

April 21, 1936.

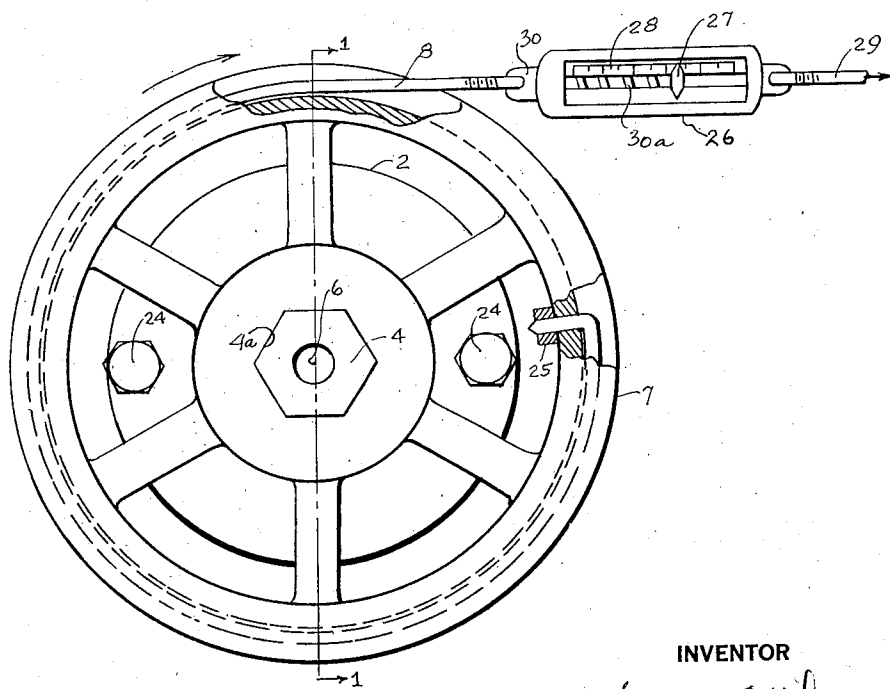
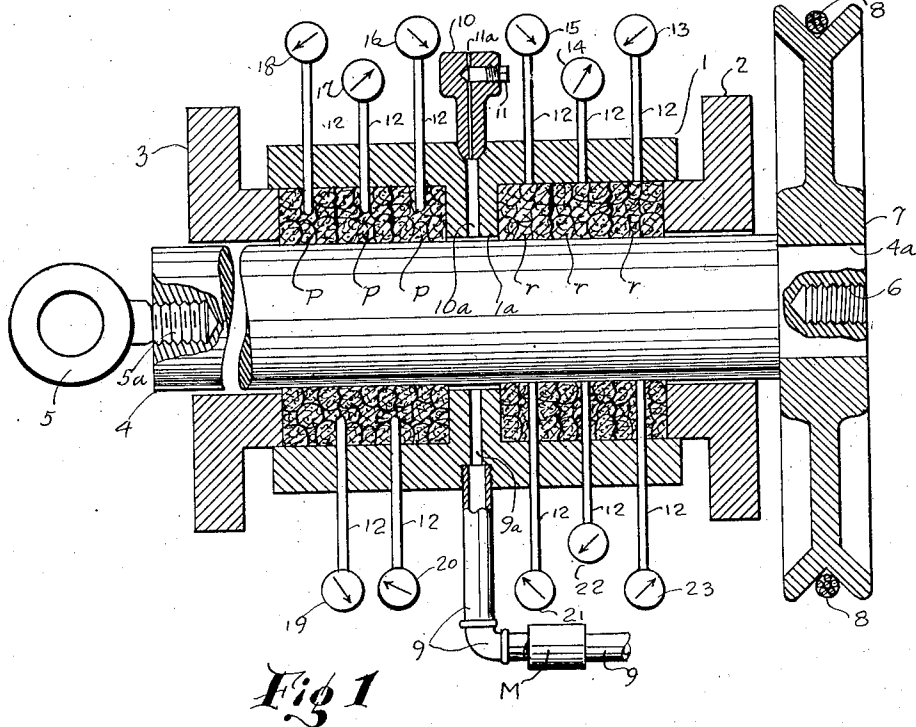
H. T. WHEELER

2,038,091

METHOD OF DETERMINING THE ELASTICITY OF POROUS PACKING STRUCTURES

Filed May 15, 1931

4 Sheets-Sheet 1



INVENTOR

Harley T. Wheeler

April 21, 1936.

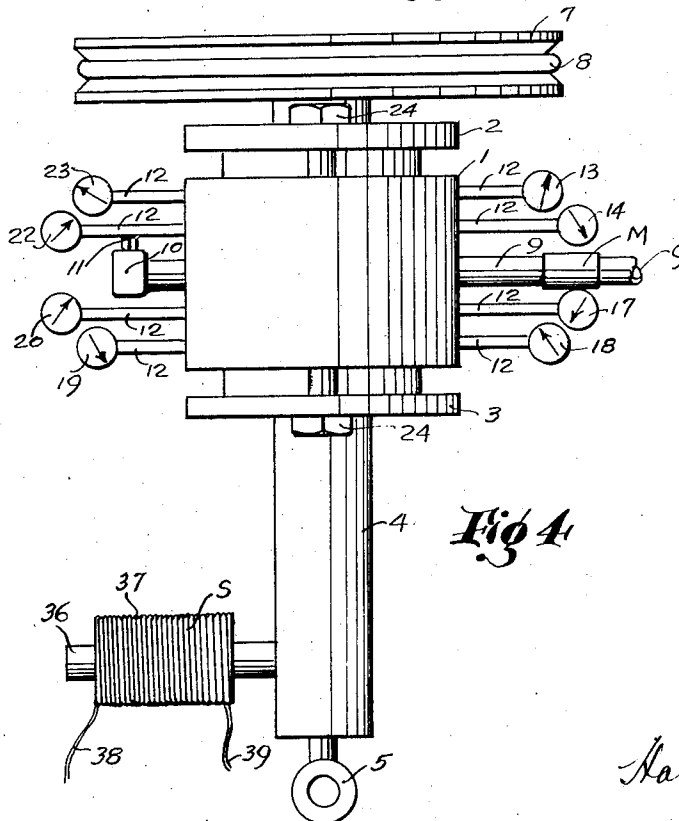
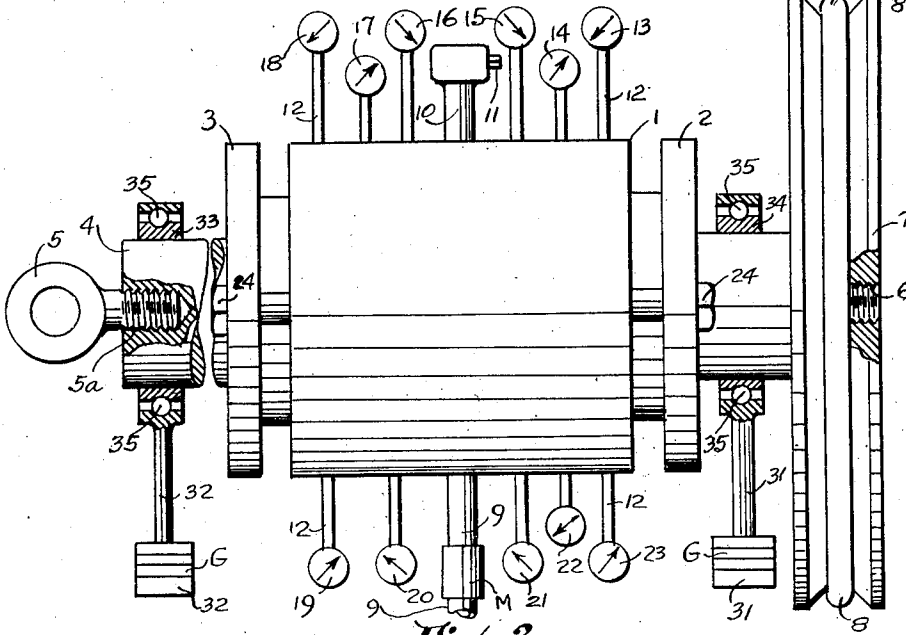
H. T. WHEELER

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METHOD OF DETERMINING THE ELASTICITY OF POROUS PACKING STRUCTURES

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4 Sheets-Sheet 2



INVENTOR.

Harley Wheeler

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4 Sheets-Sheet 3

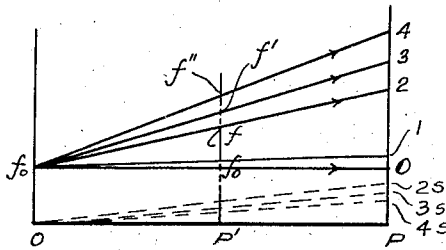


Fig 5

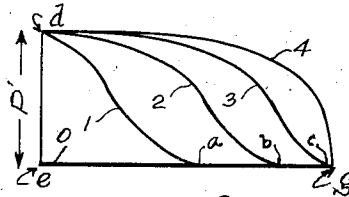


Fig 6

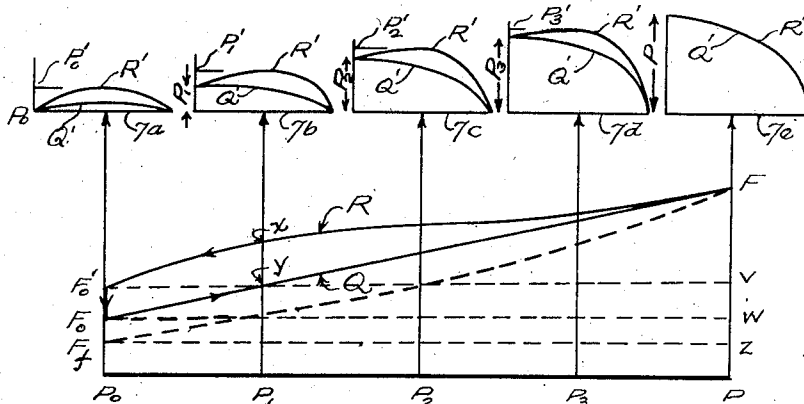


Fig 7

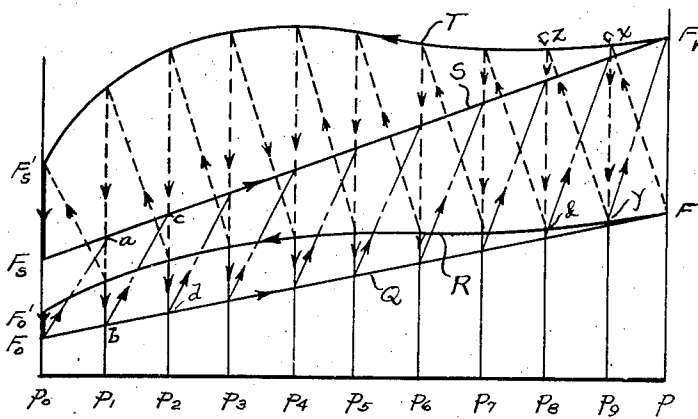


Fig 8

INVENTOR.
Harley Wheeler

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H. T. WHEELER

2,038,091

METHOD OF DETERMINING THE ELASTICITY OF POROUS PACKING STRUCTURES

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4 Sheets-Sheet 4

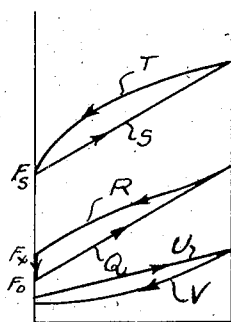


Fig 9

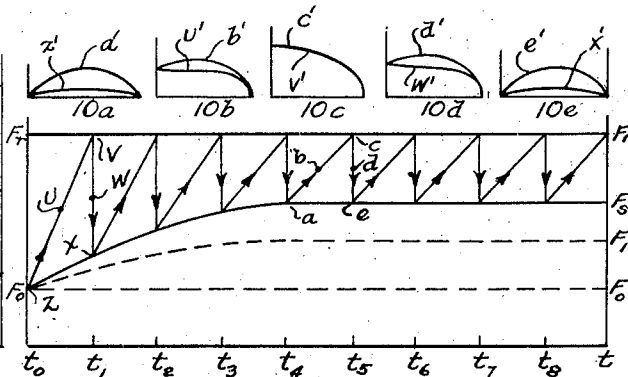


Fig 10

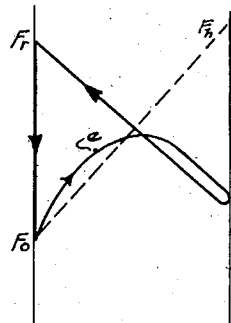


Fig 11

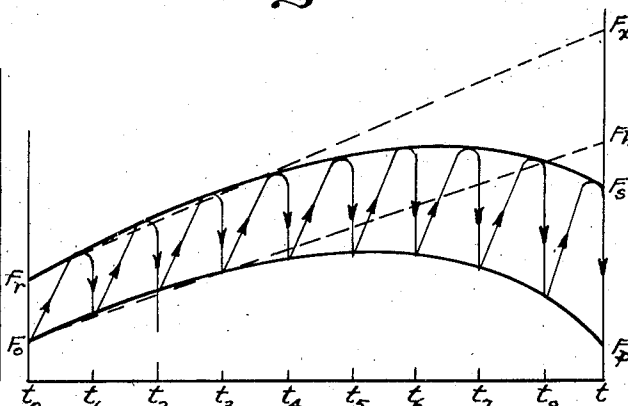


Fig 12

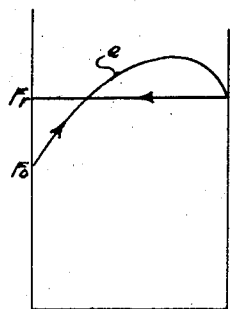


Fig 13

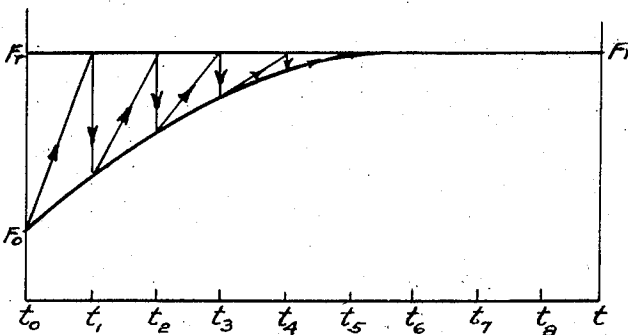


Fig 14

INVENTOR.

Harley M. Kullen

UNITED STATES PATENT OFFICE

2,038,091

METHOD OF DETERMINING THE ELASTICITY OF POROUS PACKING STRUCTURES

Harley T. Wheeler, Dallas, Tex.

Application May 15, 1931, Serial No. 537,658

1 Claim. (Cl. 73—51)

This invention relates to a method of determining the elasticity of porous elastic structures under the tension of pressure while in contact with a moving solid body, and its chief advantage lies in a capability of determining by friction, how much the elasticity of the structure is reduced by the saturation under fluid pressure.

Another advantage is that the relation of the friction created to that of the speed of movement of the solid body while the fluid pressure is being varied, may be obtained.

The term "pressure" will be used throughout the description as indicating fluid pressure as applied to the packing.

Still another advantage is that the friction due to permanent deformation of the elastic structure may be obtained.

One other advantage is that the correction may be obtained which is necessary to determine the volume of fluid required to compensate for saturation of the porous structure under pressure.

Another advantage is that the fatigue point of the elastic structure may be obtained.

Yet another advantage is that the relation of the deformation due to rigor may be obtained.

Still another and important advantage is the capability of ascertaining by means of friction the internal-pressure saturation resulting from repeated applications of pressure.

With the foregoing objects and advantages in view, other desirable features of testing will be shown during the description, accompanied by the drawings, wherein:

Figure 1 is a cross-sectional view of a testing machine in which samples of elastic porous structures, such as rod-packing, may be inserted for examination.

Figure 2 is an end view of the testing machine, of Figure 1.

Figure 3 is an elevational view of the testing machine arranged for testing bearing load on the packing.

Figure 4 is a vertical external view of the testing machine arranged to test packing for vibration.

Figure 5 is a set of graphic curves depicting the rise of friction due to variation of pressure which is applied per unit of time.

Figure 6 is a set of internal-pressure curves of a packing denoting the effect of varying the time of application of pressure.

Figure 7 is a fluxion curve of a rod-packing showing the effect on internal-pressure of reducing the pressure impressed.

Figure 8 is a fluxion curve of the successive

starting and stopping of the rod during the rise and fall of pressure, at a certain rate of time between applications of pressure.

Figure 9 shows the representative fluxion curves of a packing not saturated and saturated, due to repeated impressions of pressure.

Fig. 10 shows the maximum and minimum curve where pressure is applied intermittently.

Figure 11 is the fluxion curve of a liquid seal packing which is due to rigor, a temporary deforming of the structure which traps the fluid under pressure.

Figure 12 is the maximum and minimum curves of a packing under rigor of deformation, at a certain rate of intermittent applications of pressure.

Figure 13 is the fluxion curve of a packing at the fatigue point, or permanent deformation.

Figure 14 is the maximum and minimum curves of a packing approaching the fatigue point, while intermittently impressed with pressure.

Referring now especially to Figure 1, the main frame 1 of the testing machine contains the stuffing-boxes, the partition 1a dividing them. The partition 1a has a clearance to admit the shaft 4, without contact. The packing glands 2 and 3 adjust the packing in the two stuffing-boxes and are adjusted by the cap screws 24, 24, shown in the end view, Figure 2. Returning now to Figure 1, the rod 4 is threaded internally on both ends at 5a and 6, so that an eye-bolt 5 may be attached. The pulley 7 is seated on the rod 4 by means of a hexagon shape 4a. The flexible rope 8 is attached to the pulley 7 and is used to rotate the rod assembly.

As shown in Figure 2, the rope 8 is attached to the rim of the pulley 7 and is held in place by a clamp 25. This view also indicates the hexagon fit 4a on the end of the rod 4, fixing the pulley to the latter. The threaded hole 6 admits an eye-bolt for translation tests. The packing gland 2 is held and adjusted by the cap screws 24, 24. To rotate the rod 4 and measure the friction, a rope 8 is attached to the draw-bar 30 of the spring balance 26. The spring 30a is attached to the inside of the frame 26 and is compressed by a pull on the draw-bar 30. To the draw-bar 30 is attached a pointer 27 to indicate the pull on the spring 30a by means of a calibrated scale 28. The rope 29 is attached to the frame 26 and is connected to the source of movement.

Referring again to Figure 1, the partition 1a has a passage 9a into the clearance around the rod 4, the outer entrance of 9a being threaded to hold a piping assembly 9 to admit a fluid un-

der pressure from a suitable source. The passage 10a to the clearance around the rod 4 is threaded at its outer entrance to hold a valve body 10. The passage 10a is extended thru the body 10 by a passage 11a, a needle valve 11 being used to open or close the latter. A plurality of packing rings p, p, p in one stuffing-box are alike and equal in number to the rings r, r, r in the adjacent box, both sets being fitted and adjusted to suit the conditions under examination.

The sampling pipes 12, 12, etc., are pushed into slightly tapering sockets in the frame 1, the inside ends of the pipes being positioned to measure internal pressures in the packing or pressures of the surface adjacent to the packing. To the outer end of each pipe 12 is attached a visible dial gauge for measuring pressure. The gauges 13, 14 and 15 and the connected pipes 12, are positioned to measure the pressure of the stuffing-box wall, at the center of the rim of each packing ring r, r, r. The gauges 16, 17 and 18 and the connecting pipes 12, are positioned to measure pressure existing at the geometrical center of each annular packing ring p, p, p. The gauges 19 and 20 and the connecting pipes 12 are positioned to measure the pressure existing between the joints of the packing rings p, p, p. The gauges 21, 22, 23 and the connecting pipes 12 are positioned to measure the pressure of the film existing on the rod surface, in the middle of each packing ring, r, r, r. The foregoing are but examples of the method of investigating the internal pressures of packing by sampling tubes directed to the desired points. Any kind of packing may be so investigated.

The testing machine shown in Figure 3 is an elevation of the cross-sectional view of Figure 1. The packing to be tested is held around the rod 4 and inside the main frame 1, by the glands 2 and 3 and adjusted by the cap screws 24, 24. The rod 4 is threaded internally at both ends at 5a and 6 to admit an eye-bolt so that the shaft 4 may be translated in either direction. A pulley 7 is fixed to the shaft 4 so that a pull of the rope 8 will rotate the shaft 4 in either direction. The gauges 12 to 23 inclusive, attached to the sampling pipes 12, the latter positioned at required points in the packing assembly as demonstrated in Figure 1, will indicate the variation of internal pressure. Fluid pressure is applied to the packing thru a pipe 9 and exhausted thru the valve 10 by means of the needle valve 11. The machine described up to this point will indicate the friction due to the pressure impressed on the packing, plus whatever effect the moving parts have, to wit, the shaft 4, the eye-bolt 5 and the pulley 7. As the latter three parts are slight in weight by proportion to the effect of the applied pressure thru the piping 9, investigation of weight or bearing thrust against the packing is made possible by the addition of the weights G, G placed on the standards 31 and 32. The downward pull of the weights G, G is transferred thru the bearing balls 35, 35 to the collars 33 and 34. The ball bearing suspension eliminates any torsional effect, on the shaft 4 during rotation and maintains the weight in one position, the vertical.

Inasmuch as a bearing thrust is a dead weight in a given direction, it is desirable in some cases to investigate the friction of packing, devoid of all side thrusts. In Figure 4 is shown the testing machine, the rod 4 in a vertical position. The friction of the packing against the rod 4 will hold the latter in any position and its weight is so

slight in comparison to the friction that no thrust taking surfaces are needed to locate the shaft in an endwise position. The rod 4 may be rotated by a pull on the rope 8 thru the pulley 7. Likewise the rod 4 may be translated in either direction by connecting the spring balance 26, of Figure 2, to the eye-bolt 5. The packing samples are placed around the rod 4 and inside the main frame 1 in the stuffing-boxes provided and held by the glands 2 and 3, and adjusted by the cap screws 24, 24. The gauges 13 to 23 inclusive being attached to the pipes 12, the latter being positioned in the annular packing ring sections so that the internal pressure may be measured. Pressure is applied to the packing thru a pipe 9 and is exhausted thru a valve 11.

The matter of vibration, of high or low pitch, is a bearing load of short duration of time. In Figure 4 is shown an arrangement for producing vibration in the rod 4 by a convenient means. The assembly S is a solenoid composed of a coil of wire of turns 37 and with an iron core 36, which by position of the assembly S may be made to vibrate against the rod 4 by connecting the terminals 38 and 39 to a source of intermittent electric current. Arrangements are made at the source of current to vary the period of current reversals, the position of the assembly S with respect to the rod 4 varying the intensity of thrust.

The operation of testing packing with this machine is to insert the samples in the two stuffing-boxes and bring them to adjustment by the cap screws 24, 24. The pipes 12 are then inserted thru the openings in the main frame 1 and positioned in the various manners indicated in Figure 1, and as the particular test may demand. A fluid medium under pressure is admitted thru the pipe assembly 9 and is confined to the machine by closing the needle valve 11 in the valve body 10. The pressure indicated by the gauges 13 to 23 inclusive are recorded with the shaft 4 in a condition of motion or of rest. To secure the friction of movement, a pull is made on the rope 29 of Figure 2 and the rate of movement obtained by an instrument such as a tachometer. The spring 30a is compressed and the pointer 27 will indicate on the scale 28, a certain pull as the pulley 7 begins to move. The shaft 4 and the pulley 7 may be rotated at any rate of speed, stopped, started and may be oscillated by alternately reversing the direction of pull. When referred to the particular movement of the shaft the pull indicated by the spring scale 28, together with the pressures indicated by the gauges 13 to 23 inclusive is sufficient information to determine the characteristics of the packing, the exact methods of making these interpretations being the subject matter of this specification and of succeeding applications for letters patent hereinafter mentioned.

To determine the effect of a dead weight against packing, or to use the packing as a bearing, the arrangement shown in Figure 3 will indicate the change in characteristics when the packing reacts against the side thrust of the weights, G, G. The pressures indicated by the gauges 19 to 23 will rise, while those indicated by the gauges 13 to 18 inclusive will fall. The pull indicated by the scale 28, of Figure 2, may or may not show a difference with the addition of the weights, G, G. If sufficient weights G, G are added the packing rings will be deformed the pressure will finally escape along the rod 4. The foregoing conditions and similar changes in physical properties of the packing, when re-

ferred to the amount of the weights, G, G, the speed of rotation of the shaft 4 and the pull shown by the scale 28, are the determining factors of the characteristics of the packing, as it is tested.

In testing packing for reaction to vibration, it is desirable to eliminate all dead weight thrust, so as in Figure 4, the rod 4 is placed in a vertical position. The pull for rotation is secured by the rope 8 and recorded in amount from the readings of the pointer 27 on the scale 28, as shown in Figure 2. The solenoid S is actuated by an intermittent electric current to a desired pitch and the position of the same solenoid S with respect to the rod 4 determines the thrust of the plunger 36. The pressures of the gauges 13 to 23 inclusive, together with the pull registered on the scale 28, as referred to motion and rate of movement of the shaft 4, are determining factors of the packing characteristics under the existing physical conditions.

While testing packing for elastic recovery during the impression of pressure, bearing load, vibration and similar influences, a meter M is installed in the piping assembly 9 to measure the flow of seepage thru the packing, as is shown in Figures 1, 3 and 4.

While the foregoing methods of testing packing have been chiefly described as a means of determining the characteristics of rotation, it should be evident that oscillation and translation or any combinations of movements by the shaft 4 will give internal pressure readings and amounts of pull, in character. It should also be evident that when any of the usual movements of rods, rotation, oscillation or translation are complicated by vibration, sudden or dead weight thrusts, sudden stopping and starting, temperature rise and fall, the change from liquids to gases against the packing, the introduction of grit and foreign matter into the packing, and the like, that this testing machine will accurately indicate the internal pressures and the friction reactions in character with the changes of physical properties and the accompanying conditions.

The present invention relates to the method of determining the rate of internal flow of a pressure fluid confined within a porous structure which causes the increase or decrease of friction by a corresponding variation of the volume of the porous structure due to the impressing and releasing of pressure, and is one of a group of separate inventions which may be practiced and which are disclosed in my copending applications:

Serial No. 526,287 filed March 30, 1931, which relates to a machine for taking reactions of porous or elastic bodies under confinement and subjected to fluid pressure;

Serial No. 526,288, filed March 30, 1931, which relates to a method of determining the drop of pressure which occurs in a porous or elastic body under confinement and subjected to fluid pressure and the friction which is caused by the thrust due to the drop in pressure;

Serial No. 533,430, filed April 28, 1931, which relates to the method of determining the internal flow of a pressure fluid confined within a porous structure which causes the increase, or decrease of friction by a variation of the volume of the porous structure due to a change in the pressure impressed; and

Serial No. 578,715, filed December 3, 1931, which relates to a method of determining the

comparative stress of pressure and strain of friction in porous or elastic bodies caused by pressure fluid.

The first two laws of friction are disclosed in my application Serial No. 526,288, while laws 3, 4 and 5 will be found in my application Serial No. 533,430.

In the present invention, the total amount of energy consumed in the form of friction by repeated applications of pressure is investigated, each application of pressure being considered a cycle of pressure events, solved for any instant by the first and second laws, and for the cycle by the third, fourth and fifth laws. For any considerable length of time during which there are many pressure applications, a new set of relations is necessary which take into account the energy consumed, the temperature developed and the volume of seepage flow. The chief result of this investigation will be represented by a discrimination between the true coefficient of friction and the effective value. The true coefficient will be shown to be that value for any instant as determined by the first and second laws for the contact occurring on an increment of surface. The effective coefficient will be shown to be based on the consumption of energy to overcome an average of friction conditions. But the fluxion values of repeated impressions of pressure can only be determined thru the volume and pressure relations which are regulated by the porosity existing and which may be expressed as a measure of elasticity, or a capability of resuming an original position after an impression of pressure.

Porosity is defined as a state of being porous, and in this investigation refers to the structure of the packing as it is inserted in a testing machine or an actual stuffing-box in operation. Referring now to Figure 5, a chart having ordinates expressed in friction, f_0 , f , f' and f'' , and abscissa of impressed pressure OP' and OP , it is to be supposed that a material of the greatest possible porosity, having no resistance to the flow of pressure, is tested in the machine of Figure 1, and that the friction of rotation at zero pressure is f_0 . If there is no resistance to flow, then there will be no increase of friction due to the rise of pressure, as with line f_0O . And in Figure 6, an internal pressure diagram of the relations of Figure 5 the ordinates being made to impressed pressure and the abscissa being the length of the packing set, the pressure P' would be decreased from point d to point e in an infinitesimal length of the contact surface during a fractional length of time to flow out of the box without change of internal pressure, along the line eg , or line O . The hypothesis is untenable; if there is a complete drop of pressure in an infinitesimal length of flow, there can be no resistance to flow, hence there could be no imagined body of perfect porosity in the stuffing-box. That is, the condition of instantaneous drop of pressure means the lack of a body of any imagined degree of porosity.

A material is now inserted which decreases the flow of pressure slightly, as that of curve 1 of Figure 6, the pressure P' drops from point d to point a , or zero. There being a drop of pressure during the flow thru the packing, there will be an increase of friction, as line f_0f , of Figure 5. As the density of the packing is increased, its porosity decreases due to the refinement of the passages and pores, as for example the curves 2, 3 and 4 of Figure 6 representing a single structure of a given initial porosity, give different friction increases of f_0f2 , f_0f3 and f_0f4 respectively, ac-

cording to different rates of pressure application, line f_04 being the slowest and line f_02 being the fastest. It may be noted that the curves 2 and 3, of Figure 6, approach the maximum length of the set at point g , at points b and c respectively, the rise of impressed pressure causing a reaction of the structure, decreasing the porosity and confining the pressure. The curves 2, 3 and 4 represent the rates of time of application, a very quick application of pressure giving curve 2, and a very slow one the curve 4. Curve 4 of Figure 6 is the maximum internal pressure relation than can be obtained from pressure P' of Figure 5 by delaying the time of application, that is, for a slow application no more friction than $f_0f''4$ can be obtained. This is the point of saturation, which has been expressed in the fourth law of friction, but in this case bringing in the degree of porosity.

It is now necessary to more specifically account for the tendency of an elastic structure to occupy a larger volume during the impression of pressure and this is done by the additional terms of the volume of occupancy V which the packing is adjusted to, and the volume S of the seepage per unit of time which is measured by the meter M of the Figures 1, 3 and 4.

The degree of porosity is defined as unity when there is no restriction to flow thru the stuffing-box of Figure 1, the condition being that of an orifice discharging into the air. The porosity is further defined as being zero when there is no flow thru the structure, being equivalent to replacing the packing gland with a tight partition from the rod to the wall. Between the degrees of unity and zero is an infinite series of values which may be keyed to all of the terms before defined and proven.

The packing ring adjacent to the partition $1a$ of Figure 1, its face exposed to the impressed pressure, is now considered. If the internal pressure thruout the ring is of the same value the seepage will flow evenly thru all sections and will be equal in amount. As soon as the porosity is changed in any one section, the flow will follow the paths of least resistance. The pressure at points of greater flow, or higher porosity, will be lower than at points of lower porosity and higher density. A relation can then be established that the internal pressure of any one increment of the packing volume, times the volume S of the seepage flow thru that increment of volume can be made equal to the same relation of any other increment of packing volume, by controlling the porosity by means of the density of the structure.

Returning again to Figure 5, on the abscissa of impressed pressures are further plotted the ordinates of seepage flow per unit of time, as measured by the meter M of Figures 1, 3 and 4. It has been found that the rate of seepage flow is highest with the fastest application of pressure, slowing down in rate as the length of time of application increases. As specially referred to the friction of movement is obtained by the internal pressure measurements taken on the rod surface. A quick impression of pressure forces the material under pressure along the rod surface to form a film between the structure and the solid body before the pores of the structure have had time to absorb the pressure and react, giving a low friction value. A slow application of impressed pressure shows a slow rate of seepage flow, the structure having sufficient time to absorb and react against the rod, to close up the pores, excluding most of the pressure adjacent to the rod surface by increasing the densi-

ty and directing the flow toward the stuffing-box walls. This is reflected in the seepage lines 2s, 3s and 4s, corresponding to the friction lines 2, 3 and 4 of Figure 5.

The tendency of a porous elastic ring in fluid tension to contract toward the smallest diameter where the seepage is excluded on the rod surface, and particularly on rotating shafts, is a factor of curvature not herein considered. But at this point this action does point to the question, as to whether the packing should be fixed to the shaft so that the better circulation of seepage could be utilized at the outside contact, thus avoiding the lower porosities due to reaction, and the consequent increase of friction. The flow of seepage in its effect on the reactions of a porous elastic structure is applicable for increase or decrease of impressed pressure, as reaction is basically affected by the element of time included in the rate of flow. From the relation established between the friction and the rate of flow of seepage, a relation is stated:

The flow of seepage on the surface of a solid body in contact with a porous elastic structure in reaction due to impressed pressure, is inversely proportional to the length of time of pressure application.

As to the degree of porosity in its effect in regulating friction per unit of area; the higher the porosity, the greater the flow of seepage which tends to lubricate the surface of contact, the lower the porosity the closer the pores giving a higher actual contact per unit of area up to the point at which there are no voids, when friction becomes constant for a given impressed pressure. Hence to the five laws developed in the companion applications above identified may be added the sixth law of friction of an elastic body in contact with a solid moving body:

6. For a constant pressure, friction is inversely proportional to the degree of porosity and becomes constant at the zero value.

The seventh law follows from the sixth:

7. Friction is inversely proportional to the rate of seepage flow at the surface of contact between a solid moving body and a porous elastic structure reacting under pressure, up to the point of saturation.

Returning now to the consideration of the tendency of a porous elastic structure to occupy a larger volume during the impression of pressure, which previously has been referred to as the relation of the internal pressure and the rate of seepage flow per unit of time. Experiment, as well as practice, demonstrates that after pressure has been impressed on a set of packing, that the packing creates a greater friction afterward, for an appreciable time, and that this excess friction may be reduced by loosening the packing gland to increase the volume of occupancy. This may be done up to a certain point, when the pressure will cut a lane thru the structure and escape.

Referring now to Figure 7, a fluxion chart of a set of porous elastic packing in contact with the rod of Figure 1, the ordinates being friction of movement and plotted to a unit of measurement, the abscissa being impressed pressures to a unit of measurement starting with P_0 , and increased by P_1 , P_2 , P_3 and P . At the latter points of pressure are shown the internal pressure charts 7a, 7b, 7c, 7d and 7e respectively, the ordinates being impressed pressures P_0 , P_1 , P_2 , P_3 and P respectively, the abscissa of every chart being the length of the packing set. The fric-

tion due to the rise of normal applied pressure is represented by the line Q, that due to the reduction of pressure by curve R. The curves Q' and R' are the internal pressures for the length of the packing at the respective points of impressed pressure.

The friction f_0 is due to the "initial-set" of tightening the packing, and the line Q increases proportionally to the impressed pressure, giving the friction F at the pressure P. The pressure is then reduced at such a rate that the pressure trapped internally does not have time to drain out of the structure, giving the curve R of higher friction than line Q, that is, the reaction is reflux. At pressure P, the internal pressure curves Q' and R' are coincident giving equal friction and a unity fluxion value. At pressure P_3 , the residual maximum pressure in the structure is P_3' , less than P and greater than P_2 , and R' is greater than Q' by the means of averaged internal pressures. The mean pressure drop of curve R' is greater than that of Q', hence a higher friction is secured with the reduction of pressure.

At pressure P_2 the residual maximum pressure is P_2' , less than P_3 and greater than P_2 , giving a higher friction due to the higher mean of pressure drop. The same action occurs at pressure P_1 and P_0 , the maximum residual pressures being P_1' and P_0' , the hysteresis value $F_0' - F_0$ being due to the difference of the curves R' and Q' at the pressure P_0 .

Research has given an explanation and a value to this time-lag difference during the reduction of pressure and in terms of seepage flow and internal pressure. For an impressed pressure P_1 for example, it has been found that the friction value x may be immediately reduced to the value y by increasing the volume of occupancy, and that when this is done the measured seepage flow increases. At point x for example, it has been found that the mean effective value of the curve R' times the volume of seepage flow per unit of time, is equal to the mean effective value of curve Q' times the seepage flow per unit of time at the point y of friction. This leads to the eighth law of friction due to contact between a porous elastic structure and a solid moving body:

8. The value obtained by multiplying the mean effective internal pressure and the seepage flow per unit of time is equal for any friction obtained at any given impressed pressure.

Thus by taking the required measurements of seepage flow, the friction per unit of area contact, the volume of occupancy of the structure, and the internal pressures, the degree of porosity and the true coefficient of friction for any increment of surface can be obtained, as well as the effective value of friction. Since the volume of occupancy varies the friction of contact, the change of volume may be expressed in terms of friction and the volume of the seepage flow. If the structure is in reflux, it creates a higher friction during the reduction of pressure; for example at a given impressed pressure when the volume is increased to reduce the friction, the rate of seepage flow will rise. Then if the structure is in flux, and the volume is decreased to raise the friction, the seepage flow decreases or may return seepage to the source of pressure. The following relations are the ninth and tenth laws of friction and independent of the speed of movement:

9. The additional volume of occupancy needed to decrease the friction of contact between a

porous elastic structure and a solid moving body is equal to the increase of the volume of seepage during the time which elapses while the change of friction is occurring.

10. The decrease of the volume of occupancy necessary to raise the value of friction due to contact between a porous elastic structure and a solid moving body is equal to the decrease of the seepage flow, or the value of the seepage flow in a reverse direction, during the time which elapses while the change of friction is made.

I have found that vibration against packing causes a hydraulic action in the pores and interstices which induces a higher internal pressure than the structure would experience from the impressed pressure. This action is a form of saturation caused by movement of the solid body and is measurable by the eleventh law:

11. The value of the reaction which a porous elastic structure expends against a vibrating solid body is equal to the energy exhausted by the flow of seepage.

Should it be desirable to ascertain the reaction caused by vibration in addition to normal pressure impressed, the total energy exhausted by seepage is credited with the amount used under normal operation and pressure only. The duty imposed by vibration and misalignment is varied and any of the manifestations of internal pressure, seepage flow, the volume of occupancy, and the like may be equated to the quantities desired. This subject matter is disclosed in my application Serial 526,288 previously cited.

The most important means of obtaining the actual performance of an elastic structure in contact with a solid moving body are the elasticity relations, including the work of deformation. These are time-friction relations which obtain while the structure is reacting during the applications of pressure. It should be apparent that elasticity is linked with the density, the porosity and the tendency of the structure to become saturated with the material under pressure. Referring now to Figure 7, the coefficient of elasticity is defined as the relation of stress to strain, the impressed pressure being considered a force or stress, and the friction a reaction, or a strain. The line F_{0w} is the line of "initial-set," the ordinates from this line to the friction line Q being the actual increase of friction due to the increase of pressure. If for any point on the line Q, the impressed pressure is divided by the actual friction due to the pressure, a constant ratio is obtained, the constancy of this ratio being uniformly characteristic for all types of packing and other porous elastic structures differing only in the value of the coefficient, that is, the slope of line Q. The ratios obtained from the line R, the friction due to the reduction of pressure, the actual ordinates of friction being taken from the line $F_0'v$, are not constant for any impressed pressure, nor for any type of packing or similar elastic porous structure. As the coefficient of elasticity varies with the type of packing, it is the ideal comparison. The twelfth law of friction may then be stated as:

12. The coefficient of elasticity of a porous elastic structure in contact with a solid moving body is the ratio of the impressed pressure to the actual friction of contact caused by that pressure, and is constant for the rise of pressure only.

For any cycle of pressure events in reflux, the fluxion curve will give the hysteresis value as a direct reading in friction, as shown by Figure 7,

being $F_0' F_0$. If n seconds are required for the value $F_0' F_0$ to reduce to F_0 , then the elastic recovery will be the value $F_0' F_0$ divided by n , or a rate of friction decrease per unit of time. Thus after a structure has been subjected to pressure and is in reflux, at any point in the cycle the elastic recovery may be determined by relating the difference of friction to the time necessary for the pressure to drain out and equalize the internal pressures, and the thirteenth law of friction may be stated as:

13. At any impressed pressure, the elastic recovery of a porous elastic structure in contact with a solid moving body is the amount of friction reduced per unit of time by seepage flow.

The capability of packing of a porous elastic structure to return to its original state connotes a reflux action, that is, the structure has been temporarily deformed and has stored up some energy which it will return after an elapse of time. The energy spent in deforming the structure can only be returned thru seepage flow. Thus in Figure 7, the area $F_0 F' w$ is the area of work expended in creating friction due to increase of pressure. The work of causing the packing to react so that this friction is created is called the work of deformation, its exact value being secured from the seepage flow. If sufficient time were allowed for the structure to relax during the reduction of pressure, all of the work expended on deforming would be returned, less the friction created and the value of the seepage, which has found its way to the outside. The area $F_0 F' F_0'$ indicates a rapid reduction of pressure, but instead of the stored pressure being returned at its original potential, it is trapped and produces friction, which is a loss. The pressure finally drains out, its volume being related by the hysteresis value $F_0' F'$, having less pressure potential than the original potential by the amount of friction loss converted to an energy loss. The area $F_0 w w F_0'$ is the energy returned by hysteresis action.

Should the structure flux constantly after reduction of pressure from point P, as indicated by the dotted friction line FF' , the area $F_0 F' w$ represents the work done by the friction created, but during the reduction of pressure the friction is less, indicating an apparent gain over the reflux curve R, but actually is a loss of seepage. This will be verified by the seepage flow increase accompanied by a probable leakage of pressure. Thus part of the energy lost in a flux action is due to friction, but a greater amount is increased seepage flow. Comparing flux and reflux reactions, the economical packing will create just as much friction for the rise or fall of pressure, that is, the fluxion value must be unity to secure the most economical operation from any type. Hysteresis is a loss if motion exists before internal pressures are equalized and defluxion is a loss unreplaceable, the former thru friction and the latter from escape of pressure. The minimum loss possible is an equal loss by friction, during the rise and fall of pressure. The capability of a porous elastic structure to return part of the work expended on it is called resilience. The fourteenth and fifteenth laws define the energy necessary to operate a packing:

14. The total work of deformation expended to cause a porous elastic structure to react against a solid moving body is measured by the energy expended thru the flow of seepage.

15. The resilience of a porous elastic structure in contact with a solid moving body is equal to the

potential energy of the seepage returned to the source of energy.

It seems to be universally accepted that friction is the measure of the power required to operate a packing, and comparisons are made of similar types on this basis. This is not the fact; as friction is but one manifestation of the energy expended, being the useful work which has resulted from the reaction and contact. The balance of the energy consumed by causing the reaction is larger than the friction created and may be found by measuring the energy represented by the seepage flow. As creating friction to seal pressure is useful work, the friction is needed and desirable. The efficiency of a packing or a porous structure is then:

16. The efficiency of a porous elastic structure in contact with a moving solid body is the relation of the friction to the energy exhausted by the seepage flow.

Manifestly, it will take so much energy to seal off an impressed pressure, and according to the type of the structure, this energy will be manifested in various forms as losses. To use the friction of contact as a basis of comparison is erroneous and meaningless, unless the total energy of deformation is also taken into consideration.

Referring now to Figure 8, a fluxion diagram of starting and stopping the shaft of the machine shown in Figure 1, at regular intervals of time, and at each period of rest, increasing the pressure by regular increments, then decreasing the pressure in the same manner. The ordinates are friction to a unit of measurement, and the abscissa are impressed pressures, starting at p_0 which is atmospheric in this case, and increasing by uniform pressure increments $p_1, p_2 \dots p$, at which point the pressure is reduced by the same equal increments $p_p, p_p \dots p_0$. The line S is the friction at start from rest and R is the friction of movement at the same uniform rate, both being due to the rise of pressure. The line T is the friction at start from rest and R is the friction of movement at the same uniform rate, both being due to the reduction of pressure. When the packing is installed it is given an "initial-set", to form it around the shaft at pressure p_0 ; the friction to set the shaft in motion is F_s which instantly falls to F_0 at a uniform rotation. The shaft is then stopped for m seconds and the pressure advanced to p_1 ; the friction starting from rest is point a and falls instantly to b for the same uniform rotation; the shaft is then stopped for m seconds and the pressure advanced to p_2 ; the friction starting from rest is point c and immediately falls to d on rotation. These cycles of repeated stop and start are continued to pressure p , the friction starting from rest being the connected line F_r , which instantly drops to F for the same uniform rotation, the complete series of cycles forming the diverging lines Q and S.

At the pressure p , the shaft is stopped m seconds and the pressure reduced to p_p ; at point x is the friction starting from rest which instantly drops to y for the same uniform motion. The shaft is stopped m seconds and the pressure reduced to p_p ; the friction starting from rest is at point z which falls to δ , at the same uniform motion. The cycles of repeated stop and start are continued until the pressure is reduced to p_0 , at which point the hysteresis values $F_s' F_s$ and $F_0' F_0$ persist until the structure has had time to relax and permit the pressure to drain away.

Figure 8 is the dual fluxion relation of starting

and stopping a rod or shaft with an accompanied change of pressure, such as is common on reciprocating machines and is useful as a method of arriving at the difference of friction for rest and for motion. The friction lines S and Q, of rest and motion respectively are divergent due to the structure endeavoring to occupy a larger volume while seepage continues to flow during the rest periods. During the reduction of pressure, the lines T and R are more widely divergent than those of rising pressure, due to the impedance to flow caused by flux reaction and the change of position of the rings in the box, which is still another matter for examination. Any of the cycles may be solved for the amount of friction and for location and all of the relations of porosity and density as well as the volume of occupancy may be examined by internal pressures and the rates of seepage flow, using the laws before derived.

It has been stated that elastic recovery connotes stored up energy which the structure will return if sufficient time elapses for the pressure to drain away, and that for this to happen, the structure must be in reflux. It has also been found that if a packing which fluxes during a single impression of pressure, is subjected to repeated impressions at a rapid rate, that the structure will be in reflux. That is, a very porous structure will become saturated with pressure after repeated impressions, if the rate is sufficiently fast. Saturation may therefore occur in two ways: due to the porous structure of the packing and regardless of the length of time of application, and due to impression at a high rate of application. It should also be seen that saturation interferes with the advantages of seepage flow and will reduce the elasticity. Elasticity is desirable, saturation not desirable.

Referring now to Figure 9, the ordinates are of friction and the abscissa of impressed pressure, the fluxion line U is from a porous packing and the curve V is a flux action caused by the reduction of pressure, both for a single impression of pressure. This packing is installed in the machine of Figure 1 and the shaft 4 translated for a given stroke at a high rate of speed. Referring now to Figure 10, representing the saturation diagram of repeated impression of pressure from zero to P at uniform rates of time, the shaft is stopped and started at each rise and fall of pressure. The ordinates are friction to a unit of measurement and the abscissa are units of time t , the shaft coming to rest at each interval of time.

An "initial-set" friction of F_0 F_0 is given to the packing to coil it around the rod, and the friction from rest is F_r . As the shaft is started the friction falls from F_r to F_0 at the time t_0 and then rises again to F_r in the next time interval of t_1 accompanied by an increase of pressure from zero to P, following the line zuv , and then the shaft comes to rest. When started again, coincident with the reduction of pressure from P to zero, the friction falls along the line vw , but stops at x , a higher value than F_0 . The difference between the friction x and F_0 is due to the pressure trapped in the structure and is the saturation which forces the packing to try and occupy a larger volume of occupancy. As the repetitions of pressure continue from t_1 . . . t , the friction at zero pressure rises until it reaches the level F_s , rising no higher, as the seepage flow comes to a maximum and prevents an increase of friction. However, if the interval of time is decreased the level F_s will rise, and if increased will fall to the line F_0 F_1 , for example.

In Figure 9 the fluxion curve of a single pressure impression at moderate change is U and V, in flux. But due to the rapid impression, the lines $zuvwx$ in Figure 10 are shown in reflux by the friction lines Q and R, of Figure 9, with a hysteresis value of F_s F_0 , the same difference as obtains between the points x and F_0 of Figure 10. When the level F_s is reached, a cycle is examined along the lines $abcde$; the fluxion curve T and S of Figure 9 is still in reflux, but there is no hysteresis value for the latter, as the value F_s is constant. The hysteresis value of a single impression while saturation is increasing becomes a zero value when saturation is complete. When the latter occurs, the result comes under the heading of saturation due to continued operation.

The two cycles, $zuvwx$ and $abcde$, each have points corresponding to the same event in each cycle, are examined by the internal-pressure charts 10a, 10b, 10c, 10d, and 10e, the ordinates being in impressed pressure and the abscissa representing the entire length of the packing set. On chart 10a, z' is the internal pressure curve at point z of Figure 10, and is due to the "initial-set" value F_0 ; a' is the residual internal pressure at point a remaining from the previous cycle and is the reason for the friction increase F_0 F_s . On chart 10b, the curve u' is the internal pressure of point u due to the first impression of pressure; curve b' is the residual internal pressure at point b , from a preceding cycle, showing the effect of saturation. Chart 10c shows point c and v on a common level, the maximum internal pressure curves c' and v' coinciding due to the same pressure P, and a common friction value F_r . The shaft stops to reverse its direction and as it starts the friction falls, the chart 10d showing the effect of residual pressure. The curve w' is higher than u' of the chart 10b; but curve d' is the same as b' of chart 10b; thus the residual pressure begins to cause saturation after the first impression at time t_1 . The chart 10e is the return to the starting point of the cycle, zero pressure, the curve x' being higher than z' of the chart 10a, and e' being the same as a' of the chart 10a.

The first sixteen laws of friction as herein developed are relations of pressure and friction within the confines of the structure and its connections. The effects of external influences, such as starting and stopping the shaft and the control of the time element as regards the reversal of pressures, require further relations which, altho they are based on the first sixteen laws, are the actual measure of a packing in operation.

Referring again to Figure 10; if the fluxion values of the packing are unity, flux and reflux being in balance, repeated impressions of pressure would not raise the friction from F_0 to F_s , but the friction at zero pressure would remain as F_0 F_0 . Perfect elasticity, or instantaneous elastic recovery is desirable and may be approached by taking into account the laws which apply to elastic porous structures. On rotating shafts elastic recovery is not applicable owing to the uniform conditions of rotation and constant pressure, but does apply if the pressures are varied. Therefore all rotating shaft problems should come under the first sixteen laws. The reversal of translation and the wide variation of pressures accompanying, require the relations of elastic reaction and saturation which follow, and should be self-evident:

17. For a continued cycle of pressure impressions, the elastic reaction of a porous elastic

structure in contact with a solid moving body is the ratio of the maximum to the average minimum friction caused by the pressure.

18. For a continued cycle of pressure impressions, the degree of saturation of a porous elastic structure in contact with a solid moving body is the ratio of the increase of the average minimum friction above the "initial-set," to the maximum friction.

19. Nearly all conventional types of packing, braided, platted, moulded and sectional-metallic have been found to obey the eighteen derived laws. One exception has been found. Figure 11 shows a slow-motion fluxion curve of such a structure which is made of laminated layers of an impregnable material so arranged that pressure has an immediate ingress and egress to the space between the layers. Starting at an "initial-set" of F_0 , the friction rises approximately proportional to the impressed pressure, as indicated by the line $F_0 F_h$, until the point e is reached. Point e is termed the elastic limit, beyond which the friction is other than proportional to the increase of pressure. During the reduction of pressure, the friction rises in an inverse proportion to the point F_r , at zero pressure. On single impressions, the hysteresis value $F_r F_0$ will reduce to F_0 after a considerable elapse of time.

In Figure 12, a time-friction chart, the ordinates are of friction and the abscissa, of time increments, from $p_0, t_1 \dots t$, and the condition is reciprocation at every time interval with a coincident change of pressure from P to zero, using a packing such as that used in obtaining the curve shown in Figure 11. Starting at F_0 , the "initial-set," the friction rises to the line $F_r F_h$, then drops to the line $F_0 F_r$ before the time interval t_0-t_1 is complete, apparently losing its saturation immediately, or slightly before the reduction of pressure. During succeeding impressions of pressure, the maximum and minimum values of friction rise parallel to the lines $F_r F_h$ and $F_0 F_h$, then begin to fall to a very low value, and continuing in a low state of friction so long as the shaft is kept in motion. This exception is given as an example of the stress of deformation which occurs after the elastic limit is passed, yet which will return to the original condition, and is to be distinguished from the actual loss of elasticity of the example which follows.

In Figure 13 is shown a fluxion curve of a packing exposed to a pressure too severe for the strength of its structure. Starting at F_0 , the "initial-set," the friction rises proportionally to the pressure up to the point e , the elastic limit, then falls to F_r , and stays at the latter value during the reduction of pressure. The value $F_r F_0$ is not hysteresis, but a permanent deformation.

Referring now to Figure 14, a time-friction chart for the packing of Figure 13, gradually approaching permanent deformation, the pressure P is impressed on the structure, at time intervals of $t_0, t_1 \dots t$, and at each interval is reduced to zero. At t_0 the friction F_0 is the "initial-set," and each cycle of pressure events raises the maximum friction to the value F_r . Due to the permanent deformation occurring and increasing with each cycle, the friction at zero pressure rises on the curved line $F_0 F_r$ and coincides with the value $F_r F_r$. When the coincidence occurs, all reaction of the structure due to pressure ceases and the friction of contact becomes a constant quantity, varying only with the rate of movement.

While the point of elastic limit is shown in Figures 11 and 13, to mark the reduction of friction

as pressure continues to rise, the friction as often rises and increases the coefficient. Therefore at the elastic limit, a decreasing coefficient denotes a permanent set against the stuffing-box wall, and an increasing coefficient denotes a permanent set against the rod, or a "lock" as it is frequently called. From the foregoing relations, the following laws are derived:

19. The elastic limit is reached when the coefficient of elasticity ceases to be a constant value, during the rise of pressure.

20. The friction of contact, between a solid moving body and a porous elastic structure, when the latter is subject to the stress of deformation, is proportional to the rise of pressure up to the elastic limit, and beyond the elastic limit is inversely proportional to the rise of impressed pressure, and is consistently proportional inversely to the reduction of pressure.

21. The friction of a solid moving body in uniform motion against a porous elastic structure reacting under pressure, becomes a constant when the elastic structure is permanently deformed, regardless of the variation of pressure.

In view of the foregoing relations, it should be apparent that the term friction must be defined with respect to all of the laws derived to prevent confusion. Manifestly, the use of a measured friction related to the impressed pressure would give erratic results in applying some of the laws. There are many friction coefficients to be secured from a single porous structure due to the variations of porosity and the unequal distribution of the applied pressure, this being proven by the first and second laws. The true and the effective values of friction are therefore defined as:

22. The true coefficient of friction is the relation of the force necessary to move a solid body with respect to an increment of surface of a porous elastic structure, to the normal applied pressure on that surface.

23. The effective coefficient of friction is the relation of the total measured friction to the impressed pressure.

To further prevent confusion, the definitions of pressures as they herein referred to, are: Impressed pressure is the source of pressure to which the structure is exposed: Internal pressure is the measured gauge pressure at any point in the structure: The drop of pressure is the impressed pressure less the measured internal pressure at any point: The normal applied pressure is the internal pressure of the structure acting at right angles to the surface of the solid body at any considered point.

The most important consideration of all of the relations of friction between an elastic porous structure and a solid body is the distribution of friction as referred to the area of contact, as this relation is the limiting factor of all engineering designs. An examination of the first and second laws will show that for any impressed pressure there can be any number of mean effective internal pressures, depending upon how the drop of pressure occurs. And it has been stated that the economical relation between pressure and friction is a uniform drop of pressure thruout the structure and away from the source of pressure to secure a uniformly distributed friction per unit of contact area. Based on the latter relation, is the twenty-fourth law:

24. Friction between an elastic porous structure and a solid body is independent of the surface of contact, when the normal applied pressure is equal at all points of the contact surfaces.

The twenty-fourth law is an ideal relation and the sum and substance of all of the minor laws and relations, and is never realized due to the difficulty of distributing the normal applied pressure, whether the body is confined or unconfined. But it may be closely approximated, as will be shown by succeeding applications for Letters Patent.

The twenty-four laws may be applied mathematically without constants, being the relations of pressure impressed. Variation of speed, change of temperature, the character of the materials in contact, the viscosities of liquids and gases, and the like, are largely empirical, and while they sometimes vary proportionally to the pressure or other factors, the limits are narrow and such relations can hardly be called laws. The apparent misunderstanding in designing machinery as to the friction between parts, is a confusion as to what friction is proportional to. It is primarily proportional to the pressure, which when resolved into its proper component reactions, will give direct relations which need no constants. As

these laws reflect, the design should be based on the relations to pressure, then allowances made for the simpler factors of speed, temperature and material characteristics.

There are many variations and applications of the laws and relations herein described, but such as may be secured by the method of testing herein described and developed as I shall claim, are construed to be within the spirit of this invention.

I claim:

The method of testing confined porous elastic packing structures of different porosities in contact with a solid moving body by impressing a fluid medium under pressure successively against the various packing structures, then simultaneously measuring the internal pressures at the point of contact with said moving body and the friction created by the contact, to obtain the ratio of the change of friction due to the change of internal pressures caused by the variation of the porosity of the packing with the fluid therein.

HARLEY T. WHEELER.