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DIRECT CURRENT ELECTROMAGNETIC PUMPS

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DIRECT CURRENT ELECTROMAGNETIC PUMPS

A. H. Barnes, F. A. Smith, G. K. Whitham

Reactor Engineering Division

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DIRECT CURRENT ELECTROMAGNETIC PUMPS

A. H. Barnes, F. A. Smith, G. K. Whitham

A number of direct current conduction type electromagnetic pumps for liquid metals were constructed. Pumping capacities of over 400 gpm and efficiencies of over 50 percent were obtained. NaK alloy at temperatures up to 400 C was used in the tests. The large currents required were obtained from rectifiers or from a homopolar generator constructed for the purpose.

Since the pioneer work of Northrup in 1907[1] many investigators have designed a wide variety of apparatus for pumping liquid metals by electromagnetic means. The present interest in liquid metals as reactor coolants has served to spur the development of pumping equipment capable of handling such materials at high temperatures. The very considerable difficulties which are encountered in attempting to confine sodium or sodium potassium alloy by any form of shaft seal together with the problem of designing bearings to operate in these liquids has made the electromagnetic pump, with its absence of bearings and seals, a very attractive device.

The principle of operation of the direct current pumps[2] which we have constructed is illustrated in Figure 1. A length of thin walled stainless steel (347) or inconel tubing is pressed into a rectangular cross section. Heavy copper bars are silver soldered to opposite faces of the section (see Figure 2) and the assembly is placed between the poles of an electromagnet. Current entering through the wall traverses the liquid in the tube and develops in it a longitudinal thrust.

The magnitude of the force on the liquid is

$$F = \frac{B\,I\,r}{10} \text{ dynes} \qquad (1)$$

where B is the magnetic flux density in gauss in the liquid between the magnet poles, I is the current in amperes traversing the liquid which lies in the magnetic field, and r is the width in cm of the rectangular tube parallel to the direction of current flow.

(1) Physical Review, Vol. 24, Series 1, p. 474, 1907.

(2) A description of an a-c electromagnetic pump which was constructed at this laboratory will be found in ANL-4317.

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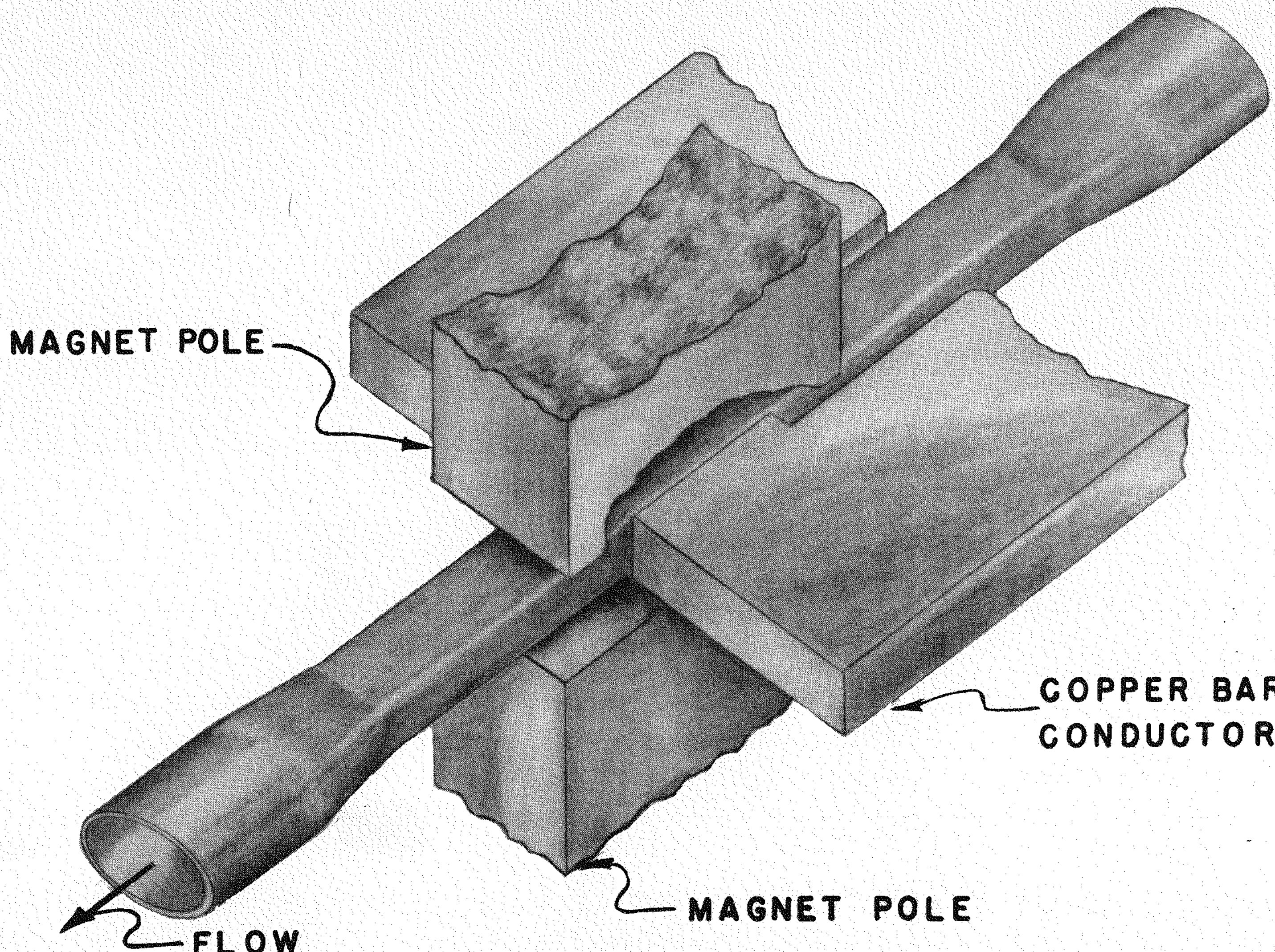

FIGURE 1

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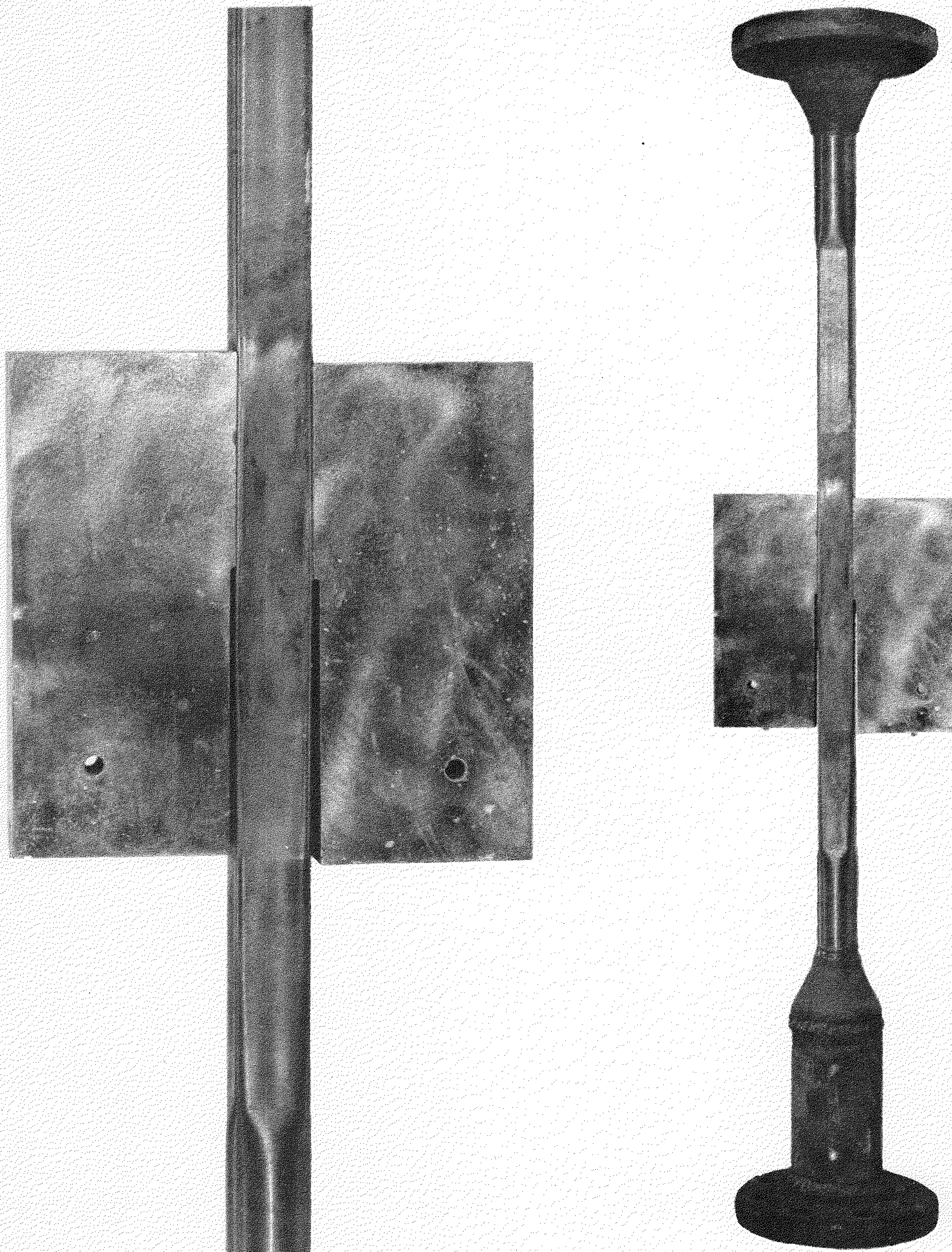

Figure 2

B-269-4

If s is the width in cm of the tube in the magnetic field direction, then since rs is the cross sectional area of the tube, the pressure developed will be

$$P = \frac{B\ I\ r}{10\ rs} = \frac{B\ I}{10\ s}\ \frac{\text{dynes}}{\text{cm}^2} \qquad (2)$$

If B is expressed in kilogauss, I in kiloamperes, and s in inches, then the above expression takes the form

$$P = \frac{0.57\ B\ I}{s}\ \ \text{lb/in}^2 \qquad (2a)$$

It has been found that the actual static pressures developed are very close to the values given by this expression when allowance is made for the current which is not effective because it is being by-passed through the tube wall.

The power developed in the moving liquid is

$$W = E_c\ I_e\ \text{watts} \qquad (3)$$

where E_c is the counter emf developed in the liquid as it moves through the magnetic field and I_e is the "effective" current, i.e., the current which traverses liquid in the region of strong magnetic field.

Since

$$E_c = B\ r\ v \times 10^{-8}\ \text{volts} \qquad (4)$$

where v is the velocity of the liquid in cm/sec,

$$E_c = \frac{B\ r\ Q}{rs} \times 10^{-8}\ \text{volts}$$

$$= \frac{B\ Q}{s} \times 10^{-8}\ \text{volts} \qquad (5)$$

where Q is the flow through the pump in cm^3/sec.

Hence

$$W = \frac{B\ Q\ I_e}{s} \times 10^{-8}\ \text{watts.} \qquad (6)$$

I_e may be calculated from (2) if for P we write the total dynamic pressure, P_d, developed in any given case. Thus,

$$I_e = \frac{10\ P_d\ s}{B} \text{ amperes} \tag{7}$$

where P_d is the measured pressure rise through the pump plus the hydraulic impedance of the pump tube.

The potential difference across the pump tube (i.e., between points at which the copper bars attach to the tube wall) will be

$$V_t = E_c + I_L R_L$$

$$= E_c + (I_t - I_w) R_L \text{ volts}$$

where I_t is the total current entering the pump, I_L is the current which crosses through the liquid lying in the magnetic field, I_w is the current which is by-passing through the tube wall, R_L is the resistance of the liquid path, and R_w is the resistance of the by-pass path through the wall. R_L can be determined by measuring the potential difference across the tube for a given current when the liquid in the tube is at rest. It may also be calculated to close approximation from

$$R_L = \frac{\rho\ r}{sp} \text{ ohms, where } \rho \text{ is the resistivity (in ohm-cm)}$$

of the liquid and p is the length of the region of contact between the tube and the copper bars, (i.e., sp is the contact area). R_w can be determined by measuring the resistance across the empty tube.

The current, I_w, by-passing through the wall will be

$$I_w = \frac{V_t}{R_w} \tag{8}$$

and hence

$$V_t = E_c + I_t R_L - V_t \frac{R_L}{R_w}$$

or

$$V_t = \frac{E_c + I_t R_L}{1 + \frac{R_L}{R_w}} \text{ volts.} \tag{9}$$

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Since the wall by-pass current is $\frac{V_t}{R_w}$, the power loss in the wall will be

$$W_w = \frac{{V_t}^2}{R_w} \text{ watts} \tag{10}$$

A certain fraction of the current will flow through the liquid in the tube along paths which are not entirely in a region of strong magnetic field. When the liquid is at rest this by-passing current is small, but as the velocity of the liquid increases, the counter emf rises and more and more current tends to flow along paths of greater ohmic resistance but of lower counter emf. Since these are paths which contribute little or no thrust to the liquid, the pressure developed gradually falls off as the liquid velocity increases.

The component of the current in the liquid which by-passes the region of strong field is

$$I_B = I_t - I_e - I_w$$

$$= I_t - \frac{10\ P_d\ s}{B} - \frac{V_t}{R_w} \text{ amperes} \tag{11}$$

and the power loss by this means is

$$W_B = I_B\ V_t \text{ watts} \tag{12}$$

The power loss due to the effective current in the liquid, I_e, is

$$W_e = {I_e}^2\ R_L = \frac{100\ {P_d}^2\ s^2\ R_L}{B^2} \text{ watts} \tag{13}$$

If R_m is the resistance of the magnet winding and, if the magnet windings are in series with the pump tube, then the power loss in the magnet is

$$W_m = {I_t}^2\ R_m \text{ watts} \tag{14}$$

If W_o is the useful fluid power output, then, $W_o = W - W_H$ where W_H is the hydraulic power loss due to the impedance of the pump tube. The efficiency of the pump may then be written as

$$\text{Eff} = \frac{W_o}{W_o + W_w + W_B + W_e + W_m + W_H} \tag{15}$$

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The numerical values obtained from the above expression agree very closely with the experimental values. Two typical cases are given in Table II. The above equations do not allow one to calculate precisely the efficiency beforehand since the value for the effective current is determined by the measured pressure rise through an existing pump. Nevertheless, they yield an insight into the sources of power loss under various conditions and permit a good estimate of efficiency to be made.

In our investigations, pumps of eight different cross section geometries have been constructed and tested. These ranged in size from 0.25" x 3.0" to 3.0" x 3.0" rectangular sections and one 4.0" diameter circular section. Both inconel and stainless steel (347) were used for the pump tubes. In some cases, the 0.032" tube wall thickness was obtained by machining down standard stainless steel pipe; in others, thin walled stainless steel tubing was used.

Table I lists the salient data for the various pumps.

For testing purposes each pump section formed part of a closed loop of either 2.0" or 4.0" pipe in which was mounted a throttling valve, flow meters (both orifice and electromagnetic), pressure gages, expansion tank, and calrod heaters immersed in the liquid. The expansion tank was located in all cases adjacent to the inlet side of the pump. Pressure gages of the bourdon tube or diaphragm type were placed at the inlet and outlet sides of the pump. The fluid power developed was taken as being (0.435 x gpm xΔp) watts where Δp was the difference between the gage readings on each side of the pump. At high flow rates turbulence could be heard in the pump tube. It was suppressed, however, by pressurizing the entire system with 5 lb/in^2 of helium. This procedure also had the effect of improving the performance of the pumps at high flow rates.

The systems were filled with NaK alloy of either the 44 percent K or eutectic (78 percent K) composition. After the systems were filled the alloy was heated to 350 C for several hours to insure wetting of the pump tube walls. During this procedure the resistance of the pump was observed to decrease by a factor of five or more, but when the walls were once thoroughly wetted the resistance continued to remain low (see Table I). No significant change in pump performance was observed upon changing from the 44 percent K alloy to the eutectic alloy.

During the early stages of the work, the magnetic field for the pumps was supplied by a small (5.0" diameter pole) electromagnet which was excited by a separate d-c supply.

Later, larger magnets were constructed especially for the pumps and were excited by the same current which passed through the pump tube so that the electrical connection was equivalent to that of a series d-c motor.

Table I

Pump Section (1) (First dimension is parallel to field direction) (Second dimension is parallel to current flow) (Third is length of thin wall section)	Copper Lead Area In Contact with Tube Wall	Magnet Poles	Tube Resistance Empty (50 C)	Tube Resistance Filled with NaK (50 C)
(1) 0.25" x 3.0" x 6"	0.25" x 1.0"	5.0" diameter	320×10^{-6} ohms	90×10^{-6} ohms
(2) 0.50" x 2.75" x 6"	0.50" x 1.0"	5.0" diameter	300	50
(3) 1.0" x 5.50" x 12"	1.0" x 1.0"	5" x 10"	660	42
(4) 1.125" x 2.50" x 20"	1.125" x 5.5"	4" x 10"	55(3)	6.0(2)
(5) 1.50" x 2.00" x 30"	1.50" x 5.0"	4" x 10"	125	7.2(2)
(6) 1.75" x 1.75" x 30"	1.75" x 5.0"	4" x 10"	100	4.25
(7) 3.0" x 3.0" x 20"	3.0" x 4.0"	4" x 10"	235	3.2
(8) 4.0" diameter x 20"	3.0" x 4.0"	4" x 10"	225	3.3

The sections of (1), (2), (4), (5), and (6) were made from 2.0" I.D. tubes. The others were made from 4.0" I.D. tubes.

(1) The pumps are referred to in the text in terms of their dimension parallel to the magnetic field direction.

(2) These pumps were made with inconel and had a higher resistance than expected. This was perhaps due to a higher "skin" resistance at the NaK-inconel interface.

(3) The wall of this pump was 0.065" thick.

Since the efficiency of the pump depends to a considerable extent on the magnitude of the power required to maintain the magnetic field, considerable effort was expended in constructing magnets with a low power dissipation. Figure 3 shows a magnet which was designed for operation at a current of 6000 amperes. The winding consisted of two 5 turn coils each turn of which was 4.0" x 4.0" in cross section. The coils were made by casting a hollow copper block and then machining out 5 turns by making a helical cut through the copper. The poles and yoke were of armco iron. The poles were 4.0" x 10" and at a 1.5" gap a field intensity of 10,000 gauss could be maintained with a power expenditure of 1260 watts.

When larger currents became available a much more compact magnet was constructed with a winding consisting of two turns of 4.0" x 4.0" cross section copper. (See Figure 4.) Each turn was a casting machined to fit over the 4" x 10" pole with close clearance. The core was armco iron and the coils were insulated from it with mica sheets.

The insulation problem is practically non-existent in these pumps because the voltage drop across the windings is less than 0.1 volt. This is a very desirable feature of this type of pump inasmuch as high temperature and radiation damage would not seriously affect pump operation. The pumps could be run continuously with liquid temperatures of 400 C without the necessity of any forced cooling.

The leads connecting the pump tube and the magnet winding were of copper bar stock 5.0" wide and of the same thickness as the pump tube (1.5" or 1.75", etc.). Since these leads were in series with the turns on the magnet winding they contributed an additional half turn to it and so aided in raising the efficiency of the system. All current carrying joints were bolted and soldered. This magnet which had a resistance of 3.4×10^{-6} ohms could produce a 10,000 gauss field across a 1.5" gap at a power expenditure of 1.0 kw.

The large direct current required for operation of these pumps was supplied initially by a selenium rectifier set of the type used commercially for electroplating. It was capable of continuous operation at any current up to 6000 amperes. When it became desirable to operate at still larger currents a homopolar generator was constructed. This machine, which is described in ANL-4361, was made very compact by employing NaK alloy as a liquid brush. It was capable of supplying currents in excess of 20,000 amperes at 0.5 volt at efficiencies of 50 to 65 percent. This is considerably higher efficiency than can be obtained from rectifier sets when supplying current at the low voltage required in this application (see Figure 5).

The magnitude of the current supplied to the pumps was either read directly with the aid of a standard 10,000 ampere ammeter shunt, or in the case of larger currents, a device operating on the field surrounding one of

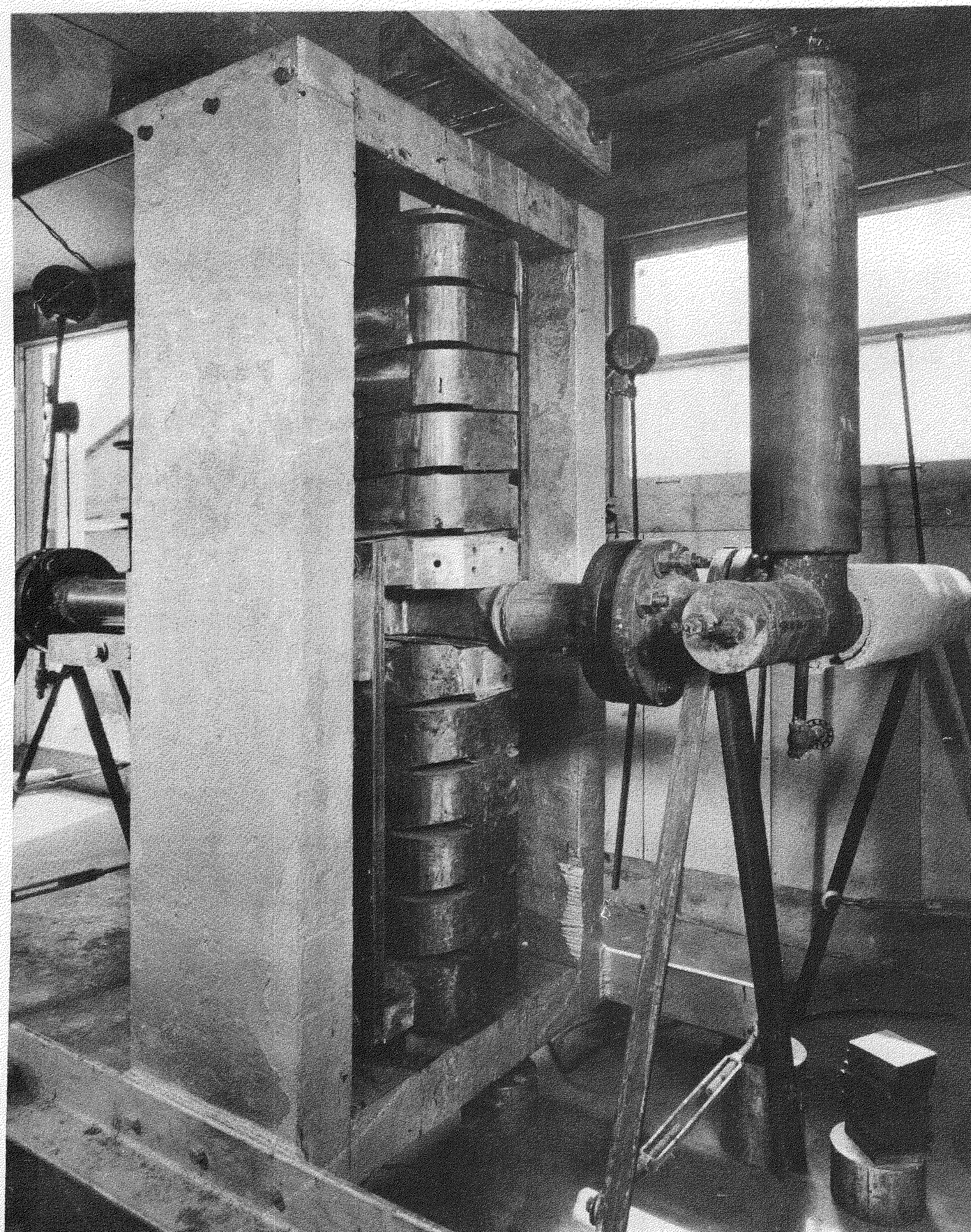

Figure 3

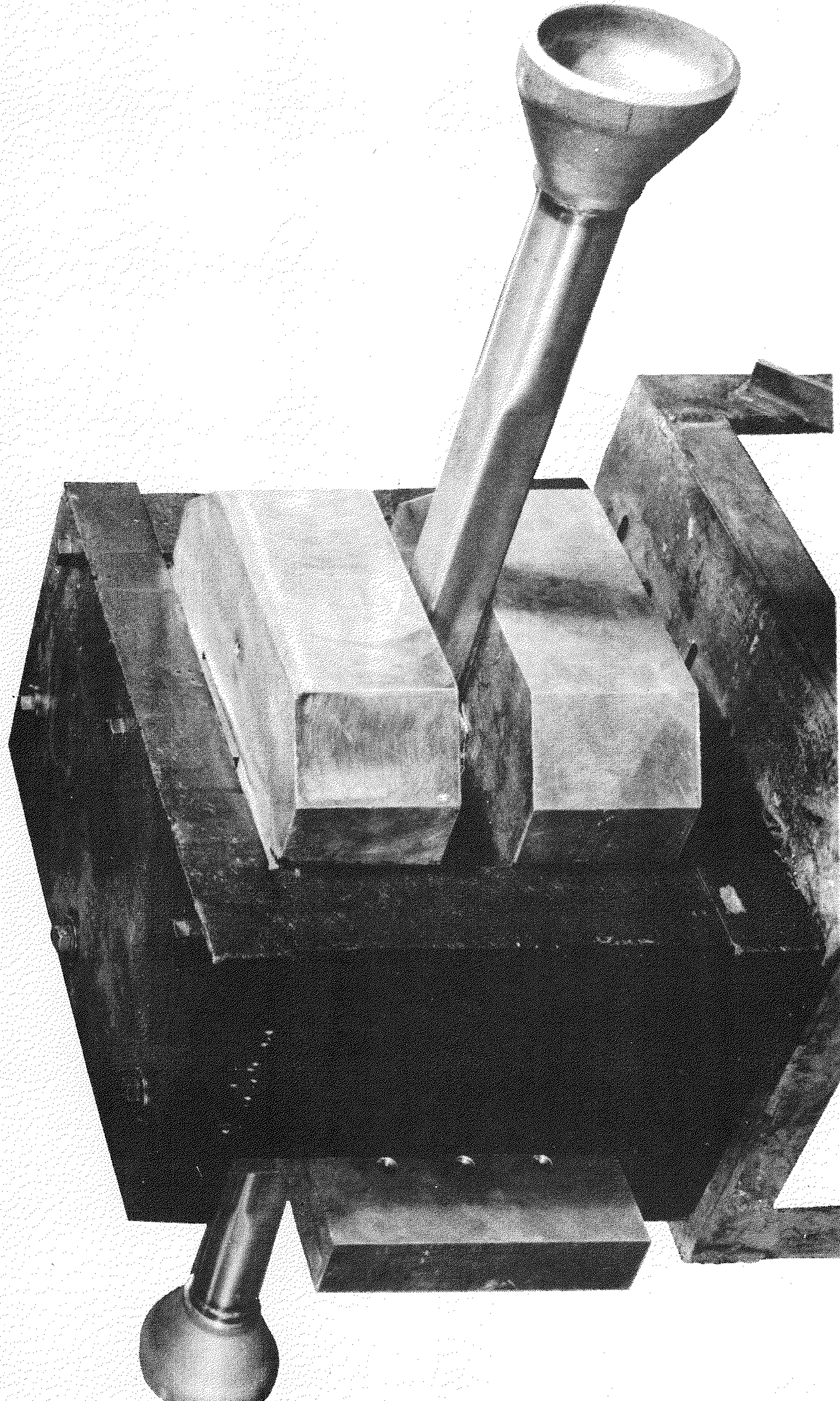

Figure 4

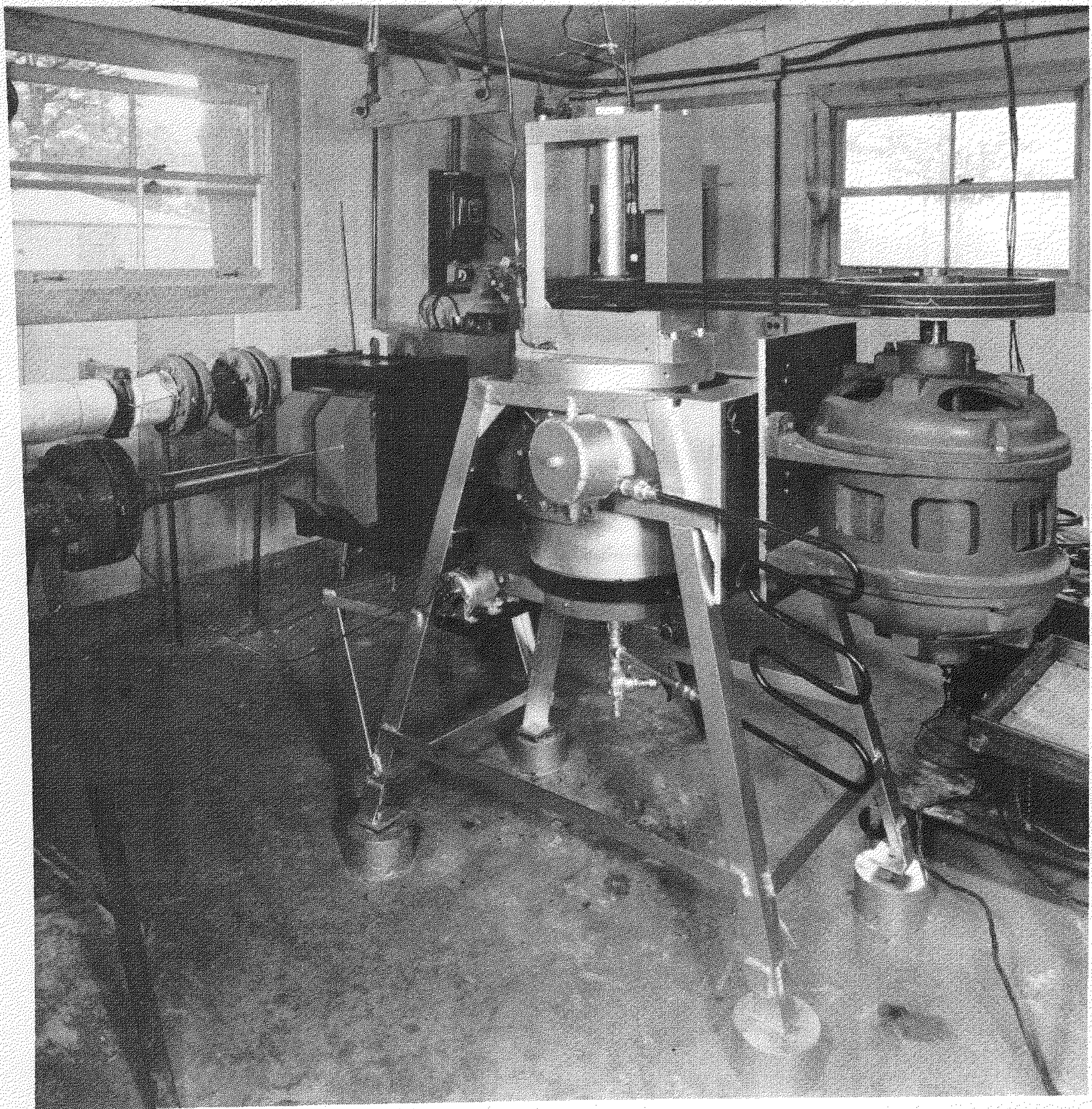

Figure 5

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the bus bars was used. This consisted of a motor driven iron block which rotated in the field of a bus bar and adjacent to a fixed pick-up coil. The induced emf in the coil was fed to an electronic voltmeter. The arrangement was calibrated against the standard shunt by loading it up to 20,000 amperes for short intervals.

The power input to the pumps was taken as the product of the current and the voltage drop across the input leads where they were joined to the magnet windings. Thus, the power input (and efficiency) includes in all cases the magnet power as well as the power delivered to the pump tube.

The static pressure developed in several pumps as the current was increased and the field kept constant is shown in Figure 6. It will be noted that the relationship is, in all cases, linear as one would expect from equation (2). The actual pressure developed is very close to the theoretical if allowance is made for the fraction of the input current which is not effective because it is passing through the tube wall (equation 8) or to a smaller extent through liquid outside of the magnetic field.

The variation of static pressure with magnetic field is shown on Figure 7. The relation is again linear in accordance with equation (2); the current being constant in this case.

The pumping capacity of the pumps is shown in Figures 8 and 9 where the rate in gpm is plotted as a function of current. The maximum pumping capacity in each case depends of course on the impedance of the pumping loop and when the throttling valve is wide open, as in this case, is further limited by the by-passing of current either through the tube wall or through liquid beyond the field region.

When the throttling valve is adjusted so as to maintain the head constant as the current is increased, curves of the type shown in Figures 10 and 11 are obtained. It will be noted that the rate of increase of capacity with current is nearly independent of head over the range shown.

The variation of pumping capacity with magnetic field is illustrated in Figure 12. It will be seen that in the case of the two smaller pumps there is a saturation effect with increasing field. The smaller pumps were found to show this effect at relatively low field intensities. In the case of the 0.25" pump increasing the field above 1000 gauss had the effect of decreasing the pumping rate even though the input power continued to increase. The 0.50" pump showed the same effect although at a higher field (5000 gauss). In the 1.0" pump the effect appeared at 2500 gauss. It was at a lower value in this case because of the greater width (perpendicular to the field) of the pump tube compared to the length of the field region. There is no indication of the effect for the 3.0" pump in Figure 12 for

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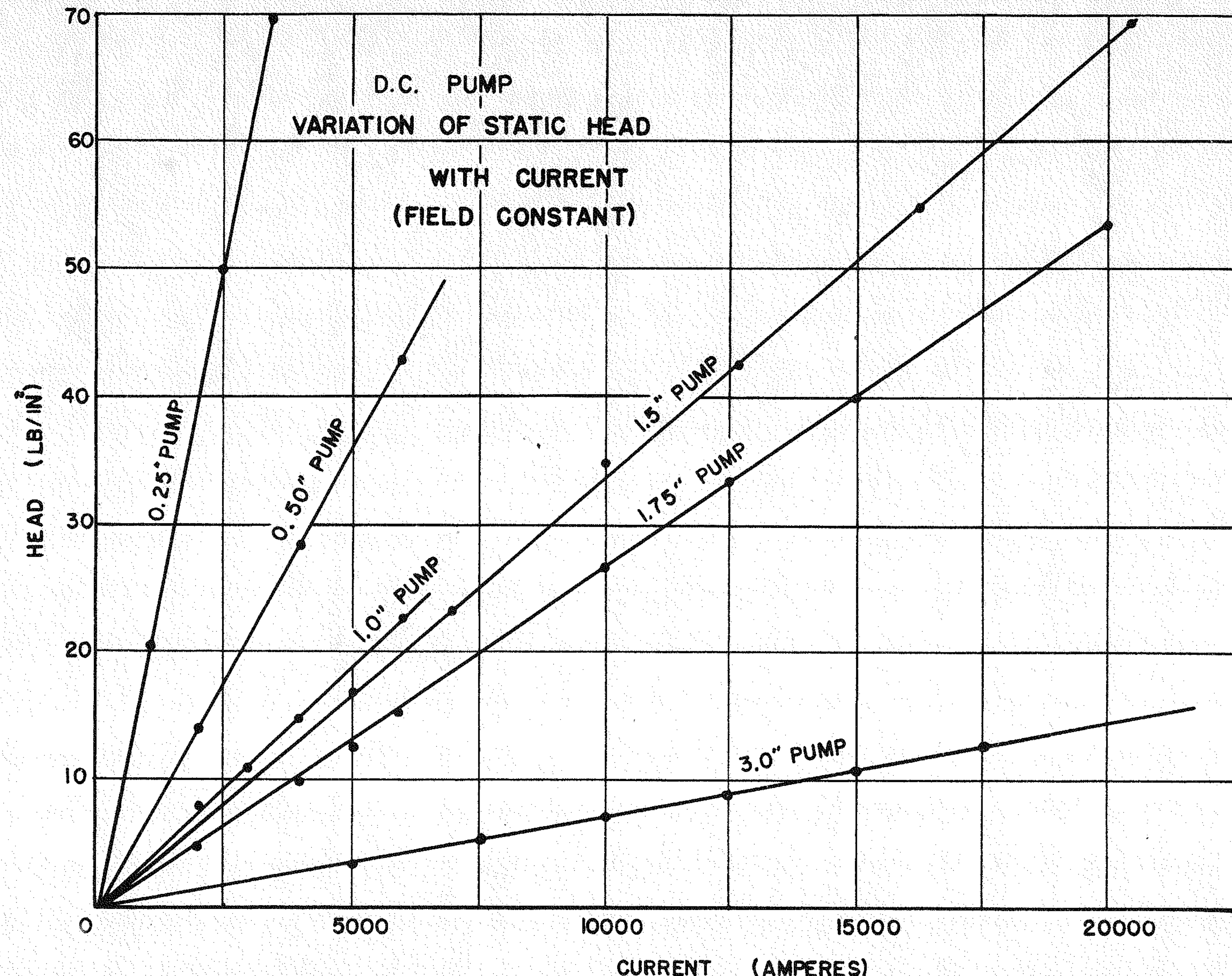

Figure 6

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VARIATION OF STATIC HEAD
WITH MAGNETIC FIELD
(CURRENT CONSTANT)

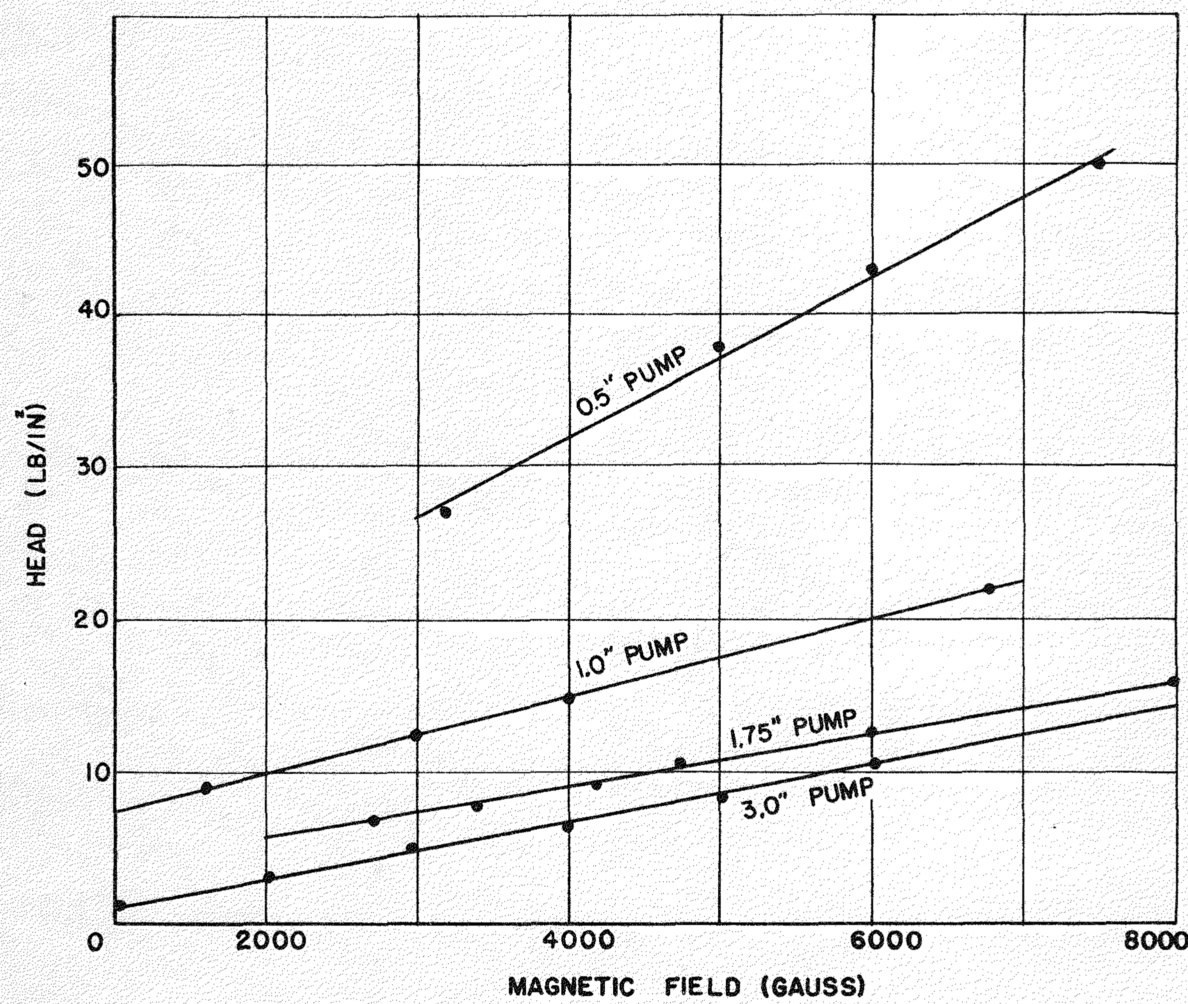

Figure 7

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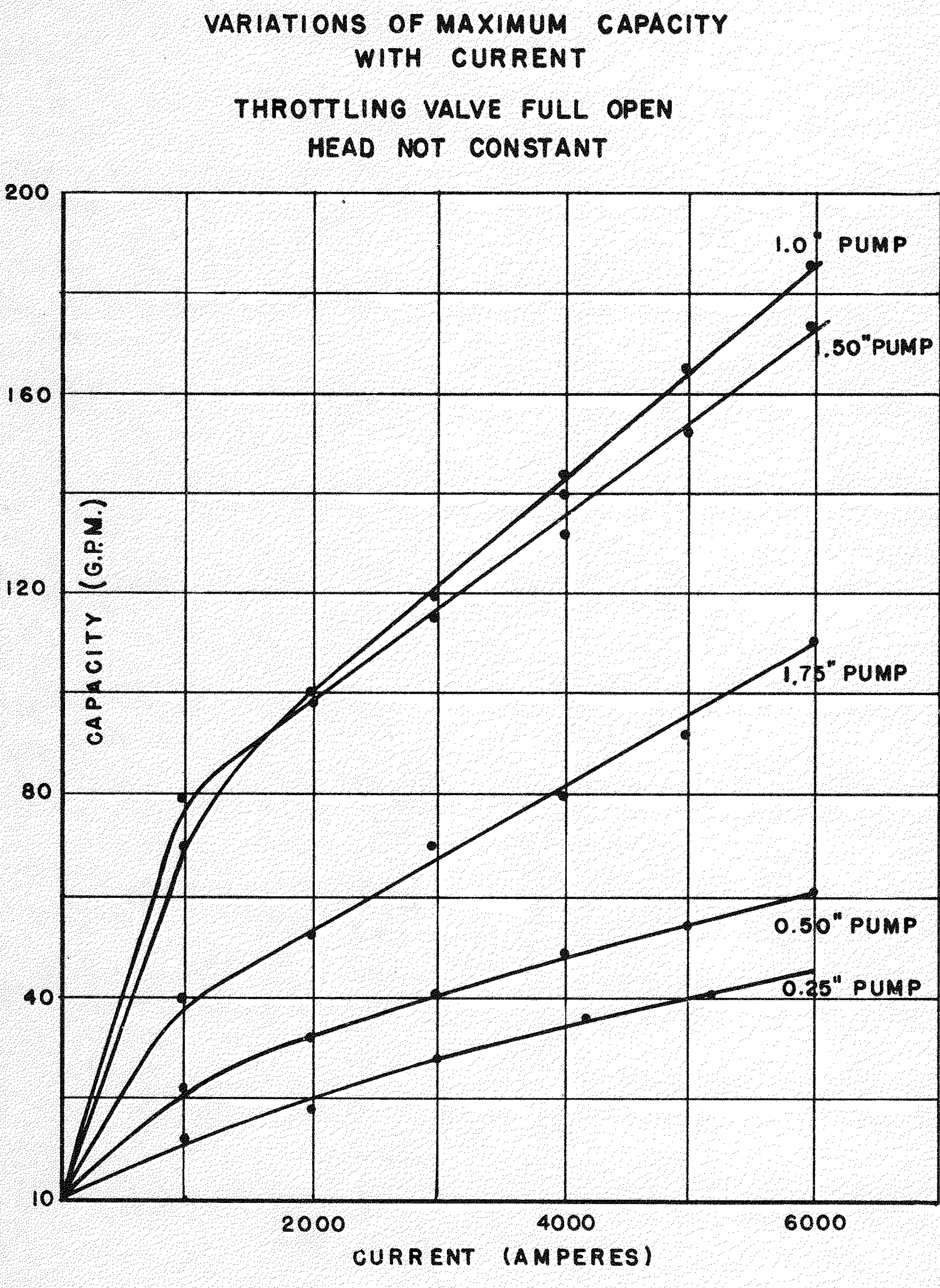

Figure 8

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VARIATION OF MAXIMUM CAPACITY
WITH CURRENT

THROTTLING VALVE FULL OPEN
(HEAD NOT CONSTANT)
300° C

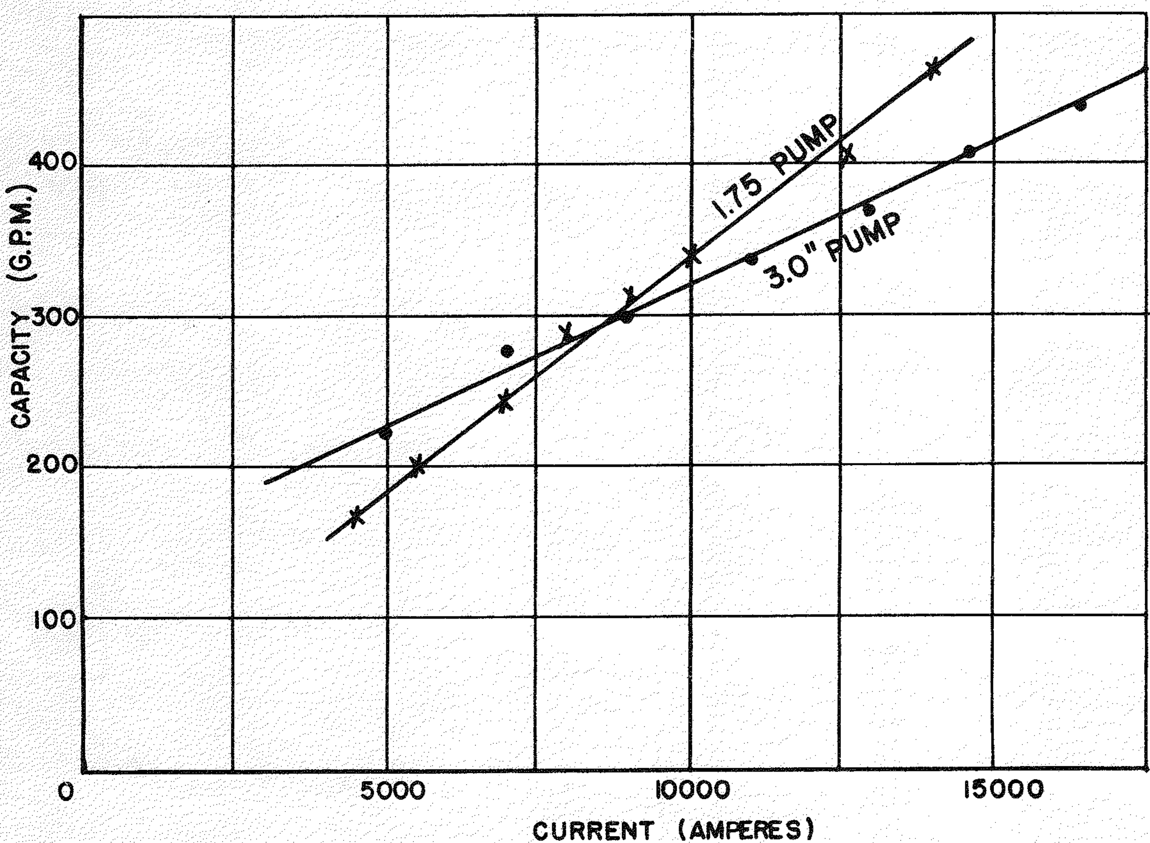

Figure 9

VARIATION OF CAPACITY WITH CURRENT

HEAD CONSTANT

(1.5" PUMP)

350° C

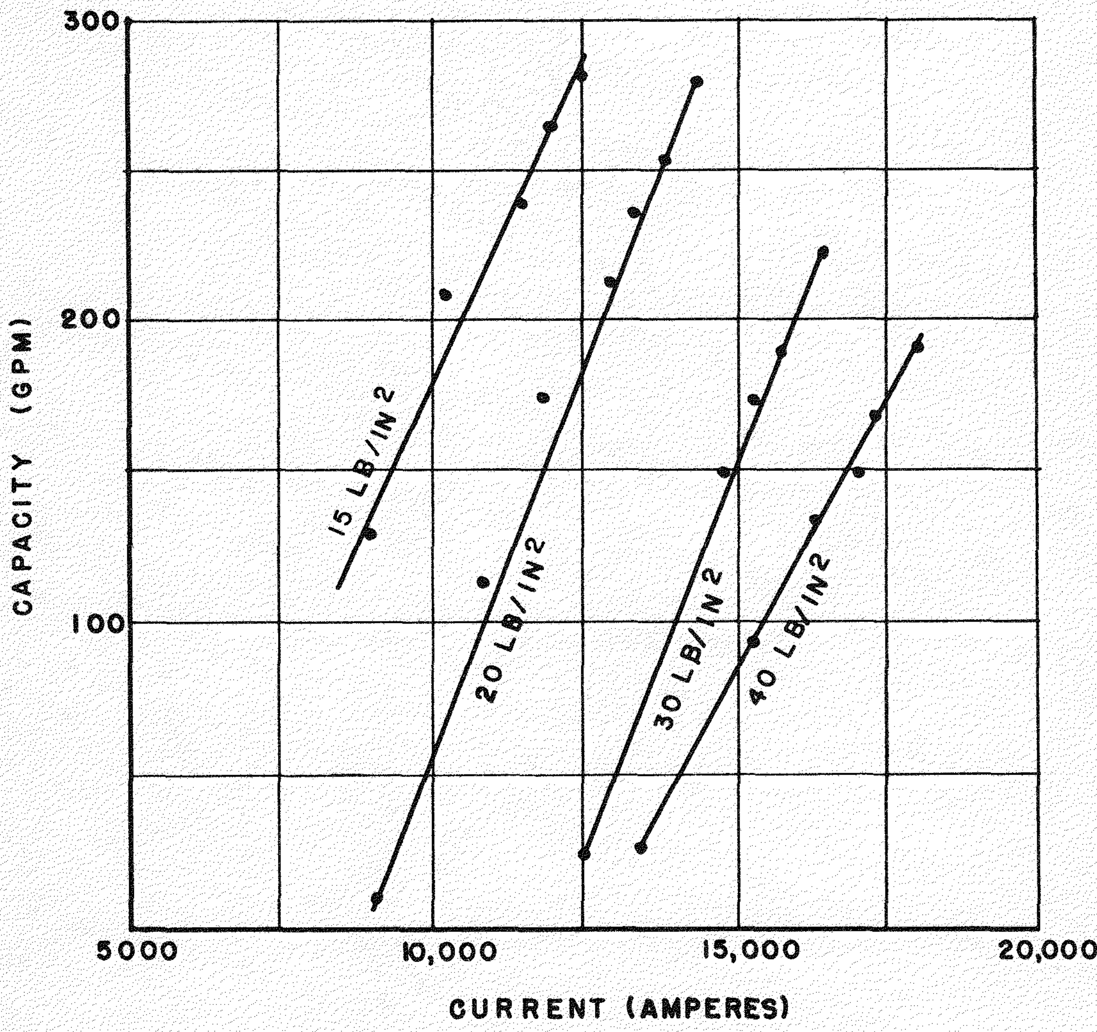

Figure 10

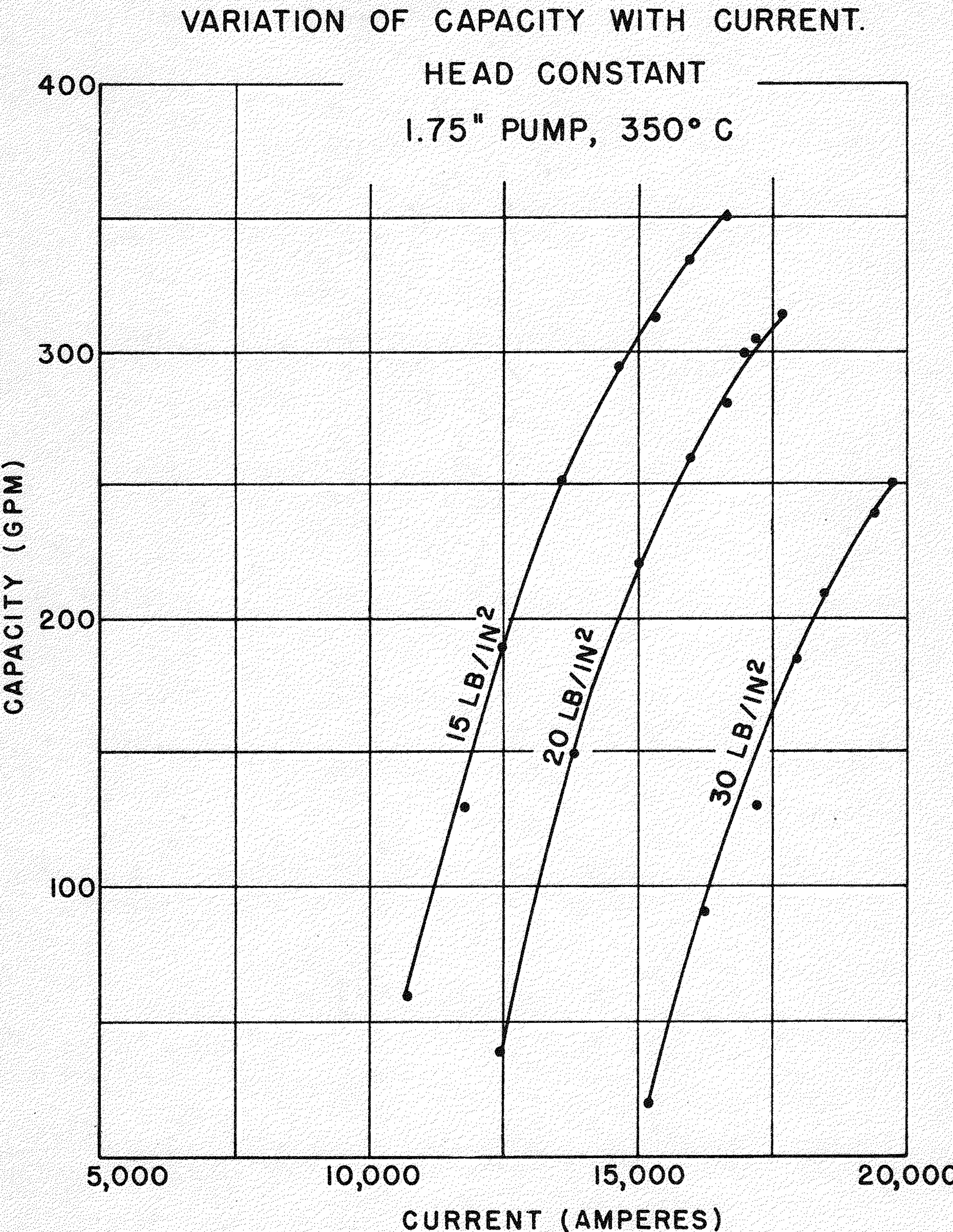
VARIATION OF CAPACITY WITH CURRENT.
HEAD CONSTANT
1.75" PUMP, 350° C
CAPACITY (GPM)
400
300
200
100
15 LB/IN2
20 LB/IN2
30 LB/IN2
5,000
10,000
15,000
20,000
CURRENT (AMPERES)

Figure 11

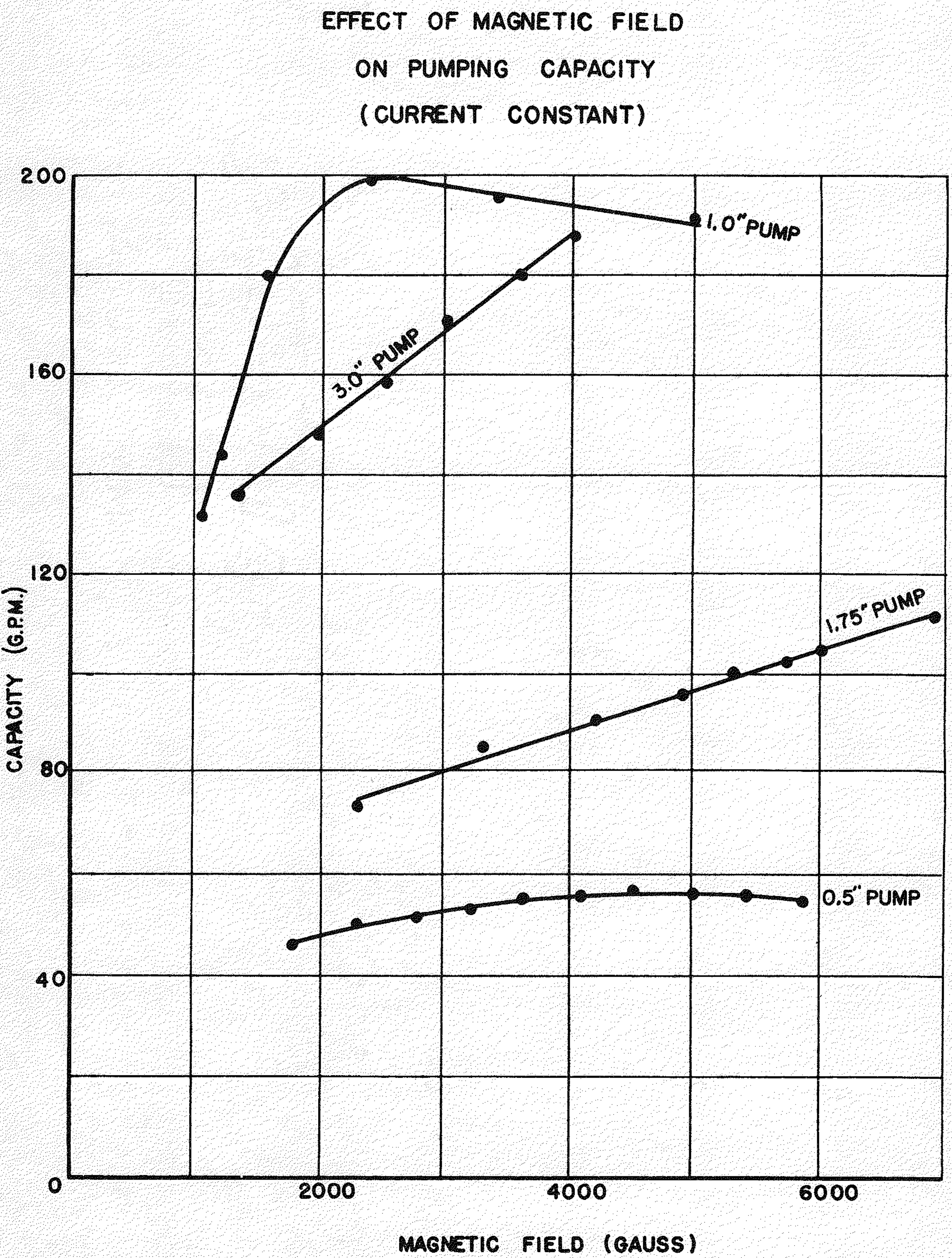
EFFECT OF MAGNETIC FIELD
ON PUMPING CAPACITY
(CURRENT CONSTANT)
200
160
120
80
40
0
2000
4000
6000
CAPACITY (G.P.M.)
MAGNETIC FIELD (GAUSS)
1.0" PUMP
3.0" PUMP
1.75" PUMP
0.5" PUMP

Figure 12

capacities up to 190 gpm but at higher capacities the effect does set in. This is shown in Figure 13 where saturation appears above 400 gpm.

The effect is due, of course, to the by-passing of current which becomes more pronounced as the counter emf increases with increasing field. This limiting of capacity is more sensitive to field than to current because it depends on the magnitude of the counter emf, E_c, and since,

$E_c \sim B\,v$, where v is the velocity of the liquid, and

$v \sim B\,I$ (Figures 9 and 12).

Hence $E_c \sim B^2 I$, so the effect tends to increase directly as the current and as the square of the field intensity.

The magnitude of the field which should be used for maximum efficiency is determined, therefore, by the by-passing limitation as well as by considerations of the power expended in maintaining the magnetic field. In general, strong fields are desirable when pump tubes of large cross section are used and also when the magnet poles are long compared with the width of the tubes.

Increasing the length of the magnetic field extends the paths which current must follow in the liquid to cross the tube beyond the field region. A series of tests were made to determine the improvement in capacity and efficiency which resulted from an increase of pole length. It was found that with the 1.75" pump tube an increase of pole length from 5" to 8" produced a 15 percent gain in efficiency. When the pole length was then further extended to 10" the increase in efficiency was only 3 percent additional. This, together with other work, seemed to indicate that magnet poles of length more than about five times the width of the pump tube did not yield an improvement commensurate with the increased magnet power entailed.

The optimum cross section geometry is determined by considerations of required head and capacity, available current supply, magnet power and current by-passing losses. Since the by-passing loss increases with counter emf and from (5)

$$E_c = \frac{B\,Q \times 10^{-8}}{s}$$

we see that large values of s will minimize the by-pass current in the liquid. On the other hand, increasing s requires an increase in magnet power. In addition, if r is decreased to maintain sr constant, there will be an increase in the by-pass current through the tube wall because the wall resistance will be decreased. The optimum cross section, therefore, is probably not far from a square section.

EFFECT OF MAGNETIC FIELD
ON PUMPING CAPACITY
(3.0" PUMP, CURRENT=16,000 AMPERES)

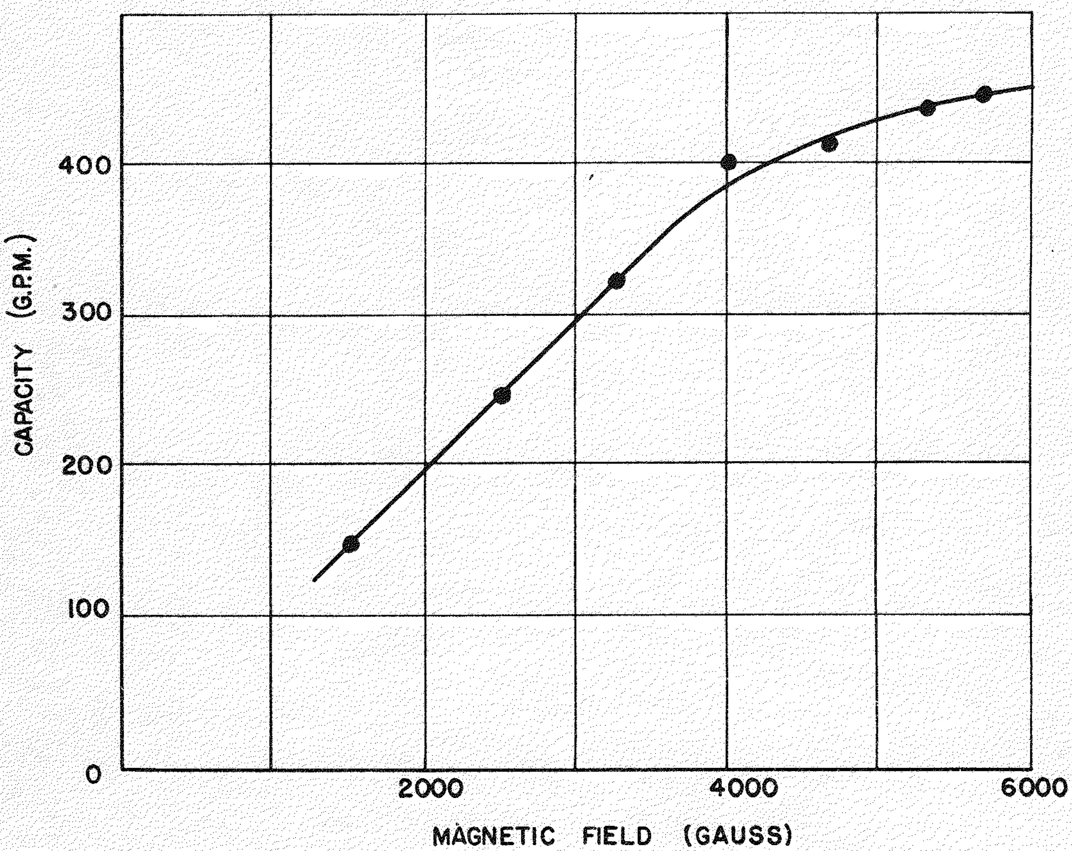

Figure 13

The magnetic field produced by the flow of current across the pump tube distorts the field between the poles by introducing a component which is parallel to the direction of liquid flow. The resultant field is thus displaced slightly upstream. A slight displacement of the magnet downstream to compensate for this effect would appear desirable. This procedure was tried but the effect was too small to be detected. Consequently, the magnet poles for all pumps were located symmetrically with respect to the current leads.

Figure 14 shows the head-capacity characteristics of several pumps when operating with constant current input at 350 C.

Figure 15 illustrates a typical head-capacity relation for the 1.5" pump operating at constant input voltage. In this case, since the current is not constant, the magnetic field is increasing (with increasing current) as the capacity decreases so that the head increases more rapidly than in the case (Figure 14) in which the current is held constant.

Figure 16 shows how the efficiency of a pump varies with current input. As might be expected, there is an optimum value of current for each pump above which the efficiency decreases due to rising I^2R losses in the tube and magnet.

Figure 17 is typical of the variation of efficiency with magnetic field intensity. The efficiency passes through a maximum not only because of the increasing power supplied to the magnet but also because of the rising by-pass current losses.

Figure 18 indicates a typical relation between efficiency and capacity when the head is maintained constant. Here again, a maximum is exhibited because increasing capacity implies increasing current and/or field with either of which the efficiency passes through a maximum.

Figure 19 illustrates the characteristics of the 1.75" pump operating at constant input voltage. Under this condition the efficiency falls off and the head decreases due to the rising counter emf and decreasing effective current.

Figure 20 shows the variation of fluid power output with input current in the case of the 1.75" pump operating with liquid at 300 C.

Figure 21 shows how the head-capacity characteristic was affected by a change in the temperature of the liquid. It will be noted that due to the lower viscosity at elevated temperatures the capacity is increased at any given head. Although the capacity increases with temperature, the efficiency either remains unchanged or falls slightly. This is because of

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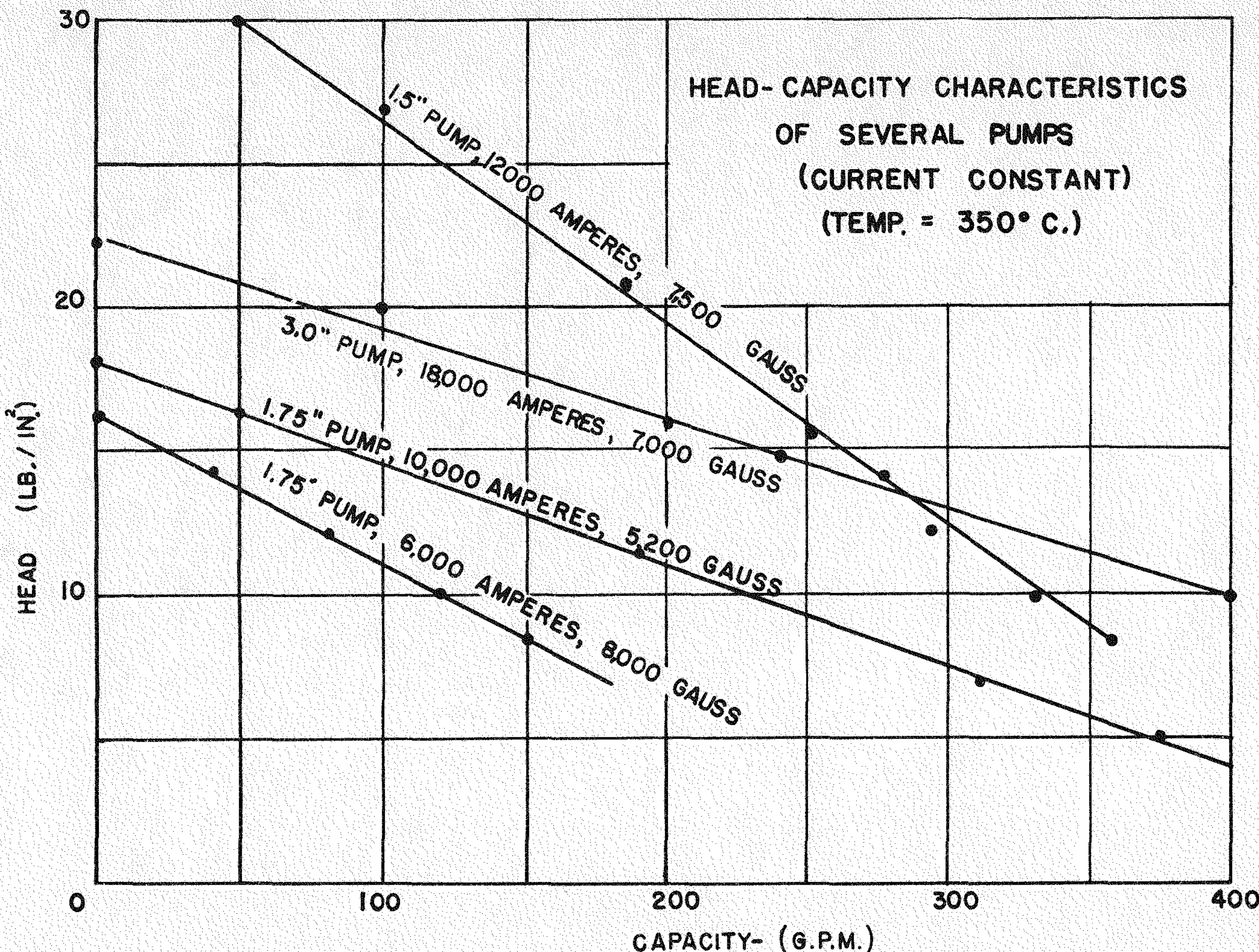

Figure 14

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HEAD-CAPACITY CHARACTERISTIC
OF 1.5" PUMP

INPUT VOLTAGE CONSTANT (0.44 VOLTS)
(TEMPERATURE = 350° C)

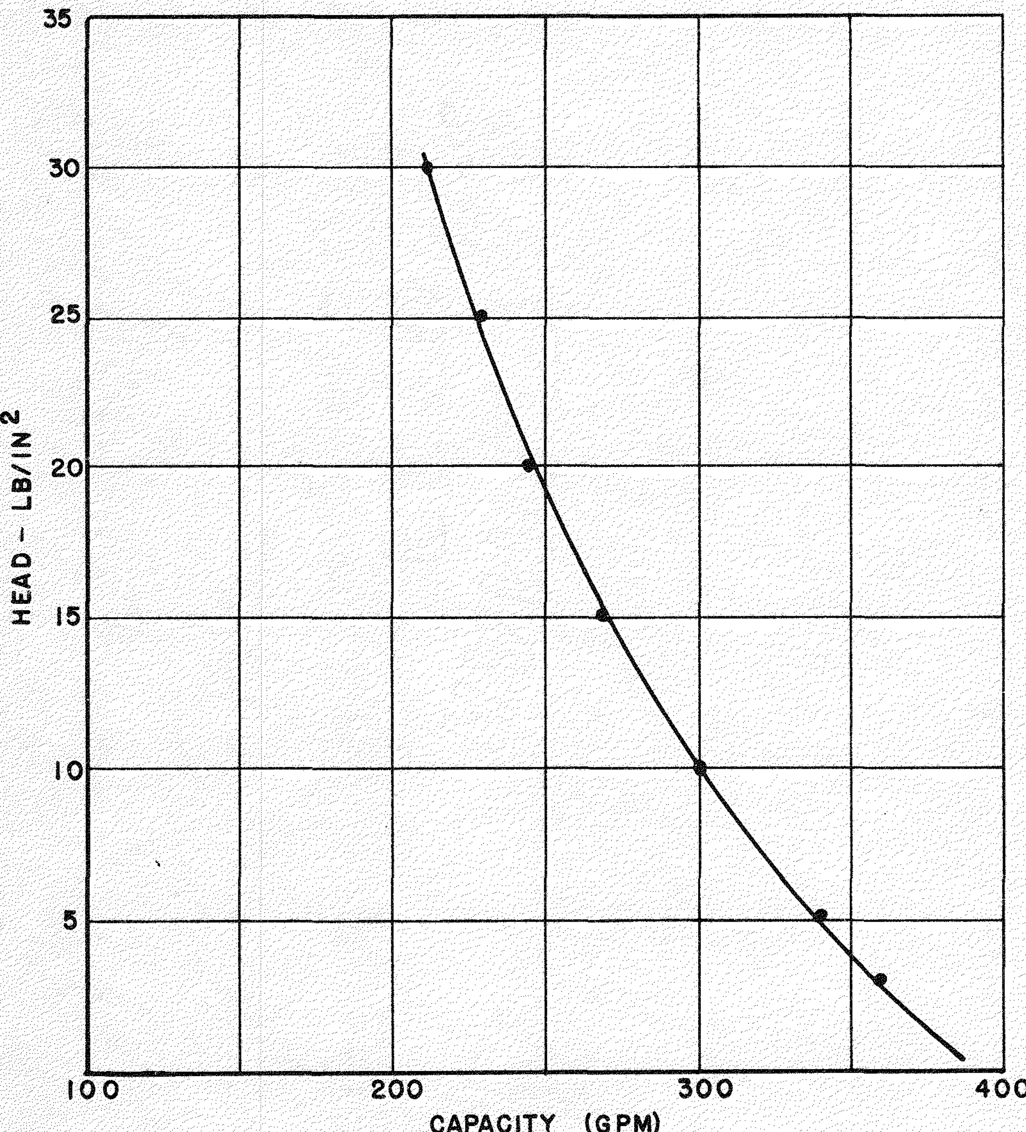

Figure 15

VARIATION OF EFFICIENCY WITH CURRENT.

1.5" PUMP, HEAD = 20 LB/IN^2

TEMPERATURE = 250° C

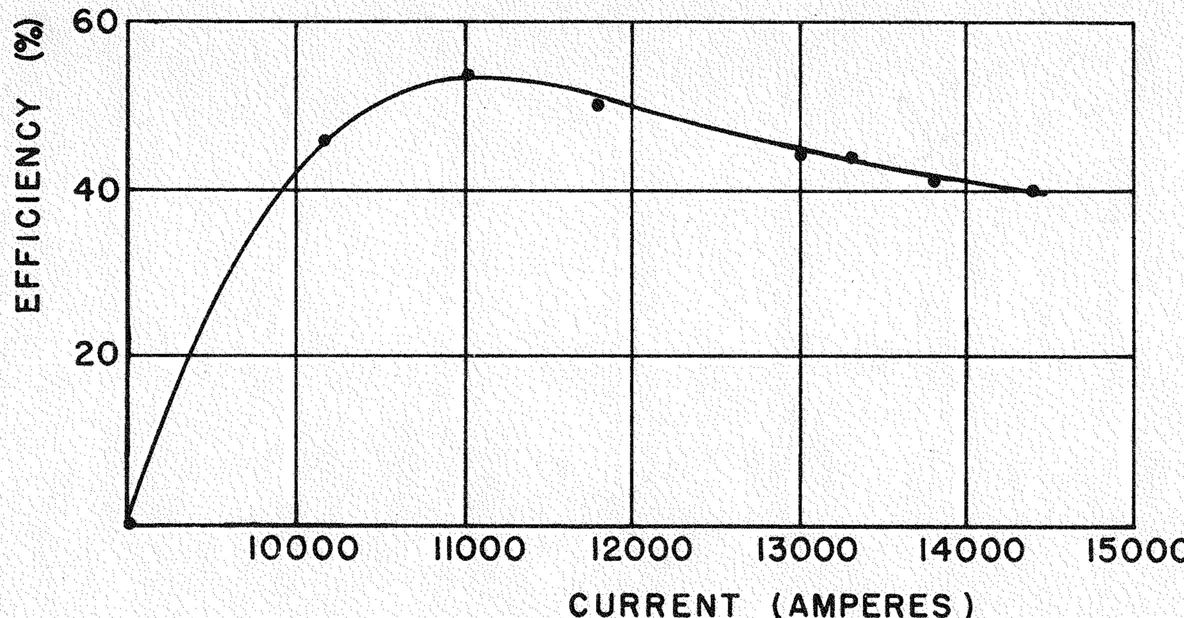

Figure 16

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VARIATION OF EFFICIENCY WITH MAGNETIC FIELD INTENSITY.

3.0" PUMP, TEMPERATURE = 250° C

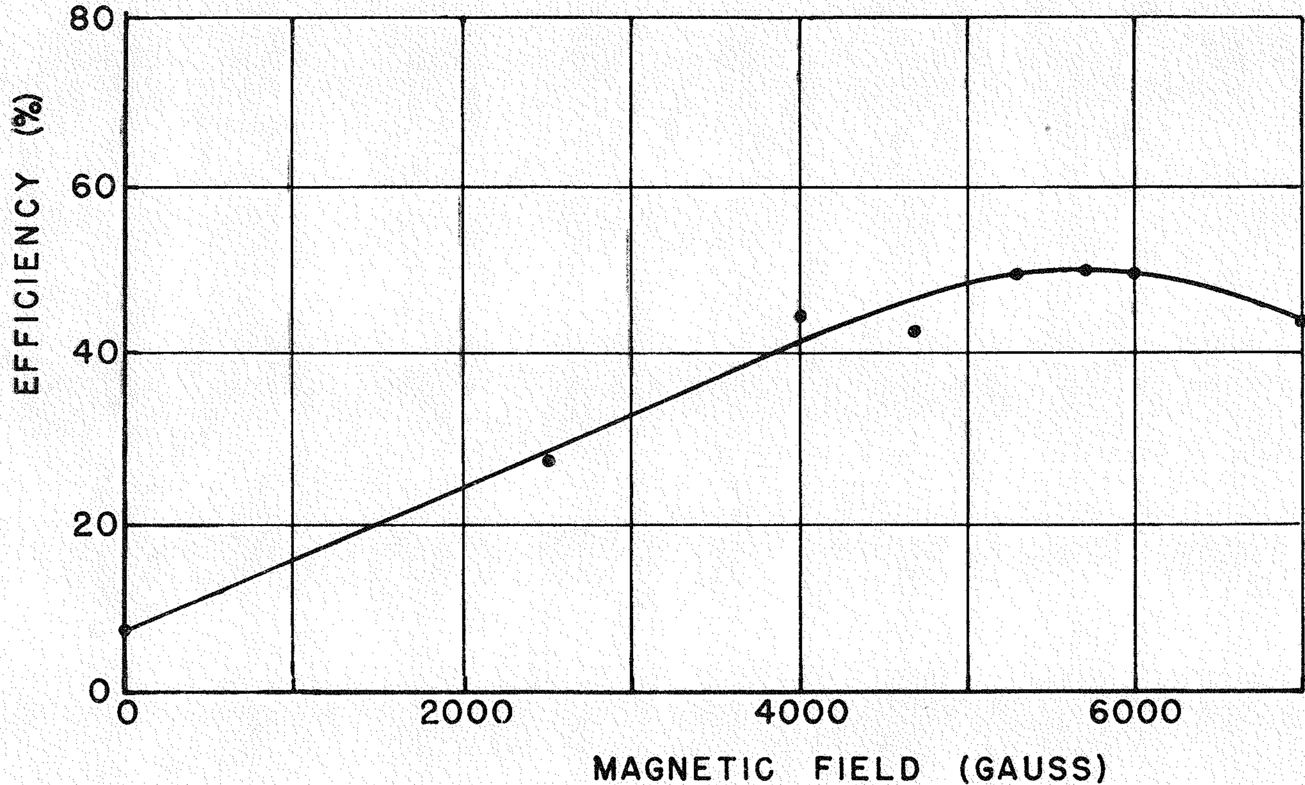

Figure 17

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VARIATION OF EFFICIENCY WITH CAPACITY.

1.5" PUMP, HEAD = 20 LB/IN^2

TEMPERATURE = 250° C

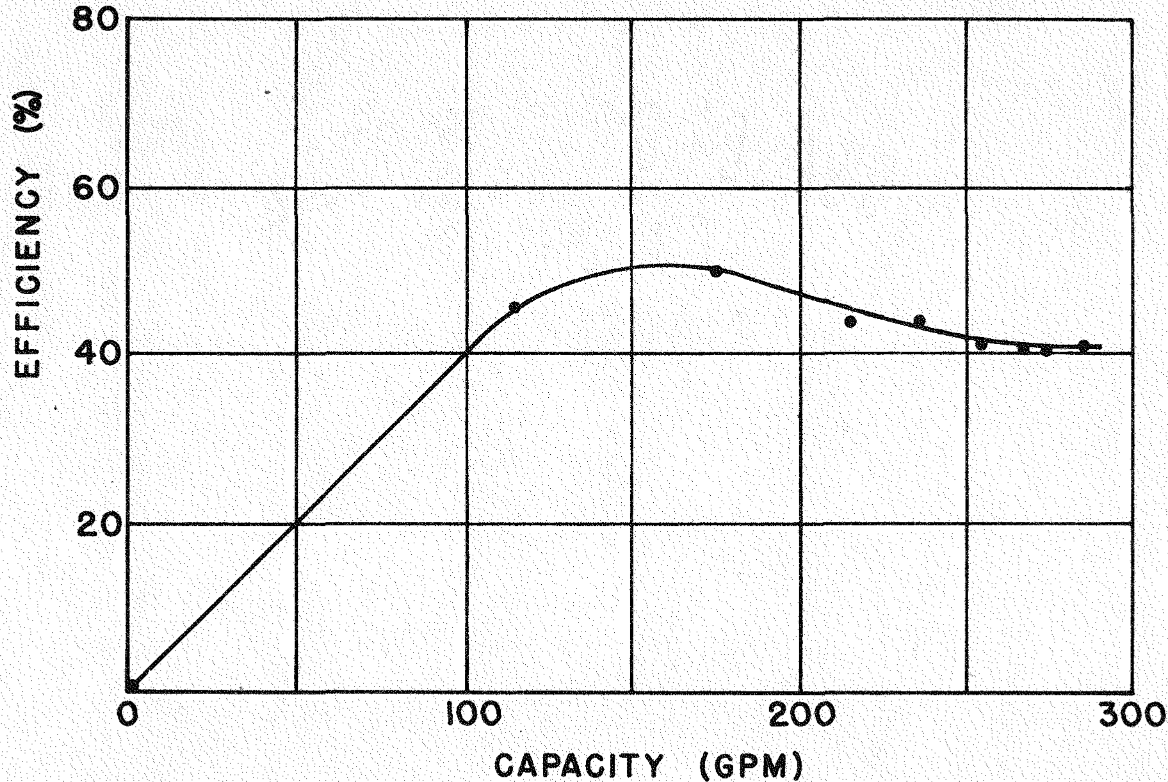

Figure 18

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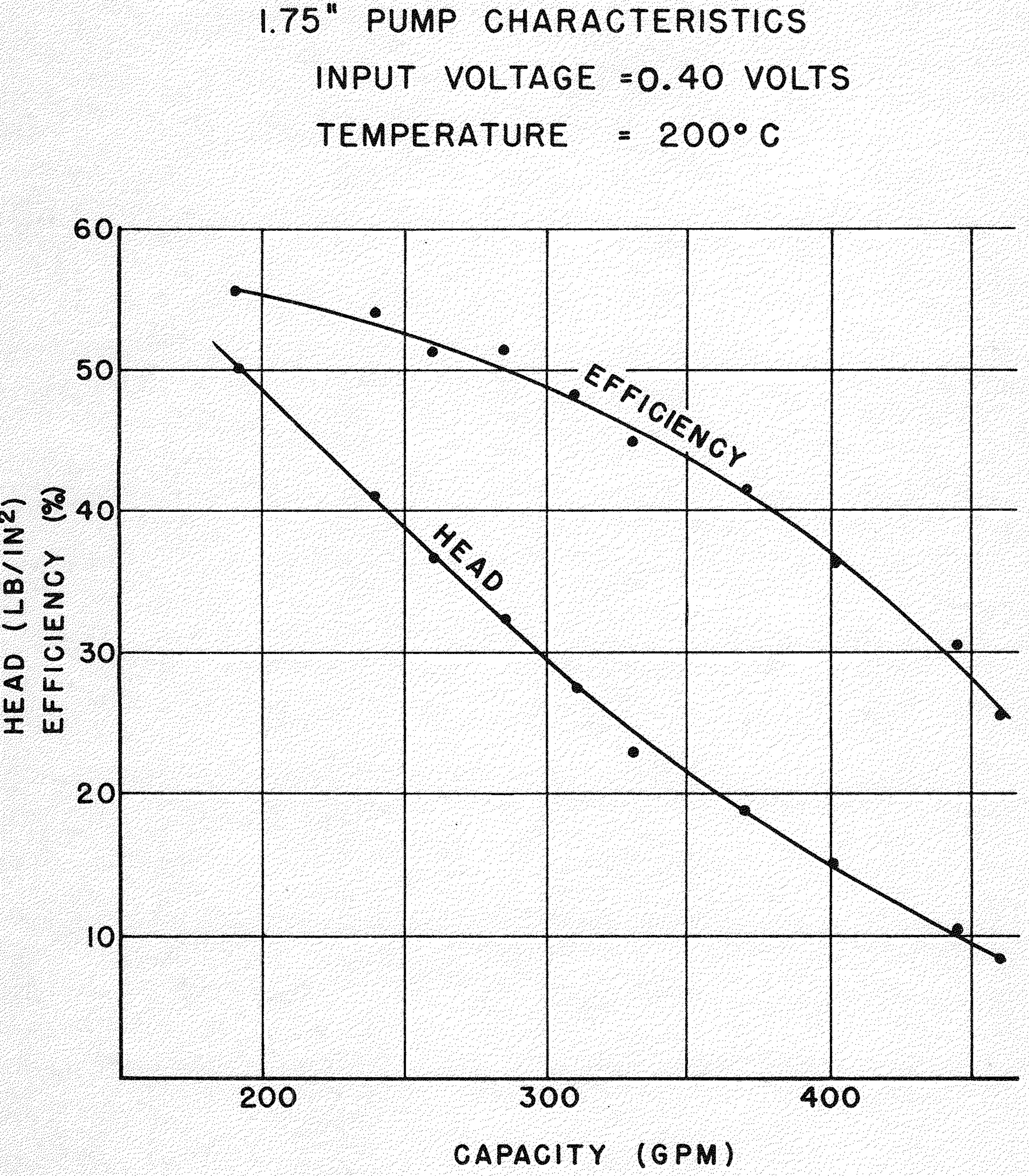

Figure 19

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VARIATION OF OUTPUT POWER WITH CURRENT.

1.75" PUMP, 300° C

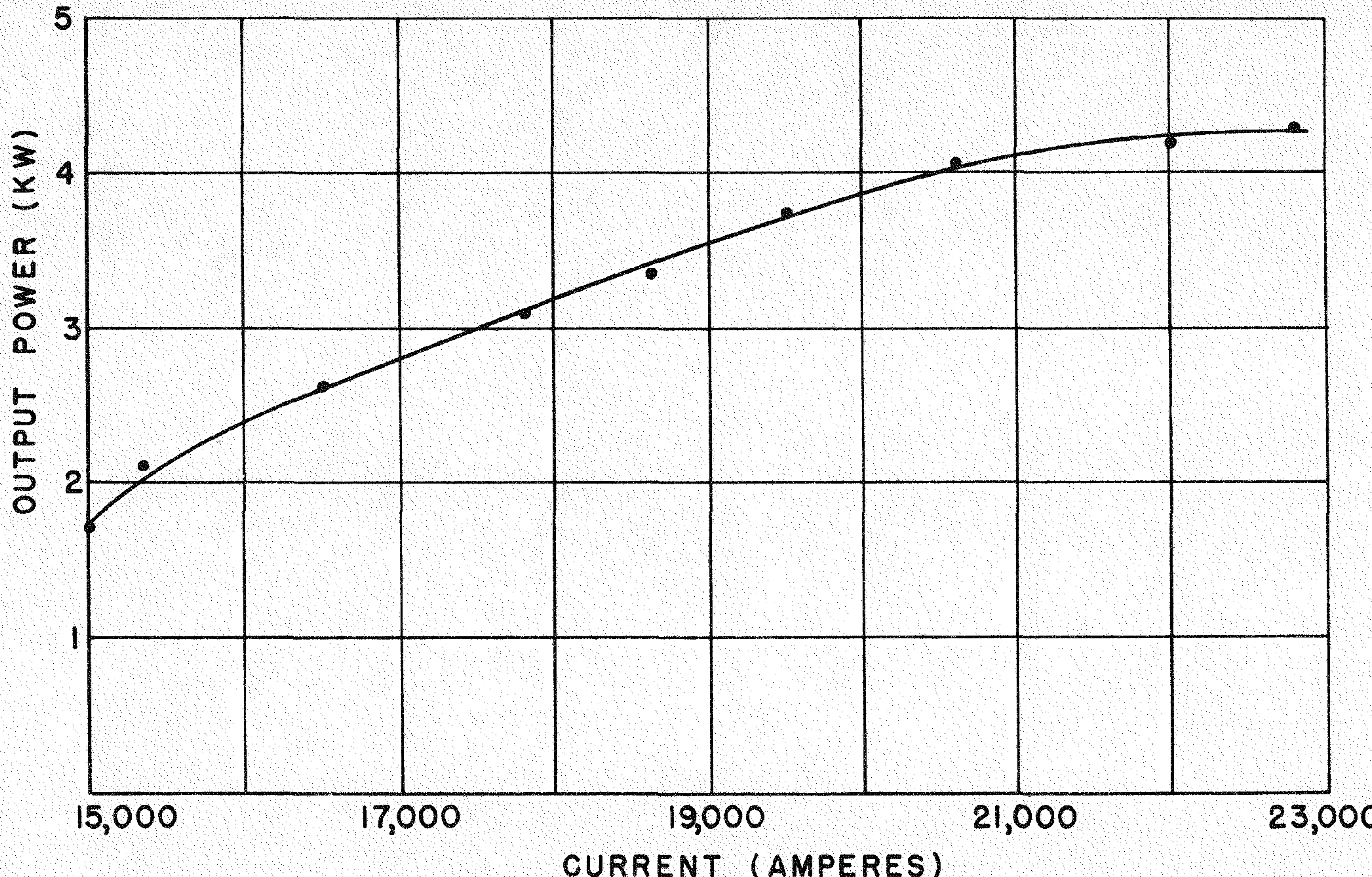

Figure 20

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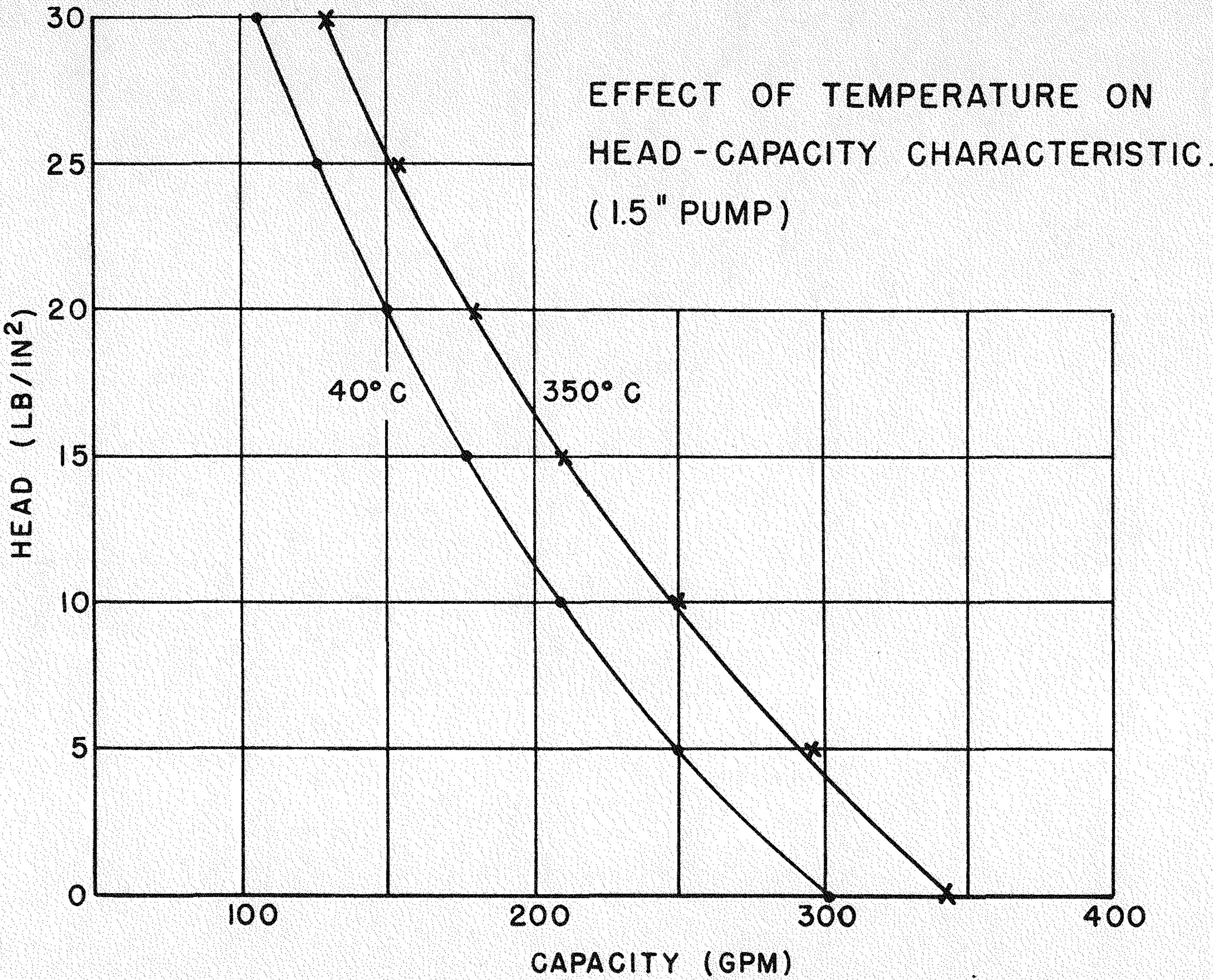

Figure 21

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the increased resistance in the liquid and in the magnet and also because of the larger by-pass losses which accompany the increase in capacity.

An analysis of power losses in the pump may be made by substituting known values in equations 7 through 15. Table II lists values obtained in this way for two operating conditions of the 1.75" pump. Figure 22 shows the trend of power losses with increasing capacity at decreasing head.

The efficiency of these pumps could be increased somewhat by using a thinner tube wall (i.e., less than the 0.032" used in the pumps described above) and by employing a longer magnetic field. An analysis of the losses incurred under various operating conditions indicates that efficiencies of over 60 percent should be possible by reducing the wall thickness to 0.020" and reducing the resistance of the magnet by 50 percent.

Thinner walls, of course, raise the question of tube failure. In one test the 1.75" pump was operated at 300 C for 1000 hours and then sectioned for metallurgical examination. Very slight erosion of the tube wall could be detected but there was no evidence of any serious deterioration and many more thousands of hours of operation appeared possible. However, as a safety precaution an outer protective jacket can be placed over the thin tube and magnet so that in the event of a tube failure the liquid would be confined.

Pumps of much greater capacity (several thousand gpm) could be constructed by simply scaling up the equipment. Since this would involve increasing the pump tube size in the field direction, it would necessitate the use of very large currents (equation 2).

Large capacity may also be obtained by placing several medium size pumping tubes in parallel between the poles of a single magnet. In this way, a relative saving in magnet power may be attained since magnet power would not increase as fast as pumping capacity. Furthermore, although the tubes would be in parallel for liquid flow they would be in series electrically so that the voltage drop across the pump would be increased. This is of great importance if the pump is operated from a rectifier set because the efficiency of the rectifier is low at low output voltages so that an increase in pump input voltage is to be desired.

The effect of separate parallel pump tubes can also be obtained by using a single wide tube and dividing it into channels by placing insulating islands longitudinally inside the tube on each side of the region between the magnet poles. These insulating islands consisting of a sandwich of thin inconel sheets separated by mica would serve to reduce the by-passing current through the liquid outside of the field region.

Table II

ANALYSIS OF POWER LOSSES

Input current (I_t)	16,300	21,800	amperes
Input voltage	0.438	0.382	volts
Input power	7,107	8,340	watts
Output capacity	350	210	gpm
Useful head	20	41.5	lb/in^2
Hydraulic impedance	3.85	1.38	lb/in^2
Magnetic field intensity	6,500	7,600	gauss
P.D. across pump tube (V_t)	0.385	0.312	volts
Effective current (I_e)	10,900	16,500	amperes
Wall by-pass current (I_w)	3,850	3,120	amperes
Liquid by-pass current (I_L)	1,450	2,180	amperes
I_e^2R loss in liquid (W_L)	515	1,160	watts
% of input power	7.3	13.9	%
By-pass power loss in wall (W_w)	1,460	970	watts
% of input power	20.5	11.6	%
By-pass power loss in liquid (W_B)	560	685	watts
% of input power	7.9	8.2	%
Magnet power (W_m)	900	1,600	watts
% of input power	12.6	19.0	%
Hydraulic loss (W_H)	580	126	watts
% of input power	8.2	1.5	%
Output power	3,040	3,800	watts
% of input power	43	46	%

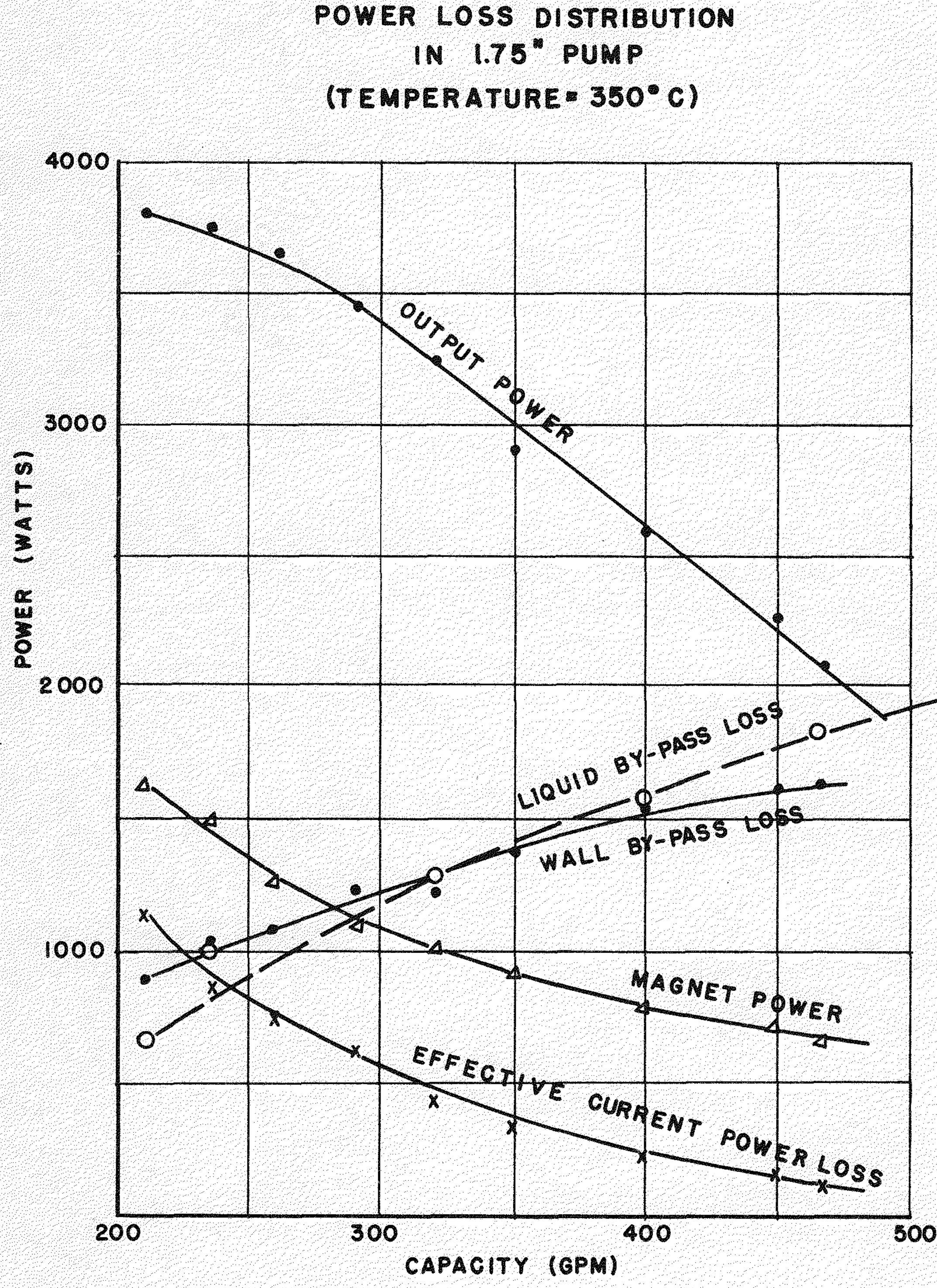
POWER LOSS DISTRIBUTION
IN 1.75" PUMP
(TEMPERATURE = 350° C)
4000
3000
2000
1000
POWER (WATTS)
200
300
400
500
CAPACITY (GPM)
OUTPUT POWER
LIQUID BY-PASS LOSS
WALL BY-PASS LOSS
MAGNET POWER
EFFECTIVE CURRENT POWER LOSS

Figure 22

The principle disadvantage of the parallel arrangement is, in addition to the difficulty of fabrication, the necessity of making the pump section very long in order to avoid unduly large end-current losses. A simple network analysis indicates that excessive losses would occur in, say, a 10 channel pump unless the insulating islands extended for several feet on each side of the magnetic field region.

The over-all efficiency of the d-c type pump involves, of course, the efficiency of the current supply system. If this is a rectifier, which at the present time is the most reliable, then for input voltage of the order of one volt a rectifier efficiency of 40-50 percent is possible. This means that the over-all efficiency of the system would be around 20 to 25 percent. If homopolar generators were used a somewhat higher efficiency could be obtained since generator efficiencies of 70-80 percent should be possible. In our case with generator efficiencies of 50-60 percent and bus bar losses of 10-12 percent the over-all efficiency was 18-22 percent.

The disadvantages of the d-c electromagnetic pump are: (1) the large currents required, (2) the relatively low efficiency, (3) in a mobile application, the high weight to power ratio ($275 \frac{\text{lb}}{\text{kw}}$ output in present pumps).

On the other hand the advantages may be listed as:

1. A completely sealed all metal system

2. No moving parts and hence no bearings to wear or require attention

3. Ability to pump liquid metals at high temperatures

4. No vibration

5. Freedom from radiation damage in the case of the d-c pump since practically no electrical insulation is required.

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