AN INVESTIGATION OF THE EFFECT OF MASS VELOCITY AND THERMAL CONDUCTIVITY ON THERMOMETRIC LAG

AN INVESTIGATION OF THE EFFECT OF MASS VELOCITY AND THERMAL CONDUCTIVITY ON THERMOMETRIC LAG

By

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PREFACE

Temperature is one of the most important controlled variables in chemical processes and the lags of temperature measurement is an important problem in process control. This investigation is in the field of temperature control, and is concerned with two problems: the study of the effect of mass velocity and thermal conductivity on the thermometric lag.

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INTRODUCTION AND REVIEW OF SELECTED LITERATURE

Temperature is one of the most important controlled variables in chemical processing. The definition of temperature given by Maxwell is "The temperature of a body is its thermal state considered with reference to its ability to communicate heat to other bodies". Heat is energy that is transferred from one body to another by a thermal process. The lag of temperature measurements presents the most problems in process control, due to the nature of heat transfer and the specific heat capacity of the materials comprising the primary measuring element.

Fundamentally, each temperature measuring problem is one of regulating heat exchange. For heat to be transferred to a temperature sensitive element from its surroundings, a temperature difference must exist between them.

The purpose of this paper is to consider the temperature measuring or Thermometric Lag for thermocouple installations. A study of the literature revealed a lack of data on the response of thermocouples in different types of protective tubes and tube packings.

The thermometric lag may be defined as the instantaneous temperature difference existing at any time between the true temperature and the temperature given by the temperature sensitive element at the same instant. Consider the situation shown in Figure 1. At 1:00 the temperature of the process was suddenly changed. Figure 1 a. The response of the temperature recorder is shown in 1 b. If these data are plotted on semi-log paper, the slope of the line in 1 c. is the lag coefficient. This lag is a heat-transfer phenomenon and therefore is dependent on those factors which affect the heat-transfer rate. The following factors influence the

Fig. 1

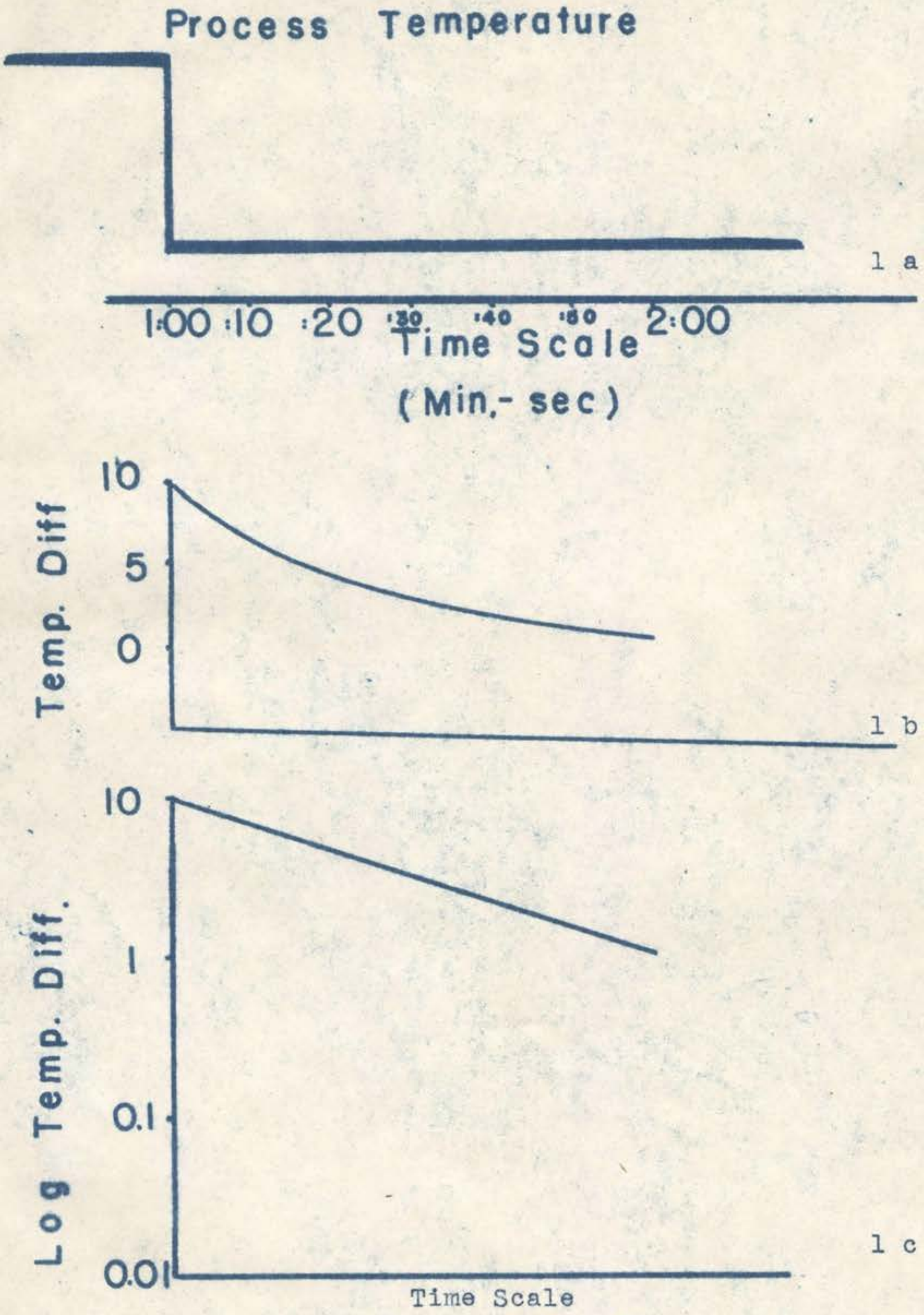

Fig. I

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responsiveness of a thermocouple:

Thermal Capacity of the Element

Thermal Conductivity of the Element

Surface Area Per Unit of Mass of the Element

Film Coefficients of Heat Transfer

In this investigation the effect of different mass velocities and packing materials with different thermal conductivities will be studied and the time required for transmission of the temperature difference measured. A chromel-alumel couple made from 28 gauge (American Wire Gauge, "Brown and Sharpe") wire will be used for all temperature determinations.

If two wires of different metals are joined together at each end so as to form a complete electrical circuit, it is found that a current flows in the circuit if one of the junctions is at a higher temperature than the other. This current is the result of an E.M.F. which is set up in the circuit and is a function of the temperature of the "hot" junction if the other--the "cold" junction is maintained at a constant temperature. This E.M.F. can be conveniently measured with great accuracy. The E.M.F. produced with variation of the temperature difference between hot and cold junctions may be written:

$$E = A\,(T - T_o) + B\,(T^2 - T_o^2) \qquad (1)$$

Where:

E--thermoelectric E.M.F. in volts
T and T_o--the absolute temperature of the hot and cold junctions respectively
A and B--the constants which depend on the metals forming the couple.

Several of the more common metals used in industrial thermocouples have been thoroughly investigated and graphs and tables (10) showing the relationship between E.M.F. and temperature have been prepared and are readily available.

When thermocouples are used in testing and experimental work, it is very important that the temperature indicated by the couples accurately represent the temperatures being investigated. When the entire hot junction of a thermocouple is maintained at a steady temperature, its temperature indication is trustworthy, provided no contaminating influences are present.

Since thermocouples are widely used in the investigation of temperature gradients in materials and the study of fluid-film temperature drops, it is desirable to know definitely how to build and install a couple to read accurately the temperature at a point. In order to minimize the error due to the heat conduction by the leads, Smith (4) advises the use of an "isothermal zone" in a groove in the tube to lead away from the thermal junction. Reviews of the literature of surface temperature measurement are reported by Othmer and Coates (3) and by Colburn and Hougen (1). Othmer (2) lists several different materials used to pack the isothermal groove. Bailey (6) gives a good discussion of the effects of temperature gradients in thermo-junctions and the errors introduced in the measurement of surface temperatures. Insinger and Bliss (8) describe a traveling thermocouple, adapted for short tubes in research work.

The temperature-time relations of fluids and solids which are either being heated or cooled may be empirically determined by inserting thermometers or thermocouples, or may be calculated from the assumed conditions, in conjunction with the physical constants of the materials, the surrounding shapes and media. The fact that thermal physical data are not so complete as they might be or that technical conditions can rarely be made to coincide with the theoretical prototypes, does not limit the value of such estimations, but does require that the accuracy of the computed results should not be overestimated. Where empirical observations and theoretical calculations may be made concurrently, new physical constants may be determined which will be found to be more reliable in predicting other time-temperature relations under different, though similar, conditions.

The Law of Heat Transfer was first enunciated by Newton. Newton's law states "the rate of cooling of a cooling body is directly proportional to the difference between the temperature of the body and the temperature of its surroundings". The transfer of heat from the surface of a solid at a temperature T_s to a fluid having bulk temperature T_b flowing past it is extremely complex, since both conduction and convection are involved: the situation is handled by defining a coefficient of heat transfer h, as found in Newton's Law which expressed mathematically is:

$$dq = h\, dA\, (T_s - T_b) \qquad (2)$$

Where:

dq = local rate of heat transfer through surface element dA

Harper (7) gave an exposition of the mathematics involved as regarded a simple thermometer.

The response curve of a temperature sensitive element can be determined from Newton's Law when stated in another form. It states "the rate of change of temperature with respect to time is proportional to the difference between the bath and the measured temperature.

In equation form:

$$\frac{dT}{d\theta} = \frac{1}{L}(T_b - T) \qquad (3)$$

where T = indicated temperature
T_b = temperature of bath
L = lag coefficient
θ = time

$$\frac{dT}{(T_b - T)} = \frac{d\theta}{L} \qquad (4)$$

Integrating (4) gives

$$-\ln \frac{T_b - T_2}{T_b - T_1} = \frac{\theta_2 - \theta_1}{L} \qquad (5)$$

If $\theta_2 = \theta$; $T_1 = T_o$; $T_2 = T$, which is temperature at time θ,

$$\ln\left(\frac{T_b - T}{T_b - T_o}\right) = -\frac{\theta}{L} \qquad (6)$$

$$\left(\frac{T_b - T}{T_b - T_o}\right) = e^{-\frac{\theta}{L}} \qquad (7)$$

$T_b - T_o$ = initial temperature difference
$T_b - T$ = unaccomplished temperature difference
$\left(\frac{T_b - T}{T_b - T_o}\right)$ = fraction unaccomplished temperature difference

1 - fraction unaccomplished temperature difference = fraction accomplished temperature difference

$$\text{Let } T^1 = 1 - \left(\frac{T_b - T}{T_b - T_o}\right) = 1 - e^{-\frac{\theta}{L}} \qquad (8)$$

$1 - e^{-\frac{\theta}{L}}$ = fraction accomplished temperature difference

Thus, for a sudden change in the measured variable an exponential response will be obtained. When $\theta = L$, $T^1 = 0.632$. Therefore, the time required to reach 63.2 per cent of the total change is equal to the lag coefficient in equation (3).

The cases where the time element involved affects the indication of a thermocouple may be classed under three headings:

1. When a thermocouple is placed in a fluid, a definite time must elapse before the indication of the thermocouple corresponds to the temperature of the fluid.

2. When the temperature of the fluid is changing at a certain rate, the indication of the couple will lag behind the actual temperature of the fluid.
3. When a couple is subjected to a cyclic temperature, the amplitude of the temperature cycle indicated by the couple will be less than the amplitude of the impressed cycle, and it will reach the corresponding points on its cycle some time later than the same points occur in the impressed cycle.

The first case will be considered in this investigation, and it can be shown that mathematical methods using the results of the first case can give very good estimations as to results of the other two cases.

EXPERIMENTAL APPARATUS

The apparatus used for this investigation is a closed piping system comprising a feed tank, a recirculation pump, a by-pass and test section and a Brown Electronik Recorder, Figure 2.

The feed tank, Figure 3, is 24 inches in diameter, 72 inches in length and is constructed of 3/8 inch mild steel with riveted longitudinal joints and welded ends. The charge is admitted on the side, two inches from the top, through a 3/4 inch line controlled by a globe valve located on the instrument panel. Heating of the charge is accomplished by introducing steam directly into the tank through the bottom and thus effecting better heat transfer between the steam and water. A globe valve and pressure gauge on the instrument panel control the flow of steam into the feed tank. A 1/4 inch outlet located at the top of the feed tank is fitted with a valve to act as a vent for non-condensable gases. This valve is cracked at all times during operation. The temperature of the charge in the feed tank is obtained by a chromel-alumel thermocouple inserted in the side of the feed tank six inches above the pump suction line. From this reading the order of magnitude of the temperature is determined. All experimental values are obtained with the bare probe, Figure 4, and the test section, Figure 5.

The liquid is withdrawn from the side outlet of the feed tank six inches above the welded end to allow for settlement of all foreign matter. All piping in the test section was 1 1/2 inch (Briggs standard gauge iron pipe). The pump used was a 1/2 H.P. Gorman Rupp, centrifugal type pump. The pump discharged through a gate valve for minimum pressure drop. The flow is next directed through the 3/8 inch orifice plate held in place

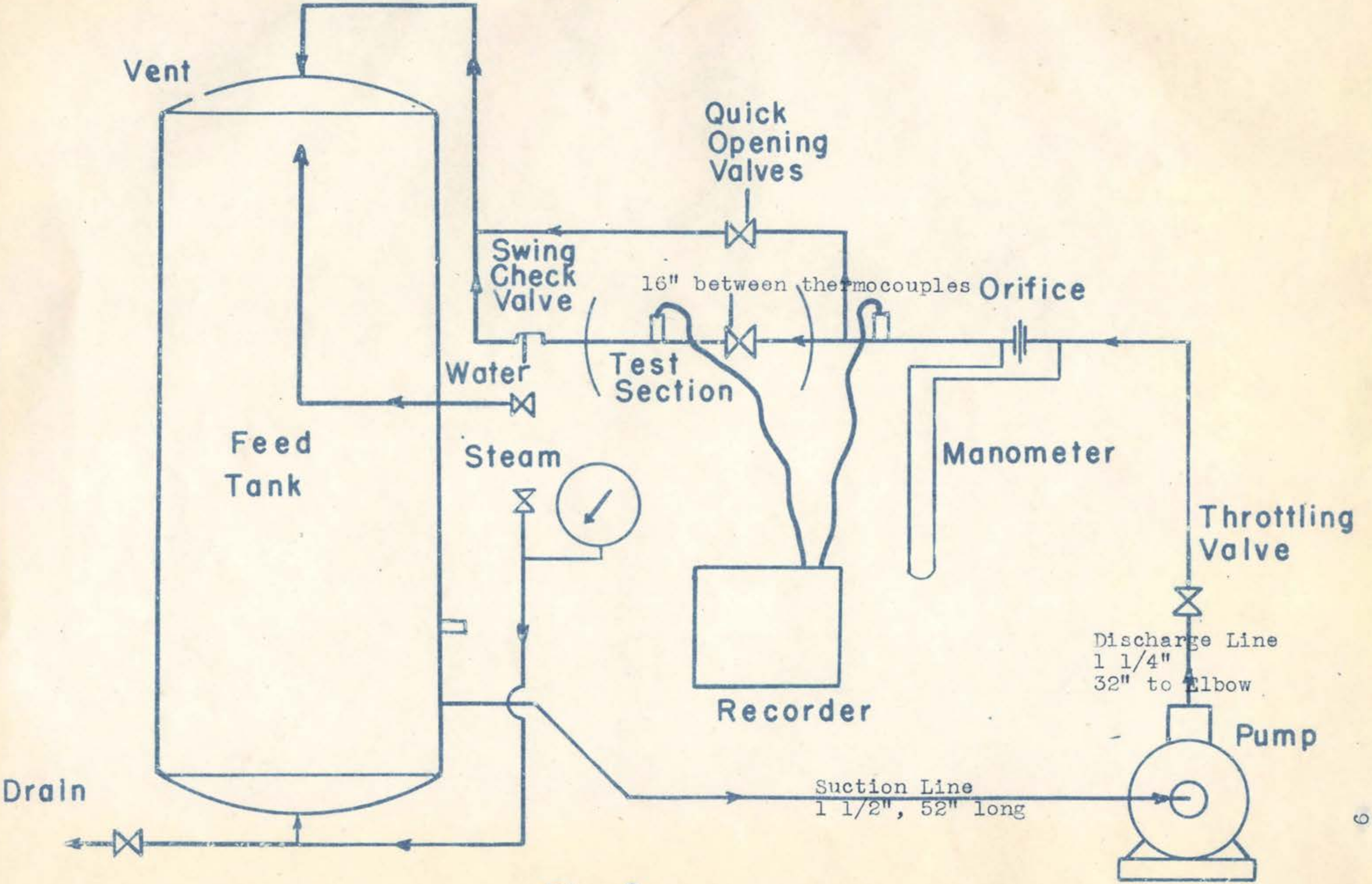
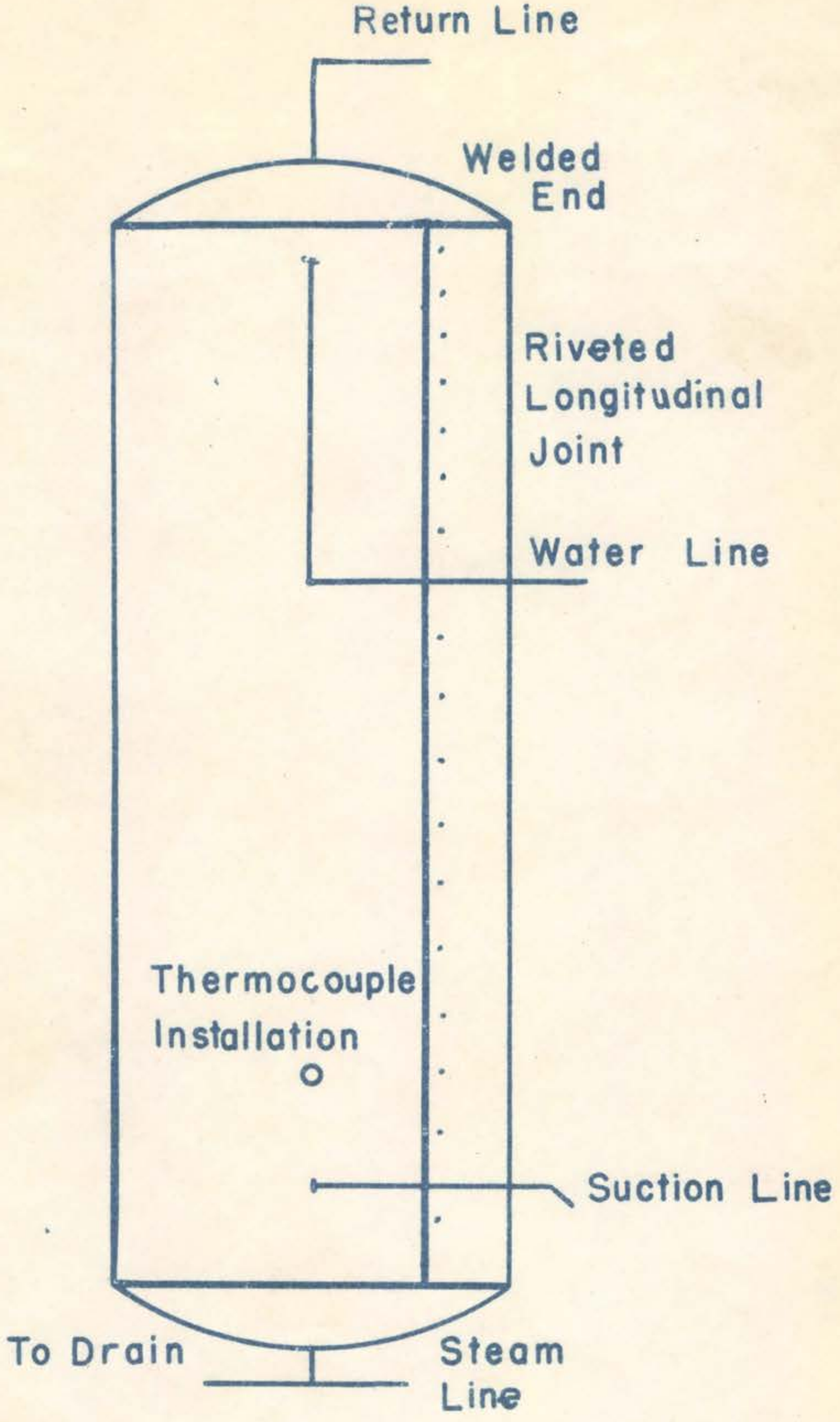

Vent
Quick Opening Valves
Swing Check Valve
16" between thermocouples
Orifice
Water
Test Section
Feed Tank
Steam
Manometer
Throttling Valve
Discharge Line 1 1/4" 32" to Elbow
Recorder
Pump
Drain
Suction Line 1 1/2", 52" long

Fig. 2

FIG. 3

RESERVOIR ASSEMBLY



RESERVOIR ASSEMBLY

Fig. 3

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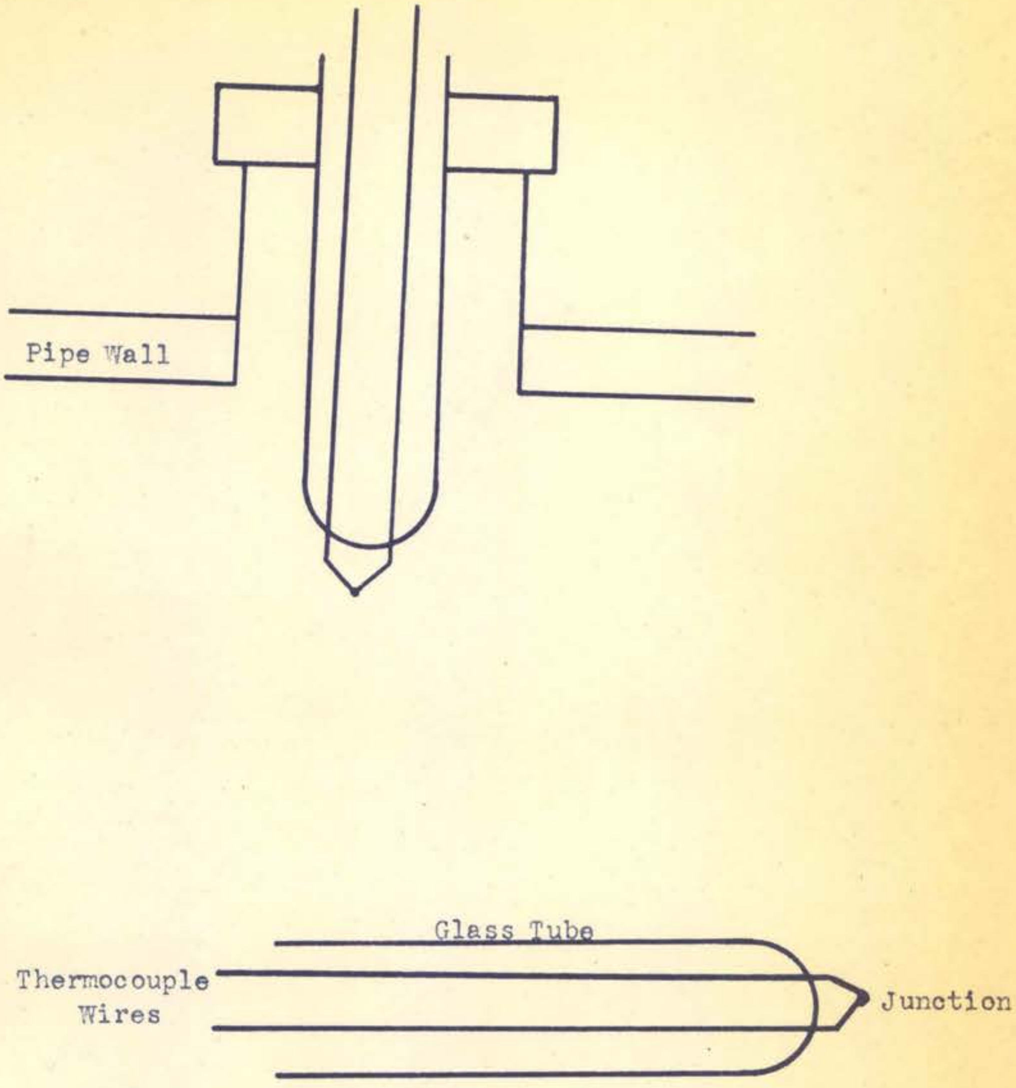
FIG. 4

TEMPERATURE PROBE



3/16" Probe

(1/8" I.D.)

6" Length

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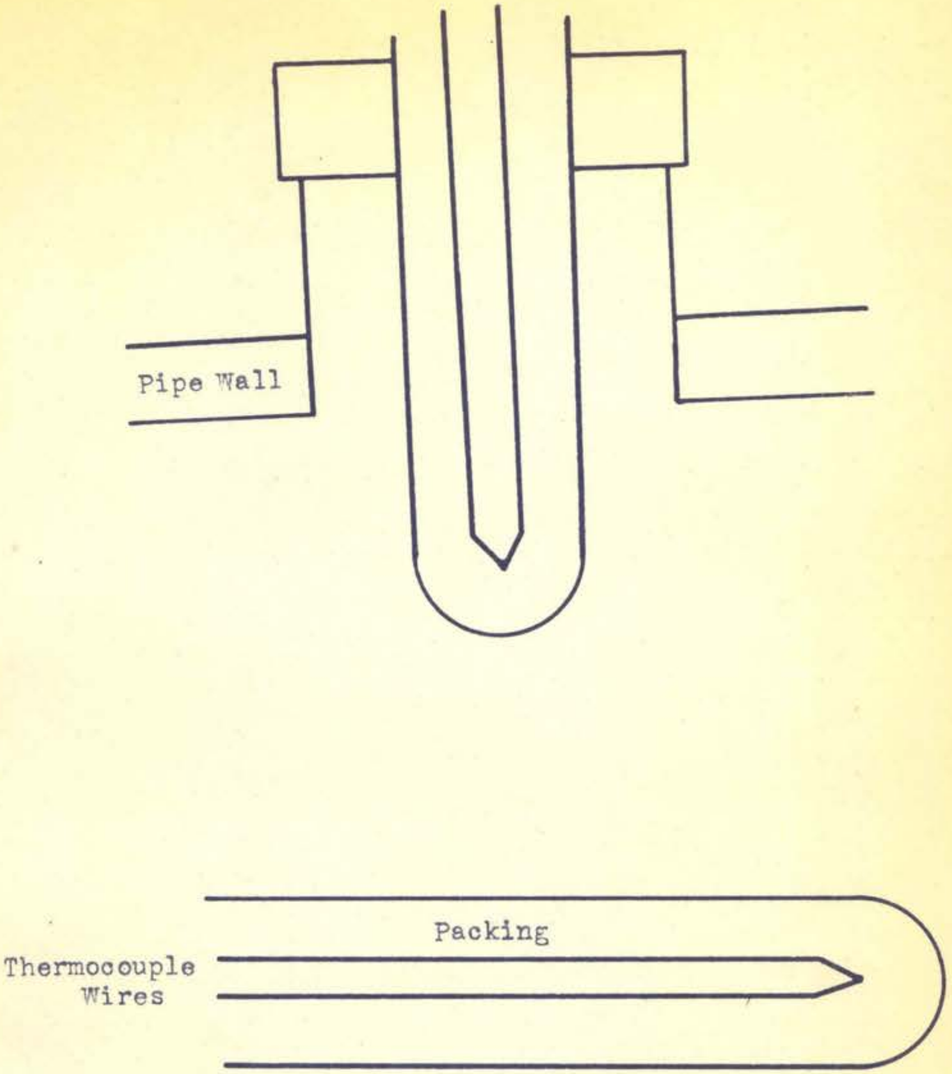
FIG. 5

TEST PROBE



3/16" Probe

(1/8" I.D.)

6" Length

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between standard 125 pound screw flanges. Pipe pressure taps were located 2 1/2 pipe diameters upstream and 8 pipe diameters downstream according to recommendations of the A.G.A.-A.S.M.E. joint fluid committee (5). Mercury is used in the manometer on the instrument panel to record the pressure differential. The orifice was calibrated in place by weighing the amount of water flowing through it in unit time.

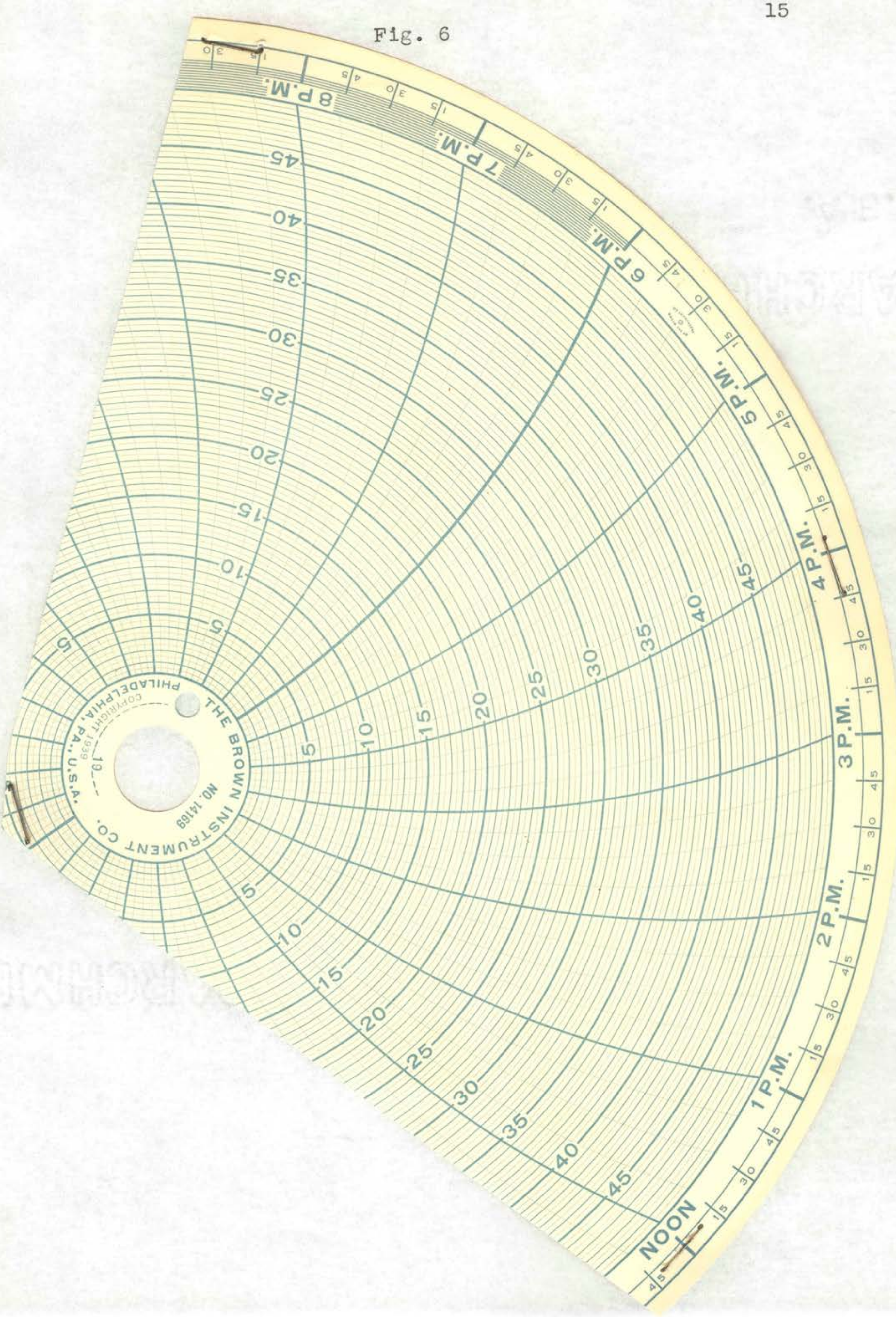
All temperatures were obtained by means of thermocouples. Chromel-alumel junctions were used for the thermocouples and the E.M.F. was measured by a Leeds and Northrup Type K potentiometer for calibration purposes. This instrument is capable of reading hundredths of millivolts directly with the third place being a close estimate. This reading is equivalent to a direct temperature reading to the nearest 0.3 of one degree F. and a close estimate to the nearest 0.03 of one degree F. The thermocouple junctions were made by the mercury-arc method.

The by-pass and test section was located close to the orifice to eliminate pressure drop and heat loss. The temperature probe which was used to determine the temperature of the hot fluid entering the test section is shown in detail in Figure 4. A detail sketch of the test probe is shown in Figure 5. All of the protective tubes were 3/16 inches in diameter with a 1/8 inch bore. Two quick opening valves and a swinging check valve were used to control the flow of the fluid as desired. From the by-pass and test section the fluid returned to the top of the feed tank for recirculation. The feed tank was filled to within two inches of the top to prevent foaming and entrainment of air in the circulating fluid.

After erection and testing of the apparatus for leaks, Johns-Mansville "Abestocel" pipe lagging was applied to the discharge line from the pump to the test section to minimize heat losses. No attempt was made to calculate these heat losses.

Temperatures of the thermocouple installations in the test section were recorded by a Brown Electronik Recorder. (See Figure 6.) The instrument is a continuous balance potentiometer type recording electronic instrument. Figure 7 shows the wiring diagram of the electronic circuit. It was chosen because the transmission lag in an electronic instrument is negligible compared to the thermometric lag. When checked against the government standardized thermometer, it gave accurate and reproducible results. Figure 8 is the calibration curve for the chromel-alumel couple used in the temperature probe.

Fig. 6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2 P.M.
3 P.M.
4 P.M.
5 P.M.
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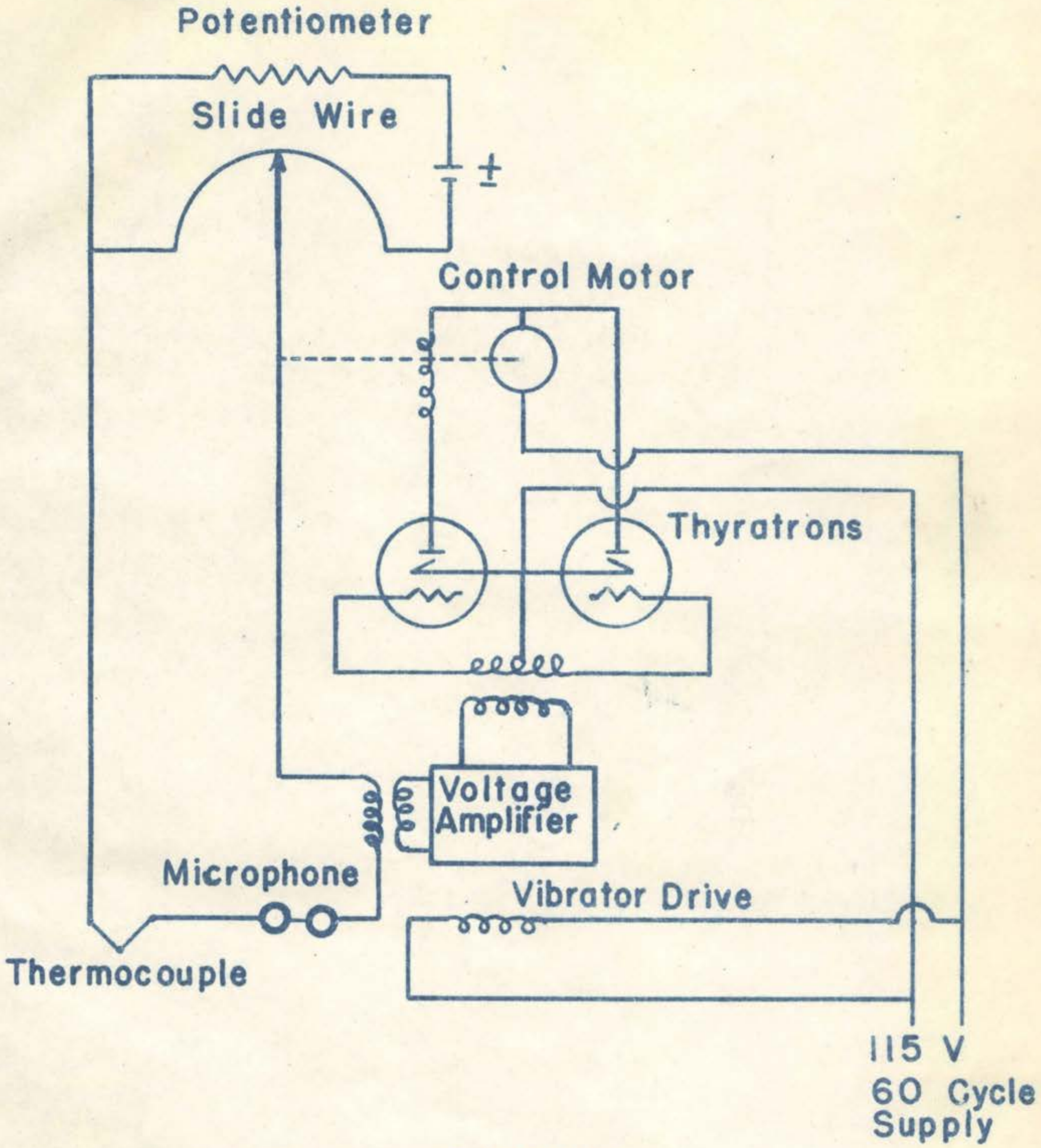
45

Fig. 7

ELECTRONIC CIRCUIT



ELECTRONIC CIRCUIT

Fig. 7

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EXPERIMENTAL PROCEDURE

During the course of the investigation, the thermocouples were calibrated before and after each individual thermocouple installation in the test section.

In starting a run, water was admitted to the feed tank and heated by live steam until the feed tank thermocouple indicated a temperature of 200 degrees F. ± 5 degrees F. The throttling valve was set at a predetermined setting for the desired mass velocity and the pump was started and the hot fluid circulated through the by-pass system until the temperature of the bare thermocouple probe immediately preceding the test section was registering a constant temperature. Equilibrium was reached in about five minutes of operation, and during this time, the Brown Electronik Recorder had been warming-up and was on a stand-by basis. A predetermined index point on the graph was chosen as a starting point and the instant it was reached the quick opening valves were quickly reversed thus directing the hot fluid past the thermocouple installation being tested.

Copper, steel and glass protection tubes were tested and each tube tested empty, filled with graphite, graphite and oil, oil and mercury. Each of various installations and packings were tested at five different mass velocities.

After each test, it was necessary to fill the test section with cold water so as to have a measurable temperature difference at the start of each run. This was accomplished by a small drain and vent on downstream end of the test section.

The short distance between the bare thermocouple probe and the test section and the insulation on the tube allows the assumption of adiabatic operation. This is not the actual case but the heat losses are so very small over the affected area that they are well within the experimental error and the accuracy of the instrument.

RESULTS AND DISCUSSION

The liquid used was tap water, which after use was found to have a pH of 7.2 and gave a positive test for Fe ions. The Fe ions were considered to be present in such small concentrations that they did not change the physical characteristics of the water. However, after each thermocouple installation was checked, new feed was introduced so as to have essentially the same conditions for each run.

The Brown Electronik Recorder draws a curve on a circular graph, Figure 6, and can be made to travel at any of several speeds. Due to the small periods of time that were to be measured, it was desirable to have as rapid a chart drive as possible. By use of a carefully machined gear, the machine was driven at a speed of 12 inches per minute. Therefore, each division on the graph represented 5 seconds, and the smallest division represented 0.5 seconds.

The data in Table I are the physical properties of the materials used in the various installations. Most of these data are from the International Critical Tables.

The data in Tables II-XIV were read directly from the graphs drawn by the machine. If these data are plotted on rectangular co-ordinate graph paper, a curve is obtained which is the equivalent of 1 b. These same data plotted on semi-log paper should give a straight line, the slope of which is the lag coefficient as defined by this paper in equation (3).

The data obtained on this experimental apparatus indicate that the mass velocity of the fluid past the temperature-measuring element does have a bearing on the lag of the installation. However, the fluid film resistance is less important than the resistance offered by the material of the protective tube.

The air in the protective tube when tested empty was the greatest offender when it came to offering resistance to heat flow. Any filling material improved the flow of heat over that obtained when empty.

Referring to graphs 1, 2, and 3, a sudden break in the time-temperature curve is noticed for each installation except the glass protective tube. This sudden break in the curve could be due to the difference in thermal expansion of the thermocouple wires. In each case, the break in the curve occurred when approximately 40 per cent of the temperature difference had been consumed. Therefore, as the thermocouple wires expanded at different rates, the junction was forced from the center of the tube and over against the side of the metal tube, eliminating the air film resistance. In the case of the steel and copper tubes, the air film was a significant resistance, whereas in the glass tube the tube offered most of the resistance to heat flow. The graphs indicate this. For example, in graph 3 the curve of the glass tube does not exhibit the sharp break shown by steel and copper protective tubes. These data indicate that dry graphite used as a packing does not have sufficient rigidity to prevent the movement of the wires due to thermal expansion as shown in graph 2.

The Gurney-Lurie charts in McAdams (11), page 36, indicate that this behavior is to be expected. Assuming that the thermocouple is in the center of the tube at the start, zero is used as the value for m and n. But when the couple touches the protective tube a value of n approaching 1 must be used. The curve should start from the origin and have a slight negative slope. After the couple has moved over against the protective tube, a displacement in the curve is expected due to the different value of n. The curve then should continue with very nearly the same slope. The curves for steel and copper exhibit this behavior as shown by graphs 1 and 2.

TABLE I

General Data (I.C.T.)

Specific Heat	BTU/lb.°F.
Cu	0.0930
Fe	0.1121
Glass	0.1864
Water	1.0
Oil	0.5
Air	0.24

Thermal Conductivity	BTU/hr.ft.^{2} (°F.ft.)
Cu	222
Glass	0.4
Steel (1% C)	26
Graphite	0.104 (200 mesh screened)
Oil	0.08 (Mineral Oil 30 A.P.I. at 60°F.)
Air	0.016
Graphite and Oil	0.20 (Part for part by weight)

Chromel	Ni	90%
	Cr	10%
Alumel	Ni	94%
	Al	2%
	Si	1%
	Mn	3%

Mass Velocity* lb./sec./ft.^{2}	ft./sec.*
68	1.09
81.5	1.31
95	1.5
109	1.73
122	1.94

*Calculated

TABLE II

Run No. 1 | Steel Tube | Test Section Temperature 68 °F.
No Packing | Fluid Temperature 200 °F.

Time Sec.	lb/sec/ft^2 68	81.5	95	122
0	68	68	68	68
15	82	85	87	89
30	100	106	110	114
45	119	133	147	148
60	151	179	187	188
75	187	188	189	190
90	189	190	192	193
105	191	192	197	199
120	192	196	200	

TABLE III

Run No. 2 | Steel Tube | Test Section Temperature 68 °F.
Graphite Packing | Fluid Temperature 202 °F.

Time Sec.	lb/sec/ft^2 68	81.5	95	122
0	68	68	68	68
15	95	100	108	139
30	128	155	188	193
45	188	190	193	202
60	191	194	201	
75	195	202		
90	202			

TABLE IV

Run No. 3

Steel Tube
Graphite and
Oil Packing

Test Section Temperature 65 °F.
Fluid Temperature 198 °F.

Time Sec.	lb/sec/ft^2 68	81.5	95	109	122
0	65	65	65	65	65
15	78	86	93	100	106
30	102	109	113	157	185
45	153	149	182	186	189
60	176	185	187	191	197
75	186	188	191	198	
90	188	191	198		
105	190	197			
120	194				

TABLE V

Run No. 4

Steel Tube
Mercury Filled

Test Section Temperature 68 °F.
Fluid Temperature 202 °F.

Time Sec.	lb/sec/ft^2 68	81.5	95	122
0	68	68	68	68
15	89	91	95	99
30	105	115	138	163
45	131	158	193	196
60	175	189	198	202
75	189	195	202	
90	190	201		
105	194			
120	197			

TABLE VI

Run No. 5 | Steel Tube
Oil Filled | Test Section Temperature 70 °F.
Fluid Temperature 198 °F.

Time Sec.	lb/sec/ft^2 68	81.5	95	109	122
0	70	70	70	70	70
15	90	92	94	95	97
30	102	108	115	121	134
45	121	155	154	175	186
60	153	180	184	188	189
75	185	187	189	191	195
90	187	191	192	194	198
105	189	196	197		
120	191				

TABLE VII

Run No. 6 | Copper Tube
No Packing | Test Section Temperature 68 °F.
Fluid Temperature 198 °F.

Time Sec.	lb/sec/ft^2 68	95	122
0	68	68	68
15	120	150	186
30	188	190	198
45	197	198	

TABLE VIII

Run No. 7

Copper Tube
Graphite and
Oil Filled

Test Section Temperature 68°F.
Fluid Temperature 198°F.

Time	lb/sec/ft^2	
Sec.	68	122
0	68	68
5	100	133
10	150	187
15	186	198
20	192	
25	198	

TABLE IX

Run No. 8

Copper Tube
Oil Filled

Test Section Temperature 68 °F.
Fluid Temperature 197 °F.

Time	lb/sec/ft^2		
Sec.	68	95	122
0	68	68	68
10	107	121	150
15	126	189	188
20	178	193	197
25	185	197	
30	188		
35	191		
40	195		

TABLE X

Run No. 9 — Glass Tube, No Packing

Test Section Temperature 70 °F.
Fluid Temperature 200 °F.

Time Sec.	lb/sec/ft^2 68	95	122
0	70	70	70
15	88	89	91
30	92	93	95
45	97	101	105
60	108	114	121
75	121	131	143
90	139	155	174
105	164	185	187
120	186	188	190

TABLE XI

Run No. 10 — Glass Tube, Graphite and Oil Filled

Test Section Temperature 68 °F.
Fluid Temperature 198 °F.

Time Sec.	lb/sec/ft^2 68	95	122
0	68	68	68
15	85	88	90
30	93	100	103
45	106	117	125
60	123	145	153
75	150	187	188
90	187	189	190
105	189	190	191
120	190	192	194

TABLE XII

Run No. 11	Glass Tube Graphite Packing	Test Section Temperature Fluid Temperature	69 °F. 197 °F.

Time	lb/sec/ft^2		
Sec.	68	95	122
0	69	69	69
15	84	86	89
30	92	99	100
45	103	109	118
60	118	129	149
75	138	160	186
90	168	186	188
105	187	188	190
120	188	189	191

TABLE XIII

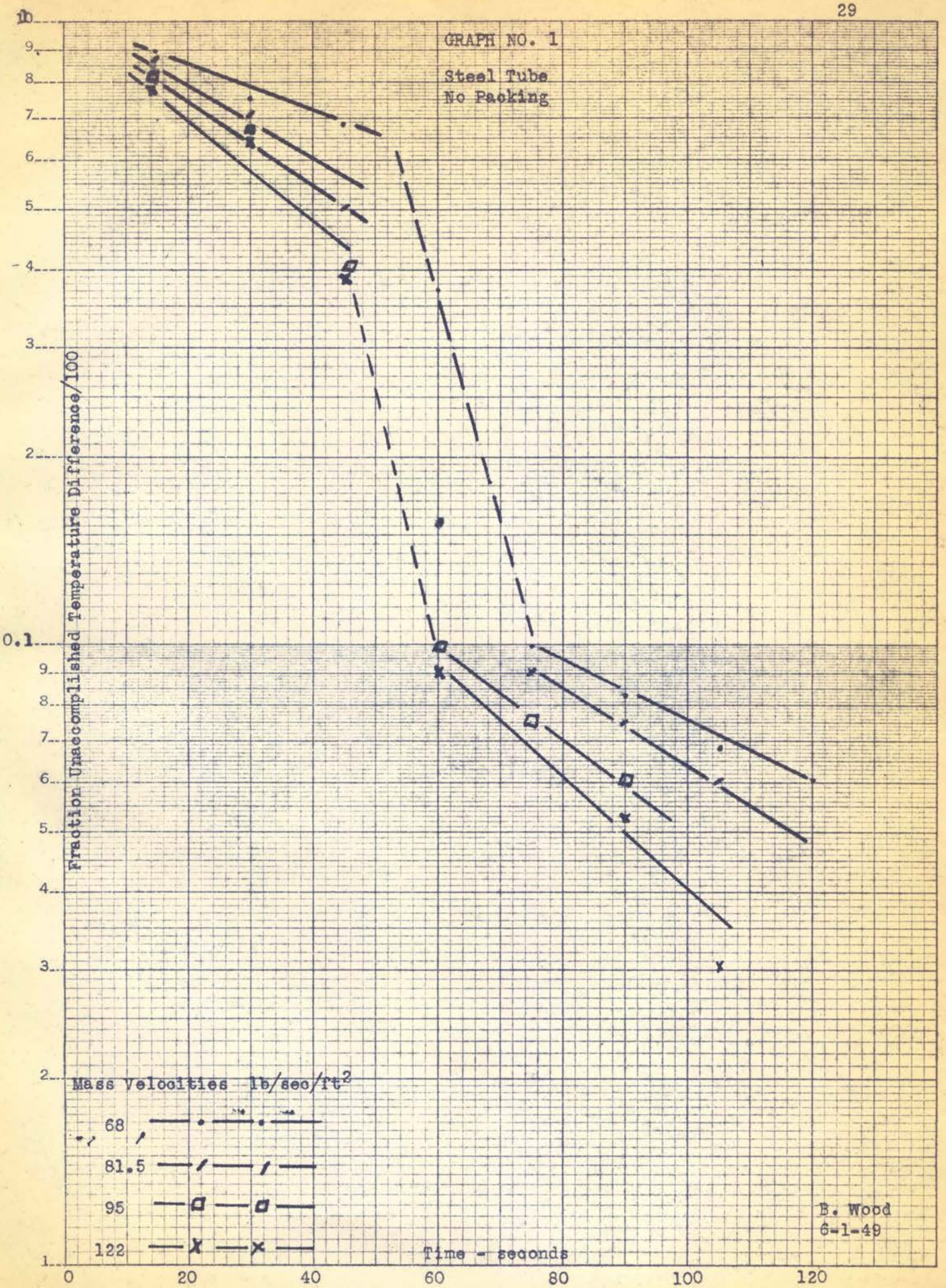
Run No. 12	Glass Tube Oil Filled	Test Section Temperature Fluid Temperature	68 °F. 200 °F.

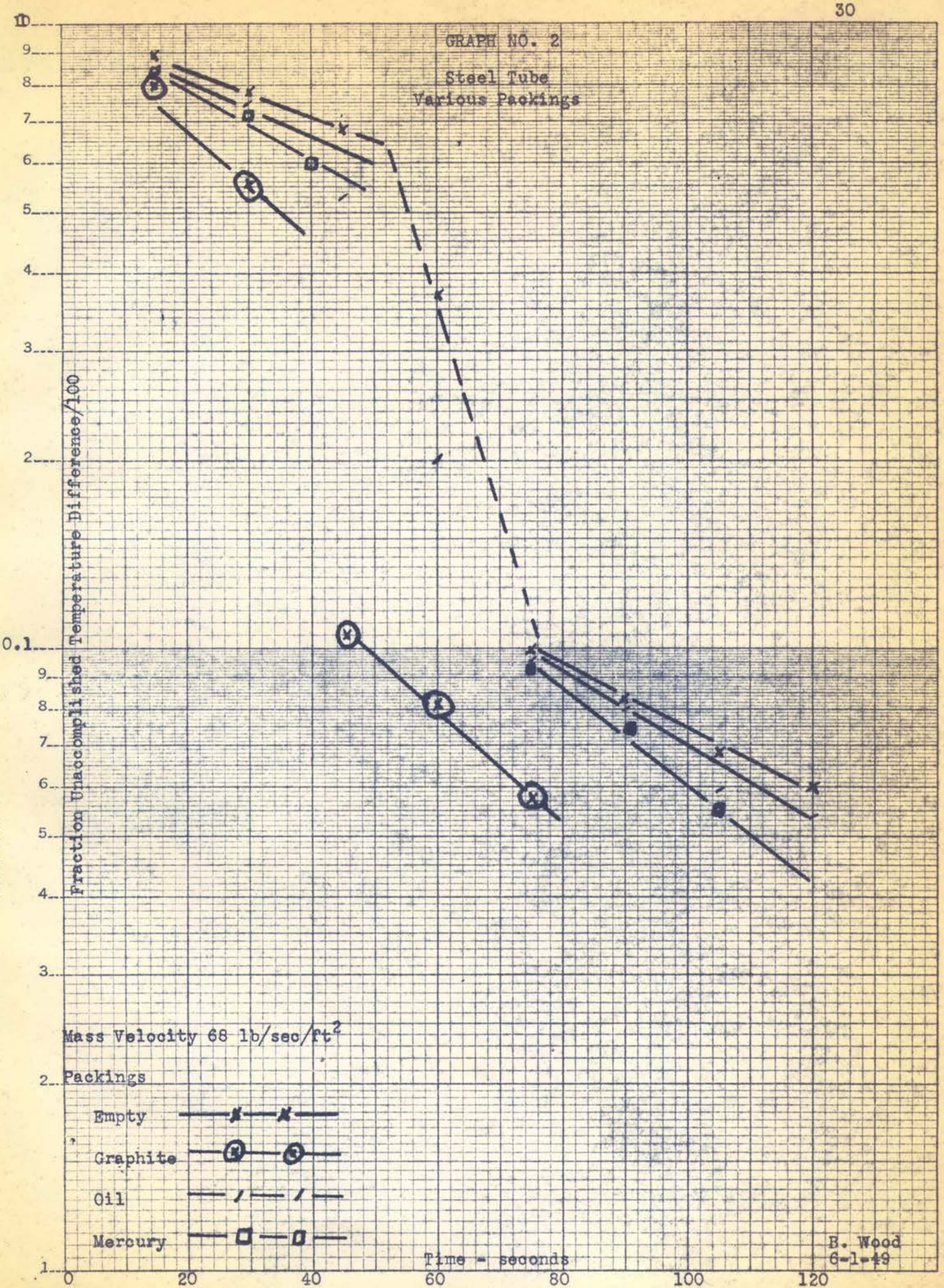
Time	lb/sec/ft^2		
Sec.	68	95	122
0	68	68	68
15	83	85	86
30	91	95	99
45	93	108	115
60	114	127	142
75	135	155	180
90	160	182	184
105	182	185	186
120	184	186	188

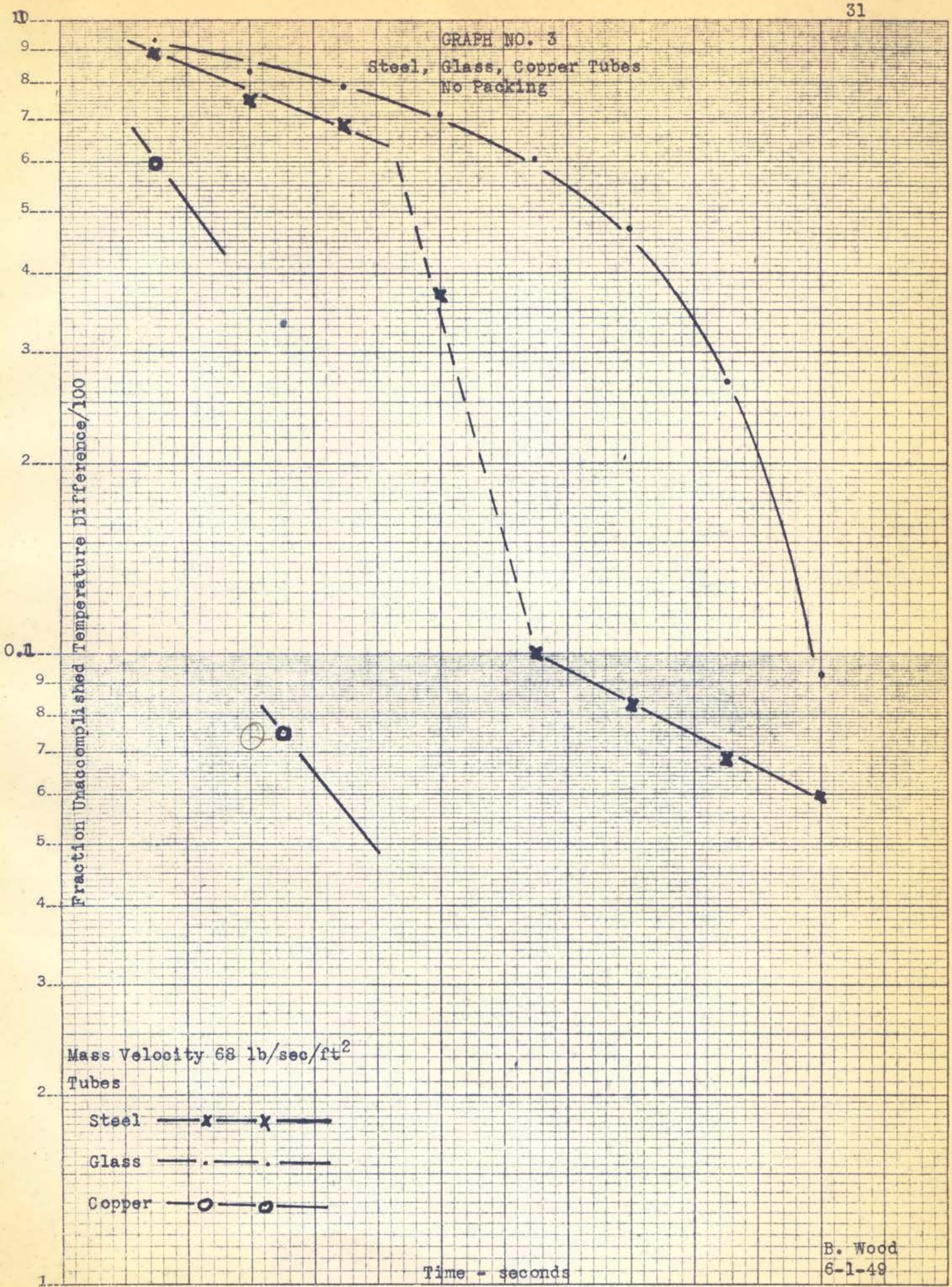
TABLE XIV

Run No. 13	Glass Tube Mercury Filled	Test Section Temperature Fluid Temperature	70°F. 197°F.

Time Sec.	lb/sec/ft^2 68	95	122
0	70	70	70
15	85	87	89
30	93	95	99
45	103	108	118
60	118	128	146
75	139	159	175
90	169	176	186
105	177	187	187
120	187	188	189


GRAPH NO. 1
Steel Tube
No Packing
Fraction Unaccomplished Temperature Difference/100
Time - seconds
Mass Velocities lb/sec/ft²
68
81.5
95
122
B. Wood
6-1-49
1.
9
8
7
6
5
4
3
2
0.1
9
8
7
6
5
4
3
2
1
0
20
40
60
80
100
120


GRAPH NO. 2
Steel Tube
Various Packings
Fraction Unaccomplished Temperature Difference/100
Time - seconds
1.0
9
8
7
6
5
4
3
2
0.1
9
8
7
6
5
4
3
2
1
0
20
40
60
80
100
120
Mass Velocity 68 lb/sec/ft^2
Packings
Empty
Graphite
Oil
Mercury
B. Wood
6-1-49
MADE IN U.S.A.


GRAPH NO. 3
Steel, Glass, Copper Tubes
No Packing
Fraction Unaccomplished Temperature Difference/100
Time - seconds
10
9
8
7
6
5
4
3
2
0.1
9
8
7
6
5
4
3
2
1
0
20
40
60
80
100
120
Mass Velocity 68 lb/sec/ft^2
Tubes
Steel
Glass
Copper
B. Wood
6-1-49

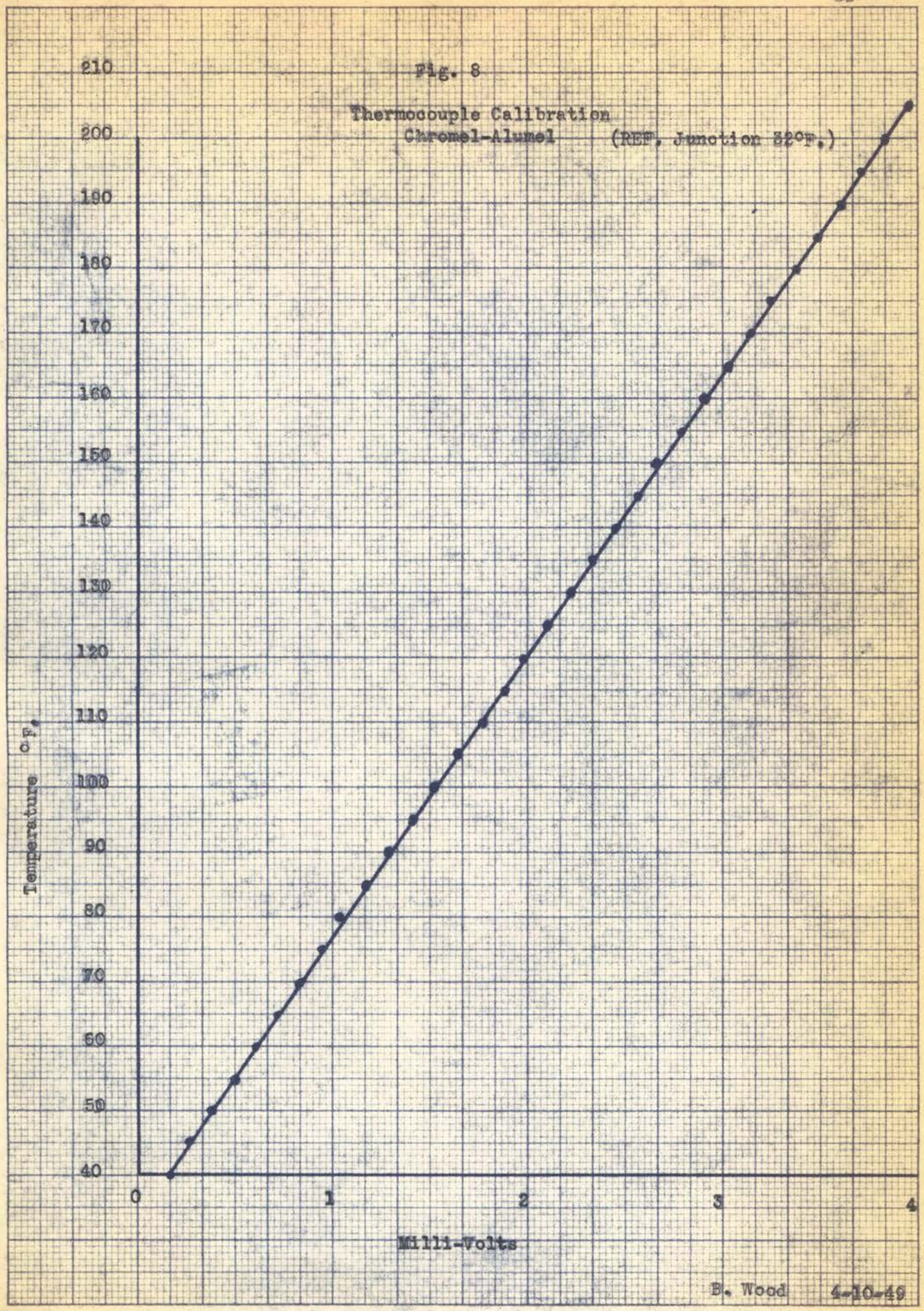


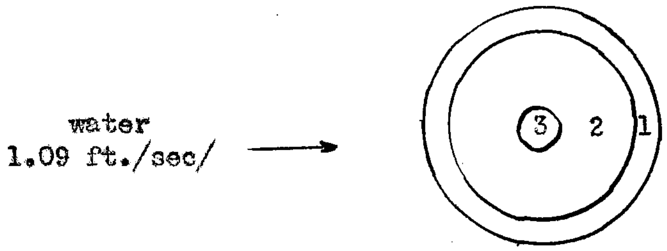
Fig. 8

Thermocouple Calibration
Chromel-Alumel (REF. Junction 32°F.)

B. Wood 4-10-49

Sample calculations for the correlation of these experimentally determined data with the theoretical relationships derived by Gurney-Lurie (21) are as follows:

Use the case of graph 2. Steel tube, graphite filled, mass velocity of 68 lb./sec/ft.^{2}, at a time of 60 sec.



1 = steel

2 = graphite

3 = couple

$r_1 = 3/32" = 0.0078$ ft. $\qquad r_1^2 = 60.8 \times 10^{-6}$

$r_2 = 1/16" = 0.0052$ ft. $\qquad r_2^2 = 27 \times 10^{-6}$

$r_3 = 0.0062" = 0.00052$ ft. $\qquad r_3^2 = 0.27 \times 10^{-6}$

For H_2O, $C_p = 1$; $k = 0.35$; $d = 3/16" = 0.0156$ ft.; $\mu = 1.0$ cp.

$$Re = \frac{Dv\rho}{\mu} = \frac{0.0156 \times 1.09 \times 62.4}{0.000672 \times 1} = 1575$$

From McAdams (11) page 222, equation 4b

$(Re)^{0.6} = 72 \qquad 0.26 \times 72 = 18.7$

$$\frac{C\mu}{k} = \frac{1.0 \times 2.24 \times 1.0}{0.35} = 6.91; \quad \frac{C\mu}{k}^{0.3} = 1.79$$

$$\frac{hD_o}{k} = 18.7 \times 1.79 = 33.5$$

$$h = \frac{33.5 \times 0.35}{0.0156} = 750$$

m = resistance ratio R_s/R_m, dimensionless.

$$R_m = \frac{1}{AU_m} = \frac{x_1}{k_1A_1} + \frac{x_2}{k_2A_2} + \frac{x_3}{k_3A_3}$$

$$R_1 = \frac{0.0078 - 0.0052}{26 \text{x} 2 \text{x} \pi \text{x} \dfrac{0.0078-0.0052}{\ln \dfrac{0.0078}{0.0052}}} = \frac{0.405}{26 \text{x} 2 \text{x} \pi} = 0.00248$$

$$R_2 = \frac{0.0052 - 0.00052}{0.104 \times 2 \times \pi \times \dfrac{0.0052-0.00052}{\ln \dfrac{0.0052}{0.00052}}} = \frac{2.30}{0.104 \times 2 \times \pi} = 3.52$$

$$R_3 = \frac{0.00052 - 0}{5 \times 2 \times \pi \times \dfrac{0.00052-0}{\ln \dfrac{0.00052}{0}}} = \text{indeterminate}$$

$$R_m = 3.522$$

$$R_s = \frac{1}{h_o A_o} = \frac{1}{750 \times 2 \times \pi \times 0.0078} = \frac{1}{3.68} = 0.0272$$

$$m = \frac{R_s}{R_m} = \frac{0.0272}{3.52} = 0.00773$$

$$Y = \frac{t_1 - t}{t_1 - t_b} = \frac{28}{132} = 0.212$$

t_1 = temperature of surroundings
t = temperature at time θ
t_b = base temperature

From McAdams (11) page 36, Fig. 11,

when $Y = 0.212$; $m = 0$; $n = 0$; $X = 0.36$

$$X = \frac{k\theta}{\rho C_p r_m^2}$$

$$= \frac{\theta}{\dfrac{\rho_1 C_{p_1}(r_1^2-r_2^2)}{k_1} + \dfrac{\rho_2 C_{p_2}(r_2^2-r_3^2)}{k_2} + \dfrac{\rho_3 C_{p_3}(r_3^2)}{k_3}}$$

$$= \frac{\theta}{\dfrac{489 \times 0.1121(60.8-27)\times 10^{-6}}{26} + \dfrac{30 \times 0.175(27-0.27)\times 10^{-6}}{0.104} + \dfrac{530 \times 0.11 \times 0.27 \times 10^{-6}}{5}}$$

$$= \frac{\theta}{0.0000714 + 0.00135 + 0.00000315}$$

$$= \frac{\theta}{0.001424}$$

$$0.36 = 701\ \theta$$

$$\theta = \frac{0.36}{701} = 0.000515 \text{ hours}$$

$$= 1.85 \text{ sec.}$$

See Table XV for values for each installation

TABLE XV

$T^1 = 0.632$

Installation	Mass Velocity lb/sec/ft^2	Experimental Time Sec.	Calculated Time Sec.
Steel Tube - Graphite Filled	68	60	1.85
	81.5	45	1.38
	95	37	1.05
	109	28	0.89
	122	24	0.74
Steel Tube - No Packing	68	60	1.93
	81.5	52	1.44
	95	45	1.30
	122	42	1.08
Steel Tube - Graphite and Oil Packing	68	36	1.10
	81.5	30	0.91
	95	24	0.76
	122	16	0.60
Steel Tube - Mercury Filled	68	53	1.47
	81.5	43	1.33
	95	33	0.95
	122	28	0.87
Steel Tube - Oil Filled	68	60	1.90
	81.5	51	1.42
	95	45	1.25
	109	40	1.13
	122	34	1.08
Copper Tube - No Packing	68	19	0.60
	95	15	0.48
	122	11	0.40
Copper Tube - Graphite and Oil Packing	68	10	0.42
	122	6	0.30
Copper Tube - Oil Filled	68	17	0.53
	95	13	0.44
	122	10	0.39
Glass Tube - No Packing	68	98	3.00
	95	88	2.72
	122	80	2.44

TABLE XV (cont'd)

Installation	Mass Velocity lb/sec/ft^2	Experimental Time Sec.	Calculated Time Sec.
Glass Tube - Graphite and Oil Packing	68	76	2.15
	95	62	1.90
	122	56	1.67
Glass Tube - Graphite Filled	68	82	2.48
	95	71	2.02
	122	60	1.78
Glass Tube - Oil Filled	68	84	2.75
	95	72	2.05
	122	63	1.81
Glass Tube - Mercury Filled	68	82	2.40
	95	71	1.97
	122	61	1.83

CONCLUSIONS

The following conclusions may be drawn from observations of the behavior of the experimental apparatus and from the data and discussion presented here.

1. The Thermal Conductivity of the protective tube exerts a very great effect on the lag of a thermocouple installation. Steel, with a thermal conductivity of 26 B.T.U./(hr.)(sq. ft.)(°F. per ft.), and glass, with a "k" of 0.4, are the main causes of high thermometric lag in the installations where used. Copper, with a "k" of 222, offers little resistance to heat flow.
2. The thermal conductivity of the filling material has a definite effect on the lag: e.g., graphite and oil mixed together and used in a steel tube increase the rate of heat transfer over 100 per cent. The resistance of glass is so great that the effect of filling material in a glass tube is very small.
3. Data for other materials can be estimated closely by cross plotting the data presented. A wide range in thermal conductivity for protective tubes was used (k = 222 for copper, 0.4 for glass), and the five packing materials range from k = 40 for the graphite-oil mixture to 0.016 for air. Most of the common materials of construction will fall within these limits, and by interpolation a good estimate can be obtained.
4. The Lag Coefficient, as defined by equation (3) and indicated on the graph, is the time that the curve reaches 63.2 per cent of the unconsumed temperature difference. The lag was found to vary from 15 seconds to 90 seconds.

5. As is seen in Table XV, the values calculated by the theoretical derivation of Gurney and Lurie are much less than the experimentally determined values. This discrepancy can be partially explained by the various differences between the experimental set-up and the theoretical prototypes used to construct the Gurney-Lurie charts. For example, the Gurney-Lurie derivation is for single homogeneous solids, while the experimental set-up utilized a hollow tube, an annular packing, and a solid thermocouple.

SUMMARY

A review of selected literature reveals that thermometric lag is a big problem in heat transfer, but very little has been done on the problem in a theoretical sense as empirical relations have been used with reasonable success. However, the advent of automatic control is making the determination of lag necessary and important.

Several thermocouple installations tested for thermometric lag at various mass velocities and with different tube packings were found to give good straight lines on semi-log paper, indicating that installations tested follow the developed theory rather closely.

Data obtained with this assembly are correlated by plotting time versus the per cent of unconsumed temperature difference. The resulting curves well illustrate the effect of changing the mass velocity past a particular thermocouple installation. Up to a certain point, the fluid film reduction helps reduce the total lag, but a point is approached where the lag of the protective tube is wholly the controlling resistance and further increases in the mass velocity have very little effect on the lag. Changing the packing helps a great deal. Air around the thermocouple has an insulating effect. The best combination seems to be a reasonably high mass velocity and a protective tube with high thermal conductivity filled with a highly conductive material.

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