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A SIMPLE ELECTROMAGNETIC FLOWMETER FOR LIQUID METALS

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A Simple Electromagnetic Flowmeter for Liquid Metals

by

R. M. Carroll

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ABSTRACT

A method of construction of electromagnetic flowmeters from stainless steel or Inconel tubing has been developed for the measurement of the flow rate of liquid sodium. The experimental results of the calibration of the flowmeters have corresponded, within the limits of experimental error, to a general theoretical equation*. With reasonable care in construction, the flowmeter should correspond to the formula to within 3%.

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*E. R. Astley, Magnetic Flowmeter Output Potentials, (G.E. R52GL42, March, 1952)

TABLE OF CONTENTS

	Page
ABSTRACT	1
INTRODUCTION	3
RESULTS AND CONCLUSIONS	5
EXPERIMENTAL	8
Method of Construction of Flowmeter Cells	8
Sodium Purification Methods	12
Method of Calibration	13
BIBLIOGRAPHY	17

LIST OF FIGURES

Fig. No.	Title	Page
1	Flowmeter and Magnet Positioning for Maximum emf	3
2	Typical Relation of Flow to Generated emf	6
3	Cross Section of Typical Flowmeter Cell with Welding Adaptors	10
4	Flowmeter Cell and Welding Adaptor	11
5	Sodium Loading System	13
6	Flowmeters in Position for Calibration	14
7	Calibration Apparatus	15

INTRODUCTION

The electromagnetic induction flowmeter is a liquid flow measuring device based on the Faraday effect (the induction of a voltage in a liquid when moving through a magnetic field). The induced voltage is proportional to the velocity of the medium and the intensity of the magnetic field and, for a given installation and liquid, depends only upon the flow rate.

Experiments now in progress which involve liquid sodium at high temperatures have made necessary the development of a flowmeter which will accurately indicate flow. Of necessity, a flowmeter which contains liquid sodium at high temperatures must be able to withstand corrosion and have a moderate degree of strength at these temperatures. These qualifications seemed best fulfilled by the 300 series stainless steels and Inconel; and these materials are also suitably non-magnetic. The flowmeter must also be constructed in such a manner that cells of known dimensions will produce a potential which will accurately reflect the flow rate. The simplest method of construction is a flowmeter formed from a section of tubing by the addition of contact wires joined directly to the surface of the tubing. The contact wires should be joined to the tube at points which are diametrically opposed. A flowmeter will yield maximum potential when the plane of the axis of the tube and the contact points is normal both to the magnetic field and the plane of the magnetic field and the tube axis.

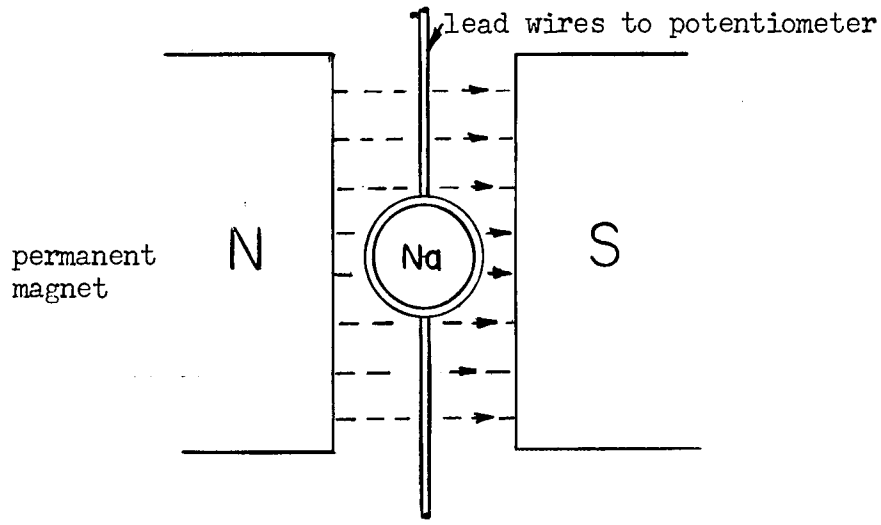

Figure 1 Flowmeter and Magnet Positioning for Maximum emf

The potential developed by an electromagnetic induction flowmeter with a conductive tube wall has been predicted by E. R. Astley* as

$$E = \frac{Bdv \quad K \quad x \quad 10^{-8}}{\frac{D^2 + d^2}{2dD} + \frac{\rho_f}{\rho_w}\frac{(D^2 - d^2)}{2dD}} \qquad \text{equation 1}$$

where

E is in volts

v is the liquid velocity in cm/sec

B is the magnetic field strength within the flowmeter in gauss at operating temperature

d is the inner diameter of the flowmeter in cm. at operating temperature

D is the outer diameter of the flowmeter in cm. at operating temperature

ρ_f is the electrical resistivity of the fluid at operating temperature

ρ_w is the electrical resistivity of the flowmeter wall at operating temperature

K is a constant dependent upon the ratio of the pole face diameter to the inside diameter of the flowmeter, equal to about 0.98 for ratios of around 3.

The formula is based on the following assumpations:

(1) Interface resistance between tube wall and fluid is negligible.

(2) The velocity distribution of the fluid is axially symetrical.

(3) A uniform magnetic field exists in the fluid while passing through the flowmeter. The constant K in the above formula is introduced because of the finite magnetic field that exists when the flowmeter is in use.

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*E. R. Astley, Magnetic Flowmeter Output Potentials, (G.E. R52GL42, March, 1952)

Since all of the factors in the above formula are constant with any one flowmeter, with the exception of the mean velocity, v, the magnitude of the voltage which is developed across the moving liquid depends on - and is therefore a measure of - the fluid flow.

$$E = v/C \qquad \text{equation 2}$$

where

$$\frac{1}{C} = \frac{Bd \times 10^{-8}}{\frac{D^2 + d^2}{2dD} + \frac{\rho_f}{\rho_w}\frac{(D^2 - d^2)}{2dD}} \qquad \text{equation 3}$$

CONCLUSIONS

The formula for the potential developed by the flow of liquid sodium through the flowmeter cell, as expressed in the theory section, may be written as $E = (1/C)\ v$, or $v = CE$, where C is a constant which is dependent upon the dimensions and material of the cell and v is the flow velocity and E is the potential developed. The following values of C were obtained experimentally and calculated theoretically for the cells constructed by the method discussed on page 9 .

Material	Cell	Experimental C	Theoretical C*	% Diff.
316 S. S.	1	34.76	33.88	-2.5
Inconel	2	17.64	16.95	-3.9
Inconel	3	34.44	33.62	-2.4
316 S. S.	4	24.91	24.68	-0.9
316 S. S.	5	24.51	24.68	+0.7
Inconel	6	34.44	33.62	-2.4
Inconel	7	17.50	16.87	-3.6
316 S. S.	8	35.40	34.83	-1.6

*E. R. Astley, Magnetic Flowmeter Output Potentials, (G.E. R52GL42, March, 1952)

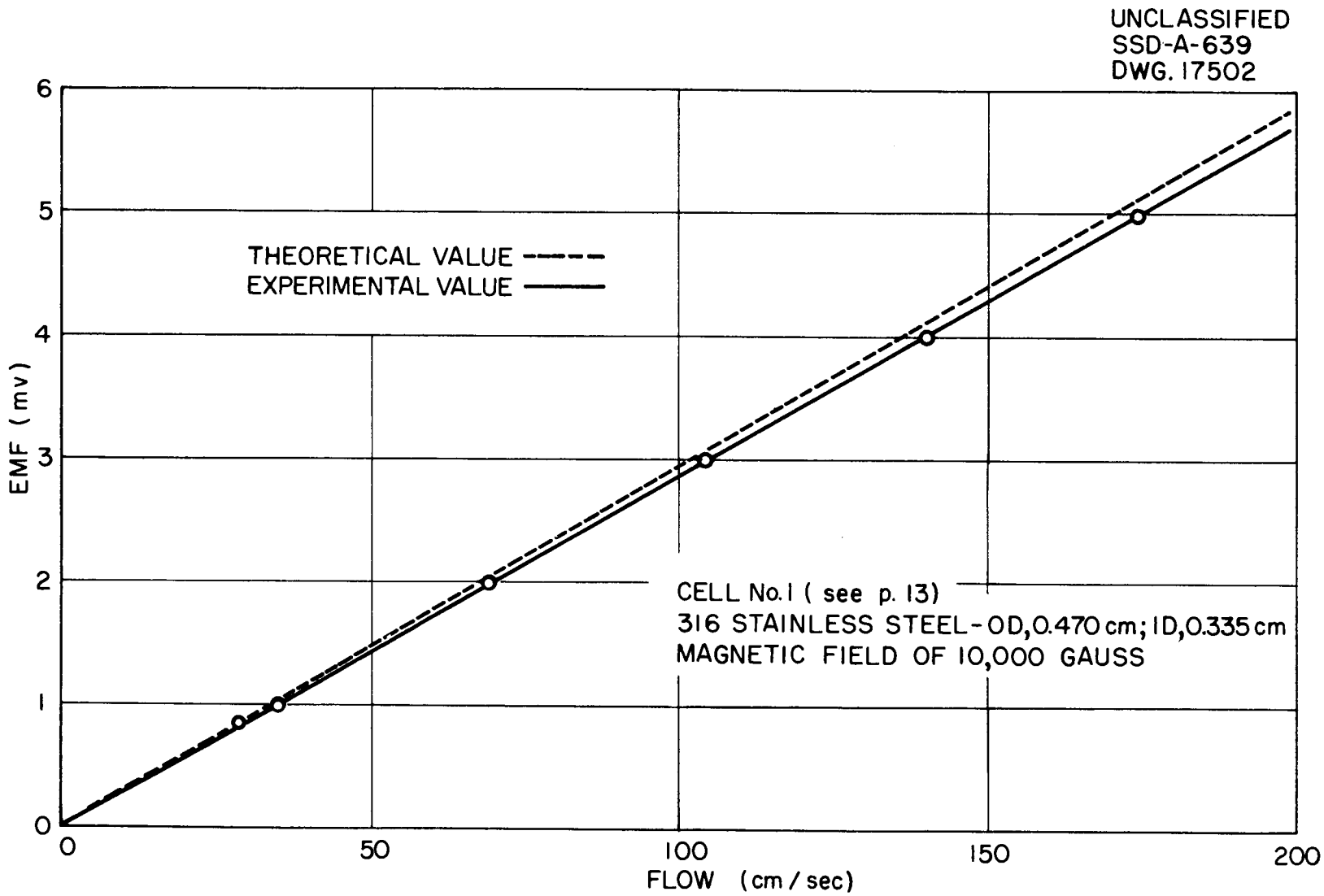

Fig. 2 TYPICAL RELATION OF FLOW TO GENERATED EMF

As indicated by figure #2, the data obtained for the value of 1/C (emf/flow) for flowmeter #1 (a typical cell) compares very well with the theoretical value for a cell of the same materials and dimensions. The experimental points for figure #2 vary from the mean by not more than 0.5%. The difference between the value of 1/C for the experimental calibration and the theoretical value is 2.5% however.

The differences between the value of C for the experimental and theoretical calibrations may be due to a combination of several factors.

(a) Inability to measure the inner diameter of the tubes to better than $\pm$ 0.0025 cm. This could account for 1.5% error for the flowmeter cells #1, #3, #6, #8 and 0.6% error for the flowmeter cells #2 and #7 and 0.9% for cells #4 and #5.

(b) Not drilling the wire contacts flush with the inner walls of the flowmeter tube. In some cases small score marks were made on the walls of the tube. This was especially noticeable in flowmeter tubes #2 and #7.

(c) Potential measurements and operator error may amount to 0.5%. Volume measurements may be 0.2% in error.

(d) The magnet flux is known to 1% accuracy. Since this has a direct relation to generated potential this could cause an error of 1% in the value of C.

The errors due to (a), (c), and (d) could combine to form a total error of as much as 3.2% and the error due to (b) could not be properly estimated. Since the trend of the differences between the values of C for experimental and theoretical measurements is for the theoretical to be less than the experimental values, then it may be supposed that some constant error, such as the magnetic field measurement for example, is biasing the results. If it were assumed that a 1.5%

constant error was involved, as could occur by possible errors in (d) and (c), then the deviations would be

Cell #1	-1.0%
#2	-2.4%
#3	-0.9%
#4	+0.6%
#5	+2.2%
#6	-0.9%
#7	-2.1%
#8	-0.1%

The deviation remaining could be attributed to (a) and (b).

In view of this amount of error, if a better degree of accuracy is desired, a machined flowmeter cell would be more suitable. This machined cell could be constructed in the same manner as described on p 9 with, however, the additional process of first machining the tube which will be used for the flowmeter so as to insure a uniform bore and wall thickness. After the contact leads are brazed in, the tube should then be carefully bored out. Indeed, if a brazing furnace is not readily available, the entire tube, along with the leads, may be machined as one piece as long as the fundamental theoretical requirements are observed. A flowmeter cell with machined walls should generate a potential predicted by theory to within 2%.

EXPERIMENTAL

Method of Construction of Flowmeter Cells:

The tubing that was necessary for the planned experiments was of approximately 1/4" I.D. and of 25 Mil wall and it was desired to have flowmeters made of the same size tubing. After many attempts to weld heavy wire to thin-walled

tubing - nearly all of which were failures and the successful welds unreproducable - a capacitor welder method of attaching fine wires to tubing was used. While this would give a signal and indicate relative flow, it was unsatisfactory because

(a) There was no method to reproduce the positions of the wires, or to assure that the wires were diametrically opposed.

(b) The contact of the wire with the tube was of varying electrical resistance, and sometimes there seemed to be oxide under the weld.

(c) The physical strength of the joint was low, and would often result in the wire falling off during operation.

In view of these unsatisfactory methods, the following construction was developed for the standard flowmeter.

The most satisfactory method of assuring that the wire contacts were diametrically opposed seemed to be in the use of holes drilled in the tube walls so that the wires could be positioned. In order to assure that the holes were correctly positioned the tubing was placed in the dividing head of a milling machine and a size #54 (= 0.055) drill used to drill into the side of the tube. With one hole drilled, the tubing was rotated 180° and the drill brought forward again. A wire of the same material as the tube and the same size as the hole was then pressed into the drilled hole. The same material was used for the contact wire so as to avoid possible thermal emf's which could occur if both sides of the flowmeter were not at the same temperature. Thermal emf's could also occur if the junctions of the two lead wires and the copper wires of the potentiometer were at different temperatures. Therefore the wire that was passed through the tube was of sufficient length so that the junction of the flowmeter lead wires with the copper wires could be made at a position of uniform temperature. The wire was then Nickel-Palladium** brazed to the tubing in a high temperature hydrogen atmosphere furnace.

**After more extensive tests it has been concluded that Nickel-Palladium braze is not satisfactory for containing sodium at high temperatures. Nicro-braz is a superior braze for this use, but it also is subject to corrosion by high temperature sodium.

After the wire was brazed to the tubing, the tubing was inserted into a lathe and the wire passing through the tube was drilled out flush with the walls of the tube. In order to prevent constrictions in the flowmeter tube when the flowmeter was welded into the rest of the system, a welding connector was devised. This connector also allowed tubes of different I.D. to be joined without the use of reducer connections. See Figures 3 and 4.

An alternate method of joining the lead wires to the flowmeter cell is to construct a jig which will hold the lead wires and the flowmeter tube in the proper configuration. This assembly may then be placed in a hydrogen furnace and the positioned wires brazed to the tube. This method has the advantage that no holes are drilled into the tube and the corrosion resistance of the braze need not be considered. It has the disadvantage that the joint of the lead wires to the tube has a much lower strength and that a different jig must be used for each size of tubing.

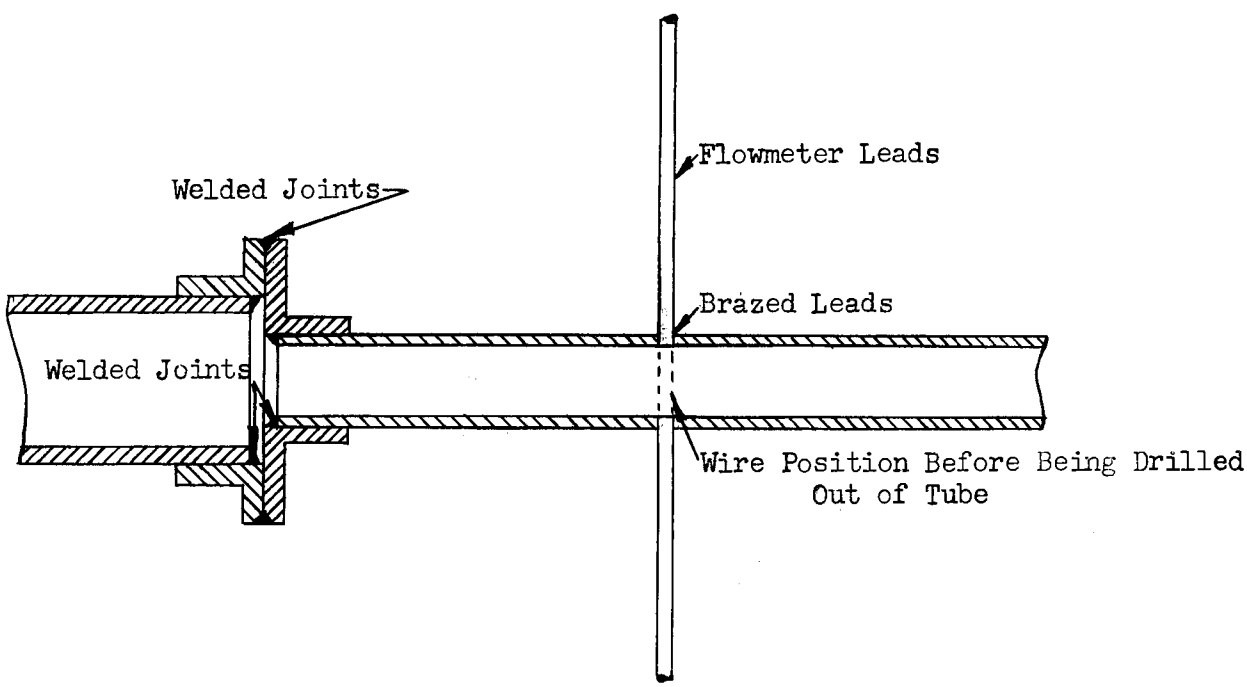

Figure 3 Cross Section of Typical Flowmeter Cell with Welding Adaptors

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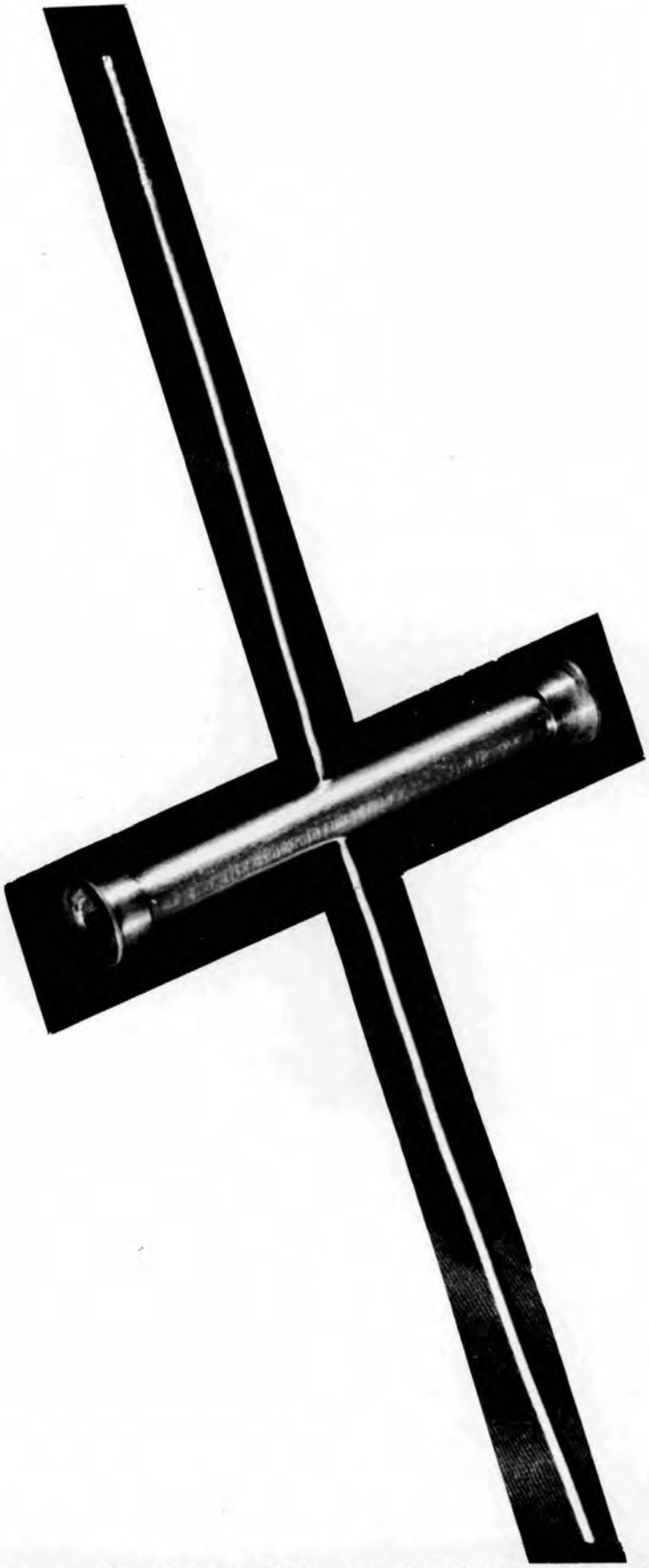

FIG. 4. FLOWMETER CELL AND WELDING ADAPTER

Sodium Purification Method

Since one of the assumptions of the theory is that there is no substance, such as an oxide, on the walls of the flowmeter between the liquid and the metal of the flowmeter wall, it was necessary to eliminate all impurities from the sodium used, and to insure that no other substances with which the sodium might react were in contact with the sodium.

A system was available (Figure 5) in which sodium could be melted, filtered and then transferred to the apparatus for flowmeter calibration. The system consisted of a melt tank which was heated by strap heaters and which contained a 347 S.S. micro-metallic filter. Sodium going through this filter then passed through a tube containing a valve to a second filter. The tube, valve, filter, and remainder of the system was heated by flexible electric heaters. When the sodium passed through the second filter it entered a metering tank. From the metering tank the sodium passed through a third filter and then through a second valve on into the calibration system.

The entire system was thoroughly cleansed of grease and any surface dirt after the system was assembled. The sodium that was placed in the loading system was first allowed to stand in a container under vacuum for 24 hours at approximately 300°C in order to outgas any compounds of sodium that vaporize at that temperature and pressure. In this period it may be assumed that a great portion of the oxides settled to the bottom of the container. The melt tank was then allowed to cool to approximately 200° so that all of the hydroxides and oxides would be in solid form. Then by use of helium gas the sodium was forced through the three separate filters (described above) and into the calibration system. In order to avoid contamination of the sodium by the helium, a special high purity helium was used.

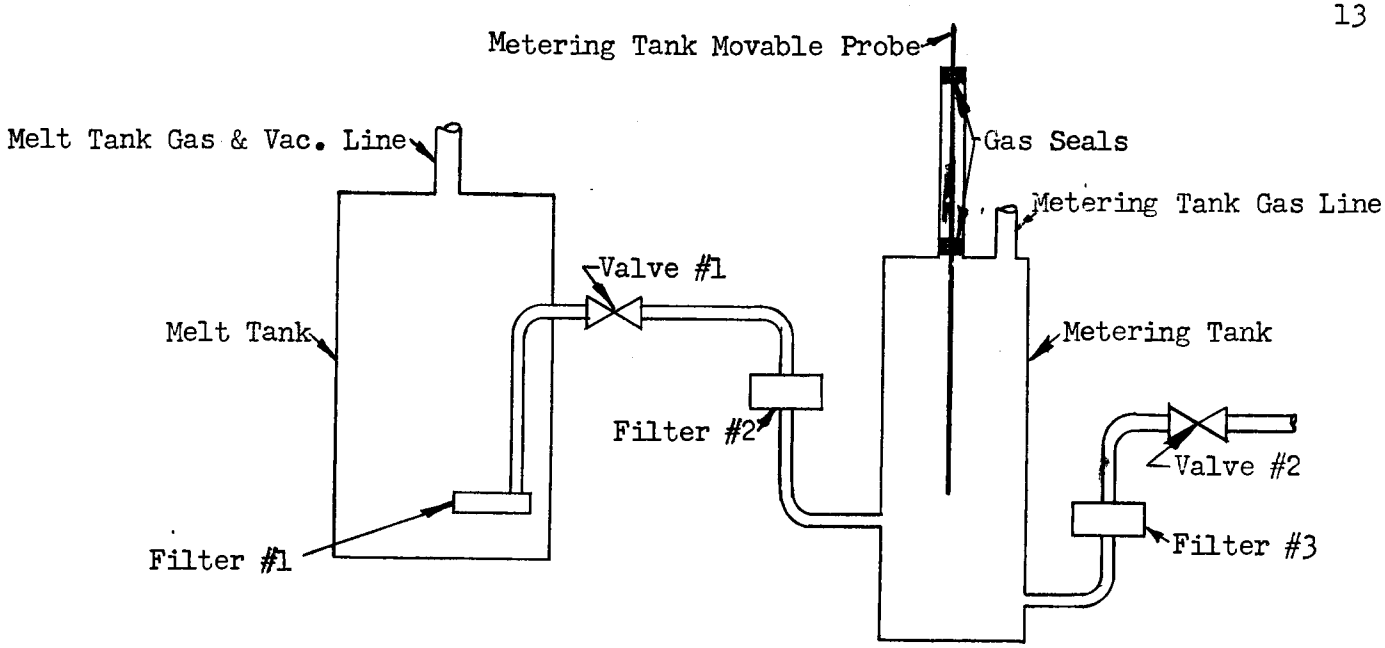

Figure 5 Sodium Loading System

Method of Calibration

Eight flowmeters were constructed in the manner described above from Inconel and 316 S. S. tubing. The dimensions of the flowmeters, measured at room temperature, are as follows:

Number	Material	Outer Diameter	Inner Diameter	Length
1	316	0.470 cm.	0.335 cm.	3 inches
2	Inconel	0.772 "	0.630 "	"
3	Inconel	0.470 "	0.335 "	"
4	316	0.638 "	0.457 "	"
5	316	0.638 "	0.457 "	"
6	Inconel	0.470 "	0.335 "	"
7	Inconel	0.770 "	0.632 "	"
8	316	0.470 "	0.328 "	"

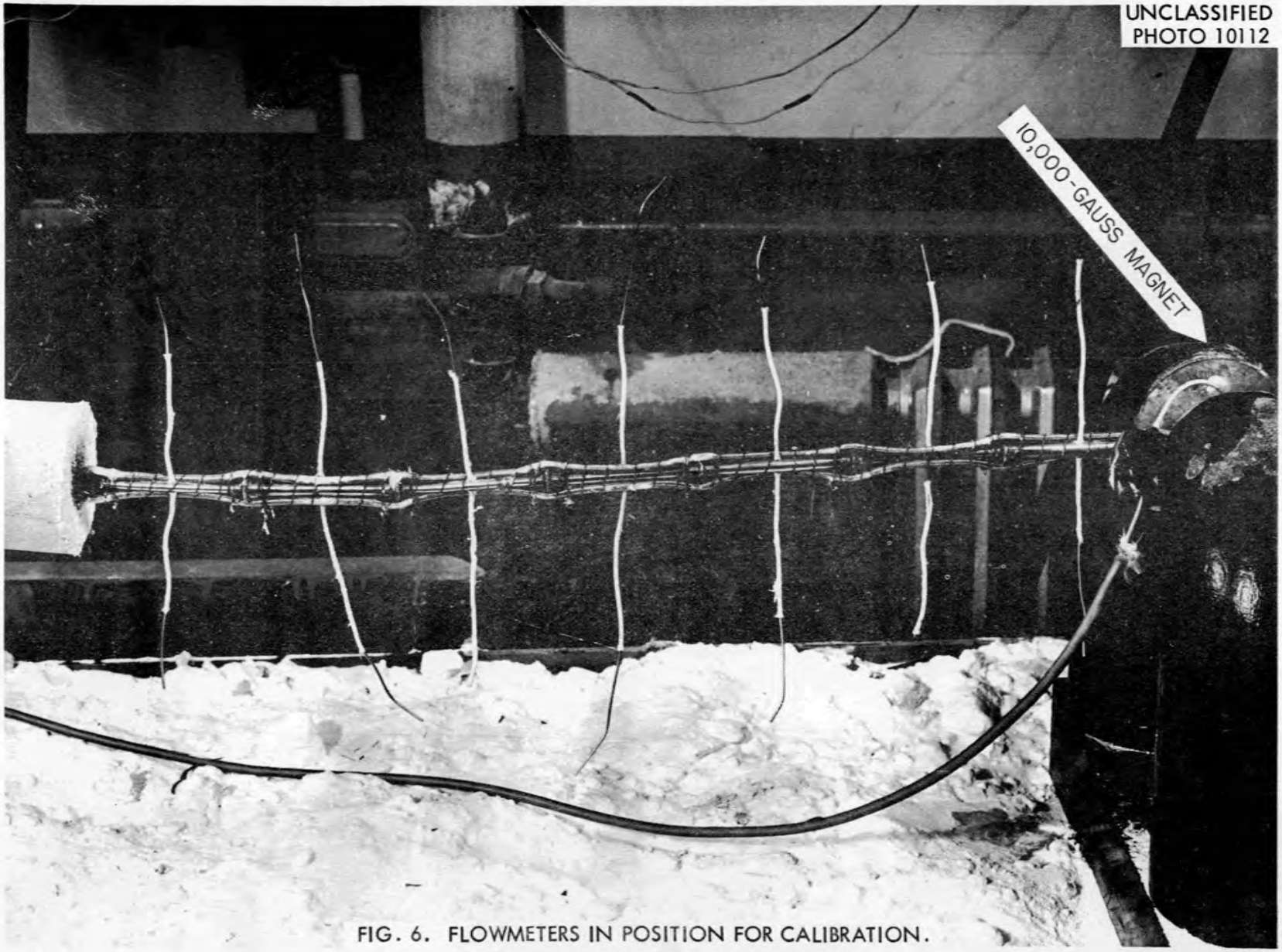

FIG. 6. FLOWMETERS IN POSITION FOR CALIBRATION.

The flowmeters were welded together so that the centerlines of the flowmeters were aligned and the junctions of the lead wires to the flowmeters were all in the same plane. (See Figure 6).

The series of flowmeters was joined to two tanks of known volumes with the axis of the flowmeter tubes horizontal, the leads vertical, and the magnetic field (supplied by a 10,000 gauss permanent magnet) horizontal and at right angles to the flowmeter tubes. (See Figure 7). Each tank had two electrical probes installed so that when the liquid sodium touched a probe an electrical circuit was completed which in turn actuated a signal device. The volume between the different length probes in each of the tanks was known to 0.5%.

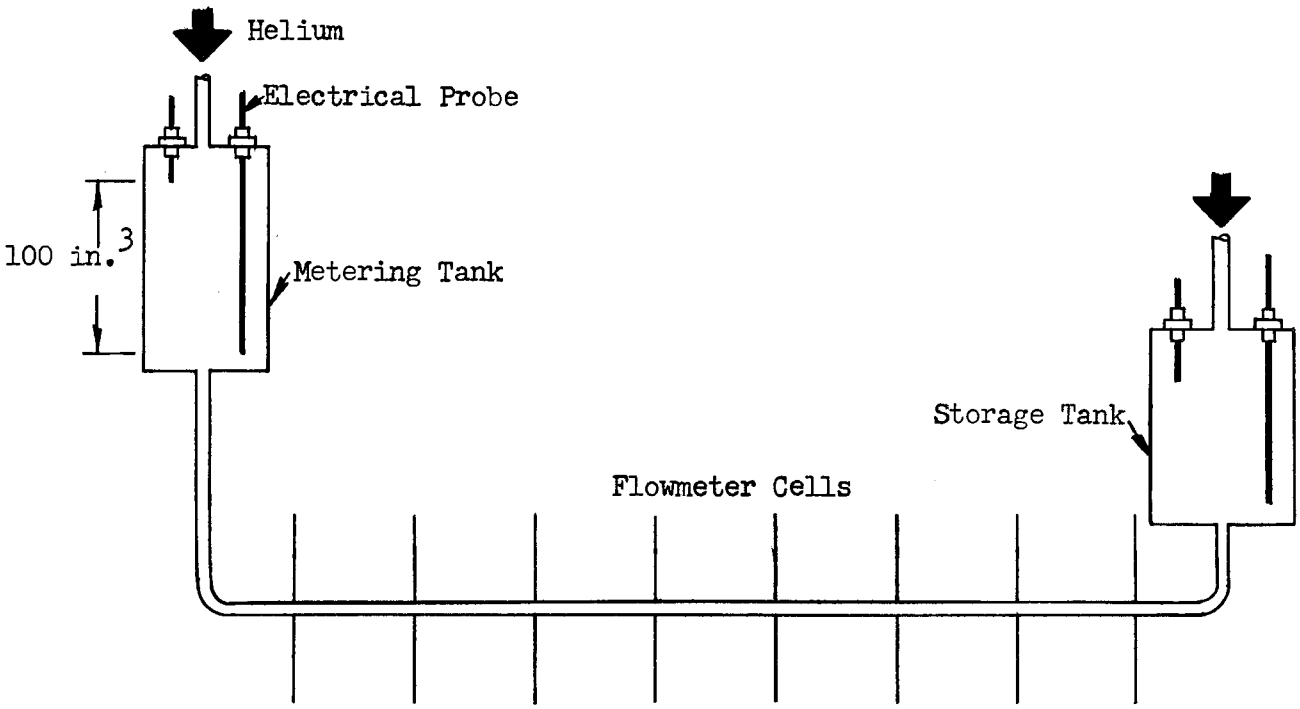

Figure 7 Calibration Apparatus

The flow of sodium from one tank to the other was obtained by differential helium pressures between the tanks. These pressures were controlled by Moore Nullmatic regulators which allowed continuous control and fine adjustments.

The relation of flow and flowmeter emf output was determined by passing the sodium from one of the tanks to the other tank through the line of flowmeters at a rate of flow which was controlled in a manner to yield a constant, arbitrary emf. The emf so generated was continually recorded on a 1 mv, single point Brown potentiometer recorder. As the sodium was transferred from one to the other tank, the pressure opposing the flow increased due to the increased level of the liquid. To maintain a uniform flow, therefore, the differential helium pressure had to be continually increased during the time required for the measured volume to pass from one tank to the other. This emf generated by the flow could be maintained constant to within the accuracy of the potential measuring recorder (1%) because of the fine degree of control of the gas pressure afforded by the Nullmatic regulator.

For emf's greater than the scale range of the Brown recorder (1 millivolt), a Leeds and Northup potentiometer was used to oppose all of the generated emf with the exception of 0.5 millivolt. Since the gas pressures were regulated to obtain a predetermined generated potential from the flowmeter, the potential desired was obtained when the Brown recorder indicated 0.5 millivolt. Any variation of potential was immediately revealed by the movement of the recorder pen away from the position of 0.5 mv.

By maintaining a constant flow, as indicated by a constant emf, and then measuring the time required for a fixed volume of sodium to be passed through the flowmeter, the rate of flow of sodium was determined. The time was measured by an electric stop watch which, including operator error, was reproducible to 0.3 sec. By obtaining in this manner the rate of flow corresponding to an arbitrary emf, and then repeating this procedure for several emf's, a general relation between rate of flow and emf generated could be determined for a given flowmeter.

All of the data were taken at 250°C. Data from a previous experiment, however, had indicated that, within the accuracy of these measurements, no change in calibration can be detected for temperatures up to 800°C.

BIBLIOGRAPHY

(1) "Electromagnetic Velometry" A. Kolin, Journal of Applied Physics, Feb. 1944.

(2) "An Alternating Field Induction Flow Meter of High Sensitivity" A. Kolin, Review of Scientific Instruments, May 1945.

(3) "Suitability Report on the Magnetic Induction Flowmeter", P. D. Jacobs, The Kellex Corp., December 1948.

(4) "The Design and Construction of a Test Loop for the Study of an Electromagnetic Pump and Flowmeter on Lithium Systems", E. I. Goodman, Massachusetts Institute of Technology, September 1950.

(5) "Magnetic Flowmeter Output Potentials", E. R. Astley, (G.E. R52GL42) March, 1952.