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TESTS ON MODELS OF NUCLEAR REACTOR ELEMENTS

III. Head Losses in Core Sub-Assemblies

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ABSTRACT

Losses have been determined for flow through models of various proposed core sub-assemblies as part of a study of the elements of a nuclear reactor. Six core sections and two axial blanket sub-assemblies have been compared on the basis of drop in piezometric head or pressure drop.

The core sub-assemblies are composed of an entrance nozzle, a lower axial blanket section, the core section, an upper axial blanket section, and a short section for the handling lug. The four parts of the sub-assembly other than the core section are designated as the axial blanket sub-assembly.

In each core section there are 144 rods within a container which has a square cross section. The primary differences between one core section and another are the means of supporting and spacing the rods. Bars or wires wrapped in spirals around the rods were used as well as a series of grids made up of wires and supported at the four corners. Also, in one core an inner wall was used to provide an annular flow passage which helps to reduce the difference in temperature at the inner and outer walls of the core.

The two axial blanket sub-assemblies tested are similar except that the second model is characterized by more gradual transitions in changes of cross section.

Other parts of this study of the elements of a nuclear reactor have been described in two previous reports dealing with head losses in complete blanket sub-assemblies[1] and with diffusion studies.[2]

A. DESCRIPTION OF TEST CIRCUIT AND MODELS

TEST CIRCUIT

A closed circuit was used for the tests of the core models to keep extraneous losses to a minimum and to make it possible to hold constant or vary the temperature of the water. The pump for the recirculating system in the fluid mechanics laboratory of the Department of Engineering Mechanics was used to supply the necessary flow under pressure. The remainder of the laboratory pumping system was separated from the circuit by appropriate valving. Numerous connections were made to make possible the bleeding of air, the controlling of the temperature, and the measuring of the discharges and pressures. Flanged connections through the testing portion of the circuit made possible the ready interchange of the various component parts.

The arrangement of the test circuit is shown in Fig. 1. Between the main control valve on the 3-in. line from the pump, and the entrance section of the sub-assembly, a plate in which a number of 1/4-in. holes were drilled was installed in a flange to break up eddies created by the valve. At the top of this leg of the circuit, connections were provided both for the filling of the system from the city water supply and for the bleeding of hot water from the system. In the return leg, which is 4-in. pipe, an orifice plate with an opening 2.8 in. in diameter was installed for discharge determination. The installation was in accordance with A.S.M.E. specifications and permitted the use of standard tabulated orifice meter coefficients.[3] The discharge values obtained are considered to be correct within 2 or 3%, although no calibration was attempted. Downstream from a second control valve in the return leg, a connection was made for the continuous addition of cooling water. City water was supplied at atmospheric pressure to a tank which was placed high enough to insure that flow into the test circuit could be maintained. The supply of city water to the system was controlled by means of a float valve, so that a constant water level would be maintained in the tank. Air bleeds were placed at the highest points in each leg of the circuit, and a thermometer was installed at the top of the 4-in. leg.

An air-water differential manometer 80 in. long was connected to piezometric openings on either side of the orifice plate and the readings provided a continuous indication of discharge. An 84-in. mercury-water manometer was used to indicate differences in piezometric head between the various openings placed in the sub-assemblies.

For most tests the system was filled with city water with all air bleeds open, and the pump was then started. Additional filling of water and bleeding of air was accomplished by means of the tank connected to the 4-in. line. The temperature was read regularly; usually little or no attempt was made to control it

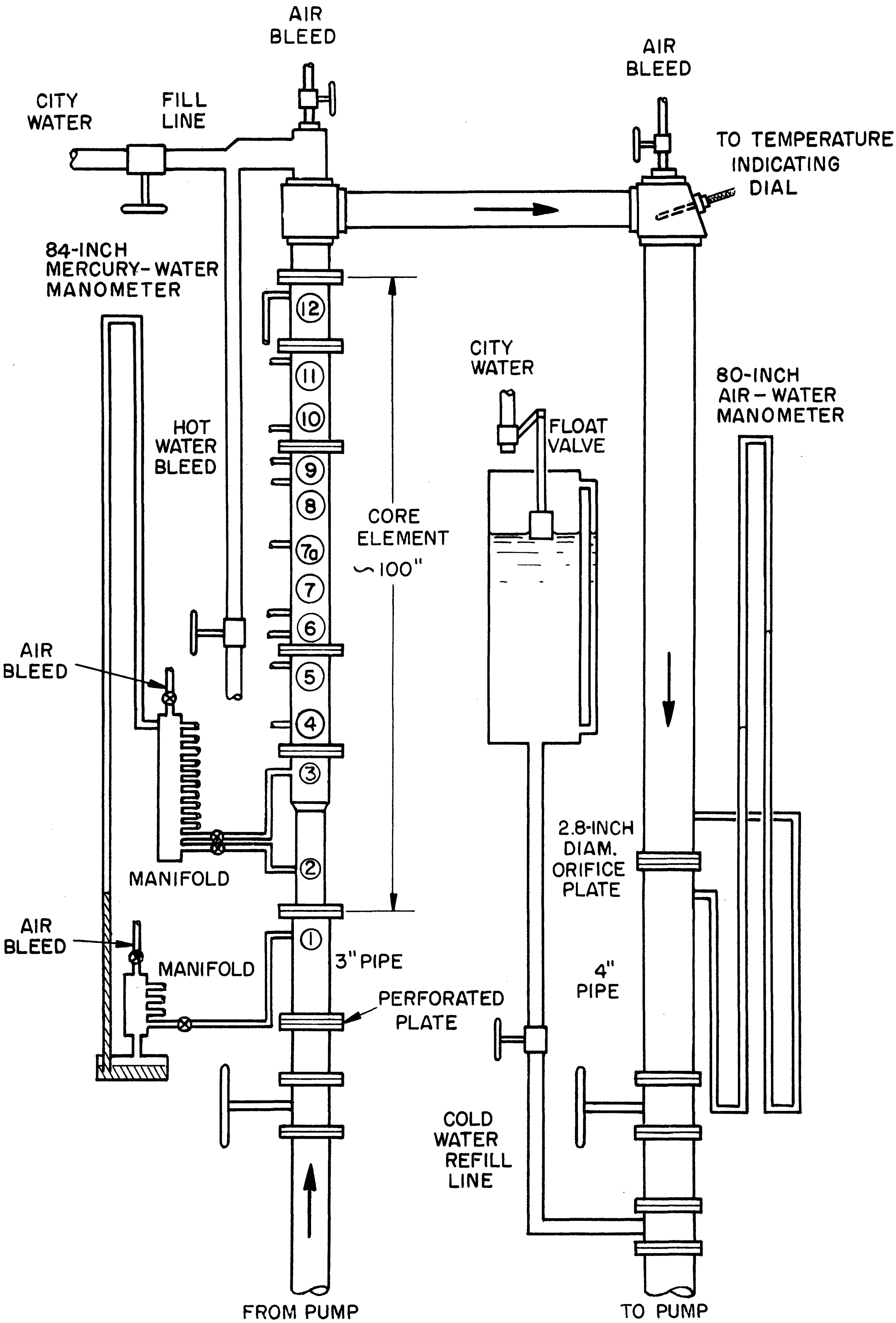

Fig. 1. Schematic diagram of test circuit.

by bleeding hot water. The temperature rise was of the order of 1°F per minute for maximum discharge. The temperatures varied from about 70° to as much as 150°F during a test. The Reynolds number was thus increased progressively during each test both by increasing the discharge and by allowing the temperature to rise.

Tests at lower Reynolds numbers (below 4×10^3 for the core section) were conducted using only the test leg of the circuit and the hot-water bleed line. Water was supplied as for higher Reynolds numbers by the laboratory pump. The discharge was determined by means of a weighing tank because the orifice plate was not sufficiently accurate at low discharges. Also, the 80-in. air-water manometer was used to measure differences in piezometric head in the sub-assembly because of the insensitivity of the mercury manometer to small differences in pressure.

The 13 piezometric openings in the sub-assembly were located and numbered as shown in Fig. 2. For locations adjacent to rods in either the core or the axial blanket, two openings were used. One was placed on the centerline of a rod and one between rods, and the lines were joined to secure the average of the two readings. All lines for the openings were connected to one or both of two manifolds which in turn were connected to the mercury-water manometer. Thus the difference in head between any two of the 13 points could be observed.

On the second model of the axial blanket sub-assembly, piezometer opening 3 was located 3-3/4 in. below the flange instead of 2-1/2 in. as indicated in Fig. 2 because of the more gradual transition used in the second sub-assembly. Also, piezometer opening 7 was located 4-1/2 in. above the flange for the core sections of Hydraulic Models Nos. 4 and 5 instead of 2-7/8 in. as indicated in Fig. 2. This change was necessary because of the different arrangements used to support the rods in these two models.

DESCRIPTION OF MODELS

The models of the sub-assemblies were full size and were fabricated from stainless steel. They were designed by members of the staff of APDA, and constructed commercially. Some difficulties were encountered, particularly with the first models, in holding to the close tolerances of the many small parts so that shimming was required to hold the rods in their proper alignment.

The distinguishing features of the 6 core sections are as follows:

Hydraulic Model No. 1 - 144 rods 0.158 in. in diameter with 0.044 by 0.02-in. spiral wrappings on 6-in. pitch; casing approximately 2.464 by 2.464 in. inside; four 0.019-in. shims.

Hydraulic Model No. 1a - Rods of same size with 0.038-in.-diameter wire spiral wrappings on 6-in. pitch; casing approximately 2.484 by 2.484 in. inside; four 0.05-in. shims.

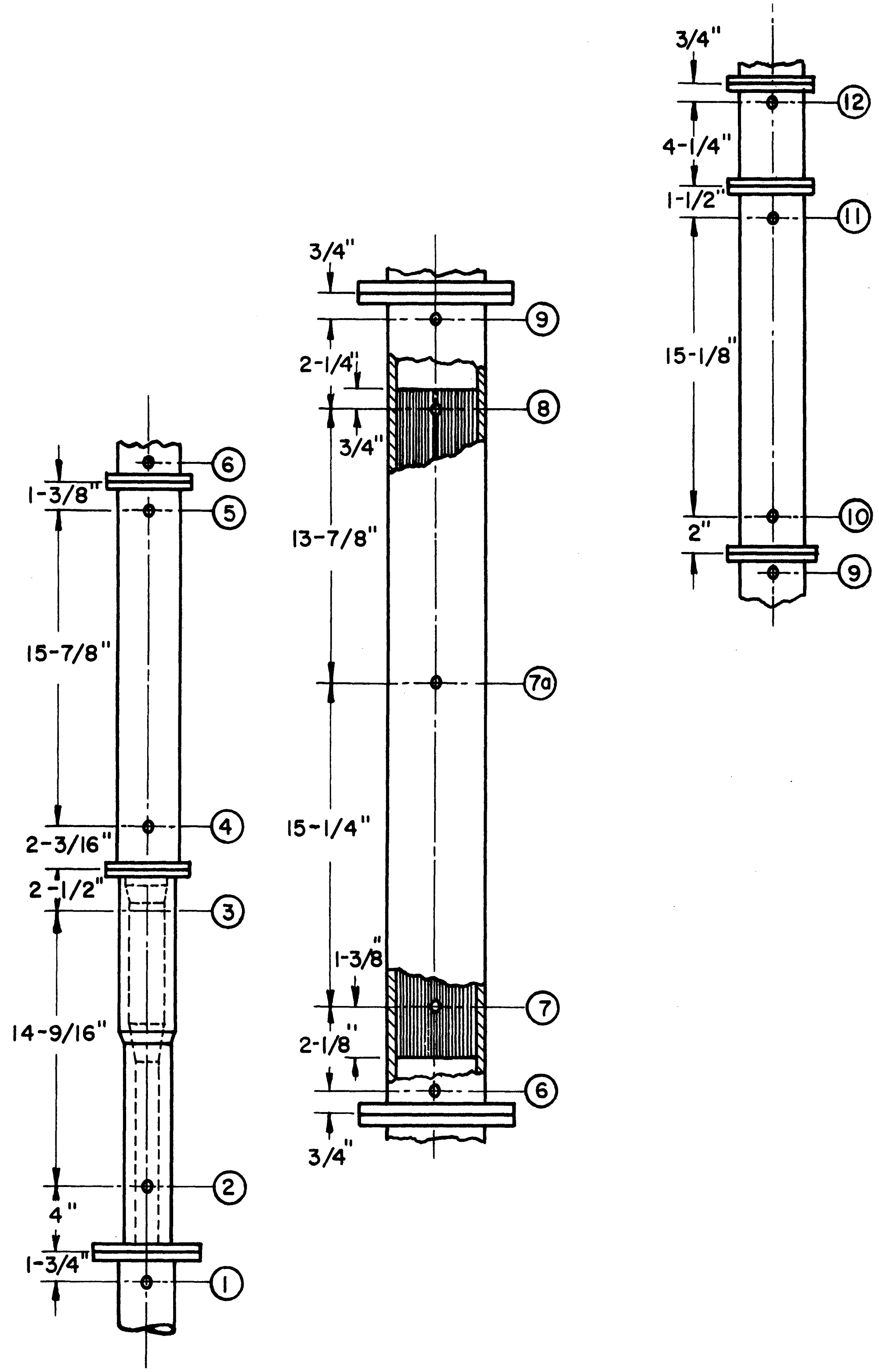

Fig. 2. Location of piezometer openings.

Hydraulic Model No. 2 - Same size rods and wrappings as used in No. 1, but on 8-in. pitch; same casing as No. 1a, with four 0.02-in. shims.

Hydraulic Model No. 3 - 144 rods 0.158 in. in diameter, wrapped with 0.045-in.-diameter wire on 6-in. pitch; same casing as No. 1a, with two 0.02-in. shims.

Hydraulic Model No. 4 - Same casing as No. 1a, no shims; 144 rods 0.158 in. in diameter without wrappings supported every 2 in. in each transverse direction by grids made up of either 5 or 6 rods 0.031 in. in diameter, grids supported at corners by 4 longitudinal wires; entire rod assembly contained within square inner liner 2.336 in. on a side and 0.012 in. thick, wrapped spirally with four 0.047-in.-diameter spacer wires, each on 15-3/8-in. pitch.

Hydraulic Model No. 5 - Same casing as No. 1a, no shims; same rods and type of support as No. 4, grids made of 5 or 6 rods 0.041 in. in diameter; no inner liner.

The variations in open area and in equivalent diameter for the core models are presented in the accompanying table. The equivalent diameters are 4 times the ratio of the open area to the perimeter (known as hydraulic radius). The values for Hydraulic Models Nos. 4 and 5 were based on the cross sections between grid supports. That of No. 4 took into account the inner liner.

Model No.	Open Area (sq ft)	Equivalent Diameter (ft)
1	0.0209	0.01036
1a	0.0186	0.00909
2	0.0210	0.01040
3	0.0209	0.00986
4	0.02235	0.01060
5	0.0234	0.01372

The two models of the axial blanket sections are comparable except for the shape of the ends of the 16 rods and the grids supporting the rods. The ends of the rods were blunt for the first model and rounded to an ogival shape for the second. The grids in the first model were fabricated from regular bar stock. The leading edges were sharpened for the second.

The nozzle entrance sections of the two axial blanket sub-assemblies differed in that the transition from round to square cross section was abrupt for the first, and both more gradual and well-rounded for the second. The entrance to the first model is also less rounded than that of the second model, and the one other change from one round section to another round section is less gradual.

The handling lugs at the upper end of each of the two models of the axial blanket sub-assemblies were similar except that the second one had fewer abrupt changes in cross section than did the other.

The Reynolds numbers used to characterize the entire axial blanket sub-assemblies were based on a section through the axial blanket containing the 16 rods. For both sub-assemblies, the open area for this section is 0.0217 sq ft and the equivalent diameter is 0.0304 ft.

B. RESULTS OF EXPERIMENTS

The changes in piezometric head were measured for various combinations of the two axial blanket sub-assemblies and the 6 core sections. As soon as the streamlined (second) sub-assembly was available, it was installed and the other was discarded. The earlier tests of core sections using the first sub-assembly were not rerun, because the drop in piezometric head through the core section is independent of the sub-assembly or very nearly so. The two plenum chambers at the upper and lower ends of the core section (piezometer openings 6 and 9) were taken as the dividing points. The drop in the sub-assembly is the sum of that from 1 to 6 and that from 9 to 12. The core is the remainder—from 6 to 9. The variations of the drops in various parts of the sub-assemblies with the blanket section Reynolds number are presented in the Appendix.

COMPARISON OF CORE SECTIONS

Results of tests of the core sections are shown in Fig. 3, in which the drop in piezometric head (6 to 9) divided by the square of the discharge is plotted as a function of a Reynolds number based on a cross section through the core. The quantity $\Delta h/Q^2$ is used in place of the usual friction factor f because all geometric quantities such as length and diameter and spacing of the rods are constant throughout a given test. Thus, in the definition equation

$$f = \frac{\Delta h}{V^2/2g} \cdot \frac{d_e}{L} = \frac{\Delta h}{Q^2} \left(\frac{\pi^2 g d_e^5}{8L} \right) \qquad (1)$$

the terms within parentheses are constant throughout tests on any core. Also, Δh includes several local losses so that the conventional meaning of f would be altered in this instance. For large discharges the changes in piezometric head were so great (greater than 85 ft of water) that they were subdivided by using 7, 7a, or 8 as an intermediate point. Design points representing a discharge of 300 gpm of sodium[4] at 600°F are shown on each curve.

The curves for the different models are not strictly comparable because the Reynolds numbers depend upon the equivalent diameters and open areas. For example, the value of $\Delta h/Q^2$ for model No. 1 is 12-1/2% greater than that for No. 3 at a Reynolds number of 10,000. However, the discharges are not the same even though the open areas are the same because the equivalent diameters are different. The discharge through model No. 3 for this Reynolds number is sufficiently larger to cause a greater drop in piezometric head than that for model No. 1 despite the reverse order of the ordinates on the plot. Although this is an extreme case, it

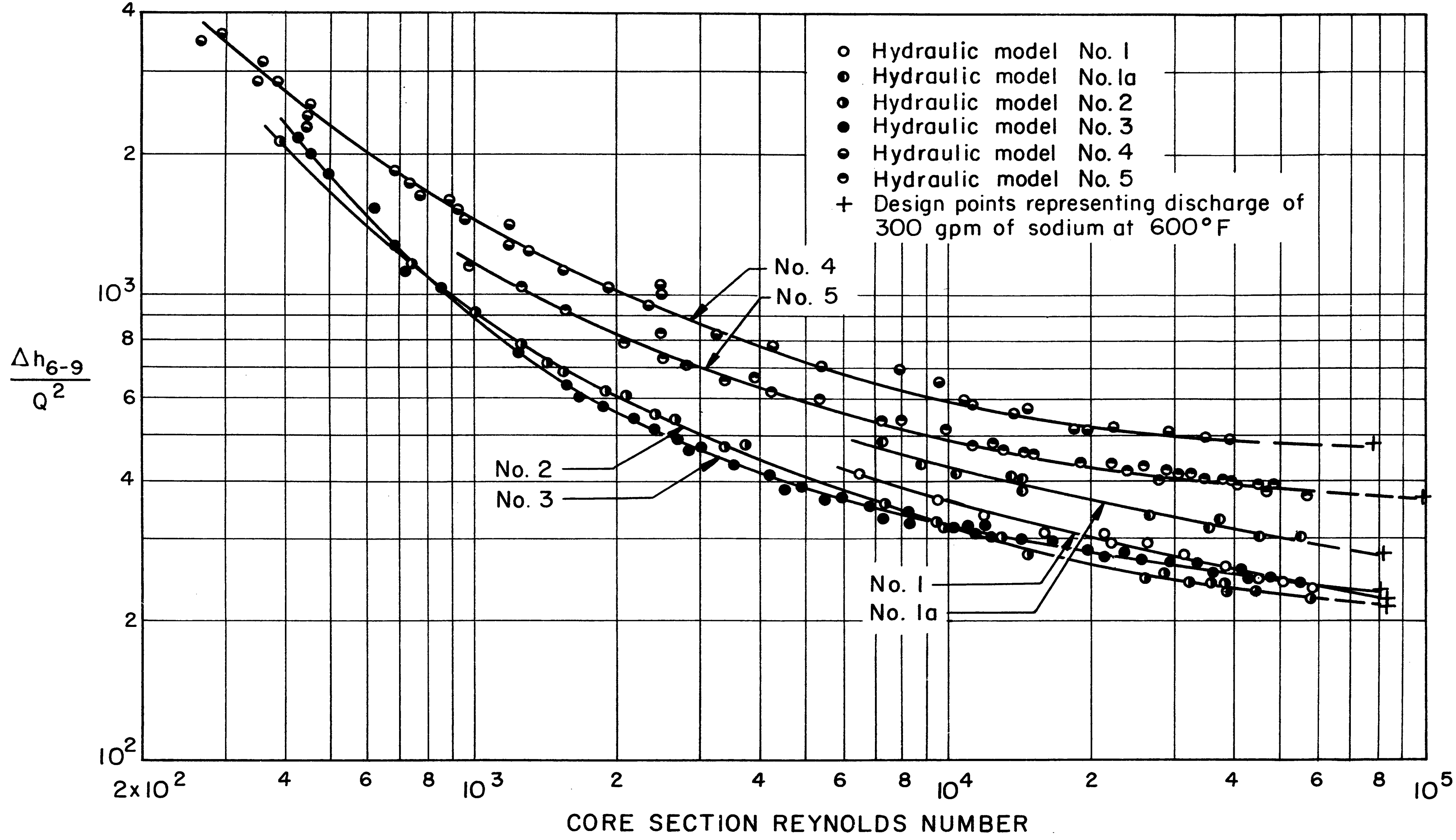

Fig. 3. Drop in piezometric head for core sections.

does illustrate the effects of shimming and other seemingly slight variations in geometry.

The relatively high drops in piezometric head for Hydraulic Models Nos. 4 and 5 compared to the others are not altered by such geometrical effects on the Reynolds numbers, however. All the models incorporating spiral windings to support the rods do have considerably less drop than those in which the rods are supported by grids. For these latter models the drop is much higher than was predicted from calculations allowing for the changes in area at the grids. An increase over the value for an equivalent smooth pipe of about 20% was predicted. The measured increase was about 100%. This extreme value was indirectly confirmed by measurements of the loss over part of the core from which the grids had been removed. In this case an increase of only a few percent was observed. Thus the grids seem to have the effect of an exceedingly large relative roughness. Even though they are spaced at 2-in. intervals, high degrees of eddying and turbulence cause the remarkably large loss.

The curves for model No. 1 (6-in. pitch) and for No. 2 (8-in. pitch) indicate that an increase in pitch decreases the drop in head. This result was surely to be expected.

COMPARISON OF AXIAL BLANKET SUB-ASSEMBLIES

The drops in piezometric head for two axial blanket sub-assemblies are indicated in Fig. 4. The value of $\Delta h'/Q^2$ is plotted against a Reynolds number based on the cross section of the <u>axial blanket</u>. The drops in head are, as stated before, the changes from piezometer openings 1 to 6 plus those from 9 to 12. Thus the drop in head through the handling lug section is included. Design points representing a discharge of 300 gpm of sodium[4] at 600°F are again shown on each curve.

The two curves are directly comparable in this case because both sub-assemblies have the same cross section in the axial blanket. Considerable improvement was brought about by the streamlining of the second model.

DIVISION OF FLOW IN HYDRAULIC MODEL NO. 4

Special tests were run to determine the proportion of the total flow for Hydraulic Model No. 4 in the annular space between the container and the inner envelope. Both the quantity of the flow in the annular space and the degree to which it follows the spiral spacer windings affect the distribution of temperature at the wall of the casing. The percentage of the total discharge which flowed outside the inner envelope versus the Reynolds number of the core section is plotted in Fig. 5. This Reynolds number is based on the open area and the equivalent diameter of the entire cross section of Hydraulic Model No. 4. The variation in the ratio for small Reynolds numbers is probably caused by an irregular change from laminar to turbulent flow. The losses caused by the grids are probably not as exorbitant for laminar flow as for turbulent.

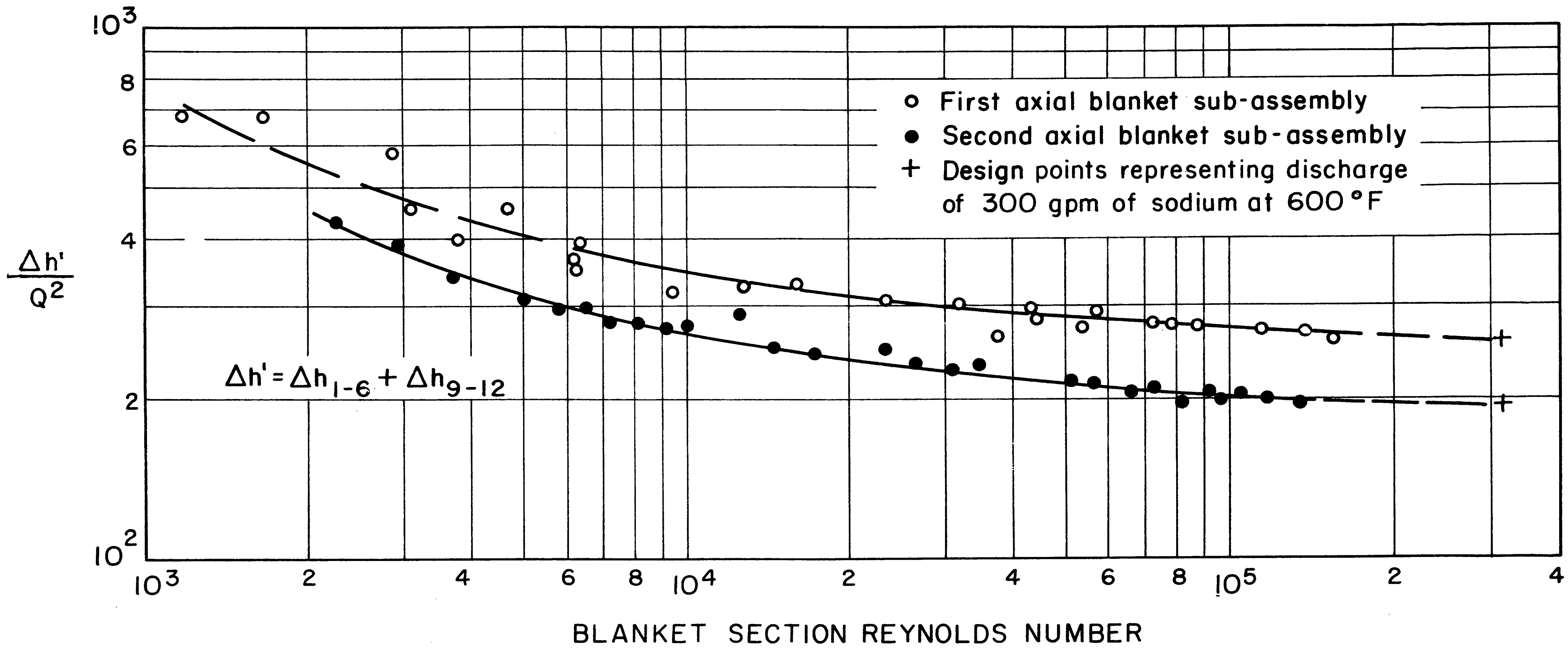

Fig. 4. Drop in piezometric head for axial blanket sub-assemblies.

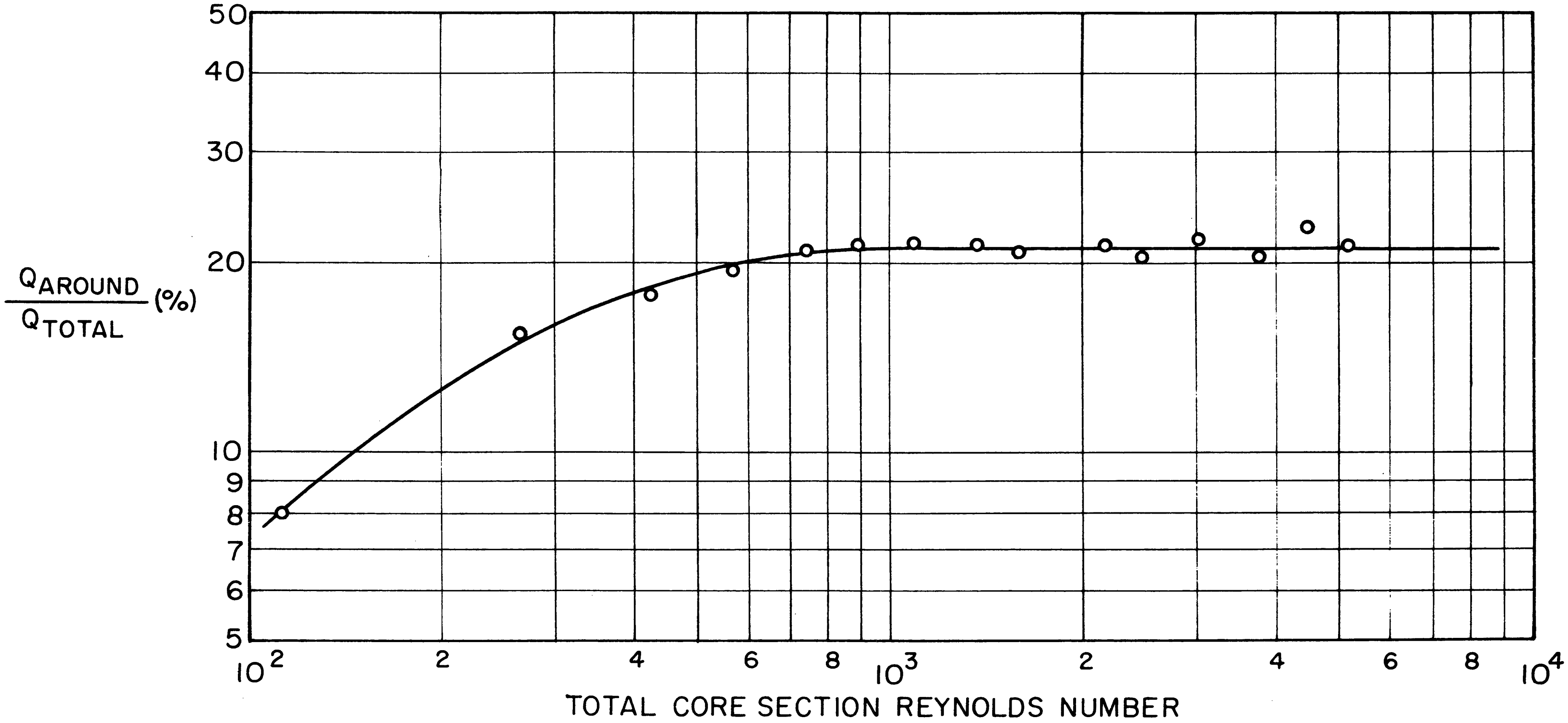

Fig. 5. Division of flow in Hydraulic Model No. 4.

The effectiveness of the spiral spacers in forcing the flow around the inner envelope was tested by injecting dye in the annular space at the upstream end of the core and determining the distribution of it at the downstream end. In Fig. 6 the location of the centroid ($\bar{x}$) of the actual dye-distribution curve is compared to that which would have occurred with no leakage at all. The ratio of the two expressed as a percentage is 92%. This value indicates that only a small amount of leakage occurs over the spiral spacers. For completely ineffective spiral spacers the mean path of dye would, of course, follow the axis of the inner envelope.

C. APPLICATION OF EXPERIMENTAL RESULTS TO DESIGN

The merits of any core sub-assembly can be compared primarily on the basis of drop in piezometric head. They also depend somewhat on the degree of eddy diffusion, ease of fabrication, and perhaps other considerations. Only the drop in piezometric head and the possibilities of reducing this drop to the minimum value consistent with satisfaction of these other requirements are considered in this report.

VARIATION OF HEAD FOR AXIAL BLANKET SUB-ASSEMBLIES

The three plots shown in Fig. 7 indicate the variation in both total and piezometric head through the first (Fig. 7b) and second (Fig. 7c) models, and through an idealized version (Fig. 7a) of the axial blanket sub-assemblies. The variations of head are expressed in feet of sodium,[4] and for a discharge of 300 gallons of sodium per minute. The temperature of sodium was taken as 600°F. The drop in head through the core section is not shown on any of the plots because it would, of course, be different for each of the six core models.

The streamlining of the axial blanket sub-assembly reduced the drop in piezometric head from 100 ft of sodium (38 psi) for the first sub-assembly to approximately 86 ft of sodium (32.6 psi) for the second sub-assembly. This is a reduction of about 14%.

The plot shown in Fig. 7a is that predicted for an ideal sub-assembly in which all surfaces are assumed to be smooth and all changes in section are made as gradual as necessary to reduce losses to a minimum. This could not, of course, be done without elongating the sub-assembly and changing radically essential elements of the configuration. The total drop in piezometric head for this idealized sub-assembly would be about 50 ft of sodium (19 psi). Thus the reduction achieved by the second sub-assembly is about 30% of the ideal reduction, and a still larger proportion of the feasible reduction.

HEAD LOSSES FOR COMPLETE SUB-ASSEMBLIES

For the final comparison of various designs only the streamlined sub-

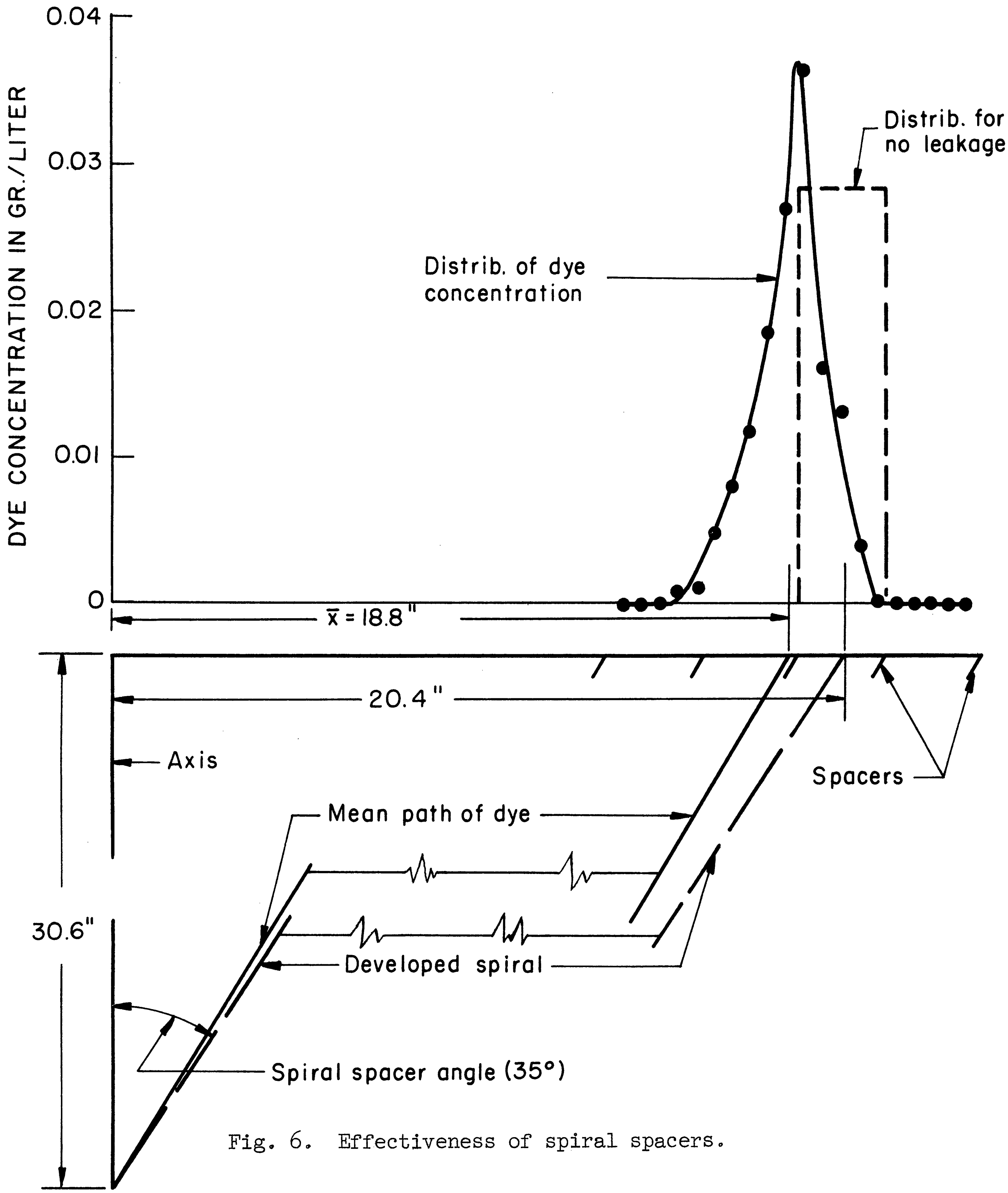

Fig. 6. Effectiveness of spiral spacers.

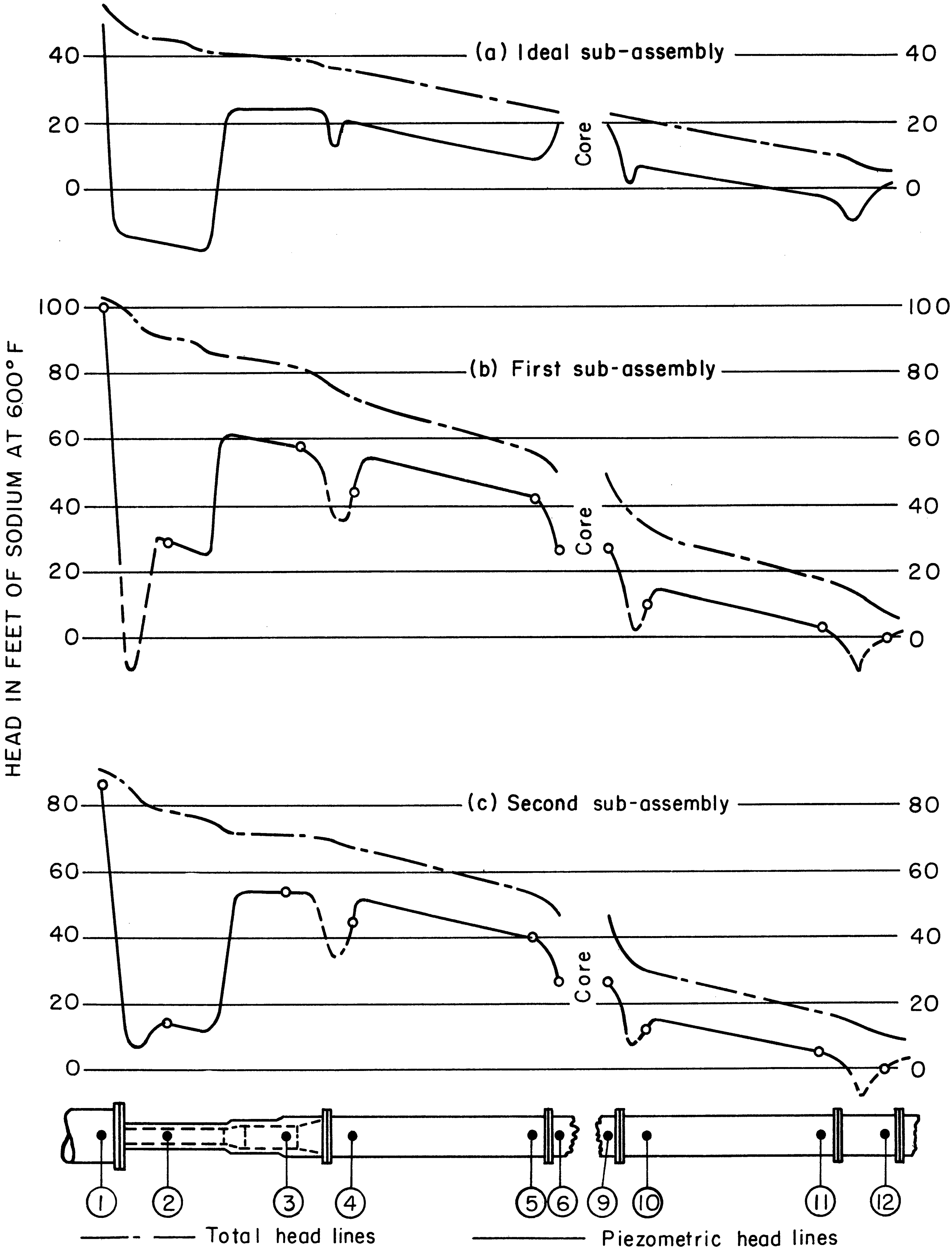

Fig. 7. Variation of head for axial blanket sub-assemblies at design discharge.

assembly and core Hydraulic Models Nos. 2, 4, and 5 are receiving further consideration. At present the grid-type support appears to be the most feasible. Hydraulic Model No. 2 is included primarily as a basis of comparison. These three complete core sub-assemblies are compared in Fig. 8 for two temperatures, 600°F and 750°F. The drop in piezometric head expressed in psi is plotted against the discharge of sodium[4] in gpm to provide a design plot based on the faired curves of Figs. 3 and 4. The pressure drop was converted directly from feet of sodium so that it is the difference in reading of two gages placed at the same level and connected by tubes of sodium to piezometer openings 1 and 12. The differences in pressure drops are attributable to losses in the core sections only; the axial blanket sub-assembly is common for all three complete sub-assemblies. The effect of changes in temperature is also apparent on this plot.

Design points representing a discharge of 300 gpm of sodium are also shown. There are actually six such points, but the effect of temperatures at the higher discharges is too small to show clearly with the scale used in Fig. 8.

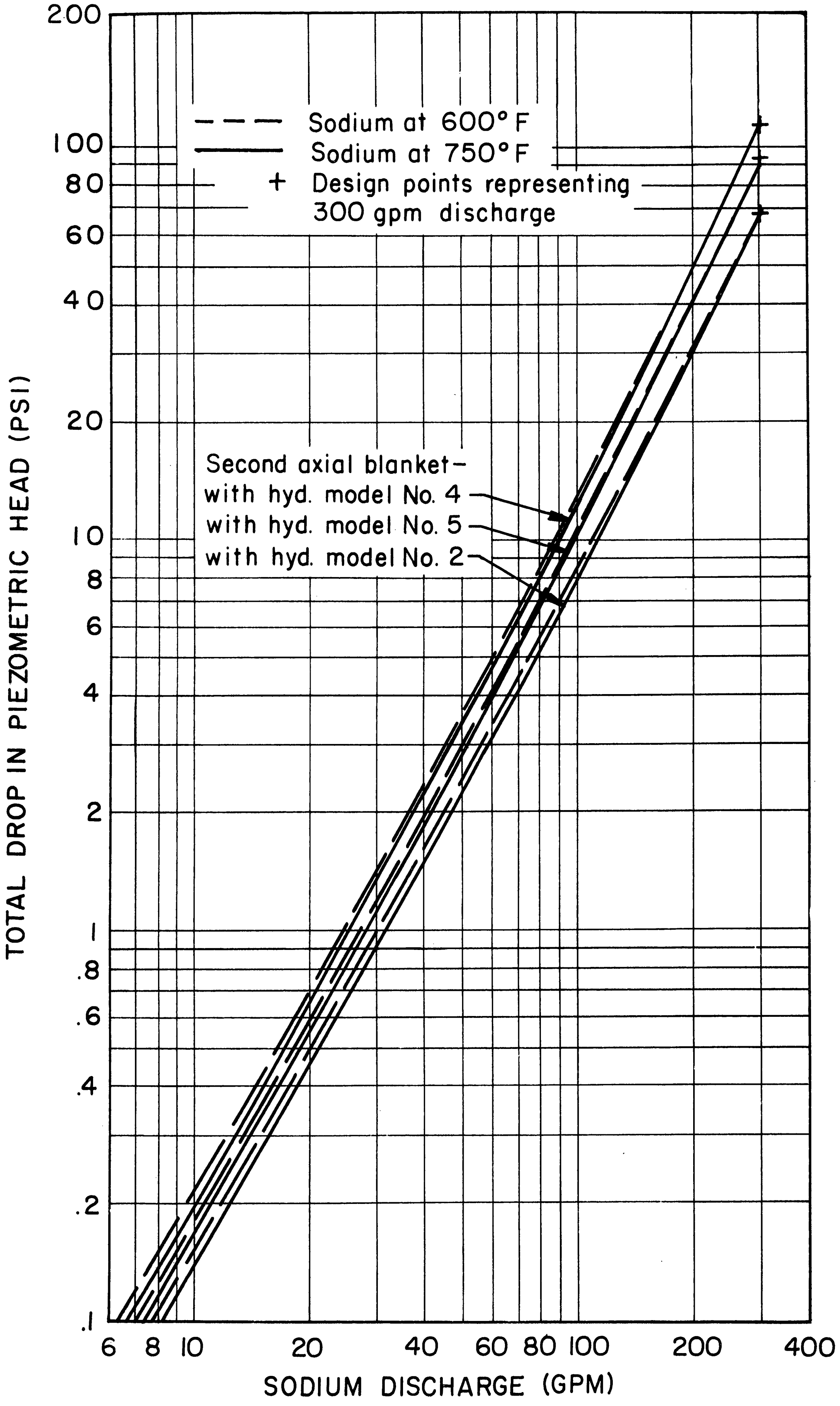

Fig. 8. Drop in piezometric head for complete core-sub-assemblies.

APPENDIX

COMPARISON OF ELEMENTS OF AXIAL BLANKET SUB-ASSEMBLIES

Detailed comparisons were made of the drop in piezometric head through the various parts of the two axial blanket sub-assemblies. Some of the results of these tests are plotted in Fig. 9 against Reynolds numbers based on the identical equivalent diameters and open areas for sections through the blanket rods.

The top pair of curves in the figure shows values of $\Delta h/Q^2$ for the two inlet nozzles, in which Δh is the drop in piezometric head from just upstream of the nozzle in the 3-in. line (piezometer opening 1) to just upstream of the transition from round to square cross section (piezometer opening 3) in the nozzles. For the model of the first sub-assembly the latter point is 2-1/2 in. below the flange, and in the second it is 3-3/4 in. below the flange. Thus the effect of the transition is not included. The second pair of curves is a similar comparison of the drop in piezometric head between piezometer openings 3 and 4. This plot indicates the effects of the round to square transition as well as the sharpening of the leading edges of the grids which support the rods.

The lower pair of curves show the drop in head between piezometer openings 11 and 12 in terms of $\Delta h/Q^2$ with and without the handling lug installed in the section. This is not a comparison of the first and second axial blanket sub-assembly handling lugs, as these are very nearly the same. The curves are included to show the effect of the presence of a handling lug.

Tests were also run using each of two support plates at the entrance to the nozzle of the old sub-assembly. The three results, for the two plates and for the streamlined nozzle, were virtually indistinguishable. Thus either plate would reduce the loss for the first nozzle to that for the second sub-assembly.

Additional curves showing the drop in piezometric head between other piezometer openings in the second sub-assembly are presented in Fig. 10. Here, in terms of $\Delta h/Q^2$, the data between openings 4 and 5, 5 and 6, 9 and 10, and 10 and 11 are plotted against the Reynolds number for the blanket section.

CALCULATION OF TYPICAL HYDRAULIC DIMENSIONS

The open area and equivalent diameter values used in computing Reynolds numbers for the core sections were calculated on the basis of measured dimensions of the models tested. The following examples for Hydraulic Models Nos. 2 and 4 are typical:

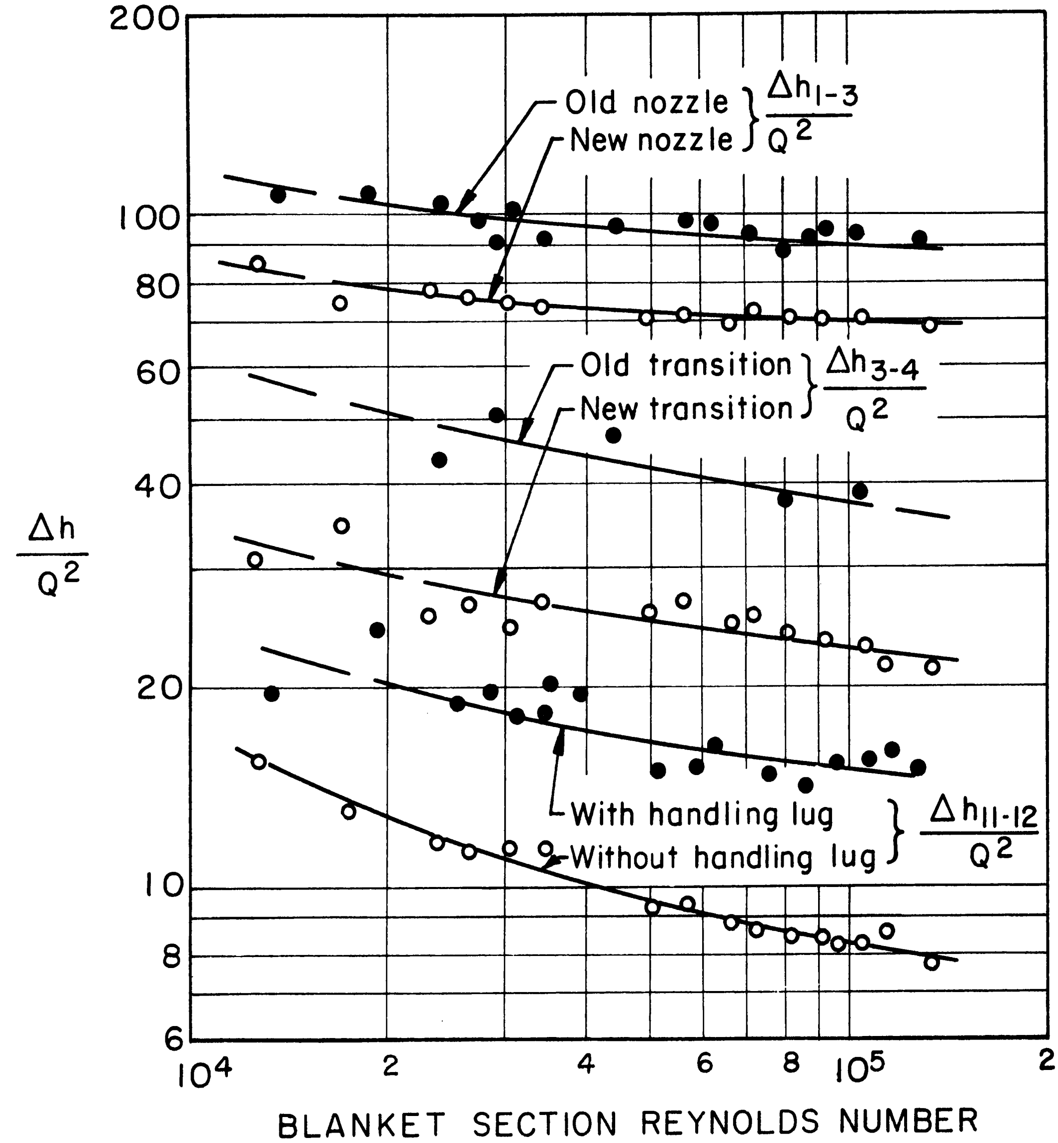

Fig. 9. Drop in piezometric head through parts of axial blanket sub-assemblies.

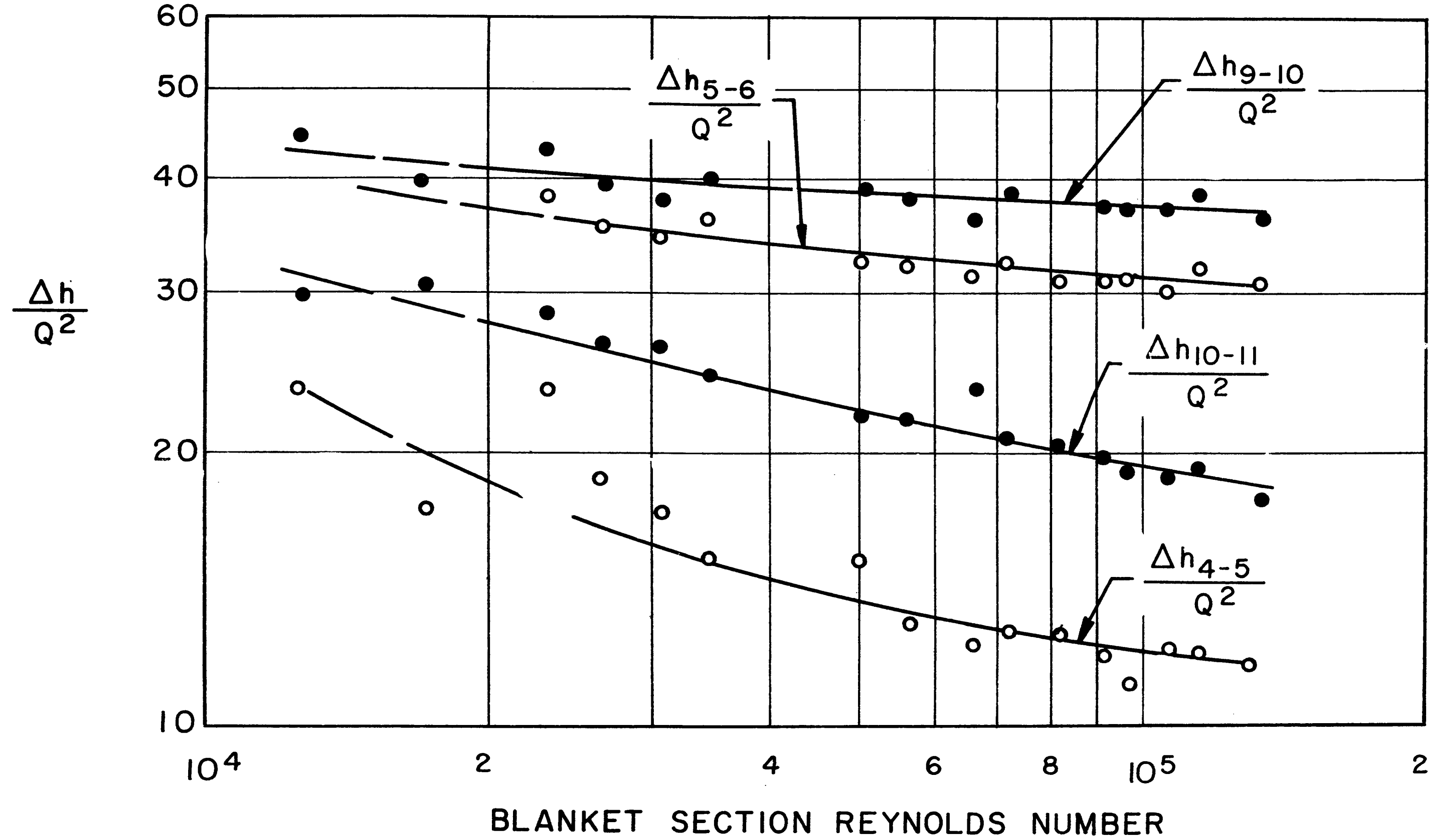

Fig. 10. Drop in piezometric head through parts of second axial blanket sub-assembly.

HYDRAULIC MODEL NO. 2

Open Area: 2.444 in. square after shimming
less 144 rods 0.158 in. in diameter
less 144 bar windings 0.044 by 0.02 in.
or 3.02 sq in. or 0.0210 sq ft.

Wetted Perimeter: 4 sides of 2.444 in.
plus 144 rods of π(0.158)-in. circumference
plus 144 rods of (0.044 + 0.044 + 0.02) in.
or 96.8 in. or 8.06 ft.

Equivalent Diameter: Four times open area of 0.0210 sq ft divided by wetted perimeter of 8.06 ft or 0.0104 ft.

HYDRAULIC MODEL NO. 4

Open Area: 2.484 in. square
less inner liner 9.34 in. by 0.012 in. thick
less 144 rods 0.158 in. in diameter
less 4 longitudinal wires 0.047 in. in diameter
less 4 spiral windings 0.047 in. in diameter
or 3.22 sq in. or 0.02235 sq ft.

Wetted Perimeter: 4 sides of 2.484 in.
plus 144 rods of π(0.158)-in. circumference
plus 8 wires of π(0.047)-in. circumference
plus 18.59 in. for both sides of inner liner
or 100.64 in. or 8.39 ft.

Equivalent Diameter: Four times open area of 0.02235 sq ft divided by wetted perimeter of 8.39 ft or 0.0106 ft.

CALCULATION OF TYPICAL POINT ON FIG. 8

The basis of the design curves presented in Fig. 8 can be explained in detail by an illustration of how a typical point was obtained. For example, the total drop in piezometric head through the new axial blanket sub-assembly and core Hydraulic Model No. 4 at a discharge of 100 gpm of sodium at 600°F is 13.3 psi. The calculations for this point would be:

(1) Core section Reynolds number $= \dfrac{Vd_e}{\nu} = \dfrac{Qd_e}{A\nu} = \dfrac{(.2225)(.0106)}{(.02235)(4 \times 10^{-6})} = 26350$

$\Delta h/Q^2$ from Fig. 3 is 503 at this Reynolds number;

(2) Axial blanket Reynolds number $= \dfrac{Qd_e}{A\nu} = \dfrac{(.2225)(.0304)}{(.0217)(4 \times 10^{-6})} = 78000$

$\Delta h'/Q^2$ from Fig. 4 is 205 at this Reynolds number;

(3) Total $\Delta h/Q^2 = 503 + 205 = 708$;

Total $\Delta h = 708(.2225)^2 = 35.1$ ft of sodium at 600°F.

(4) Drop in head in psi $= \dfrac{\gamma \Delta h}{144} = \dfrac{54.6(35.1)}{144} = 13.3$.

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