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ENGINEERING PRACTICE SCHOOL
CARBIDE AND CARBON CHEMICALS DIVISION
Union Carbide and Carbon Corporation

MEMORANDUM

EPS-X110

KT-100

September 13, 1950

TO: T. F. Furlong
FROM: E. I. Goodman (Leader), R. Bakal
SUBJECT: The Design and Construction of a Test Loop for the
Study of an Electromagnetic Pump and Flowmeter on
Lithium Systems,

INTRODUCTION

Electromagnetic pumps have been used successfully for the pumping of liquid metals such as mercury, sodium, and sodium-potassium alloys. The pumps operate by means of the force produced on a conductor while carrying current in a magnetic field. In the pumping of liquid metals the conductor is the liquid, through which a current is sent. The flow rates of these liquid metals can then also be measured by the reverse effect, i.e., the voltage induced by a conductor traveling through a magnetic field.

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The purpose of the present investigation is to design an apparatus for the study of electromagnetic (EM) pump and flowmeter operation using liquid lithium, in the range of 400 to 1000 F. This apparatus will be used in an investigation which would lead to the answers to the following questions:

- a) Can lithium be handled effectively with an EM pump?
- b) Can lithium be successfully metered with an EM flowmeter?

If the meters operate satisfactorily, a further objective will be the meter calibration, which may then in turn be used to calibrate the EM pump. The maximum linear velocity desired is 5 fps in a 3/16 in. i.d. tube which is equivalent to a volumetric flow of 3.45 cu ft/hr. Although EM devices have been used successfully on other liquid metal systems, no work using lithium has been reported. The factor which makes successful operation of EM pumps and flowmeters questionable on lithium systems is the high resistivity of the lithium, as shown below in comparison with the resistivity of sodium. An increase in the ratio of the liquid metal resistivity to tube wall resistivity increases the amount of current that goes through the tube wall. This by-passed current is consequently not available for activating the EM pump or flowmeter.

Temperature ($^{\circ}$ F)	Resistivity (microhm - cm)	
	Na	Li
212	9.6	
445		45.3
482	14.9	
662	18.4	
750		98
1110		107

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The current widespread interest in liquid lithium system is a result of its unique physical properties which make it promising as a high temperature heat transfer medium for nuclear reactors. Certain of these characteristics are:

- a) high thermal conductivity
- b) low vapor pressures at elevated temperatures (e.g., 40 mm of Hg at 1800°F)
- c) low neutron absorption cross section of one of the lithium isotopes
- d) high specific heat

Work on this problem started on August 24, 1950, and continued through September 12, 1950, at the ORNL group located at the Electromagnetic Separation Plant (Y-12).

Design

General - The apparatus described in this report is designed to provide two distinct flow systems. The first is a batch flow system pressured by helium. The flow is from a surge tank through a length of tubing provided with several EM flow metering stations, to a measuring tank in which the average flow rate can be determined. If the EM flowmeter operates successfully, it can then be calibrated. The second flow system uses the EM pump to continuously cycle the liquid lithium from the surge tank, through the several metering stations and back to the surge tank. Calibration of the pump can then be accomplished either by means of the EM flowmeter or the measuring tank.

A third tank is provided for charging the system and the removal by filtration of any high melting impurities in the lithium, notably the nitride. Once the proper amount of lithium has entered the surge tank, the filtering tank is sealed off, and the test loop becomes a completely closed unit.

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Figure 1 is an elevation view drawn approximately to scale of the EM test loop and system. (For a detailed description of system see Appendix A.)

Figure 2 contains plots of the expected electromotive forces in the flowmeter vs. temperature at a constant flow rate of 3.45 cu ft/hr (see Appendix D). The smaller tube develops higher electromotive forces than the larger tube, while the electromotive forces developed in the larger tube are less sensitive to temperature changes.

The resistivity ratio of lithium to 316 stainless steel vs. temperature is also plotted in Figure 2. This plot together with the above mentioned plots indicate that the lower the resistivity ratio, the greater the electromotive force developed in the flowmeter. The high resistivity ratio of lithium to 316 stainless steel is one of the major physical limitations for the successful operation of the EM flowmeter with lithium.

Design Considerations

General - Handling methods for liquid metals at elevated temperature are at present in an elementary stage of development. Lithium systems, because of the extreme reactivity of the molten metal, are particularly difficult to operate. The apparatus described in this report was designed with these special handling problems in mind and is based on a proposed operating procedure (see Appendix). Since complex arrangements usually entail increased operating difficulties and possible points of failure, the system was kept as simple and yet as reasonably flexible as possible.

Lithium Reactivity - The extreme activity of liquid lithium fixed a number of design factors.

- 1) All parts of the system exposed to lithium were made of 316 or 347 stainless steel (8). Stainless steel splash shields were used to reduce the possibility of lithium coming into contact with certain non-stainless members.
- 2) The system is pressure tested and thoroughly cleaned and degreased before operation as even very small amounts of impurities increase the lithium reactivity.

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LITHIUM TEST LOOP

R-241-5

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FIG.
1

KEY
 ○ - E for $\frac{5}{16}$ " TUBING

□ - E for 1" TUBING

▽ - R of LITHIUM to
 316 STAINLESS STEEL

T (°F)

FLOW RATE 3.45 CU FT / HR

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EMF (E) & RESISTIVITY RATIO (R)

vs.
 TEMPERATURE

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FIG.

2

- 3) The system is airtight, all connections are welded, except tank tops, and completely closed after the lithium is once charged. It is maintained at all times under a positive pressure of helium to prevent air inleakage. Commercial helium is used rather than argon because of its higher purity and freedom from trace amounts of nitrogen.
- 4) Before the charging process the system is evacuated, the lithium is forced through a Micro Metallic, stainless steel filter into the actual test loop. This filtration removes any impurities or surface coatings introduced with the solid lithium.
- 5) A minimum of bends, fittings, and welds are used in the system. "S" traps are used in place of mechanical valves.

Thermal Expansion of Lithium - Since lithium undergoes a 1.5% expansion on melting, the operating procedure and heating circuits are designed to eliminate the possibility of tube failure under excessive pressure during melting.

The tube heating sections are kept short and are provided with individual switches so that one end of the melting lithium is always in contact with a liquid phase. The thermocouples placed in the metering sections and elsewhere indicate just how far along the pipe the melting has progressed.

Heating Requirements - Calculations have been made on the maximum heat required to bring the system components up to operating temperatures. Results from the calculations are tabulated below for the filtering tank, surge tank (identical with measuring tank) and 1 foot lengths of 5/16 in. and 1 in. o.d. tubing. A reasonable insulation thickness was assumed for each unit and increased if the calculated outside insulation temperature was much above 100°F.

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	Filtering Tank	Surge Tank	One Foot of Tubing	
			<u>5/16 in.</u>	<u>1 in.</u>
Max. Temp. (°F)	600	1000	1000	1000
Insulation thickness (in.)	2	3	2	2
(1) Total Heat Needed (BTU)	9300	8200	50	260
Heat Loss at Max. Temp. (BTU/hr)	320	390	300	400
Max. Heater Capacity (W)	2000	3000	480	480
Approx. Heating Time (hrs)	2	2	1/2	1/2
Max. Surface Insulation Temp. (°F)	125	140	90	90

(1) Total heat needed to bring component to maximum temperature from 60°F, including tank or pipe, lithium latent heat, and lithium but excluding insulation and heat losses.

After the system is brought to operating temperature the heaters will be used at only a small part of their capacity in making up heat losses. This condition is a result of arbitrarily keeping the heating time, required to bring the tanks to temperature, low to insure maximum operating time each day.

The capacity of the calrod heater used on the tubing is two to four times as large, depending on the tube diameter, as is needed to bring the tubes up to operating temperature in half an hour. Since each section is heated individually, and its temperature checked periodically overheating will be avoided.

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Further calculations show that the temperature drop through uninsulated 5/16 in. and 1 in. o.d. tubing at 90 lb/hr of lithium (equivalent to a velocity of 5 fps in the 5/16 in. tube) is small, being 10° and 20°F/ft. of length respectively. When 2 in. of insulation is applied to the piping the temperature drop is reduced to approximately one third of these values. Thus the total temperature drop through 6 ft of piping would be less than 50°F.

Since the temperature drop over the unheated metering sections is relatively small it will not be necessary to heat the tubing during the runs. The lithium temperature in the surge tank may be raised to compensate for the temperature drop in the pipes.

Choice of Heaters

Chromalox strip heaters had been used successfully in previous work with heated tanks in liquid metal systems, and the sizes and capacities were found to be appropriate for the present system. Calrod heaters were selected for the tubing on the basis of better thermal contact, the small volume occupied and superior performance with similar systems.

System Size

The system was designed to hold a total of 2.5 to 3.0 lbs of lithium. The weight of lithium was chosen because it was small enough for reasonably safe handling, but ample for obtaining flows in the desired range and within the pump capacity.

EM Flowmeter

Uncertainty as to the proper or optimum geometry of the EM flowmeter tube lead to the incorporation in the system of the several metering sections. The pipe diameters chosen represent the range of immediate interest, while it is hoped that the flattened 1 in. section will show the effect of changes in the geometry of the metering cross section. It should be noted that not only the diameter but also the wall thickness will affect the meter response. The tubing sizes decrease in the downstream direction as calculations have indicated that entrance effects are minimized with this arrangement.

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APPENDIX

A. Design Details

1. Materials of Construction - Due to the extreme reactivity of lithium particularly at high temperatures, all parts of the system that were exposed to lithium were made of 316 stainless steel with the exception of the pump cell, which was 347 stainless. Certain sections of the equipment which would not contact the liquid lithium, such as the top flanges on the filtering tank and the helium and vacuum piping on top of each of the tanks, were made of iron or ordinary steel. Stainless steel splash shields were provided to protect the vacuum and helium inlet and also the seal between the tank top and level indicating probe (see detail drawing of measuring tank, Fig. 3).
2. Filtering Tank - The filtering tank was constructed from a 10 in. length of standard 6 in. stainless steel piping with a welded stainless steel bottom, through the center of which was a 2 1/2 in. o.d. stainless steel Buchner Funnel (Micro Metallic Grade H, average pore size 5 microns). The tank bottom was bevelled on the inside from 1/2 in. thickness to 1/4 in. at the funnel. Standard 6 in. iron pipe flanges were used for the tank top, bolted with a aluminum gasket for closure. One chromel-alumel thermocouple was welded to the tank wall and another was inserted in a 9 3/4 in. stainless steel thermowell through the tank top. Other thermocouples were welded to the outside of the Buchner funnel and to the "S" trap in the tubing leading from the tank. A 1/4 in. steel pipe in the tank top was connected to the helium and vacuum lines through two 1/4 in. Kerotest valves.
3. Surge and Measuring Tanks - These tanks were made of 12 1/2 in. length of standard 4 in. stainless pipe with welded cap bottoms and flanged, bolted tops. Each tank had one thermocouple extending from the top through a stainless steel thermowell ten inches long and another thermocouple welded to outside of the tank wall. Both tanks were connected to the helium and vacuum lines in the same manner as the filtering tank. The surge tank was provided with a single probe which will indicate when the lithium level comes to within 2 3/4 in. from the tank top during charging, while the measuring tank has two probes indicating when the lithium level is 11 1/2 and 3 1/2 in. from the top of the tank. These probes will be used for the flowmeter calibration.

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DETAILED DRAWING
OF MEASURING TANK *R-241-11*

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FIG.
3

4. EM Meter and Pump Stations, Piping - A 1 in., 16 gage stainless steel tube extends from the bottom of the surge tank through a 90° elbow to the EM pump station or cell. This cell, of 347 stainless, was supplied with the pump and is a 10 in. length of 1 in. i.d. tubing flattened at the center to a long narrow cross section approximately 1/4 in. x 1 in. x 1 1/2 in., the long dimensions being horizontal. Two silver plated copper bus bars are silver soldered horizontally along the narrow side section to the flattened portion of the cell and bolted at the other end to corresponding copper bus bars from the pump. The cell is centered in the pump electromagnet air gap. The downstream end of the pump cell is butt-welded to the first of five flow metering stations, in this case a 10 in. length of 316 stainless steel similar to the pump cell in design but not including the bus bars. The bus bars are replaced by electrodes of 1/16 in. diameter 316 stainless steel rod, which are used to pick up the potential produced by the flowing lithium. The ends of these rods are threaded for 6-32 NF STD. THD. nuts and will serve as terminals for the potentiometer lead wire. Each of the other four metering stations has an identical pair of electrodes welded at the ends of the horizontal tube diameter at the center of the metering station. The metering stations are 8 in. lengths of 1, 5/8, 7/16, and 5/16 in. o.d. circular tubing, in that order, all 16 gage (0.065 in.) except for the 7/16 in. tubing which is 20 gage (0.035 in.). The tube ends were expanded slightly where necessary and chamfered to reduce friction losses.

The rest of the system tubing is 5/16 in. o.d., 16 gage. From the last metering station the tubing makes a 90° bend and extends upward to a standard pipe tee. The other vertical leg of the tee is connected to the bottom of the measuring tank through an "S" trap while the tubing from the horizontal leg, after passing through a "U" trap, returns to the top of the surge tank. Several inches upstream from the surge tank the tubing is joined, through a second pipe tee, by the line from the "S" trap below the filtering tank. These "S" traps are sections of 5/16 in. o.d. tubing bent into an "S" shape with a 1 1/2 in. radius of curvature. By allowing the lithium, which is always present in one half of the trap, to freeze, the traps can be used as valves. This eliminates the use of mechanical valves, which do not function satisfactorily in lithium systems at elevated temperatures.

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5. Heating Circuits and Control - All three tanks are heated by chromalox strip heaters while calrod heaters are used on all tubing. The filtering tank heating jacket consists of ten 115 V, 200 W, No. PT-702 strip heaters (7 1/2 in. by 1 7/16 in.) in parallel, controlled by a 0 to 115 V, 30 amp variac. The heating jackets for the surge and measuring tanks consist of ten 115 V, 300 W, No. NH09 strip heaters (9 1/2 in. by 7/8 in.). Maximum sheath temperature for both types of heaters is 1200°F. Since the filtering tank will be used only once in charging it is planned to thereafter transfer this 30 amp variac from the filtering tank to the measuring tank. Control of the surge tank is automatic with a Wheelco Pyrometer, No. 224-TCB with a range of 0 to 2400°F, which is designed for operation with chromel-alumel thermocouples. The pyrometer is connected to either the thermowell or outside wall thermocouple by a two-position selector switch.

Calrod heaters with a maximum capacity of 40 w/in. of length at 115 V and maximum sheath temperature of 1500°F are used for all tubing and around the Micro Metallic, Buchner funnel. Heater lengths of 44 and 32 in. (effective heating lengths of 30 and 18 in., respectively) are used and connected in parallel across the 115 V, 30 amp variacs. Two of these variacs are used, one for the calrod sections from the surge tank to the pipe tee below the measuring tank and the second for the lithium recycle line and lines to it from the filtering and measuring tanks. Each heating section is wired with a separate switch so that individual sections may be turned on or off at will. A single calrod heater is welded to all the tubing except the pump cell and metering stations. No heaters are used in the center portions of these sections, and the calrods are doubled back over the ends of each metering station.

6. Insulation - Magnesia insulation ($k = 0.55 \frac{\text{BTU}}{(\text{hr})(^\circ\text{F})(\text{sq ft/in.})}$ is used throughout). A 2 in. thickness is used on the filtering tank and all tubing, while 3 in. of insulation is used on the surge and measuring tanks. Certain sections of the tubing are provided with hollowed block insulation which is wired on but can be removed when necessary. These sections are the three "S" traps and the

P.241-13

central 3 in. sections of the metering stations. The insulation is removed when it is desired to freeze the lithium in the trap and on the individual metering station during the investigation of that particular section. No insulation can be applied at the central section of the pump station because of the lack of space.

7. Temperature Measurement - All thermocouples used in the test loop were chromel-alumel. A total of nineteen were employed, three in the filtering tank, two each in the surge and measuring tank, six in the pump and metering stations (one at each station), and six at various points in the 5/16 in. o.d. connecting tubing. Except for the three that were inserted in the tank thermowells, the thermocouples were welded to the outer walls of the tanks and tubing. Those that were on the pump and metering stations were placed just on the downstream side of each central section or air gap. Three of the thermocouples used for the connecting tubing were welded at the dip of the three "S" traps while the remaining three were located approximately at the center of long lengths of tubing (see Fig. 1). The thermocouples welded to the tanks were placed at the bottom of the tanks near the center.

All of the thermocouples except for the two on the surge tank are connected to a large selector switch which in turn is connected to the indicating circuit of the Wheelco Pyrometer. The control circuit of this Wheelco will not be used. The two couples from the surge tank are connected to a second indicating and controlling Wheelco. Temperature control on the other heating sections is manual, with the use of 115 V variacs and individual section switches. These control circuits are more fully described under Heating Circuits and Control.

8. Electromagnetic Pump - The EM pump used in this system is a product of General Electric, Catalog No. 9159849G1 and operates on alternating current over the range 0 to 270 V and 0 to 30 amps. Detailed instructions and description of the pump can be found in G. E. Instructions 30074.

The pump consists of a transformer, the primary of which is fed through two capacitor banks and a 0 to 270 variac from the 230V outside lines. The Transformer secondary is a single turn of copper bus bar connected in series with the pump cell by means of the silver plated copper bar soldered to the cell. (See Fig. 4).

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An air gap in the laminated core of the transformer provides the necessary magnetic field. Control of the pump is maintained through the 0 to 270 variac and the pump voltage, amperage, and wattage are measured by suitable meters on the pump side of the variac. The pump is mounted on iron unistruts through non-magnetic dural mounting angles. The mounting is arranged so that the pump position may be varied to facilitate lining up the system.

9. Electromagnetic Flow Meter - Five flow metering stations of varying geometry are provided and have been previously described. A permanent magnet with a field strength of approximately 3000 gauss is mounted so that it may be shifted from one station to the next. The induced potential is picked up on the stainless steel electrodes and measured on a potentiometer.
10. Miscellaneous - Helium is supplied from a gas bottle through a pressure reducing valve and Moore 0 to 30 psi pressure regulating valve. A Cenco Hyvac pump is used in the vacuum system together with a Stokes-McLeod vacuum gage (0 to 700 micron range). Rubber hosing, 1 in. o.d., 1/2 in. i.d., is used to connect the top of the tanks with the vacuum pump and helium bottle. Each tank is fitted with connections for both helium and vacuum through standard 1/4 in. steel pipe and 1/4 in. Kero-test valves.

A Simpson utility meter is used to measure the resistance across the tank wall and level indicating probe. This resistance drops as the rising liquid level shorts out the tank wall and probe. The stainless rod is silver soldered to a mica "spark plug" type insulator which is screwed into the tank top.

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B. Proposed Experimental Procedure

The work will consist of three phases:

1. Charging lithium into the system
 2. Calibration of the EM Flowmeter
 3. Testing and calibration of the EM pump.
-
1. Charging the system - Solid lithium (2.5 to 3.0 lbs) saturated with kerosene will be placed in the filtering tank, and the top bolted down. The entire system, previously pressure-tested for leaks, will be evacuated and then put under a slight positive helium pressure. The filtering tank, surge tank, and all piping will be heated to 500°F and allowed to remain at this temperature for 30 min. Additional helium pressure will be put on the filtering tank to force the lithium through the Micro Metallic filter and into the system proper, flow being to both the surge tank and "S" trap in the recycle line. Care must be taken so that enough lithium flows through the recycle line to completely plug the "S" trap when the lithium is allowed to freeze. When the lithium in the surge tank reaches the height of the probe, as indicated by the resistance meter, the filtering tank heating and excess positive pressure will be turned off, and insulation on the "S" trap below the filter removed, allowing the lithium in it to freeze. Temperature measurements will be taken on all heated parts of the system at short intervals. The filtering tank will be isolated from the actual test loop after charging.
 2. Calibration of the EM Flowmeter - Before each days operation the lithium will have to be melted. The surge and measuring tanks will be heated first. After the lithium in the surge tank has melted, as indicated by the tank thermocouples, the first pipe-section heaters below the tank will be turned on, and the lithium in them melted. Successive heaters will then be turned on as the helium in each section of pipe is melted. Only the tubing from the surge tank to the measuring tank will be heated, the recycle line being left frozen to prevent flow through it. The removable blocks of insulation will be removed from the "S" traps on the recycle line, the line from the measuring tank, and the metering station being studied. Temperature measurements will be taken periodically.

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P.W. - PRIMARY WINDING
S.W. - SECONDARY WINDING

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ELECTRICAL CIRCUIT DIAGRAM
FOR THE EM PUMP

DATE 9-12-50	DRAWN BY R.B.	FILE NO. EPS-X110	FIG. 4
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When the system has reached the operating temperature desired, the heaters on the pump and meter stations will be turned off, and a positive helium pressure, in excess of the slight pressure kept on all parts of the system at all times to prevent air inleakage, will be applied to the surge tank. The lithium will be forced from the surge tank through the metering stations into the measuring tank and then, by removing the excess pressure, be returned to the surge tank by gravity. This will be done two or three times to mix the lithium, obtain uniform temperatures, and check the system's operation. This process will then be repeated, taking data on temperature, potentiometer deflection, and time necessary for the lithium to occupy the known volume between the two level indicating probes in the measuring tank. Several runs will be made at each temperature in the desired range and at each metering station. The data will be averaged and used as the flowmeter calibration. The field of the permanent magnet will be measured periodically with a gauss meter.

At the end of each days operation all heaters will be turned off and the lithium allowed to solidify.

3. Testing and Calibrating the EM Pump - Starting up for the pump testing will be almost the same as the procedure described for the meter calibration. However, the measuring tank and "S" trap leading to it will remain frozen, as the lithium is now to be continuously recycled to the surge tank. The removable insulation is to be taken from the measuring tank "S" trap and the metering station being used. After the system reaches the desired temperature the tubing heaters are turned off, the EM pump is started and adjusted, and the lithium cycled around the test loop. Data on the pump operation (voltage, amperage, and wattage), system temperatures, and the flow meter deflection are to be taken after some time is allowed for steady flow conditions to be reached. The pump voltage can then be related to the flow rate through the flow meter calibration. Again several runs at each temperature and pump voltage will be taken and the data averaged.

R.241-18

C. General Introduction and Theoretical Background for EM Pumps and Flowmeters

The increased use of molten metals as a heat transfer medium has led to the development of EM pumps. The disadvantages of the centrifugal type pumps with liquid metals are:

1. Pumps have to be constructed from or lined with material which will be unaffected by the corrosive action and high temperature of the molten metal.
2. Pumps must have special bearings and seals to prevent leakage of the liquid metal.

In EM pumps the bearing and seal problems are eliminated since there are no moving parts. There are two types of electromagnetic pumps:

1. The first type uses alternating current to produce eddy currents in the molten metal. These eddy currents interact with the magnetic field and cause a rotating motion of the liquid.
2. The second type is the Einstein-Szilard pump, which is based on the principle that a conductor carrying a current in a magnetic field produces a force which will move the conductor. The conductor in the case of this pump would be the liquid metal. The magnitude of this force produced on the conductor is given by:

$$F = \frac{BI d}{10} \text{ (dynes)} \quad (1)$$

and its direction is perpendicular to the lines of force and the current (B in gauss, I in amperes, and d in cm).

In the flow of a liquid metal in a conducting pipe, power from the EM pump is distributed as follows:

1. power lost in overcoming the counter emf developed in the fluid.
2. power lost from the effect of the current by-passing the fluid through the tube wall.

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3. power lost from the effect of the current going through the liquid metal, i.e. I^2R losses.
4. power lost in the magnet of the EM pump.
5. power lost in overcoming the hydraulic impedance of the pump cell.
6. power converted to the kinetic energy of the liquid metal.

The last term is the only useful work put out by the pump. All EM pump design has been focused on minimizing the pump losses outlined above (1 through 5). Overall efficiencies of over 50% have been attained (2).

In EM pumps the capacity goes through a maximum in relation to magnetic field strength. This effect is thought to be due to the by-passing of current in the outer annular layer of fluid and becomes more pronounced as the counter emf produced in the fluid increases with increasing magnetic field. The optimum magnitude of the field for an EM pump is therefore determined partly by the current by-passing effect in the fluid and partly by the power expended in maintaining the field.

The same theory that applies to an EM pump can be applied to an EM flowmeter. With a conductor moving in a magnetic field an emf is developed as given by the expression:

$$E = BdV \times 10^{-8} \text{ volts (B in gauss, d in cm, and V in cm/sec)} \quad (2)$$

This equation indicates that an electromagnetic device can be utilized to measure flow since V is a function of E at constant magnetic flux and constant cross section.

The advantages of using an EM flowmeter are:

1. A linear calibration curve results from a velocity vs. electromotive force plot.
2. The calibration is independent of temperature, density, viscosity and velocity profile of the fluid.

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3. There is no time lag (i.e. pulsations in the flow rate can be measured accurately).
4. There are usually no constricting, protruding or movable parts such as in a venturi or orifice meter.
5. Flow rates as low as 0.0001 cu in./sec can be measured (7).

The flowmeters would not necessarily be limited to conductors because the polarity of non-conductors may be used as a measure of the velocity of the non-conducting fluid.

In the practical case of having the molten metal flowing through a conducting pipe, new problems arise because of the short circuit developed between the pipe walls and the fluid. Work done at the Babcock and Wilcox Company (1) has shown that the following equation could be used to predict the electromotive force produced by a conductor flowing through a conducting tube to within $\pm 4\%$:

$$E = BVd 10^{-8} \left[\frac{2 \frac{d}{D}}{1 + \left(\frac{d}{D}\right)^2 + \left(\frac{e_f}{e_w}\right) \left[1 - \left(\frac{d}{D}\right)^2\right]} \right] \quad (3)$$

(B in gauss, V in cm/sec, d in cm).

The assumptions used in deriving the above equation are as follows:

1. Interface resistance between tube wall and fluid is negligible.
2. The velocity distribution of the fluid is axially symmetrical.
3. A uniform magnetic field exists in the fluid while passing through the flowmeter.

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For the above equation to be useful the following has to be true:

1. The fluid must wet the tube wall.
2. The dimensions of the flow section must be determined precisely.
3. The resistivities of the fluid and the tube wall must be known.

Data on the resistivities of liquid metals and metal tubing and pipes are not very complete, particularly data on the change of resistivity with temperature.

Fig. 3 is a plot of the theoretical electromotive forces expected in the present investigation at various temperatures using the Babcock and Wilcox formula and available resistivity data. The temperature effect is not as noticeable in the 1 in. o.d. tube as in the 3/16 in. o.d. tube.

Table AI Values for Fig. 3

T(F)	ρ_L (microhm-cm)	ρ_{ST} (microhm-cm)	R (dimensionless)	E(5/16 in.tube) (mv)	E(1 in.tube) (mv)
445	45	89	0.506	1.55	0.434
745	98	102	0.960	1.32	0.410
1110	107	117	0.920	1.34	0.412

B = 3,000 gauss

Wall Thickness = 1/16 in.

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Table AII Physical Constants for System

Volume of Tanks (cu in.)

Filtering	283
Surge	162 (127 cu in. from bottom up to the probe)
Measuring	162 (117 cu in. from bottom up to top probe; 104 ± 2 cu in. between probes).

Areas of Tubes and Linear Velocities at Volumetric Flow Rate of

3.45 $\frac{\text{cu ft.}}{\text{hr}}$

Tube o.d. (in.)	5/16	7/16	5/8	1
Area (sq in.)	0.0276	0.111	0.196	0.602
Velocity (fps)	5.00	1.24	0.704	0.230

Time to fill volume between probes in Measuring Tank at
Maximum velocity 63 sec.

Maximum change in static head during calibration of EM
flowmeter 0.416 psia

In addition to the flowmeter formula the Babcock and Wilcox report recommends a design for an EM flowmeter. The flowmeter consists of:

1. two permanent magnets to provide a high magnetic field strength.
2. two soft iron slabs to spread the field and make it uniform.

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In addition, the following are provided to continuously measure the magnetic flux density:

1. a brass disc which is rotated in the magnetic field with two brass wires, one at its hub and the other at its periphery.
2. a stainless steel housing for the fibre bearings which support the disc shaft.
3. a synchronous motor and condenser.

The electromotive force measured across a radius of the rotating disc, known as a homopolar generator, is a continuous indication of the magnetic flux density.

D. Table of Nomenclature

B	=	magnetic flux density, gauss
C	=	specific heat, BTU/(lb)(°F)
d	=	i.d., in.
D	=	o.d., in.
E	=	electromotive force, volts
EM	=	electromagnetic
F	=	force, dynes
h	=	heat transfer coefficient, BTU/(hr)(sq ft)(°F)
I	=	electrical current, amperes
k	=	thermal conductivity, BTU/(hr)(ft)(°F)
V	=	average velocity, fps
W	=	weight rate of flow, lb/hr
ρ_F	=	electrical resistivity of fluid, microhm - cm
ρ_L	=	electrical resistivity of lithium, microhm - cm
ρ_{ST}	=	electrical resistivity of steel, microhm - cm
ρ_W	=	electrical resistivity of wall, microhm - cm

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