THE UNIVERSITY OF MICHIGAN
INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

ELECTROMAGNETIC PUMP PERFORMANCE WITH VARIOUS LIQUID METALS

Frederick G. Hammitt
John L. Summers

November, 1960

IP-474

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial support of The Chrysler Corporation in obtaining some of the data reported. In addition to the authors those who assisted primarily in the project were E. M. Brower and John Robinson research personnel of The University of Michigan.

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NOMENCLATURE

P	Pressure
B	Magnetic Induction
I	Electric Current
i	Electric Current Density
E	Voltage
G	Volumetric Flow Rate
ρ	Density
η	Efficiency
ΔH	Head rise
N	Rotating Speed (RPM)
X, Y, Z	Cartesian Coordinates

1.0 INTRODUCTION

Very little data is presently available on the comparative performances of an electromagnetic pump operating with different fluids. It is the purpose of this paper to attempt to fill a portion of this gap.

A closed-loop facility has been erected by the Nuclear Engineering Department of The University of Michigan to be used for the study and demonstration of heat transfer and pumping effects with liquid metals. The loop is powered by a General Electric Company, alternating current, conduction-type electromagnetic pump. The performance of this pump using NaK is well known from the manufacturer's tests.(1). For the present loop, mercury has been chosen as the initial working fluid because of its general ease of handling and instrumentation. Since the physical properties of mercury, of interest from the viewpoint of heat transfer and pumping characteristics, do not differ greatly from those of fluids of greater present technological importance in the nuclear field, this may be sufficient. However, it may be desirable in the future to convert to either NaK or Na.

Performance data for this pump is then available for mercury from the present tests, and NaK from the manufacturer's data. In addition, the pump was previously used at The University of Michigan in a molten bismuth loop providing very rudimentary data on performance with this fluid.

The data from the General Electric pump is supplemented by comparative performance data for a somewhat similar pump between mercury and sodium, received from MSA Appliances Corporation.(2)

The observed data are compared with theoretical expectations based on a simplified theory, and the variations discussed.

2.0 THEORETICAL EXPECTATIONS

2.1 Electromagnetic Pump Idealized Theory

The Faraday (conduction) type electromagnetic pump operates in a manner similar to a direct-current electric motor; i.e.: when a conductor of length, L, carrying an electric current, I, is placed in a magnetic field of strength, B, a force is produced on the conductor which is perpendicular to both the current and the magnetic field and is equal to $F = LIB$. In the case of electromagnetic pumps the conductor is the liquid metal itself and the force is evidenced by a pressure rise in the fluid.

Consider a parallelopiped element, dxdydz, of liquid metal in the cell or throat of the pump (Figure 1). A current density, I_y, passes through the liquid in the y-direction and a magnetic field of strength, B_x, exists in the x-direction. The force exerted on the element is given in terms of the pressure gradient in the z-direction (See Appendix):

$$\frac{dP}{dz} = B_x i_y \tag{1}$$

The total pressure produced in the pump cell along a streamline is found by integrating Equation (1), assuming the streamlines are parallel to the pump cell walls:

$$\Delta P = \int_o^L B_x i_y d_z \tag{2}$$

Then, if magnetic field and current density are uniform along the axis:

$$\Delta P = B_x i_y L = KBIL$$

where K depends on the cell geometry.

It is assumed that current density and magnetic field are also uniform across the cell so that there is no cross-flow and the pressure rise produced in all streamlines is the same.

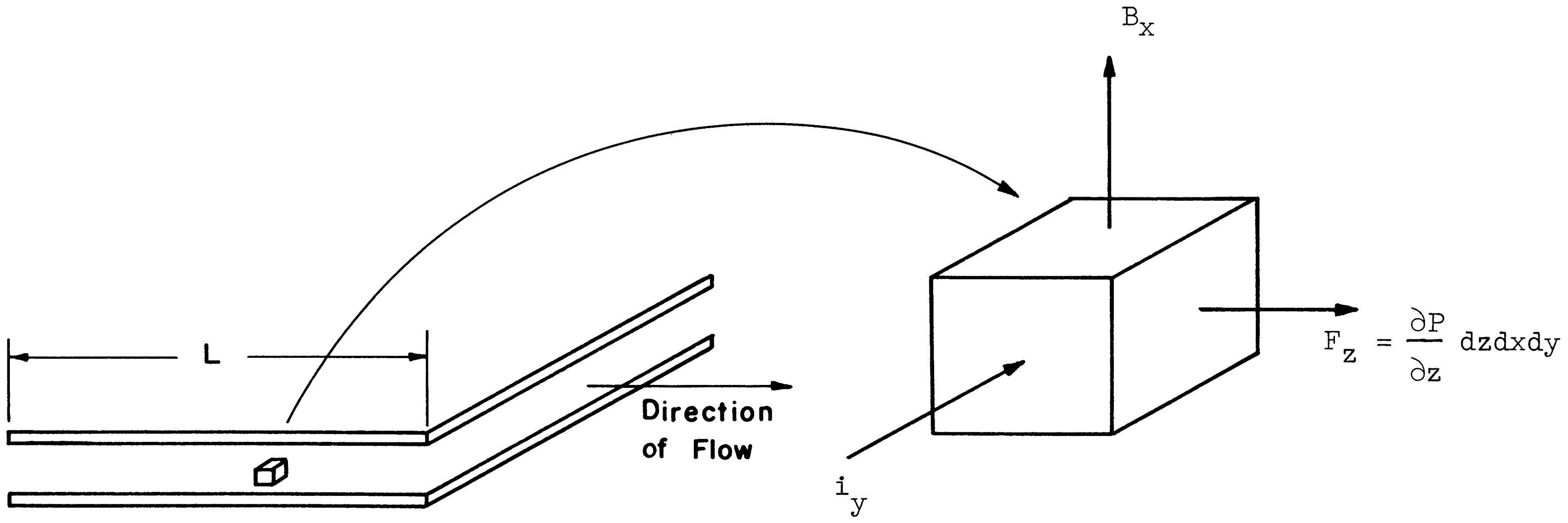

Figure 1. Representation of Conduction-Type Pump Cell

If the pump core is not saturated we may assume:

$$B \alpha E \tag{4}$$

and if the impedance remains constant:

$$\Delta P \alpha E^2 \tag{5}$$

Also by the laws of fluid-dynamics, for a given fixed external system:

$$G \tilde{\alpha} \sqrt{\Delta P/\rho}$$

or $$G \tilde{\alpha} E/\sqrt{\rho} \tag{6}$$

pump work $$\tilde{\alpha} \Delta PG \alpha E^3/\rho \tag{7}$$

and $$\eta = \Delta PG/EI \tilde{\alpha} \frac{\Delta PG}{E^2}$$

so $$\eta \tilde{\alpha} E/\sqrt{\rho} \tag{8}$$

These relations are modified by saturation of the core and various losses. These losses include, in this particular pump where alternating current is used, eddy current heating of the core piping, support structure, and fluid, losses due to non-uniform flux and current, friction and turbulent hydraulic losses in the pipe and pump cell, hysteresis in the core, and contact resistence (lack of "wetting") between fluid and pump cell.

2.2 Comparison with Turbopump Performance

The well-known "affinity laws" describing the performance of a turbomachinery component are:

$$\Delta H \alpha N^2 \tag{9}$$

$$G \alpha N \tag{10}$$

and pump work $$\alpha \rho \Delta HG \alpha \rho N^3 \tag{11}$$

A comparison of Equations (5), (6), and (7) with (9), (10), and (11) shows that voltage for the electromagnetic pump replaces rotating speed for the turbopump. The analogy appears complete except for the role of density. The different roles of density are due to the fact that the pressure (a force term) is related directly to voltage in the electromagnetic pump, while the fluid head (energy input per unit mass) is related to rotating speed in the turbopump. For this reason, the performance of electromagnetic pumps in terms of efficiency depends directly upon the density of the fluid, while that of turbomachines does not except for the rather small influence of different Reynolds Numbers.

2.3 Deviations of Electromagnetic Pump Performance from Ideal Theory

The greatest cause of discrepancy from the ideal theory discussed above in the comparisons between different fluids in the same pump is apparently non-uniformity in degree of "wetting" between the fluids; i.e.: the electrical contact resistence between the material of the pump cell and the liquid metal. This resistence is apparently very significant in some cases and not at all in others. It depends on the material combination as well as the degree of cleanliness of the surface, the fluid purity, the presence of an oxide or nitride film on the surface, etc.

It is known that Na or NaK "wet" austenitic stainless steels very well. However, considering the experience in the present loop and that of other investigators(4,5), mercury or bismuth do not. Possible methods for obtaining "wetting" and their degree of success will be considered in the discussion of the experimental results. However, the presence or lack of such "wetting" is sufficient to cause an order of magnitude difference in the pressure differential of the pump. For this reason it would appear that, with fluid-container combinations for which wetting is uncertain, electromagnetic flow meters would not be practical.

Other causes of deviation from the ideal theory comparisons were listed earlier. These are self-explanatory and are not of such great effect as that of "wetting".

3.0 EXPERIMENTAL RESULTS

The experimental results described in this paper are derived from a mercury loop at The University of Michigan which will be described below as well as from results reported by General Electric Company and MSA Appliances Corporation.(2)

3.1 Description of Mercury Loop

The mercury loop facility is shown in Figure 2. The loop is rectangular, about four feet by eight feet, of 3/4 inch, schedule 40, type 304 stainless steel. One of the longer sides is devoted to a heating section consisting of a schedule 160 stainless steel pipe wound with resistence wire and equipped with thermocouple and velocity probe positions. The opposite side is a cooler consisting of a two inch pipe concentric to the loop pipe, the intervening annulus being water-cooled. One of the short ends contains the pump and a bellows-sealed globe valve; the opposite end contains a venturi section for flow measurement.

The length of the pump cell is 13 inches between flanges. It consists of one inch type 304 stainless steel tubing of about 50 mils, flattened near the center to an outside cross-section of about 1/2 inch by two inches for a length of one inch. On each edge solid nickel electrodes are welded. When bolted to the secondary of the pump transformer coil, these carry the electric current through the pump cell. The flattened section fits an opening in the laminated core of the pump such that the magnetic flux must traverse the cell and fluid inside. There is of course some bypassing of current and magnetic flux through the walls of the pump cell.

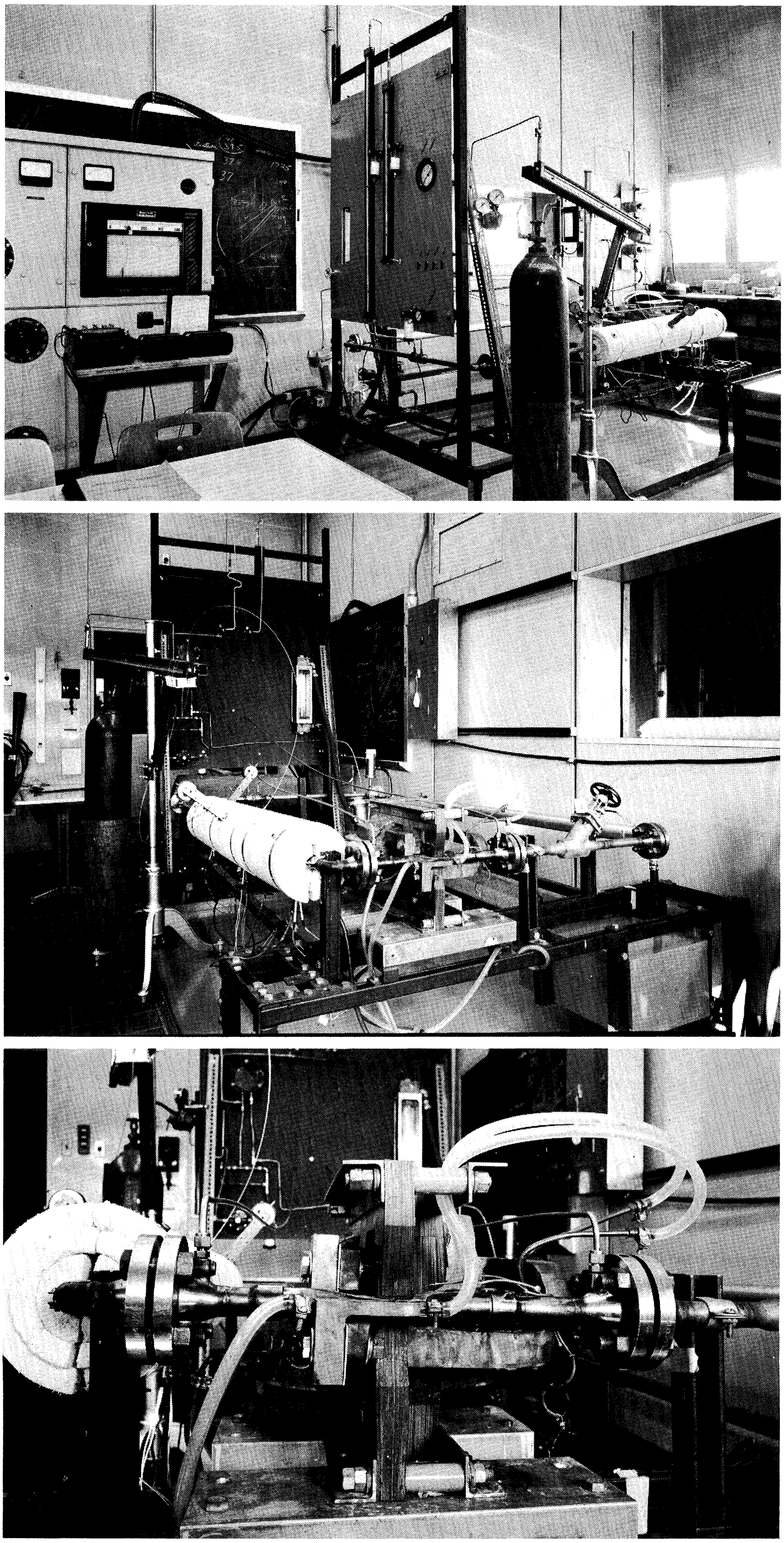

Figure 2. Mercury Loop Facility and EM Pump

The pump itself is a General Electric Company model 915984G7 AC electromagnetic conduction pump. It was originally designed for use with molten bismuth, a fluid with specific resistivity of about 140 micro-ohm-cm, (specific resistivity of mercury is 100 micro-ohm-cm.) and requiring a Croloy pump cell for satisfactory corrosion performance. Characteristic curves for this pump with NaK taken from General Electric Company test data are shown in Figure 3.

3.2 Mercury Loop Instrumentation

Flow is measured over a broad range of Reynolds Numbers by a venturi section, which was previously calibrated with water, and a weigh tank. According to conventional fluid-dynamic theory the velocity coefficient of such an instrument is a function only of Reynolds Number, and experience shows that for high Reynolds Numbers it is practically constant. The validity of such assumptions for molten lead-bismuth alloy and water in a given instrument was established by Johnson(6) at the University of California. It is only reasonable to assume its validity also for mercury.

For a given volumetric flow, the Reynolds Number for mercury is about ten times that for water. For this reason it was necessary to continue the calibration for water to much larger volumetric flow-rates than were expected for mercury.

The venturi pressure differential from inlet to throat is read on a simple manometer attached to the panel board.

Pressure differentials between pump inlet and discharge are also read by a manometer on the panel board. This differential is also the pressure drop of the loop, excluding the pump cell.

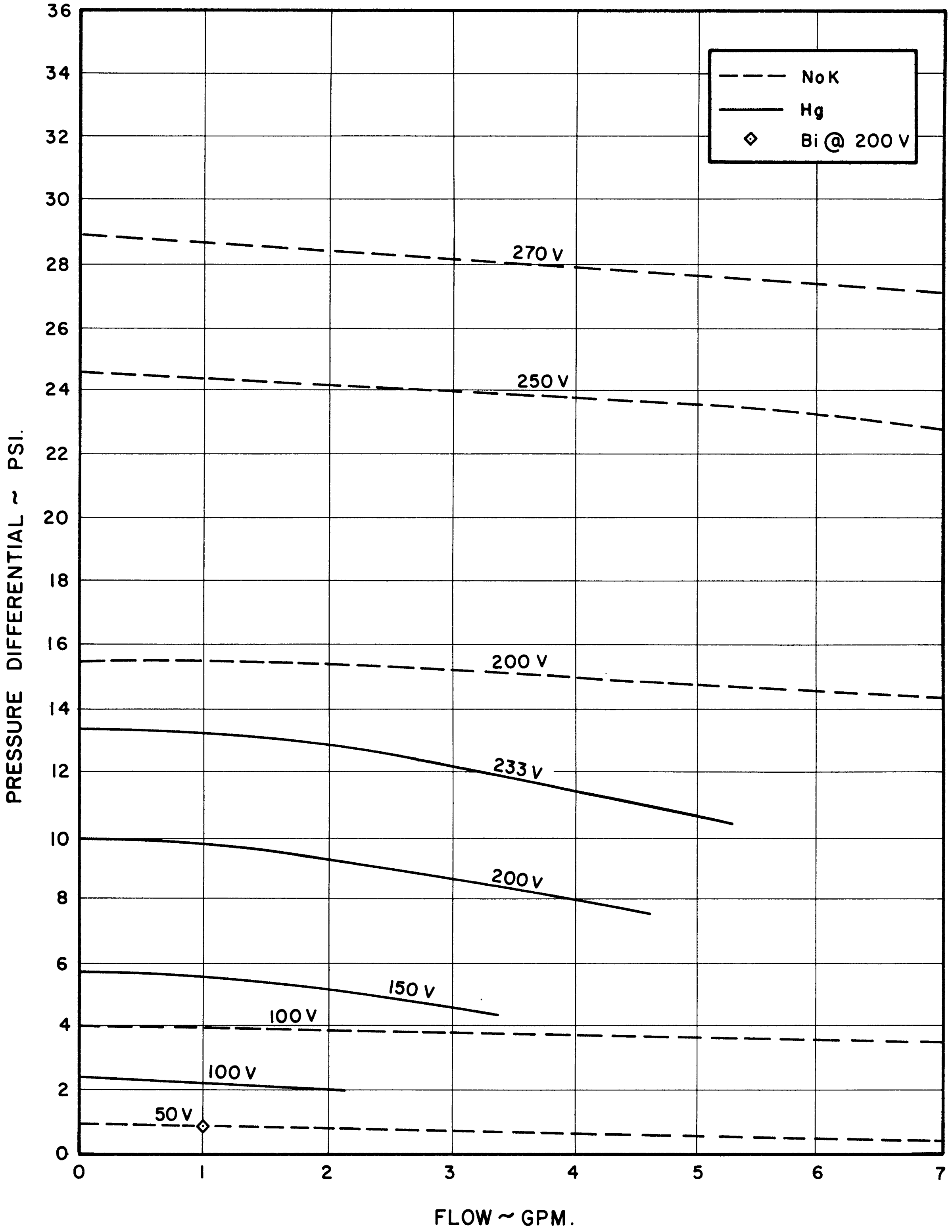

Figure 3. Pump Characteristic Curves - Variable System (GE Pump No. 9159849)

Temperatures are measured at various locations by thermocouple.

Pump voltage and power are read by standard precision instruments. Wattage is measured directly because of a varying power factor.

3.3 Results Obtained from Mercury Loop

Curves of the pressure differentiral across the pump versus volumetric flow with pump voltage as the curve parameter taken from the mercury loop are also included on Figure 3. The curves were obtained by holding constant voltage and varying the system resistence, either by changing valve settings or inserting orifices in one of the flanges. It will be noted that these are very similar to the characteristic curves of a centrifugal pump if the constant voltage curves are considered to be curves of constant rotating speed. A comparison of the shut-off pressure differentials (pressure differentials for zero flow), or other corresponding performance points, shows that these vary approximately as the square of the voltage as predicted from the ideal theory previously discussed. This is also true for the NaK curves from the manufacturer shown on the same figure.

According to the same ideal theory, the pressure differentials for the two fluids at corresponding points of the curves, as the shut-off point for example, and at a fixed voltage, should be the same. Actually, it is noted that the pressure differential obtained with mercury is less by a factor of about 0.65. This is no doubt partially due to the higher resistivity of mercury. However, it is also probably partly caused by a higher surface resistence between the pump cell and the fluid with mercury.

Figure 4 shows some of the same data in a slightly different manner. Volumetric flow-rate and pressure differential are plotted against pump voltage for a fixed system resistence; i.e.: fixed valve setting. It is noted

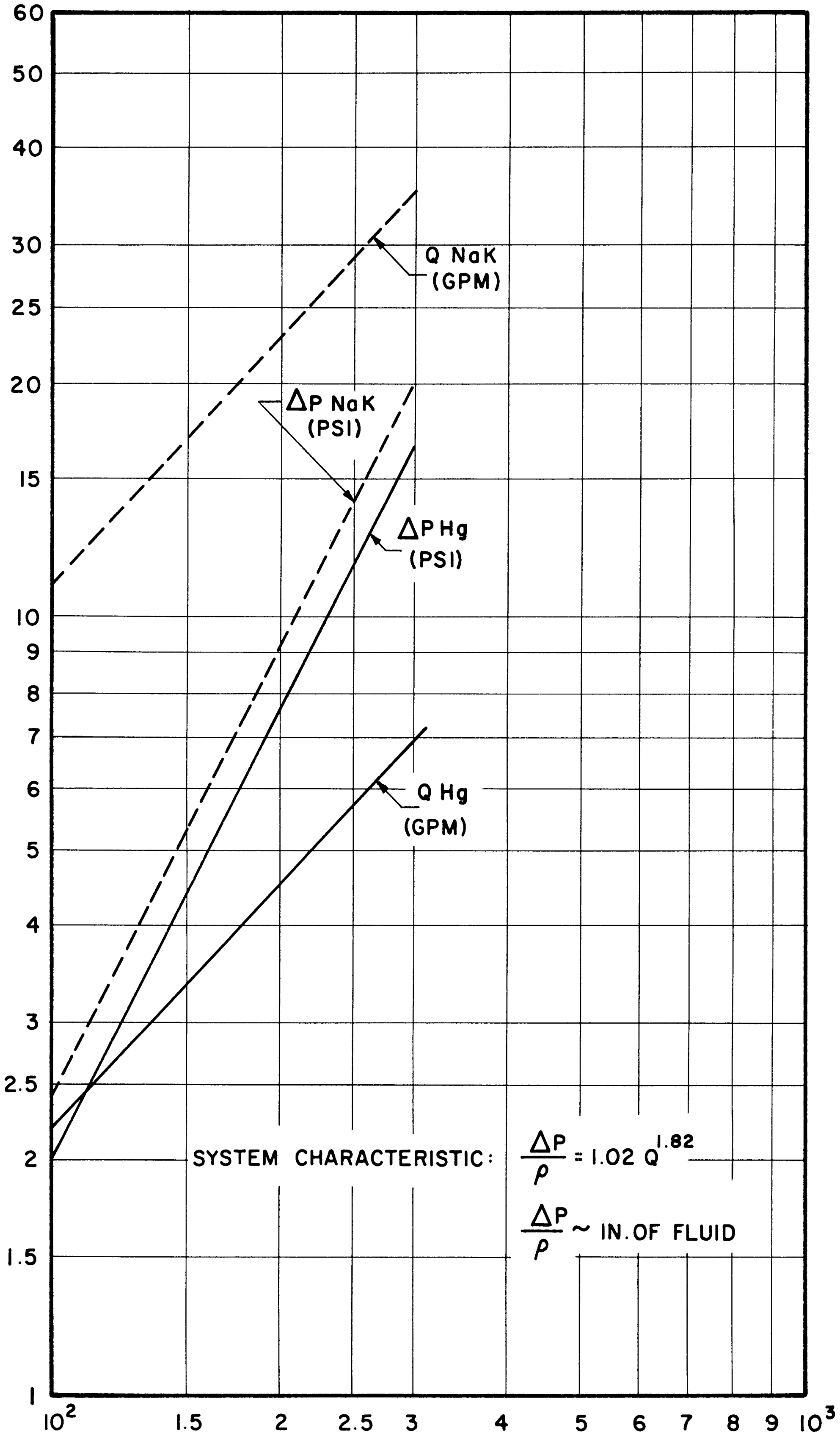

Figure 4. Pump Characteristic Curves Fixed System (GE Pump No. 9159849)

that the pressure differential curve for NaK is slightly higher than that for mercury as previously mentioned, and that the flow-rate for NaK is very much higher, by a factor of about five. If the pressure differentials were equal for the two fluids, it would be expected that the volumetric flows would differ by the ratio of square roots of the densities, i.e.: $\sqrt{13.5/0.8} = 4.1$. Actually the difference is greater because the pressure differential with NaK is somewhat greater.

Constant voltage curves of efficiency versus flow for mercury are shown in Figure 5 and those for constant system resistence in Figure 6. It is noted that the highest measured efficiency with mercury is of the order of 0.25 percent and that efficiency for constant system resistence increases almost linearly with the voltage. This linearity with voltage is to be expected since power input is proportional to the voltage squared while the pump work is proportional to voltage cubed as shown in Equations (7) and (8). Equation (8) also shows that for corresponding performance points the efficiency should be inversely proportional to the square root of the fluid density. However, no efficiency data for another fluid under comparable conditions was available.

For a variable system resistence, (Figure 6) efficiency is virtually linear with flow-rate, falling on a single straight line regardless of the voltage. In other words, a given flow rate corresponds to a given efficiency, regardless of external system resistence and voltage required to supply this flow against the system resistence, at least within the range of the tests. No theoretical explanation is presently apparent.

Pumps attaining efficiencies of the order shown on these curves would of course hardly be of interest in power plant applications. However, they are useful for laboratory scale research loops where the benefits of no

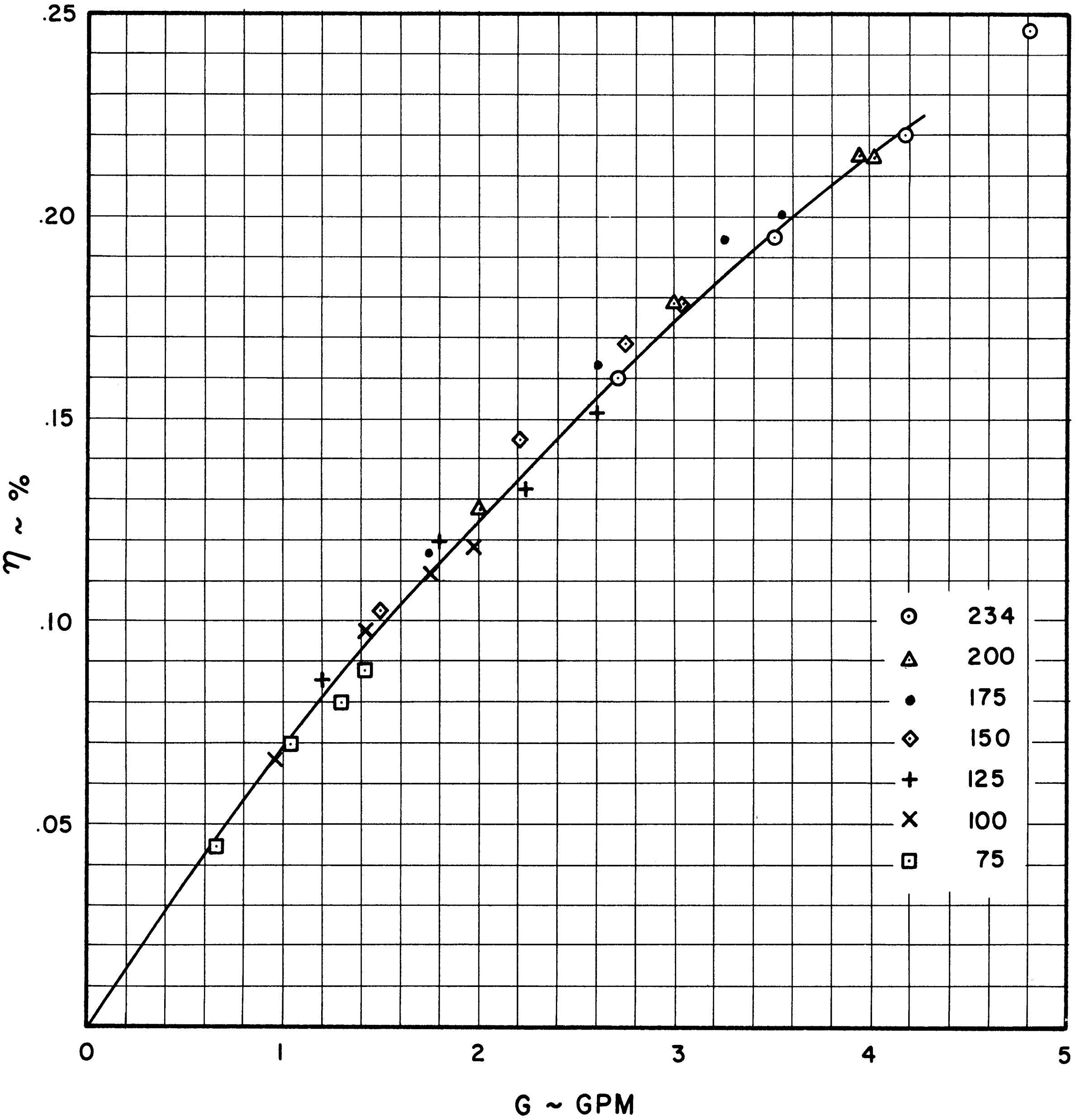

Figure 5. Efficiency vs Flow Rate Variable System (GE Pump No. 9159849)

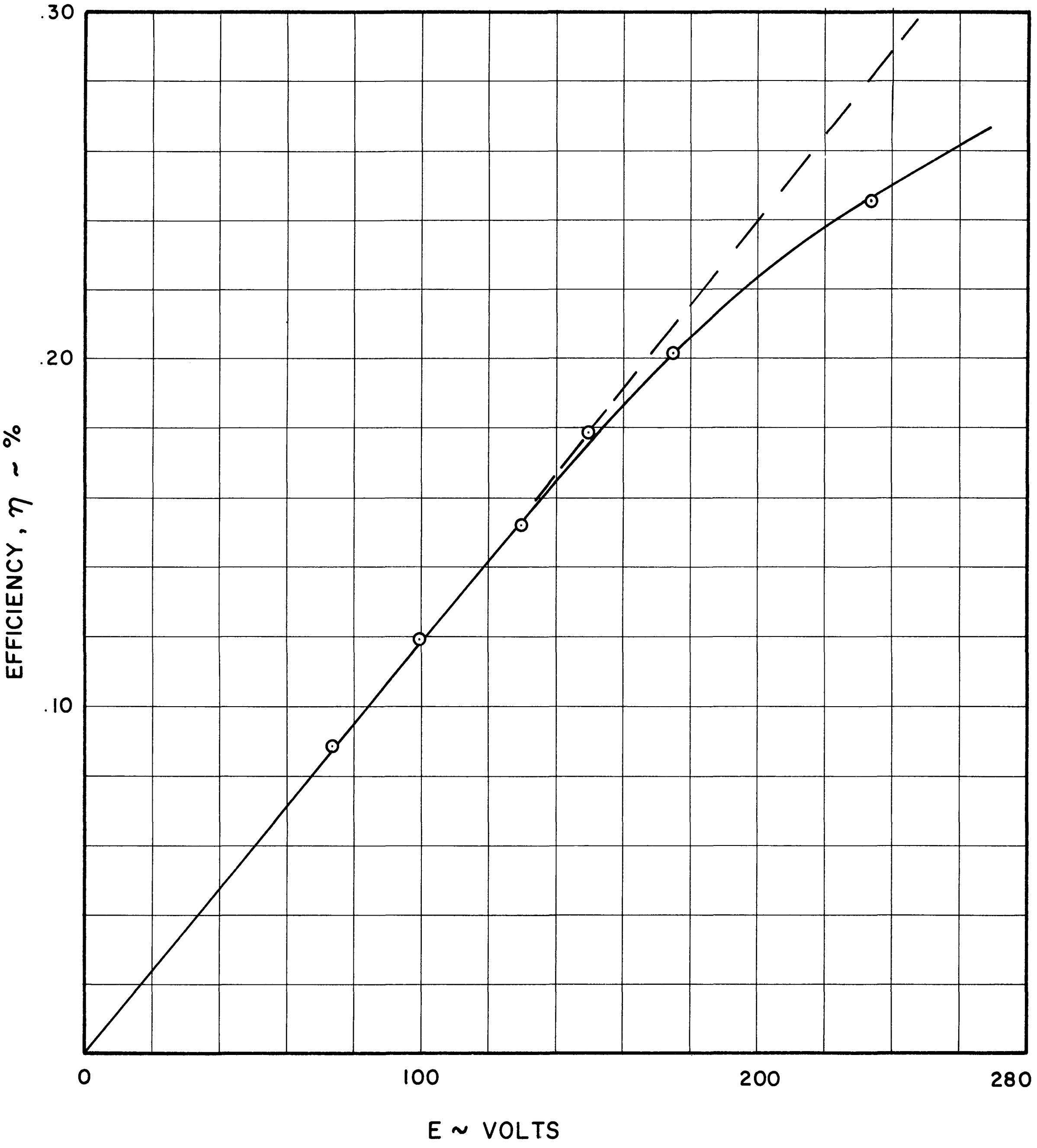

Figure 6. Efficiency vs Voltage Fixed System (GE Pump No. 9159849)

moving seals or other moving parts outweighs the disadvantage of low efficiency. It has been demonstrated of course that electromagnetic pumps of an order of magnitude better efficiency can be built in large sizes so that such pumps do have possible powerplant application.

3.4 Additional Data

3.4.1 Molten Bismuth and Mercury in Croloy Pump Cell

The pump, installed eventually in the mercury loop, had been previously operated in a molten bismuth loop. For this application a Croloy (low carbon steel with small chrome and molybdenum content) pump cell was used. Precise data were not obtained due to the difficulty of obtaining suitable pressure instrumentation with the molten bismuth (testing of the pump was not a primary objective of the project). However, the best estimate of the operating point is shown on Figure 3. It is noted that the pressure obtained for a given voltage is about a factor of ten less than for mercury which is a fluid of quite similar physical properties. There are two likely reasons for the discrepancy in the opinion of the authors, both of probable major significance:

a) Lack of good "wetting" with the materials combinations

b) Increased electrical losses in the magnetic pump cell with alternating current.

The same Croloy pump cell was used subsequently in the mercury loop. Precise data was not taken. However, the pumping was extremely poor, giving operation roughly similar to that with bismuth. The reasons for the poor performance are believed to be the same as those for the bismuth.

3.4.2 Callory Chemical Comparison of Mercury and NaK

Comparative performance tests between NaK and mercury at somewhat different temperature levels in a given electromagnetic pump (approximately similar to University of Michigan pump) were conducted by MSA Research Corporation.(2) The results are shown in Figure 7. It is noted that the curves are very similar to those obtained on the GE pump, and the ratio between NaK and mercury pressure rise about the same.

3.5 Wetting Problem with Mercury and Stainless Steel

As previously mentioned, the lack of a substantial electrical resistence between the material of the pump cell and the fluid is necessary for good operation. This condition apparently exists for NaK or Na and austenitic stainless steel provided no oxygen or other impurities are admitted to the system. It does not exist to nearly the same extent with molten bismuth and Croloy according to the experience at the University of Michigan and elsewhere.(4) Also, the obtaining of such a condition with mercury(5) and either Croloy or austenitic stainless steel has been shown to be a matter of some difficulty.

Attempts to obtain wetting by various means of surface treatment such as etching with acid or plating of the steel with platinum, copper, nickle, or combinations of these have been found to give spotty and non-permanent results.(5,7) It was suggested by Dr. Raseman of BNL(4) that tinning of the inside of the pump cell might be effective. This was tried and produced the performance results of Figure 3. It is believed that the "wetting" was good since the pressure differentials do not fall very greatly below those obtained with NaK for which good "wetting" is known to exist.

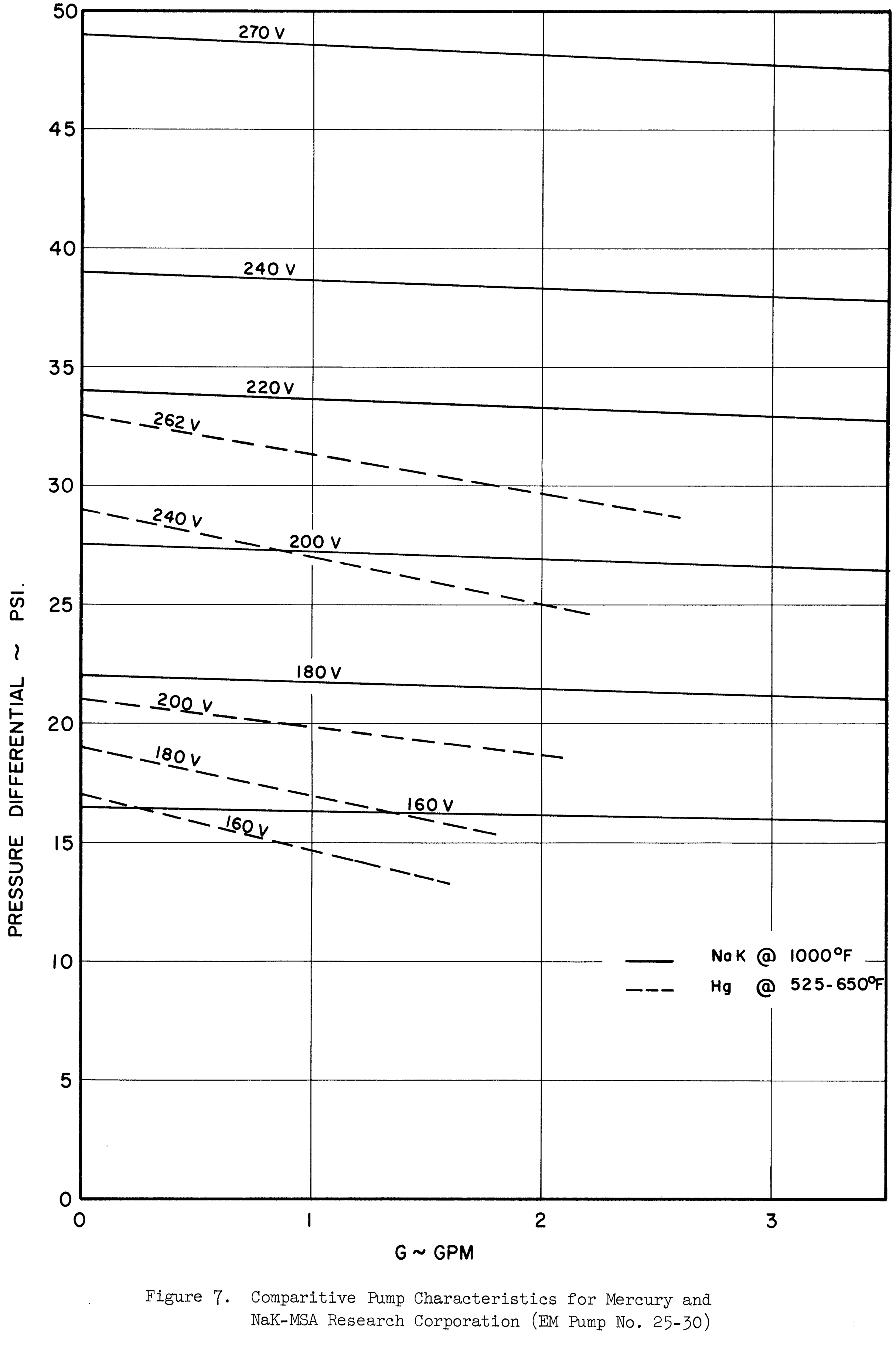

Figure 7. Comparitive Pump Characteristics for Mercury and NaK-MSA Research Corporation (EM Pump No. 25-30)

It was found in these tests that maintenance of an inert gas atmosphere in the loop when the mercury was removed was necessary to the continued existence of the "wetting". However, the "wetting" then persists unchanged over a period of months at least.

4.0 CONCLUSIONS

Experimental and theoretical comparisons have been made between the performance of a conduction-type alternating current electromagnetic pump using NaK and mercury in an austenitic stainless steel pump cell. It has been found that the comparisons approach those predicted on the basis of simplified theory if good "wetting" is obtained. In addition, rough results are reported for molten bismuth and mercury in a magnetic (Croloy) pump cell. In these cases the performance is an order of magnitude less than that for the previous combinations, probably because of the magnetic test section with alternating current and the lack of good "wetting".

It is noted that the performance curves of a pump of this type are quite analogous to those of a turbopump, if voltage is considered to replace rotating speed. The analogy is not complete because of the somewhat different role of density in the relations.

APPENDIX

Force on Element (Figure 1)

$$dF_z = \frac{\partial p}{\partial z}\ dz\ \ dA_z = \frac{\partial p}{\partial z}\ dzdxdy \tag{A-1}$$

also

$$dF_z = B_x(i_y dA_y)\ dy = B_x i_y dxdydz \tag{A-2}$$

Combining (A-1) and (A-2), and realizing that P is a function only of z,

$$\frac{dP}{dz} = B_x i_y --- \tag{A-3}$$

The above is also Equation (1) in the report.

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