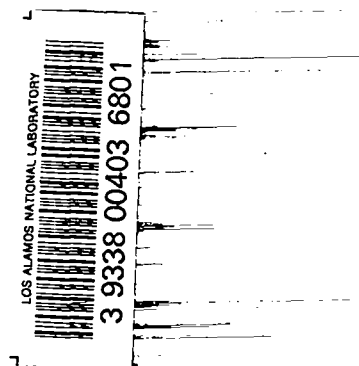


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**An Experimental dc Electromagnetic Pump
for a Molten Plutonium Alloy**



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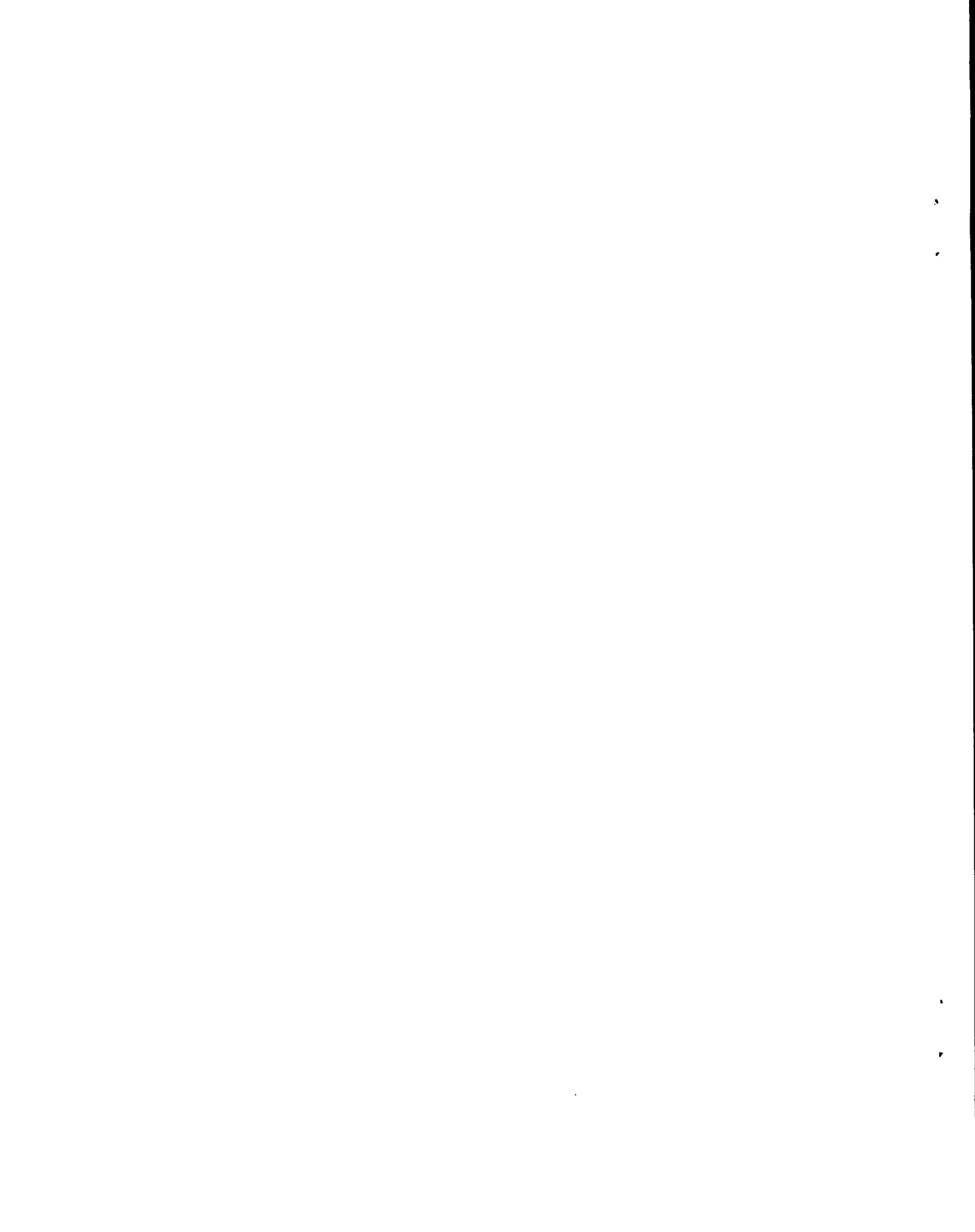
Report distributed: December 9, 1965

An Experimental dc Electromagnetic Pump
for a Molten Plutonium Alloy

by

Gary L. Caldwell





ABSTRACT

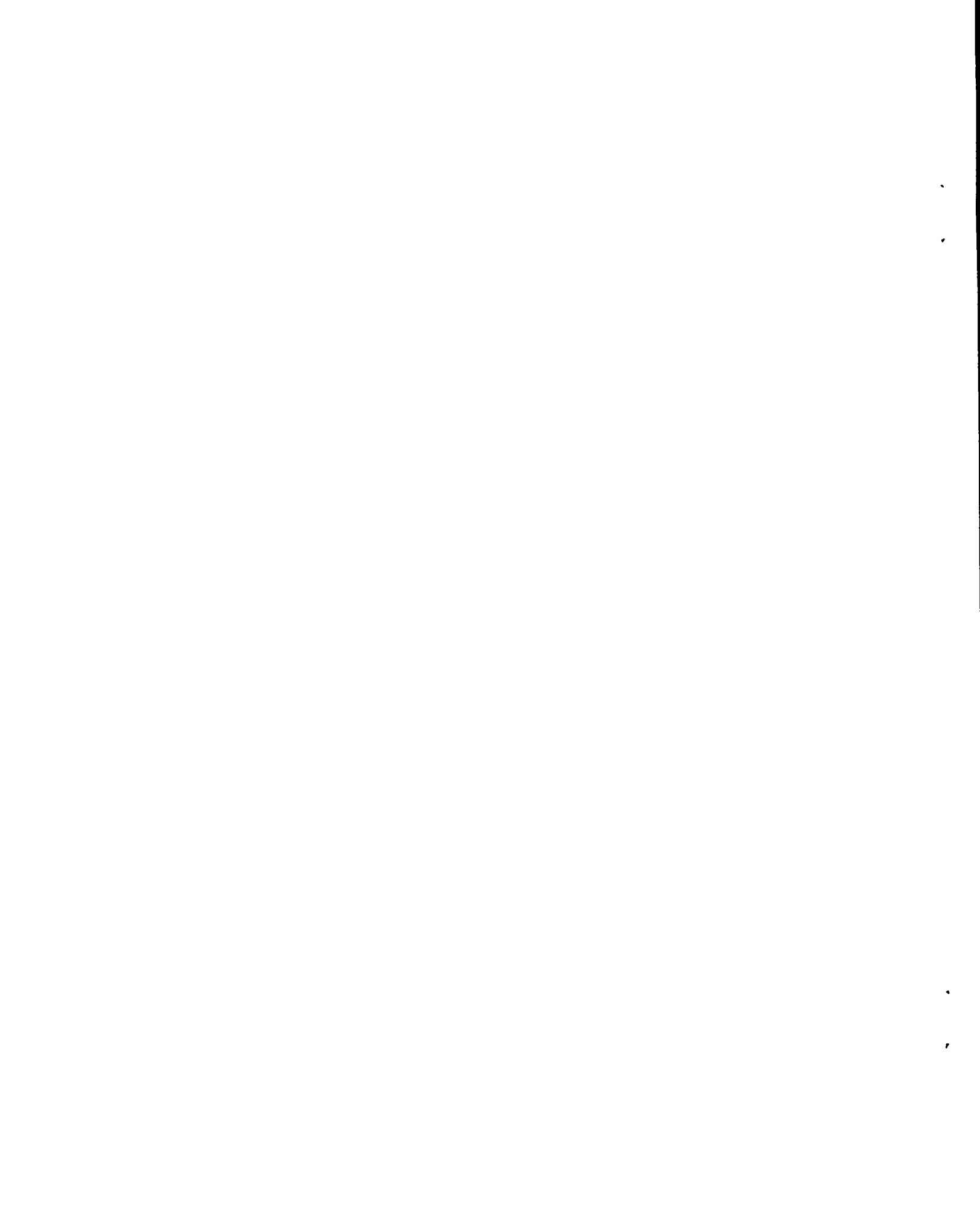
A direct-current electromagnetic pump was used to pump a molten plutonium-cobalt-cerium alloy in a small isothermal closed loop made of tantalum. The purpose of the experiment was to determine operational characteristics of such a pump and an electromagnetic flowmeter in the same loop. Developed pump head was determined by observing radiographically the fluid levels in manometer pressure taps on the inlet and outlet of the pump section.

Two models of the system were constructed to study operational characteristics of an electromagnetic pump and flowmeter when used with a fluid of relatively high electrical resistivity and density. In these models mercury was the pumped fluid, and copper and tantalum were the containment materials.

Operation of the pump with the molten plutonium alloy was very successful, and the results were within expectations.

ACKNOWLEDGEMENTS

The author would like to acknowledge the contributions of two individuals in particular who devoted a great deal of time and effort to getting this project completed: J. Woolsey, who did all the machining, welding, and brazing, and N. B. Edenborough, who performed almost all of the radiography. Thanks are also due to various members of K, GMX, and CMB Divisions who provided valuable assistance.



INTRODUCTION

The ability to pump molten plutonium (or its alloys) would be of considerable interest in the development of fast reactor systems using such a liquid as the fuel. Since the fluid is a moderately good conductor of electricity, there is a possibility of utilizing an electromagnetic (E. M.) pump for the purpose. The absence of moving parts and of penetrations into the pumping system are obvious advantages in view of the hazardous nature of the material involved. Both ac and dc E. M. pumps have been used for liquid metals, especially sodium and sodium-potassium alloys, which have low resistivities and densities.¹ For a liquid metal of relatively high resistivity, an ac design would probably be more efficient, but a dc (Faraday-type) pump was selected for the present experiments because of its inherent simplicity. The fluid to be pumped was an alloy of plutonium, cobalt, and cerium with a melting point in the vicinity of 450° C, representative of alloys under study for reactor applications. The resistivity of the alloy just above the melting point is about 140 $\mu\Omega$ -cm, and the density approximately 10.8 g/cm³.

An E. M. pump and an E. M. flowmeter, to measure the fluid flow rate, were combined in a single closed loop. In the pump section, a direct current and a magnetic field at right angles produce a driving force on the fluid conductor in a direction perpendicular to both current and field. The result is a motion

(or pumping) of the fluid. It was proposed in the experiments to determine the pump head by radiographic observation of fluid levels in manometer taps on the inlet and outlet of the pump section.

In the flowmeter section of the loop the situation is essentially the reverse of that in the pump section. The conducting liquid flowing at right angles to a magnetic field produces a current in a direction perpendicular to both flow and field directions. An emf is thus developed between two electrodes inserted in the fluid in the direction of the current flow. Apart from some corrections, the output emf for a given E. M. flowmeter is proportional to the flow rate.²

Because very few dc E. M. pumps have been previously employed for liquid metals of such relatively high resistivity and density as the molten plutonium alloy, preliminary experiments were carried out with model loops using mercury as the pumped fluid. Observations could then be made at room temperature, thus greatly simplifying the operational procedure. The resistivity of the mercury was about $97 \mu\Omega\text{-cm}$ and the density 13.6 g/cm^3 . Two model E. M. pump loops were constructed; one was made of copper, because it is readily wetted by mercury, and the other was of tantalum, the material from which the loop for the molten plutonium alloy was to be constructed. The main objectives of the model loop experiments were (a) to determine operational characteristics of a dc E. M. pump with a fluid of relatively high resistivity and density, and (b) to evaluate the accuracy of the E. M. flowmeter.

DESCRIPTION OF APPARATUS

General Description

The experimental apparatus, shown schematically in Fig. 1, consisted of the pump loop, made of tantalum, with its associated E. M. pump and E. M. flowmeter. The loop rested on a steel support plate inside a 32-in.-long containment vessel made from 0.322-in.-thick Type 321 stainless steel pipe 8 in. in diameter. The gas in the vessel was helium to prevent oxidation of the tantalum at the high operating temperature of the loop. The system was heated by means of 220-V ac clamshell heaters around the containment vessel; a power of approximately 1 kW was needed to maintain the desired temperature of 480° to 500° C in the pump loop. Interior temperatures were recorded by three chromel-alumel thermocouples extending through Swagelok glands into the vessel.

The containment vessel was sealed with a top lid consisting of a 1-in.-thick stainless steel plate. Various feedthroughs, for the copper conductors carrying current to the pump and to the electromagnet (water-cooled Conax glands) and for the thermocouple connections, passed through this lid and were insulated with Teflon seals. To avoid thermal damage to the seals, the temperature of the Teflon had to be kept below 220° C. The upper 6 in. of the wall of the containment vessel was consequently thinned down to 1/8 in. in order to reduce heat conduction from the hot section. Cooling coils, through which cold

4 COPPER FEEDTHROUGH LEADS CONAX GLANDS

SWAGELOK FITTING FOR
PROBE & 3 THERMO-
COUPLES

GAS LINE

COOLING COILS

LID

SUPPORT ROD

RADIATION SHIELD

COPPER POWER
LEAD

THERMO-
COUPLE

T₀ PUMP LOOP

SUPPORT PLATE

ELECTROMAGNET

LEAK PROBE

T₀ CATCH PAN

PLUTONIUM ELECTROMAGNETIC PUMP EXPERIMENT

Fig. 1. Schematic of Experimental Apparatus

water flowed, and radiation shields, indicated in Fig. 1, also helped to prevent excessive heating of the seals. The containment vessel was surrounded by a 4-in.- thick layer of Suporex insulation and enclosed in aluminum sheeting.

A photograph of the complete apparatus is shown in Fig. 2 in which the upper (cooler) portion of the stainless steel containment vessel is seen protruding from the insulation layer. The heavy black cables carry the dc current from the power supplies to the electromagnet.

If a leak had occurred in the tantalum loop, the molten alloy dripping into the catch pan at the bottom of the containment vessel (see Fig. 1) would have caused an electrical relay to shut off all power supplies to the system. Power would also have been shut off if the temperature of the loop exceeded or fell below preset upper and lower limits, respectively. In the interest of safety, all operations and the recording of data were performed by remote control. Visual observation was always possible, however, through a window in the wall of the control room.

Tantalum Pump Loop

The pump loop (Fig. 3) consisted of a reservoir, two manometer tubes, E. M. pump, and E. M. manometer section. The loop was constructed from high-purity tantalum tubing and sheet (0.025-in. wall thickness), since this is the only practical material known to withstand attack by the molten plutonium alloy at high temperature. All welding and brazing were performed in an inert atmosphere of argon gas, and the completed loop (without pump-tube ears and flowmeter electrodes) was annealed in a vacuum furnace at 1400°C for 1 hour. Figure 4 is a photograph of the pump and flowmeter in place. When the loop was operating, the fluid flowed downward through the pump section and upward through the flowmeter section.

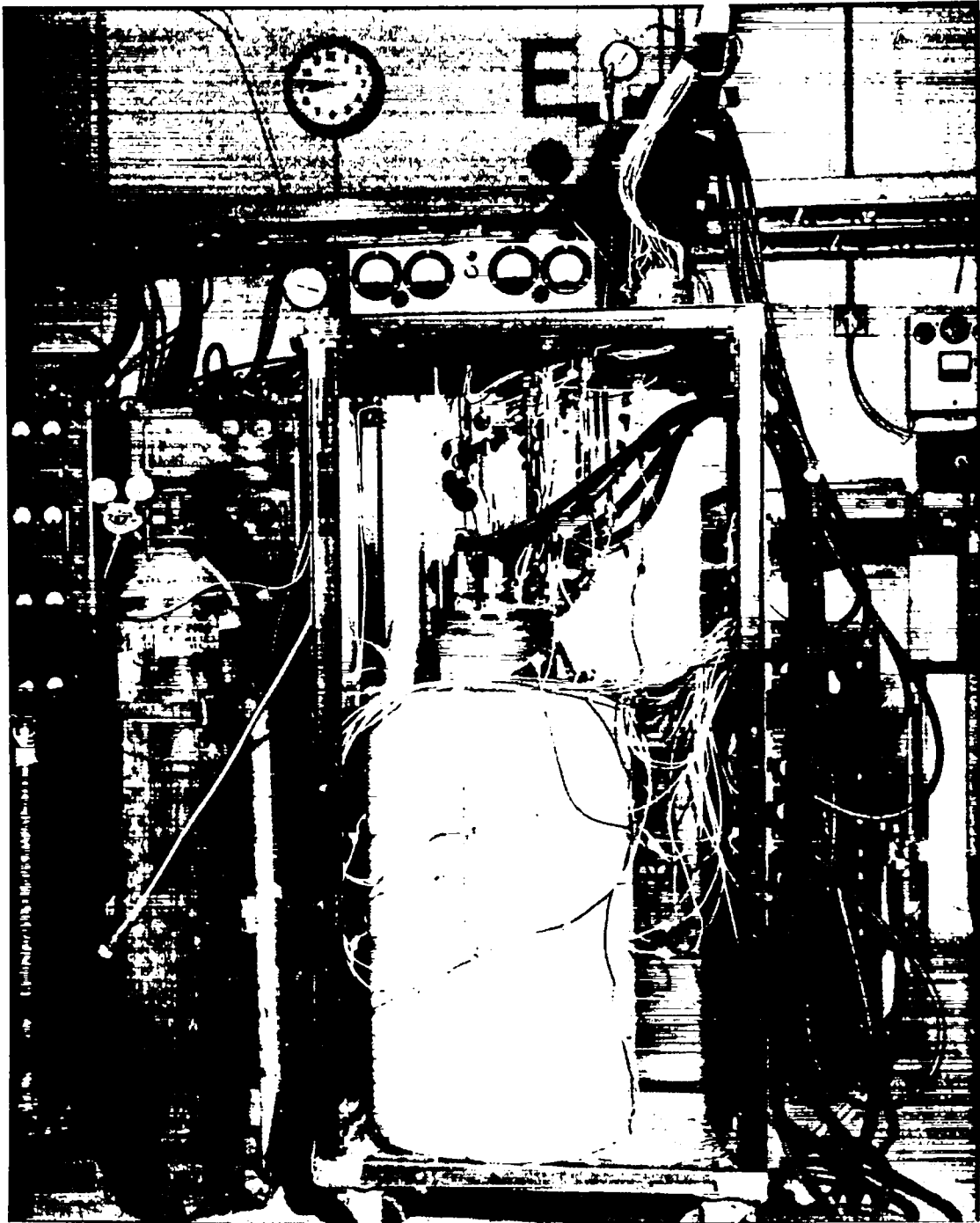


Fig. 2. Experimental Apparatus with Wiring and Insulation in Place

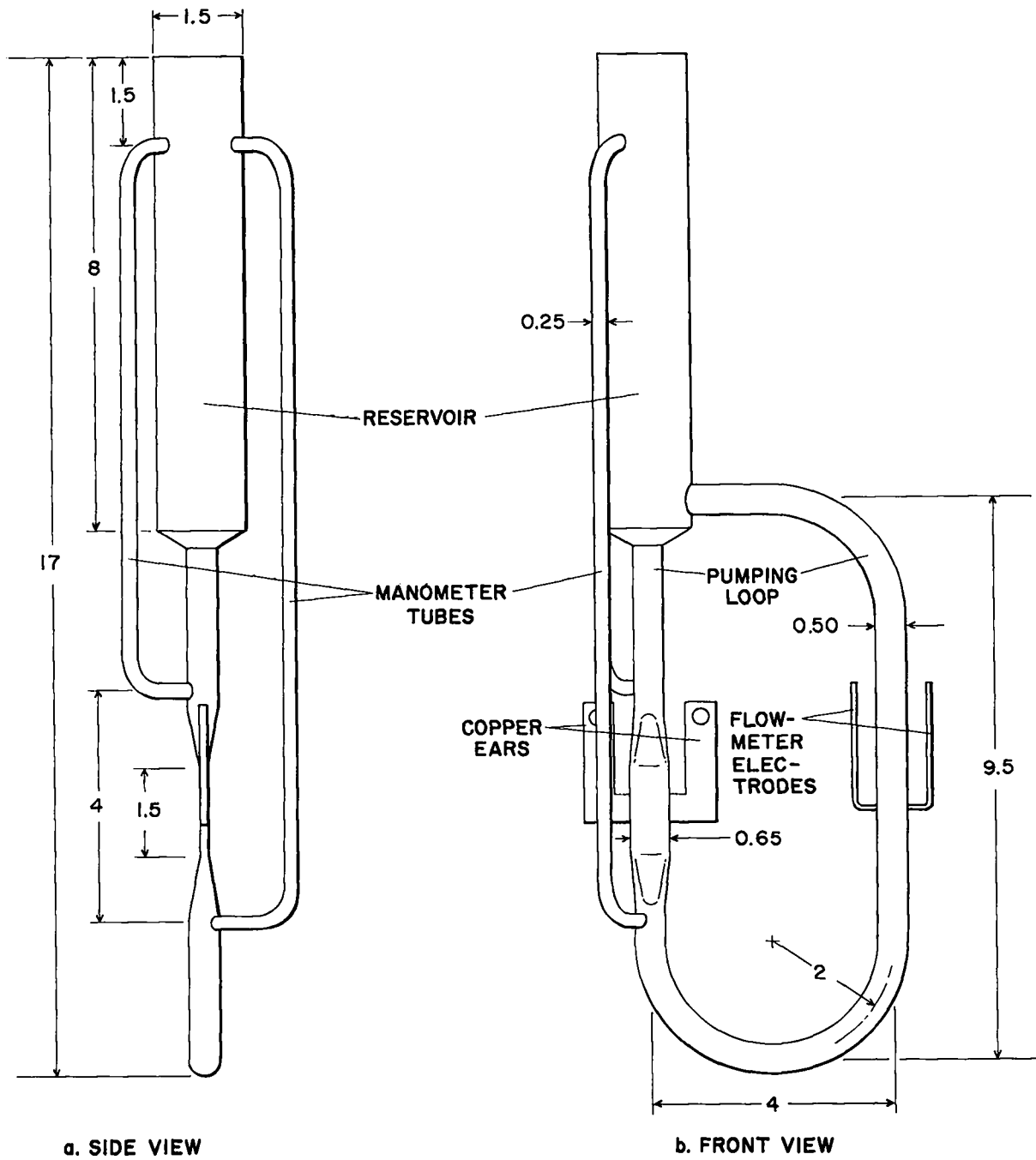


Fig. 3. The Pump Loop with Dimensions in Inches

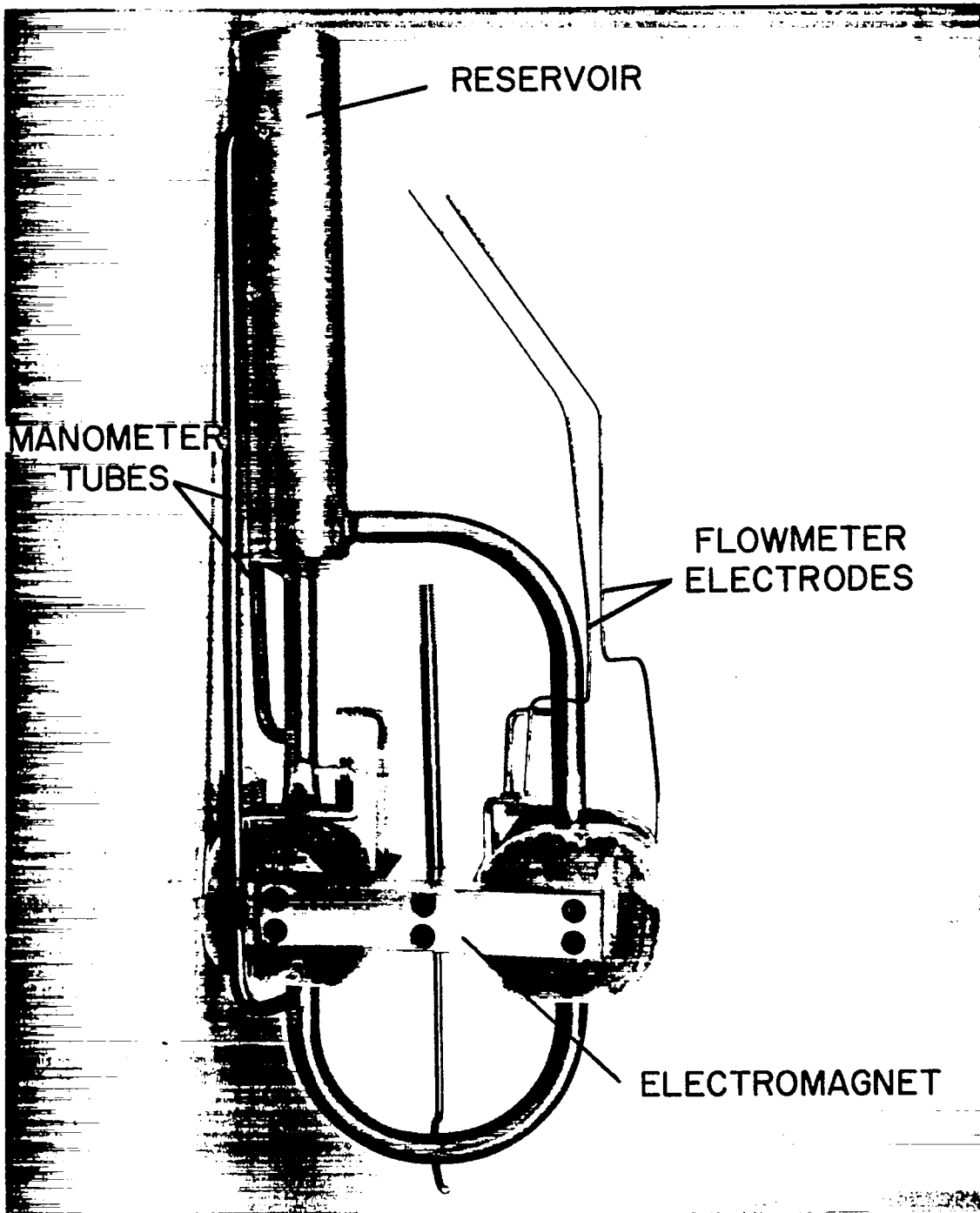


Fig. 4. The Tantalum Pump Loop for Molten Plutonium Alloy

The Reservoir: The reservoir tube had three main purposes: it was the chamber used for loading and melting the solid plutonium alloy slugs, it acted as a surge tank for the circulating molten alloy, and it served as a reservoir of fluid to allow the liquid levels in the manometer tubes to change as needed. The level of the fluid in the reservoir was always maintained above that of the outlet of the pumping loop, shown at the right in Figs. 3b and 4. The cover gas above the molten alloy in the reservoir was argon of high purity.

Manometer Tubes: The two manometer tubes served as pressure taps on the inlet (above) and outlet (below) of the pump section and also as direct pressure measuring devices. The pressure was indicated by the height of the molten alloy in the manometer tubes when referenced to the level in the reservoir as determined radiographically with a 100-curie source of cobalt-60. By locating the two tubes so that they were 120° apart, it was possible to observe the fluid levels in the manometer tubes and in the reservoir in a single radiograph (Fig. 5). The upper portions of the tubes entered the reservoir tube in the gas-phase portion of the latter. Thus, all three liquid levels were subjected to the same cover gas pressure.

E. M. Pump Section: The pump section was an integral part of the pump loop conduit. The normal circular cross section was flattened, however, to an internal height of 0.10 in., as indicated in Fig. 6, in order to approximate the rectangular cross section of an ideal E. M. pump tube (see Fig. 14). Because of the high resistivity of the plutonium alloy, it was necessary to increase the resistance of the wall in order to reduce the proportion of pump current flowing through the latter. This was achieved by decreasing the wall thickness of the pump section from the normal 0.025 in. to 0.015 in. Any greater reduction in thickness might have jeopardized the integrity of the loop system.

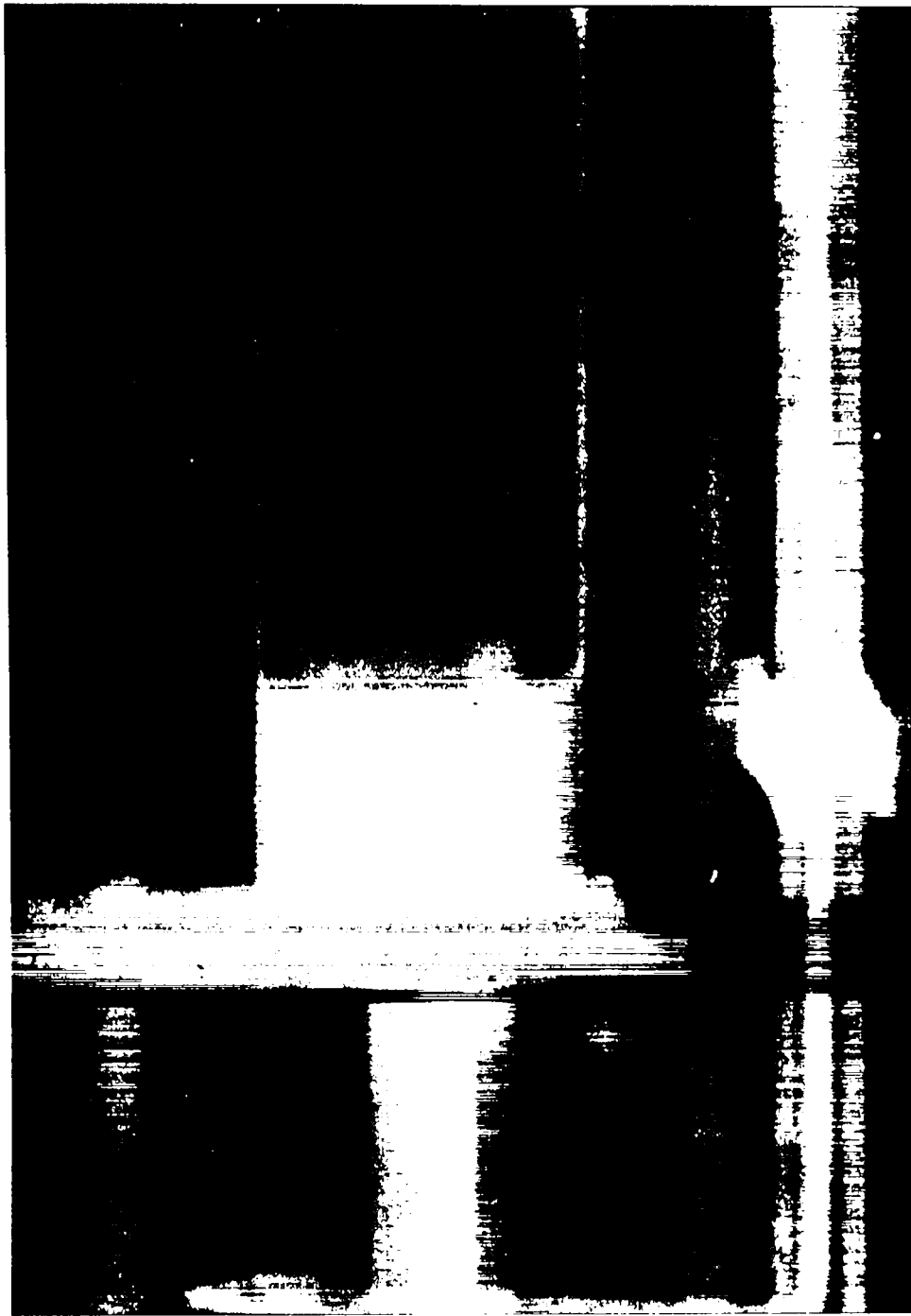


Fig. 5. Radiograph Showing Levels of Molten Plutonium Alloy in Manometer Tubes and Reservoirs

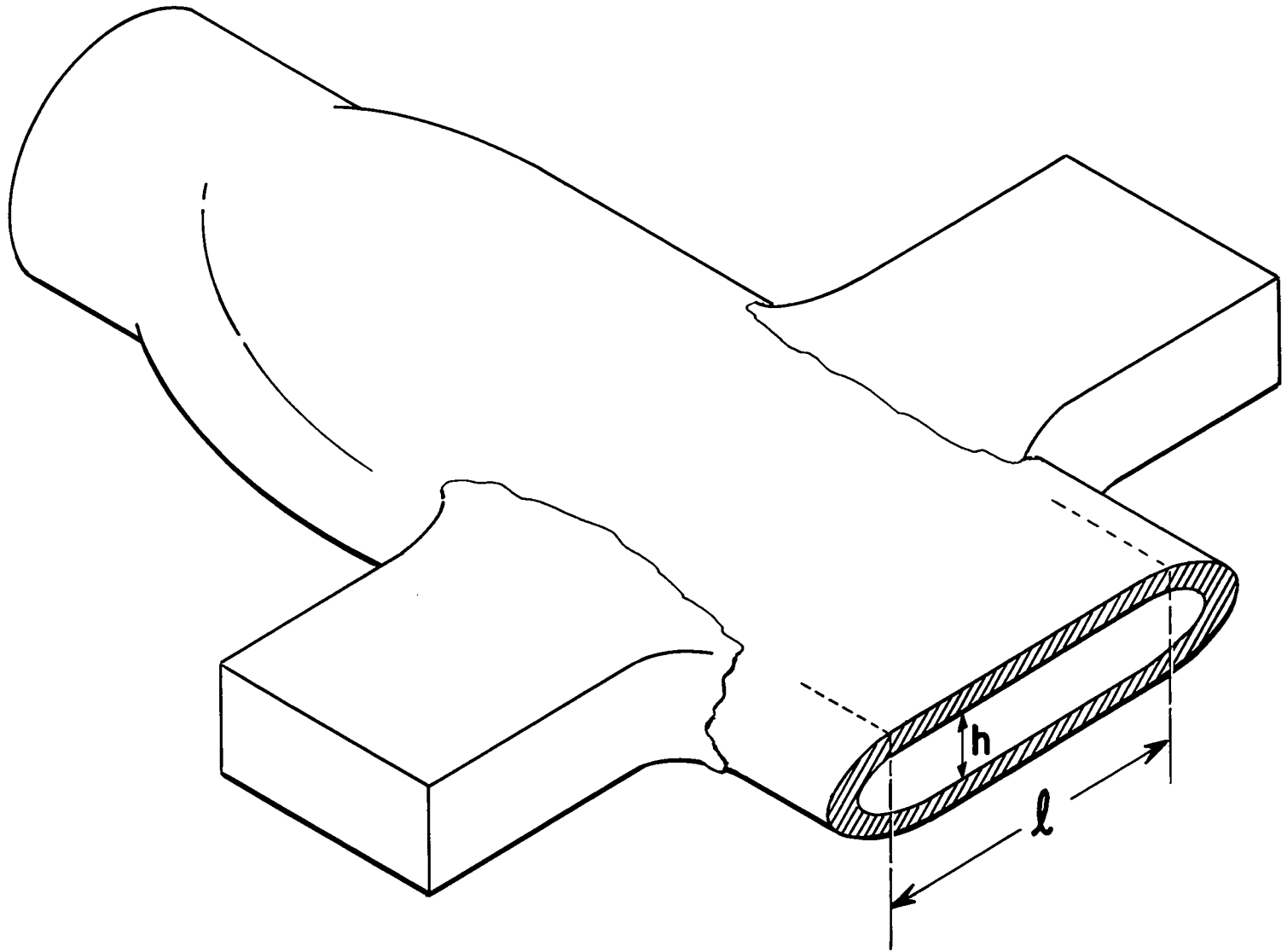


Fig. 6. Representation of E. M. Pump Section

Copper ears (1/2 in. x 1/8 in.) were fastened onto the center of the pump section to provide electrical connections for the pump current (cf. Figs. 3 and 6). Copper was preferred to tantalum for this purpose because of its lower electrical resistance and excellent ductility at high temperature. Since inert gas (helium) was used in the steel containment vessel, oxidation of the copper was no problem. The copper ears were fused directly onto the tantalum tube using an inert arc welding torch without addition of brazing material. Metallographic examination of samples showed that a good mechanical bond was formed by this process with no interstitial penetration of the tantalum by copper. The strength of the bond was equivalent to that of tantalum itself, and thermal cycling tests, between room temperature and 700°C, indicated that the bond would not be destroyed as a result of differential expansion upon heating.

E. M. Flowmeter: The flowmeter section was merely a part of the flow loop to which two tantalum wires of 0.030-in. diameter were attached to serve as electrodes for measurement of the voltage output. The wires were welded directly to the tube diametrically opposite one another and in the plane formed by the tube and the pump-section ears. Because of difficulty of inserting the electrodes into the softened tantalum during the welding operation, the wires were not flush with the wall of the flowmeter tube, but extended somewhat into the interior. The spacing of the electrodes was determined by radiographing the loop, using a 20-MeV betatron as a source of x-rays. The protuberance of the electrode wires into the molten plutonium alloy was not sufficient to produce any significant distortion of the flow pattern.

In the course of the model studies with the pump loops of copper and of tantalum, with mercury as the liquid metal being pumped, the reliability of the E. M. flowmeter was established. This was done by cutting off the bottom

180° turn in the pumping circuit and replacing it with a length of Tygon tubing having a small Lucite Venturi flowmeter attached. The flow of mercury was then down through the pump, through the Tygon tubing and Venturi flowmeter, and up through the E. M. flowmeter. The flow rates calculated for the E. M. flowmeter output voltage (see p. 27) were in excellent agreement with those given by the Venturi meter at flow rates up to at least 0.4 gpm of mercury.

The Electromagnet: The electromagnet used in the experiment was actually two magnets--one for the pump and the other for the flowmeter--sharing a common center pole piece. The pole pieces, whose dimensions are shown in Fig. 7, were made of Armco iron, because of its high Curie temperature and permeability. The permeability decreases, however, with increasing temperature, and in order to minimize the resulting leakage flux when operating at high temperature, the coils producing the magnetic flux were placed as close to one another as possible on either side of the flow tubes. The spacing of the pole pieces was just sufficient to permit 0.030-in.-thick mica insulation to be placed around the flattened pump section (left side of Fig. 7) and the flowmeter section (right side) of the circuit.

The flux coils were wound with 3/4-in.-wide, 1/8-in.-thick copper strip, with mica strips between the windings; there were approximately five turns in each of the four coils. The complete assembly of the electromagnet and its location on the pump loop can be seen in Fig. 4. During pumping experiments, the current through the pump magnet coils ranged, in different measurements, from zero to 350 A, but that in the flowmeter magnet coils was always 300 A. Direct measurements of flux indicated that the interaction between the two magnetic fields was small, being less than 7 percent at most. Figure 8 shows the magnetic flux as a function of current in the magnet coils.

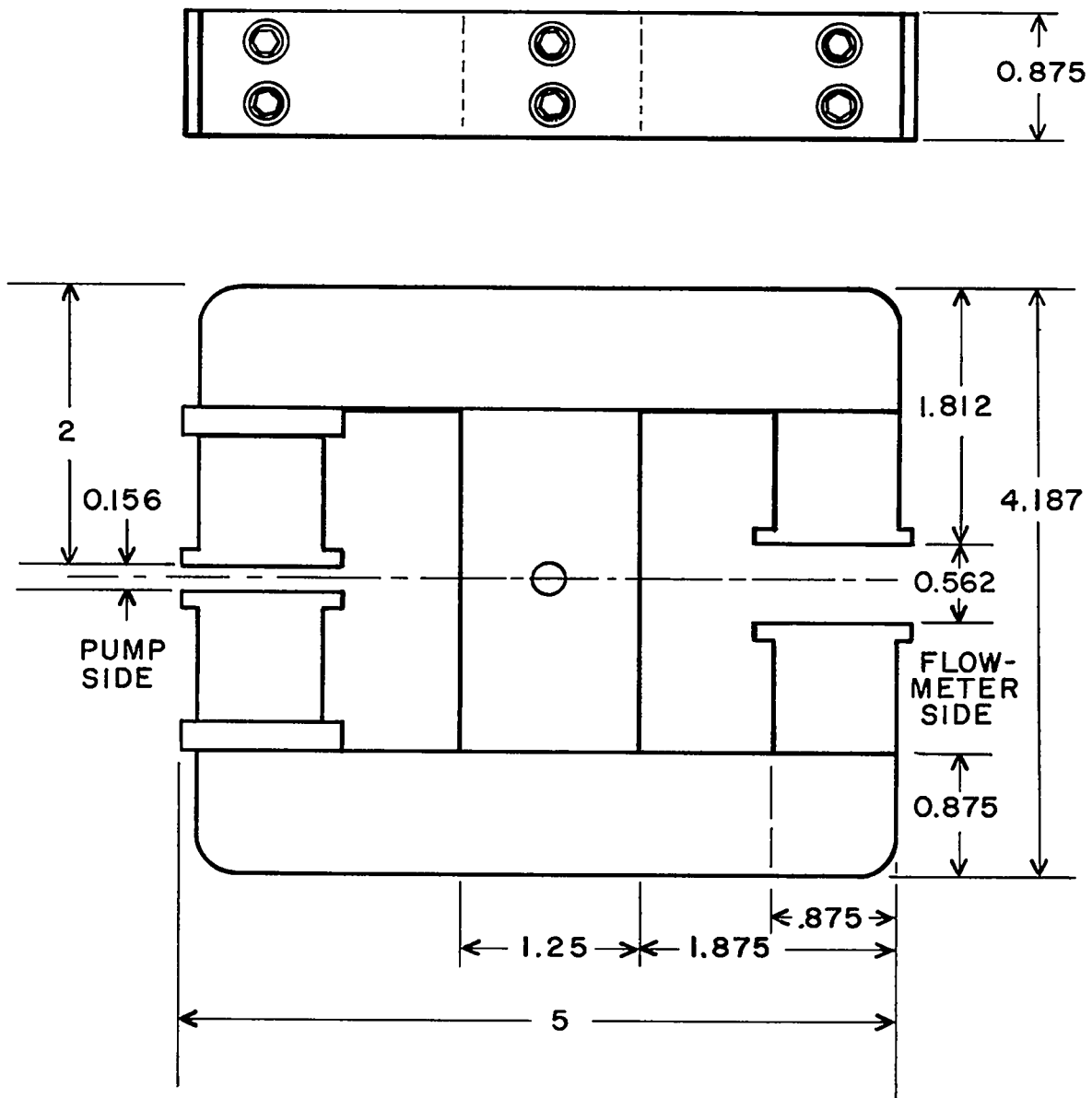


Fig. 7. Dimensions (in inches) of Electromagnet Pole Pieces

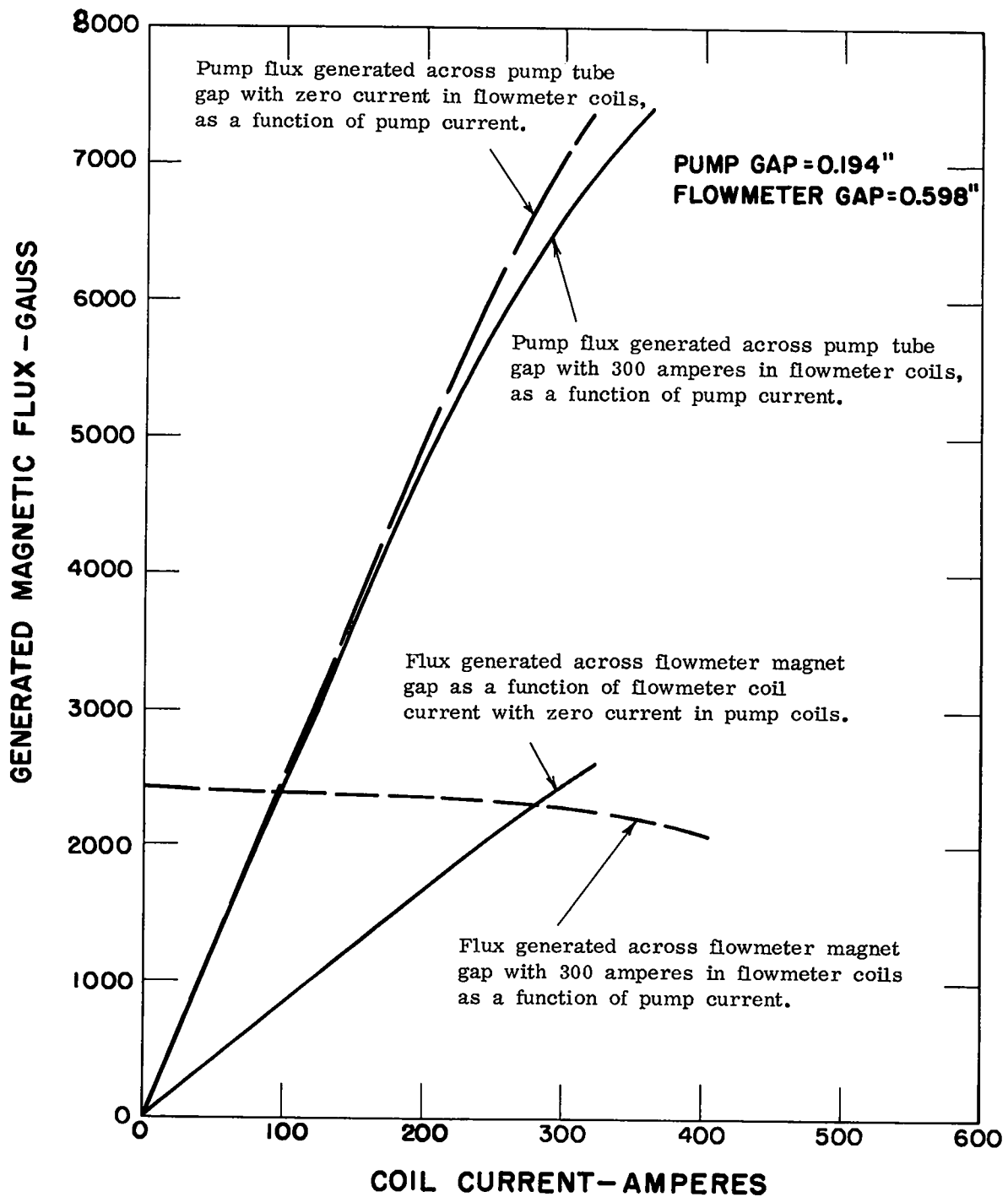


Fig. 8. Pump and Flowmeter Flux as a Function of Current

Pump Current: The dc pump used in the experiments was of the series-connected type. In other words, the same current that passed through the pump magnet flux coils was also the driving current for the pump itself, via the copper ears described earlier.

OPERATIONAL PROCEDURE

Preparation for Experiment

Before the tantalum cap at the top of the reservoir tube was sealed, 982 grams of a plutonium (57.7 w/o)-cobalt (9.4 w/o)-cerium (32.8 w/o) alloy, containing 6.29 g Pu/cm³, were loaded into the reservoir in solid form. The usual precautions were taken in the handling of plutonium materials. The tantalum loop, containing air, was placed in a pumpdown chamber which was evacuated and flushed twice with high-purity argon gas. The tantalum cap of the reservoir tube was then welded in place; a heavy copper collar around the end of the tube served to reduce the amount of heat transferred to the solid plutonium alloy.

The loop, now containing argon as cover gas, was mounted on the support plate of the test assembly, and all the electric wiring was connected and checked. The assembly, shown in Fig. 9, was then lowered into the 8-in. - diameter stainless steel containment vessel, and the top lid was welded in place. The vessel was evacuated and flushed several times with helium. After all heaters, thermocouples, insulation, and cooling coils were checked out, the outer aluminum cover sheeting was installed and the system was ready for operation.

The power to the clamshell heaters was increased, and the temperature of the loop rose gradually. In order to prevent damage to the thin-walled tantalum vessel as a result of the increasing internal pressure of the argon gas,

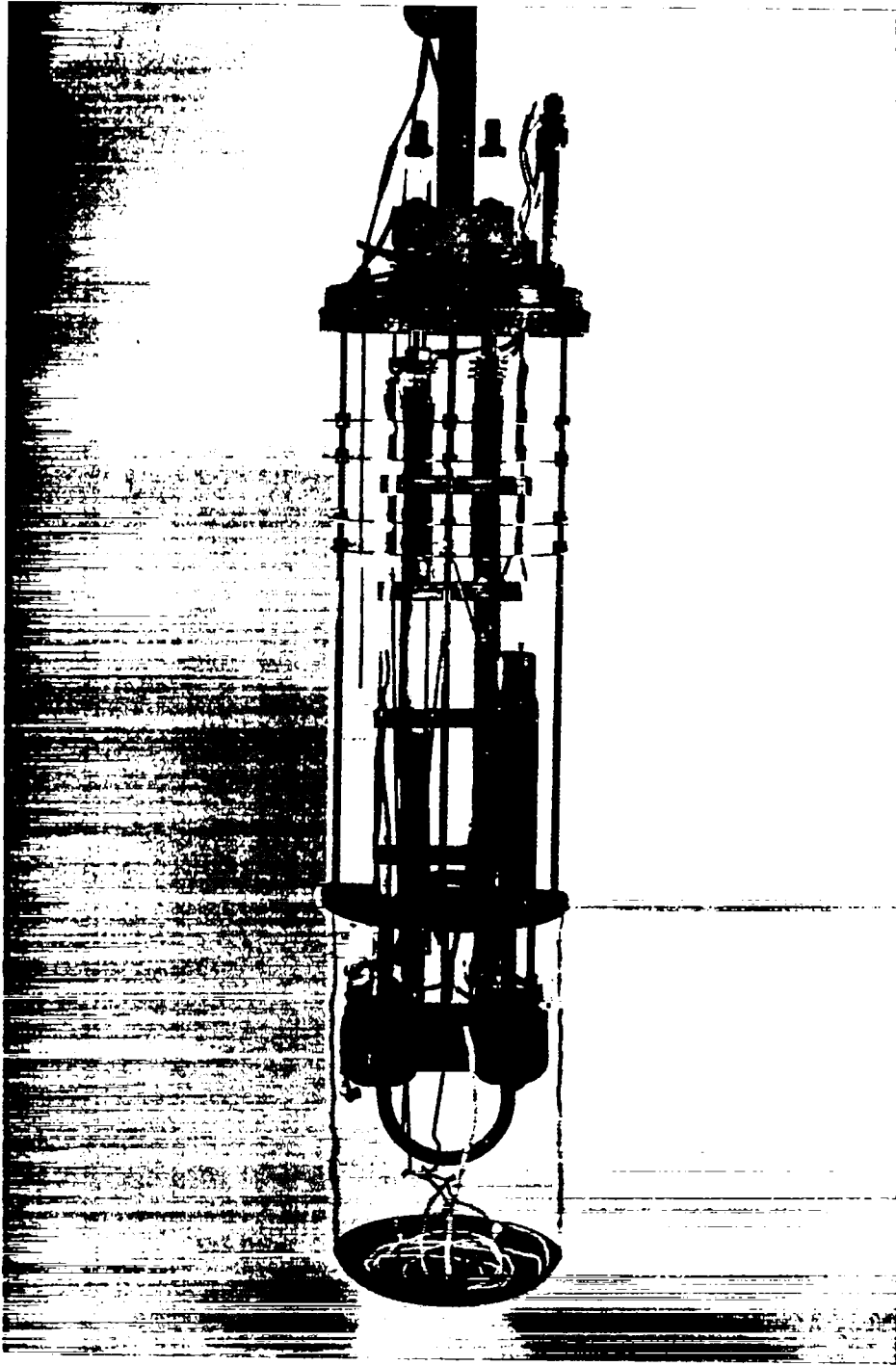


Fig. 9. Complete Experimental Assembly Ready for Lowering into Containment Vessel

upon heating, the helium pressure in the containing vessel was increased correspondingly. The gas temperatures in the loop and in the containing vessel were measured, and the argon and helium were maintained at the same pressure by assuming applicability of the ideal gas laws, i. e. , $P_1/T_1 = P_2/T_2$.

The meltdown of the fuel was indicated in two ways. First, the thermocouple attached to the wall of the reservoir tube showed a definite temperature arrest close to 446° C. Second, the resistance of the pump section, as determined from the voltage between the pump-tube ears with a constant current of 10 A across the tube, showed a sharp decrease at about the same temperature. The low value of the resistance after melting suggested that wetting of the tantalum by the liquid plutonium alloy occurred immediately. This assumption was substantiated by the fact that no significant further change in resistance was observed during operation of the system. A radiograph taken directly after meltdown indicated that the solid alloy had melted completely.

Experimental Observations

When the desired temperature, usually between 480° and 500° C was attained, the currents in the pump and flowmeter magnet coils were brought to the desired values simultaneously. As stated earlier, the flowmeter coil current was always approximately 300 A, but the pump current was varied. Readings were taken of the pump current, flowmeter current, pump tube voltage drop, E. M. flowmeter voltage output, and loop temperature before and after each radiograph. A radiograph of the three liquid levels was obtained with the source-to-object distance of 36 in. and the source-to-film distance of 48 in. This arrangement resulted in some magnification of the level differences, and the necessary correction was derived using the meniscus in the reservoir tube as the reference line. The corrected difference between the levels in the two

manometer tubes was then used, in conjunction with the known density of the molten alloy (10.8 g/cm^3 at 470°C and 10.7 g/cm^3 at 550°C), to obtain the observed pump output pressure.

It is of interest to note that even when the pump was not operating, there was a difference of about 0.25 in. in the levels; this was ascribed to capillary action arising from the very high surface tension ($\sim 1000 \text{ dynes/cm}$) of the liquid alloy. Apparently, wetting of the tantalum by the liquid alloy did not occur above the equilibrium level in the manometer tube subjected to downward liquid motion only. For level displacements greater than 0.25 in., however, the capillary action in each tube was balanced, so no correction was required.

The exposure time for the radiograph was 5 min, and during this period the temperature of the circulating fluid increased somewhat owing to Joule heating in the pump section. All readings were repeated and recorded at this slightly higher temperature. The currents and flowmeter readings were lower because of the increase in resistance of the fluid accompanying the increase in temperature.

EXPERIMENTAL RESULTS

The results of a number of experiments with different pump currents and over a range of temperatures are summarized in Table I. The two sets of data for each experiment refer to observations made before and after radiography, respectively. In addition to the measurements recorded in Table I, many other experiments of flow rate were made, with pump currents up to 350 A, but no radiographs were taken. The pump output pressures are therefore not available.

The voltage readings of the flowmeter were subject to a correction arising from a thermoelectric emf between the two junctions where the tantalum electrodes were connected to copper extension wires. One of these junctions was nearer the containment vessel wall, and was consequently at a somewhat higher temperature than the other. The emf generated in this manner was measured after each experiment for zero flow conditions, and a correction, amounting to about 0.03 to 0.08 mV, was applied to the measured flowmeter output voltage to give the values, E , quoted in Table I.

To obtain the flow rate, Q , use was made of the E. M. flowmeter equation¹ which may be written in the form

$$\frac{E}{Q} = 3.18 \times 10^{-4} \frac{B_f m'}{d^2} K_1 K_2 \text{ mV/gpm}, \quad (1)$$

TABLE I
TABULATED EXPERIMENTAL DATA WITH CALCULATED RESULTS

Run No.	Pump Current	Flowmeter Current	Pump Tube Voltage Drop	Average Loop Temperature	Corrected Flowmeter Output	E/Q	Flowrate	Average Measured Output Pressure
	I amp	amp	mV	* C	E mV	mV/ gpm	Q gpm	P psi
1	0	0	0.01	470	0	- - -	0	0.01
2	100	300	24.0	487	0.335	1.042	0.32	0.194
	100	294	24.3	488	0.357	1.042	0.34	
3	200	300	52.0	488	0.782	1.030	0.76	0.60
	201	296	52.0	500	0.791	1.043	0.77	
4	300	300	77.0	475	1.071	0.979	1.10	1.21
	294	294	77.5	500	1.081	0.987	1.10	
5	50	303	12.3	485	0.151	1.047	0.14	0.14
	51	296	12.3	490	0.154	1.049	0.15	
6	76	303	18.2	485	0.255	1.045	0.24	0.175
	75	296	18.4	490	0.255	1.045	0.24	
7	0	0	0.01	485	0	- - -	0	0.11
8	102	301	24.7	482	0.355	1.040	0.34	0.23
	102	295	24.8	485	0.360	1.040	0.35	
9	126	303	31.0	490	0.475	1.038	0.46	0.30
	126	296	31.4	491	0.475	1.038	0.46	
10	150	302	38.2	488	0.585	1.034	0.56	0.42
	150	295	38.5	493	0.580	1.035	0.56	
11	175	303	44.5	490	0.674	1.029	0.66	0.52
	173	295	45.0	500	0.674	1.033	0.65	
12	226	302	58.2	493	0.874	1.015	0.86	0.80
	223	297	59.2	507	0.874	1.018	0.86	
13	202	303	52.5	495	0.789	1.025	0.77	0.67
	202	298	53.0	508	0.809	1.027	0.79	
14	0	0	0	473	0	- - -	0	0.10
15	252	303	63.8	473	0.93	1.000	0.93	0.91
	245	294	64.3	500	0.95	1.011	0.94	
16	50.5	303	12.2	476	0.144	1.044	0.14	0.103
	50.5	293	12.1	486	0.150	1.047	0.14	
17	100	303	24.3	485	0.368	1.041	0.35	0.17
	100	293	24.5	492	0.371	1.047	0.35	
18	86	303	20.9	483	0.307	1.047	0.30	0.16
	87.5	298	21.3	492	0.321	1.047	0.31	
19	201	302	51.0	482	0.779	1.021	0.76	0.65
	199	294	51.5	500	0.785	1.025	0.77	
20	201	303	52.2	490	0.813	1.023	0.79	0.66
	201	298	52.8	508	0.819	1.027	0.80	
21	201	300	52.8	507	0.822	1.027	0.80	0.65
	201	295	53.0	522	0.830	1.031	0.81	
22	200	301	52.8	514	0.829	1.029	0.80	0.65
	200	300	53.8	525	0.841	1.031	0.82	
23	201	302	53.8	520	0.848	1.030	0.82	0.65
	201	300	54.7	535	0.851	1.034	0.82	
24	201	303	53.8	530	0.846	1.034	0.82	0.65
	199	300	54.5	545	0.855	1.035	0.83	
25	100	302	25.9	546	0.402	1.057	0.38	0.22
	100	300	26.2	548	0.416	1.058	0.39	

where E is the flowmeter voltage in mV, Q is in gpm, B_f is the flowmeter magnetic field strength in gauss, m in. is the distance between the flowmeter electrodes, as determined by radiography (p. 17), and d in. is the inside diameter of the flowmeter tube; K_1 and K_2 are factors which correct for conduction by the tantalum walls and for the finite size of the magnet, respectively.^{1,2}

The magnetic field strengths for a constant E. M. flowmeter magnet current of 300 A and for various pump magnet currents were determined by direct measurement, as stated earlier, and are shown in Fig. 8. Since B_f , m , d , and the correction factors are all known, E/Q can be calculated; the results are recorded in Table I.* Since E , the flowmeter output voltage, has been measured, the flow rate Q can be readily evaluated for each experiment.

The flow rate of the molten alloy as a function of the pump input current is shown in Fig. 10; the data points are for measurements made in experiments with and without radiography. The clusters of points at 100 and 200 A represent measurements at somewhat different temperatures. The faired line may be regarded as applying to a system temperature of $485 \pm 15^\circ \text{C}$. It will be noted that the line exhibits a change in slope at a current of about 250A; this is accounted for by a corresponding change in the curve of pump magnet flux vs current (Fig. 8).

The variation of the developed pump output pressure with the pump current is indicated in Fig. 11. The vertical bars show the range of the actual observations which were averaged to obtain the output pressure values recorded in Table I. The uncertainties arise mainly from the difficulty in determining level differences from the radiographs. The large uncertainty at 297-A pump current was caused by the liquid level in the inlet manometer tube dropping so low that the actual liquid level was covered by the shadow of the support plate.

*It should be noted that if there had been no interaction of the pump and flowmeter magnetic fields, E/Q would have been essentially constant in these experiments. The actual variation is relatively small.

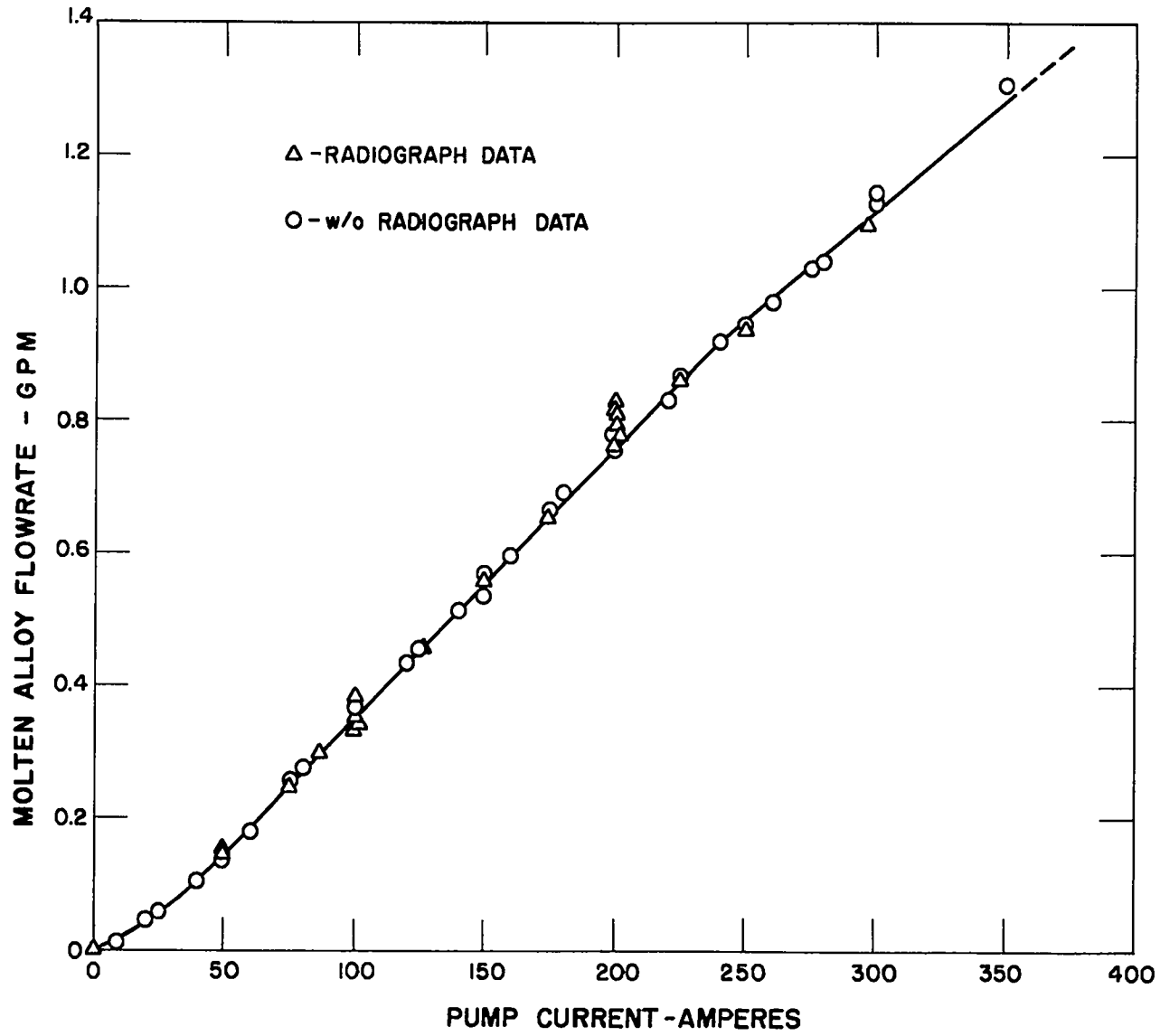


Fig. 10. Molten Alloy Flow Rate vs Pump Current

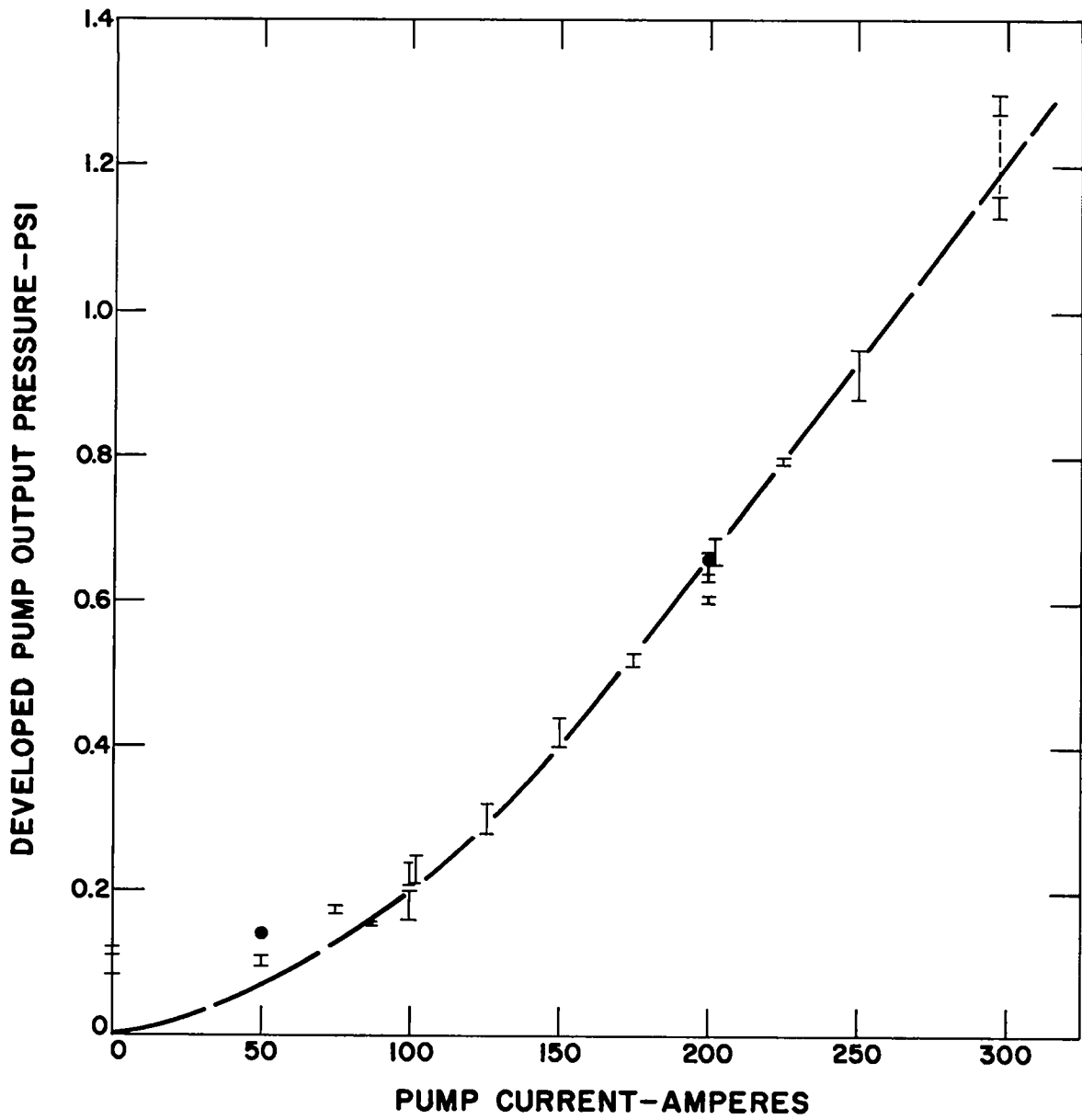


Fig. 11. Pump Output Pressure vs Pump Current

CALCULATIONS OF PUMP CHARACTERISTICS

The values of the pump output pressure are plotted against the molten alloy flow rates in Fig. 12, using the data in Table I. The dashed curves represent the ideal performance of the E. M. pump at the indicated pump currents. The data for the ideal pump performance curves were obtained from the equation¹ which gives the flow rate in gallons per minute,

$$Q = \frac{4.0 h}{B} \left[IR_B - \frac{1.75 \times 10^6 Ph}{B} (R_B + R_e) \right] \text{ gpm,} \quad (2)$$

where h in. is the inside height of the pump tube in the direction of the magnetic flux, i. e., 0.1 in. in the present case (see Fig. 6); B is the pump magnetic field strength in gauss; I is the pump current in amperes; P is the total pump output pressure in psi including pressure loss through the pump tube itself; $R_B \mu\Omega$ is the total bypass resistance (through wall and fluid) for noneffective pump current as explained below; and $R_e \mu\Omega$ is the effective resistance of the fluid in the pump section. The quantities h , B , and I , are known for each experiment; hence, if R_B and R_e can be determined, the ideal flow rate, Q , and the ideal pump output pressure, P , could be calculated.

In order to evaluate R_B and R_e , consider the equivalent circuit of the E. M. pump in Fig. 13; I is the total pump current, I_e is the current traversing

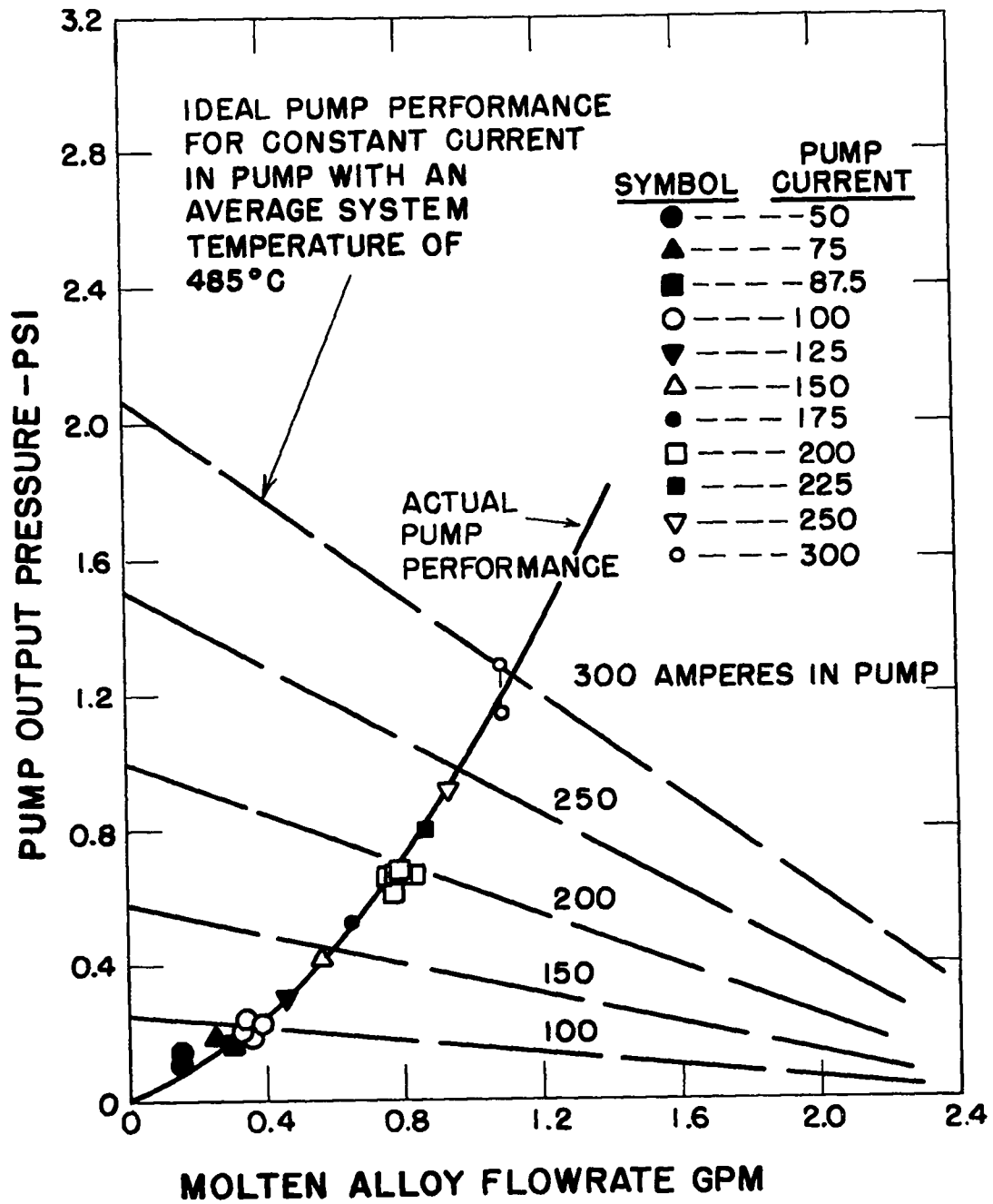


Fig. 12. Pump Characteristic Curves

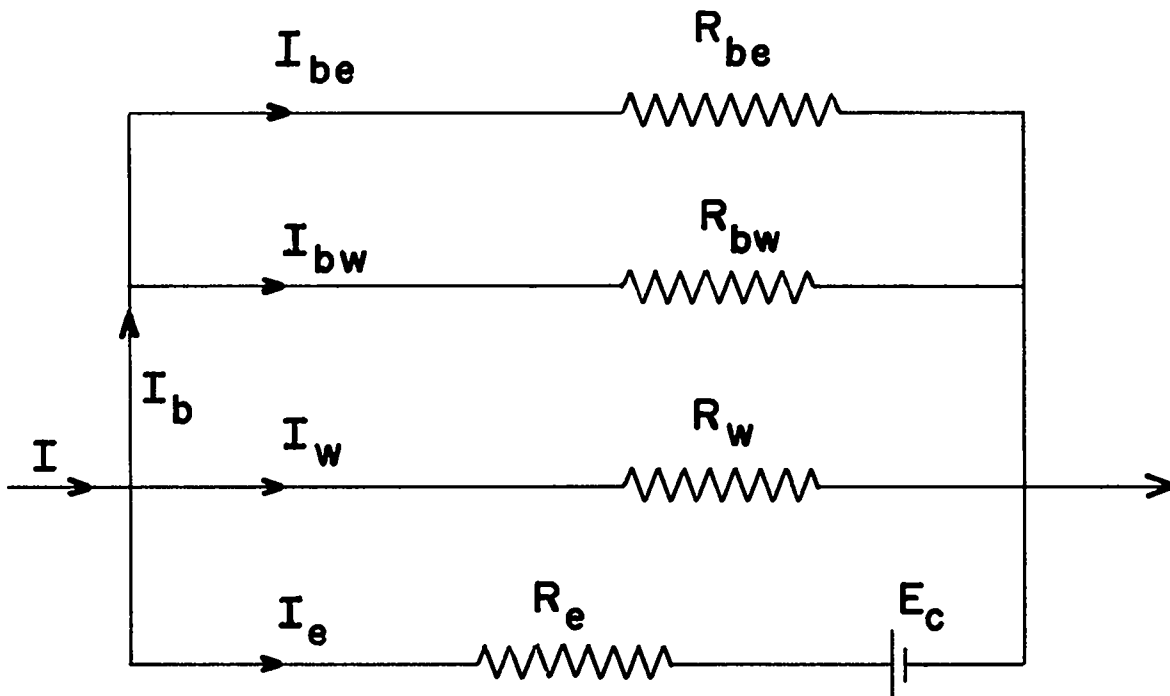


Fig. 13a. Current Distribution Schematic

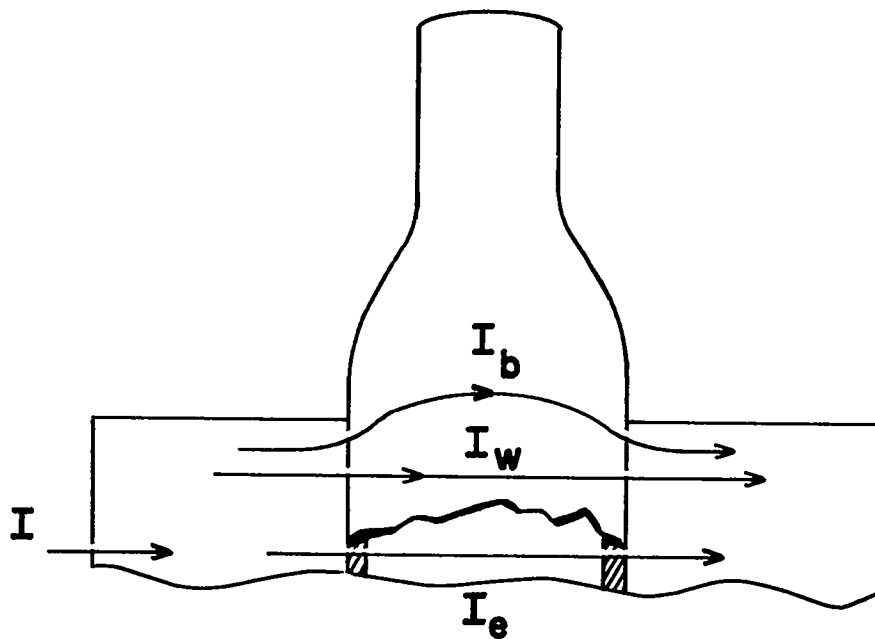


Fig. 13b. Actual Current Distribution

the fluid located in the region of the strong magnetic field, I_w is the current crossing the pump region of the tube through the wall, and I_b is the sum of the currents passing through the wall (I_{bw}) and the fluid (I_{be}) in the regions of weak magnetic field at the entrance and exit portions of the pump tube. The corresponding resistances are shown in the figure. The resistance R_B in Eq. (2) is then given by

$$\frac{1}{R_B} = \frac{1}{R_w} + \frac{1}{R_{be}} + \frac{1}{R_{bw}} \quad (3)$$

Hence, to evaluate R_B , the quantities R_w , R_{be} , and R_{bw} must be determined.

If R' is the measured resistance of the pump tube with no fluid in the interior, then from Fig. 13,

$$\frac{1}{R'} = \frac{1}{R_w} + \frac{1}{R_{bw}}$$

so that

$$R_{bw} = \frac{R' R_w}{R_w - R'} \quad (4)$$

For an ideal E. M. pump with a rectangular cross section (Fig. 14),

$$R_w = \frac{\rho_w l}{2ct(2.54)} \mu\Omega, \quad (5)$$

where ρ_w is the electrical resistivity of the wall material in $\mu\Omega\text{-cm}^2$, l in. is the width of the pump tube in the direction of current flow, c in. is the width of the pump-tube ear in the direction of fluid flow, and t in. is the wall thickness of the pump tube section; 2.54 is the factor for conversion from inches to centimeters. All the quantities on the right of Eq. (5) may be regarded as known, and so R_w can be determined. Furthermore, if R' is measured, then R_{bw} can be calculated from Eq. (4). Thus, R_w and R_{bw} may be evaluated. It should be

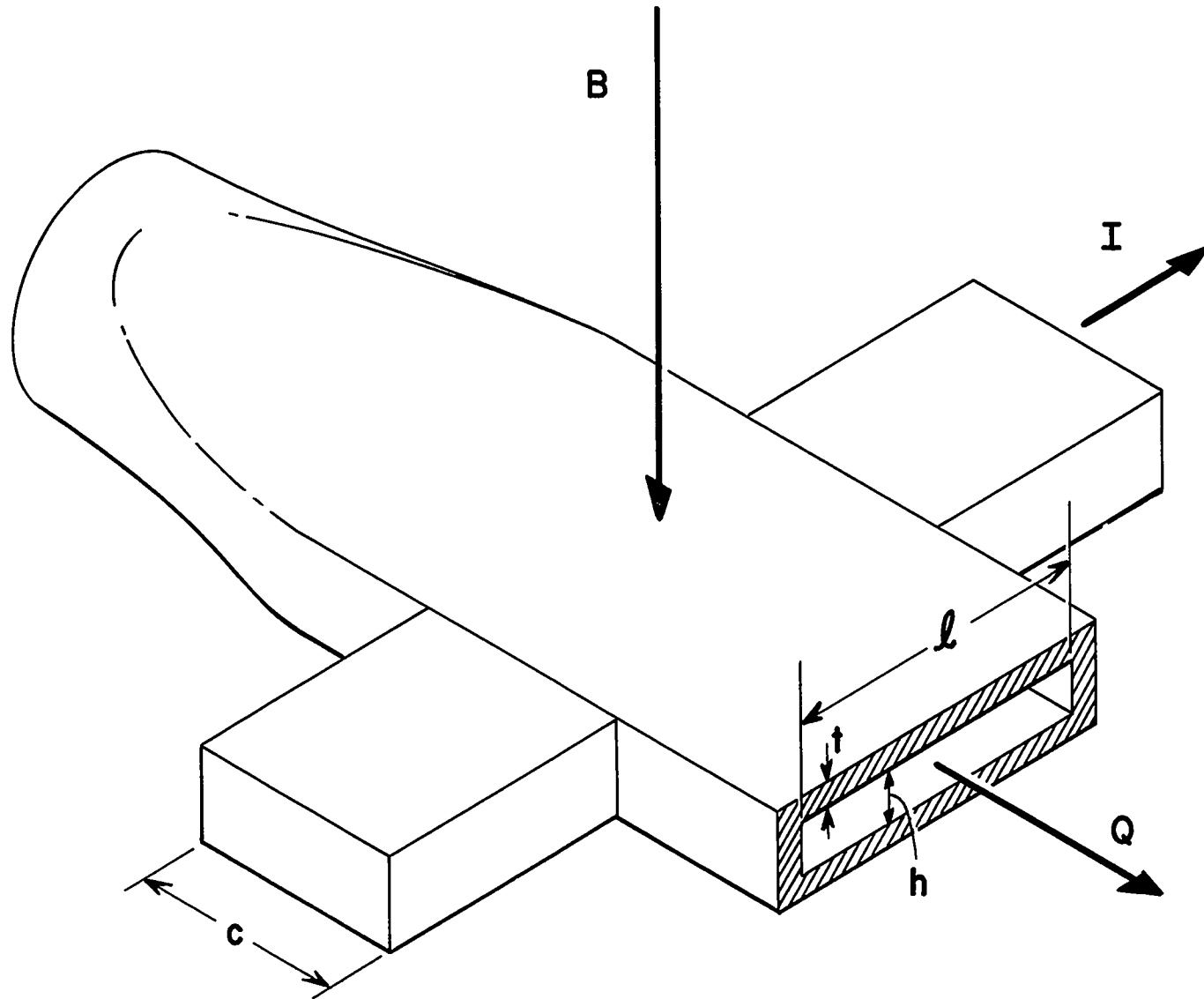


Fig. 14. Dimensions of Ideal E.M. Pump Section

noted that since the actual pump cross section is not rectangular, an approximation must be made in obtaining l , the pump tube width. This is chosen, somewhat arbitrarily, in the manner shown in Fig. 6.

Let R'' be the measured resistance of the pump section when filled with fluid; it follows from Fig. 13 that

$$\frac{1}{R''} = \frac{1}{R_e} + \frac{1}{R_w} + \frac{1}{R_{bw}} + \frac{1}{R_{be}} \quad (6)$$

The value of R_e for the fluid is given by

$$R_e = \frac{\rho_e l}{ch(2.54)} \mu\Omega, \quad (7)$$

where ρ_e is the resistivity of the fluid in $\mu\Omega\text{-cm}$, and h inches, as before, is the inside height of the pump tube, i.e., 0.1 in.; the other quantities have the same significance as in Eq. (5). Since R_w and R_{bw} have already been determined, R_{be} can be readily calculated from Eq. (6). All the quantities required for the evaluation of R_B by means of Eq. (3) are thus known.

The appropriate dimensions for the E. M. pump described in this report are:

$$\begin{array}{cccc} \frac{h}{0.10 \text{ in.}} & \frac{t}{0.015 \text{ in.}} & \frac{l}{0.639 \text{ in.}} & \frac{c}{0.50 \text{ in.}} \end{array},$$

and the indicated resistivities and measured resistances at 485° C are:

$$\begin{array}{cccc} \frac{\rho_w}{34.9 \mu\Omega\text{-cm}} & \frac{\rho_e}{140 \mu\Omega\text{-cm}} & \frac{R'}{231 \mu\Omega} & \frac{R''}{120 \mu\Omega} \end{array}.$$

From these values it is found by the procedure described above that

$$R_w = 583 \mu\Omega \quad R_e = 705 \mu\Omega \quad R_B = 158 \mu\Omega.$$

By using the foregoing data and the measured values of B, the ideal flow rate for selected values of I and P can be calculated by means of Eq. (2). The results are plotted to give the dashed curves in Fig. 12. It is seen that, in general, the experimental points do not differ very greatly from the ideal values. Such differences as do exist are due to pump head losses and to observational errors.*

Two other characteristic properties of the E. M. pump can be obtained from Eq. (2). The theoretical static (or shutoff) pressure, P_0 , for zero flow, is obtained by setting $Q = 0$. It is then found that

$$P_0 = \frac{5.7 \times 10^{-7} BI}{h} \cdot \frac{R_B}{R_B + R_e} \quad (8)$$

The results obtained from this expression are indicated by the intercepts of the dashed curves in Fig. 12 on the ordinate (pump output pressure) axis.

The shutoff flow rate, Q_0 , for zero pump pressure is derived from Eq. (2) when P is zero; thus,

$$Q_0 = \frac{4.0h}{B} IR_B \text{ gpm} \quad (9)$$

where I is in amperes, B in gauss, and R_B in $\mu\Omega$. If there were no interaction between the magnetic fields of the E. M. flowmeter and the pump, I/B would be constant for the given system. Since h is constant and R_B can be considered constant, Q_0 should be constant. The value of Q_0 calculated for the experimental pump loop ranged from 2.6 to 2.8 gpm, for pump currents up to 300 A.

The efficiency of the E. M. pump is defined as the ratio of the useful mechanical power generated, PQ, to the electrical power input, I^2R' ; thus,

$$\text{Eff.} \propto \frac{PQ}{I^2R'} \quad (10)$$

*An attempt was made to determine the pressure losses through the pump tube as a function of Reynolds number, based on model studies with water. The effort was not too successful, in agreement with the conclusions of others.^{3,4}

By utilizing the known values of P , Q , I , and R' , the efficiency of the E. M. pump for pumping the molten plutonium alloy at 485°C was calculated as a function of the pump current. The results are plotted in Fig. 15; it is seen that the efficiency is quite low, but it increases with the magnitude of the pump current (and flow rate). In Eq. (10), the losses due to power dissipated in the magnet coils and in the electrical connections are neglected. If these are taken into consideration, however, the efficiency of the pump would be somewhat less than that given in Fig. 15.

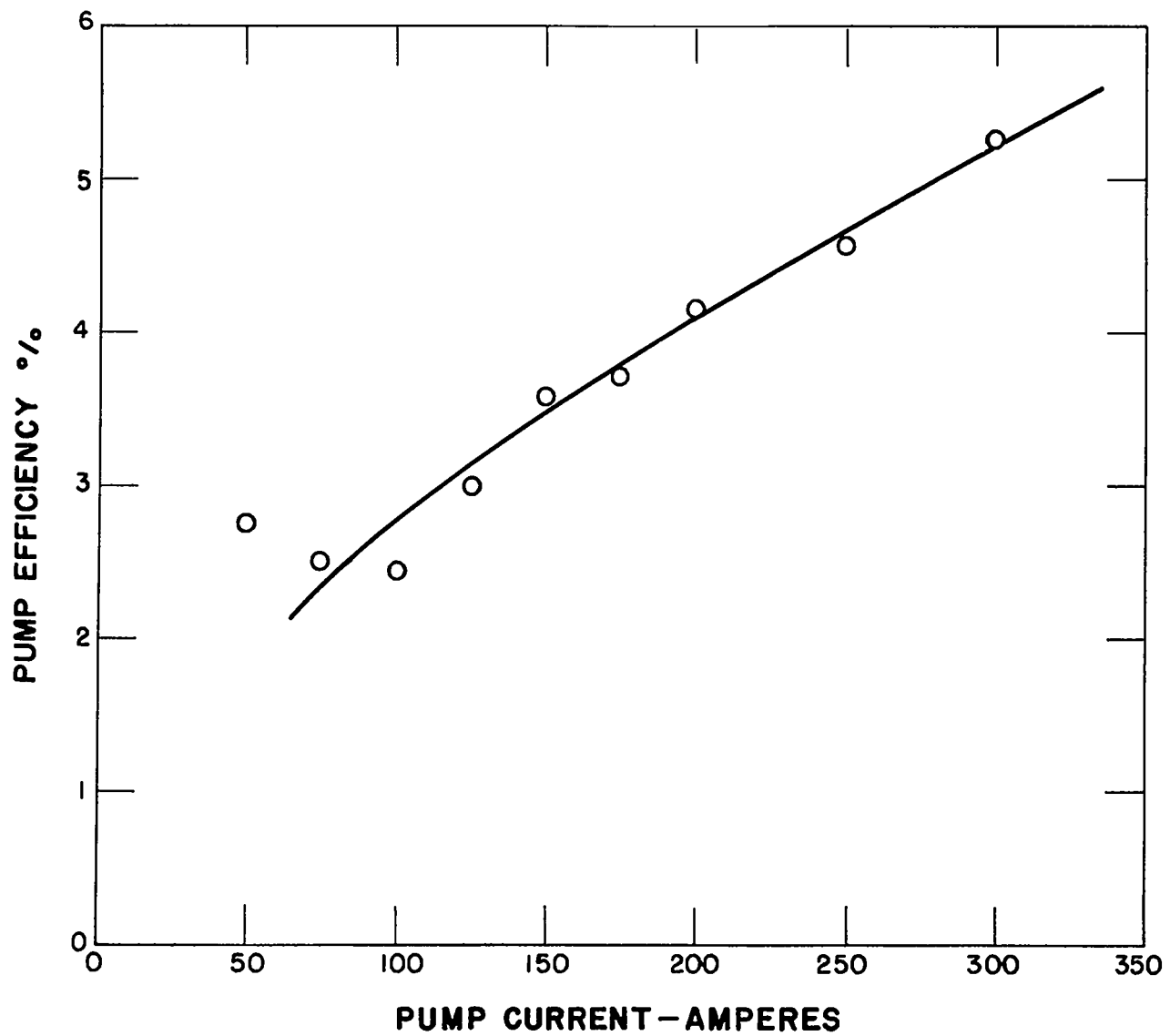


Fig. 15. E.M. Pump Efficiency vs Pump Current

CONCLUSIONS

The experiments described above show that the particular molten plutonium-cobalt-cerium alloy used can be pumped satisfactorily by means of a dc E. M. pump and that the flow rate can be determined readily by an E. M. flowmeter. The system reaches a stable operating condition in a short time and remains stable. The molten alloy wets tantalum immediately, and no problems should be encountered because of nonwetting. Pumping of a fluid of such high resistivity is very inefficient, but it is possible that greater efficiency could be achieved with an ac pump. In any event, in accordance with the general behavior of E. M. pumps, the efficiency would be increased in a system that has a higher flow rate than was feasible in the experiments.

The technique of using a tandem electromagnet with a common center pole for both E. M. pump and E. M. flowmeter appears to be quite practical, at least in a small circulating loop. With a little effort, the design could probably be improved, e. g. , by increasing the cross-sectional area of the center pole piece, so that the interaction of the magnetic fluxes was negligible.

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