NAA-SR-5369
REACTORS-POWER
35 PAGES

DEVELOPMENT OF A VARIABLE ORIFICE FOR HNPF FUEL CHANNELS

BY

C. J. BAROCZY
J. A. HAGEL
W. D. LEONARD

ATOMICS INTERNATIONAL

A DIVISION OF NORTH AMERICAN AVIATION, INC.
P.O. BOX 309 CANOGA PARK, CALIFORNIA

CONTRACT: AT(11-1)-GEN-8
ISSUED: MAY 1 1961

DISCLAIMER

DISTRIBUTION

This report has been distributed according to the category "Reactors - Power" as given in "Standard Distribution Lists for Unclassified Scientific and Technical Reports" TID-4500 (15th Ed.), August 1, 1959. A total of 620 copies was printed.

CONTENTS

TABLES

FIGURES

ABSTRACT

Control of the exit temperature of the coolant from each fuel channel of the Hallam Nuclear Power Facility reactor is obtained by adjusting the coolant flow rate by means of a remotely operated variable orifice. Two variable orifices were designed and the hydraulic characteristics determined. Both orifice designs utilized a tapered plug moving in and out of a restricted flow passage at the upper end of the fuel channel. Data were obtained on pressure drop vs flow rate at different orifice plug positions; all measurement were made using water, and data were converted to equivalent values for sodium. Either type of orifice was capable of adjusting flow rate to match the power output of a fuel element at any location in the reactor core. The temperature sensitivity (change in exit temperature per unit change in orifice plug position) of the first type of orifice was low (10°F/in.) when used in combination with a central fuel element, and high (700°F/in.) when used with a peripheral element. The temperature sensitivity of the second type was more uniform (varying from 90°F/in. to 250°F/in.). Consequently, the second type of orifice was selected for the HNPF.

I. INTRODUCTION

Thermal performance of the core of a nuclear power reactor can be improved by controlling the coolant flow rate in each fuel channel to obtain uniform exit temperatures. To accomplish this, the coolant flow rate through each fuel channel must be proportional to the power generated by the fuel element in that particular channel. Fixed orifice plates can provide the impedance for control of flow through each fuel element; however, fixed orifice plates do not allow for "in-core" trim to overcome mismatch of flow rate and channel power. To make minor adjustments with such a system, the reactor must be shut down while the orifice plates are replaced. A remotely operated variable orifice would permit adjustment of the impedance to flow within the fuel channel to be made from outside the core during reactor operation. The development of such a variable orifive for use with the first core loading in the Hallam Nuclear Power Facility is the objective of the work reported here.

The most practical location for a variable orifice in the HNPF core is at the exit (top end) of each fuel channel. In this location, the fuel element hanger tube can be utilized as a support for the mechanical components necessary to adjust the variable orifice. A tapered plug, moving in and out of a constricted section at the exit end of each fuel channel process tube, can vary the flow impedance by changing the annular flow area.

Originally, a variable orifice which exhibited a linear change in flow rate vs plug position (at a constant pressure drop across the reactor core) was considered a satisfactory design objective. Subsequently, it became apparent that undesirably large changes in coolant exit temperature could result from only a small change in plug position over some regions of plug travel, while in other regions of plug travel a large change in plug position could cause very little change in coolant exit temperature. This type of temperature response is not desirable from an operations standpoint. Consequently, the geometry of the orifice was modified to a configuration which would effect a more uniform change in exit temperature with change in plug position.

Simultaneously with the development of the orifice, changes were made in the fuel element design to incorporate findings from exponential experiments, hydraulic tests, and trial fabrication tests on the fuel element. Accordingly, the orifice was altered to compensate for those changes which influenced the flow impedance. The principal changes involved: (1) an increase in the outside diameter of the fuel rod cladding from 0.625 to 0.650 in.; (2) a change in the disconnect mechanism which permits the fuel element to be separated from the orifive and upper hanger plug; and (3) a decrease in the power ratio (ratio of power produced in a center element to power produced in a peripheral element) from 4.0 to 3.2. This last change resulted in a decrease in the maximum flow rate expected during full-power operation from 28 lb/sec to 22.5 lb/sec. In addition, the fuel from the central rod of the 19-rod ruel element was removed, but this did not alter the hydraulic characteristics (the 18-rod element consists of 19 tubes with the central tube empty). Consequently, in this report all fuel elements will be referred to as 19-rod fuel elements.

The approach followed in developing the HNPF variable orifice was first to determine analytically the general configuration of the orifice structure (viz; the tapered plug, plate, and hole) and the immediately adjacent flow-section. Due to the irregularity of the flow in the vicinity of the orifice, an accurate analysis was difficult. An orifice, with the configuration indicated by analysis, then was fabricated and experiments were performed to determine the precise geometry required to obtain the flow control desired. All tests were performed using water as the test fluid. As the 250-Mwt HNPF reactor will be sodium-cooled, application was made of the principles of dimensional similitude to permit conversion of the data obtained with water to equivalent values for sodium.

II. DESIGN OF VARIABLE ORIFICES

The variable flow control orifices are, in effect, valves whose impedance to coolant flow can be adjusted remotely from outside the core during reactor power operation. Each orifice consists of a tapered plug moving in and out of a constricted section at the exit end of each fuel-channel process tube.

The plug is operated by a mechanical drive linkage extending upward through the hanger tube and top plug. This drive mechanism is constructed to prevent neutron streaming through the mechanism itself, and it is sealed to prevent escape of reactor pool cover gas.

A. VARIABLE ORIFICE I (UNIFORM CHANGE OF WEIGHT FLOW)

The first variable orifice (Figure 1) was designed to obtain a linear change in flow rate vs orifice plug position, when attached to a 19-rod fuel element with

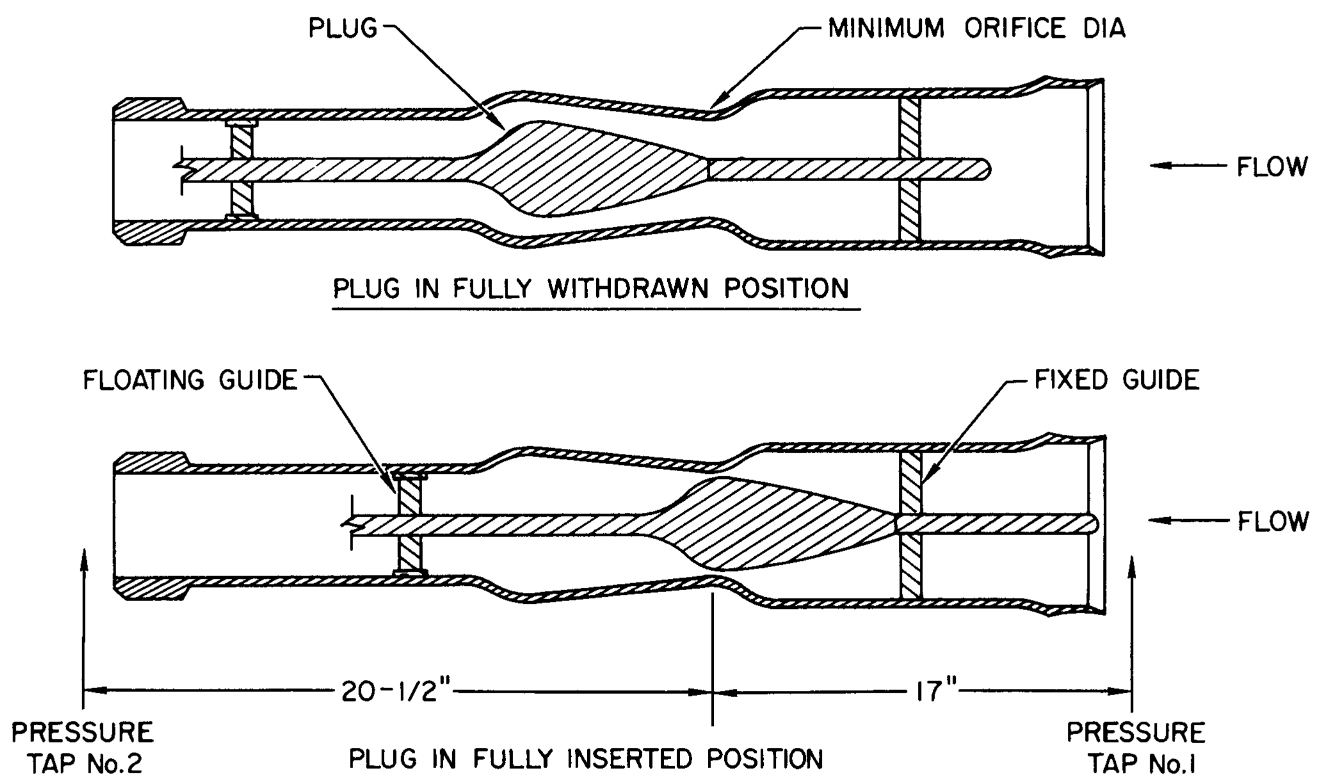


Figure 1. Variable Orifice, Type-I

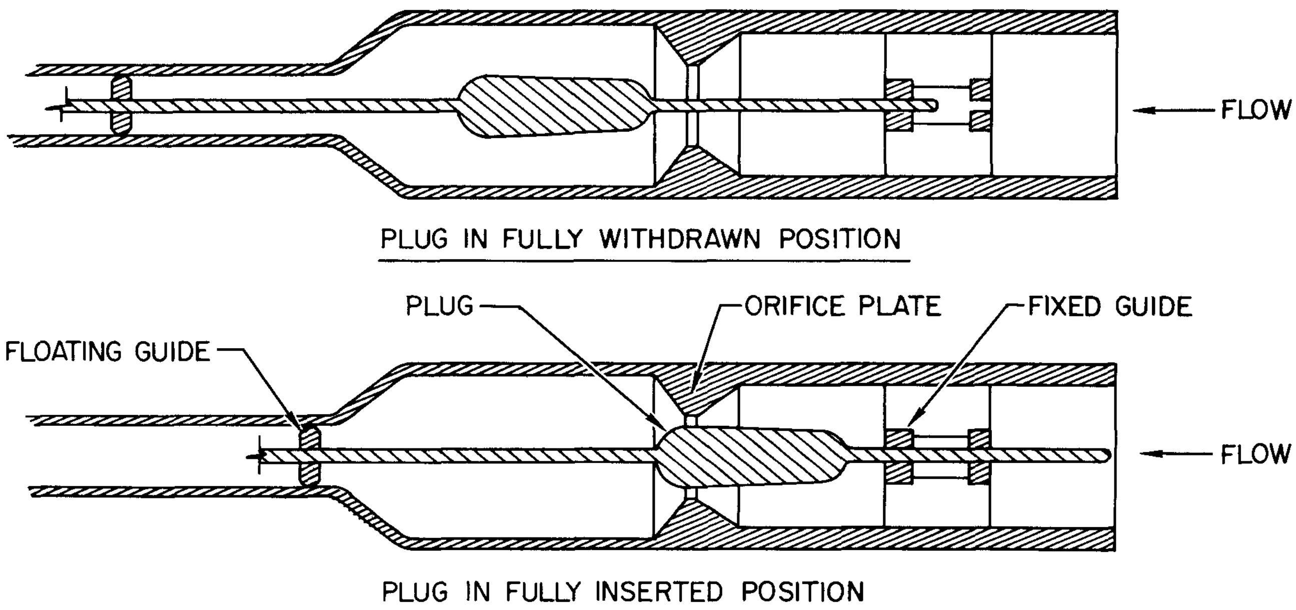
5.0 sq in. of fuel area. A family of curves relating orifice pressure drop to flow rate for various orifice plug positions was established, based on the requirement for a linear relationship of flow rate and plug travel. The analysis utilized to determine the design of orifice which would approximate these curves was based upon the fact that the major pressure losses through the orifice were expansion-contraction losses. Thus, an expression relating the pressure loss through a geometry of varying flow area was used as the primary relationship for the analytic determination of the orifice geometry. This expression utilized standard contraction-expansion loss coefficients in an integrative manner across the active length of the variable orifice.

During full-power operation, the maximum permissible pressure drop across the HNPF core will be 17 psi. At the time that Variable Orifice I was designed, the flow rate of sodium coolant expected was 28 lb/sec past a fuel element at the center of the core, and 7 lb/sec past a fuel element at the periphery of the core. The first step in designing Variable Orifice I was to assume an orifice plug shape that would be relatively easy to fabricate; namely, a conical shape. Next, the required annular space around the plug was computed so that in the fully inserted position the orifice would cause a pressure drop of 17 psi at a flow rate of 7 lb/sec. Then computations were made to ascertain that in the fully open position the orifice would not cause a pressure drop greater than 3 psi at a flow rate of 28 lb/sec. The 3-psi limit is obtained by subtracting the pressure drop of 14 psi expected across the fuel element from the maximum permissible value of 17 psi.

The design thus evolved (Figure 1) was that of a conical-shaped plug moving through a restricted area of a streamlined hour glass-shaped channel. The inlet diameter of the channel was 4.00 in., and the exit diameter was 2.50 in. The orifice restriction area was located about halfway along the length of the channel, and the channel diameter at this point was 2.375 in. The length of travel of the plug and the axial length of the conical contour of the plug were each 4 in. The maximum diameter of the plug was at the trailing edge (the "base" of the cone). Initially, this maximum diameter was 2.345 in.; later, the plug was machined down to a diameter of 2.340 in. and then to 2.250 in. for the purpose of determining the influence of the plug diameter upon the pressure drop vs flow characteristics.

B. VARIABLE ORIFICE II (UNIFORM CHANGE OF EXIT TEMPERATURE)

The orifice will be adjusted so that the exit temperature of the coolant from each channel is equal to the design exit temperature of 945°F. To avoid rapid or excessive changes in the exit temperature of any channel during adjustment, it is desirable that movement of the orifice plug result in moderate and uniform temperature changes. The Type II orifice (Figure 2) in combination with a 19-rod fuel element with 5.2 sq in. of fuel area was designed to obtain this desired "sensitivity" (uniform change in coolant exit temperature <u>vs</u> plug position).



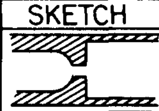
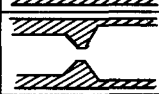
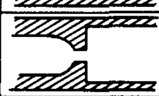
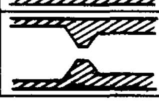
TYPE	PLUG MAX. DIA	ORIFICE PLATE		CHANNEL DIA	
		MIN. DIA	SKETCH	UPSTRM	DNSTRM
	(in.)			(in.)	
A	2.078	2.200		3.500	3.250
B	2.078	2.200		3.500	3.250
C	2.691	2.795		3.500	3.250
D	2.078	2.200		3.250	3.500

Figure 2. Variable Orifice, Type-II

To determine the Type II design, the same analytic procedure was used to determine pressure drop and its relationship to geometry as for the Type I design. However, to satisfy the new design objectives, a relationship between coolant exit temperature and fuel channel coolant flow rate was necessarily incorporated into the analysis, as follows.

The sensitivity of the orifice, S, is defined as

$$S = \frac{dt_o}{dx}$$

where

t_o = sodium outlet temperature, °F, and

x = plug position, in.

The outlet sodium temperature can be expressed as

$$t_o = \frac{B}{w} + t_i$$

where

B = a function of the power generated in the element, lb-°F/sec

w = flow rate of sodium past the element, lb/sec

t_i = inlet sodium temperature, °F.

Differentiating this expression with respect to x, the sensitivity becomes,

$$S = \frac{-B}{w^2} \frac{dw}{dx} .$$

As it is desired that the orifice produce a uniform change in outlet temperature per unit change in orifice plug position, S must be a constant. Then, integrating the equation above, the following relation between flow rate and plug position is obtained.

$$\frac{1}{w} = \frac{S}{B} x + C$$

where C is the constant of integration. Then, since the range of flow control desired is 22.5 lb/sec to 7 lb/sec, and since the orifice plug travel has been fixed at 4 in., w = 22.5 at x = 0 (orifice plug fully withdrawn); and w = 7 at x = 4 (orifice plug fully inserted). Substituting into the equation above, $\frac{S}{B}$ = 0.0246, and C = 0.0444, or

$$w = \frac{1}{0.0246x + 0.0444} .$$

This expression for w, the sodium flow rate, is then substituted into an expression relating pressure drop to w and to A (the flow area of the orifice). The flow area required determines the shape of the orifice plug. After substituting the flow area A as a function of plug position x, a curve can be prepared of sodium flow rate vs orifice plug position at any constant pressure drop (e.g., the expected core pressure drop).

The Type II variable orifice (Figure 2), designed in the preceding manner, contains a parabaloid-shaped plug moving through a restricted flow area in a hollow cylindrically shaped channel. The orifice restriction area (essentially an orifice plate) is located about halfway along the length of the channel. The length of travel of the plug is 4 in.; the axial length of the plug is also 4 in. The Type II orifice was gradually modified during the course of testing so that, in all, four configurations of the Type II design were tested. Pertinent dimensions of these four configurations are tabulated below.

TABLE I

TYPE II ORIFICE CONFIGURATIONS

Orifice Type	Maximum Plug Diameter (in.)	Minimum Orifice Plate Diameter (in.)	Channel Diameter	
			Upstream (in.)	Downstream (in.)
IIA	2.078	2.200	3.500	3.250
IIB	2.078	2.200	3.500	3.250
IIC	2.691	2.795	3.500	3.250
IID	2.078	2.200	3.250	3.500

In the Type IID orifice, it was necessary to reverse the upstream and downstream dimensions because of a design change in an adjacent disconnect mechanism which permits separation of the fuel element.

III. TEST EQUIPMENT AND PROCEDURE

A. TEST LOOP

The apparatus used to make the pressure-drop measurements (shown schematically in Figure 3) is comprised of two parallel pipe loops attached to a centrifugal pump which is 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 flow-metering section and a 24-ft vertical section for placement of an experimental fuel element. An 18-kw immersion heater installed in the inline 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 Type 410 stainless steel for the pump.

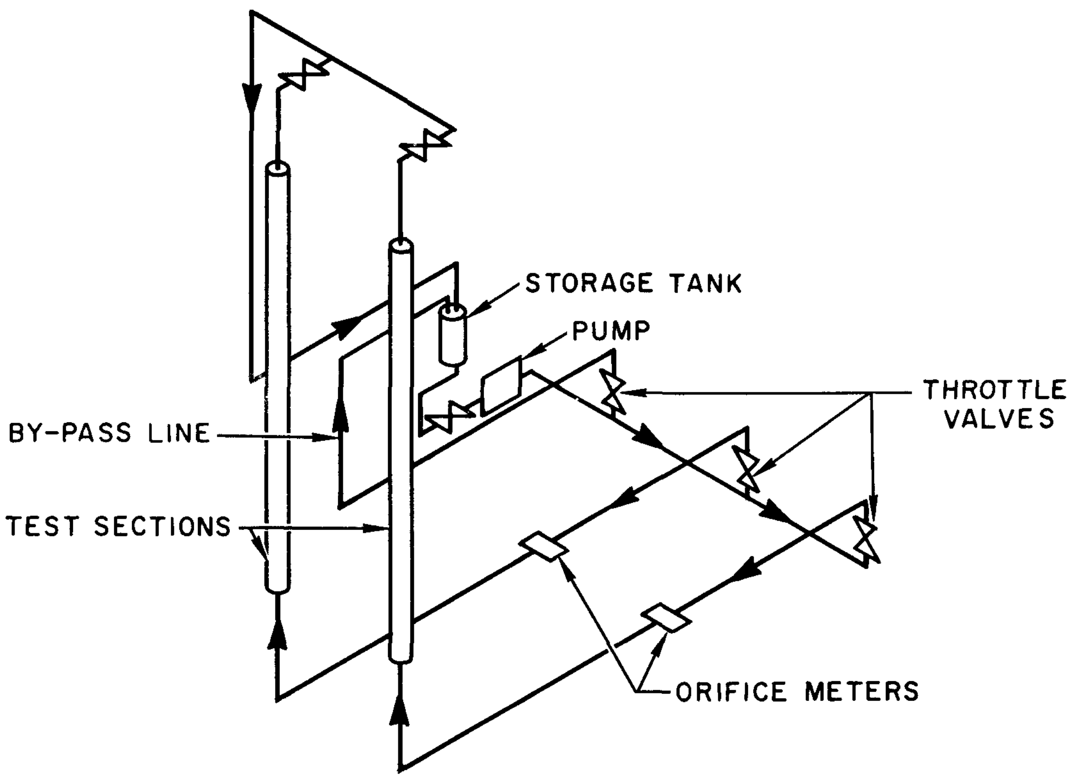


Figure 3. Flow Diagram of HNPF Hydraulic Loop

Demineralized water is circulated by the pump through a check valve and then into a manifold, from which it can be delivered to any combination of a by-pass line and the two parallel test loops by adjustment of globe valves. The by-pass line delivers water discharged from the pump directly to the storage tank. Water entering the test loops passes through a horizontal flow-metering section (containing straightening vanes upstream of a sharp-edged orifice plate), then upward through the vertical test section. Flowing through a gate valve, the water travels into a return downcomer common to the two vertical test section legs. The downcomer leads directly into the water-storage tank.

B. INSTRUMENTATION

Flow rates in the test section were determined by measuring pressure drops across an ASME sharp-edged orifice plate with manometers connected to taps in the orifice-plate flanges. High flow rates were measured with either mercury or a 2.95 sp gr fluid* in a U-tube manometer. Low flow rates were measured with the 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 one percent.

Orifice pressure drops were obtained by use of U-tube manometers, which indicated the differential pressures between piezometer rings attached to the variable orifice under test. The indicating fluids used were mercury and 2.95 sp gr fluid, depending upon the magnitude of the pressure drops being measured.

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

Bourdon-tube gauges were used in the pump suction, pump discharge, and in the test-section exit region to indicate test-loop pressures. Pressure readings were used to monitor the conditions in the loop but were not used in any calculations; consequently these gauges were not calibrated.

C. TEST ORIFICES

The variable orifices were fabricated out of Type 304 stainless steel. Flanges were welded to their exterior to facilitate mounting the orifice near the top end of one of the vertical test sections in the test loop.

---

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

Orifice plug position was varied by an external gear and pinion mechanism which meshed with a threaded section on the top end of the rod attached to the orifice plug. This rod was sealed against water leakage with concentric "O" rings located in a blind flange at the top of the test section. The orifice plug could be locked at any desired position, and location was determined on an external scale originally indexed to a known orifice plug position.

D. TEST PROCEDURE

Principles of dimensional similitude were applied to permit determination of fluid pressure drops for a sodium system 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 full-scale models of the variable orifice to provide geometric similarity, and by adjusting the water temperature and velocity to provide Reynolds number similarity to the sodium system. The annular flow area through the orifice, at constant plug position, is influenced by thermal expansion. Since the water temperature is necessarily less than the sodium temperature, the water flow area is less than the actual flow area with sodium. So, to obtain equivalent flow areas (hence equivalent hydraulic characteristics) the plug position in water is made slightly different from the plug position in sodium. The maximum difference in plug positions introduced by these thermal effects is 1/32 in., which is negligible compared to the 4-in. total plug travel. The temperature effect on model geometry can therefore be neglected.

Water was heated to 170°F to approach the kinematic viscosity of sodium under core exit temperature conditions (945°F). (The purpose of heating the water was to allow simulation of Reynolds numbers with lower water-flow rates than would be required if cold water were used.) The orifice plug position was varied over the full 4-in. travel, and water flow rates were varied between 2.67 lb/sec and 44 lb/sec to provide the range in Reynolds numbers equal to that expected in the HNPF reactor at different power levels. Measurements were taken of ambient temperature, water temperature, and the pressure drops across both the variable orifice and the flow metering orifice. 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 variable orifice.

Pressure drops across the variable orifice were measured by a differential manometer connected across the orifice at two pipe diameters upstream and five pipe diameters downstream of the orifice area. The inside diameter of the flow channel at the upstream pressure tap was 4.2 in; at the downstream tap, 2.5 in. (The velocity difference resulting from this condition was taken into account in computing the actual pressure loss.)

Three series of tests were performed with the Type I variable orifice (Figure 1) mounted in the loop. Three different plug diameters (maximum of 2.250, 2.340, and 2.345 in.) were tested; the minimum orifice channel diameter was retained constant at 2.375 in. for all three plug diameters. As a final test, the variable orifice with a plug diameter of 2.340 in. was attached to the 5.0 in.^{2} 19-rod element[2]; and the pressure drops were measured across the entire assembly and across the fuel element.

Four configurations of the Type II variable orifice (Figure 2) were tested. Pressure drop measurements were obtained at various flow rates with the orifice plug in the following positions: fully withdrawn, inserted 1 in., 2 in., 3 in., and 4 in. (fully inserted). As a final test, each Type II orifice was attached to the 5.2 in.^{2} 19-rod element; and the pressure drop was measured across the entire assembly and across the fuel element.

IV. TEST RESULTS

A. VARIABLE ORIFICE - TYPE I (UNIFORM CHANGE OF WEIGHT FLOW)

The Type I orifice was designed to effect a smooth, essentially uniform change of flow rate with respect to plug movement over a 4-in. travel. Data were obtained for Type I orifices with three different clearances between the plug and the constricted section (minimum diameter of 2.375 in.) through which the plug moves. Figure 4 is a plot of pressure loss vs flow rate of sodium for orifice plug diameters of 2.345, 2.340, and 2.250 in., resulting in minimum diametrical clearances between orifice plug and orifice channel of 0.030, 0.035, and 0.125 in. In the fully open position, the change in plug diameter has a negligible effect, and data points for the three plug sizes all fall on one curve; at a flow rate of 28 lb/sec, the pressure loss is well below the upper limit of 3 psi. In the fully-closed position, the change in plug diameter does have a significant effect; the pressure loss at any given flow rate decreases as the diametrical clearance is increased. At a flow rate of 7 lb/sec and with a diametrical clearance of 0.125 in. (Type IC), the pressure loss is less than the desired value of 17 psi; however, at this flow rate the orifices with minimum diametrical clearances of 0.030 in. (Type IA) and 0.035 in. (Type IB) did meet the pressure-loss requirement. On the basis of these tests, the Type IB orifice with a clearance of 0.035 in. was selected for further study because the pressure drop vs flow rate characteristics came closest to the values desired.

Data were obtained with the Type IB orifice by moving the plug to various positions between fully withdrawn and fully inserted, and are plotted in Figure 5. These curves show that at any given flow rate the pressure loss increases as the orifice plug is inserted into the constricted region.

Figure 6 is a plot of the experimental pressure-loss data of the orifice alone (from Figure 5) added to the experimental data obtained with a 19-rod fuel element with 5.0 in.^{2} of fuel area.* Samples of data from subsequent tests, performed with the variable orifice and fuel element in combination, are shown as points on the plots for the fully inserted and fully withdrawn positions. As these sample points obtained from experimental data fall directly on the predicted curves, the validity of making such an addition is verified.

*Ref: NAA-SR-4385, "Hydraulic Characteristics of HNPF Preliminary Design Fuel Elements," page 18, by S. Sudar and D. Rosh.

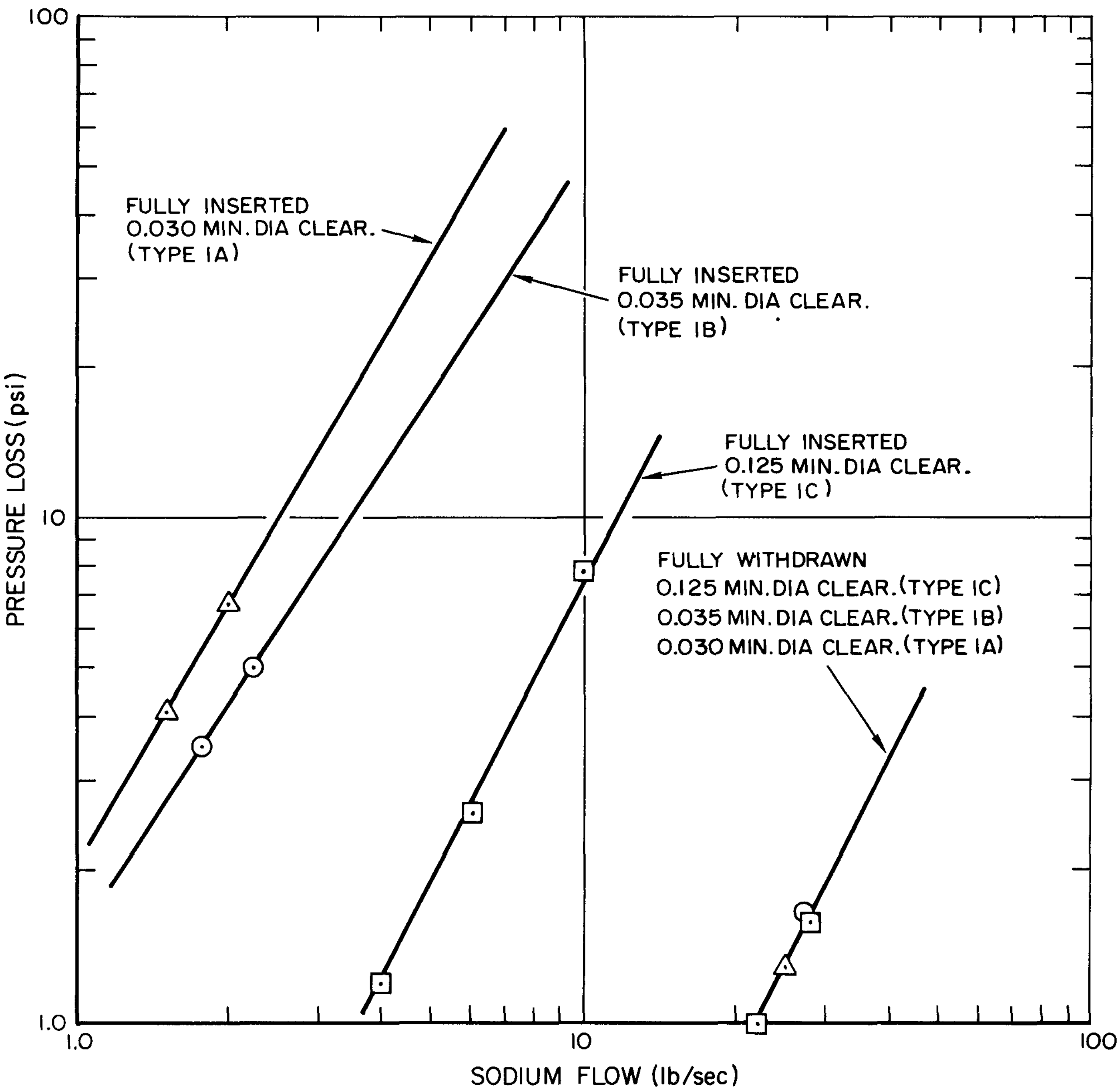


Figure 4. Pressure Loss Across Type-I Variable Orifice with Various Diametral Clearances

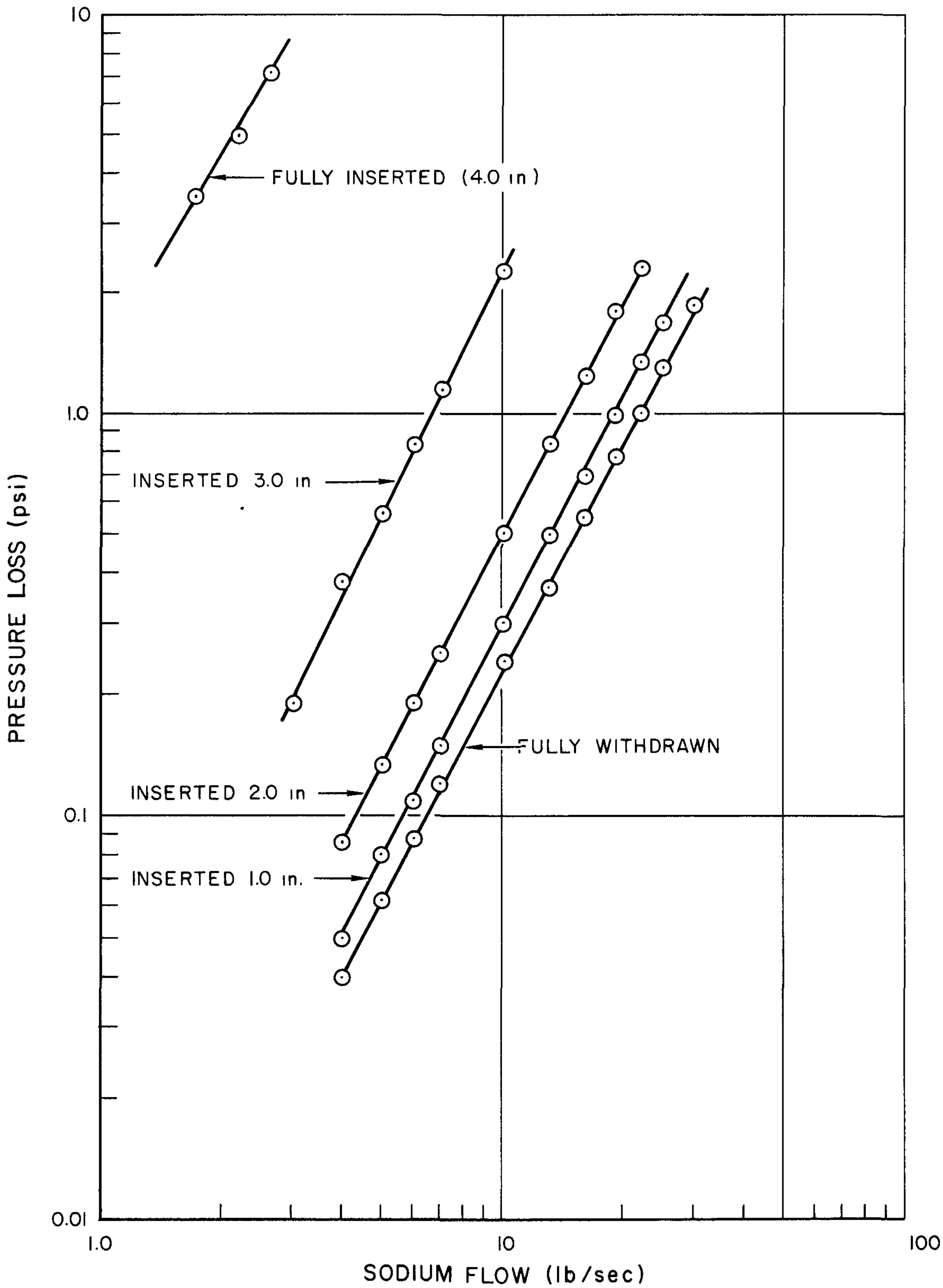


Figure 5. Pressure Loss Across Type-IB Variable Orifice at Different Plug Positions

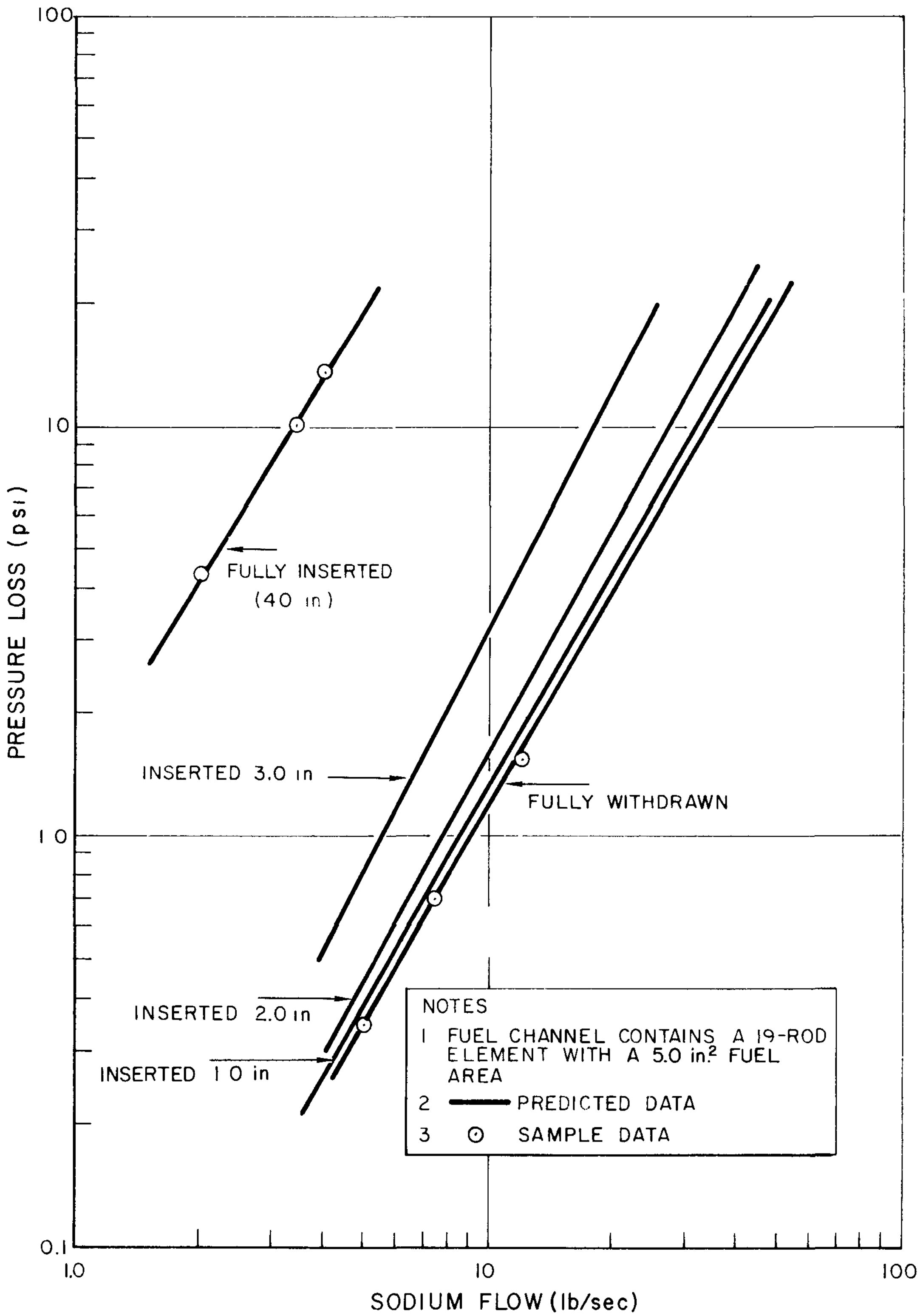


Figure 6. Pressure Loss Across HNPF Fuel Channel with Type-IB Variable Orifice

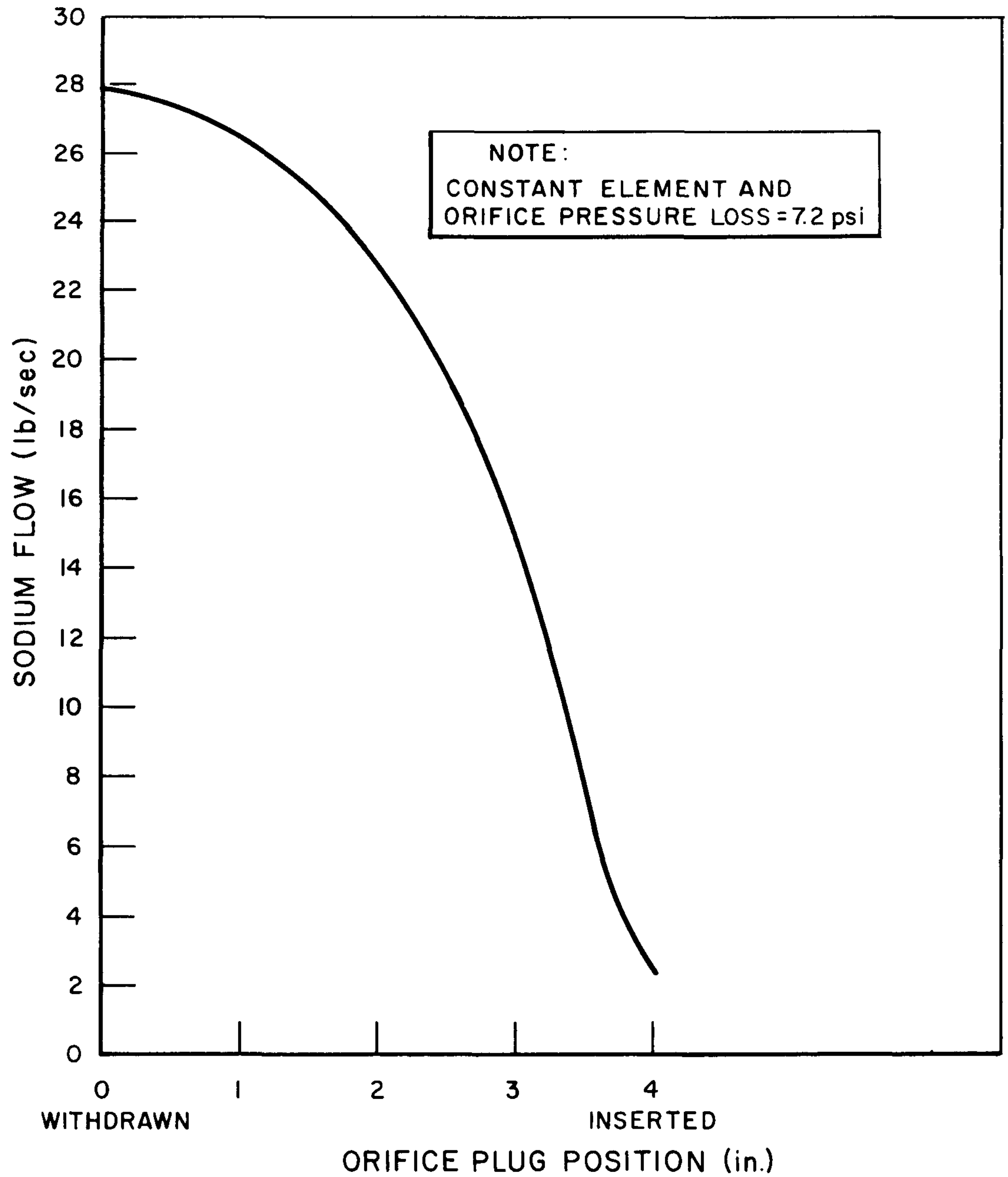


Figure 7. Sodium Flow Rate Through HNPF Fuel Channel with Type-IB Variable Orifice

It is planned to operate the fuel element at the center of the HNPF reactor core with the orifice plug in the fully withdrawn position, this plug position resulting in the lowest possible pressure loss for any given flow rate. During full-power operation, the flow rate expected through a central channel was 28 lb/sec. Figure 6 shows that the pressure loss, using a Type IB orifice, would be 7.2 psi at this flow rate with the orifice plug fully withdrawn.

Figure 7 is a cross-plot of the data in Figure 6 at a constant core pressure drop of 7.2 psi. Examination of the curve in Figure 7 indicates that the Type I orifice will permit flow control over the desired range of 28 lb/sec down to 7 lb/sec by inserting the plug approximately 3-1/2 in. This curve also indicates a smooth, essentially uniform change of flow rate with respect to plug position over the entire 4-in. traverse of the plug.

Figure 8 was plotted to determine the relationship between the exit temperature of the coolant and orifice plug position at a constant reactor power level. Curves are plotted for fuel elements positioned at the center of the core (exposed to maximum flux) and at the periphery of the core (exposed to minimum flux); curves for fuel elements positioned at intermediate locations in the core will fall between the two curves shown in Figure 8. The curves are based upon the previously given relationship

$$t_o = \frac{B}{w} + t_i$$

where the inlet temperature, t_i, is 607°F, and the constant B, in units of lb-°F/sec, is 9464 for a central channel and 2366 for a peripheral channel. (Values of B were obtained by substituting the desired outlet temperature, t = 945°F, and the center and peripheral channel flow rate of 28 and 7 lb/sec, in the above equation.) It may be seen from Figure 8, that if an outlet temperature of 945°F is desired, the orifice plug should be fully withdrawn in a central channel and inserted approximately 3-1/2 in. for a peripheral channel. Under these conditions, undesirably large temperature excursions could result during small orifice adjustments for a peripheral channel unless great care was exercised.

If the design temperature rise across the core exists across a particular channel, i.e., if the orifice is adjusted properly, then

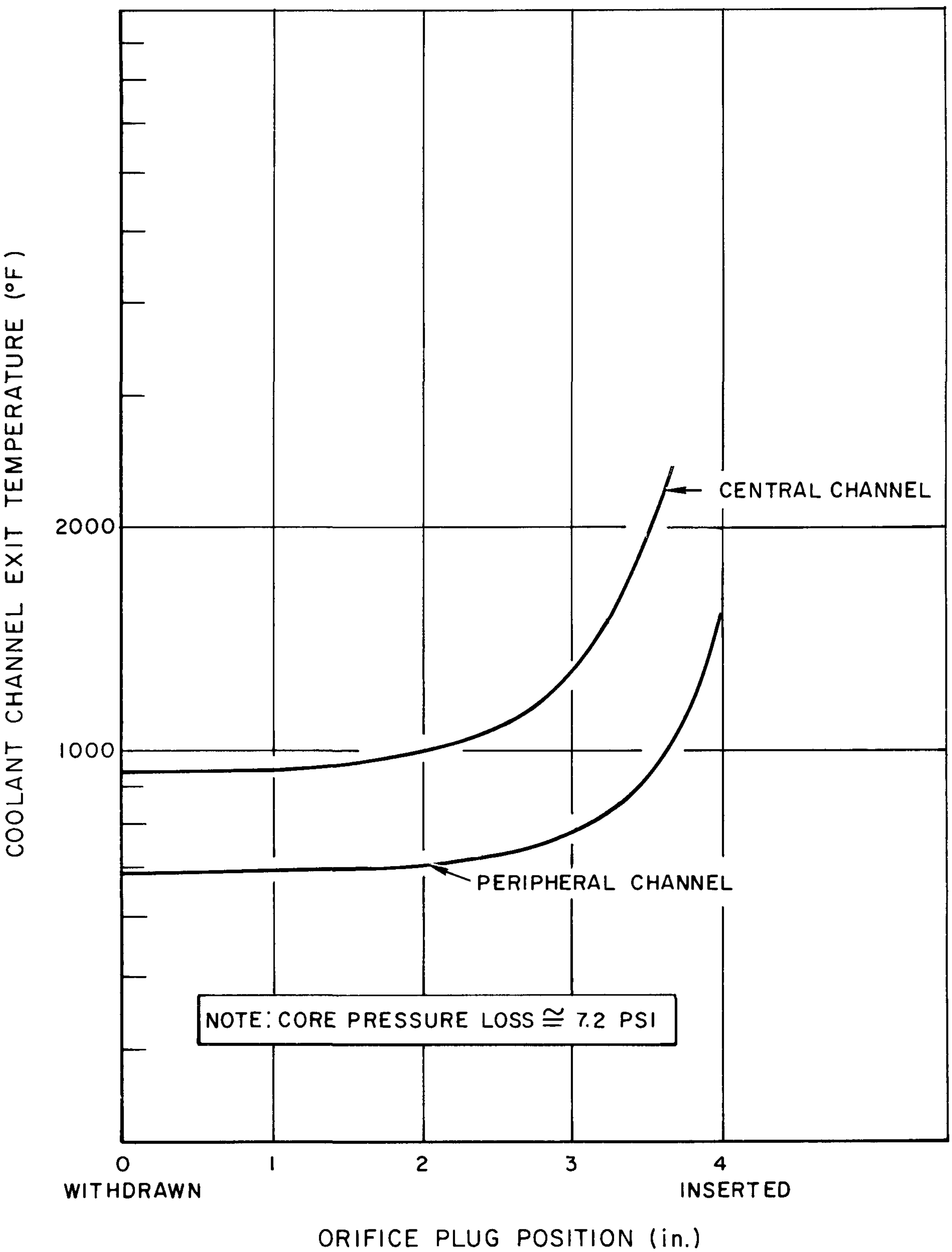


Figure 8. Exit Temperature of HNPF Coolant Channel with Type-IB Variable Orifice

$$t_o = \frac{B}{w} + t_i = 338 + 607 = 945°F.$$

substituting B/w = 338 in the equation for sensitivity,

$$S = \frac{-B}{w^2}\frac{dw}{dx}, \text{ and}$$

the following equation is obtained,

$$S = \frac{-338}{w}\frac{dw}{dx}.$$

Then, using this equation and Figure 7, the sensitivity of the orifice at full power was determined as a function of flow rate or of plug position, and therefore as a function of coolant-channel position in the core, where the outlet sodium temperature is 945°F for all channels. This relationship is plotted in Figure 9; it may be seen that the orifice exhibits an undesirably large temperature sensitivity for fuel channels near the periphery of the core.

Although the Type I orifice did have a smooth, essentially uniform change in flow rate with respect to plug position, its extreme temperature sensitivity was an undesirable characteristic. Further effort was then directed toward an improved orifice which would not exhibit such an extreme sensitivity.

B. VARIABLE ORIFICE - TYPE II (UNIFORM CHANGE OF EXIT TEMPERATURE)

The Type II orifice was designed to give a uniform rate of coolant exit temperature change with respect to change in plug position in any part of the 4-in. plug travel, as contrasted with the Type I orifice where a 1-in. change in plug position could result in a change in exit temperature varying from 10 to 900°F.

Data were obtained for Type II orifices with four different geometries of the plug and constricted section through which the plug moves. Figure 10 shows the variation of pressure loss with flow rate for various plug positions in orifices of the different configurations. The slope of these curves for the fully open position is approximately 1.8 which indicates that the expansion and contraction losses in

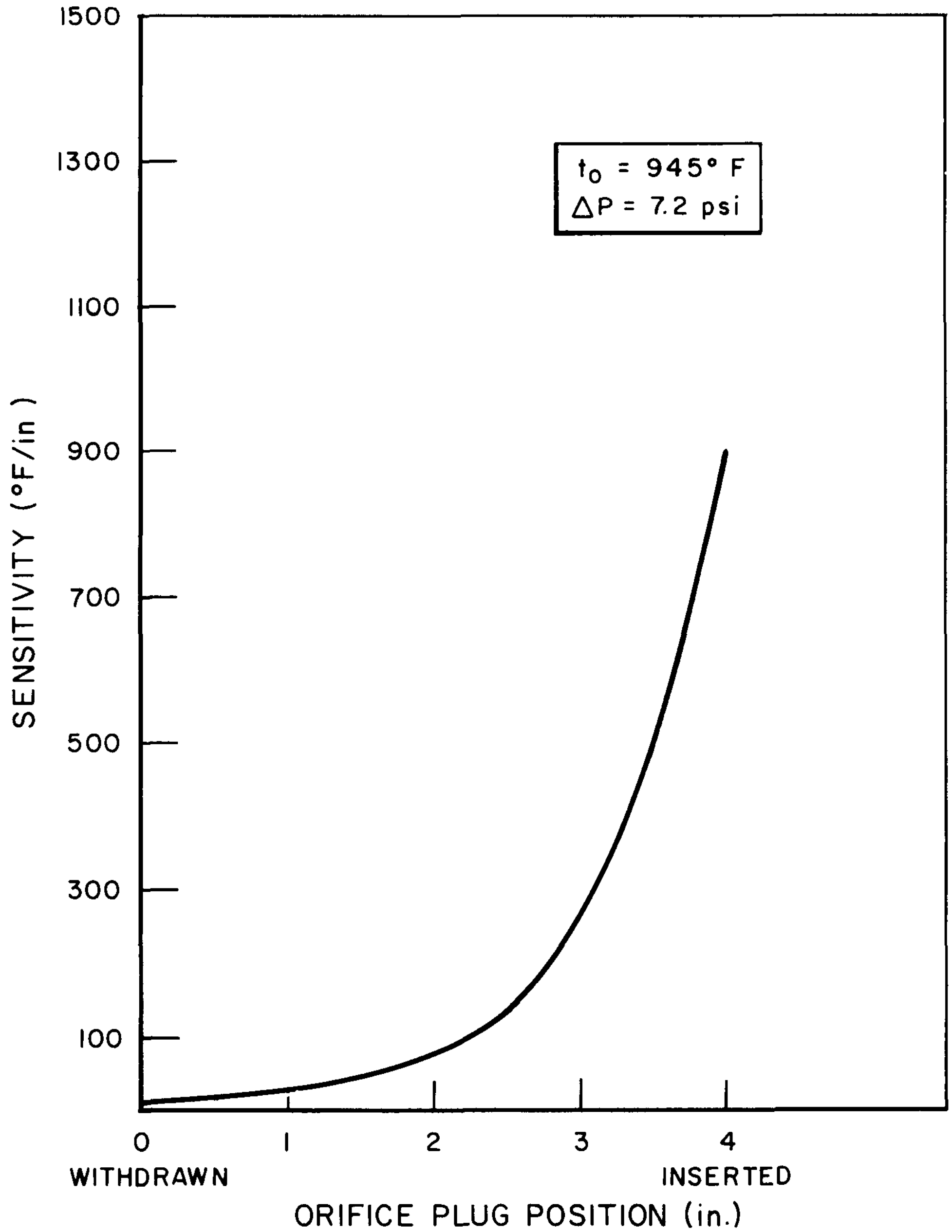


Figure 9. Temperature Sensitivity of Type-IB Variable Orifice

the section are negligible compared with the frictional loss. For the fully closed position the slope of the curves is approximately 2.0, which indicates that the major effect is that of contraction and expansion in the constricted section.

Table II is based upon data from Figure 10 and compares the pressure drop across the four orifices for flow rates equivalent to center channel and peripheral channel flow rates during full-power operation.

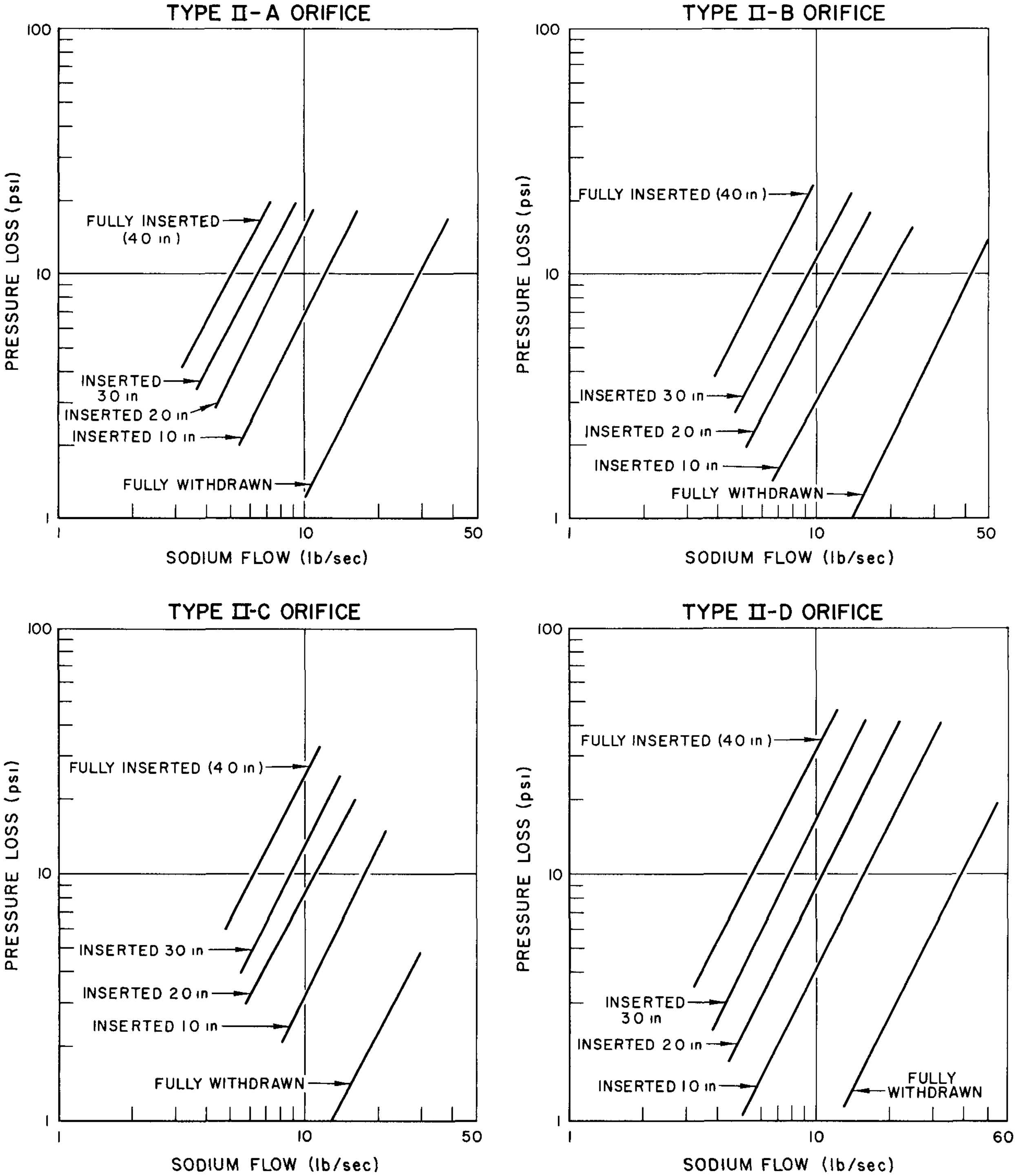


Figure 10. Pressure Loss Across Type-II Variable Orifice at Four Different Plug Positions

TABLE II

PRESSURE DROPS ACROSS TYPE II ORIFICES DURING FULL-POWER OPERATION

Plug Position	Flow Rate (lb/sec)	Orifice Pressure Drop (psi) IIA	IIB	IIC	IID
Fully Withdrawn	22.5 center channel	5.8	2.6	2.75	4.3
Fully Inserted	7.0 peripheral channel	18.5	12.0	12.0	15.0

These values indicate that the pressure loss at any given flow rate is similar for the Type IIB and IIC, slightly higher for the IID, and much higher for the IIA orifice.

Figure 11 is a plot of pressure drop vs orifice plug position for Type II orifice attached to a 19-rod 5.2 $in.^2$ fuel element. Points were obtained by adding pressure-drop data for the orifice alone (Figure 10) to the experimental pressure-drop data for the fuel element alone.*

Table III compares the pressure drop across the four Type II orifice configurations attached to fuel elements, for flow rates equivalent to center channel and peripheral channel flow rates at full reactor power.

TABLE III

PRESSURE LOSSES ACROSS TYPE II ORIFICES ATTACHED TO FUEL ELEMENT DURING FULL-POWER OPERATION

Plug Position	Flow Rate (lb/sec)	Element-Orifice Pressure Loss (psi) IIA	IIB	IIC	IID
Fully Withdrawn	22.5 center channel	12.5	9.2	9.4	10.9
Fully Inserted	7.0 peripheral channel	19.2	13.0	13.0	16.0

*Ref: NAA-SR-5340, "Hydraulic Characteristics of HNPF 19-rod Fuel Elements," page 15, by J. A. Hagel.

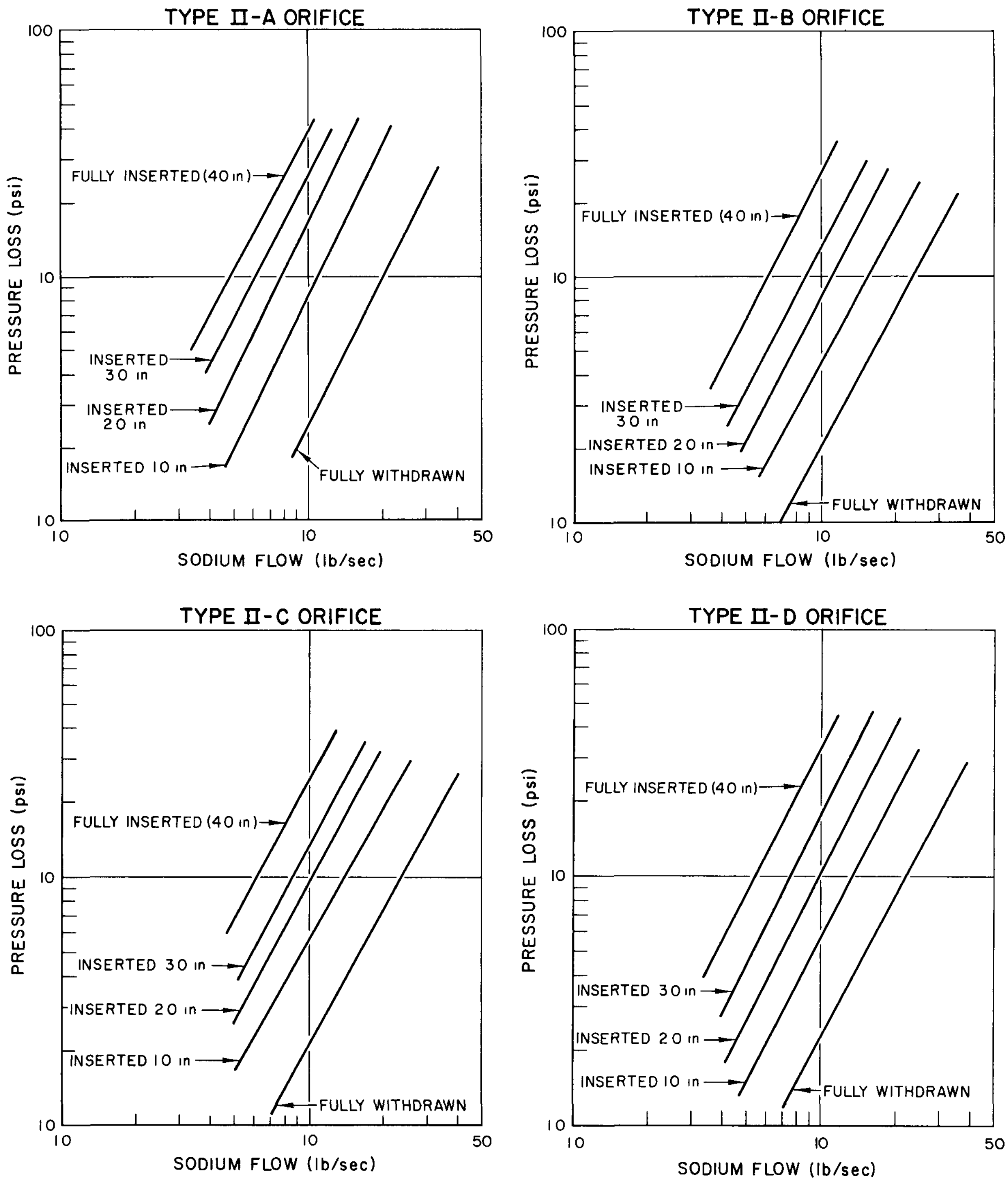


Figure 11. Pressure Loss Across HNPF Fuel Channel with Type-II Variable at Four Different Plug Positions

The element-orifice combinations exhibit the same general behavior for the different orifices, as do the orifices without a fuel element attached.

Figure 12 is a cross-plot of the data in Figure 9 at constant core pressure drops determined by the pressure loss through the orifice-fuel element combination at the expected maximum flow rate of 22.5 lb/sec.

These curves are concave upwards, in contrast to the concave downward curves shown in Figure 7 for the Type I orifice. The concave downward curves result in a sensitivity which increases in value as the plug is inserted; the concave upward curves result in a more uniform value of sensitivity, because as the plug is inserted (1/w increases) the value of dw/dx decreases.

As indicated previously, if the orifice is adjusted properly, the sensitivity of the orifice can be expressed as

$$S = \frac{-338}{w} \frac{dw}{dx} .$$

Using this equation and Figure 12, the sensitivity of the orifice at full power can be determined as a function of flow rate; and, therefore, as a function of position in the core where the outlet temperature is 945°F for all channels (Figure 13). The curves for the Type II orifices in Figure 13 exhibit less overall variation than does the curve for the Type I orifice in Figure 9. In addition, the maximum sensitivity for the Type II orifice is well below the maximum value of 900°F/in. for the Type I orifice.

Any of the first three Type II orifices would be acceptable for HNPF use from the standpoint of obtaining the necessary flow control with satisfactory sensitivity and without excessive pressure losses. The Type II-B orifice offered the best combination of operating characteristics. However, a design change in the fuel-element disconnect mechanism resulted in different upstream and downstream diameters, and necessitated the design of the Type II-D orifice. While the operating characteristics of the Type II-D orifice were not quite as good as the Type II-B orifice, the differences were not great enough to warrant further effort at improvement. As the Type II-D orifice was the ultimate selection for use in HNPF, the behavior of this particular orifice was further examined.

Figure 14 shows the variation of exit temperature with plug position, for a Type II-D orifice in either a central or a peripheral coolant channel, when the

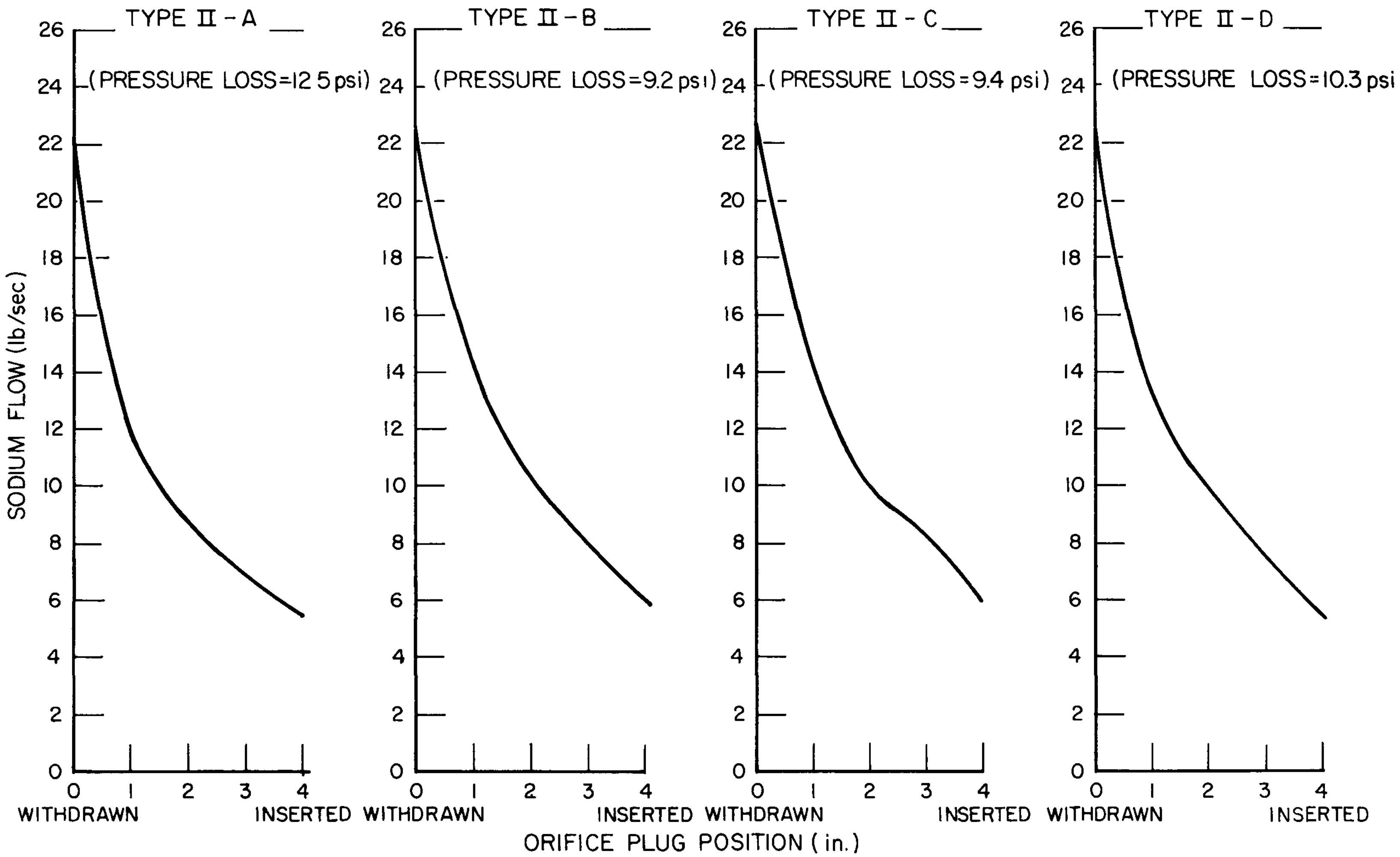


Figure 12. Sodium Flow Rate Through HNPF Fuel Channel with Type-II Variable Orifice

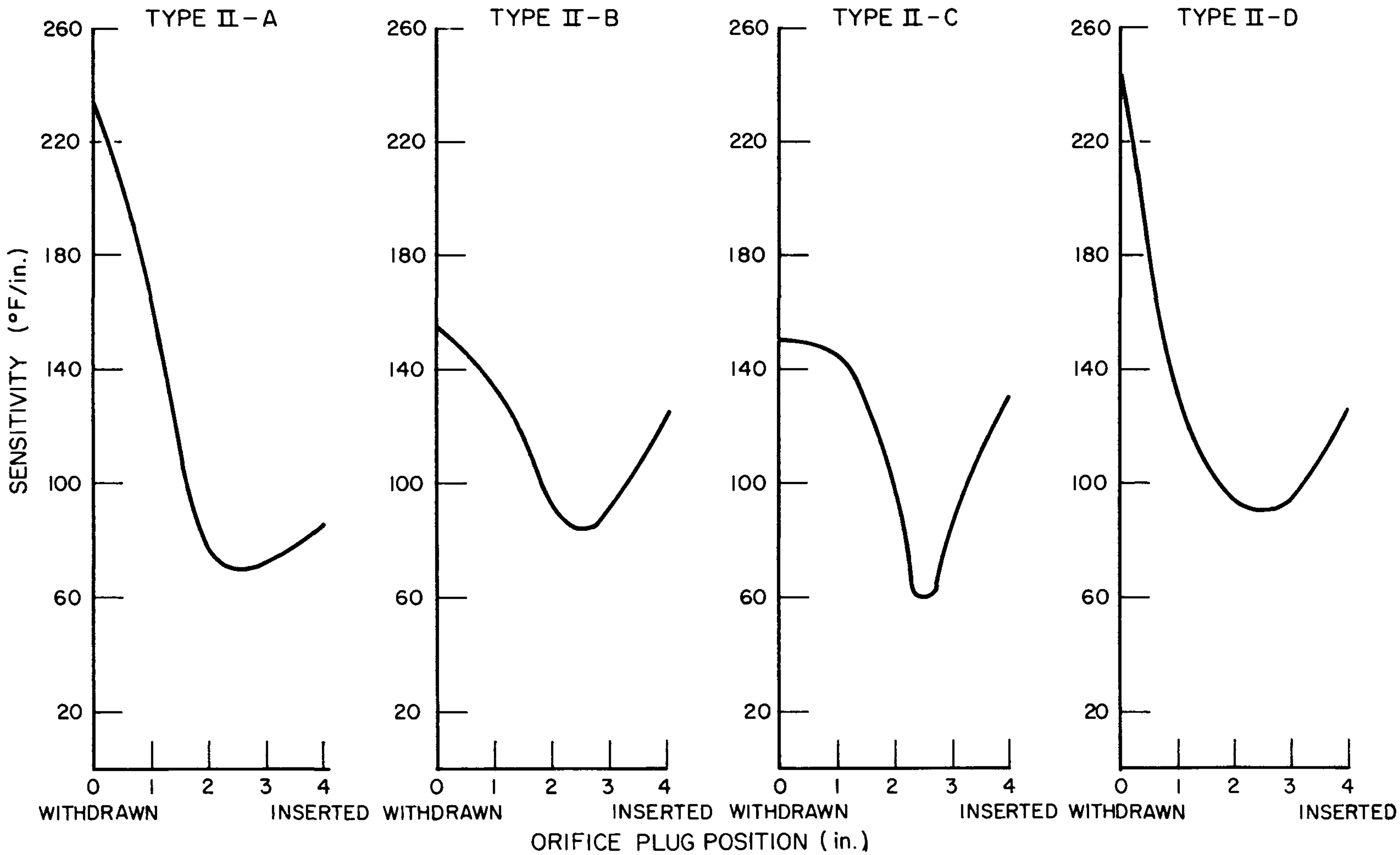


Figure 13. Temperature Sensitivity of Type-II Variable Orifice

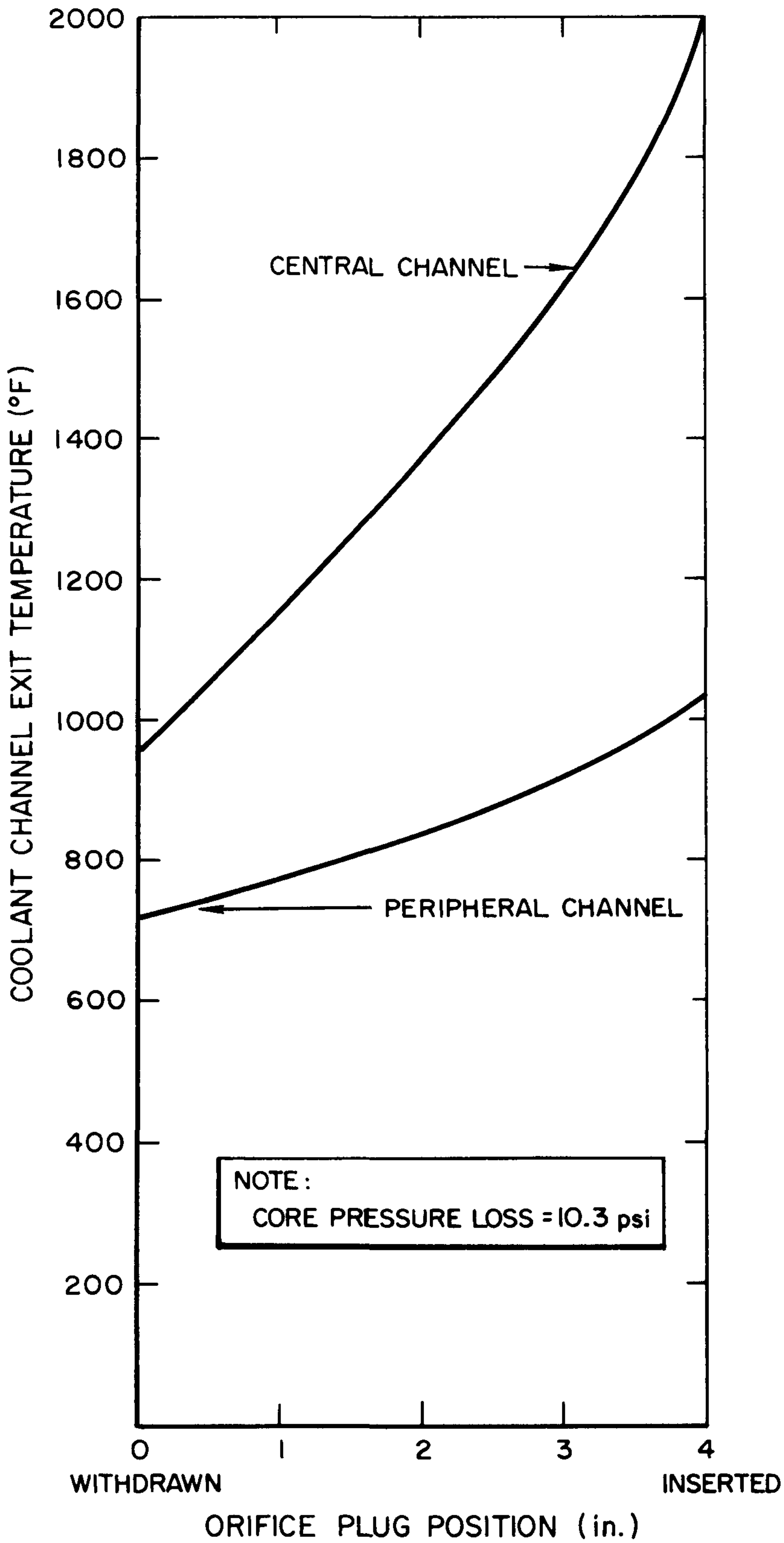


Figure 14. Exit Temperature of HNPF Coolant Channel with Type-IID Variable Orifice

reactor is operating at full power. The curves for coolant channels at intermediate positions in the reactor core will fall between these two curves. As the orifice plug in a central channel is inserted, the exit temperature will increase from the desired value of 945°F (fully withdrawn) to 2000°F (fully inserted). A peripheral channel, on the other hand, normally should operate with the plug inserted approximately 3-1/4 in. If the orifice plug in a peripheral channel is fully inserted, the exit temperature will increase to 1040°F; as the plug is withdrawn, the temperature will decrease to a minimum value (fully withdrawn) of 720°F.

The major part of the orifice adjustment is to be performed at low reactor power. For this analysis, the reactor power is assumed to be 20% of full power when the orifices are initially adjusted. When the reactor is operating at full power, t_o = 945°F, and t_i = 607°F; and the flow rate in the center channel will be 22.5 lb/sec. Then, since B = 7600 lb-°F/sec at full power in the center channel, B = 1520 lb-°F/sec at 20% reactor power in the center channel. At 20% power, the flow through the center channel will be 22.5 x 0.20 or 4.5 lb/sec if the design inlet and outlet temperatures are maintained. Following the same procedure as that outlined above for 100% power, the temperature sensitivity of the Type II-D orifice can be obtained as a function of plug position for 20% power. This information has been plotted in Figure 15, along with a similar plot for full-power operation from Figure 13. Comparison of the temperature sensitivities of the Type IID orifice at full-power and at 20% power shows little difference in the temperature sensitivity at any given position in the core. In the above analysis, it was assumed that the total sodium flow through the core would be matched to the total reactor power; i.e., at 20% power, the sodium flow rate would be 20%.

A better procedure for adjusting the orifices would be to do the adjusting at 20% power and 100% flow. Under these conditions, the orifices would be adjusted to give a temperature increase across the core of 20% of the design value, or 67.6°F. A plot of the temperature sensitivity at 20% power and 100% flow as a function of plug position is included in Figure 15. At 100% flow and 20% power, it may be seen that the sensitivity is reduced by a factor of five over that obtained at 100% flow and 100% power. After the orifices have been adjusted to give the desired temperature increase, the power can then be raised to 100% power, with little or no additional adjustment needed.

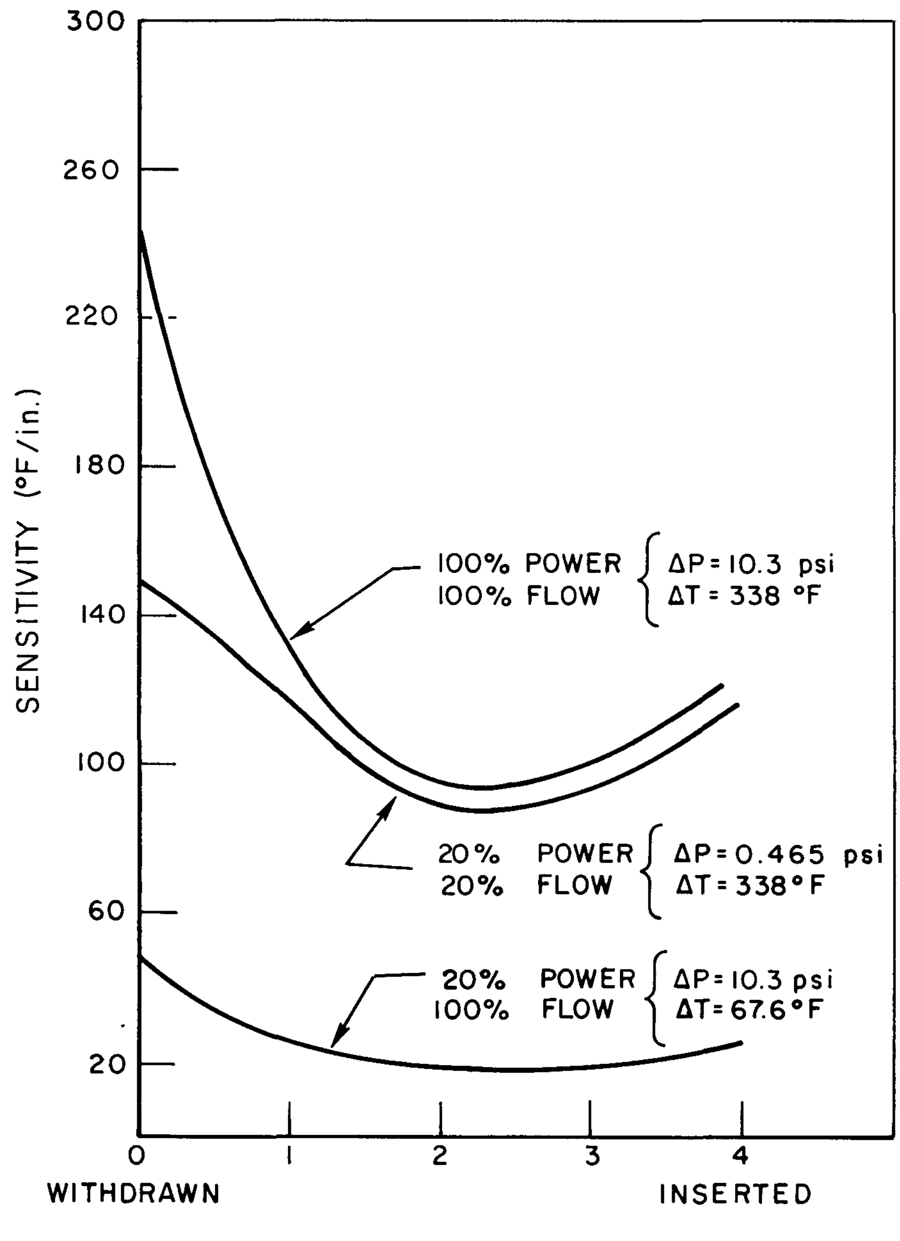


Figure 15. Temperature Sensitivity of Type-IID Variable Orifice at Different Power Levels

V. CONCLUSIONS

Measurements of the hydraulic characteristics of the first type of variable orifice, attached to a 19-rod fuel element, resulted in a curve of change of flow rate with orifice plug position that was concave downward. The temperature sensitivity of this orifice was extremely low (10°F/in.) when fully withdrawn and extremely high (900°F/in.) when the plug was fully inserted. The second type of variable orifice, attached to a 19-rod fuel element, was characterized by a curve of change of flow rate with orifice plug position that was concave upward. The temperature sensitivity of this orifice was reasonably uniform (90 to 240°F/in.) over the entire range of orifice plug travel. A variable orifice of the second type (Type IID) is suitable for use in the first core loading of the HNPF. This orifice should permit adequate control of the flow rate, and should not cause excessive fluctuations of the coolant exit temperature during trimming adjustments.