 26). It was not feasible to model the Reynolds number because of an unreasonable model size resulting from use of the existing pumping system. Using the Euler number as the basis of similitude resulted in the following ratios:

1. Velocity through the inlet piping

Model: $V = 13.38 \text{ ft/sec}$

Prototype: $V = 14.4 \text{ ft/sec}$

Ratio: $V_r = 0.929$

2. Reynolds Number, inlet pipe

Model: $N_{re} = 2.1 \times 10^5$

Prototype: $N_{re} = 5.55 \times 10^6$

Ratio: $N_{rer} = 0.038$

3. Velocity in Annulus

Model: $V = 1.33 \text{ ft/sec}$

Prototype: $V = 1.46 \text{ ft/sec}$

Ratio: $V_r = 0.911$

SK-3-12574

FIGURE 1. Split Core Reactor Arrangement IV

FIGURE 2. *Annular Inlet Model*

BNWL-952

FIGURE 3. Annular Inlet Model Sketch

4. Reynolds Number - Annulus
 Model: $N_{re} = 4.18 \times 10^4$
 Prototype: $N_{re} = 1.11 \times 10^6$
 Ratio: $N_{rer} = 0.038$
5. Length Ratio
 $L_r = 0.104$
6. Basis of Similitude⁽²⁾
 $N_{eur} = 1$
 $\Delta Pr = 1$

FLOW VISUALIZATION

The annular inlet test program required visual observations of the coolant flowing into and within the annular zone. The inlet piping and reactor vessel were fabricated of clear plastic to allow these observations. Further aids to determine the mixing of the clear colorless water within the annular zone were employed. These aids, including (1) streamers, (2) dyes, and (3) pellets, are described in the following paragraphs.

Streamers

Small triangularly shaped brass streamers or flags were attached to the inner surface of the clear plastic main reactor vessel with pins (Figure 2). The streamers were free to rotate about the pins and thus indicated the direction of the water flowing within the annular zone. Clear protractor rosettes were positioned over each streamer for direct angular measurement.

One vertical row of four streamers located on the vertical centerline of an inlet pipe, along with three vertical rows of five streamers located on 15° intervals left and right, encompassed a quarter sector of the vessel.

2. D. S. Trent. Applications of Geometric Models for FFTF Hydraulic Core Mockup, BNWL-575. Pacific Northwest Laboratory, November 1967.

During testing, it was determined that the streamers would indicate very generally the direction of coolant flow. The large variations in streamer angular positions noted in each test required considerable interpolation of the data. This variation was found to be greatest in the highly turbulent zone surrounding the four inlets. Typical patterns derived from streamer observation are shown in Figure 4. The evaluation of these patterns became more evident when studies were conducted with the injection of dyes. The direct impingement of the coolant stream against the reactor core vessel wall (before installation of the inlet diffusers) produces diverse circulating currents within the upper regions of the annular zone which do not repeat themselves in a consistent manner.

The general flow pattern with uniform inlet flow rates formed an inverted "V" dispersion of the water media, with higher velocities located toward the outside of the "V".

During tests in which the inlet flow rates of the four inlets were unbalanced, the angular spread of the "V" was increased in the direction of the reduced flow. Though removal of the streamers was originally planned following the initial tests, they were left in position during all test sequences for added information.

Dye Injection

The test model was designed to permit injection of colored dyes at various locations on the inlet piping. This dye (india ink of several colors) was injected through hypodermic needles, bent to direct the dye parallel to the stream flow and positioned at the inlet pipe centerline.

The first injection point investigated was located about one inch upstream of the inlet discharge into the annular zone. At this location, a horizontal and vertical traverse of the inlet nozzle demonstrated the dispersal of the dye into the

Flow Rate 60 gal/min

Flow Rate 80 gal/min

Flow Rate 100 gal/min

FIGURE 4. *Annular Inlet Model Typical Streamer Patterns*

annular zone to be extremely dependent upon needle position. The majority of the dye dispersed in the direction the needle was moved from the tube centerline, i.e., little mixing was occurring within the inlet stream. Relocation of the needle farther upstream in the inlet pipe demonstrated much less tendency for the dye dispersal within the annular zone to be dependent upon horizontal or vertical needle positioning.

The dye injection proved to be the best of the methods selected for observing flow and mixing characteristics of the coolant. Several motion pictures were made at 50 frames/sec of the dye injections at various inlets into the annular zone. The results of these movies are described later in the report.

The dispersal and mixing of the water as it flows from the horizontally positioned inlet pipes and strikes the vertically oriented curved wall of the reactor vessel is similar to the impingement of a free jet against a flat plate (Figure 5). The impingement of this jet of coolant against a reactor vessel wall, as visualized in this reactor concept, could result in major consequences if one of the inlet streams were subjected by a malfunction of the upstream heat exchanger to a hot or cold transient. In this instance, a maximum reactor coolant temperature rise of 350 °F above normal operating temperatures could occur (no-attemperation) with a complete heat exchanger failure. The resulting thermal shock might seriously affect the vessel integrity.

The impingement of the inlet stream against the curved reactor vessel wall, coupled with the close proximity of the cover plate, produces a horizontal velocity component exceeding the vertical component by about three times. The further dispersal of the water produces a vertically oriented high velocity zone where the higher velocity horizontal streams meet. This zone is located at 45° between the inlets under balanced inlet flow conditions. A low velocity zone forms immediately below each

Time 0.1 Sec

0.2 Sec

0.3 Sec

0.4 Sec

FIGURE 5. *Impingement of Inlet Stream Against Reactor Vessel Wall 10% (40 gpm total flow)*

inlet. The ratio of horizontal to vertical velocities is about 2 to 1. An inverted "V" pattern is observed when using dyes (note dye dispersal in Figure 6). The symmetrically oriented vertical velocity zones entering the hemispherically shaped lower head cause the formation of vortices, a result discussed later in this report.

Pellets

Neutrally buoyant polystyrene pellets painted a fluorescent red color were injected into one inlet stream to aid the flow analysis. Though the benefit from observing flow patterns through the use of the pellets was not great, it did substantiate the previously discussed zone of high and low velocity, assisted in providing better velocity measurements, and in determining the magnitude of the vortices.

MOTION PICTURES

Movie photography was employed as a tool for visually observing, at a much slower rate, the flow distribution and relative velocity within the annular zone. The moving pictures were obtained at a rate of 50 frames/sec (normal movie speed is 16 frames/sec) and viewed with the aid of an analyst projector. This type of projector made possible the viewing of the film at reduced speeds or by individual frames. Colored dyes and the colored pellets injected from individual inlets provided the contrast for visual observations. Although both black and white and colored films were used, the colored film produced the best results with the colored dyes.

Each movie was taken with a sequence of balanced and unbalanced individual inlet flow conditions ranging from 100% to 10% of modeled reactor flow. When the movies were viewed at a slow projection rate, the mixing flow patterns could be observed quite clearly. Unfortunately, the movie sequences could not be included in the report. However, one series at a balanced 10%

NOTE: Photo 1 - 0.2 sec after dye injection
Photo 2 - 0.4 sec after dye injection
Photo 3 - 0.6 sec after dye injection
Photo 4 - 0.8 sec after dye injection
Photo 5 - 1.0 sec after dye injection
Photo 6 - 1.2 sec after dye injection

FIGURE 6. *Annular Inlet Model Flow Distribution
Within Annulus*

FIGURE 6. (Contd)

(40 gal/min flow rate shows the water impingement against the reactor vessel (Figure 5). Another, at 50% (200 gal/min) flow rate (Figure 6) shows the installed diffusers and flow straighteners. The first strip of pictures, comprising every fifth frame, represents a time interval of 0.1 sec and the second strip, every tenth frame, or 0.2 second. The dye was injected into the inlet stream from a point about 3 ft upstream of the vessel. This inlet is in the center of the pictures. The inverted "V" dispersion of the dye can be observed forming in the later film sequence. The 200 gal/min series was chosen because the dye concentration is greater and the dispersal pattern more easily seen. The diagrams shown in Figure 7 represent typical water velocity profiles found within the annular zone. Figure 7A represents the combined horizontal and vertical velocity components as the dye disperses from the inlet. The velocities shown for each point are the overall average velocity from the coolant inlet, and were derived from measurements taken from the film sequences. Figure 7B (curves A & C) describe only the vertical velocity component from the point where the dye reaches the 45° axis. The velocity component was measured downward along the 45° axis from this point of intersection. Curve B (Figure 7B) is the vertical velocity component located immediately below the inlet (0°).

MODIFICATIONS

The model was fabricated from Drawings SK-3-13200* and SK-3-13201.* In order to make the model more prototypic of changing reactor concepts and as a method to reduce problems discovered in operation, several modifications were incorporated. Additions made to the model after the initial setup and before actual testing was started are detailed in the following discussion.

* Not shown in this report.

A. TEST CONDITIONS (HORIZONTAL AND VERTICAL COMPONENTS)

Flow: 90 gal/min each inlet (360 gal/min total)

Average Velocity: 1.2 ft/sec

Point	Film frames/sec	Time, sec	Vert. in.	Horiz. in.	Velocity ft/sec
A	10	0.2	2.5	6	2.7
B	20	0.4	6	12	2.8
C	30	0.6	11	14	2.5
D	10	0.2	2.5	0	1.0
E	10	0.2	2.5	5.5	2.5
F	20	0.4	10	10	3.2

B. TEST CONDITIONS (VERTICAL COMPONENT ONLY)

Flow: 400 gal/min each inlet (400 gal/min total)

Average Velocity: 1.3 ft/sec

Flow Straighteners and Deflectors Installed

Point	Film frames/sec	Time, sec	Vert. in.	Horiz. in.	Velocity ft/sec
A	20	0.6	14	0	2.0
B	54	1.1	12	0	0.9
C	27	0.5	15.5	0	2.4

FIGURE 7. Annular Velocity Determination (From Films)

Restrictor Plate

A perforated plate was positioned at the inlet to the fuel duct zone to partially simulate the pressure drop of the fuel ducts. The plate increased the pressure within the annular zone to 10 psi at a 100% flow rate. The restrictor plate is shown in Figure 2.

Deflector Skirt

The deflector skirt was added between the straight section of the reactor vessel and the hemispherical lower dome. Its function was to direct the water flow towards the inlet and to provide a more streamlined flow path.

Melt-Down Plates

Melt-down plates were added to the lower plastic dome. This feature tended to restrict the sweep of the water as it flowed toward the plenum zone. The following additional modifications were made in an attempt to correct the problem of vortex formation within the inlet zone.

Flow Straighteners

These straighteners were located about 2 ft upstream of each inlet discharge to correct any maldistribution of water as it enters the annular zone. Some spiraling flow condition, caused by the flow regulating valve and piping elbow was considered possible within the inlet pipes. The straighteners were composed of six vanes 8 in. in length. No noticeable effect on flow patterns or vortex formation was evident with the installation of these devices.

Flow Deflectors

During the testing program, it became apparent that the direct impingement of the jet of water from each inlet against the reactor core vessel was unsatisfactory. Flow deflectors

as shown in Figure 2 and 5 were installed to provide a smooth 90° transition for the incoming water.

The deflectors were fabricated so that their vertical angularity could be adjusted 45° either left or right. The deflectors provided a more uniform flow distribution within the annular zone, especially in the immediate area of the reactor inlet nozzle. However, the 2 to 1 vertical velocity variation remained in the lower portion (45° and 0° positions, respectively). By tipping the deflectors 30° from vertical, water velocities within the annular zone were found to be nearly uniform and no vortices were formed. The pressure drop between the inlet to the annular zone and the inlet to the fuel duct zone increased significantly during this test (about 4 psi). Tipping the deflectors 15° produced a lesser effect and allowed the formation of small vortices at the plenum inlet.

VORTEX FORMATION

Vortices noted at the entrance to the inlet plenum within the lower dome during the initial model tests remained evident throughout all testing except when circumferential velocities were produced (Figure 8). The earliest effort to eliminate the vortices by making the model more prototypical of advanced concept design through the addition of the restrictor plate, deflector skirt, and melt-down plates produced no noticeable effect. Likewise, the addition of the flow straighteners had no apparent effect upon vortex suppression, nor did the deflectors when aligned vertically. The rotation of the deflectors 15° did, however, noticeably affect vortex reduction and, when rotated 30° from the vertical, no vortices were observed.

The vortex formation is believed to be caused by the unequal water velocities within the annular zone. This inequality, in which vertically oriented high velocity zones form at 45° to the inlets with corresponding low velocity zones immediately below the inlets, extends into the lower inlet dome where

FIGURE 8. *Annular Inlet Model
Typical Vortex Formations*

FIGURE 8. *Annular Inlet Model*
 Typical Vortex Formations

four evenly spaced vortices form. The relatively stable axis of the vortices was located at about 45° to the inlet positions. Each vortex, with a swirling cone of about 8-10 in. in diameter, rotated in opposite direction to the one adjacent. The lines appearing as scratches on Figure 8 are air bubbles within the vortex cone. These bubbles are helpful in visualizing the vortices in water. The vortices remained relatively constant during all tests even though the flow rate was varied from 10 to 100% and the flow through the four inlets was unbalanced in some tests. The only tests in which no vortices were present were those in which the deflectors were rotated 30° from vertical. In this test series, a uniform circumferential velocity component was developed. A 360° rotation of the water occurring within the height of the annular zone caused a significant increase in the differential pressure between the inlet stream and the inlet to the fuel ducts.

ACKNOWLEDGMENT

The author gratefully acknowledges the assistance of F. H. Nunamaker during apparatus fabrication and testing, and the overall technical consultation services provided by L. R. Sweetin.

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