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HEAT TRANSFER IN PULSATING FLOW

A THESIS

Presented to

the Faculty of the Graduate Division

by

Roy Allen Wells

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Mechanical Engineering

Georgia Institute of Technology

June, 1960

A STUDY OF RATES OF FLOW THROUGH CERTAIN TYPES OF MOVING PARTS

A THESIS

Presented to

the Faculty of the Division of Graduate Studies

Georgia School of Technology

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Mechanical Engineering

by

Clarence Robinson Weeden

1947

A STUDY OF RATES OF FLOW THROUGH CERTAIN

TYPES OF MOVING PARTS

Approved:

Date Approved by Chairman Jan 14, 1948

ACKNOWLEDGMENTS

I want to express my thanks to Dr. R. L. Sweigert for suggesting my problem. Professor Robert L. Allen was my counsel during the periods of the design and the building of a necessary new type of fluid-metering device and during the study of the fluid flow from this device; and his guidance is very much appreciated. Also, I should like to thank Dr. Gerald A. Rosselot, Director of the Engineering Experiment Station at the Georgia School of Technology for the use of the facilities of the Experiment Station and for the aid of his staff in the building of the device that made possible the results found in this thesis. My appreciation is further expressed to Professors H. B. Duling and Frank F. Groseclose, who assisted me by supplying electric and time mensuration instruments from their respective departments, and to Dr. Roy S. King, Dr. Joseph H. Howey, Dr. Paul Weber, and Dr. Homer S. Weber, who encouraged me by their interest and whose help was invaluable.

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LIST OF ABBREVIATIONS

1.	a.c.	Alternating Current
2.	A	Amperes
3.	p.s.i.	Pounds per square inch
4.	V	Volt
5.	hp	Horsepower
6.	rpm	Revolutions per minute
7.	in.	Inches
8.	O.D.	Outside diameter
9.	I.D.	Inside diameter
10.	N. C.	National course
11.	S. K. F.	S. K. F. Industries Bearing Manufacturing Company

A STUDY OF FLOW THROUGH CERTAIN TYPES OF MOVING PARTS

INTRODUCTION

Purpose

In all existing intermittent fluid-metering devices, whose discharges are accompanied by a large pressure drop, there is generally either a mechanically or hydraulically operated reciprocating valve.[1] Mechanically or hydraulically actuated intermittent fluid-metering valves have, however, either inertia lags or pressure-wave disturbances when operated at high frequency, since the fluid, before emission, is retained under compression.[2] These disadvantages in existing intermittent metering valves are serious, and in some instances, no cure or solution is apparent.[3]

It was believed that a better high-pressure, intermittent fluid-meter might be developed through the positive regulation of the action of a rotated port passing an orifice. The original design of a fluid-metering device built by the author, and a study of the intermittent flow of an oil from it, is presented in the following thesis.

[1] P. H. Schweitzer, "Injection Nozzle Design", American Society of Mechanical Engineers Transaction 52, OGP, 15 (1930).

[2] A. M. Rothrock, "Pressure Fluctuation in a Common-Rail Injection System", American Society of Mechanical Engineers Transaction 52, OGP, 14 (1930).

[3] C. B. Dicksee, "Fuel Injection", Automobile Engineer 25, 91-97 (1935).

Objectives

Four objectives were selected as the basis for this thesis, as follows:

1. To design an intermittent-flow, high pressure-drop oil-metering device, which would expel the oil from an orifice without the complication of the conventional, spring-loaded, injection-nozzle reciprocating valve;

2. To produce a rotating-port oil-metering device with an orifice which would emit a measured discharge during a fraction of each cycle, then cut off that slug, expel it, and have no after-dripping following a discharge;

3. To determine the quantity of oil discharged per cycle from a certain orifice when the oil was caused to flow by a known pressure drop;

4. To study the characteristics of discharge from that orifice by visual and photographic aids.

EQUIPMENT

The Design of the Metering Device

Since the type of research indicated by the title of this thesis suggests that a study was possible only if a mechanism was made, it is believed that a detailed description of the device built is of major importance in the development of this paper. The type of flow analysis desired required a functional design of a strange kind, and none was found to exist which would serve as a means of obtaining the data for the flow study selected. The materials, design, methods of construction and assembly, and auxilaries needed to make this metering device a workable unit are herewith presented.

The metering device consists of a rotating, axially oil-fed drum which contains a radial free-floating hollow pin whose outer surface conforms with the curvature of the drum bearing.[4] Oil pressure within the hollow drum keeps the thrust of the radial pin against the drum bearing. Oil cannot flow from within the drum and out through the hollow radial pin unless an aperture in the bearing of the drum is in the path of the hole in the radial pin.

Oil enters the drum through a hollow spindle which is made integral with the drum by a weld. A packing gland minimizes the lateral leakage of oil along the periphery of the spindle.[5] Any leakage by this spindle is drained by an atmospherically vented concentric recess machined in the end of the bearing of the drum.

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[4]Figure 2, items 5 and 4, p. 42

[5]Figure 2, item 8, p. 42

Consequently, the drum rotates in its bearing upon an oil film stabilized by atmospheric pressure.[6]

The bearing of the drum is fitted into a steel housing.[7] The oil is emitted from the housing by an orifice and tube, which are in radial alignment with the radial pin hole of the drum at the instant the pin sweeps by the orifice. The high-pressure oil supplied to the metering device comes from a pressure-stat-controlled rotary pump equipped with an accumulator.[8] The oil within the accumulator has an air cushion above it, which aids in keeping constant pressure during metered discharges through the orifice. Pressures from 0 to 1200 p.s.i. gage are possible. The pump is driven by a 24-V, 90-A direct current motor. The pump motor receives power from a motor-generator set with a 24-V battery ballast.[9] The set is manually adjusted until the pump motor instrument panel ammeter and voltmeter readings indicate the proper values for the pump load.[10]

The drum is rotated by a 25-hp synchronous motor driving a variable speed transmission with a magneto-type tachometer whose range is from 1050 to 5500 rpm.[11]

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[6]Figure 2, items 5 and 4, p. 42

[7]Figure 2, items 5 and 1, p. 42

[8]Figure 3, item 5, p. 43

[9]Figure 4, Motor Generator Set, p. 44

[10]Figure 3, items 2 and 3, p. 43

[11]Figure 3, items 10, 9, and 1, p. 43

The metering device is contained by a hot-rolled machined-steel cylinder 4 in. O.D., 2 In. I.D., and 7 in. long and bushed to 1.750 in. I.D. by a nickel-iron bearing 2 in. long and inserted flush with one end of the steel housing.[12]

The cylinder head and the cap end are of steel 1/2 in. in minimum thickness. Each is held securely to the cylinder by twelve 1/2-in. N.C. thread Fillister head screws that were screwed into tapped holes centrally and uniformly located with reference to the cylinder wall thickness.[13]

The head of the metering device is fitted with an adapter, to align correctly a 5/16-in. drill rod driving spindle of the meter drum with the axis of rotation of the transmission shaft.[14] The 5/16-in. drill-rod spindle has a No. NW04 S. K. F. double-row self-aligning ball bearing mounted on it so that a lateral spindle adjustment can be made.[15]

The spindle-transmission coupling is a serrated free-floating unit. The female half of the serrated coupling is keyed and locked to the transmission shaft, and it has no end play. Upon this portion of the coupling is mounted a degree-graduated disc 4-in.-diameter. By the use of the strobotac, the shaft speed can be checked by synchronizing the neon light flashes of the strobotac to the angular velocity of the graduated disc.

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[12]Figure 2, items 1 and 4, p. 42

[13]Figure 2, items 14, 15, 6, and 1, p. 42

[14]Figure 2, items 16, 3, and 5, p. 42

[15]Figure 2, items 3 and 12, p. 42

Two coil springs hold the floating spindle shaft bearing firmly against a micrometer screw. The adjustment of this micrometer screw causes the S. K. F. bearing, the spindle, and the drum to be moved longitudinally. The drum port then has a new longitudinal position with reference to its cylinder wall orifice. This adjustment, in thousandths of an inch, controls the drum-to-cylinder orifice alignments for each run. The revolving drum can be adjusted axially to give no discharge, then in increments to the position yielding full discharge.[16]

The drum is connected to the drill-rod spindle by a single universal joint having 1/8-in. shear pins. These shear pins are a safeguard against damage in the event of bearing-to-drum seizure. The drum is recessed for the universal-joint assembly. There is no opening from the drum recess to the hollow portion, containing the oil, to be metered. The drum is revolved and adjusted by the thrust-bearing mounted spindle end and receives oil under pressure to the drum interior through a hollow spindle from the other end.

The Development of the Metering Drum

The metering drum was developed after a series of refinements and finally resulted in the oil entering the drum axially and being discharged radially through the radial pin hole of the drum when it passed the cylinder-bushing orifice.

The first drum was made as a plain journal 1.748 in. O.D. 2 in. long and was used to determine the leakage between the drum and the

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[16] Figure 2, items 5, 11, 16, 12, and 3, p. 42

bushing which was voided from the orifice. The oil pressure was applied at both ends of the periphery of the drum.

The second drum was made of mild steel 1.748 in. O.D. and 1-3/4 in. long. Midway between the drum faces a 0.500-in. diameter hole was bored and lapped radially to receive a 0.5495-in.-diameter, 3/4-in.-long drill-rod pin. This pin had a 0.125-in. hole drilled in its center axially. Several runs were made with this pin in the drum. When it was evident that the device would function, a new radial pin was inserted in the drum. The latter radial pin had a bore of 0.050 in. The smaller bore reduced the amount of fluid to be emitted at one time. As a result, the flow rate was then less than the rated capacity of the oil pump. It was then possible to use graduates to measure the discharge per minute.

The drum contained a plug diametrically opposite to the radial pin. Two compression springs were placed in the drum before the plug was screwed into the drum. One of these springs pressed against the radial pin. The other spring pressed against synthetic packing around the radial pin. When the plug was screwed into the drum, the springs were compressed. These springs then tended to eject the radial pin and seal the oil from leaking out about the periphery of the pin. After the plug was assembled, its outer surface was ground to the contour of the drum.

The radial metering pin had three forces which tended to eject it: the static force of the compression spring, the hydraulic force, and the centrifugal force. Opposing this ejection was the surface of the bushing. The bushing and the metering pin surfaces of mutual contact were lapped together. A leak between these surfaces was improbable. To prevent the movement of the metering radial pin about its axis, a small flat was cut in its periphery, and a set screw adjusted against the flat so that the pin might move radially, but without twist.

The metering hole of the pin was initially lined up with the orifice by a calibrated gage plug.[17] When this alignment was satisfied, the micrometer screw was adjusted against the driving-spindle thrust bearing. The orifice and metering radial pin holes were then in line. After the calibrated gage plug was removed, the drum could be rotated at the desired speed, and the metering radial pin hole would instantaneously coincide with the orifice for each cycle.

By the use of the micrometer screw (40 threads per inch) the axial position of the drum could be moved by thousandths of an inch. Thereby various micrometer adjustments could be made to give from maximum to no discharge, with the other conditions remaining constant. The micrometer screw was locked by a set screw for each setting to prevent any shift in the axial position of the drum during a run. Flats 1/4 in. wide were machined axially to the root of the micrometer thread, so that duplicate settings with known increment displacements were assured without thread damage from set screw impressions.

It was necessary to keep the lubricant in the clearance space between the bushing and the drum at atmospheric pressure. Since the oil from the pump to the drum was highly compressed, it was necessary

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[17]Figure 2, item 2, p. 42

to make a packing gland to assure the minimum of oil leakage as the oil entered the rotating drum. The periphery of the packing gland was sealed by the bushing of the drum. The bore of the packing gland contained the hollow spindle. The diameter of the bore and the outside diameter of this hollow spindle were 3/16 in. and 3/8 in. respectively. The periphery about which the oil could leak was negligible. Graphited flax packing in the gland made a good oil seal, and did not score the spindle throughout the runs.

The drum rotated in a screw-locked bushing. A recessed annular groove in the bushing bled any oil leaking past the packing gland. This groove was vented to a storage tank, which was open to the atmosphere. Thus, it was possible to recover seal leakage, maintain atmospheric pressure between drum and bushing, and to keep a record of the temperature of the oil drained from the recess of the bushing. The first bushing tried was an oil impregnated bronze casting. This bushing was later replaced by an internally ground and lapped close-grained cast-iron bushing.

The steel cylinder meter housing was recessed to let in a split-steel thrust ring.[18] The ring was made to take the hydraulic thrust at the cap-end of the steel cylinder meter housing. A steel bushing, a lead packing ring, a packing gland assembly, the bushing of the drum, and the cylinder head were compressed against the thrust ring by the tension of the cylinder head screws.[19] A set screw in the cylinder wall and the drum bushing prevented the rotation of the bushing.

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[18]Figure 2, items 1 and 10, p. 42

[19]Figure 2, items 9, 8, 4, 14, 10, and 6, p. 42

The cylinder and bushing were radially drilled with a 0.050-in.-diameter drill. This hole was then counterbored and tapped for a 1/8-in. copper tube to a depth of 3/4 in. From this orifice the oil discharge could be studied quantitatively by screwing a 1/8-in. copper tube 12 in. long into the tapped hole.[20] Without the tube the discharge could be analyzed qualitatively.

The packing gland leakage was drained by a 1/8-in. hole drilled through the cylinder into the recess of the drum-bushing. By counterboring and pipe-tapping this hole it was possible to connect the packing-gland oil leakage to a copper tube and return it to the supply tank.[21] The temperature of the oil was observed by the aid of a thermometer inserted in a "T" fitting.[22]

So that the force exerted by the oil on the end-cap might be minimized the steel bushing was bored and lapped to 0.750 in., and piston was placed in this bore. An Amagat oil pressure-seal was used on the piston to eliminate oil leakage. The piston was made integral with a 2-in. ram which fitted the cylinder.[23] Thus, piston and ram were used as a thrust reducer against the end-cap during runs or a booster pump for a static pressure test on the metering device. The static pressure test was accomplished by oil supplied to the ram through the end-cap of the cylinder.

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[20]Figure 1, item 6, p. 41

[21]Figure 1, item 3, p. 41

[22]Figure 1, item 2, p. 41

[23]Figure 2, items 13, 9, and 1, p. 42

Several experimental drums were made before a practical type was developed. A piece of bar stock was rough machined on centers to 1-3/4 in. plus O.D. and 2-1/2 in. long. One end was counterbored to a diameter of 5/8 in. and to a depth of 3/8 in. to let in a universal joint, which was to drive the drum by means of a 1/8-in. drill-rod pin inserted through a 1/8-in. hole drilled diametrically through the drum and the universal joint. The joint had floating clearance in the recess. A 3/4-in. hole was drilled axially from the other end of the drum to 1/8-in. from the counterbored face. Then a piece of 3/4-in. drill-rod 3/4-in. long was brazed to the end of the drum, thereby sealing the drum core and making an outboard projection for the drum. This projection was uniformly machined to 3/8 in. plus O.D. a distance of 3/4 in. from the end. Two 1/4-in. holes spaced on 1-3/16-in. centers, diametrically opposite on the face of the drum, were drilled through the length of the drum so that an Allen set-screw wrench might be used to tighten up the gland and force the packing about the projection of the drum. A hole was bored radially and lapped to a 1/2-in.-diameter. A 7/8-in.-diameter counterbore was then made to within 1/2 in. of the opposite surface and was then tapped for a 1-in. N. F. threaded plug 1/2 in. deep.

The 1/2-in.-diameter 3/4-in.-long drill-rod radial pin of the drum was drilled and lapped to 0.050 in. axially through the center of the pin. A flat was then made as a bearing for a 10/32 set screw which was inserted longitudinally from the universal joint end of the drum. This screw was adjusted to prevent the rotation of the pin, but it permitted radial displacement. A 7/16-in. O.D. compression spring was compressed between the plug and the radial pin. That portion of the exposed radial pin within the core of the drum was packed by synthetic rubber washers 7/8 in. O.D. and 1/16 in. thick. A compression spring that telescoped the radial pin was compressed between the packing and the plug.

The Assembly of the Metering Device

There was a definite order to the assembly of the metering device. The parts of the drum were assembled. The radial pin was locked. The plug was tightened by a pin-type spanner wrench. Then the drum was mounted on its centers and ground to 1.750-in.-diameter. The radial pin was depressed and the periphery of the drum was ground to 1.748-in.-diameter, and the projection of the drum was ground to 0.375-in.-diameter.

The split-lock thrust ring was inserted in the cylinder groove, and the steel bushing was pressed against the ring. A 1/16-in. lead ring was placed against the steel bushing. The packing gland assembly was placed against the lead ring, and the bushing of the drum was pushed into the cylinder next to the packing assembly. The drum, the universal joint, and the driving spindle were assembled, and the drum was slipped into its bushing with the radial pin released. The packing was drawn about the projection of the drum by an Allen wrench inserted, through the holes provided in the drum, into the packing compression flange adjusting screws.

The cylinder head was slipped over the spindle and compressed against the drum-bushing by the twelve 1/2-in. N. C. threaded Fillister head screws. The spindle ball-bearing assembly was mounted with compression springs placed between it and the spindle packing gland flange.[24] Next, the variable-speed-head flange-adapter was assembled on the cylinder head. A calibration pin was inserted through the orifice into the radial pin hole.[25] The ball bearing assembly was locked by its lock nut when the micrometer screw location was zeroed. All axial adjustments were then satisfied by the micrometer screw.

The serrated male coupling was assembled on the spindle and locked by a lock nut, and the metering device was mounted on the variable-speed unit with the coupling engaged. Upon the female coupling member, the graduated disc was locked by setscrews. Finally the metering device was sealed by the insertion of the ram and piston unit, and the securing of the cap to the cylinder.

The oil-line system was then connected to the metering device. Oil under pressure was admitted through the wall of the cylinder at a point between the steel bushing and the packing gland for the projection of the drum.[26] The oil then flowed through the bore of the projection of the drum to the core of the drum and out the radial-pin hole whenever it became exposed to the orifice. A copper tube was used to return to the storage tank the oil that leaked from the packing gland. A hole was drilled through the cylinder into the lock-ring recess so as to bleed any oil leaking by the piston or ram.

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[24] Figure 2, items 12 and 7, p. 42

[25] Figure 2, item 2, p. 42

[26] Figure 1, item 4, p. 41

Accessories

A microchronometer was used to accurately time the measured discharge from the orifice over a selected period.[27] Five, twenty-five, one hundred, and two thousand milliliter graduates were used to quantitatively measure the discharge over a time period. A thermometer was used to indicate the temperature of the oil that was vented from the drum bearing. A strobotac and a strobolux were used to check the speed of the drum against the tachometer reading.[28] They were also used to observe various developments of the spray pattern from the orifice. High-speed moving pictures were taken (2000 frames per second) to provide a permanent record of the spray during successive cycles. The frame-by-frame study of the pictures made possible a qualitative analysis of the spray pattern of the oil as it was metered each cycle.[29] Photographs were taken to provide a record of the project with detail pictures to supplement the description.[30] The pressure of the oil fed to the metering device was observed by means of a 3000 p.s.i. Bourdon tube gage.[31] The instrument panel mounted on the Vari-Drive power unit contained a tachometer, an ammeter, and a voltmeter which were used to check drum speed and pump-motor load.[32]

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[27]Figure 3, item 4, p. 43

[28]Figure 3, item 7, p. 43

[29]Figure 6, p. 46

[30]Figures 1, 2, 3, 4, and 5, pp. 41-45

[31]Figure 1, item 1, p. 41

[32]Figure 3, items 9, 1, 2, and 3, pp. 43

DISCUSSION

Procedure

Mensuration instruments to be used in this study were calibrated (as indicated in the appendixes) to determine their dependability.

All data were taken upon a hydraulic-type oil whose characteristics are listed in the appendix.[33]

A stable oil temperature recorded in the leaking oil stream served to indicate when the heat transfer for a particular drum speed had been stabilized. Each run was made at constant speed, and the portion of overlap of the pin-hole diameter to the orifice diameter was kept constant. The oil pressure was varied after at least three readings of the rate of flow were in agreement. Increments from 100 p.s.i. to 1000 p.s.i. gage pressures were the variables for each run, and the discharges from the orifice per minute were observed.

The equipment was shut down after each run. The micrometer screw was adjusted to change the overlap for the next run. The drum speed was not changed until all the data for the four overlap positions were recorded. (One-fourth overlap, one-half overlap, three-fourths overlap, and full overlap). This procedure assured a minimum of oil temperature variation per run since the peripheral speed of the metering drum was held constant.

Two drum speeds, 1050 and 2000 rpm, were chosen so that a typical comparison of the characteristics of the metered oil discharges

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[33]Table XII, p. 37

from this device might be ascertained.[34] A plain journal was used to determine the leakage to the orifice when the journal oil film was under pump pressure.[35] The plain journal oil film was relieved of the pump pressure by the use of the packing gland and drain, and the leakage from the orifice noted.[36]

A strobolux was very useful in determining the consistency of discharges as the runs were being conducted. However, a high-speed motion-picture-camera film was used to record a portion of that which the strobolux revealed during this research. Through the use of either a strobolux or motion picture a thorough qualitative analysis was made of all the runs.

The quantitative analysis was made by the use of a graduate, a tachometer, and the metered discharge. Both a strobotac and a tachometer were used to ascertain the angular velocity of the metering drum. As a result of the use of these instruments the quantitative discharge per cycle was readily computed.

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[34] Figures 7 through 12, pp. 47-52

[35] Table I, p. 20

[36] Table II, p. 21

Results

The metering device herein described had only an infinitesmal leak at the orifice which did not exceed one per cent of the metered discharge.

A plot of the discharges per minute for an orifice-to-port overlap against varying pressure drops across that orifice, for a particular constant angular drum velocity, was not found to be a straight line. All curves, for the runs plotted generally indicated a parabolic trend.[37] The discharge-pressure curve slope became progressively less as the pressure drop across the orifice was increased.

It was found from the curves that, for a constant pressure and a certain orifice-to-port alignment, the discharge per cycle was inversely proportional to the test speeds.[38]

The depth of the penetration of the discharge from the orifice into the air and the virtually complete atomization of each discharge was recorded by the high speed motion pictures.[39] The motion pictures revealed consistent discharges each cycle.

The strobolux flashed duplicate spray patterns when an arbitrary phase study of the oil discharge was made under a given set of variables. The discharge per minute remained consistent for a particular set of variables.

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[37]Figures 7 through 12, pp. 47-52

[38]Figures 8 and 12, pp. 48, 52

[39]Figure 6, p. 46

Each table covering a specific run contains readings in groups of three. No significant discrepancy in these readings was noted which would suggest any inconsistency of data for the one-half, three-fourths, and full overlap (orifice-to-port), alignments. The one-fourth overlap readings produced a curve which indicates the opening was too small for the flow of the fluid studied. It is evident that no flow will take place through an infinitesmal orifice unless a large pressure drop exists to literally extrude the fluid.

The actual oil discharged from this metering device compared to an ideal steady flow of the oil, all other conditions being the same, was found to be about 40% for a one-half, three-fourths, or full overlap for the selected drum speeds.

Conclusion

The rotating port-by-orifice oil discharge was accurately timed, effectively atomized, and uniformly ejected.

There was no secondary discharge after the drum port swept by the orifice, and no leakage took place between discharges.

The spring-loaded hydraulically-operated high-pressure high-frequency injection valves do not maintain a uniform pressure head, since their operation necessitates a variable pressure. Such a variable fluid compression tends to cause irregularities in oil displacement through these valve orifices. There was no observed pressure fluctuation of the oil to this metering orifice, and the consistency of discharge from the orifice was observed every cycle.

As was observed in the curves, the discharge was not restricted by a minimum pressure as it is in some types of injection nozzles which require a high valve-opening pressure (V.O.P.), and these valves must first be lifted by the V.O.P. before the discharge through the orifice begins. This rotary metering device discharged independent of pressure, and did not alter that pressure at the source before, during, or after a discharge.

There are a very small number of moving parts in this device as compared to the conventional devices referred to in this work. Furthermore, this device has only rotary motion, whereas the conventional devices are reciprocating. It may be concluded that the device resulting from this project operates reliably and thus may have some possibility of industrial application where the intermittent flow is achieved by periodic metering.

TABLE I

Performance Data of the Metering Device
Leakage of Oil Through the Orifice
Before Adapting an Oil Seal

Bearing Inside Diameter 1.750"
Journal Outside Diameter 1.748"
Distance of either Journal Shoulder to Orifice 1"
Pressure 600 p.s.i.

R.P.M.	Journal Leakage	Temp. Oil, °C.
5000	565 cc/min.	62
4500	525 cc/min.	62
4000	500 cc/min.	62
3500	460 cc/min.	61
3000	434 cc/min.	61
2500	400 cc/min.	59
2000	367 cc/min.	60
1500	328 cc/min.	59
1050	242 cc/min.	58

TABLE II

Performance Data of the Metering Device
Leakage of Oil Through the Orifice
After Adapting an Oil Seal

Bearing Inside Diameter 1.750"
Journal Outside Diameter 1.748"
Distance of either Journal Shoulder to Orifice 1"
Pressure 1000 p.s.i.

R.P.M.	Journal Leakage	Temp. Oil, °C.
5000	1 cc/min.	62
4000	1 cc/min.	62
3000	1 cc/min.	62
2000	1 cc/min.	60
1050	1 cc/min.	58

TABLE III

Performance Data of the Metering Device
Orifice Diameter: 0.125"
Orifice Alignment: Full Overlap

Run	Oil Pressure p.s.i. gage	Speed R.P.M.	Oil Seal Temp. °C.	Discharge Rate cc/min.
1	500	1050	40	214
2	500	1050	40	214
3	500	1050	40	214
				Average 214
4	500	2000	41	216
5	500	2000	41	215
6	500	2000	41	218
				Average 216
7	500	3000	44	214
8	500	3000	44	208
9	500	3000	45	214
				Average 212
10	500	4000	46	216
11	500	4000	46	216
12	500	4000	46	124
				Average 215
13	500	5000	50	219
14	500	5000	50	216
15	500	5000	50	218
				Average 218

TABLE IV

Performance Data of the Metering Device
Orifice Diameter: 0.050"
Orifice Alignment: No Overlap
Meter Drum: 1050 R.P.M.

Run	Oil Pressure p.s.i. gage	Oil Seal Temp. °C.	Discharge Rate cc/3 min.	cc/min.
1	100	33	cc/3 min.	
2	100	33		1/6
3	100	33	1/2	
4	150	34	cc/3 min.	
5	150	34		1/4
6	150	34	3/4	
7	200	35	cc/3 min.	
8	200	35		1/4
9	200	35	3/4	
10	250	36	cc/3 min.	
11	250	36		1/2
12	250	36	3/2	
13	300	36	cc/3 min.	
14	300	36		2/3
15	300	36	2	
16	350	36	cc/3 min.	
17	350	36		2/3
18	350	36	2	
19	400	34	cc/3 min.	
20	400	34		5/6
21	400	34	5/2	
22	450	35	cc/3 min.	
23	450	35		5/6
24	450	35	5/2	
25	500	35	cc/3 min.	
26	500	35		1
27	500	35	3	

TABLE IV (cont'd)

Performance Data of the Metering Device
Orifice Diameter: 0.050"
Orifice Alignment: No Overlap
Meter Drum: 1050 R.P.M.

Run	Oil Pressure p.s.i. gage	Oil Seal Temp. °C.	Discharge Rate cc/3 min.	cc/min.
28	600	35	cc/3 min.	
29	600	35		1
30	600	35	3	
31	700	35	cc/3 min.	
32	700	35		1
33	700	35	3	
34	800	35	cc/3 min.	
35	800	35		1
36	800	35	3	
37	900	35	cc/3 min.	
38	900	35		1
39	900	35	3	
40	1000	35	cc/3 min.	
41	1000	35		1
42	1000	35	3	

TABLE V

Performance Data of the Metering Device
Orifice Diameter: 0.050"
Orifice Alignment: One-half Overlap
Meter Drum: 1050 R.P.M.

Run	Oil Pressure p.s.i. gage	Oil Seal Temp. °C.	Discharge Rate cc/min.
1	100	33	5
2	100	33	5
3	100	33	5
4	150	34	8
5	150	34	8
6	150	34	8
7	200	36	10
8	200	36	10
9	200	36	10
10	250	36	11
11	250	36	11
12	250	36	11
13	300	36	12
14	300	36	12
15	300	36	12
16	350	36	14.5
17	350	36	15
18	350	36	15
19	400	34	17.5
20	400	34	18
21	400	34	17.5
22	450	35	18.5
23	450	35	18.5
24	450	35	18.5

TABLE V (cont'd)

Performance Date of the Metering Device
Orifice Diameter: 0.050"
Orifice Alignment: One-half Overlap
Meter Drum: 1050 R.P.M.

Run	Oil Pressure p.s.i. gage	Oil Seal Temp. °C.	Discharge Rate cc/min.
25	500	35	19.5
26	500	35	20
27	500	35	20
28	550	35	21
29	550	35	21
30	550	35	21
31	600	35	23.5
32	600	35	24
33	600	35	24
34	700	35	27
35	700	35	27
36	700	35	27
37	800	35	32
38	800	35	31.5
39	800	35	32
40	900	35	33
41	900	35	33
42	900	35	33
43	1000	35	34
44	1000	35	34
45	1000	35	34

TABLE VI

Performance Data of the Metering Device
Orifice Diameter: 0.050"
Orifice Alignment: Full Overlap
Meter Drum: 1050 R.P.M.

Run	Oil Pressure p.s.i. gage	Oil Seal Temp. °C.	Discharge Rate cc/min.
1	100	33	12.5
2	100	33	13
3	100	33	12.5
4	150	34	17
5	150	34	17
6	150	34	17
7	200	35.5	19.5
8	200	35.5	20
9	200	35.5	20
10	250	36	23
11	250	36	23
12	250	36	23
13	300	36	28
14	300	36	27
15	300	36	28
16	350	36	30
17	350	36	31
18	350	36	31
19	400	34	36
20	400	34	36
21	400	34	36
22	450	35	40
23	450	35	40
24	450	35	40

TABLE VI (cont'd)

Performance Date of the Metering Device
Orifice Diameter: 0.050"
Orifice Alignment: Full Overlap
Meter Drum: 1050 R.P.M.

Run	Oil Pressure p.s.i. gage	Oil Seal Temp. °C.	Discharge Rate cc/min.
25	500	35	42
26	500	35	42
27	500	35	42
28	550	35	45
29	550	35	45
30	550	35	45
31	600	35	47
32	600	35	47
33	600	35	47
34	700	35	52
35	700	35	52
36	700	35	52
37	800	35	57
38	800	35	57
39	800	35	57
40	900	35	62
41	900	35	62
42	900	35	62
43	1000	35	65
44	1000	35	65
45	1000	35	65

TABLE VII

Performance Data of the Metering Device
Orifice Diameter: 0.050"
Orifice Alignment: One-quarter overlap
Meter Drum: 2000 R.P.M.

Run	Oil Pressure p.s.i. gage	Oil Seal Temp. °C.	Discharge Rate cc/min.
1	100	37	None
2	100	37	None
3	100	37	None
4	200	37	1
5	200	37	1
6	200	37	1
7	300	37	3
8	300	37	3
9	300	37	3
10	400	37	5.5
11	400	37	5.5
12	400	37	5.5
13	500	37	8.5
14	500	37	8.5
15	500	37	8.5

TABLE VIII

Performance Data of the Metering Device
Orifice Diameter: 0.050"
Orifice Alignment: One-half overlap
Meter Drum: 2000 R.P.M.

Run	Oil Pressure p.s.i. gage	Oil Seal Temp. °C.	Discharge Rate cc/min.
1	100	37	3
2	100	37	3
3	100	37	3
4	200	37	8.5
5	200	37	8.5
6	200	37	8.5
7	300	37	10.5
8	300	37	10.5
9	300	37	10.5
10	400	37	16.5
11	400	37	16.5
12	400	37	16.5
13	500	37	20
14	500	37	20
15	500	37	20

TABLE IX

Performance Data of the Metering Device
Orifice Diameter: 0.050"
Orifice Alignment: Three-quarter Overlap
Meter Drum: 2000 R.P.M.

Run	Oil Pressure p.s.i. gage	Oil Seal Temp. °C.	Discharge Rate cc/min.
1	100	37	9.5
2	100	37	9
3	100	37	9
4	200	37	16.5
5	200	37	16.5
6	200	37	16.5
7	300	37	21
8	300	37	21
9	300	37	21
10	400	37	26
11	400	37	26
12	400	37	26
13	500	37	31.5
14	500	37	31.5
15	500	37	32

TABLE X

Performance Data of the Metering Device
Orifice Diameter: 0.050"
Orifice Alignment: Full Overlap
Meter Drum: 2000 R.P.M.

Run	Oil Pressure p.s.i. gage	Oil Seal Temp. °C.	Discharge Rate cc/min.
1	100	31	11
2	100	31	11
3	100	31	11
4	150	31	13.5
5	150	31	13
6	150	31	13
7	200	31	17.5
8	200	31	17.5
9	200	31	17.5
10	250	31	20.5
11	250	31	20.5
12	250	31	20.5
13	300	31	24.5
14	300	31	24.5
15	300	31	25
16	350	32	28.5
17	350	32	28.5
18	350	32	29
19	400	32	33
20	400	32	32.5
21	400	32	33
22	450	32.5	35.5
23	450	32.5	35
24	450	32.5	35.5
25	500	33	37.5
26	500	33	37.5
27	500	33	38

TABLE X (Cont'd.)

Performance Data of the Metering Device
Orifice Diameter: 0.050"
Orifice Alignment: Full Overlap
Meter Drum: 2000 R.P.M.

Run	Oil Pressure p.s.i. gage	Oil Seal Temp. °C.	Discharge Rate cc/min.
28	550	33	40
29	550	33	40.5
30	550	33	40.5
31	600	35	43
32	600	35	43.5
33	600	35	43
34	650	36	47
35	650	36	46.5
36	650	36	47
37	700	36	48.5
38	700	36	49
39	700	36	49
40	750	37	52
41	750	37	52.5
42	750	37	52.5
43	800	37	57
44	800	37	56.5
45	800	37	57
46	850	38	57.5
47	850	38	58
48	850	38	58
49	900	38	59
50	900	38	58.5
51	900	38	58.5

TABLE X (Cont'd.)

Performance Data of the Metering Device
Orifice Diameter: 0.050"
Orifice Alignment: Full Overlap
Meter Drum: 2000 R.P.M.

Run	Oil Pressure p.s.i. gage	Oil Seal Temp. °C.	Discharge Rate cc/min.
52	950	38	61.5
53	950	38	61.5
54	950	38	62
55	1000	38	64
56	1000	38	64
57	1000	38	64

TABLE XI

Analysis of Motion Pictures Taken of the Spray from the Metering Device

Cycle No.	Total Frames	Continuity of Ejection Frames	Visible Spray Frames
1	16	2	4
2	18	2	5
3	21	3	6
4	24	3	6
5	26	3	6
6	27	3	6
7	29	3	6
8	29	3	6
9	31	3	6
10	33	4	6
11	36	4	7
12	37	4	7
13	37	4	7
14	37	4	7
15	40	4	7
16	41	5	7
17	41	5	7
18	44	5	7
19	45	5	7
20	45	5	7
21	47	5	7
22	47	5	7
23	47	5	7
24	49	5	7
25	50	5	7
26	51	5	7
27	51	5	7
28	53	6	8
29	53	6	8
30	53	6	8
31	54	6	8
32	55	6	8
33	55	6	8
34	56	6	8
35	57	7	9
36	57	7	9
37	57	7	9
38	57	7	9
39	58	7	9
40	59	7	9

TABLE XI (Cont'd)

Analysis of Motion Pictures
Taken of the Spray from the
Metering Device

Cycle No.	Total Frames	Continuity of Ejection Frames	Visible Spray Frames
41	60	7	9
42	60	7	9
43	61	7	9
44	61	7	9
45	61	8	10
46	61	8	10
47	62	8	10
48	62	8	10
49	62	8	10
50	62	8	10
51	62	8	10
52	62	8	10
53	62	8	10
54	62	8	10
55	62	8	10
56	62	8	10
57	62	8	10
58	62	8	10
59	62	8	10
60	62	8	10
61	62	8	10
62	62	8	10
63	62	8	10
64	62	8	10
65	62	8	10
66	62	8	10
67	62	8	10
68	62	8	10
69	62	8	10
70	62	8	10
71	62	8	10
72	62	8	10
73	62	8	10
74	62	8	10

TABLE XII

The Results of the Oil Viscosity Test
On
The Oil Metered

Saybolt Universal Second Viscosity

Reading	Flow Time Min.	Sec.	Oil Temp. °F.	Bath Temp. °F.	Amt. c.c.	Viscosity seconds
1	9	32	82	82	60	572
2	7	33	88	88	60	453
3	6	46	92	92	60	406
4	5	50	96	96	60	350
5	5	3	100	100	60	303
6	4	37	106	106	60	277
7	3	55	112	113	60	235
8	3	25	116	116	60	205
9	3	9	120	120	60	189

Specific Gravity (60°F.) = .891

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APPENDIX I

General Test Material

A: A.C. - D.C. Motor-Generator Set
Manufacturer - Westinghouse
Capacity - 600 Amperes, 75 Volts, D.C.

B: Varidrive Testameter
Manufacturer - U. S. Motors Company
Model - OTBD
Type - 15-30-300
Serial No. 300144
Speed Range - 1050-12,000 R.P.M.

Tachometer: Weston Magneto Tachometer
Model - 724 Type - C2
No. 23397
Resistance - 200 Ohms.
6 Volts/1000 R.P.M.
Max. R.P.M. - 2000

Ammeter: Weston D.C.
Model - 271
No. 55996

Voltmeter: Weston D.C.
Model - 271
No. 51190

C: D.C. Motor - Rotary Gear Oil Pump Drive
Manufacturer - Pesco Products Company
D.C. Motor: 95 Amperes 21 Volts
4000 R.P.M. 2.5 H.P.
Temperature Rise - 75°

Rotary Gear Pump: 1200 pounds per square inch
Maximum gage pressure, with
adjustable pressure control
electric relays.
Part No. 1E620B

D: Oil - Air Ballast Tank
Capacity - 1.5 gallons oil

E: Oil Storage Tank
Capacity - 3-1/2 gallons oil

APPENDIX I (Cont'd.)

General Test Material

F: Instruments:

a. Electric Microchronometer.
b. 3000 pounds per square inch Foxboro Bourdon Tube Pressure Gage.
c. Strobolux.
d. Strobotac.
e. Fastex Hi-Speed Moving Picture Camera and Photo Flood Lights.
f. Stop Watch.
g. 100°Centigrade Taylor Thermometer.
h. Snap Shot Camera.
i. 5 milli-liter, 25 milli-liter, 100 milli-liter, and 2000 milli-liter measures.

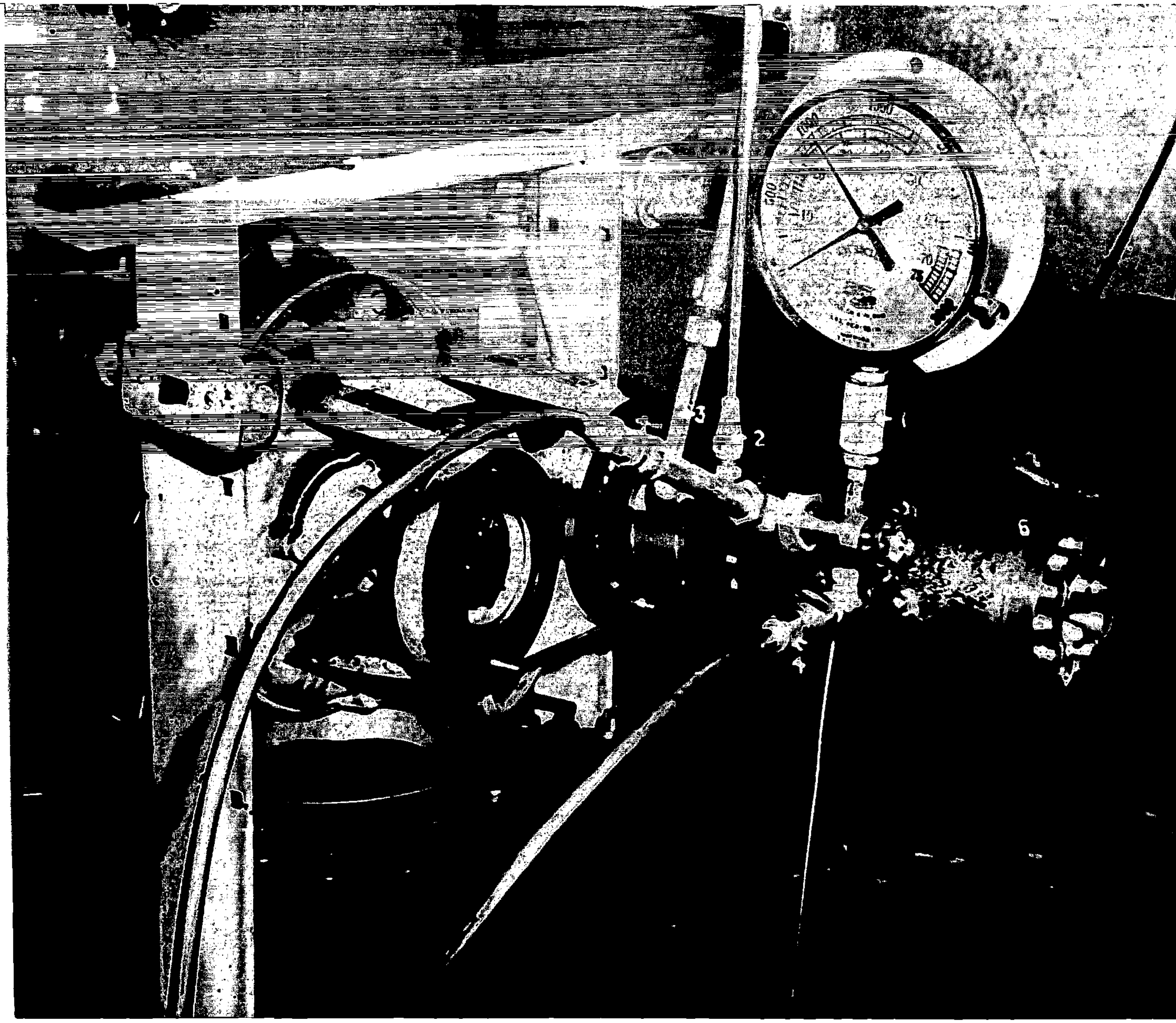


Figure 1

1. Pressure Gage
2. Thermometer Well
3. Oil leakage
4. Oil supply line
5. Meter Assembly

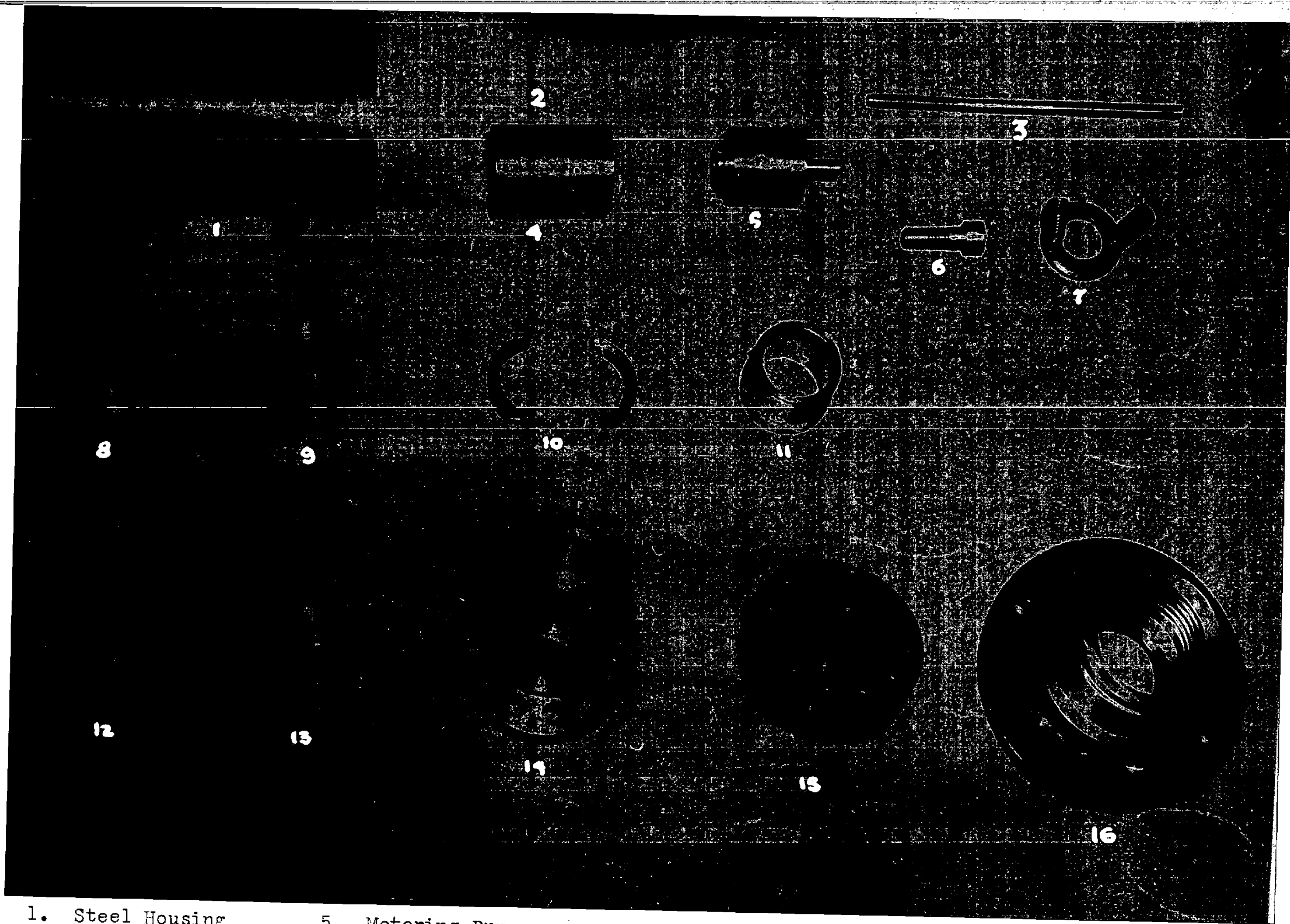


Figure 2

1. Steel Housing
2. Calibration Pin
3. Driving Spindle
4. Nickel-Iron Bushing
5. Metering Drum
6. Fillister Head Screw
7. Thrust for Spindle Bearing
8. Paching Gland
9. Steel Piston Bushing
10. Steel Thrust Ring
11. Micrometer Screw
12. S.K.F. Bearing
13. Ram and Piston
14. Metering Head
15. End Cap
16. Adaptor

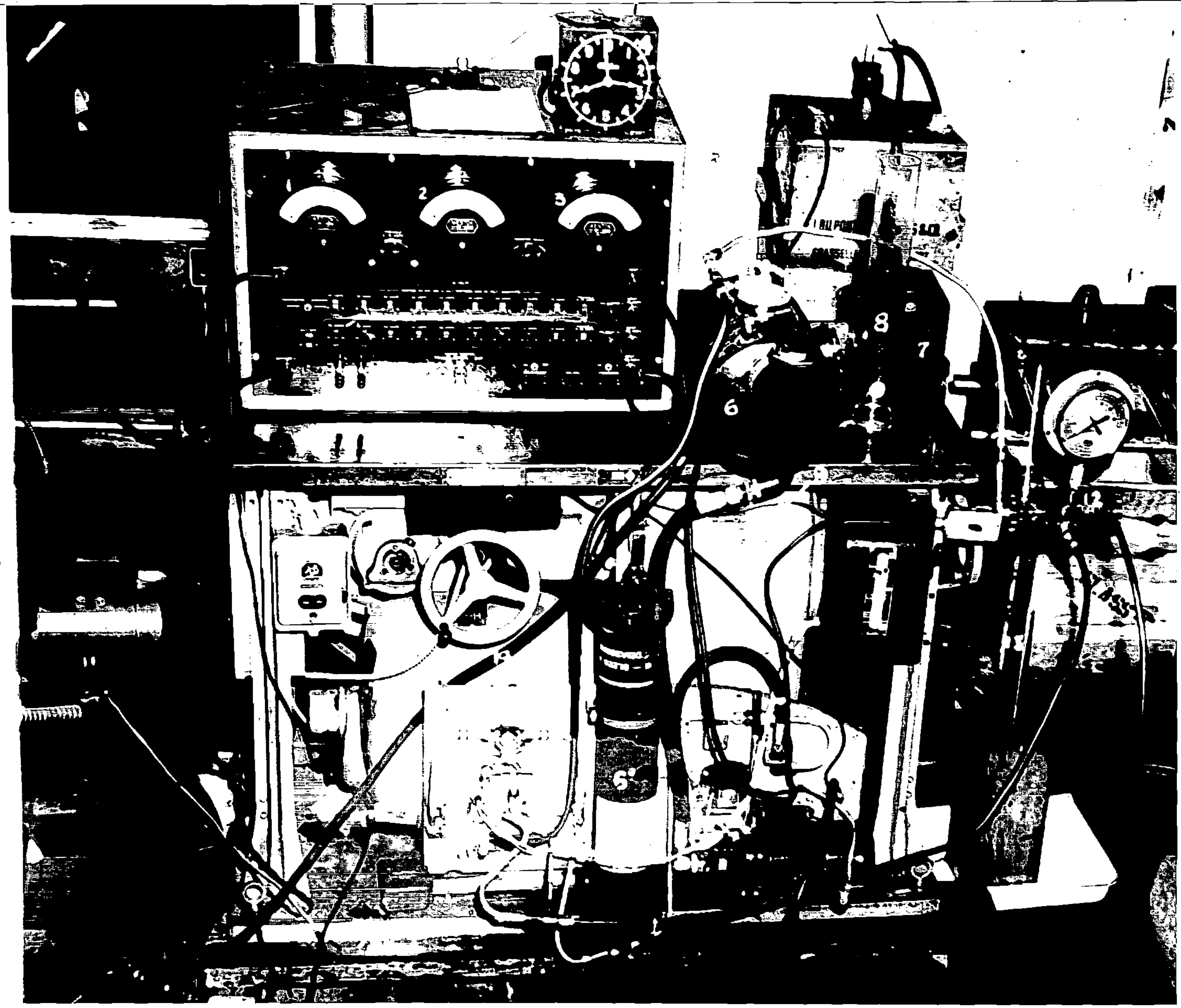


Figure 3

1. Tachometer
2. Ammeter
3. Voltmeter
4. Microchronometer
5. Accumulator
   Pump on right
   Pump relays on
6. Oil Tank
7. Strobotac
8. Graduate
9. Vari-Speed Drive
10. 25 hp Motor
11. Motor Generator Set
12. Metering Device
13. Discharge

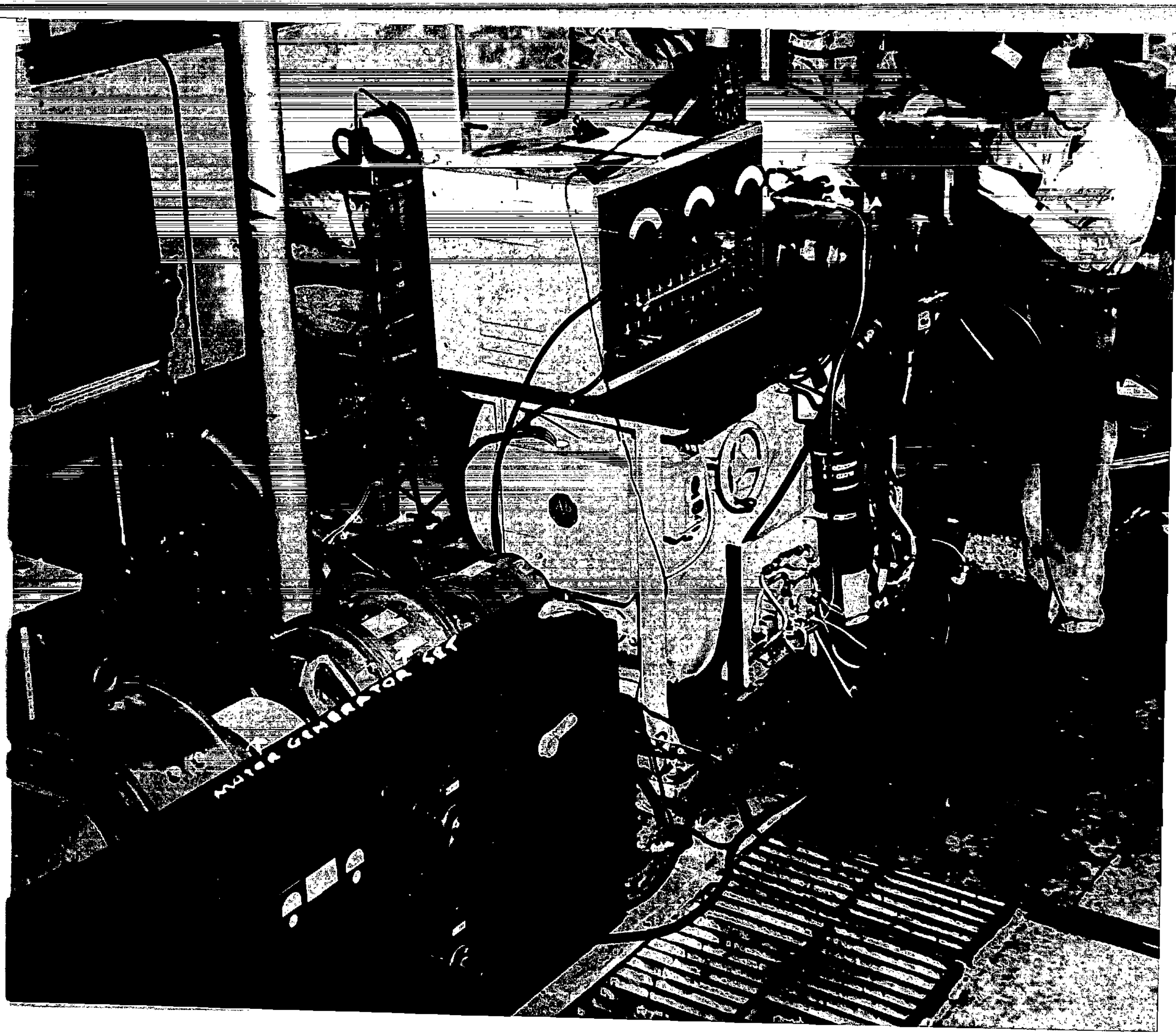


Figure 4

Motor Generator Set

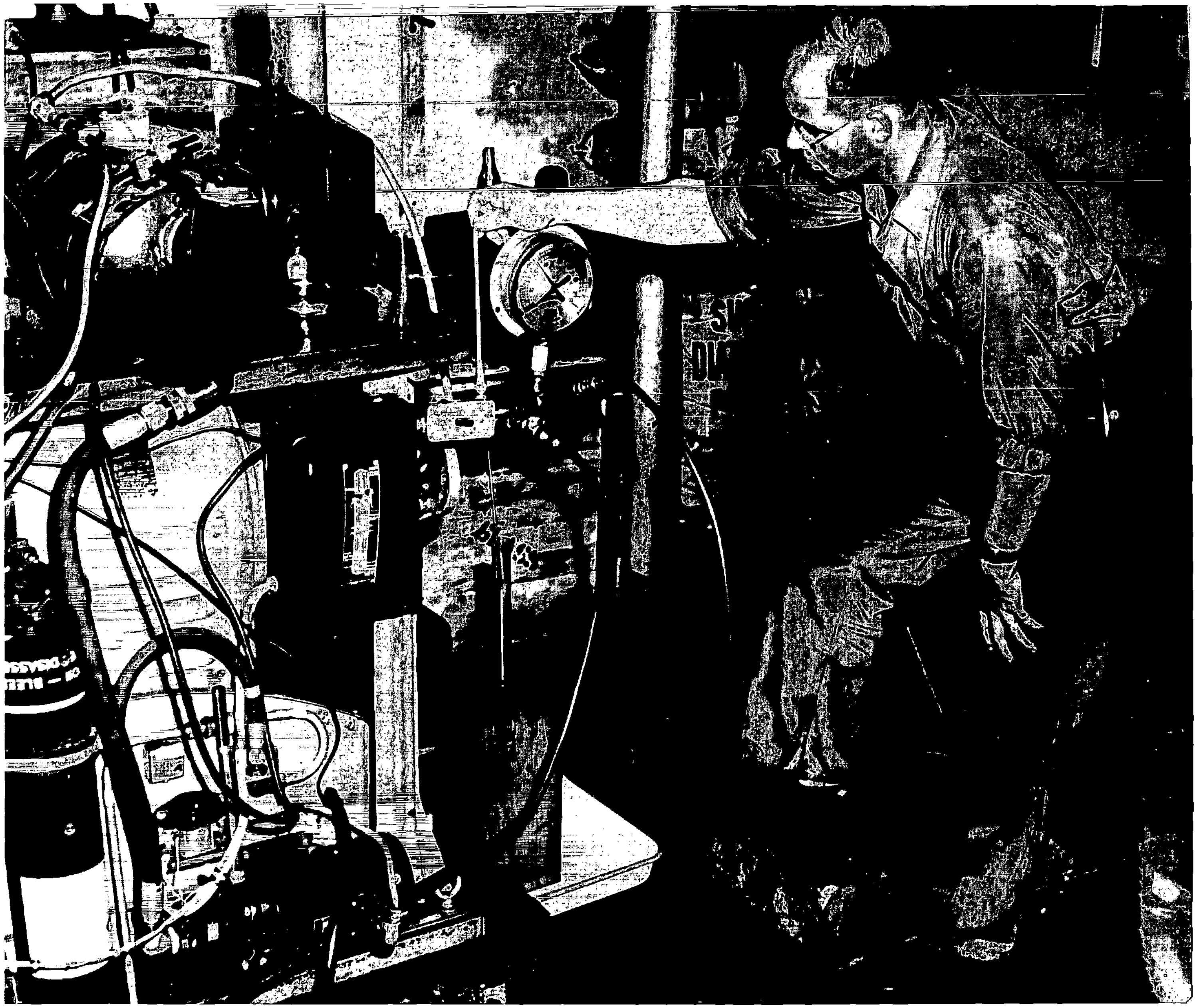


Figure 5

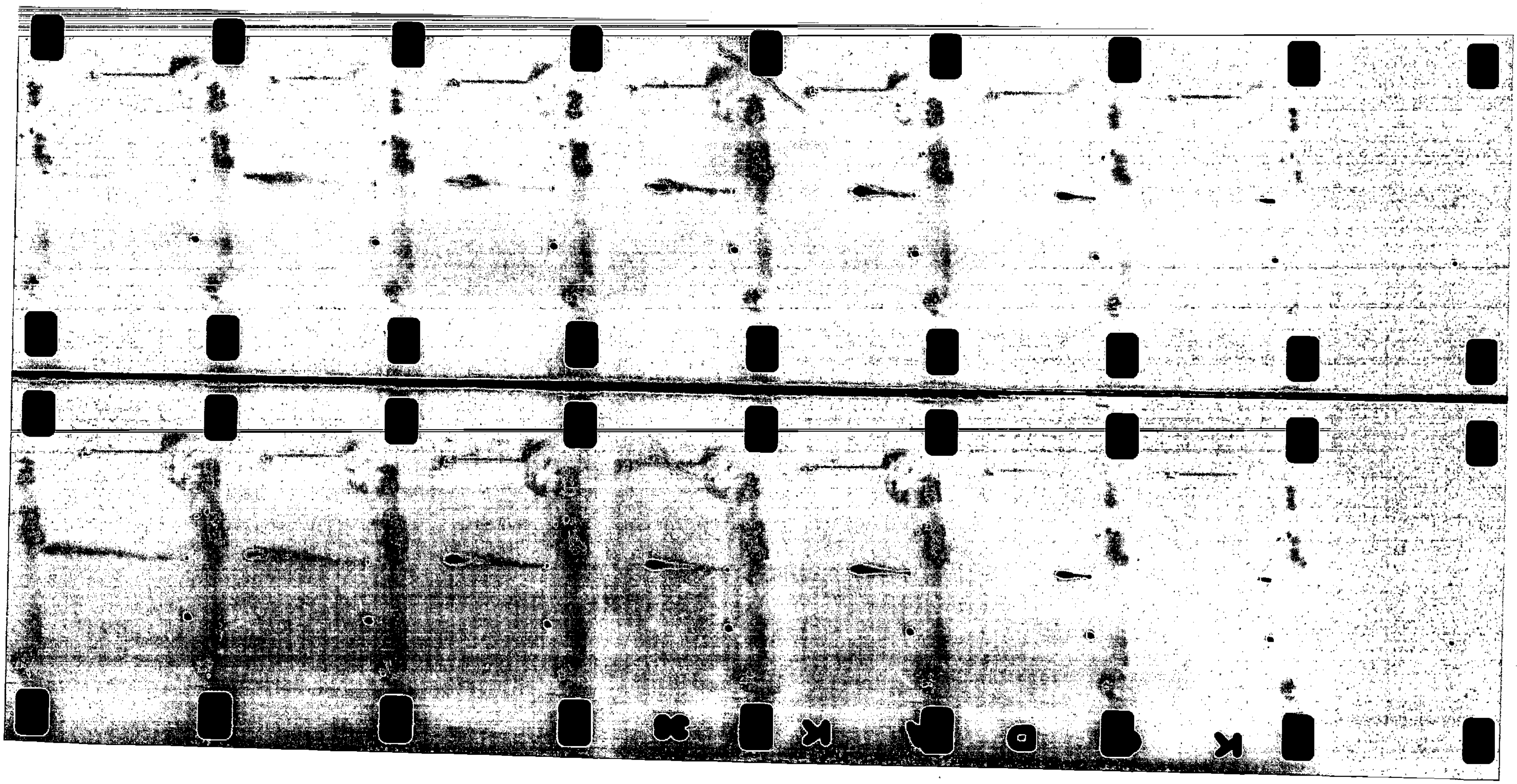


Figure 6

Samples of the High Speed Motion Picture Film
(2000 Frames/Sec.) Showing a Single Metered Oil Discharge

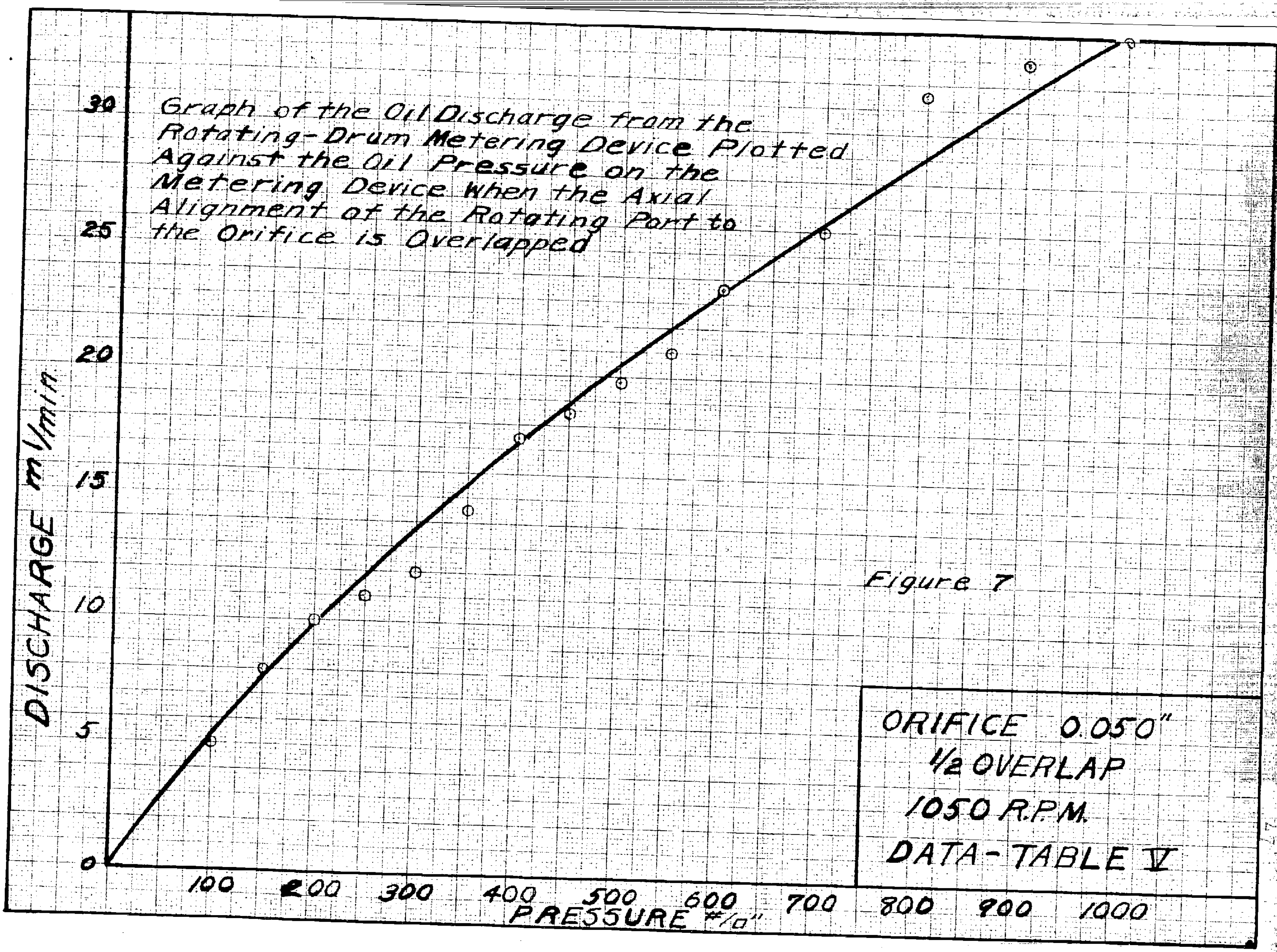
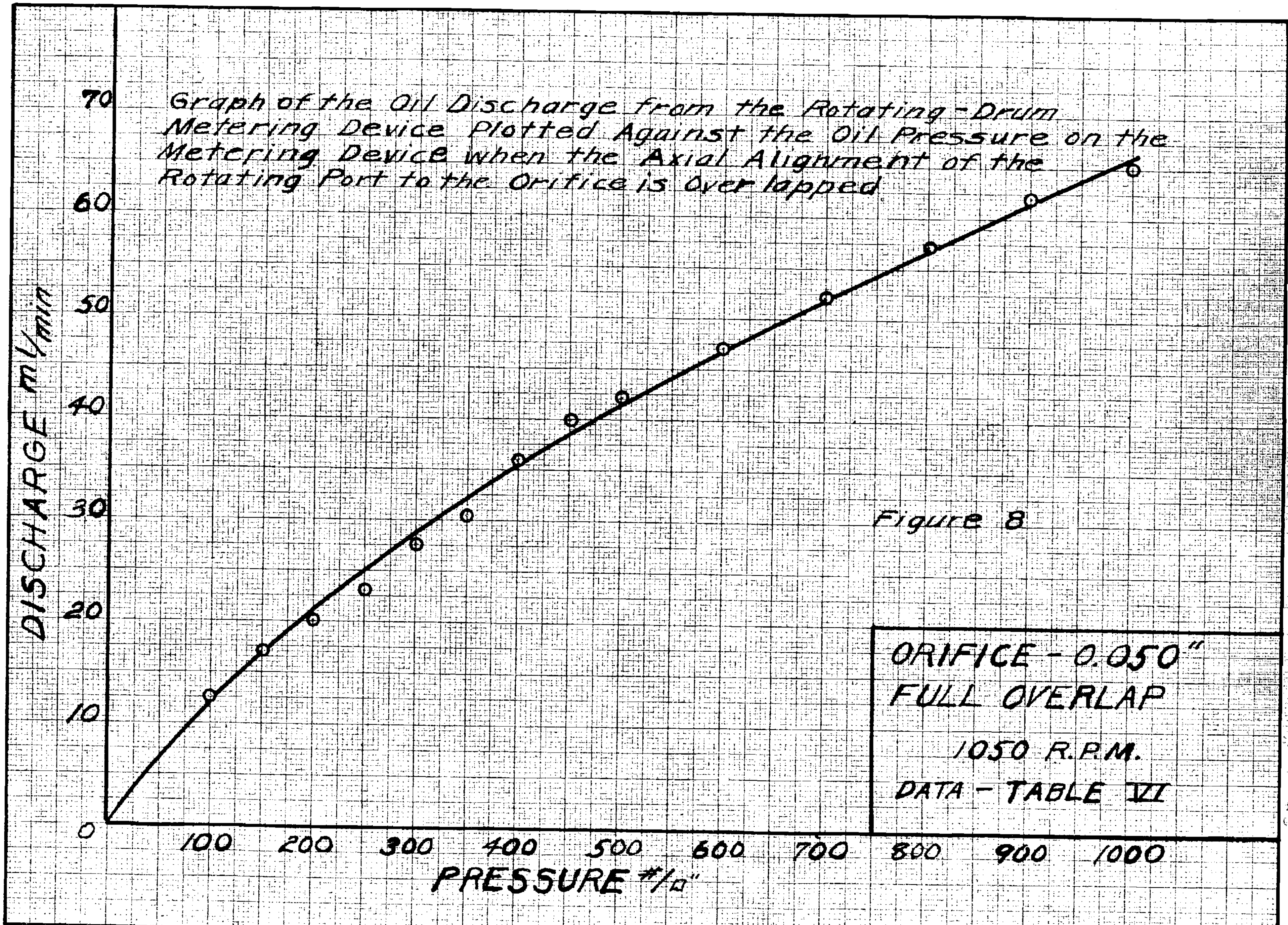
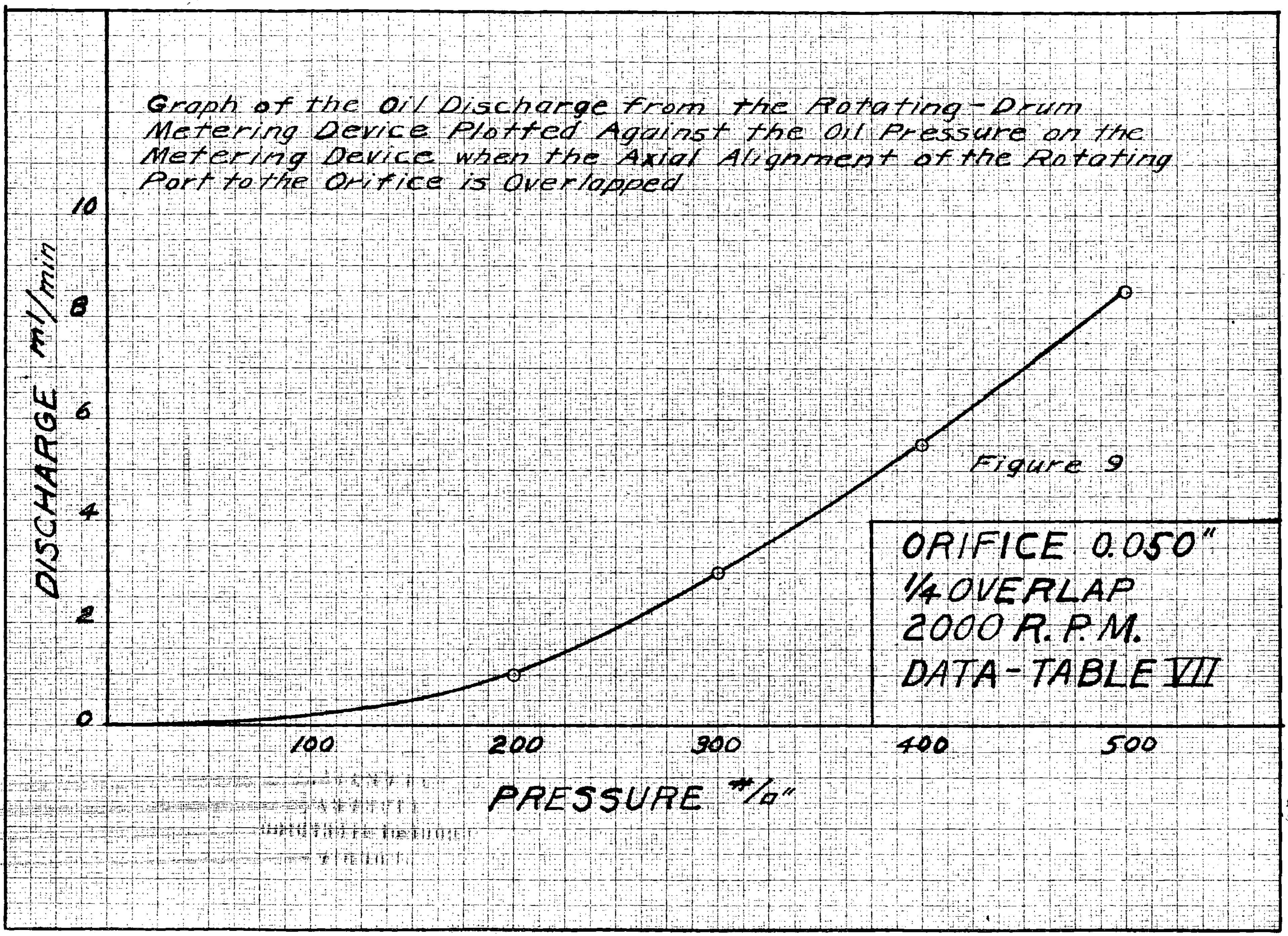

Graph of the Oil Discharge from the Rotating-Drum Metering Device Plotted Against the Oil Pressure on the Metering Device When the Axial Alignment of the Rotating Port to the Orifice is Overlapped
DISCHARGE ml/min
PRESSURE #/□"
0
5
10
15
20
25
30
100
200
300
400
500
600
700
800
900
1000
ORIFICE 0.050"
1/2 OVERLAP
1050 R.P.M.
DATA-TABLE V

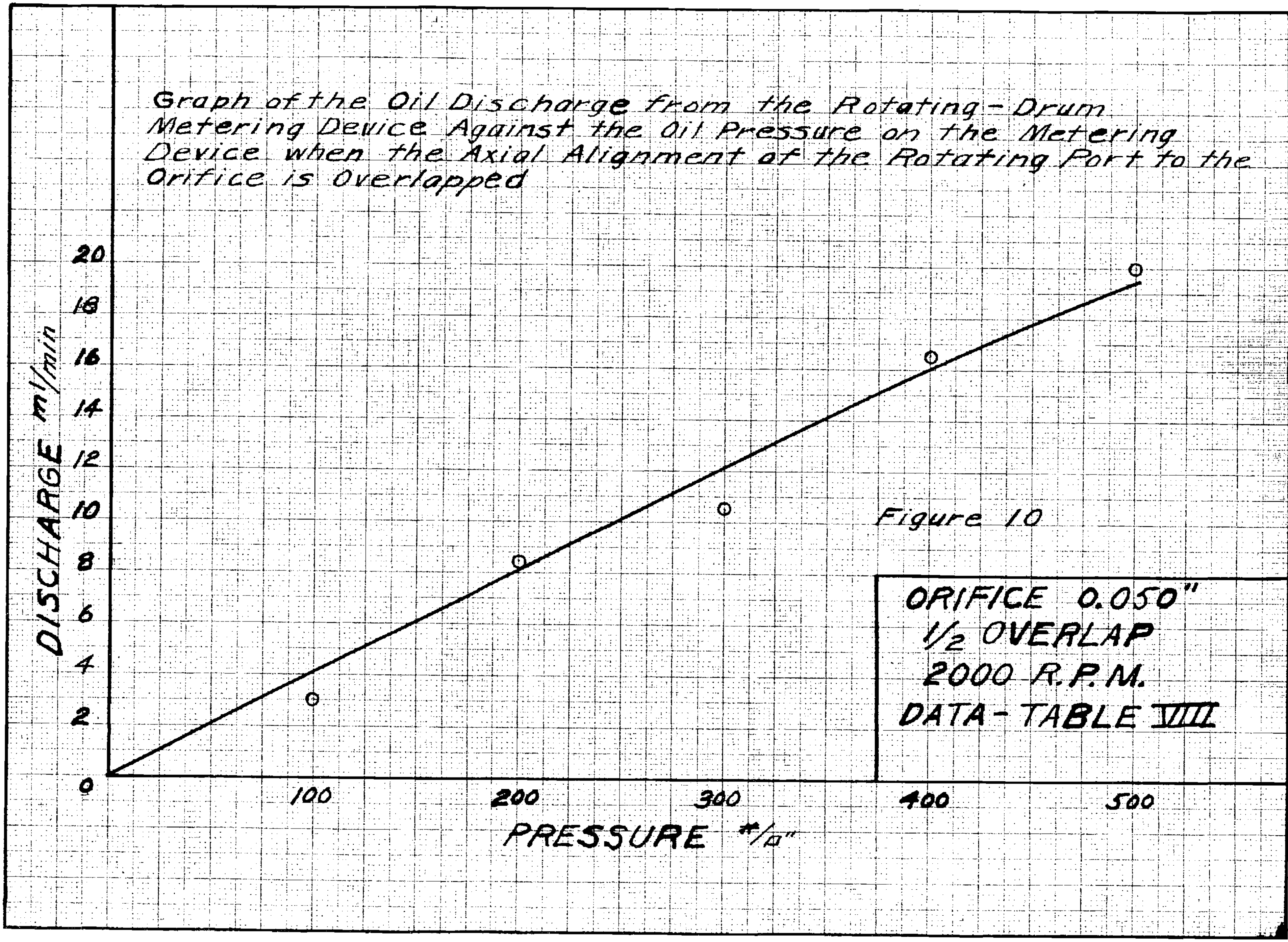
Figure 7

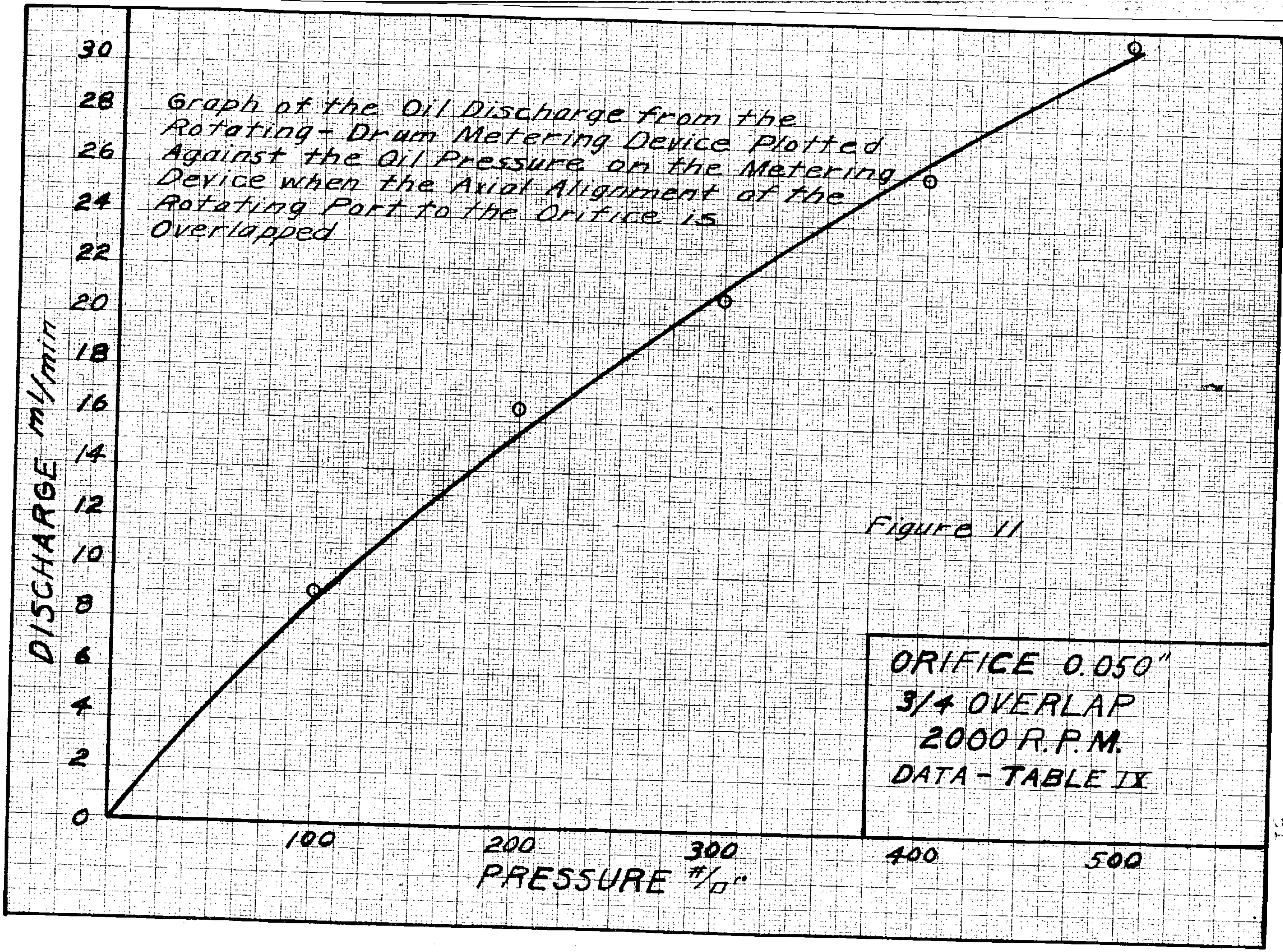

Graph of the Oil Discharge from the Rotating-Drum Metering Device Plotted Against the Oil Pressure on the Metering Device when the Axial Alignment of the Rotating Port to the Orifice is Overlapped
DISCHARGE ml/min
0
10
20
30
40
50
60
70
100
200
300
400
500
600
700
800
900
1000
PRESSURE #/□"
Figure 8
ORIFICE - 0.050"
FULL OVERLAP
1050 R.P.M.
DATA - TABLE VI



Graph of the Oil Discharge from the Rotating-Drum Metering Device Plotted Against the Oil Pressure on the Metering Device when the Axial Alignment of the Rotating Port to the Orifice is Overlapped

Figure 9


Graph of the Oil Discharge from the Rotating-Drum Metering Device Against the Oil Pressure on the Metering Device when the Axial Alignment of the Rotating Port to the Orifice is Overlapped
DISCHARGE ml/min
0
2
4
6
8
10
12
14
16
18
20
100
200
300
400
500
PRESSURE #/□"
ORIFICE 0.050"
1/2 OVERLAP
2000 R.P.M.
DATA - TABLE VIII
Figure 10


Graph of the Oil Discharge from the Rotating-Drum Metering Device Plotted Against the Oil Pressure on the Metering Device when the Axial Alignment of the Rotating Port to the Orifice is Overlapped
DISCHARGE ml/min
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
100
200
300
400
500
PRESSURE #/□"
Figure 11
ORIFICE 0.050"
3/4 OVERLAP
2000 R.P.M.
DATA - TABLE IX

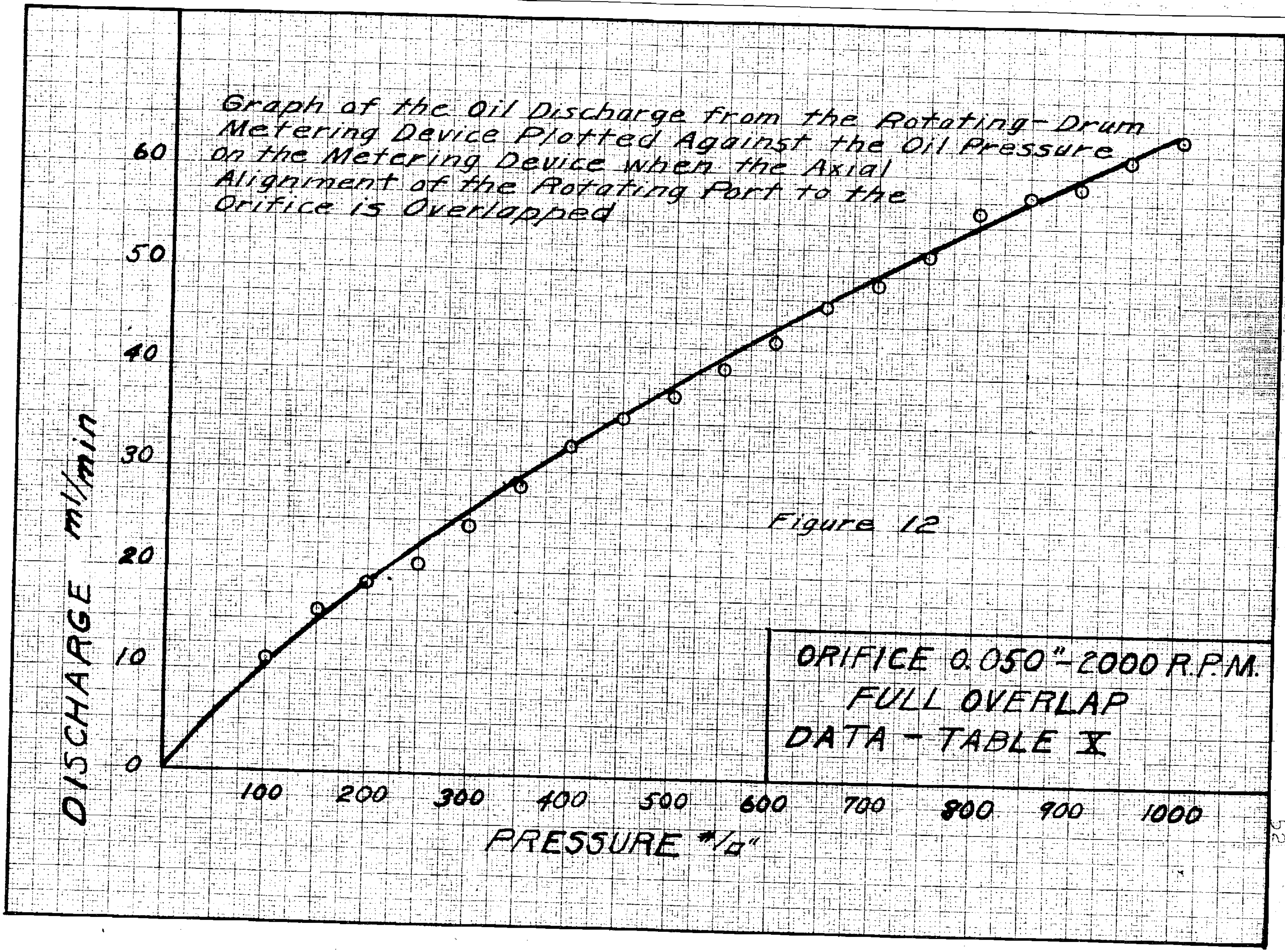

Graph of the Oil Discharge from the Rotating-Drum Metering Device Plotted Against the Oil Pressure on the Metering Device when the Axial Alignment of the Rotating Port to the Orifice is Overlapped
DISCHARGE ml/min
0
10
20
30
40
50
60
100
200
300
400
500
600
700
800
900
1000
PRESSURE #/□"
ORIFICE 0.050"-2000 R.P.M.
FULL OVERLAP
DATA - TABLE X

Figure 12

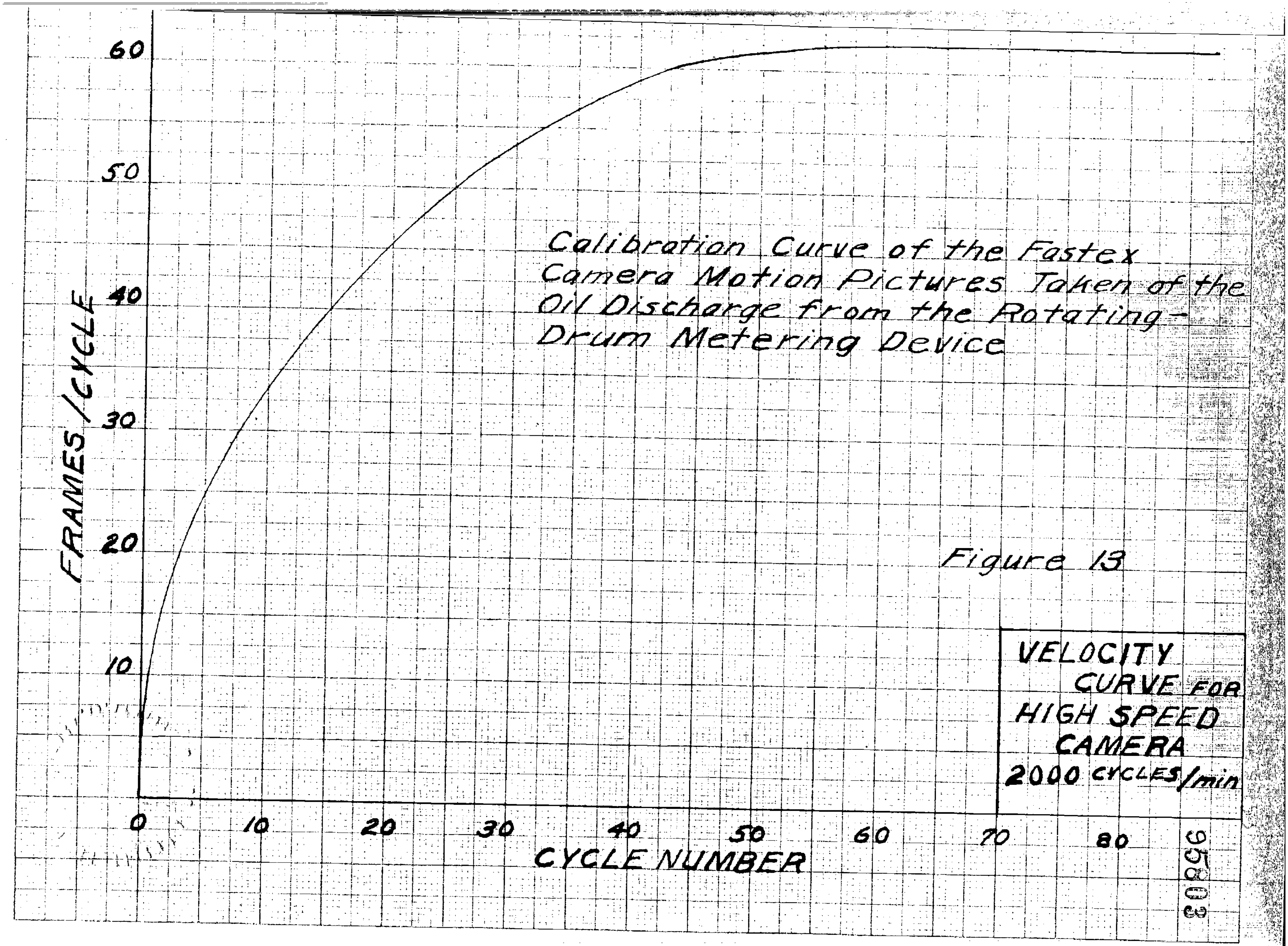

Calibration Curve of the Fastex Camera Motion Pictures Taken of the Oil Discharge from the Rotating-Drum Metering Device
FRAMES / CYCLE
CYCLE NUMBER
0
10
20
30
40
50
60
70
80
VELOCITY CURVE FOR HIGH SPEED CAMERA
2000 CYCLES/min
9603

Figure 13