UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

- - -

HYDRAULIC LABORATORY REPORT NO. 150

- - -

CONTINUATION OF STUDIES TO DETERMINE SUITABLE METHOD FOR STARTING AND STOPPING THE PUMPS AT GRANBY DAM PUMPING PLANT

COLORADO-BIG THOMPSON PROJECT, COLORADO

by

J. N. BRADLEY, ENGINEER

- - -

Denver, Colorado,
Sept. 20, 1944

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

- - - - -

HYDRAULIC LABORATORY REPORT NO. 150

SUBJECT: CONTINUATION OF STUDIES TO DETERMINE SUITABLE METHOD
FOR STARTING AND STOPPING THE PUMPS
AT GRANBY DAM PUMPING PLANT
COLORADO BIG THOMPSON PROJECT, COLORADO

- - - - -

By J. N. BRADLEY, ENGINEER

- - - - -

Under Direction of

J. E. WARNOCK, SENIOR ENGINEER

and

R. F. BLANKS, SENIOR ENGINEER

- - - - -

Denver, Colorado,
Sept. 20, 1944

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

Branch of Design and Construction
Engineering and Geological Control
and Research Division

Laboratory Report No. 150
(Supplements Laboratory
Report No. 113)
Hydraulic Laboratory
Compiled by: J. N. Bradley
Reviewed by: J. E. Warnock

Denver, Colorado
September 20, 1944

Subject: Continuation of studies to determine suitable method for starting and stopping the pumps at Granby Dam pumping plant - Colorado-Big Thompson project, Colorado.

1. Purpose of investigation. The tests described in this report constitute a continuation of those previously described in hydraulic laboratory report 113, "Studies to determine suitable methods for starting and stopping the pumps at the Granby pumping plant," by J. N. Bradley, Fred Locher, W. A. Morgan, and T. F. hammett, June 15, 1942. As the pumping plant and the problems involved have been described in the above report, these will be treated briefly here.

The plant ultimately will house four pumps, of approximately 6,000 horsepower each, which will be subject to discontinuous operation requiring frequent starting and stopping. The starting or the stopping of pumps of this size under full load would cause dimming of lights and interference with the operation of automatic equipment throughout the vicinity, as the rate of power input to the pump motors would, in some cases, exceed the rate of response of the generators at Green Mountain Dam. The tests described both here and in the previous report were performed in an effort to alleviate this condition.

The purpose of the tests described herein was to study the feasibility of starting the pumps while throttling the flow in the intake lines. The main objective in this case was to eliminate the purchase of valves for the discharge lines. The information desired is best stated in a memorandum to the Chief Electrical and Mechanical Engineer by Mr. I. A. Winter, "Proposed laboratory study of starting the Granby pumps while throttling flow in the suction pipes - Granby Pumping Plant - Colorado-Big Thompson Project," dated May 2, 1944. Investigation of the following points was requested:

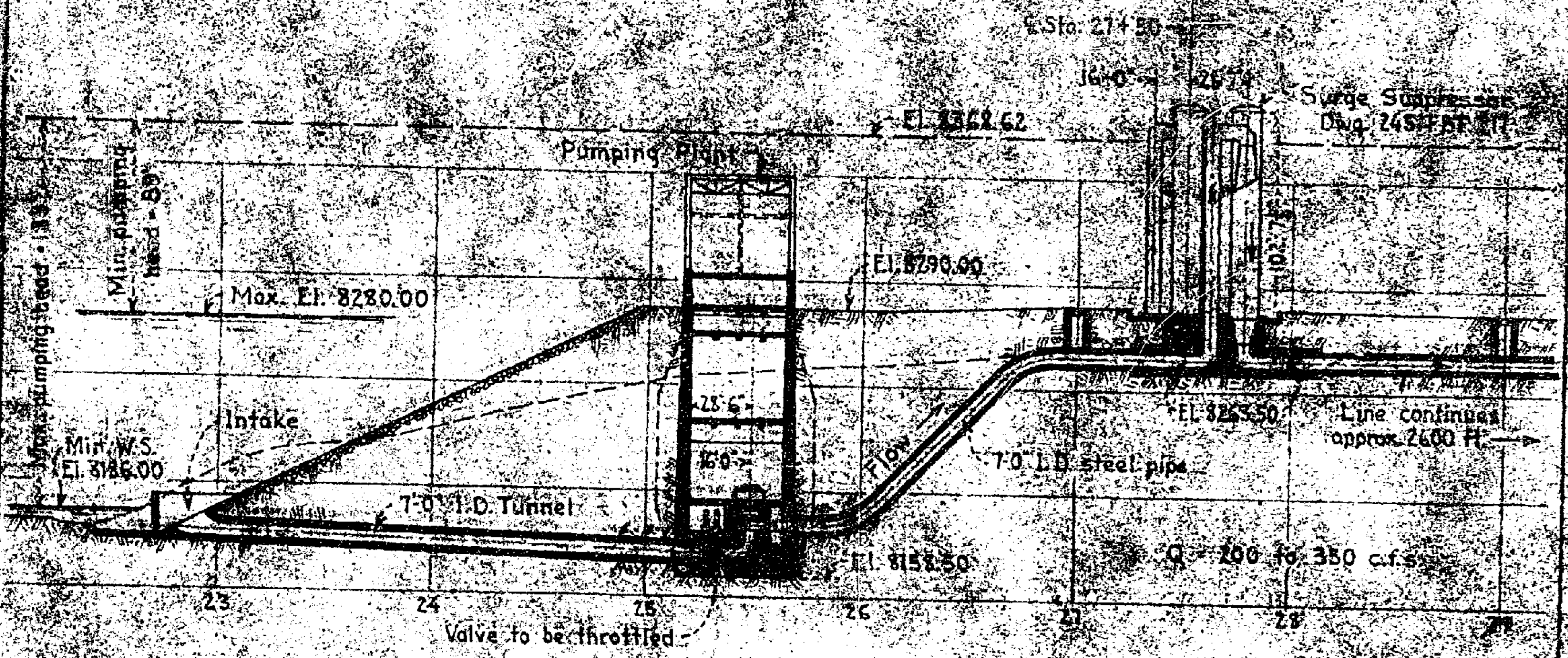
(a) Surging in the discharge line when the inflow is less than the normal capacity of the pump under heads ranging from the minimum to the maximum.

(b) Observation of the tendency of the pump to cavitate excessively during the starting cycle.

(c) Observation of the behavior of the water entering the suction tube of the pumps at high velocities.

The initial pump house valve layout is shown on figure 1, HYD-113. For the valve and the pipe layout used in this second series of studies, shown on figure 1 of this report, the discharge valve originally used was eliminated and two intake valves were provided instead of one. One valve was to be used for throttling and the other was to provide for emergency closure. It was proposed to start a pump with one intake valve closed and the discharge line full of water. With the pump up to speed, the intake valve would be opened at a constant rate until full load was imposed on the pump. The procedure was to be reversed when stopping the pump.

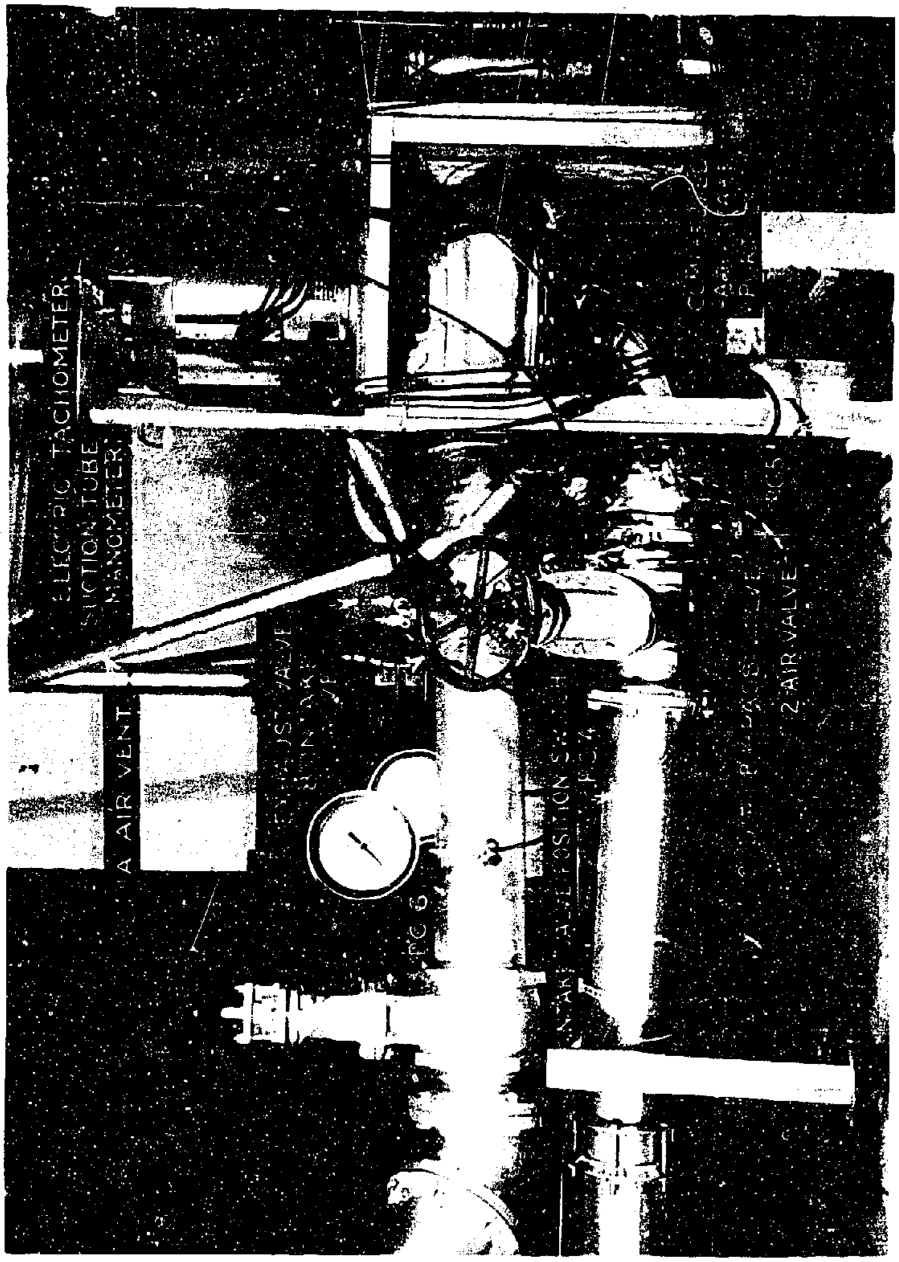
2. <u>The test equipment</u>. Arrangement of the test equipment for these studies was essentially the same as for the initial investigation, as is evident from a comparison of figures 6 and 7, HYD-113, and figure 2 of this report. The same 8-inch vertical pump was used in both cases. In the former tests a tank reservoir was employed to supply water to the pump, while in the latter tests a booster pump was connected in series with the intake line, making prototype pressures possible. The model approximated a general scale of 1:7 (table 1, HYD-113) except for the discharge line. The confining walls of the laboratory restricted the height of the discharge pipe to one-third of its scaled value and the length to only a fraction of the scaled distance



GRANBY PUMPING PLANT
SECTION THRU INTAKE LINE, PUMP HOUSE AND DISCHARGE LINE

16

FIGURE 2



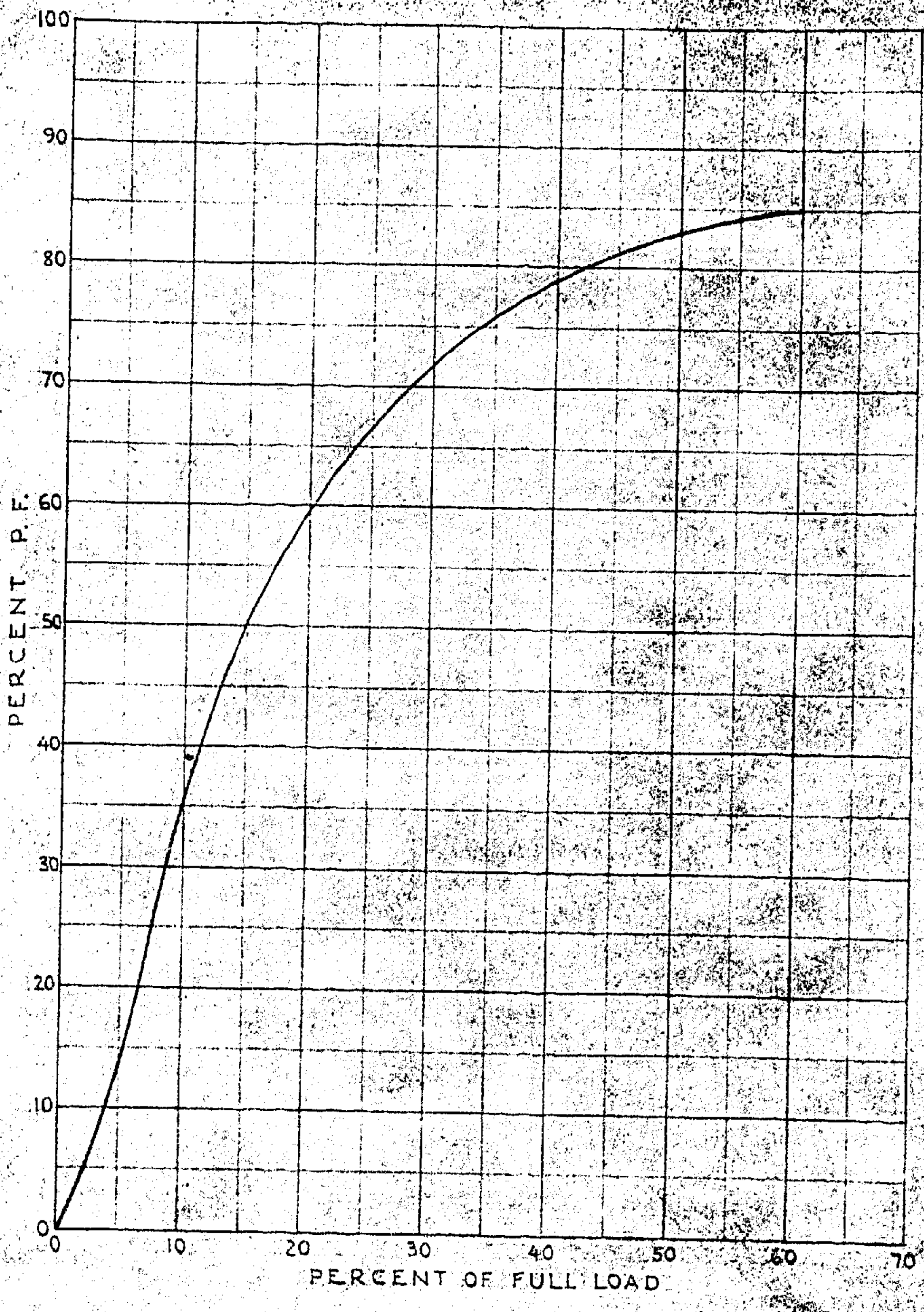
MODEL TEST LAYOUT FOR
GRANBY DAM PUMPING PLANT

to be traversed by the prototype conduit.

Instrumentation consisted of a voltmeter, an ammeter, and a wattmeter connected as shown in figure 13, HYD-113, between a single phase and the ground. Three electric, strain-gage type, pressure cells (P.C. 4, P.C. 5, and P.C. 6) were located as shown on figure 2 of this report for recording pressure changes in the intake, the pump suction tube, and the discharge line. In addition to the above instruments, electric tachometers were provided to measure the speed of the motor and the rate of opening of the intake valve. Instantaneous records of the pressure cells, the motor speed, the valve position, and the electric current were recorded by the laboratory oscillograph. An attempt was made to record the voltage, but, due to the fact that the oscillograph contained no shielded channels, the 60-cycle frequency was superimposed on the record of every channel. After discovering that the voltage fluctuation amounted to no more than 5 percent, this measurement was not considered important. A record of the power required by the motor was also desired, but a watt element was not available for the oscillograph. The primary interest in this study concerned surges in power rather than actual values, and these are clearly manifest in the current trace on the oscillograms. It should be kept in mind, however, that the general shape of the power record would vary considerably from the current trace. Although the voltage remained relatively constant, the power factor during these tests varied from zero to 85 percent, as can be observed from figure 3. This curve shows the power factor plotted with respect to the rated capacity of the motor for the actual range over which it operated during these tests. In no case did the motor on the test pump operate at greater than half of its rated capacity.

The pressure cells were a type used for the first time in the laboratory, and they will therefore be described here as a matter of record. A cell (figure 4) consisted of two steel arms, one stationary and the other movable. The movable arm was rigidly connected to a diaphragm

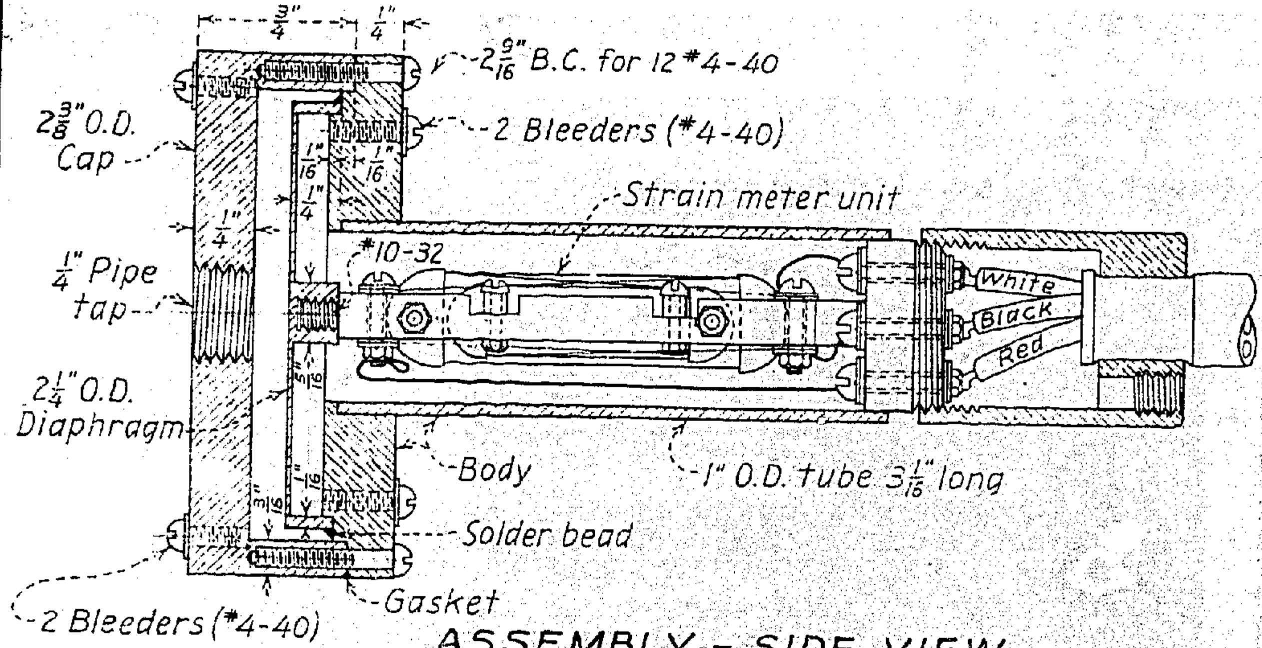
FIGURE 3



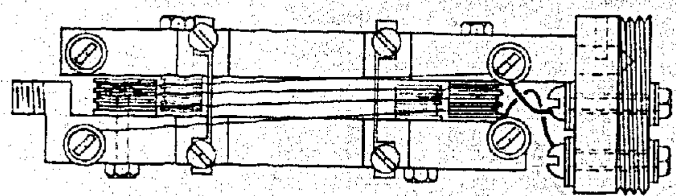
GRANBY PUMP TESTS

POWER FACTOR CURVE FOR BINGHAM TEST PUMP
BASED ON 15 H.P.

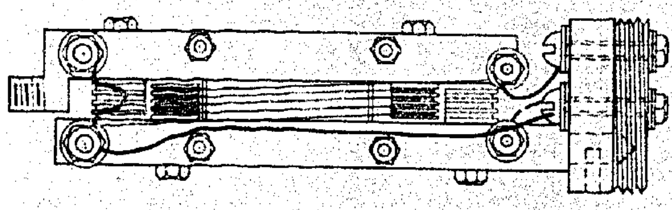
16



ASSEMBLY - SIDE VIEW



STRAIN METER UNIT - TOP VIEW
SHOWING WIRING OF EXPANSION COIL



STRAIN METER UNIT - BOTTOM VIEW
SHOWING WIRING OF CONTRACTION COIL

NOTES

Sealing chamber filled with G.E. No. 227 insulating compound. Strain meter unit filled with castor oil leaving 2 c.c. air space. Pressure chamber filled with water before embedment. Strain meter unit same as in Carlson stress meter.

LABORATORY ELECTRIC HYDROSTATIC PRESSURE GAGE

which flexed as pressure changes were applied to its opposite side. Two coils of wire, one consisting of four loops and the other of five loops, were strung over porcelain insulators mounted between the steel arms. The coils were strung to oppose one another in such manner that a movement of the diaphragm would increase the tension on one and reduce the tension on the other. Movement of the diaphragm in the opposite direction would reverse the strain, making the instrument adaptable for the measurement of intermittent, positive, and negative pressures. Piano wire, 0.0025 inch in diameter, possessing a fairly high strain sensitivity, gave most satisfactory results of a number of wires investigated. The dual coil served to equalize the variation of resistance produced in the two wires by temperature changes. Upon final assembly, to limit temperature change the coils were encased in oil. The output of these cells was sufficient to make possible the elimination of vacuum-tube amplifiers at the input to the oscillograph.

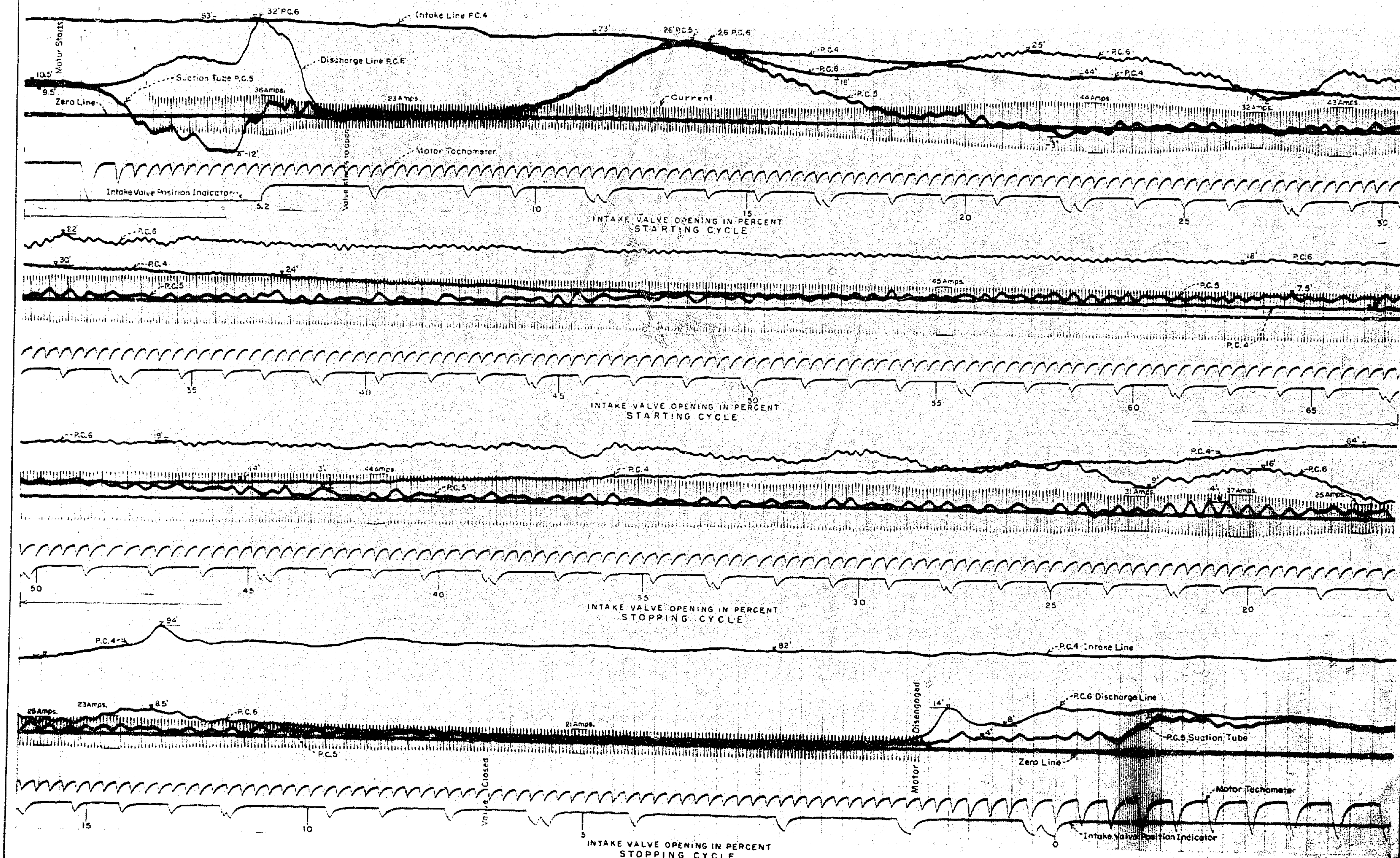
3. Test procedure. Referring to figure 2, the first test was performed with the 2-inch bypass valve open, the 8-inch discharge valve open, the 8-inch intake valve closed, and both lines filled with water. The booster pump on the intake line was started, thus producing a definite prototype pressure on the upstream side of the intake valve. Then the test pump was started, after which the 8-inch intake valve was opened at a steady rate. With this valve fully open, the 2-inch bypass valve was closed, completing the starting cycle. The stopping cycle constituted the same procedure in reverse.

It was desired to investigate this procedure of operation, both with and without aeration. Air could be supplied to the suction tube of the pump through the 2-inch vent, shown on figure 2. This would correspond to approximately a 14-inch vent in the prototype. A pipe of the same size (figure 2) served as a bypass between the suction and the discharge lines of the pump. The purpose of the bypass in these tests was to provide circulation for cooling while the intake valve was closed.

Three variables were involved in this method of operation: (1) the static pressure on the intake line, which varied from 10 to 120 feet in the prototype; (2) the rate of opening and closing of the intake valve; and (3) the area of the air vent. As stated previously, the discharge line was not to scale; however, the results showed this factor to be unimportant in this case. Testing was performed over the complete range of the three variables. In compiling the results it was found that two tests sufficed to show that throttling of the flow in the intake line was not a desirable method of operation.

4. Starting and stopping cycles with air vent open. The oscillogram on figure 5 shows the conditions in the starting and the stopping cycle with the 2-inch air vent (figure 2) open to the atmosphere. With the test pump at rest, the pressure on the intake line (P.C. 4, figure 2) was 83 feet of water, the suction-tube pressure (P.C. 5) was 10.5 feet, and the pressure on the discharge line (P.C. 6) was 9.5 feet. The starting of the test pump is indicated by the current trace on figure 5 and also by the motor tachometer which registered each revolution of the pump. The frequency of the oscillograph galvanometers was not sufficient, upon starting of the motor, to produce an accurate trace of the current from the standpoint of amplitude.

Approximately one second after the test pump was started (figure 5), a positive pressure surge amounting to 32 feet of water occurred in the discharge line, which was likewise reflected in the current trace, the latter registering a surge of 36 to 23 amperes. Although negative in sign, a corresponding pressure surge of 12 feet of water was recorded in the suction tube of the pump. The second surge, the peak of which occurred at a valve opening of about 14 percent, registered a positive pressure of 26 feet in both the suction tube and the discharge line. As the intake valve was opened at a uniform rate, repetition of the surging occurred in the discharge line and the suction tube of the pump until the intake valve reached approximately 40 percent open. For valve openings of 40 to 100 percent the pressures



GRANBY PUMP TESTS
OSCILLOGRAMS OF STARTING AND STOPPING CYCLES WITH SUCTION TUBE VENTED AND BY-PASS OPEN
THROTTLING ACCOMPLISHED WITH INTAKE VALVE

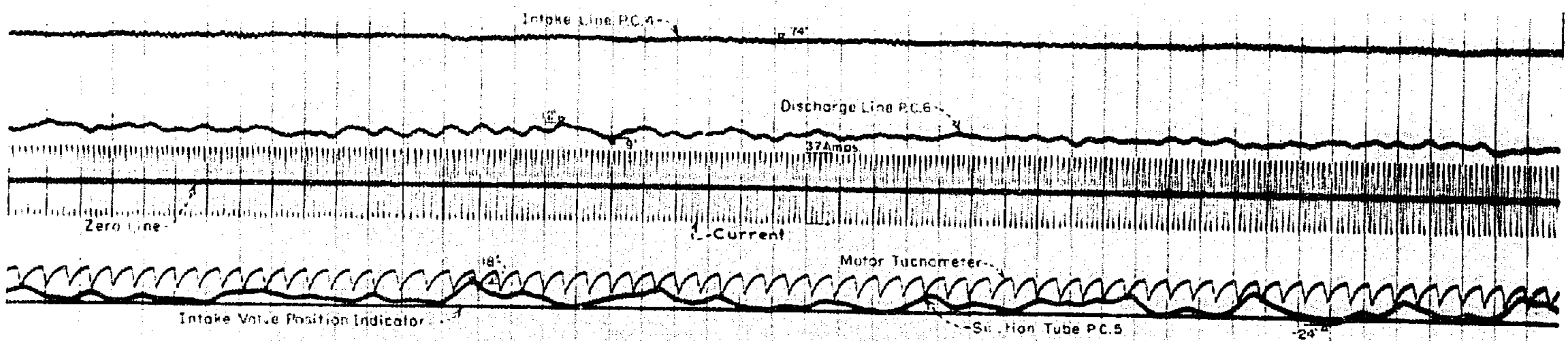
at the three cells became quite steady with little change in magnitude. For this reason, the oscillographic records have not been reproduced for the complete starting and stopping cycles. The lower portion of figure 5 shows the record of the pressures and the current for the stopping cycle. In this case the operating procedure was the opposite of the starting cycle. The pressure surges for this case were not as severe as for the starting cycle; however, distinct surges in the current occurred throughout both cycles. For the valve partially open, surging was audible in the model as air was intermittently pulled through the air vent pipe. In no case was the flow through the vent steady.

As a means of demonstrating that the rate of opening or closing of the intake valve had little bearing on the pressure fluctuations, a short oscillogram was made with the intake valve held at a critical operating point. This is shown as the lower record on figure 6, which indicates pressure surges in the discharge line of 25 to 5.5 feet of water, with corresponding current surges of 40 to 25 amperes. Each surge was accompanied by an audible intake of air through the vent pipe. The condition shown on figure 6 persisted, with little variation for valve openings of 5 to 30 percent.

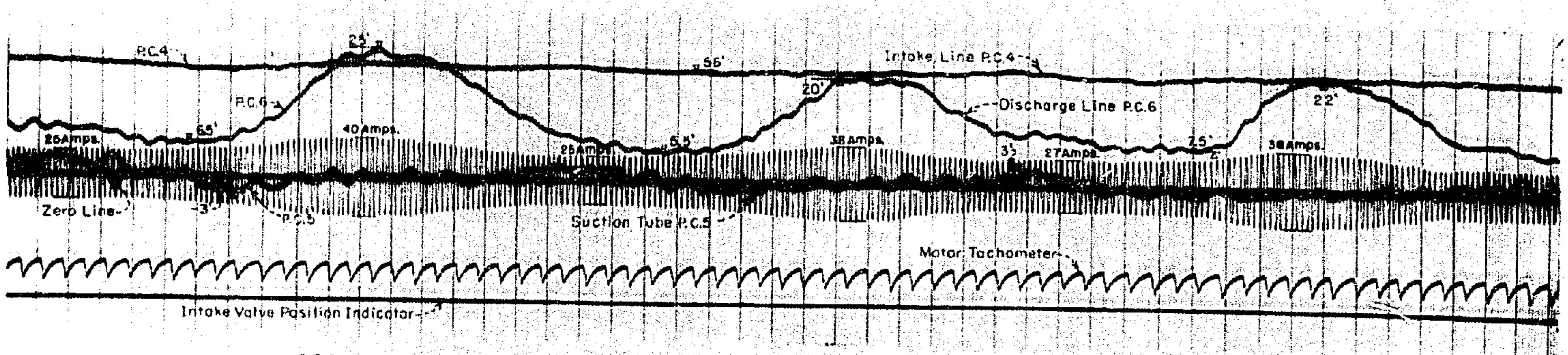
With pressure-surge indications such as these manifest in a model having a discharge line much underscaled, it is certain that pressure changes in the prototype would be more severe than those indicated by the model. As the pressure changes are accompanied by corresponding fluctuations in the power required by the motor, the above plan for starting and stopping the Granby pumps is not considered feasible.

5. <u>Starting and stopping cycles without aeration</u>. The oscillogram on figure 7 is a record of the instantaneous pressures and the current obtained for operation similar to that above-described except that the valve in the air-supply vent was closed. With the pump at rest, the pressure in the intake line (P.C. 4) was 82 feet of water, the pressure in the discharge line (P.C. 6) was 9.5 feet, and the

FIGURE 6



OSCILLOGRAM OBTAINED AT CRITICAL OPERATING POINT — 14 PERCENT VALVE OPENING
SUCTION TUBE NOT VENTED — BY-PASS OPEN

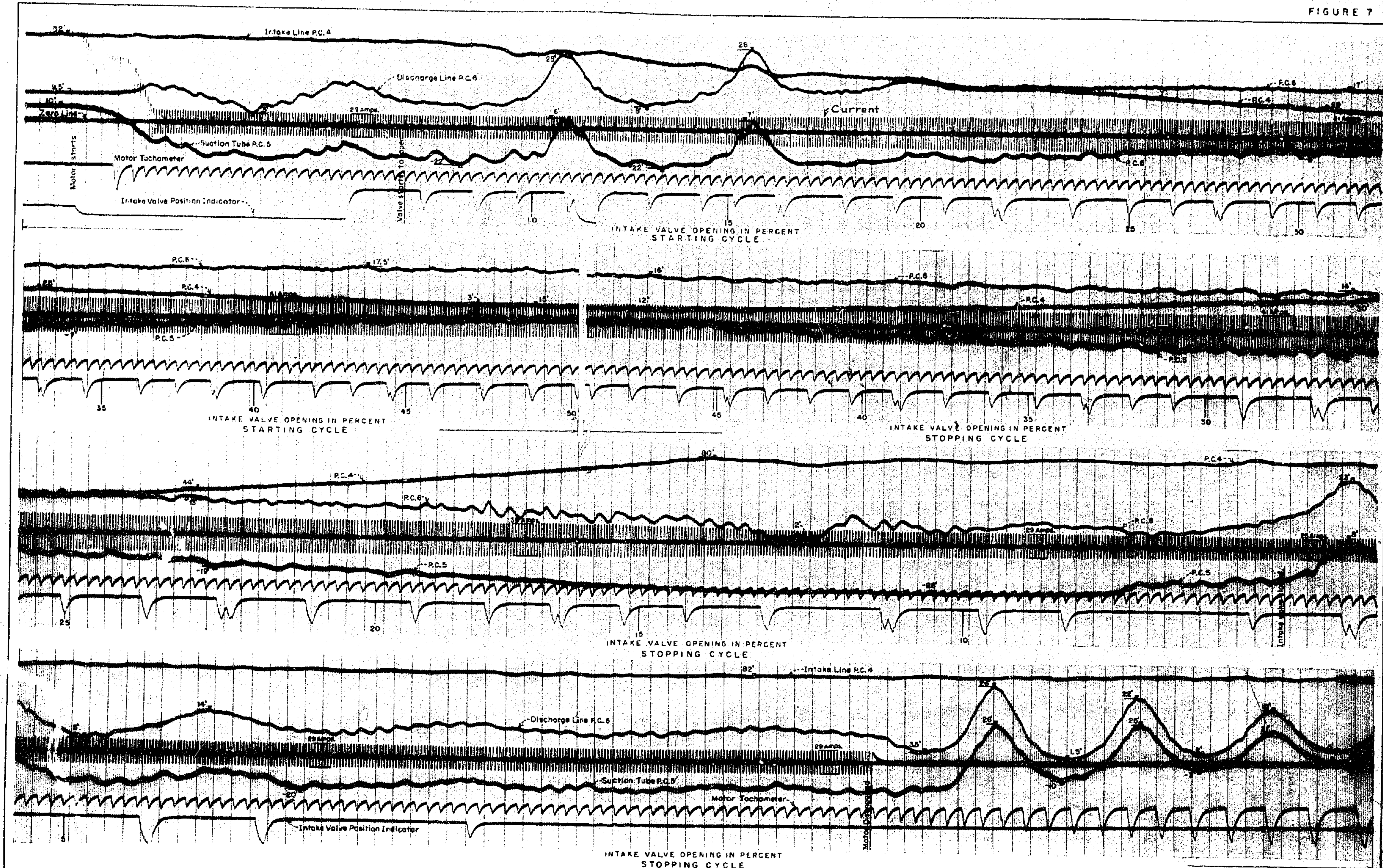


OSCILLOGRAM OBTAINED FOR CRITICAL OPERATING ZONE — 5 TO 30 PERCENT VALVE OPENING
SUCTION TUBE VENTED — BY-PASS OPEN

GRANBY PUMP TESTS

THROTTLING ACCOMPLISHED WITH INTAKE VALVE

FIGURE 7



GRANBY PUMP TESTS
STARTING AND STOPPING CYCLES WITHOUT AERATION — BY-PASS OPEN
THROTTLING ACCOMPLISHED WITH INTAKE VALVE

pressure in the suction tube of the pump (P.C. 5) was 10 feet. Upon starting of the motor, the pressure in the suction tube dropped to a negative 22 feet of water, while the pressure in the discharge line fluctuated from 3 to 28 feet. A corresponding positive surge was reflected in the suction tube of the pump. As the intake valve was unseated, a loud crackling noise occurred which persisted, although decreasing in intensity, until the valve was about 20 percent open. The crackling noise was cavitation produced by the high-velocity jet shooting along the invert of the suction tube. For the smaller valve openings, water was supplied to the test pump at a deficient rate, thus producing an initial negative pressure in the suction tube. In addition, the high-velocity jet issuing from under the gate leaf tended to skip over the invert of the suction tube because of gate-slot interference and imperfections in the surface downstream, producing localized negative pressures. The additive effect of these two actions caused the pressure along the suction-tube invert to be reduced to the vapor pressure of water, thus developing conditions conducive to cavitation although P.C. 5, located on the side of the suction tube, did not indicate pressures this low. As the intake valve continued to open, the static intake head dropped to 15 feet of positive pressure at 50 percent valve opening, the pressure in the pump suction tube reversed to slightly positive, and the pressure in the discharge line increased approximately 7 feet over the original pressure in overcoming friction caused by flow in the line. The oscillogram reproduced on figure 7 was cut at a valve opening of 50 percent, as pressure fluctuations beyond this point were insignificant.

The pressure record for the stopping cycle is shown in the lower portion of figure 7. As the valve opening reached 10 percent, the pressure in the pump suction tube fell to a negative 28 feet, or the vapor pressure of water at this altitude. The low pressure was accompanied by a crackling noise which is indicative of the presence of cavitation. In addition to the crackling noise, the fluid passing through the pump was a mixture of air and water, the air being released from the water by vaporization. This air, as demonstrated in the preceding section, would be very undesirable in the prototype. Following complete closure of the intake valve, a series of surges occurred in both the discharge line and the suction tube of the pump, but little fluctuation was evidenced in the current trace. Upon disengagement of the pump motor from the power source, water hammer developed in the discharge line and the suction tube. This also would be undesirable in the prototype when one considers that extremely long lines are involved. Figure 7 is interesting in that the current is steady throughout both cycles in spite of the pressure conditions.

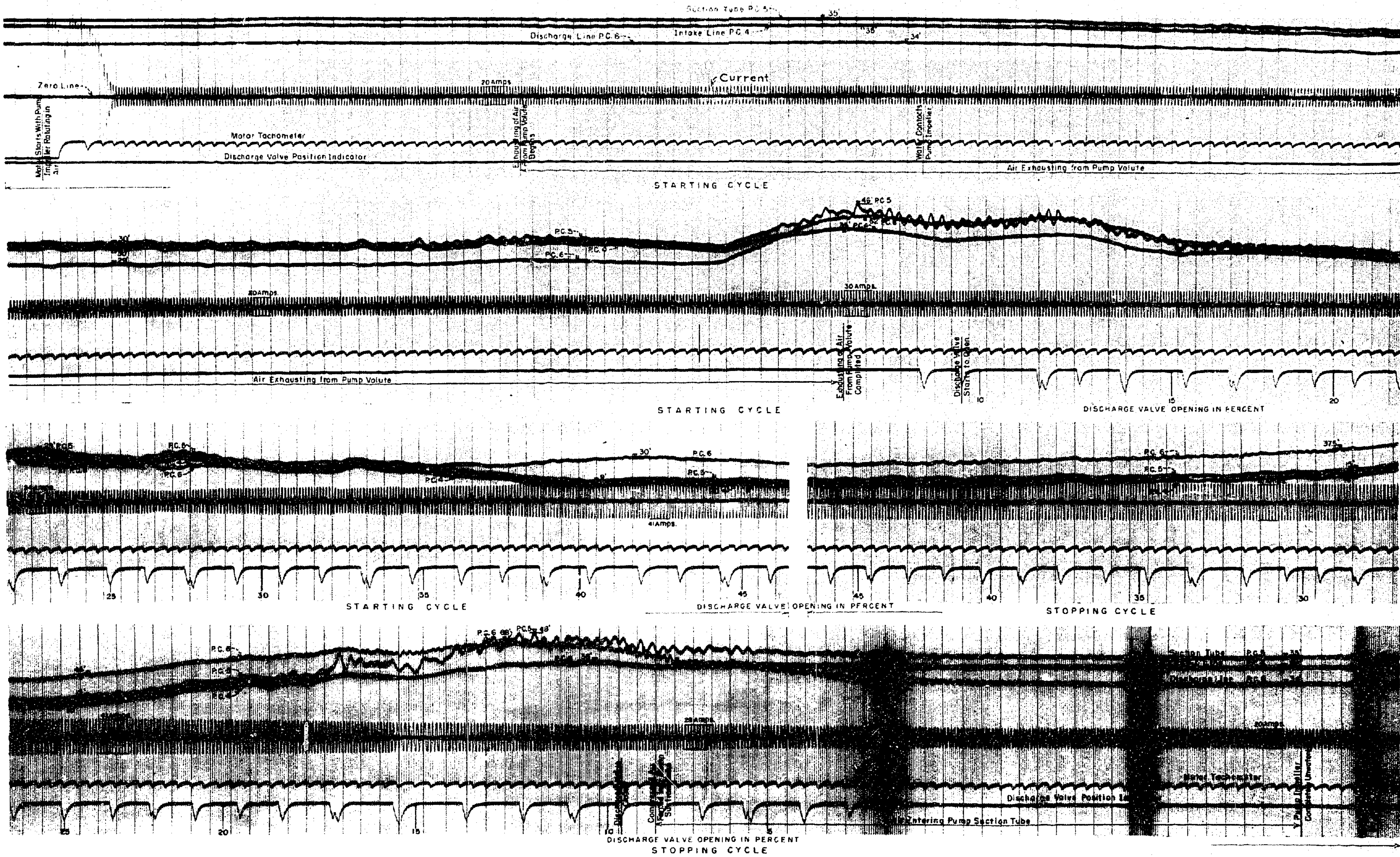
A short oscillogram was made of the most critical operating point for this condition of operation, which appeared to be at a valve opening of approximately 14 percent. Although the suction-tube pressure was a negative 24 feet of water, the pressures in general were steady, which demonstrates that in this case the rate of opening and closing of the intake valve would not materially affect the pressures of figure 7. Nevertheless, this type of operation is not recommended for the Granby pumps.

To remedy the above operating disadvantages, it is suggested that the throttling be accomplished by a valve placed in each discharge line as proposed originally. It is felt that these valves will more than pay for themselves in reduced maintenance costs and fewer operational difficulties, to say nothing of the advantages to be gained in the reduction of power and pressure surges during the starting and the stopping cycles.

6. <u>Throttling with discharge valve</u>. Since the oscillograms shown in HYD-113 were made, the laboratory oscillographic equipment has been greatly improved. For this reason the test shown on figure 18 A and B of that report was repeated. In that test the pump was brought up to speed with auxiliary water jets, while in the present tests the pump was started electrically, with the impeller rotating in air. Referring

to the photograph on figure 2 and the oscillogram on figure 8 of this report - with the 8-inch discharge valve closed, the bypass valve open, and the intake valve open, compressed air was forced into the suction tube of the pump, thus unwatering the pump impeller. The test pump was then started in air, electrically, at which point the oscillographic record on figure 8 begins. The entrapped air then was expelled steadily through a small valve on the discharge side of the pump, causing gradual submergence of the impeller. The timing of this procedure is recorded on figure 8. Upon completion of the air removal, the sudden rise in all three pressure curves indicates the point at which the test pump became fully primed. The stopping cycle, shown in the lower part of the figure, was the reverse of the starting cycle, and, in this case, the pressures for both cycles were similar. The stopping cycle consisted of closing the discharge valve at a constant rate. Upon complete closure, compressed air was forced into the suction tube of the pump, unwatering the rotating impeller at a steady rate. When fully unwatered, the motor on the test pump was deenergized. Pressure fluctuations can be controlled to a large extent, in this case, by decreasing the rate of opening and closing of the discharge valve and decreasing the rate of intake and expulsion of compressed air to the pump chamber. In the case of the model pump, the operation was carried out at a moderate speed in order that the record would not be too long and cumbersome to reproduce. There is no lower limit to the speed of this process in the prototype.

In addition to stabilization of pressures, this method of operation has the outstanding advantage of requiring less power when starting and stopping. Figure 8 shows that it required 20 amperes to turn the pump impeller in air against 30 amperes to do the same thing in water (figures 5 and 7). Starting the impeller in air should therefore reduce the initial power demand by perhaps one-third. However, no conclusions can be drawn from the instantaneous current trace at the beginning of each test, as the frequency of the galvonometer elements was insufficient to record correctly the larger amplitudes.



GRANBY PUMP TESTS

STARTING AND STOPPING CYCLES WITH PUMP IMPELLER RUNNING IN AIR — BY-PASS OPEN
THROTTLING ACCOMPLISHED WITH DISCHARGE VALVE

7. <u>The bypass valve.</u> Although this subject was discussed in HYD-113, it will be mentioned again for emphasis. The bypass is an essential factor for smooth operation in the starting and the stopping cycles. During the starting cycle the bypass makes possible circulation for cooling. During the stopping cycle it serves as a drain for water trapped on the discharge side of the pump and as a regulator for controlling the rate of unwatering of the impeller. Without the bypass it is not possible to relieve entirely the pressure developed on the discharge side of the pump, which, if not relieved, will reflect in surges and an increase in the power requirement to the motor previous to disengagement.

Provision of an 8-inch pipe with gate valve should be conservatively adequate for the bypass in the prototype. The valve can be set to unwater the impeller at the desired rate on the shut-down cycle. Upon determination of this point, a stop or limit switch can be installed on the bypass valve to limit its travel. It will be necessary to determine in the field the maximum valve setting, together with the compressed-air pressure and the rate at which air should be admitted to the suction tube of the pump.

8. <u>Summary and conclusions.</u> From an hydraulic standpoint, throttling with the intake valve is fundamentally unsound in that extremely low pressures are created unnecessarily. In high head design this is to be avoided wherever possible, for past experience has shown the results to be either unsatisfactory or unpredictable. The application of venting to relieve the condition, unnecessarily created by low pressures, merely complicates the problem in this case, as a mixture of air and water is an unstable fluid and pressures throughout such a fluid will be found as unstable as the fluid itself. In the case of the Granby pumps, where surges in pressure are directly affected by the power requirements of the motors, neither cavitation nor venting should be tolerated, as both produce an unstable fluid.

In conclusion, the following recommendations are suggested in in connection with the starting and the stopping of the Granby pumps:

(a) Throttling of discharge through the Granby pumps by use of valves on the intake lines is inadvisable.

(b) The most satisfactory method, to date, constitutes starting and stopping the pump impellers in air and throttling the flow with discharge valves, as discussed in section 6.

(c) Installation of the bypass should not be overlooked when a valve is used in the discharge line, as it provides a means of cooling the water by circulation during the period that the discharge valve is closed and the impeller is turning in water. Also, it will serve to control the rate at which the power decreases during the stopping cycle.

(d) The compressed-air intake port functions best when located midway in the suction tube of the pump. The air-exhaust port should be located on the discharge side of the pump, preferably in a small dome on top of the pipe where water will not interfere with the escaping air.

- - -