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HYDRAULIC CHARACTERISTICS OF HNPF 8-ROD FUEL ELEMENT

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ABSTRACT

Pressure drop and vibration characteristics were determined for an 8-rod fuel element model of the design intended for use with uranium carbide (UC) in the Hallam Nuclear Power Facility (HNPF). Measurements with water as the test fluid were converted to equivalent values for sodium, the HNPF coolant, using the principles of dimensional similitude. Initially UC elements will be included in an HNPF core loading comprised primarily of 19-rod U-Mo fuel elements. In this core loading the UC fuel element requires 17.5 lb/sec of sodium coolant at a core pressure drop of 11 psi. The measured fuel element pressure drop ranged from 0.27 to 5.6 psi over the sodium flow range from 3.5 to 17.4 lb/sec. The existing HNPF variable orifice can adjust flow for this fuel element over the range from 5.7 to 21 lb/sec at a core pressure drop of 11 psi. No significant vibration of the fuel rods was induced by the flow of water.

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I. INTRODUCTION

Measurements of the pressure drop across an 8-rod UC fuel element were required to determine if elements of this design would be properly cooled when included in an HNPF (Hallam Nuclear Power Facility) core loading composed primarily of 19-rod fuel elements. In addition, studies of the vibrational characteristics of the 8-rod UC fuel element were necessary to determine if excessive stresses in the fuel rod cladding would result from vibrations induced by the flowing coolant. Therefore, the objectives were to measure the coolant pressure drop and to determine the maximum amplitude of fuel rod vibrations under design flow conditions. Water was used as a test fluid; data obtained were converted to equivalent values for sodium using the principles of dimensional similitude.

II. EIGHT-ROD FUEL ELEMENT

The fuel element which is to utilize uranium carbide fuel in the HNPF is an 8-rod cluster held vertically in a process tube (Figure 1). The cluster is an assembly of eight stainless steel tubes loaded with enriched uranium carbide fuel slugs, which are placed radially around a central corrugated tube. Twelve mechanical spacers placed 18 in. apart and positioned by the corrugated tube retain the fuel cladding tubes in a circular array. There is a thermal bond of sodium in the annular gap between the fuel and cladding. Fuel rods terminate in a guide casting at the bottom and a hanger casting at the top. The hanger fixture attaches to the process tube and to the variable orifice assembly which is located above the fuel element.

Fuel element dimensions pertinent to hydraulic and vibrational characteristics are:

a) Overall fuel-element length — 18 ft 5-3/8 in.

b) Fuel-rod length — 15 ft 4 in.

c) Cladding OD — 0.952 in.

d) Cladding ID — 0.932 in.

e) Fuel slug diameter — 0.892 in.

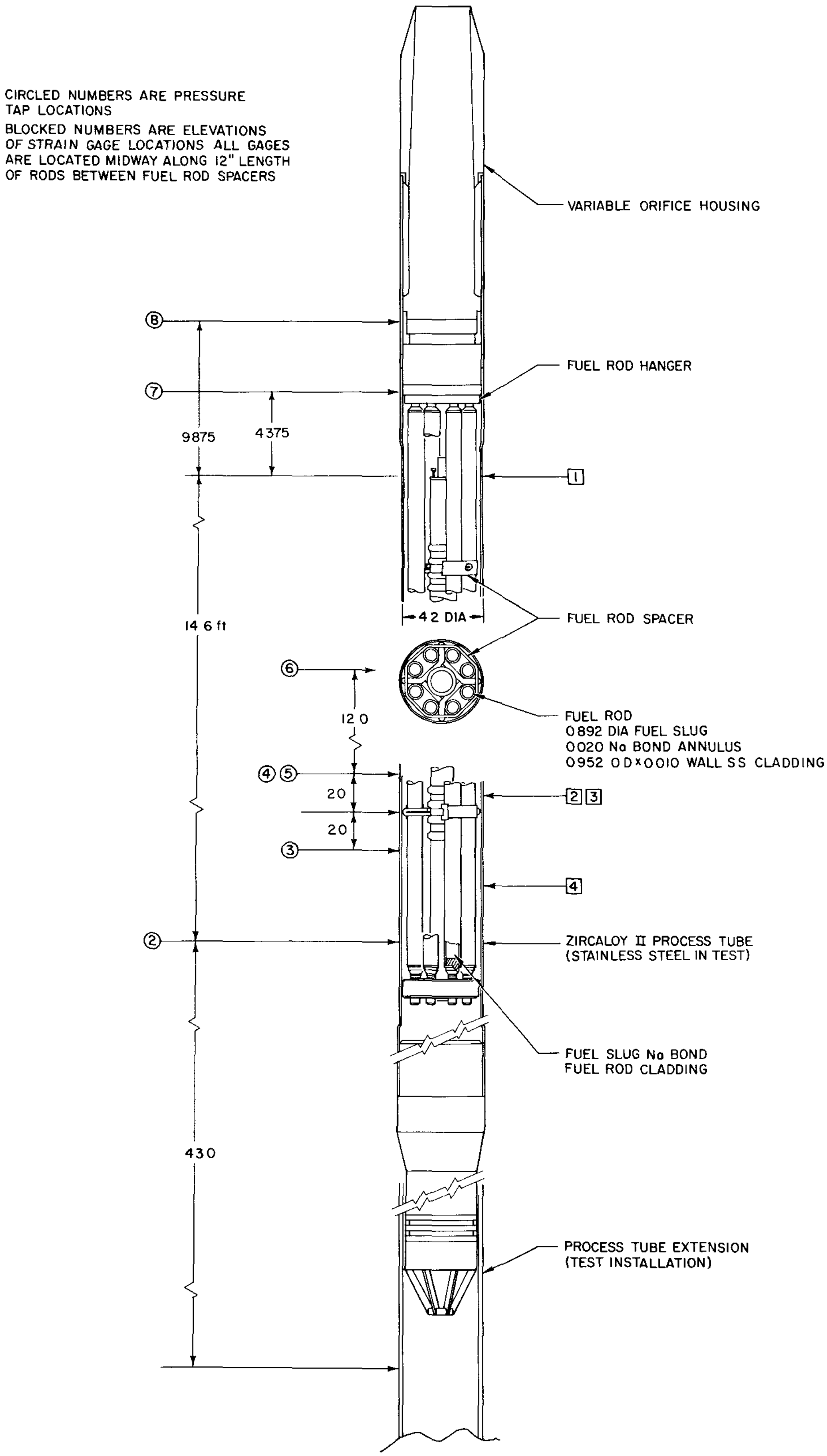

Figure 1. HNPF 8-Rod Fuel Assembly

f) Fuel slug length — 2 to 6 in.

g) Process-tube OD — 4.200 in.

h) Flow area (not including spacers) — 6.49 $in.^2$

i) Corrugated tube major diameter — 1-5/8 in.

j) Corrugated tube minor diameter — 1-7/16 in.

An experimental fuel element model was fabricated to the above dimensions and suspended vertically in a test section in the hydraulic loop. For the model, kerosene was utilized as a bond and lead slugs were substituted for UC.

III. TEST APPARATUS

A. TEST LOOP

The apparatus used to make the pressure-drop measurements (shown schematically in Figure 2) is comprised of two, parallel, pipe loops attached to a pump capable of circulating 700 gpm of water with 200 ft total differential head. Valves in the system permit individual operation of the two parallel loops, each of which contains a flowmetering section and a 24-ft vertical section for placement of an experimental fuel element. An 18-kw immersion heater installed in the in-line water-storage tank provides the necessary heat for the system. Materials of construction include plastic-coated carbon steel for the piping and tank, bronze for all valves, and 410 stainless steel for the centrifugal pump.

B. INSTRUMENTATION

To determine flow rates in the test section, pressure drops were measured across an ASME sharp-edged orifice plate with manometers connected to taps in the orifice-plate flanges. Orifice pressure drops were measured with either mercury of a 2.95 sp gr fluid* in a U-tube manometer or with 2.95 sp gr fluid in an inclined manometer. The flowmeter had been previously calibrated against a calibrated orifice meter and found to be accurate within 1%.

Fuel-element pressure drops were obtained by the use of U-tube manometers which indicated the differential pressures between piezometer rings attached to the process tube mockup. Indicating fluids used were mercury, 2.95 sp gr fluid, and carbon tetrachloride, depending upon the magnitude of the pressure drops being measured.

Fuel rod vibrations were determined by the use of 16 strain gages (Budd Metal-Film Gages) cemented to the exterior length of four fuel rods (Figure 1). Gage locations were selected at points of possible maximum rod deflection. All gages were oriented in a direction parallel to the axis of the fuel rods; two gages were used at each station and the gages were positioned at locations separated by a 90° arc. Lead wires from the gages were run vertically down the rods and out of the fuel-channel entrance tube through a seal. Each gage

*Meriam No. 3 Fluid, manufactured by the Meriam Instrument Co., Cleveland, Ohio.

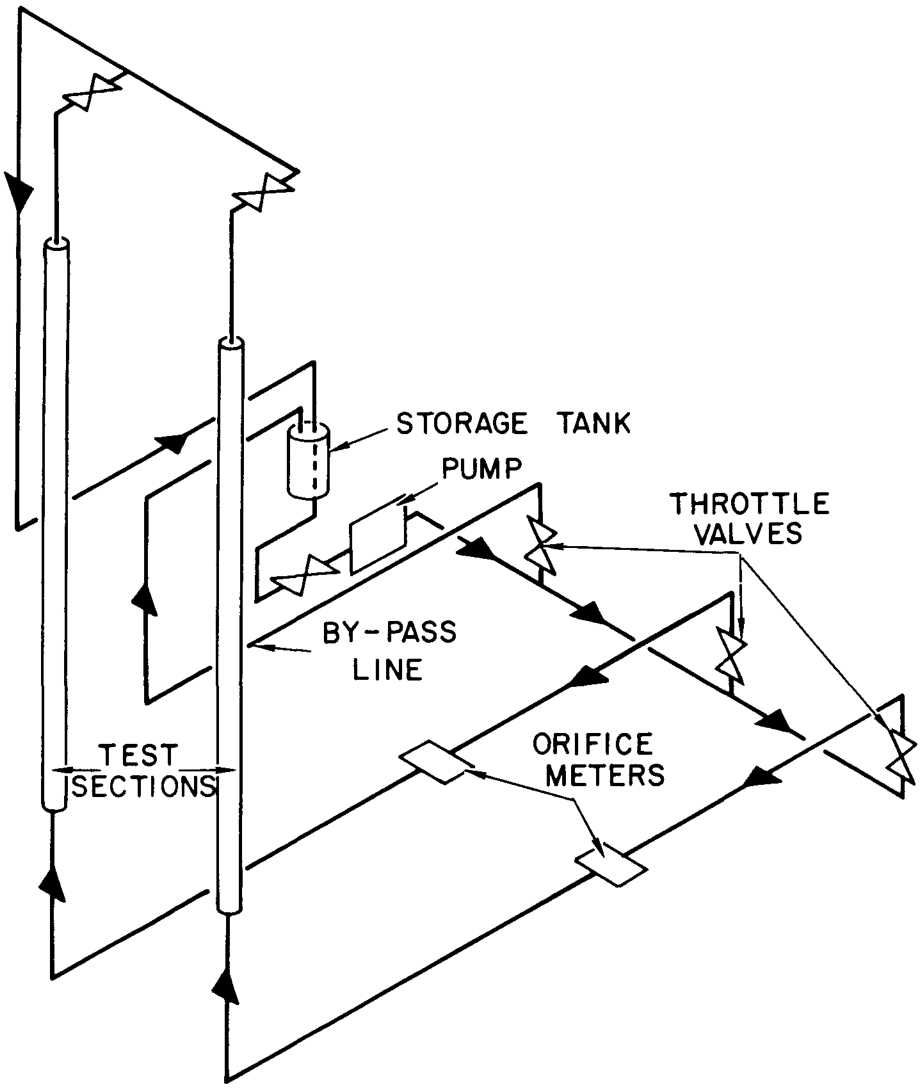

Figure 2. Flow Diagram of HNPF Hydraulic Loop

had seven coats of waterproofing; the lead wires, two coats. The gages were connected through individual bridge balances to a carrier amplifier and readout of the system was performed with an oscillograph. An oscilloscope connected in parallel with the oscillograph permited immediate visual monitoring of the strain signal during the test.

A circular-scale temperature indicator utilizing a dc potentiometer circuit calibrated for an iron-constantan thermocouple in the 0 to 300°F range was used to indicate system temperatures. The indicator accuracy was ±1/4%. Iron-constantan thermocouples were attached to the loop piping and supply tank wall. Thermocouples on loop piping measured the water temperature at the entrance and exit of the test section.

Bourdon gages were installed in the pump suction, pump discharge, and in the test-section exit region for indication of the test-loop pressures. These gages were only used to monitor the fluid pressure in the test loop; readings were not used in any calculations.

IV. PROCEDURES

A. TEST PROCEDURE

Principles of dimensional similitude were utilized to permit determination of the sodium system pressure drops from measurements obtained in a water system. The dynamic similarity requirements which assure similarity of flow processes for the two systems where incompressible fluids are considered and surface tension and gravity forces can be neglected, are geometrical similarity and Reynolds number similarity. These requirements were met experimentally by employing a full-scale model of the fuel element to provide geometric similarity and by adjusting the water temperature and velocity to provide Reynolds number similarity to the sodium system.

The exact nature of hydraulically induced vibrations in parallel rods under parallel fluid flow is not well known. In addition, the determination of vibrational characteristics of parallel rods in sodium systems from measurements obtained in a water system has not been satisfactorily described. It was considered sufficient, for the purpose of this work, to accept the similitude concepts employed for pressure-drop flow test procedure as applicable to the vibration-test procedure, since experimental fluid velocities and density exceeded those for sodium, at equal Reynold's numbers. For vibration studies, it is important that, in addition to the use of a full-scale model of the fuel element, the model shall also be constructed of materials with density and physical properties similar to those to be used in the actual element. The model fuel element used in these tests was constructed from the materials specified in the fuel element design, with the exception of substitution of kerosene for the sodium bond and lead fuel slugs rathan than UC. The effect of these differences on fuel rod vibration is discussed in a later section.

Water was heated to 170°F to approach the kinematic viscosity of sodium under average core-temperature conditions (776°F) and then was circulated through the test loop. The water was heated to allow simulation of reactor Reynolds numbers with lower water-flow rates than would be required if cold water were used. Water-flow rates were then varied to provide the range in Reynolds numbers equal to that found in the reactor at different power levels. Measurements were taken of ambient temperature, water-temperature, the pressure drops across the orifice flowmeter and the fuel element, and the responses of the strain gages on the fuel element rods. System pressure was maintained at a level high enough to prevent cavitation in the test section by adjustment of a control valve positioned downstream of the fuel element. Four separate test runs were made over the complete flowrate range to determine the precision of the pressure drop measurements.

Fuel-element pressure-drop measurements were taken across the entrance and exit of the fuel element assembly and across fuel rod spacers at locations noted on Figure 1.

Oscilloscope survey and oscillograph records were taken for all strain gages at various flowrates to determine dynamic vibration characteristics. In addition, tests were performed to determine the natural vibration frequency of the fuel rods. To induce vibration of the fuel rods, the fuel rod hanger and spacer were struck with a rubber hammer Vibrations were recorded as oscillograph traces of the strain gage responses. These tests to determine the natural frequency of the fuel rods were performed both with and without water inside the process tube.

B. METHOD OF CALCULATION

Experimental data obtained with water as the test fluid were converted to equivalent values for sodium using the principles of dimensional similitude. Geometric similarity was obtained by use of a full scale model. Dynamic similarity was therefore obtained by testing at Reynolds numbers in the water system equal to those developed in the sodium system. Data obtained in these tests were converted to equivalent values for sodium by calculating ΔP_{Na} and W_{Na} as follows:

$$\Delta P_{Na} = \frac{(v^2 \rho)_{Na}}{(v^2 \rho)_{H_2O}} \Delta P_{H_2O} \quad ,$$

and

$$W_{Na} = \frac{\mu_{Na}}{\mu_{H_2O}} W_{H_2O} \quad ,$$

where,

v = kinematic viscosity

μ = dynamic viscosity

ρ = density

ΔP = pressure drop

W = flowrate.

These relationships obtain for equal Reynold's numbers and are derived elsewhere[1,2].

V. RESULTS AND DISCUSSION

A. PRESSURE LOSS

Pressure drop measurements were performed prior to application of the strain gages and lead wires at flow rates equivalent to the reactor coolant requirements from 20 to 150% of full power. Pressure losses are tabulated in Table I and presented graphically in Figure 3.

TABLE I

PRESSURE LOSSES FOR THE HNPF 8-ROD UC FUEL ELEMENT

Reactor Power Level (%)	20	100
Sodium flow rate (lb/sec)	3.5	17.4
Overall pressure loss (psi)	0.27	5.6
Entrance loss (psi)	0.007	0.11
Exit loss (psi)	0.01	0.21
Spacer loss (psi)	0.0045	0.095

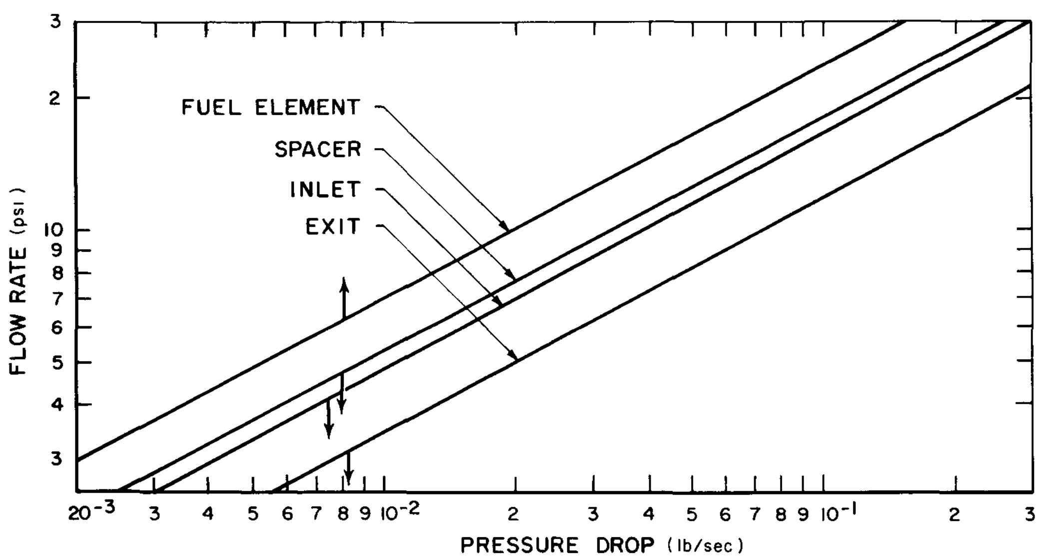

Figure 3. Pressure Drop vs Flow Rate for 8-Rod UC Fuel Element

1. <u>Fuel Bundle Friction Factor</u>

The Darcy friction factor is defined by the equation

$$f = \Delta P \left(\frac{\ell}{D} \frac{\rho V^2}{2g} \right)^{-1} \quad .$$

with

f = friction factor, dimensionless

ΔP = pressure drop, lb/ft^2

ℓ = length, ft

D = hydraulic diameter, ft

ρ = density, lb/ft^3

V = velocity, ft/sec

g = gravitational acceleration, ft/sec^2

Friction factors for the fuel rod bundle were calculated using pressure drops measured between taps 5 and 6 as shown on Figure 1 and are tabulated below.

TABLE II

8-ROD FUEL BUNDLE FRICTION FACTORS

Sodium Flow Rate (lb/sec)	Reynolds Number	Friction Factor	Smooth Tube Friction Factor
3.5	30,000	0.042	0.023
7.0	60,000	0.040	0.020
10.5	90,000	0.038	0.018
14.0	120,000	0.037	0.017
17.4	150,000	0.036	0.016

The D used to calculate friction factor was based on the flow area and wetted perimeter at the major diameter of the corrugated tube.

2. Spacer Loss

The spacer loss was determined from measurements between taps 3 and 4 on Figure 1. The loss chargeable to the spacer is equal to the measured loss from H to I minus the pressure drop which would occur had there been no spacer between these taps. The spacer pressure drop curve on Figure 3 was determined in this way.

3. Entrance and Exit Losses Coefficients

Loss coefficients were determined for the entrance and exit fittings on the fuel element. These losses (in terms of velocity head) are plotted in Figure 4. These coefficients do not agree well with published coefficients for equal flow area ratios due to the complex geometrical configuration. They are in approximate agreement with results from tests on other HNPF fuel elements[1,2].

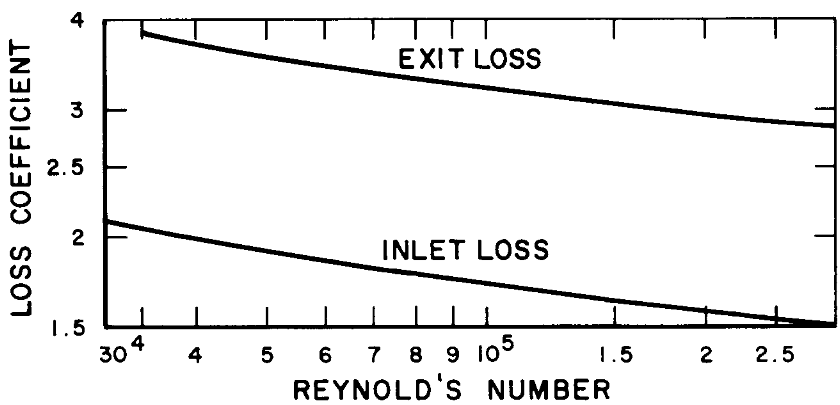

Figure 4. Fuel Element Inlet and Exit Pressure Loss Coefficients

B. VIBRATION

1. Natural Frequencies of Fuel Rods

Calculated and experimentally determined natural frequencies of the fuel rods are presented in Table III. Experimental values were computed from oscillographic traces of strain gage output. The natural frequency of a rod is a function of its geometry, end condition, mass, and modulus of elasticity and may be calculated from

$$\omega_n = a_n \sqrt{\frac{EI}{mL^4}}$$

with

ω_n = natural frequency, sec^{-1}

a_n = numerical constant dependent on end conditions (in this case 1.0)

E = modulus of elasticity, $lb/in.^2$

I = moment of inertia about neutral axis, $in.^4$

m = mass per unit length, $lb/in.^2-sec^2$

L = length between spacers, in. (in this case 18 in.).

TABLE III

NATURAL FREQUENCY OF FUEL RODS

	Experimental (cps)	Calculated (cps)
Air	20	30.5
Water	20	-

The model fuel rods were loaded with lead slugs and kerosene was substituted for the sodium bond. Use of kerosene would have virtually no effect on the fundamental mode of cladding vibration because there is little difference in density between sodium and kerosene. Furthermore the bond fluid contributes only a negligible fraction of fuel rod mass as far as vibration is concerned. The mass per unit length is predominantly determined by the fuel slugs. The use of lead (density = 11.3) slugs instead of UC (density 13.6) in the model fuel element would theoretically increase the natural frequency by 10%.

2. Vibration of fuel Rods Under Coolant Flow

The coolant flow patterns in the 8-rod UC fuel element were observed by dye injection into the flowing water stream. Dye injected near the inner surface of the fuel rods diffused to the outside surface in a random fashion within 18 in. of injection point under all flow conditions. While such fluid mixing is not required for cooling purposes, it does exist and therefore produces forces on the fuel rods in a radial direction. A restoring force is produced in deflected fuel rods due to the cladding elasticity. In addition, a damping force resisting rod motion is developed by the viscosity and mass of the coolant.

The vibration pattern in any structure normally begins with the fundamental mode because this requires the minimum energy input. Increasing input force increases the amplitude of vibration in the fundamental mode until the point is reached where the second mode requires less input energy. At this point, the mode shifts from fundamental to second mode.

Previous studies of fuel rod vibration[3] predict such low amplitudes of vibration that critical amplitude for transition from fundamental to second mode vibration would not be expected to occur. The fuel rods were therefore instrumented for studies of the fundamental mode. Very sensitive (<10 μin. /in.) strain gage readout circuitry was employed (with Budd Metal Film Gages) for the vibration tests. No discernible strains were detected in the fuel rod cladding at water flow rates up to 40 lb/sec. For a strain of 10 μin. /in. , the fuel rod cladding would deflect 0.0005 in. at the center of the 18-in. span between spacers. The fuel element design permits a fuel rod to deflect about 1/8 in. Therefore, no geometrical restraint impeded the motion. Since no strains were observed, it is concluded that hydraulically induced vibration will not cause damage to the fuel rods.

C. APPLICATION OF VARIABLE ORIFICE TO 8-ROD UC FUEL ELEMENT

The HNPF reactor core is equipped with manually variable orifices to control the individual coolant channel flow rates. These orifices permit adjustment of channel flow during operation to provide equal exit temperatures from all channels. The initial core loading at the HNPF is of 18-rod fuel clusters. With this core loading, the total core pressure drop (fuel element plus variable orifice assembly) is 11 psi at full power operation. A number of 8-rod UC fuel elements will be inserted in the predominantly 18-rod core at some future date. The predicted coolant flow requirement for the 8-rod elements in that core loading is 17.4 lb/sec at full power operation. The existing variable orifices must be capable of adjusting the flow rate to this value. To determine the flow control capability of the variable orifice attached to the 8-rod element, the measured fuel element pressure drop was added to the variable orifice pressure drop which was determined previously.[4] These data are plotted on Figure 5 for different variable orifice positions from fully inserted to fully withdrawn. Figure 6 is a cross plot of Figure 5 and shows flow rate vs variable orifice position at a core pressure drop of 11 psi. The range of flow control is from 5.7 to

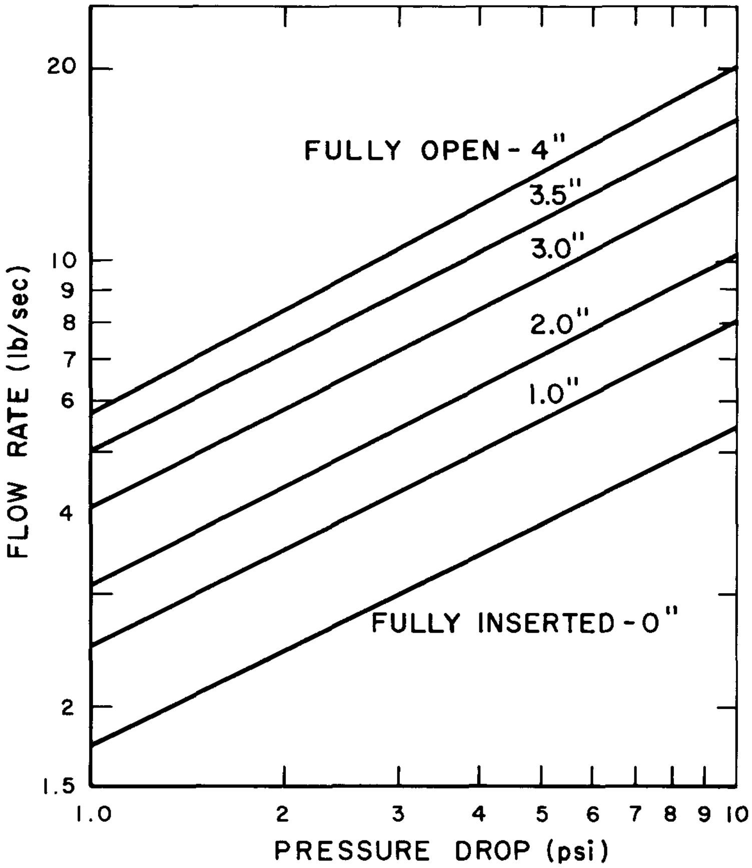

Figure 5. Flow Rate vs Pressure Drop for 8-Rod Fuel Element plus Variable Orifice Assembly

21 lb/sec which is more than adequate for use with the 8-rod fuel element in a predominatnly 18-rod core loading.

A measure of the variable orifice effectiveness as a flow control device is the so-called "sensitivity."[5] Sensitivity refers to the change in coolant outlet temperature which results from an adjustment in variable orifice position. The HNPF variable orifice requires a total of 256 adjustments to span the 4 in. of orifice travel. Figure 7 shows the orifice sensitivity as a function of orifice position. It may be noted that the sensitivity is less than 2-1/2°F per adjustment increment over the entire range of orifice travel. Therefore no damage can result to the elements or core structure due to an individual adjustment.

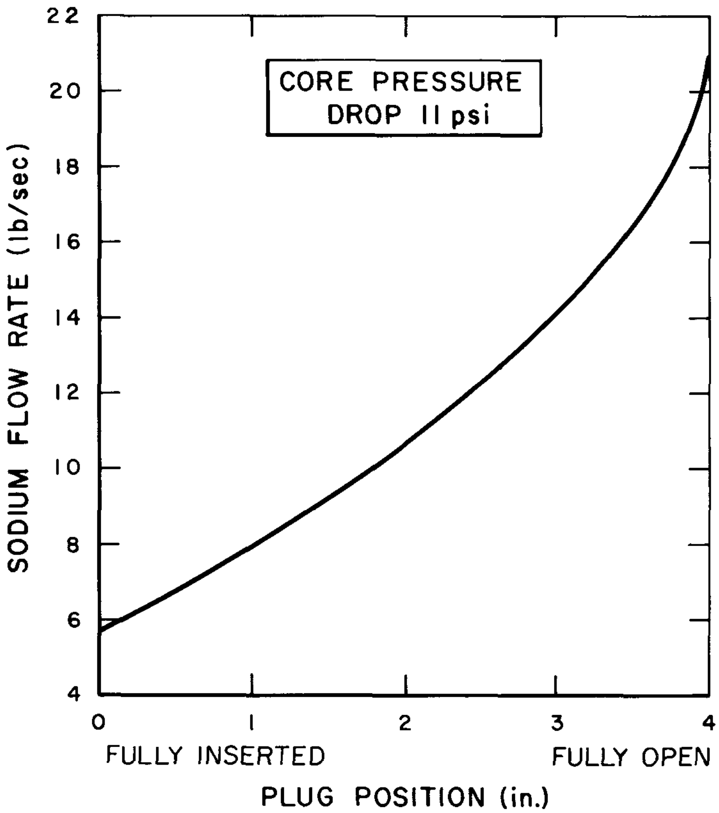

Figure 6. Flow Rate vs Variable Orifice Plug Position 8-Rod UC Fuel Element

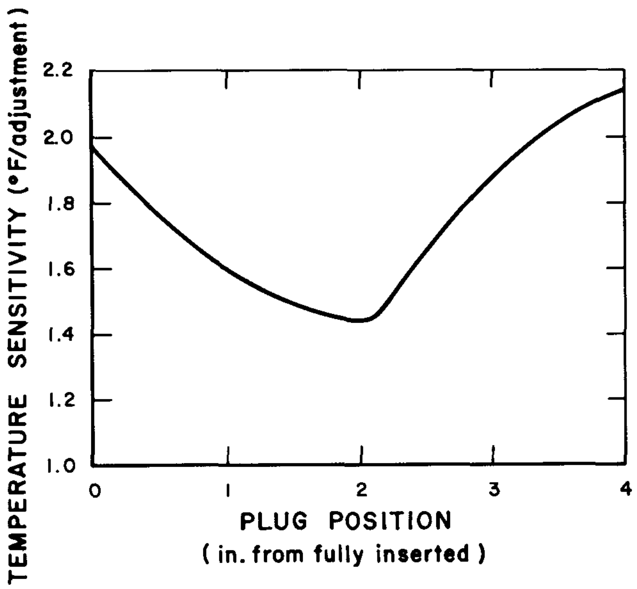

Figure 7. Temperature Sensitivity vs Orifice Position

VI. SUMMARY

Hydraulic characteristics of an 8-rod UC fuel element were studied using water as a test fluid to simulate sodium, the coolant in the reactor. A full size model was employed and the principles of dimensional similitude were used to convert water test data to equivalent values for sodium.

Pressure drop measurements on the fuel bundle yielded values from 0.27 to 5.6 psi over the flow range from 3.5 to 17.4 lb/sec which corresponds to a power level range of 20% to full power. The total pressure drop of the 8-rod bundle-variable orifice assembly was determined by adding the previously determined orifice pressure drop to the measured fuel bundle drop. The range of orifice flow control was determined for a core pressure drop of 11 psi which corresponds to the drop across the HNPF core composed primarily of 19-rod elements. This range of 5.7 to 21 lb/sec is more than adequate to provide cooling for the fuel element. The temperature sensitivity of the variable orifice attached to an 8-rod element was determined to be less than 2-1/2°F per adjustment increment.

No significant vibrations were observed in the fuel rods during dynamic water tests. Therefore, no significant stresses should occur in the cladding due to hydraulically induced vibrations.

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