Sept. 20, 1960

J. E. SMITH ET AL

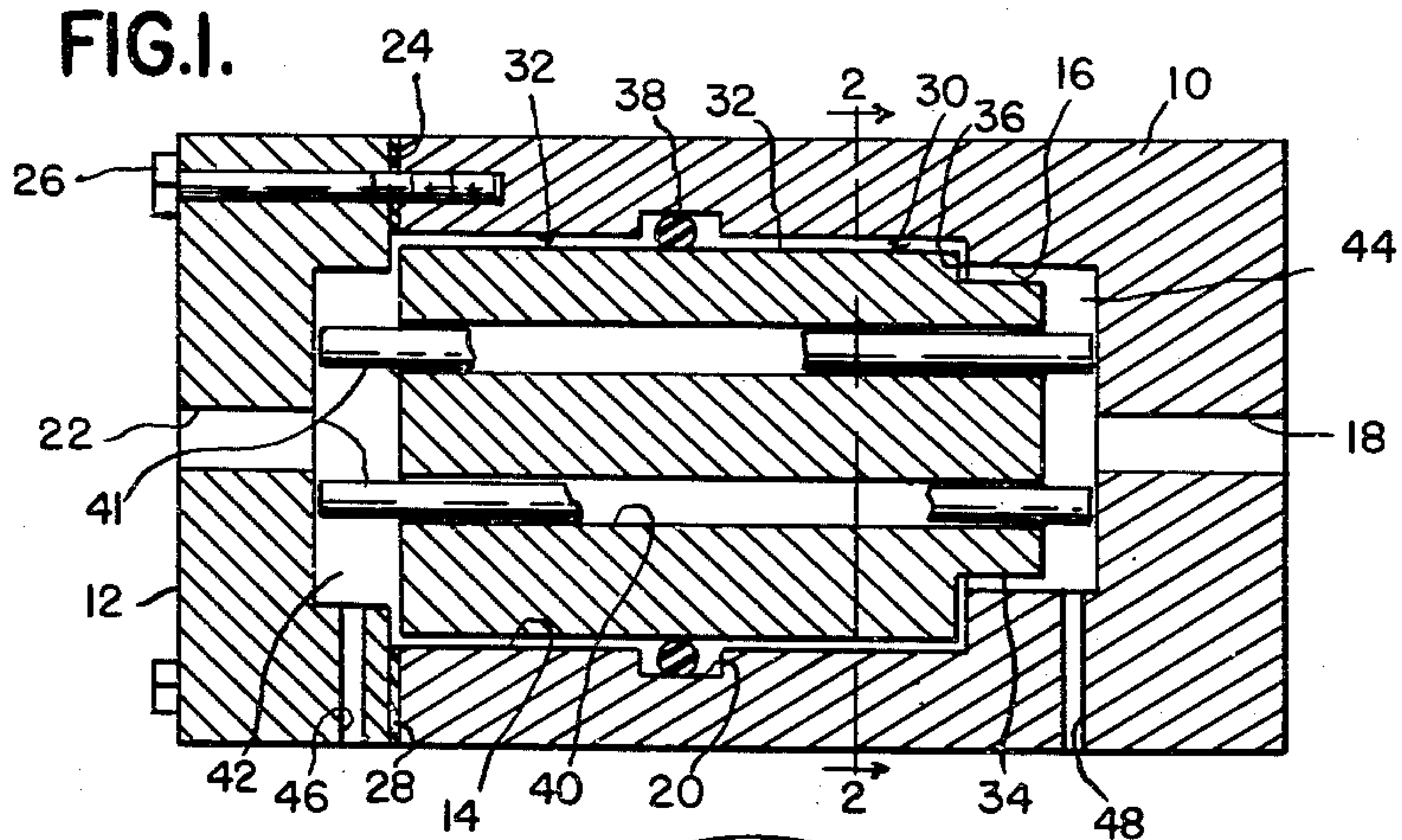
2,953,167

HYDRAULIC RESISTOR

Filed Aug. 22, 1955

3 Sheets-Sheet 1

FIG.1.



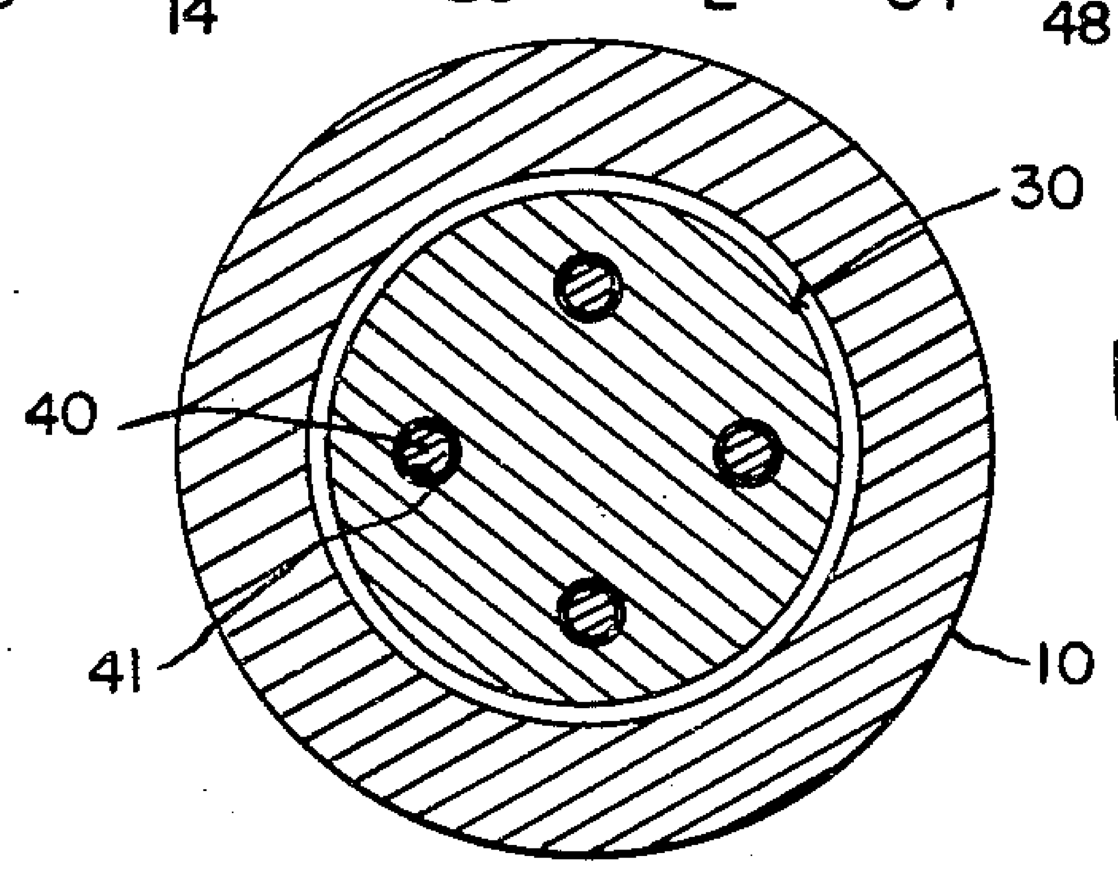
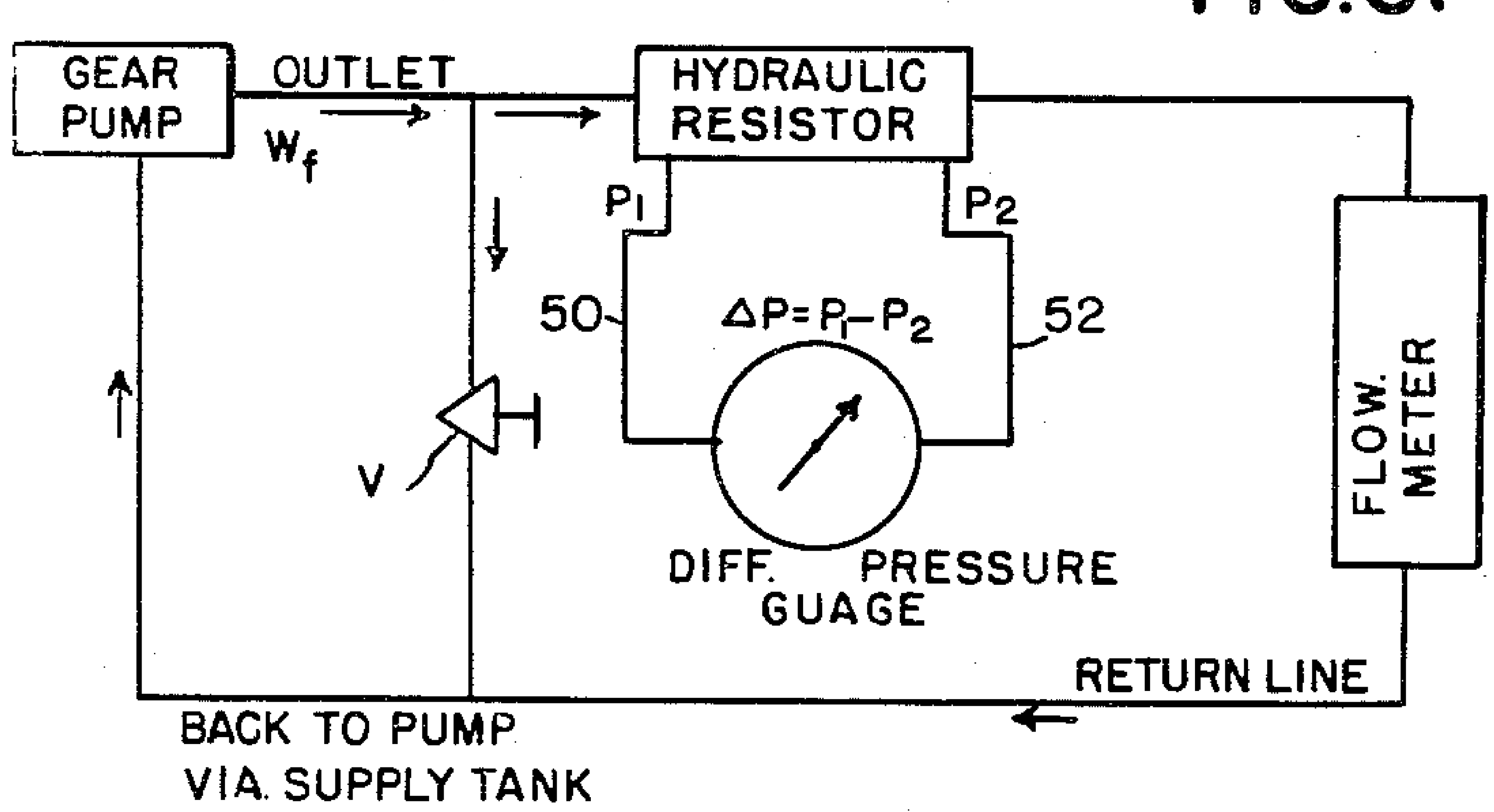


FIG.2.

FIG.3.



INVENTORS
JOHN E. SMITH
ROBERT S. FLEMING
ALTON G. DeCLAIRE, JR.
GEORGE B. STROH
BY Whittemore, Hulbert & Belknap ATTORNEYS

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HYDRAULIC RESISTOR

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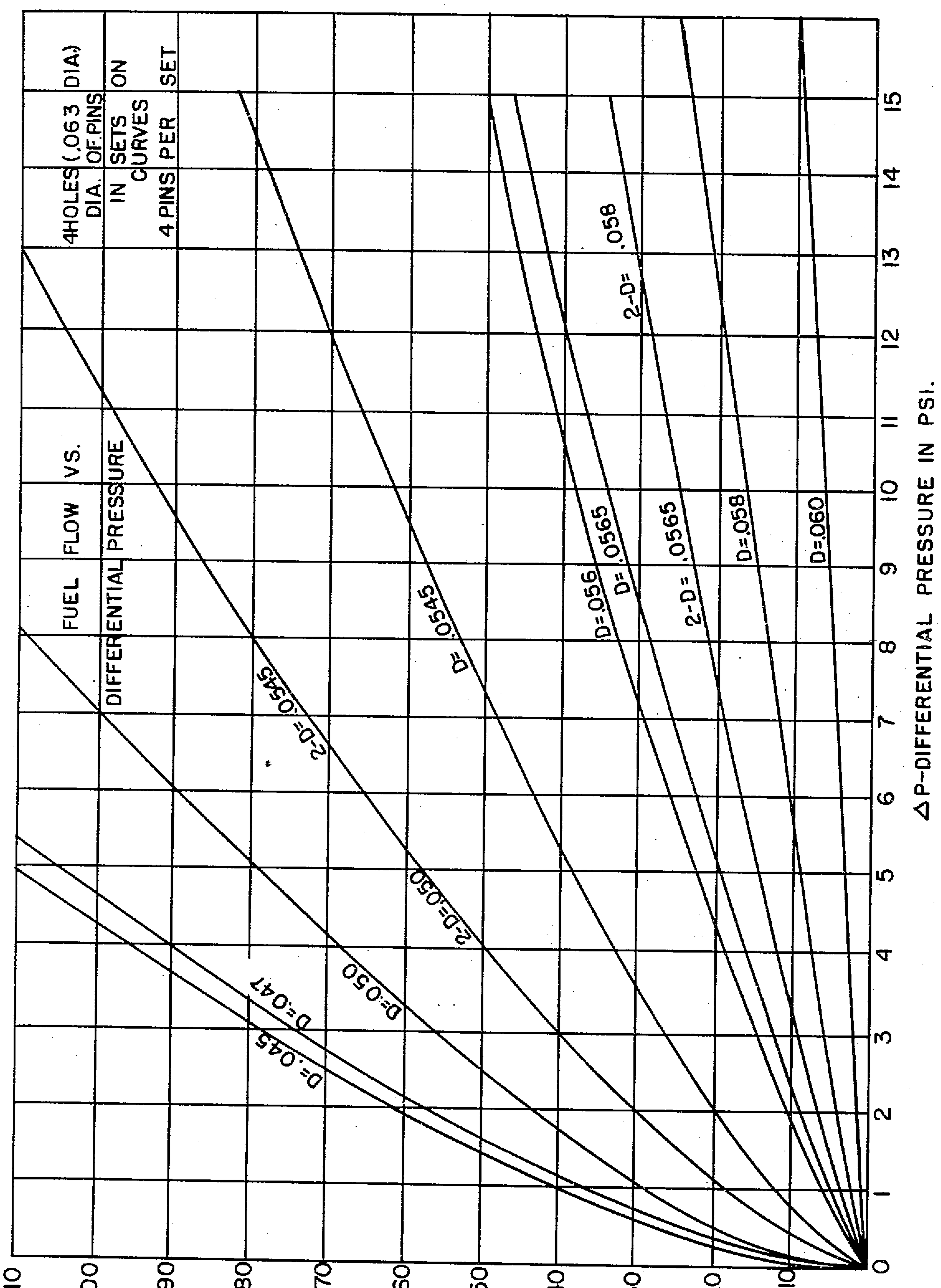

FIG. 4.

INVENTORS
JOHN E. SMITH
ROBERT S. FLEMING
ALTON G. DeCLAIRE, JR.
GEORGE B. STROH

BY Whittemore, Hulbert & Belknap ATTORNEYS

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HYDRAULIC RESISTOR

Filed Aug. 22, 1955 3 Sheets-Sheet 3

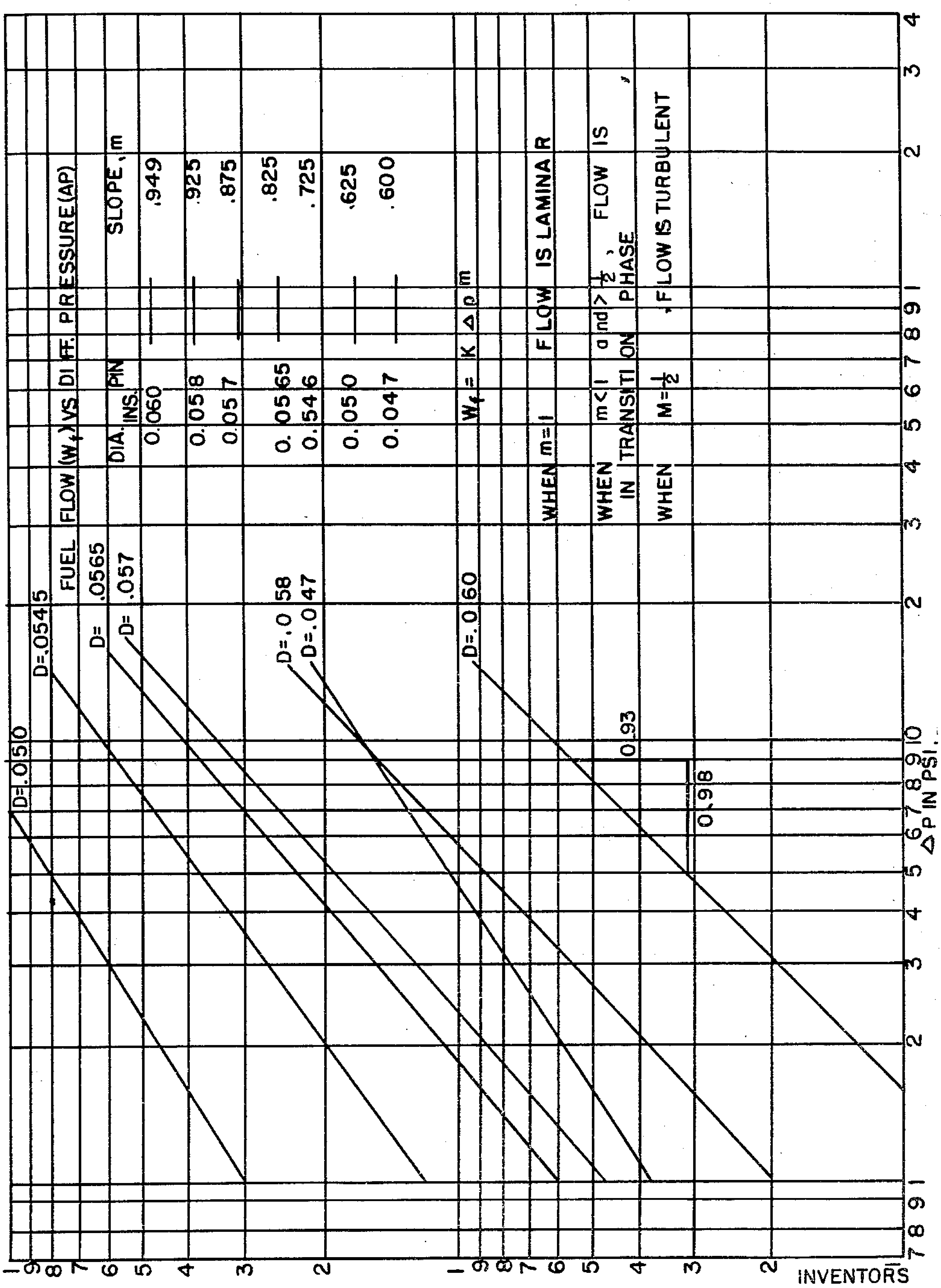

FIG.5.

INVENTORS
JOHN E. SMITH
ROBERT S. FLEMING
ALTON G. DeCLAIRE, JR.
GEORGE B. STROH

BY Whittemore, Hulbert & Belknap ATTORNEYS

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HYDRAULIC RESISTOR

John E. Smith and Robert S. Fleming, Detroit, Alton G. De Claire, Jr., Harper Woods, and George B. Stroh, Detroit, Mich., assignors to Holley Carburetor Company, Detroit, Mich., a corporation of Michigan

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9 Claims. (Cl. 138—40)

The present inventon relates to a hydraulic resistor.

It is an object of the present invention to provide a hydraulic resistor effective to have a predetermined impedance to liquid flow therethrough.

More specifically, it is an object of the present invention to provide a hydraulic resistor which may be selectively set to have laminar flow resulting in liquid flow directly proportional to differential pressure across the resistor, or to have transitional flow (that is, a flow intermediate in characteristics between laminar flow and true turbulent flow).

It is a further object of the present invention to provide a hydraulic resistor including a plurality of passages and associated therewith means for controlling the nature of flow through the several passages so as to produce an overall predetermined impedance to flow.

It is a feature of the present invention to provide a hydraulic resistor including means forming one or more cylindrical passages adapted to be connected into a hydraulic flow line in association with pin means received in each of said cylindrical passages having its diameter so related to the internal diameter of the passage with which it is associated as to produce a desired type of liquid flow therethrough.

Other objects and features of the invention will become apparent as the description proceeds, especially when taken in conjunction with the accompanying drawings, wherein:

Figure 1 is a longitudinal sectional view through a hydraulic resistor.

Figure 2 is a sectional view on the line 2—2 Figure 1.

Figure 3 is a diagrammatic view showing the connection of the hydraulic resistor into a hydraulic circuit.

Figure 4 is a chart showing flow plotted against differential pressure when employing the hydraulic resistor.

Figure 5 is a diagram showing the manner of determining values of the exponent m.

In many cases, in running tests involving liquid flow as for example, in testing carburetors or the like, it is important to provide a hydraulic resistor having a known predetermined and preferably adjustable resistance to liquid flow.

Basically, it has been found that true laminar flow, in which the flow of liquid is directly proportional to the pressure drop across the resistor, can be provided in a simple and effective manner by employing a true cylindrical passage having a true cylindrical pin received in the passage, the diameter of the pin being slightly smaller than the internal diameter of the cylinder to simulate leakage between a piston and sleeve.

By controlling the clearance, length and differential pressure applied across the resistor, the flow can be made truly laminar in which W_f (the flow of fuel or liquid) is directly proportional to ΔP (differential pressure).

Moreover, it is found that by varying pin size with reference to a specific cylindrical passage, the nature of the flow may be varied. As is well known, turbulent flow through a conventional orifice is represented by the expression $W_f = K\Delta P^m$ where the exponent m is equal to 0.5. The same equation follows for laminar flow where the exponent m is equal to 1.0. With the present hydraulic resistor it is possible to produce flow represented by the same equation in which the exponent m has any desired value greater than 0.5 and not more than 1.0. Moreover, by employing a plurality of passages and pins in parallel it is possible to produce a hydraulic resistor offering substantially any desired impedance to flow.

Referring now to the drawings, a simple form of hydraulic resistor constructed in accordance with the present invention is illustrated in Figures 1 and 2. The resistor comprises a casing consisting of a cup-like body **10** and a removable cap or closure **12**. The cup-like body **10** is provided with a cylindrical chamber **14** open at one end of the body and provided at its opposite end with a reduced extension **16**. The end of the body **10** adjacent the extension **16** is closed except for a passage **18** adapted to serve as an outlet connection for the resistor. Intermediate from the ends of the cylindrical chamber **14** is an outwardly extending annular channel **20** for a purpose which will presently appear.

The removable cap or closure **12** is provided with a passage **22** serving as the inlet connection for the resistor. The cap **12** is provided with an annular shoulder **24**. The cap **12** is retained in sealed relation to the body **10** by suitable means such for example as fastening screws **26** and the gasket indicated at **28**.

Located within the interior of the casing is a compound cylinder indicated generally at **30** having a cylindrical portion **32** received in the cylindrical chamber **14** and having a reduced cylindrical extension **34** received in the reduced extension **16** of the chamber **14**. The dimension of the cylindrical portion **32** is such that its ends are adapted to be engaged by the annular shoulder **24** of the cap and an annular shoulder **36** formed by the reduced extension **16** of the chamber **14**. Thus, the cylinder **30** is retained against substantial axial movement within the casing.

In assembly suitable sealing means such for example as the O-ring indicated at **38**, is received in the channel **20** and provides an effective seal between opposite ends of the cylinder **30**. The cylinder **30** is provided with a plurality of accurately sized and finished cylindrical openings **40**, all of which are preferably of the same identical size. In assembling the hydraulic resistor, pins **41** are located in the cylindrical passages **40**. These pins preferably are of a length sufficient to extend between the adjacent surfaces of the cap **12** and the end surfaces of the reduced extension **16** of the chamber as illustrated. In addition, the pins are accurately dimensioned as will subsequently be described in detail.

With the parts assembled as illustrated in Figure 1, it will be observed that the liquid inlet connection **22** communicates with an inlet header space **42**, and an outlet header space **44** connects the outlet ends of the cylindrical passages **40** to the outlet passage **18**. Passages **46** and **48** respectively extend from the exterior of the casing to the header spaces **42** and **44**.

Referring now to Figure 3 there is diagrammatically illustrated an arrangement in which the hydraulic resistor is connected in a hydraulic circuit as labeled on the figure. It will be observed that a differential pressure gauge is connected across the test fixture and has conduits **50** and **52** by means of which it is connected to the passages **46** and **48** of the hydraulic resistor.

The outlet of the gear pump is variably controlled by an adjustable valve V so as to provide the required pressure drop ΔP across the hydraulic resistor. The actual flow of liquid through the resistor is measured by the meter.

The resistance or impedance to flow afforded by the hydraulic resistor is determined by the number of cylindrical passages **40** which are open to flow and by the dimensions of the pins **41** received therein. In the illustrated embodiment of the present invention four of the cylindrical passages are provided although of course a much larger number could be provided if desired. If it is desired to reduce the overall flow of fluid any number of the cylindrical passages **40** may be plugged.

In general, true laminar flow takes place through a passage **40** containing a restricting pin **41** when the diameter of the pin is close to the internal diameter of the opening. If the diameter of the pin is reduced in size, flow intermediate between laminar and turbulent flow takes place, and in the present instance this flow is referred to as transitional flow.

Referring again to the formula $W_f=K\Delta P^m$, flow in accordance with this formula is said to be turbulent when the value of the exponent m is equal to 0.5, flow is said to be laminar when the value of the exponent m is 1.0, and in accordance with the description herein flow is said to be transitional when the value of the exponent m is greater than 0.5 but less than 1.0

The present apparatus permits the production or adjustment of the hydraulic resistor to substantially any required condition by the selection of the size and number of pins employed and by the selection of the number of cylindrical passages employed. Assume for example, that the use of two passages using identical pins of a certain size satisfies the requirements except that the value of the exponent m is slightly less than desired. Substitution of the next larger size of pins produces a value of the exponent m which is slightly larger than desired. In order to produce a value of m close to the desired value, one pin of the larger size will be provided in one passage and a pin of the smaller size will be provided in the remaining passage. This will have the effect of producing a value of the exponent m substantially midway between the values previously obtained by the use of identical pins. In the same manner, if it is desirable to increase total flow (or increase the value of K in the equation) this may be accomplished by employing more passages. In the specific example previously described, two additional passages could be employed using pins of the two different sizes referred to in the foregoing.

From the foregoing it will be observed that by proper selection of the number of passages and size of pins, the hydraulic resistor may be assembled or adjusted to produce a wide range of fluid flow resistance.

Referring now to Figure 4 there is illustrated a chart showing values obtained in a hydraulic resistor provided with four cylindrical passages and in which all of the passages are provided with pins. Each of the curves obtained shows the diameter of the pin or pins and it will be observed that in some cases all of the pins are of the same size and in other cases pins of two different sizes are employed. In this case the internal diameters of the cylindrical passages are .063″ and the length of passages is .500″. As will be observed from the chart, the curves obtained are the result of plotted ΔP (differential pressure in pounds per square inch) against W_f (measured in this instance in pounds per hour).

The present invention is base upon a recognition of the fact that hydraulic flow is ordinarily described as of two types, laminar and turbulent. These can be illustrated by watching smoke rise from a cigarette in a still room. The smoke rises undisturbed in laminae or layers for a short distance above the cigarette. This is laminar flow. When the smoke is diffused and breaks up it is turbulent flow. The controlling factor of the nature of flow is the Reynolds number. The Reynolds number for flow through a circular pipe is:

$$N_R=\frac{VD}{\gamma}$$

where:

V is the velocity of the fluid in ft. per sec.,
γ is the kinematic viscosity in ft.^{2} per sec.,
D is the diameter of the pipe in feet.

When $N_R \leqslant 2000$, the flow is normally laminar while from about 2000 to 3000 the flow is in a transition phase between laminar and turbulent flow. For laminar flow in pipes, the weight rate of flow (W_f) is $\alpha\Delta P$ while for turbulent flow $W_f\alpha\Delta P^{1/2}$. If the flow through the hydraulic resistor could be made laminar, then $W_f\alpha\Delta P$. A formula for laminar flow between a piston and sleeve has been derived, which is

$$W_f=\frac{Kb^3D\Delta P}{\gamma L}$$

The clearance between the piston and sleeve is b, the diameter of the piston is D, and the length is L. Certain values of b, L and ΔP assure laminar flow. The hydraulic resistor of Figures 1 and 2 has been designed to embody these principles in a practical device. A fixed number of small holes have been drilled in the fixture and pins are inserted in the holes. The flow area, a function of b, can be controlled closely by the size of the pins. The same flow area could be obtained by drilling very small holes but the size needed is so small that it would not be practical to attempt drilling the hole.

Referring now to Figure 4, the flow is laminar when the plot of W_f against ΔP is linear. As the diameter of the pins decrease, the clearance increases, and the curve varies more and more from a straight line, indicating the flow is changing from laminar to turbulent. When the flow is laminar, $W_f\alpha\Delta P$, but for turbulent flow $W_f\alpha\Delta P^{1/2}$. There is a transition phase between laminar and turbulent flow where $W_f\alpha\Delta P^m$, with $1>m>1/2$. The value of m is found by plotting W_f versus ΔP on log log graph paper and measuring the slope of the line. ($W_f=K\Delta P^m$, $\log W_f=m \log K\Delta P$, $y=mx$, m is slope of line.) This is shown in Figure 5 for seven sets of pins, varying from 0.060″ diameter to 0.047″ diameter. The resulting plot is a series of straight lines with the slope of a line equal to the exponent of ΔP for that particular set of pins. The values of m and the diameters of the pins used to make seven sets are found in Figure 5.

For any value of ΔP, in the hydraulic resistor range, any value of W_f can be obtained.

One method is to increase the fuel flow by increasing the number of holes reamed into the cylinder. Using the cylinder described in Figure 1, with .063″ diameter holes and a wall thickness of .050″, the maximum number of holes that can be reamed in the cylinder is ten.

Another method of changing the fuel flow can also be obtained by changing the size of the pins. For example, a value W_f for a specific ΔP might be needed that is midway between the values obtained by using sets of 0.056″ and 0.057″ pins. Then a set would be made of half 0.056″ pins and half 0.057″ pins, which will give W_f very close to the value wanted. Fine adjustment can be made by inserting smaller or larger pins. By interchanging the pins the value of W_f for any ΔP can be controlled very closely. In other words, this procedure demonstrates that this design is infinitely adjustable.

For the .060″ diameter pins the plot of W_f versus ΔP is linear, indicating laminar flow. The plots for the .058″ diameter pins to the .0545″ diameter pins deviate slightly from a straight line, indicating a transition phase between laminar and turbulent flow. The plots of the

.0545" pins to the .045" pins show that the flow is more in a turbulent phase than it is laminar.

The exponent of ΔP, which is an indication of the nature of the flow, can be found in Figure 5. The slope of the curve, W_f versus ΔP plotted on log log graph paper, is the exponent of ΔP. This value varies from .949 for the .060" diameter pins to .600 for the .047" diameter pins. Thus, the slopes of all the curves are greater than .500, so the flow is not entirely turbulent but in the transition phase.

The drawings and the foregoing specification constitute a description of the improved hydraulic resistor in such full, clear, concise and exact terms as to enable any person skilled in the art to practice the invention, the scope of which is indicated by the appended claims.

What we claim as our invention is:

1. A hydraulic resistor having inlet and outlet connections and a plurality of cylindrical passages of the same internal diameter having open ends in communication with said connections, a cylindrical pin in each of said passages and extending the full length thereof, some of said pins being of different diameters, each of said pins having a uniform diameter smaller than but sufficiently close to the internal diameter of the passage in which it is located to produce a liquid flow therethrough represented by $W_f=K\Delta P^m$, where W_f is liquid flow, K is a constant, ΔP is the pressure differential across said resistor, and the exponent m has a value greater than 0.5 but not more than 1.0.

2. A hydraulic resistor comprising a casing having inlet and outlet connections and an enlarged chamber therein, a body in said chamber having a plurality of identical cylindrical passages therethrough, said casing comprising a removable cap to provide access to said body, and sets of pins of different accurately predetermined sizes extending completely through said passages to determine the nature of fluid flow therethrough to provide for selective control of flow characteristics.

3. A hydraulic resistor comprising a housing having a main chamber open at one end and having a reduced chamber portion extending beyond the other end of the main chamber, a removable cap covering the open end of said main chamber and having a recess of cross-section smaller than that of said main chamber, a body in said main chamber having end abutment portions larger than said reduced chamber portion and recess to space the ends of said body from the bottom of said reduced chamber portion and recess, said body having a plurality of cylindrical passages of equal diameter extending therethrough, and pins in said passages having a length greater than the length of said passages to cause the ends of said pins to extend beyond the ends of said passages into said reduced chamber portion and recess, sealing means between said body and main chamber, and passage means communicating with said reduced chamber portion and recess.

4. An adjustable hydraulic resistor comprising a housing having a main chamber open at one end and having a reduced chamber portion extending beyond the other end of the main chamber, a removable cap covering the open end of said main chamber and having a recess of cross-section smaller than that of said main chamber, a body in said main chamber having end abutment portions larger than said reduced chamber portion and recess to space the ends of said body from the bottom of said reduced chamber portion and recess, said body having a plurality of cylindrical passages of equal diameter extending therethrough, a plurality of pins of uniform diameter located in said passages and extending beyond the ends thereof, the diameters of different pins being of different size, said pins being selected to produce a flow across said resistor which is intermediate laminar to turbulent.

5. An adjustable hydraulic resistor comprising a housing having a main chamber open at one end and having a reduced chamber portion extending beyond the other end of the main chamber, a removable cap covering the open end of said main chamber and having a recess of cross-section smaller than that of said main chamber, a body in said main chamber having end abutment portions larger than said reduced chamber portion and recess to space the ends of said body from the bottom of said reduced chamber portion and recess, said body having a plurality of cylindrical passages of equal diameter extending therethrough, a plurality of pins of uniform diameter located in said passages and extending beyond the ends thereof, the diameters of different pins being of different size, said pins being selected to produce a flow across said resistor which is intermediate laminar to turbulent, some of said passages being plugged to control total volume of flow.

6. A hydraulic resistor having inlet and outlet connections and a plurality of accurately dimensioned cylindrical passages of uniform identical diameter having open ends in communication with said connections, a plurality of removable and replaceable pins received in said passages, said pins being longer than said passages and of different diameters, each of the pins being of uniform diameter smaller than but sufficiently close to the diameters of said passages to produce liquid flows therethrough, when pins are received in said passages, the diameters of the different pins being such as to cause a flow across the resistor which is represented by

$$W_f=K\Delta P^m$$

where W_f is the liquid flow, K is a constant, and ΔP is the pressure differential across the resistor, in which the exponent m has a value intermediate 0.5 and 1.0.

7. A hydraulic resistor having inlet and outlet connections and a plurality of accurately dimensioned cylindrical passages of uniform identical diameter having open ends in communication with said connections, means comprising removable and replaceable cylindrical pins received in said openings to determine the nature of hydraulic flow therethrough, said pins being of such different selected sizes relative to the passages in which they are received that flow across said resistor is represented by the formula $W_f=K\Delta P^m$, where W_f is flow, K is a constant, ΔP is the pressure differential across the resistor, and in which the exponent m has a value intermediate 0.5 and 1.0.

8. A hydraulic resistor having inlet and outlet connections and a plurality of cylindrical passages of known diameter connected in parallel between said inlet and outlet connections, a removable and replaceable cylindrical pin of known diameter received in each of said passages, each of said pins having a diameter less than the diameter of the passage in which it is received to determine the nature of the hydraulic flow therethrough, the difference in diameters between at least one of said passages and the pin received therein being different from the difference between the diameter of another of said passages and the pin received therein, the differences in passage and pin diameters being such as to cause a flow across the resistor which is represented by $W_f=K\Delta P^m$, where W_f is the liquid flow, K is a constant, and ΔP is the pressure differential across the resistor, in which the exponent m has a value intermediate 0.5 and 1.0.

9. In a hydraulic resistor for controlling mass flow rate in accordance with the formula $W_f=K\Delta P^m$, where W_f is mass flow, K is a constant, ΔP is the pressure head and the exponent m is the logarithmic slope of the curve defining the mass flow rate through said resistor for varying values of ΔP, and having a plurality of accurately dimensioned cylindrical passages of uniform known diameter for conducting said mass flow,

means for selectively varying the value of m between 0.5 and 1.0, said means comprising a plurality of removable and replaceable cylindrical pins of known diameters and received within and cooperating with said cylindrical passages to restrict mass flow therethrough, the difference in diameters between at least one of said passages and the pin received therein being different from the difference between the diameter between another of said passages and the pin received therein, the differences in passage and pin diameters being such as to produce a total mass flow through the resistor which

is intermediate the values of mass flow which would result from strictly laminar and strictly turbulent flow.

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