A STUDY OF THE PROCESSES OF CHARGING AND DISCHARGING CONSTANT VOLUME TANKS WITH AIR

by

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Signatures of Authors...

....
Department of Mechanical Engineering

May 25, 1953

Professor Earl B. Millard
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Dear Professor Millard:

In partial completion of the requirements for a Bachelor of Science degree we hereby submit our thesis, which is entitled: "A Study of the Processes of Charging and Discharging Constant Volume Tanks with Air."

We greatly enjoyed working on this project, and obtained from it a fuller understanding of the problems encountered in setting up an experiment from scratch and trying to obtain usable results from it.

We would like to thank Professor J. L. Shearer, our thesis advisor, for his assistance in setting up the problem, and for his continued help and interest during the term. We would also like to thank Bill Gould and Tom Cerulli of the Dynamics and Control Laboratory for all the advice and assistance they gave us.

Sincerely yours,

C. K. Wadner

F. D. Skinner

ABSTRACT

This thesis represents a study of the type of processes which take place when air is either compressed or expanded in a constant volume tank. In order to establish a criteria for solving this problem, dimensional analysis was used. By first realizing that the processes must be polytropic, it was possible to set up the polytropic constant "n" as a function of the other variables of the system. After solving for the dimensionless groups, it was decided to plot "n" against the group $\frac{k_o g R_o T_o t^2}{A_t}$ where:

k_o = the polytropic constant for an adiabatic process for air

g = acceleration of gravity

R_o = the gas constant for air

T_o = initial temperature of gas inside the tank

t = time of discharging or charging

A_t = tank surface area

This would be done for various initial pressures inside the tank at the start of the run, but the pressure ratio ($p_{initial}/p_{final}$) was to be held constant. In order to see what correlation there was between various pressure ratios, the final pressure was then allowed to vary while the initial pressure inside the tank was held constant. Finally, in order to see what affect different size tanks had on the process, two different tanks were used in the experiment.

The results were:

1) The various curves obtained for n vs $\frac{k_o g R_o T_o t^2}{A_t}$ were all within 3% of each other.
2) The assumption that the involved processes are isothermal is a fairly accurate one.

3) It can be seen from the point distribution that as the pressure ratio decreased, the polytropic constant "n" increased. Also, the higher initial pressures in the case of discharging and higher final pressures in the case of charging tended to produce the same increase in "n".

4) Values for the overall coefficient of heat transfer "U" were determined for both tanks. The large tnak had coefficients varying from 0.140 to 0.309 BTU/hr ft^2 °F, while the small tank had coefficients varying from 0.202 to 0.482 BTU/hrft^2°F

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INTRODUCTION

Object of the Experiment

In the designing of gas servomechanisms, using a constant volume tank as the gas supply, it is usually assumed that the transfer of the gas from the tank into the servo takes place as an isothermal process.

The object of this experiment is to determine how accurate this assumption is, and further, to apply dimensional analysis to the process in order to determine whether any characteristic curve or curves may be obtained. Two different tanks are utilized in order that it can be determined whether any correlation exists between various sized tanks.

It is also desired to get an idea of what the overall coefficient of heat transfer is for these processes.

PRELIMINARY ANALYSIS

Before the question of what type of process is taking place in charging and discharging a constant volume tank can be intelligently answered by laboratory experiment, a method of attack must be formulated, and a sound method of evaluating the data must be established. In order to accomplish this, the problem must be looked at analytically. The question was, what would be the best criteria to show what type of process is taking place?

In order to formulate a method of attack, the polytropic constant "n" was investigated. For air, or any other perfect gas, any compression or expansion process is inherently polytropic. The upper limit is the adiabatic process, and the lower limit is the isothermal process. The formula for a polytropic process is pv^n = constant. The "n" for the upper limit (or adiabatic process) is = k = 1.4, and for the lower limit (or isothermal process) is = 1.0, and it can vary between these limits for all other processes. Thus, if the "n" for the processes in question can be determined, the type of process will also be determined.

The question now arises, how can "n" be evaluated. There are two methods which can be used. The following derivations show these two methods:

One method of determining "n".

$pv^n = \text{constant} \qquad \text{or} \qquad p_\circ v_\circ^n = p_f v_f^n$

However, since $pv = RT$ or $v = \frac{RT}{p}$

$$p_\circ\left(\frac{RT_\circ}{p_\circ}\right)^n = p_f\left(\frac{RT_f}{p_f}\right)^n$$

$$\frac{p_\circ}{p_f} = \left(\frac{T_f p_\circ}{T_\circ p_f}\right)^n$$

$$\ln\frac{p_\circ}{p_f} = n \ln\left(\frac{T_f p_\circ}{T_\circ p_f}\right)$$

$$n = \frac{\ln\frac{p_\circ}{p_f}}{\ln\left(\frac{p_\circ T_f}{p_f T_\circ}\right)}$$

This formula holds for $p_\circ$ greater than p_f (the subscript f refers to final conditions and the subscript $\circ$ refers to initial conditions). If the final pressure is greater than the initial pressure, as is the case for the charging process, there is some question as to the validity of $pv = RT$ since the system is no longer homogeneous. The gas already in the tank at the beginning of the run is at a high temperature relative to the gas entering. As these two gas masses mix, the rise in temperature due to the compression of the gases is somewhat retarded by the cool entering gas. This tends to cause the process to be isothermal and for this reason it was decided to assume the formula holds for both the charging and discharging processes.

Alternate method for determining "n"

As before, $p_\circ v_\circ^n = p_f v_f^n$

Since the mass of the gas inside the tank and the volume of the gas does not change from the end of the charging or discharging run until the steady state conditions are reached:

$$v_f = v_{ss} = \frac{RT_{fss}}{p_{fss}}$$

If room temperature does not change during this time:

$$T_{fss} = T_\circ$$

Then:

$$v_f = \frac{RT_\circ}{p_{fss}}$$

And:

$$p_\circ\left(\frac{RT_\circ}{p_\circ}\right)^n = p_f\left(\frac{RT_\circ}{p_{fss}}\right)^n$$

$$\frac{p_\circ}{p_f} = \left(\frac{p_\circ}{p_{fss}}\right)^n$$

$$\ln\frac{p_\circ}{p_f} = n \ln\frac{p_\circ}{p_{fss}}$$

And finally:

$$n = \frac{\ln\frac{p_\circ}{p_f}}{\ln\frac{p_\circ}{p_{fss}}}$$

The first solution is the method that was employed on the test runs. The reason for this choice are given under the section on methods of taking data.

In order to be able to express the experimental results in useful form, the problem was attacked with dimensional analysis. The first thing to be done here was to list all the variables on which "n" is dependent. These variables were divided into three groups.

1) Those variables associated with the tank.

2) Those variables associated with the valve.

3) Those variables associated with the air.

The tank variables are:

1.	The mass of the tank	M
2.	The surface area of the tank	A_t
3.	The volume of the tank	V

The valve variables are:

1.	The discharge area	A_o
2.	The discharge coefficient	C_q

The gas variables are:

1.	The initial pressure	p_o
2.	The initial temperature	T_o
3.	The final pressure	p_f
4.	The time of discharge	t
5.	The gas constant	R_o
6.	"n" for adiabatic process	k_o

Since the final pressure and the time of the run are known, the discharge area of the valve is already specified. Therefore, it was dropped from the analysis.

Therefore: $n = f(M, A_t, V, C_q, p_o, T_o, k_o, p_f, t, R_o)$

There are four basic dimensions represented here, and since there are 11 variables, there must be 7 π groups. By solving, the following π's are found:

1. $\pi_1 = n$
2. $\pi_2 = C_q$
3. $\pi_3 = k_o$
4. $\pi_4 = \dfrac{p_o}{p_f}$

5. $\pi_5 = \frac{A_t^3}{V^2}$

6. $\pi_6 = \frac{MgR_oT_o}{P_oV}$

7. $\pi_7 = \frac{k_ogR_oT_ot^2}{A_t}$

Once these dimensionless groups had been established, it was felt that the necessary tools to begin the experimental work were at hand. The variables which would have to be measured were known, and it was felt that the results could be plotted as n vs π_7 since π_7 is probably the group which is the most easy to vary, it being the only group that contains the time of discharge. Therefore, π_7 was to be varied, while the other groups were to be held constant (except $\pi_1 = n$ which varies as a result of varying π_7).

However, there were several items which had to be measured before the apparatus could be set up. A tank had to be acquired and its mass, volume, and surface area determined.

To determine the mass of the tank, it was weighed and its weight divided by the acceleration of gravity. To find the volume, the tank was filled with water just after it had been weighed, weighed again with the water in it. This determined the weight of the water added, and by dividing the weight of the water by its density, the volume of the water was determined. The volume of the tank then equals the volume of the water added.

To find the surface area, it was necessary to measure the circumference and the height of the tank and multiply the two quantities together.

Looking ahead to the measurements that would have to be made during each run so that the proper equipment could be procured, the following was decided:

1) It was necessary to know the initial and final pressures inside the tank.

2) It was necessary to know the initial and final temperatures inside the tank.

3) In order to evaluate the overall coefficient of heat transfer for the process, it was necessary to know the temperature of the outer surface of the tank.

In order to make the measurements indicated in item one above, a pressure gage was needed. One was obtained that had a range of 2000 psi. The gage was calibrated on a dead weight tester, and the calibration curve for this gage is included in Appendix III.

In order to measure the required temperatures, thermocouples were to be installed in the tank, and around the outside surface. The method for installing the thermocouples inside the tank is discussed in detail in the section of this report dealing with the test set-up (see page 9). The thermocouples were all made from one spool of copper-constantan thermocouple wire, and a sample was calibrated, the deviation and corrected calibration curves being included in Appendix III.

In order to read the thermocouples other equipment was required, such as a potentiometer, a thermos bottle for the reference junction, and a selector switch so as to be able to read all the thermocouples.

Since the paramente to be varied is the time of discharge or charging, as the case may be, a valve in the air line was needed. It was felt that more accurate results could be gotten if this valve could be operated instantaneously. Therefore, two valves were used; a needle valve to adjust the flow rate for the various runs and a solenoid valve to allow accurate starting and stopping of the flow.

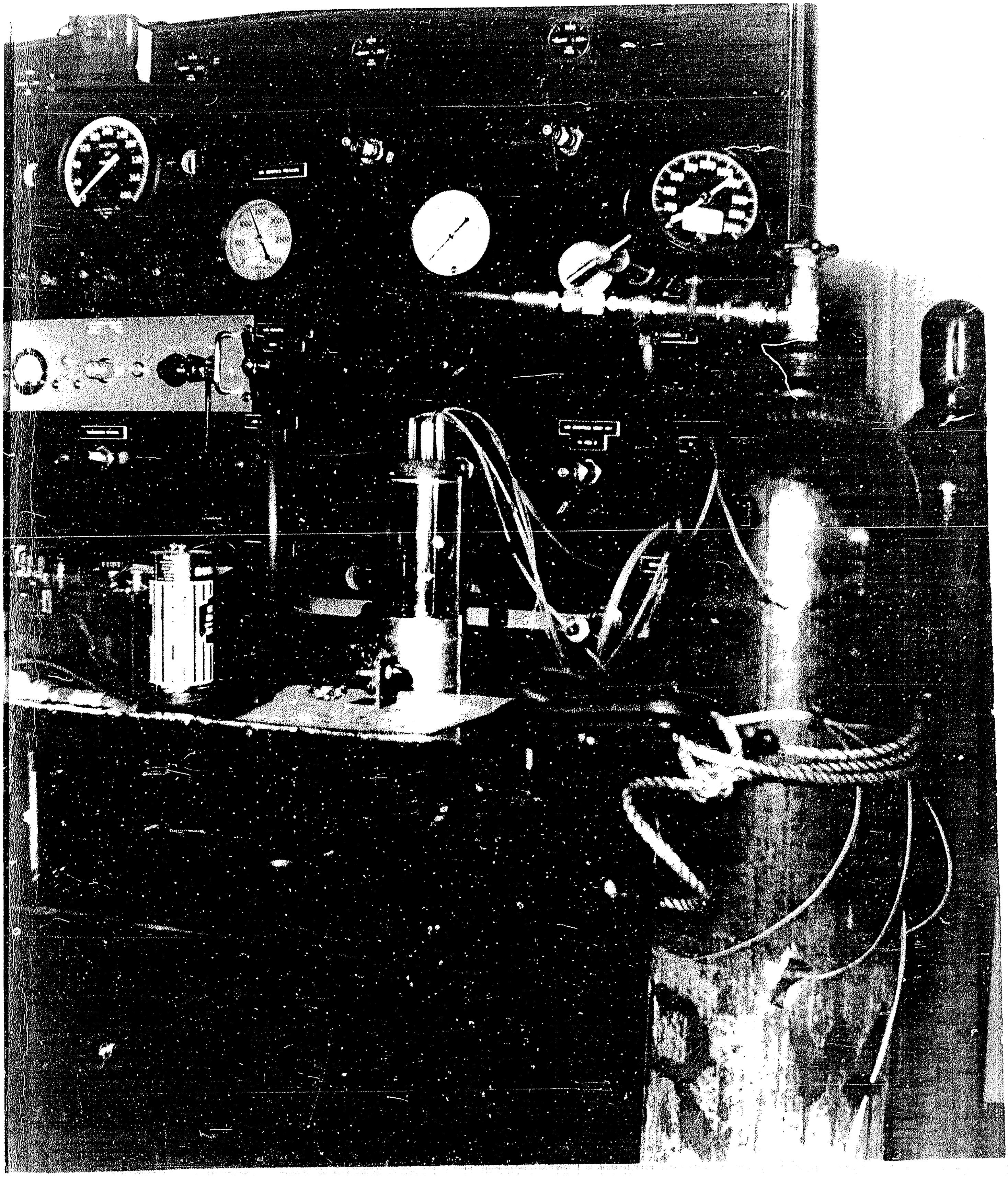
Other equipment needed included hose and fittings to connect the air supply with the tanks, and a stop watch with which to measure the time of flow. Now that the materials needed was known, the job of setting up the apparatus was begun.

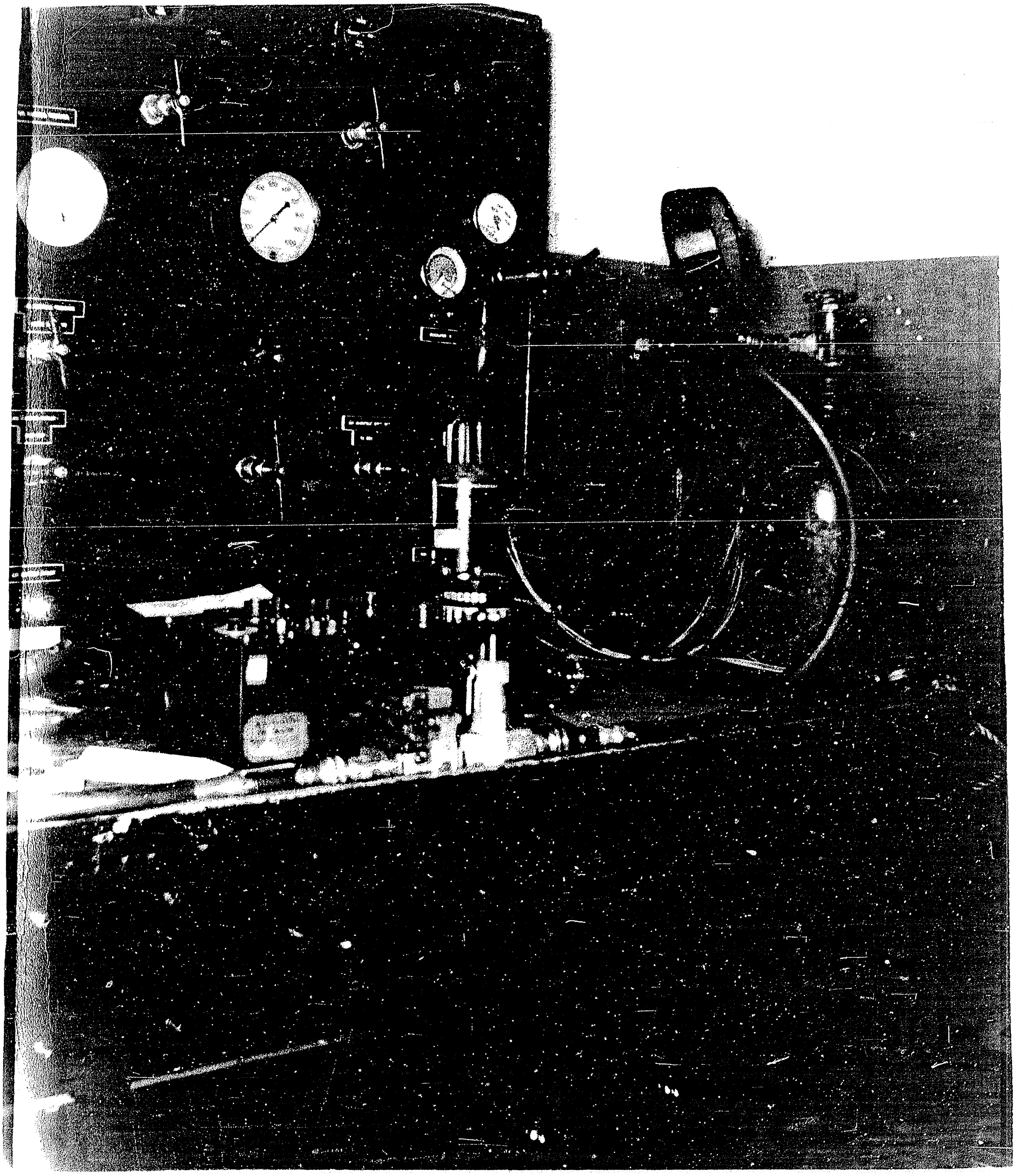
TEST SET-UP

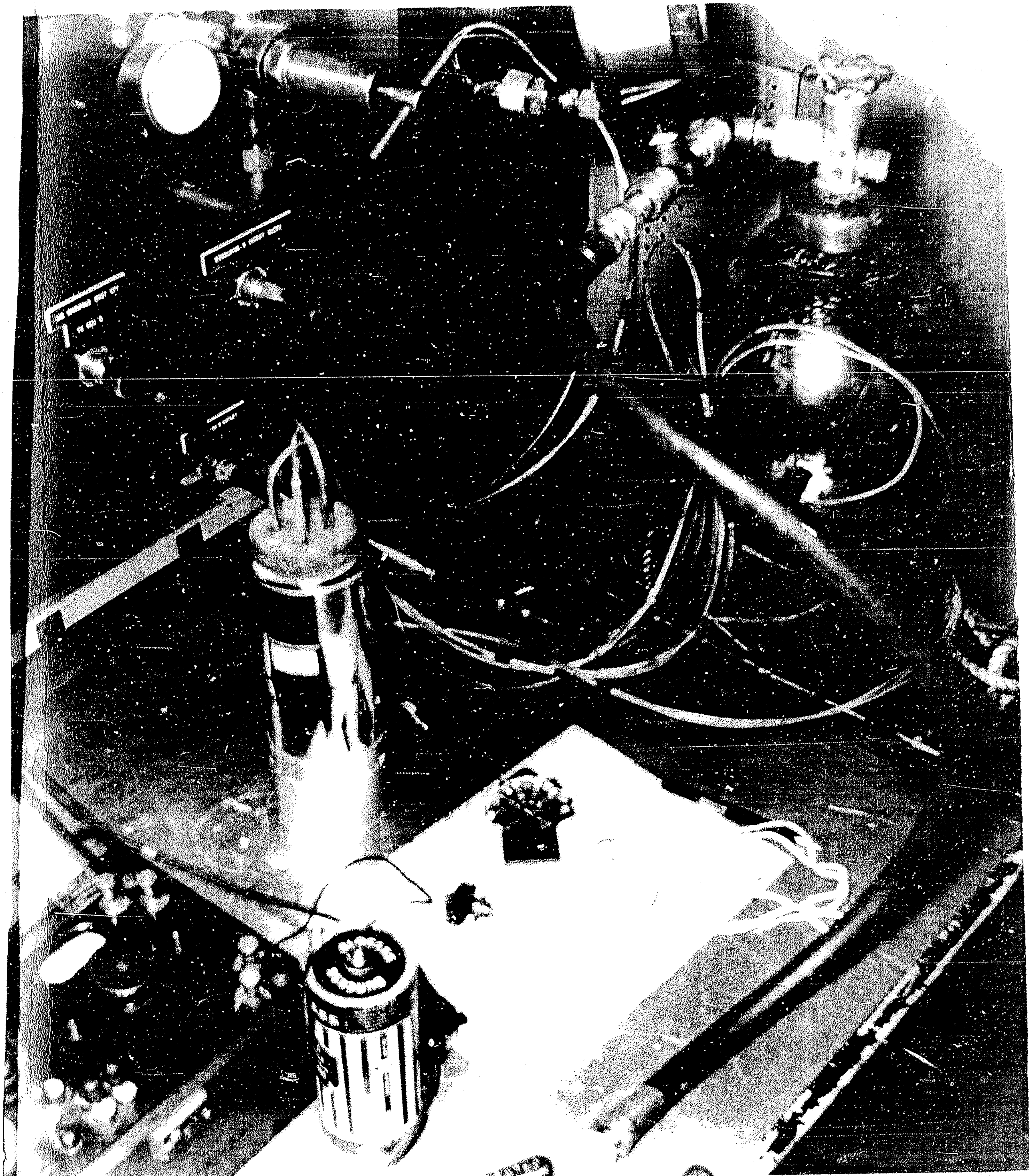
The test set-up consisted of a nitrogen tank which was used as the test tank. Air lines were run from the tank to the air supply board through two valves. One was a needle valve which was used to vary the flow rate, and the other was a solenoid valve which was used to start and stop the test, the needle valve not being touched except between runs. A pressure gage was inserted in the air line at the tank inlet. Twelve thermocouples were placed on the outside of the tank, four around the top, four around the middle, and four around the bottom. The four thermocouples at each section were connected in series and thus an average temperature was measured. Three thermocouples were to be inserted inside the tank, one extending to the bottom, one to the middle, and the other being at the top. These three thermocouples were also connected in series, and thus the average temperature of the interior would be measured. The problem now was how to get these thermocouples inside the tank without causing a leak?

By asking advice from the lab technicians, it was discovered that the thermocouples could be put inside the tank by means of a small thermocouple lead, especially made for this purpose, with the ability to withstand pressures up to 2000 psia. This thermocouple lead is a metal rod which passes through a stainless steel jacket. The rod was sealed in place with glass (see fig 1a).

By drilling holes in a brass plug, and soldering







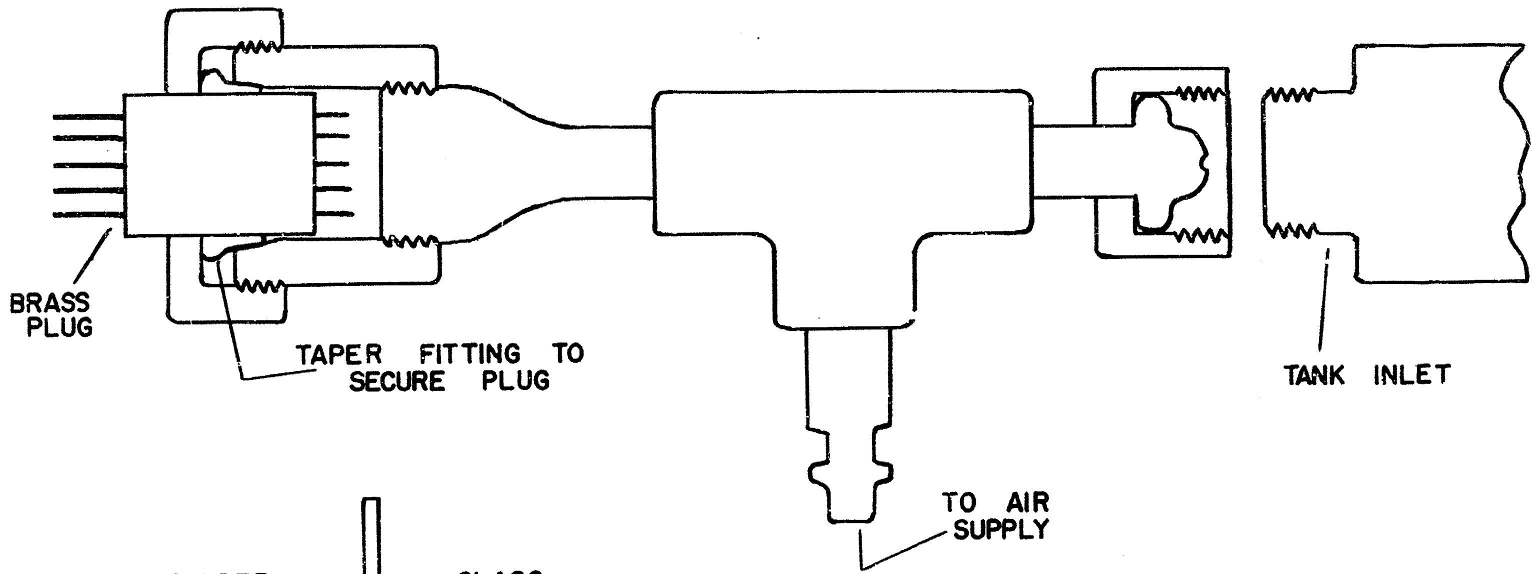


FIG 1b. THERMOCOUPLE INLET ASSEMBLY

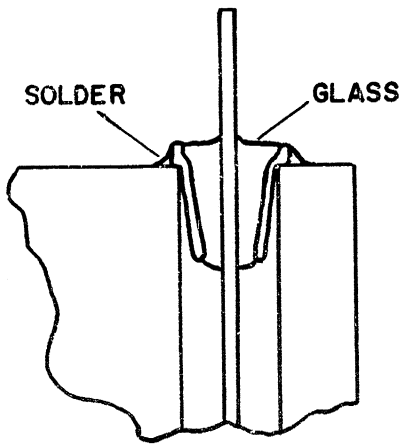


FIG 1A. THERMOCOUPLE LEAD

the thermocouple leads in place, a means of getting the thermocouples inside the tank without causing a leak in the system could be accomplished. (See fig 1b). However, this little lead caused more trouble than was thought possible. The first time they were tried, some solder got inside the drilled hole and shorted out the thermocouples. This meant the lead had to be removed, the hole reamed, and the process begun over again. The second time, the glass seal cracked from the heat of the solder.

After much time and trouble, all the leads were in place and all functioning properly. After a few runs on the tank, it was found that the thermocouples inside were not giving a reading. When the apparatus was dismantled, it was found that one of the thermocouples had become disconnected from the inside pole of the lead. No more trouble with the thermocouples or the leads was encountered after this break had been repaired, but for the benefit of anyone who may continue on with this experiment, it should be pointed out that this is a definite trouble spot.

METHOD OF TAKING DATA

For any given tank, the dimensionless groups

$\pi_5 = \frac{A_t^2}{V^2}$; $\pi_2 = C_q$; and $\pi_3 = k_o$ will all remain constant. This leaves as variables:

$\pi_1 = n$; $\pi_4 = \frac{p_o}{p_f}$; $\pi_7 = \frac{k_o g R_o T_o t^2}{A_t}$; and $\pi_6 = \frac{M g R_o T_o}{p_o V}$

(It was origionally intended to hold π_6 constant for a series of runs at a specified initial pressure but since it includes the room temperature which is constantly changing, the best that could be expected is that the results would show a trend caused by this variable. The results do show such a trend which is discussed in detail in the section on results.)

The order of taking data was decided on as follows:

1) Pick a value for π_4
2) Pick a value for p_o
3) Take a series of runs a various times of discharge
4) Pick new values for p_o and repeat 3)
5) Pick new values for π_4 and repeat steps 2),3),and 4)

The following are the actual values used for π_4 and p_o.

For discharging the large tank:

$\frac{p_o}{p_f}$	p_o in psia
4.72	1015
	815
3.00	1015
	815

There were no charging runs for the large tank.

For discharging the small tank:

$\frac{p_o}{p_f}$	p_o in psia
6.50	1215
	915
	615
4.72	1215
	1015
	815
	615
	515
3.00	1215
	915
	615

For charging the small tank, the dimensionless group π_4 becomes $= \frac{p_f}{p_o}$, and p_f is chosen rather than p_o

$\frac{p_f}{p_o}$	p_f in psia
6.50	1215
	615
4.72	1015
	615
3.00	1215
	615

The methods of taking data for the charging and for the discharging processes are the same with the exception that between steps 3) and 4) (steps are listed below) the air pressure is left on for the charging process, while for the discharging process the air pressure is turned off and the exhaust valve is opened. The general procedure is:

1) With the apparatus completely assembled, the steady state temperature is noted.
2) The tank is charged to the initial pressure chosen for that run and is kept at this pressure until the steady state temperature is again attained.
3) The needle valve is adjusted to produce the desired air flow.
4) When the steady state is reached the solenoid valve is opened.
5) A stop watch is started at the same instant the solenoid valve is opened.
6) When the final pressure is reached, the solenoid valve and the stop watch are both turned off.
7) The millivolt reading from the thermocouple series inside the tank is read at the same instant the solenoid valve is closed.
8) The millivolt readings from the other thermocouple series are read by setting the selector switch.
9) Steps 2) to 8) are repeated.

It will be remembered that in the preliminary analysis two methods were developed for determining "n". By running several test runs we determined that:

1) There is virtually no lag in our thermocouples, and so T_f can be measured accurately to within one half °F.

2) The time necessary to reach steady state after charging or discharging is of the order of one hour.

3) The change between p_f and $p_{f_{ss}}$ cannot be accurately measured on our pressure gage.

For these reasons we decided to use the first method:

$$n = \frac{\ln \frac{p_o}{p_f}}{\ln \frac{p_o T_f}{p_f T_o}}$$

It was also realized that quite a bit of time could be saved due to the fact that at the end of a discharging run the temperature inside the tank was lower than the steady state temperature. This means that if the tank were immediately charged up to the desired initial pressure, the temperature inside the tank would not have to fall as far to reach steady state as it would if the tank had been charged from the steady state condition.

One problem arose in connection with reading the final temperature inside the tank. It became necessary to place a reversal switch on the thermocouple leads so that temperatures below 0.00 °F could be read.

RESULTS

The main portion of the results are represented in the graphs following this page. These graphs represent the following conditions:

Graph 1 Discharging the large tank with $\pi_4 = \frac{p_o}{p_f} = 4.72$ and 3.00 and with p_o = 1015 and 815 psia

Graph 2 Discharging the small tank with $\pi_4 = 3.00$ and with p_o= 1215, 915, and 615 psia

Graph 3 Discharging the small tank with $\pi_4 = 4.72$ and with p_o = 1215, 1015, 815, 615, and 515 psia

Graph 4 Discharging the small tank with $\pi_4 = 6.50$ and with p_o= 1215, 915, and 615 psia

Graph 5 Charging the small tank with $\frac{p_f}{p_o} = 3.00$, 4.72, and 6.50 and with p_f = 1215, 1015, and 615 psia

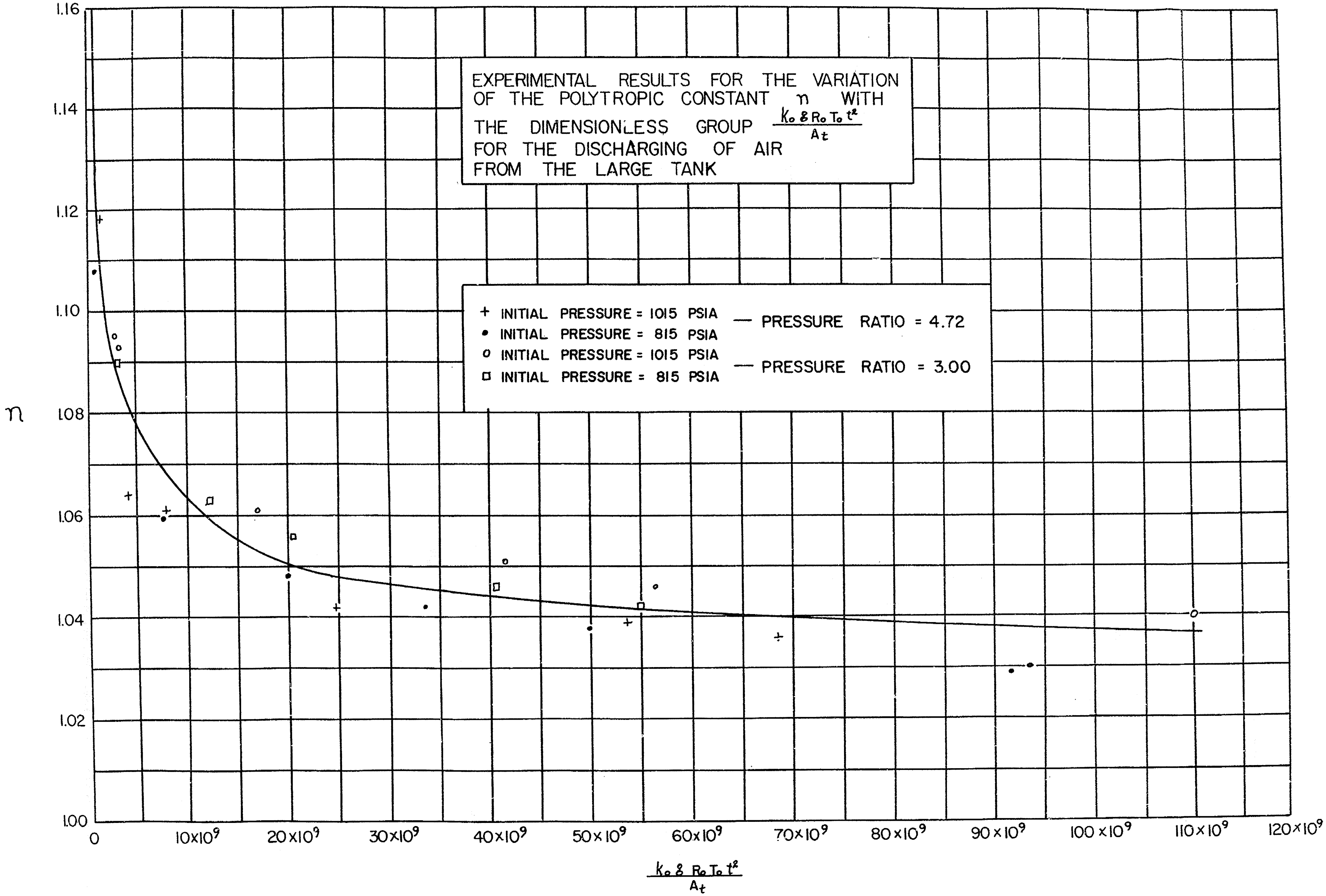
Graph 6 Graph 5 with expanded scales

Graph 7 Graphs 2, 3, 4, and 5 plotted together

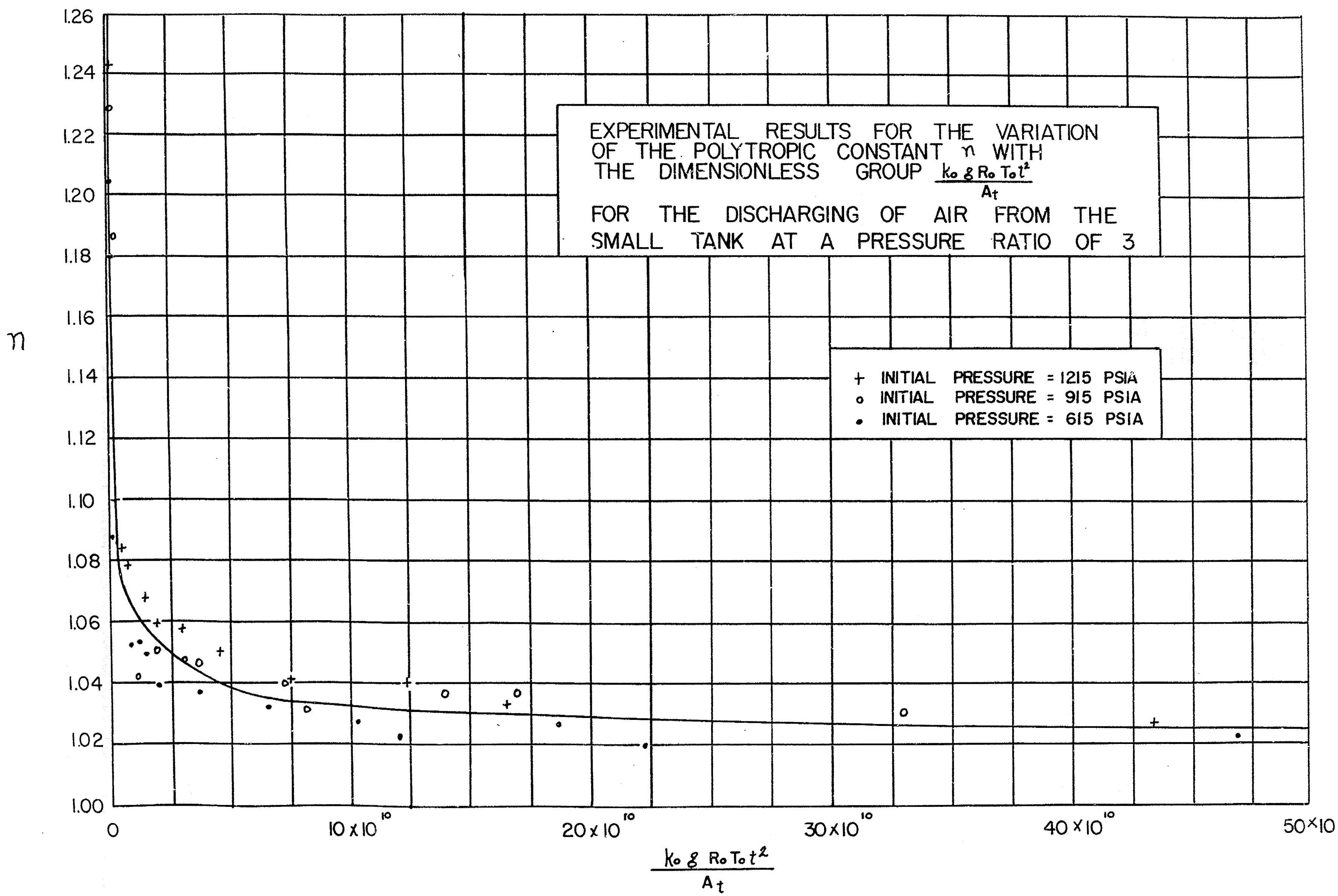
Graph 8 Graphs 1 and 6 plotted together

The results for the overall coefficient of heat transfer are as follows:

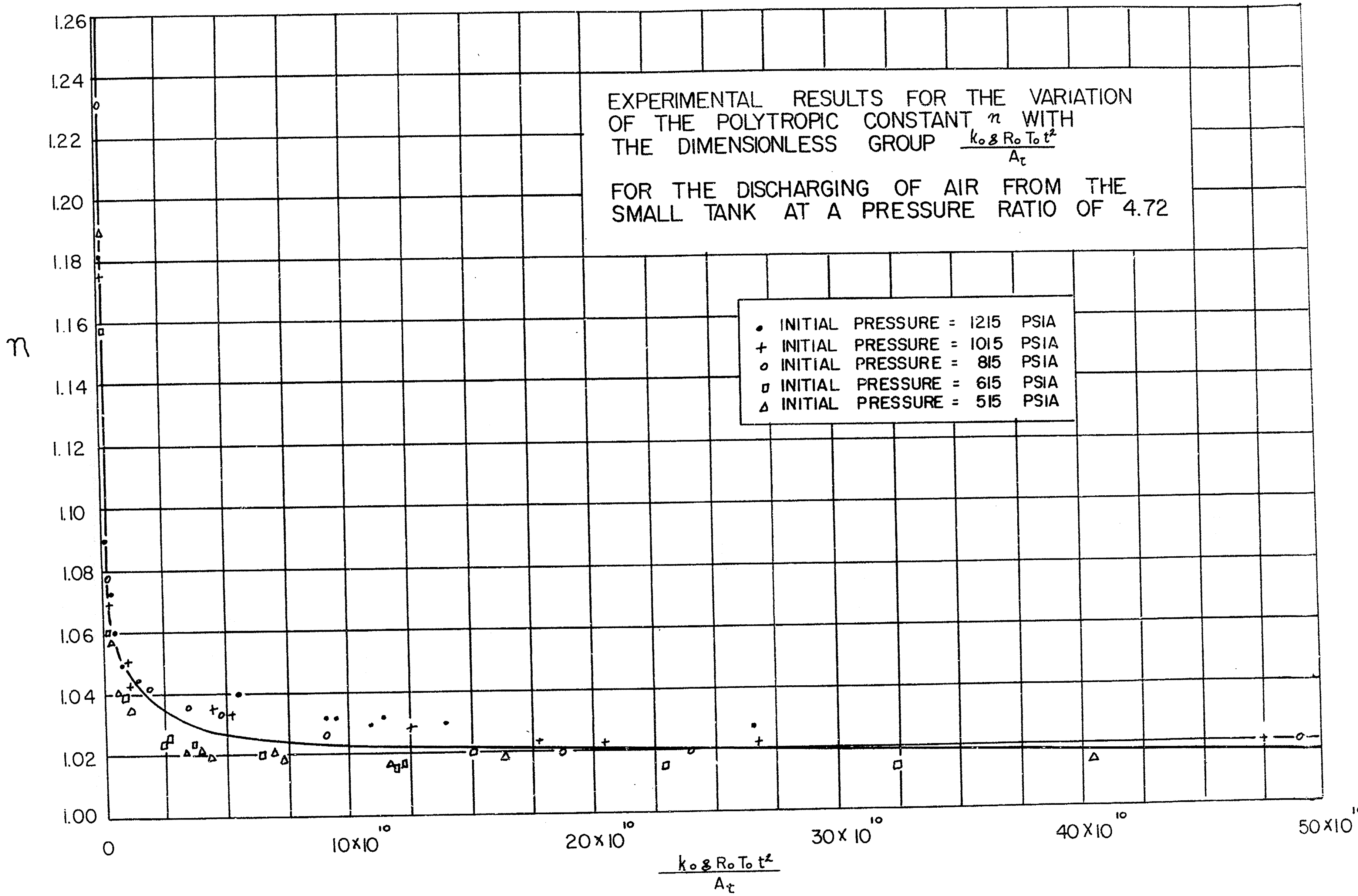
Large Tank		Small Tank	
Run No.	U in BTU/hr ft² °F	Run No.	U in BTU/hr ft² °F
1	0.197	33	0.297
9	0.252	53	0.357
21	0.309	49	0.342
26	0.140	79	0.202
		72	0.205
		145	0.273
		153	0.482
		90	0.260
		129	0.339
		114	0.410
		109	0.225



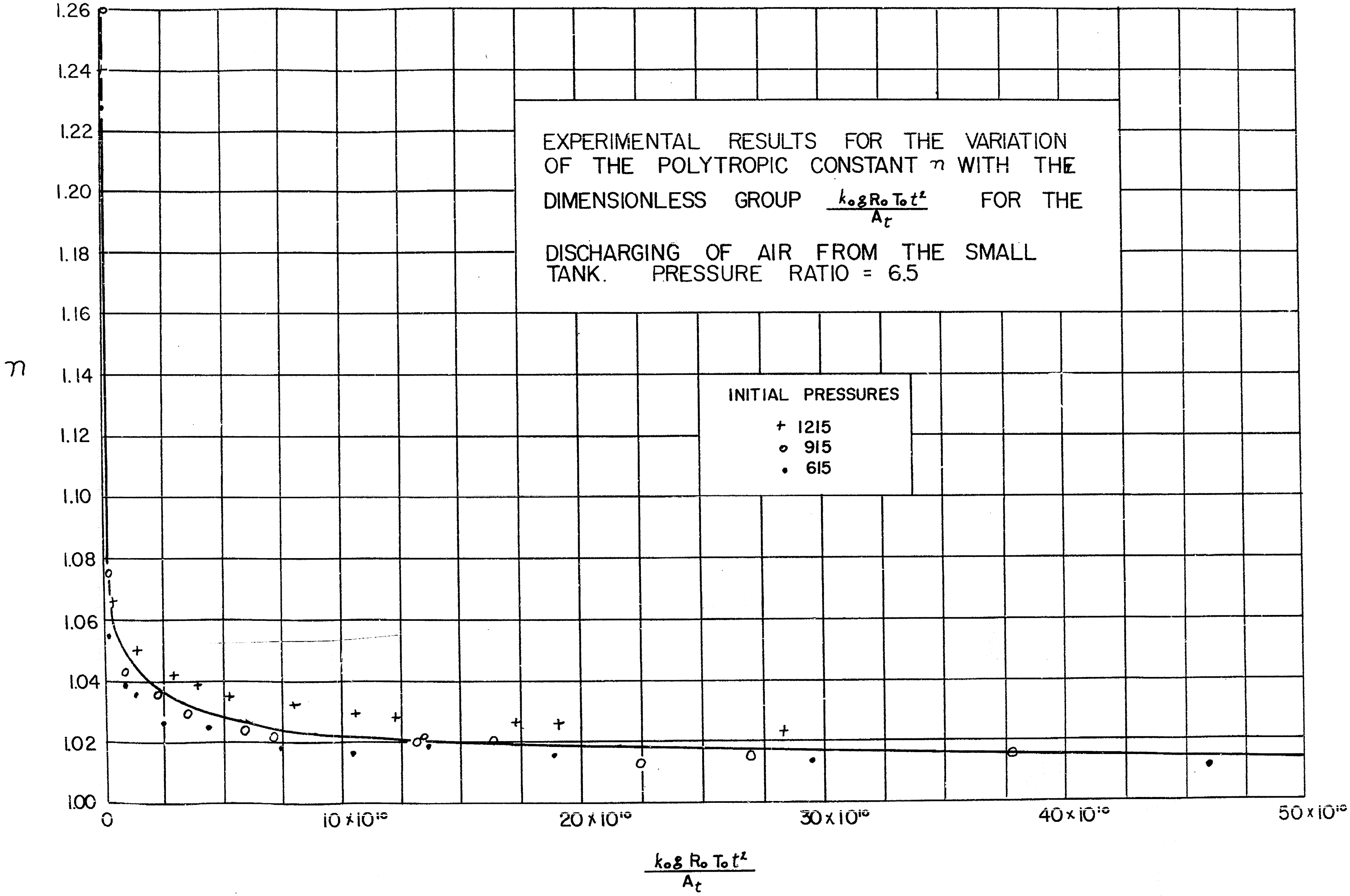
GRAPH I. RESULTS FOR DISCHARGING THE LARGE TANK



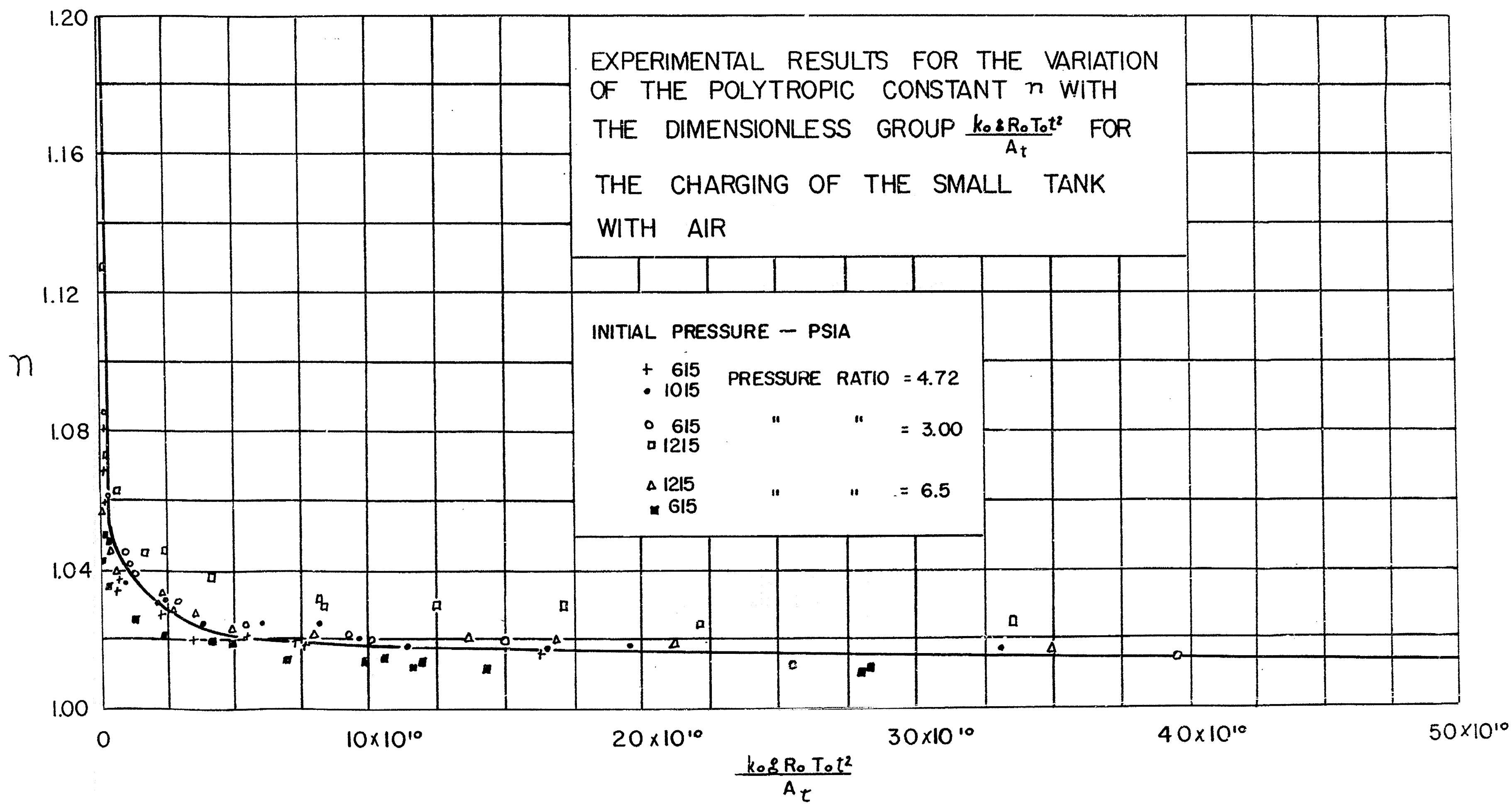
GRAPH 2. DISCHARGING SMALL TANK AT PRESSURE RATIO = 3



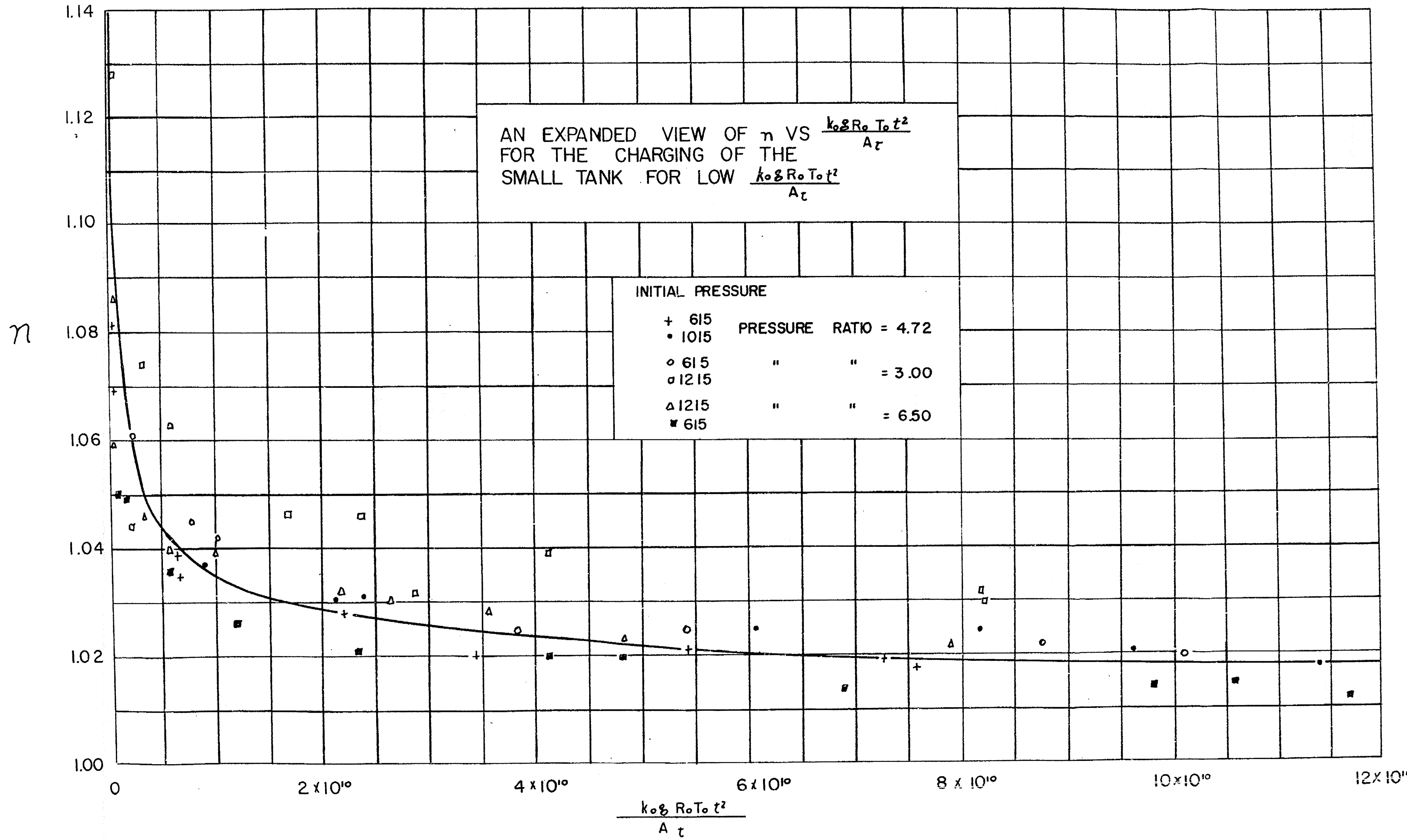
GRAPH 3. DISCHARGING SMALL TANK AT PRESSURE RATIO = 4.72



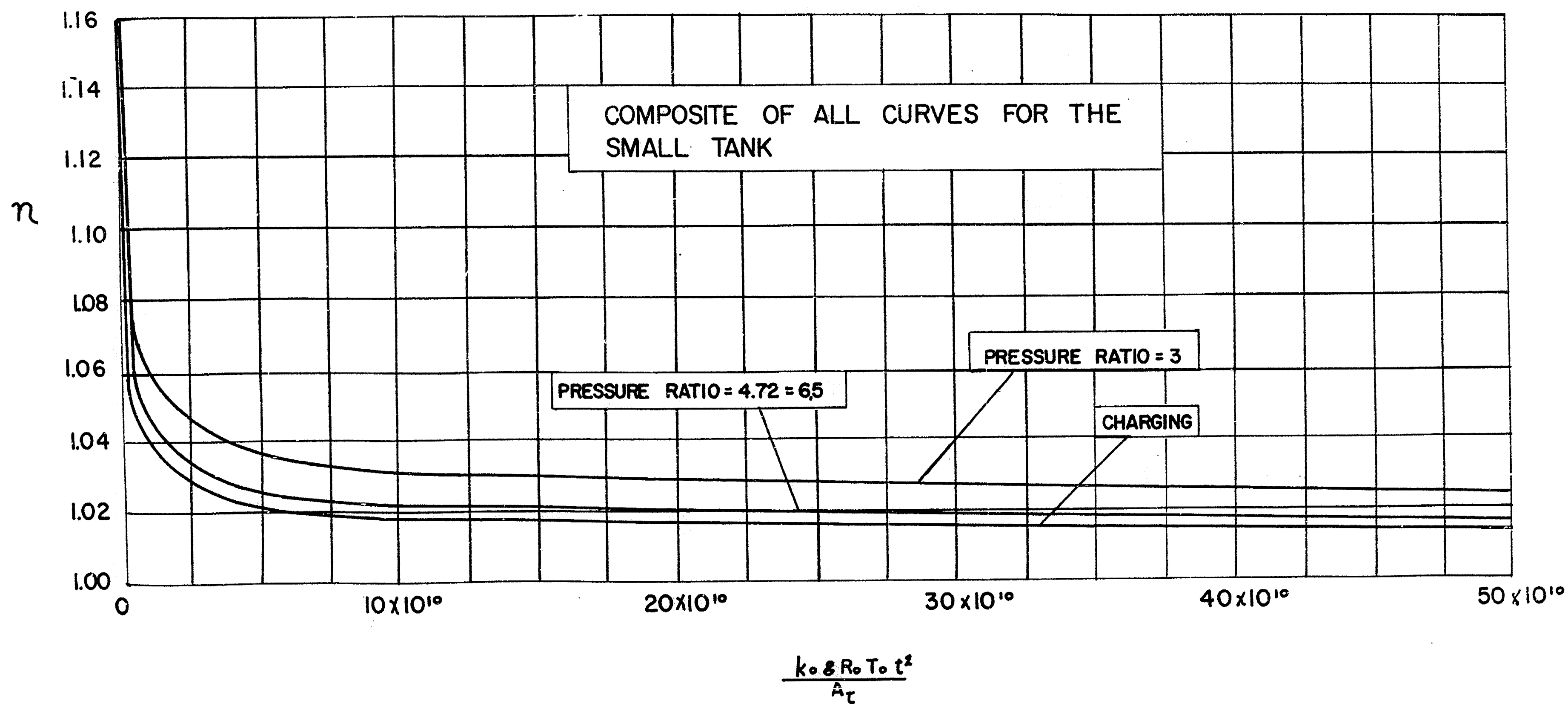
GRAPH 4. DISCHARGING SMALL TANK AT PRESSURE RATIO = 6.5



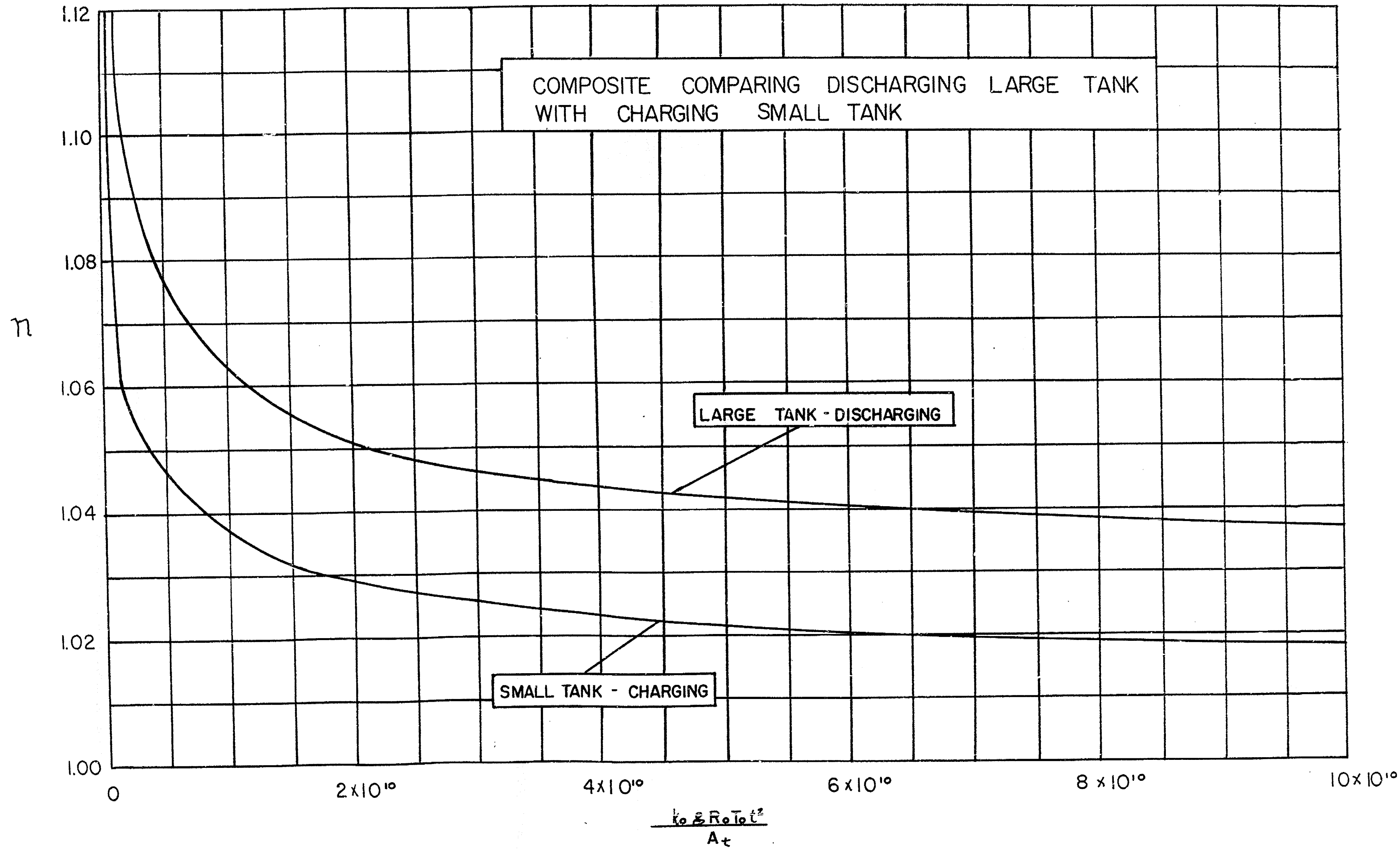
GRAPH 5. CHARGING OF SMALL TANK



GRAPH 6. EXPANDED VIEW - CHARGING SMALL TANK



GRAPH 7. COMPOSITE FOR SMALL TANK



GRAPH 8. COMPARISON OF LARGE TANK DISCHARGING TO SMALL TANK CHARGING

CONCLUSIONS AND RECOMMENDATIONS

Interpretation of Graphs

One line was drawn through all the points on each graph, for although there is some spread in the points the greatest amount of spread is less than 0.03 parts in 1.00 or 3.0 %

A few of the curves are practically identical - Graph 3 (discharging small tank at a pressure ratio of 4.72), Graph 4 (discharging small tank at a pressure ratio of 6.50), and Graph 5 (charging small tank at pressure ratios of 3.00, 4.72, and 6.50) all appear to yield the same curve, as can be seen from Graph 7. Graph 2 (discharging small tank at a pressure ratio of 3.00) seems to fall above the other curves by about 0.01 part in 1.00 or 1.0 %

In comparing the discharge curve of the large tank, Graph 1 with Graph 6 (expanded scale charging curve for the small tank) (These curves are compared on Graph 8) we see that Graph 1 is about 3.0 % higher than Graph 6.

From a visual inspection of all the curves obtained it can be seen that they all fall within a range of approximately 3.0 %.

Within this 3.0 % range, however, two definite trends may be noticed. The first one is that for any given pressure ratio, the points for discharging from or charging to a higher pressure always fall above those for a lower pressure. The second trend is that a lower pressure ratio has points above those for a higher pressure ratio.

From inspection it is seen that the assumption that these processes are almost isothermal is not too far wrong. For π_7 greater than 3 to 20 billion (depending on the curve) n is less than 1.05, or in other words, n is within 5.0 % of the isothermal value of 1.00. This compares to a total discharge time of from 1 to 2½ minutes for the small tank and approximately 7 minutes for the large tank.

The overall coefficient of heat transfer for the big tank varies from 0.140 to 0.309 BTU/hr ft^2 °F For the small tank it varies from 0.202 to 0.482 Since some very broad assumptions were made to obtain U, about the only sure things which can be said concerning these values are that 1) They agree favorably with each other, and 2) Even considering the assumptions made, it is very probable that these values are of the right order of magnitude.

It is believed that many phases of this thesis should be expanded before any definite conclusions could be drawn. The two noticable trends which were mentioned above should be further studied by taking lower pressure ratios and higher pressures. The affect of both these factors is to raise the value of n for the n vs. π_7 curve This would tend to increase the percentage difference between the points determining the curve and would perhaps require that two curves instead of one be drawn through the points. The raising of this curve would also increase the percentage difference between n and the isothermal n which equals 1.00. If this percentage difference increased enough, a point could be reached where the assumption of an isothermal process is no longer justified.

The determination of U could be improved on by utilizing more thermocouples inside the tank in order to get more accurate readings for the internal temperature distribution. A completely new approach might be developed, perhaps that of studying the expansion of the gas at the bottom of the tank, the work done by it, and the heat added to it.

It is felt that a much closer correlation between the large and small tanks could be obtained if the $\frac{\text{Mass} \times \text{Area}}{\text{Volume}}$ ratios of the two tanks were the same. Dividing $\pi_6 = \frac{M g R_o T_o}{p_o V}$ by $\pi_7 = \frac{k_o g R_o T_o t^2}{A_t}$ we get:

$$\frac{\pi_6}{\pi_7} = \frac{MA_t}{v} \times \frac{1}{k_o p_o t^2}$$

The only variables influenced by changing tanks are M, A_t, and v. Therefore, if $\frac{MA_t}{V}$ remains constant, there would probably be a much closer correlation between the n vs π_7 plots. This problem could be a possible future thesis.

We believe that the time spent working on this thesis was quite profitable and that future expansion of this topic along the lines suggested above would be quite worth while.

APPENDIX I

PRELIMINARY DATA

1. The following data was used in determining the deviation of our thermocouples from the standard.

Corrected boiling point of water	100.074 °C
Thermocouple reading at 100.074 °C	4.270 mv
Standard reading at 100.074 °C	4.279 mv

2. The following data was used in determining the π's found by dimensional analysis.

a. Data for large tank:

Weight of tank empty	126.25 pounds
Weight of tank when full of water	223.25 pounds
Weight of water in tank	97.00 pounds
Temperature of water added to tank	50.00 °F
Density of water at this temperature	62.41 $\frac{\text{pounds}}{\text{foot}^3}$
Height of tank	48.50 inches
Circumference of tank	29.50 inches

b. Data for small tank:

Weight of tank empty	13.50 pounds
Weight of tank when full of water	20.25 pounds
Weight of water in tank	6.75 pounds
Temperature of water added to tank	50.00 °F
Density of water at this temperature	62.41 $\frac{\text{pounds}}{\text{foot}^3}$
Height of tank	15.50 inches
Circumference of tank	14.50 inches

EXPERIMENTAL DATA - LARGE TANK
DISCHARGING

Explanation of terms:

P_o is the initial pressure of the gas within the tank.

P_f is the final pressure of the gas within the tank.

T_o is the initial temperature of the tank and the gas within it.

T_f is the final temperature of the gas within the tank.

T_1 is the final temperature of the top section of the tank.

T_2 is the final temperature of the middle section of the tank.

T_3 is the final temperature of the bottom section of the tank.

Date 1953	Run	P_o psig	P_f psig	time min	sec	$3T_o$ mv	$3T_f$ mv	$4T_1$ mv	$4T_2$ mv	$4T_3$ mv
3-30	1	1000	200	4	8.3	2.99	0.00	2.36	2.56	2.85
3-30	2	1000	286		53.1	2.75	-1.94	2.65	2.69	2.95
3-31	3	1000	200	12	7.6	2.85	1.00	2.15	2.35	2.55
3-31	4	1000	200	7	19.1	2.81	0.60	2.12	2.42	2.66
3-31	5	800	158	1	23.3	2.74	-1.97	2.61	2.76	2.94
4-2	6	800	158	14	7.2	2.73	1.34	2.44	2.66	2.85
4-11	7	1000	200	2	57.3	2.99	-0.11	2.61	2.92	3.11
4-11	8	800	158	3	45.3	3.19	0.33	2.97	3.34	3.54
4-14	9	800	158	14	13.0	2.96	1.40	2.72	2.93	3.18
4-14	10	800	158	6	31.3	2.97	0.59	2.64	2.91	3.14
4-14	11.	800	158	8	30.8	2.93	0.88	2.68	2.93	3.17
4-16	12	1000	200	10	41.3	3.12	1.10	2.63	2.88	3.09
4-16	13	800	158	10	20.9	2.95	1.02	2.59	2.91	3.10
4-16	14	1000	200	1	40.0	3.16	-2.09	2.62	3.23	3.43
4-17	15	1000	323	2	26.2	3.28	0.00	3.17	3.51	3.63
4-17	16	1000	323	2	38.2	3.13	0.00	2.73	3.13	3.30
4-17	17	1000	323	6	3.7	3.13	0.94	2.75	3.09	3.30
4-17	18	800	257	10	50.5	2.95	1.40	2.82	3.03	3.25
4-21	19	1000	323	9	26.5	3.06	1.28	2.69	2.95	3.11
4-21	20	1000	323	11	1.0	2.83	1.14	2.38	2.63	2.84

Date 1953	Run	P_o psig	P_f psig	time min	sec	$3T_o$ mv	$3T_f$ mv	$4T_1$ mv	$4T_2$ mv	$4T_3$ mv
4-21	21	1000	323	15	24.3	2.84	1.35	2.39	2.67	2.87
4-21	22	1000	323		51.6	2.78	-2.28	2.82	3.12	3.20
4-22	23	800	257	9	18.8	3.15	1.53	3.04	3.41	3.54
4-22	24	800	257	6	37.2	3.06	1.16	3.04	3.33	3.53
4-22	25	800	257	2	30.9	3.06	-0.03	2.79	3.30	3.67
4-22	26	800	257	5	9.4	2.94	0.77	2.72	3.15	3.44

EXPERIMENTAL DATA - SMALL TANK
DISCHARGING

Explanation of terms:

P_o is the initial pressure of the gas within the tank.

P_f is the final pressure of the gas within the tank.

T_o is the initial temperature of the tank and the gas within it.

T_f is the final temperature of the gas within the tank.

T_1 is the final temperature of the bottom section of the tank.

T_2 is the final temperature of the top section of the tank.

Date 1953	Run	P_o psig	P_f psig	time min	time sec	T_o mv	T_f mv	$4T_1$ mv	$4T_2$ mv
4-24	27	1000	200		56.7	1.19	0.00	3.85	4.09
4-24	28	1000	200	12	34.7	1.15	0.82	3.64	3.83
4-24	29	1000	200	1	57.9	1.11	0.36	3.41	3.78
4-24	30	1000	200	4	9.9	1.12	0.56	3.26	3.69
4-24	31	1000	200	7	44.8	1.05	0.64	3.21	3.51
4-24	32	1000	200	3	51.7	1.08	0.49	3.22	3.66
4-24	33	1000	200	6	28.2	1.07	0.59	3.12	3.58
4-24	34	1000	200	17	30.5	1.08	0.74	3.22	3.55
4-24	35	1000	200	1	44.0	1.05	0.18	3.15	3.51
4-24	36	1000	200	2	25.0	1.06	0.35	3.06	3.74
4-24	37	1000	200	8	17.1	1.06	0.64	3.06	3.62
4-24	38	1000	200	9	27.7	1.04	0.66	3.07	3.55
4-24	39	1000	200		15.9	1.07	-1.27	3.26	3.85
4-28	40	1200	233	1	5.5	1.14	-0.05	3.27	3.71
4-28	41	1200	233	1	22.5	1.15	0.13	3.12	3.70
4-28	42	1200	233	5	31.2	1.12	0.55	2.90	3.45
4-28	43	1200	233	6	10.1	1.10	0.54	2.79	3.36
4-28	44	1200	233	4	16.3	1.11	0.44	2.66	3.35
4-28	45	1200	233	5	39.2	1.02	0.45	2.65	3.05
4-28	46	1200	233	6	3.1	1.04	0.50	2.58	3.21
4-28	47	1200	233	13	52.0	1.06	0.66	2.82	3.28
4-29	48	1200	233	9	25.0	1.14	0.66	3.22	3.47

Date 1953	Run	P_o psig	P_f psig	time min	time sec	T_o mv	T_f mv	$4T_1$ mv	$4T_2$ mv
4-29	49	1200	233	6	50.3	1.11	0.58	3.06	3.55
4-29	50	1200	233		47.6	1.12	-0.28	3.01	3.78
4-29	51	1200	233		14.4	1.13	-1.33	3.40	4.03
4-29	52	800	158	8	6.4	1.00	0.64	3.07	3.39
4-29	53	800	158	8	56.6	1.02	0.63	3.00	3.34
4-29	54	800	158	12	49.4	1.04	0.67	2.96	3.28
4-29	55	800	158	5	23.8	1.02	0.56	2.93	3.47
4-29	56	800	158	4	2.5	1.08	0.50	2.89	3.50
4-29	57	800	158	3	19.8	1.09	0.46	2.88	3.58
4-29	58	800	158	2	30.8	1.08	0.38	2.91	3.62
4-29	59	800	158	2	10.4	1.08	0.33	2.92	3.66
4-29	60	800	158	1	36.7	1.09	0.25	2.83	3.72
4-29	61	800	158	1	11.5	1.04	0.07	2.97	3.69
4-29	62	800	158		49.4	1.10	-0.14	3.05	3.75
4-29	63	800	158		6.6	1.10	-1.76	3.41	4.08
4-30	64	600	115	6	19.2	1.11	0.80	3.75	4.17
4-30	65	600	115	10	23.5	1.10	0.84	3.71	4.18
4-30	66	600	115	6	22.2	1.08	0.76	3.60	4.00
4-30	67	600	115	7	5.6	1.10	0.78	3.58	4.05
4-30	68	600	115	8	42.8	1.10	0.82	3.57	3.93
4-30	69	600	115	2	52.7	1.06	0.61	3.44	3.96
4-30	70	600	115	2	57.5	1.05	0.60	3.48	3.99
4-30	71	600	115	3	29.7	1.08	0.64	3.40	3.99
4-30	72	600	115	4	43.4	1.05	0.72	3.42	3.97
4-30	73	600	115	1	43.4	1.08	0.39	3.34	4.02
4-30	74	600	115	1	1.6	1.08	0.09	3.42	4.07
4-30	75	600	115		8.3	1.05	-1.15	3.67	4.18
5-1	76	500	94	4	57.8	1.00	0.68	3.51	3.82
5-1	77	500	94	6	18.6	1.00	0.71	3.43	3.70
5-1	78	500	94	9	37.7	0.99	0.72	3.33	3.61
5-1	79	500	94	15	7.8	0.94	0.74	3.30	3.52
5-1	80	500	94	3	24.5	0.94	0.55	3.32	3.62
5-1	81	500	94	3	37.9	0.99	0.58	3.23	3.65
5-1	82	500	94	4	52.4	0.91	0.54	3.22	3.44

Date 1953	Run	P_o psig	P_f psig	time min	sec	T_o mv	T_f mv	$4T_1$ mv	$4T_2$ mv
5-1	83	500	94	3	52.6	0.91	0.55	3.13	3.50
5-1	84	500	94	7	26.9	0.92	0.59	3.19	3.52
5-1	85	500	94	1	29.8	0.98	0.28	3.18	3.72
5-1	86	500	94	1	54.6	0.97	0.35	3.15	3.75
5-1	87	500	94		8.4	1.02	-1.48	3.69	4.24
5-1	88	900	290	2	23.1	1.08	0.48	3.34	3.88
5-1	89	900	290	3	7.7	1.08	0.52	3.27	3.77
5-1	90	900	290	5	14.9	1.05	0.64	3.24	3.68
5-1	91	900	290	3	27.3	1.08	0.53	3.18	3.72
5-1	92	900	290	4	56.8	1.10	0.61	3.18	3.72
5-4	93	900	290	15	37.9	1.14	0.85	3.77	3.98
5-4	94	900	290	6	42.8	1.15	0.72	3.57	3.84
5-4	95	900	290	10	26.4	1.11	0.74	3.46	3.85
5-4	96	900	290	1	56.5	1.14	0.41	3.41	4.03
5-4	97	900	290	7	29.3	1.08	0.65	3.38	3.74
5-4	98	900	290		7.0	1.09	-1.02	3.65	4.20
5-4	99	900	290		47.7	1.05	0.00	3.35	4.05
5-4	100	600	190	1	45.1	1.05	0.39	3.37	3.92
5-4	101	600	190	1	58.9	1.08	0.45	3.52	3.90
5-4	102	600	190	2	12.7	1.08	0.48	3.41	3.87
5-4	103	600	190	2	36.4	1.03	0.53	3.38	3.89
5-4	104	600	190	3	31.0	1.02	0.56	3.33	3.77
5-4	105	600	190	4	41.7	1.04	0.65	3.38	3.82
5-4	106	600	190		5.4	1.08	-0.89	3.58	4.10
5-5	107	600	190	5	53.3	1.00	0.67	3.31	3.60
5-5	108	600	190	6	24.8	0.91	0.63	3.15	3.48
5-5	109	600	190	7	56.6	0.95	0.65	3.12	3.45
5-5	110	600	190	12	33.5	1.01	0.73	3.28	3.54
5-5	112	600	190		20.3	1.08	-0.73	3.57	3.94
5-5	113	600	190		48.8	1.09	0.10	3.55	3.95
5-7	114	1200	390	12	0.9	1.10	0.76	3.40	3.57
5-7	115	1200	390	7	26.2	1.06	0.64	3.15	3.44
5-7	116	1200	390	5	0.8	1.07	0.59	3.00	3.51
5-7	117	1200	390	6	26.2	1.06	0.60	2.94	3.39
5-7	118	1200	390	3	54.3	1.06	0.48	2.89	3.47

Date 1953	Run	P_o psig	P_f psig	time min	time sec	T_o mv	T_f mv	$4T_1$ mv	$4T_2$ mv
5-7	119	1200	390	3	7.8	1.09	0.42	2.83	3.55
5-7	120	1200	390	2	34.0	1.09	0.38	2.91	3.52
5-7	121	1200	390	2	5.8	1.07	0.28	2.76	3.49
5-7	122	1200	390	1	36.4	1.07	0.19	2.80	3.54
5-7	123	1200	390	1	17.5	1.08	0.11	2.90	3.64
5-7	124	1200	390		52.1	1.08	-0.04	2.92	3.73
5-7	125	1200	390		4.4	1.12	-1.13	3.15	4.04
5-7	126	600	80	2	8.9	0.98	0.25	2.93	3.34
5-7	127	600	80	6	48.4	0.98	0.59	3.02	3.41
5-7	128	1200	172	14	29.9	1.15	0.70	3.31	3.62
5-7	129	1200	172	7	57.0	1.12	0.54	3.09	3.44
5-7	130	1200	172	9	43.9	1.10	0.60	3.01	3.37
5-7	131	1200	172	5	57.8	1.04	0.40	2.81	3.24
5-7	132	1200	172	7	36.9	1.02	0.45	2.72	3.14
5-7	133	1200	172	6	24.1	1.01	0.40	2.65	3.15
5-7	134	1200	172	5	9.1	1.06	0.38	2.62	3.25
5-7	135	1200	172	4	10.8	1.07	0.33	2.56	3.23
5-7	136	1200	172	3	34.6	1.09	0.26	2.55	3.34
5-7	137	1200	172	3	7.2	1.10	0.22	2.56	3.32
5-7	138	1200	172	2	12.9	1.10	0.09	2.54	3.40
5-7	139	1200	172	1	12.8	1.10	-0.20	2.77	3.65
5-7	140	1200	172		6.9	1.11	-2.26	3.42	4.04
5-8	141	600	80	4	59.2	1.01	0.62	3.40	3.63
5-8	142	600	80	5	57.4	1.04	0.68	3.38	3.70
5-8	143	600	80	12	25.4	1.05	0.77	3.44	3.74
5-8	144	600	80	9	55.4	1.06	0.74	3.42	3.79
5-8	145	600	80	7	55.8	1.07	0.72	3.44	3.78
5-8	146	600	80	3	47.8	1.09	0.56	3.42	3.90
5-8	147	600	80	2	53.5	1.07	0.50	3.40	3.92
5-8	148	600	80	2	7.5	1.09	0.34	3.32	3.90
5-8	149	600	80	1	40.8	1.09	0.28	3.35	3.99
5-8	150	600	80		54.6	1.11	-0.03	3.39	4.03
5-8	151	600	80		5.4	1.11	-2.14	3.73	4.42
5-8	152	900	126	8	40.1	1.08	0.74	3.50	3.73
5-8	153	900	126	11	12.8	1.15	0.78	3.34	3.61

Date 1953	Run	P_o psig	P_f psig	time min	sec	T_o mv	T_f mv	$4T_1$ mv	$4T_2$ mv
5-8	154	900	126	9	27.7	1.13	0.75	3.20	3.43
5-8	155	900	126	6	37.2	1.15	0.67	3.14	3.50
5-8	156	900	126	7	21.2	1.16	0.69	3.10	3.57
5-8	157	900	126	6	41.9	1.16	0.67	3.09	3.59
5-8	158	900	126	4	25.5	1.16	0.61	3.08	3.63
5-8	159	900	126	4	52.1	1.16	0.64	3.14	3.64
5-8	160	900	126	3	25.4	1.17	0.51	3.00	3.64
5-8	161	900	126	2	42.1	1.17	0.39	3.02	3.62
5-8	162	900	126	1	43.7	1.17	0.25	2.99	3.63
5-8	163	900	126		56.6	1.17	-0.30	3.18	3.94
5-8	164	900	126		5.2	1.18	-2.40	3.61	4.05

EXPERIMENTAL DATA - SMALL TANK CHARGING

Explanation of terms:

P_o is the initial pressure of the gas within the tank.

P_f is the final pressure of the gas within the tank.

T_o is the initial temperature of the tank and the gas within it.

T_f is the final temperature of the gas within the tank.

T_1 is the final temperature of the bottom section of the tank.

T_2 is the final temperature of the top section on the tank.

Date 1953	Run	P_o psig	P_f psig	time min	time sec	T_o mv	T_f mv	$4T_1$ mv	$4T_2$ mv
5-11	165	115	600		17.2	1.09	2.61	4.37	5.04
5-11	166	115	600		18.8	1.10	2.44	4.73	5.12
5-11	167	115	600	3	23.0	1.10	1.50	4.74	5.18
5-11	168	115	600	1	29.2	1.04	1.72	4.76	4.96
5-11	169	115	600	2	42.8	1.04	1.55	4.72	5.06
5-11	170	115	600	4	14.9	1.09	1.50	4.87	5.15
5-11	171	115	600	5	1.2	1.10	1.44	4.76	5.06
5-11	172	115	600	7	21.6	1.10	1.40	4.66	5.08
5-11	173	115	600	1	27.4	1.08	1.78	4.70	5.05
5-11	174	115	600	4	55.2	1.10	1.45	4.62	5.10
5-11	175	200	1000	8	4.9	1.10	1.48	5.09	5.44
5-11	176	200	1000	5	13.2	1.09	1.55	5.02	5.46
5-11	177	200	1000	5	40.1	1.08	1.50	4.85	5.40
5-11	178	200	1000	10	30.5	1.07	1.43	4.95	5.28
5-12	179	200	1000	6	10.2	1.05	1.42	4.85	5.22
5-12	180	200	1000	7	27.2	0.99	1.35	4.63	5.06
5-12	181	200	1000	2	51.1	0.97	1.55	4.66	5.11
5-12	182	200	1000	2	50.4	0.99	1.54	4.64	5.19
5-12	183	200	1000	4	31.4	1.00	1.45	4.63	5.22
5-12	184	200	1000	2	41.1	0.98	1.55	4.60	5.20
5-12	185	200	1000	1	44.4	1.01	1.72	4.70	5.26
5-12	186	200	1000		37.8	1.01	2.15	4.55	5.29

Date 1953	Run	P_o psig	P_f psig	time min	sec	T_o mv	T_f mv	$4T_a$ mv	$4T_a$ mv
5-12	187	190	600	4	15.3	1.09	1.41	4.74	5.01
5-12	188	190	600	5	47.8	1.10	1.38	4.67	4.97
5-12	189	190	600	7	3.2	1.09	1.33	4.53	4.90
5-12	190	190	600	11	28.8	1.08	1.28	4.60	4.94
5-12	191	190	600	9	12.5	1.10	1.26	4.47	4.75
5-12	192	190	600	5	25.0	1.05	1.35	4.54	4.75
5-12	193	190	600	3	6.3	1.07	1.50	4.47	4.77
5-12	194	190	600	3	34.4	1.07	1.44	4.52	4.77
5-12	195	190	600	1	36.6	1.07	1.68	4.50	4.85
5-12	196	190	600	1	50.0	1.07	1.65	4.48	4.84
5-12	197	190	600		50.4	1.08	1.89	4.45	4.80
5-12	198	190	600		23.6	1.08	2.25	4.34	4.82
5-13	199	390	1200	5	14.0	1.10	1.50	5.14	5.44
5-13	200	390	1200	6	26.6	1.06	1.45	4.93	5.13
5-13	201	390	1200	8	36.6	1.01	1.36	4.84	5.18
5-13	202	390	1200	5	14.2	1.01	1.44	4.74	5.18
5-13	203	390	1200	7	35.3	1.00	1.39	4.74	5.07
5-13	204	390	1200	10	37.6	0.99	1.31	4.66	4.96
5-13	205	390	1200	2	22.4	0.96	1.60	4.64	4.97
5-13	206	390	1200	2	50.2	0.97	1.55	4.60	5.05
5-13	207	390	1200	3	43.4	0.97	1.50	4.64	5.06
5-13	208	390	1200	1	25.7	0.98	1.80	4.56	5.12
5-13	209	390	1200	1	3.0	0.99	1.96	4.59	5.20
5-13	210	390	1200		13.9	1.00	2.65	4.21	5.17
5-14	211	172	1200	8	26.1	1.00	1.44	4.89	5.24
5-14	212	172	1200	13	24.0	1.00	1.37	4.77	5.07
5-14	213	172	1200	6	46.8	0.98	1.49	4.75	5.14
5-14	214	172	1200	7	33.0	0.98	1.45	4.72	5.17
5-14	215	172	1200	10	50.5	0.98	1.39	4.72	5.14
5-14	216	172	1200	2	42.5	0.95	1.70	4.71	5.21
5-14	217	172	1200	2	58.8	1.00	1.68	5.02	5.25
5-14	218	172	1200	3	27.8	0.96	1.63	4.78	5.26
5-14	219	172	1200	5	10.1	0.95	1.48	4.60	5.05
5-14	220	172	1200	4	2.3	0.94	1.50	4.54	4.95

Date 1953	Run	P_o psig	P_f psig	time min	sec	T_o mv	T_f mv	$4T_1$ mv	$4T_s$ mv
5-14	221	172	1200	1	50.6	0.91	1.77	4.57	4.94
5-14	222	172	1200	1	24.0	0.97	1.90	4.49	5.05
5-14	223	172	1200	1	5.6	0.95	2.02	4.45	5.02
5-14	224	172	1200		32.3	1.00	2.36	4.46	5.09
5-14	225	80	600	3	43.9	0.99	1.42	4.05	4.52
5-14	226	80	600	5	44.4	0.99	1.32	4.05	4.47
5-14	227	80	600	4	1.8	0.97	1.43	4.12	4.45
5-14	228	80	600	4	50.3	0.96	1.30	4.00	4.33
5-14	229	80	600	6	18.6	0.93	1.23	3.94	4.32
5-14	230	80	600	9	46.4	0.92	1.16	3.95	4.21
5-14	231	80	600	6	17.3	0.95	1.22	3.89	4.21
5-14	232	80	600	6	56.6	0.95	1.22	3.97	4.22
5-14	233	80	600	9	42.6	0.96	1.18	3.91	4.15
5-14	234	80	600	5	59.1	0.91	1.24	3.92	4.15
5-14	235	80	600		43.5	0.91	2.00	4.00	4.29
5-14	236	80	600		49.6	0.92	1.93	4.15	4.52
5-14	237	80	600	1	24.1	1.03	1.85	4.41	4.65
5-14	238	80	600	2	48.4	1.06	1.56	4.34	4.62
5-14	239	80	600	2	0.6	1.06	1.66	4.37	4.68
5-14	240	80	600		31.5	1.10	2.26	4.34	4.71

APPENDIX II

PRELIMINARY CALCULATIONS

I. Calculation of terms necessary to evaluate the π's for the large tank.

1. Mass of the tank:

$$M \text{ (mass)} = \frac{\text{Weight of the tank}}{12\ g}$$

$$M = \frac{126.25}{12 \times 32.2}$$

$$M = 0.3267\ \frac{\text{lb sec}^2}{\text{in.}}$$

2. Volume of the tank:

$$V \text{ (volume)} = \text{Volume of water added to tank}$$

$$= \frac{\text{Weight of water}}{\text{Density of water}}$$

$$= \frac{97 \times 1728}{62.41}$$

$$V = 2685.7\ \text{in}^3$$

3. Surface area of the tank:

$$A_t \text{ (surface area)} = \text{circumference} \times \text{height}$$

$$A_t = 48.5 \times 29.5$$

$$A_t = 1430.75\ \text{in}^2$$

4. Calculation of π_7:

$$\pi_7 = \frac{k_o g R_o T_o t^2}{A_t}$$

k_o is the volumetric exponent for an adiabatic process (k_o for air is 1.4).

R_o is the gas constant for air ($53.35\ \frac{\text{ft lb}}{\text{lb }^\circ F_{abs}}$).

T_o is the initial temperature of the air.

t is the time of discharge.

Therefore:

$$\pi_7 = \frac{1.4 \times 32.2 \times 53.35 \times 144\ T_o t^2}{1430.75}$$

$$\pi_7 = 242.06\ T_o t^2$$

5. Calculation of π_6:

$$\pi_6 = \frac{M g R_o T_o}{P_o V}$$

$$\pi_6 = \frac{0.3267 \times 32.2 \times 144 \times 53.35 \times T_o}{2685.7\ P_o}$$

$$\pi_6 = 30.09 \frac{T_o}{P_o}$$

II. Calculation of terms necessary to evaluate the π's for the small tank.

1. Mass of the tank:

$$M \text{ (mass)} = \frac{\text{Weight of the tank}}{12\ g}$$

$$M = \frac{13.5}{12 \times 32.2}$$

$$M = 0.035 \frac{\text{lb sec}^2}{\text{in.}}$$

2. Volume of the tank:

$$V \text{ (volume)} = \text{Volume of water added to tank}$$

$$= \frac{\text{Weight of water}}{\text{Density of water}}$$

$$= \frac{6.75 \times 1728}{62.41}$$

$$V = 187 \text{ in.}^3$$

3. Surface area of the tank:

$$A_t \text{ (surface area)} = \text{circumference} \times \text{height}$$

$$A_t = 14.5 \times 15.5$$

$$A_t = 225 \text{ in.}^2$$

4. Calculation of π_7:

$$\pi_7 = \frac{k_o g R_o T_o t^2}{A_t}$$

k_o is the volumetric exponent for an adiabatic process.

R_o is the gas constant for air.

T_o is the initial temperature of the air.

t is the time of discharge.

Therefore:

$$\pi_7 = \frac{1.4 \times 32.2 \times 53.35 \times 144\ T_o t^2}{225}$$

$$\pi_7 = 1539\ T_o t^2$$

5. Calculation of π_6:

$$\pi_6 = \frac{M g R_o T_o}{P_o V}$$

$$\pi_6 = \frac{0.035 \times 32.2 \times 144 \times 53.35 \times T_o}{187\ P_o}$$

$$\pi_6 = 46.31\ \frac{T_o}{P_o}$$

CALCULATIONS - LARGE TANK

1. Pressure ratio of 4.72 (ratio of absolute pressures).

1.1 Initial pressure = 1000 psig

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o °F abs	T_f °F abs
1	0.997	0.000	77.35	32.00	1015	215	537.04	481.69
3	0.950	0.333	75.36	47.38	1015	215	535.05	507.07
4	0.937	0.200	74.77	41.28	1015	215	534.46	500.97
7	0.997	-0.037	77.35	30.28	1015	215	537.04	489.97
12	1.040	0.367	79.34	48.92	1015	215	539.03	508.61
14	1.053	-0.697	79.91	- 1.30	1015	215	539.60	458.39

Run	$\frac{P_o}{P_f}$	$\frac{P_o T_f}{P_f T_o}$	$\ln \frac{P_o}{P_f}$	$\ln \frac{T_f P_o}{T_o P_f}$	n
1	4.72	4.320	1.552	1.462	1.061
3	4.72	4.470	1.552	1.500	1.036
4	4.72	4.435	1.552	1.490	1.042
7	4.72	4.300	1.552	1.460	1.064
12	4.72	4.455	1.552	1.495	1.039
14	4.72	4.020	1.552	1.390	1.118

Run	t	t^2	$\pi_7 = 242\ T_o t^2$
1	248.3	61,300	7,955,000,000
3	727.6	530,000	68,600,000,000
4	439.1	192,500	24,840,000,000
7	177.3	31,400	4,080,000,000
12	641.3	411,000	53,600,000,000
14	100.0	10,000	1,308,000,000

1.2 Initial pressure = 800 psig

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o °F_{abs}	T_f °F_{abs}
5	0.913	-0.663	73.68	0.35	815	173	533.37	460.04
6	0.910	0.447	73.55	53.68	815	173	533.24	512.37
8	1.063	0.108	80.35	37.00	815	173	540.04	496.69
9	0.987	0.467	77.00	53.50	815	173	536.69	513.19
10	0.990	0.197	77.10	41.10	815	173	536.79	500.79
11	0.977	0.293	76.55	45.52	815	173	536.24	505.21
13	0.983	0.340	76.80	47.70	815	173	536.49	507.39

Run	$\frac{P_o}{P_f}$	$\frac{P_o T_f}{P_f T_o}$	$\ln \frac{P_o}{P_f}$	$\ln \frac{T_f P_o}{T_o P_f}$	n
5	4.72	4.070	1.552	1.403	1.108
6	4.72	4.535	1.552	1.510	1.029
8	4.72	4.340	1.552	1.468	1.060
9	4.72	4.515	1.552	1.508	1.030
10	4.72	4.405	1.552	1.483	1.048
11	4.72	4.445	1.552	1.490	1.042
13	4.72	4.460	1.552	1.498	1.038

Run	t	t^2	$\pi_7 = 242\ T_o t^2$
5	83.3	6,900	890,000,000
6	847.2	712,000	91,800,000,000
8	225.3	59,800	7,810,000,000
9	852.0	722,000	93,600,000,000
10	391.3	152,500	19,810,000,000
11	510.8	259,000	33,600,000,000
13	620.9	384,000	49,900,000,000

2. Pressure ratio of 3.00 (ratio of absolute pressures).

2.1 Initial pressure = 1000 psig

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o °F abs	T_f °F abs
15	1.093	0.000	81.69	32.00	1015	338	541.38	491.69
16	1.043	0.000	79.48	32.00	1015	338	539.17	491.69
17	1.043	0.313	79.48	46.45	1015	338	539.17	506.14
19	1.020	0.427	78.48	51.67	1015	338	538.17	511.36
20	0.943	0.380	75.03	49.50	1015	338	534.72	509.19
21	0.947	0.450	75.20	52.72	1015	338	534.89	512.41
22	0.927	-0.760	74.30	- 4.40	1015	338	533.99	455.29

Run	$\frac{P_o}{P_f}$	$\frac{P_o T_f}{P_f T_o}$	$\ln \frac{P_o}{P_f}$	$\ln \frac{T_f P_o}{T_o P_f}$	n
15	3.00	2.723	1.099	1.001	1.095
16	3.00	2.735	1.099	1.004	1.093
17	3.00	2.818	1.099	1.034	1.061
19	3.00	2.844	1.099	1.046	1.051
20	3.00	2.860	1.099	1.050	1.046
21	3.00	2.878	1.099	1.058	1.040
22	3.00	2.560	1.099	0.940	1.170

Run	t	t^2	$\pi_7 = 242\ T_o t^2$
15	146.2	21,400	2,800,000,000
16	158.2	25,000	3,260,000,000
17	363.7	131,800	17,090,000,000
19	566.5	320,000	41,600,000,000
20	661.0	436,000	56,400,000,000
21	924.3	851,000	110,000,000,000
22	51.6	2,650	342,000,000

2.2 Initial pressure = 800 psig

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o $°F_{abs}$	T_f $°F_{abs}$
18	0.983	0.467	76.80	53.50	815	272	536.49	513.19
23	1.050	0.510	79.80	55.49	815	272	539.49	515.18
24	1.020	0.387	78.48	49.85	815	272	538.17	509.54
25	1.020	-0.010	78.48	31.55	815	272	538.17	491.24
26	0.980	0.257	76.70	43.88	815	272	536.39	503.57

Run	$\frac{P_o}{P_f}$	$\frac{P_o T_f}{P_f T_o}$	$\ln \frac{P_o}{P_f}$	$\ln \frac{T_f P_o}{T_o P_f}$	n
18	3.00	2.863	1.099	1.052	1.042
23	3.00	2.860	1.099	1.050	1.046
24	3.00	2.830	1.099	1.040	1.056
25	3.00	2.739	1.099	1.008	1.090
26	3.00	2.816	1.099	1.032	1.063

Run	t	t^2	$\pi_7 = 242\, T_o t^2$
18	650.5	422,000	54,900,000,000
23	558.8	311,000	40,600,000,000
24	397.2	157,000	20,400,000,000
25	150.9	22,700	2,956,000,000
26	309.4	95,100	12,350,000,000

CALCULATIONS - SMALL TANK DISCHARGING

3. Pressure ratio of 4.72 (ratio of absolute pressures).

3.1 Initial pressure = 1000 psig

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o °F abs	T_f °F abs
27	1.19	0.00	83.8	32.0	1015	215	540.3	491.7
28	1.15	0.82	84.0	69.4	1015	215	543.7	529.1
29	1.11	0.36	82.3	48.6	1015	215	542.0	508.3
30	1.12	0.56	82.7	57.8	1015	215	542.4	517.5
31	1.05	0.64	79.7	61.4	1015	215	539.4	521.1
32	1.08	0.49	81.0	54.6	1015	215	540.7	514.3
33	1.07	0.59	80.6	59.1	1015	215	540.3	518.8
35	1.05	0.18	79.7	40.4	1015	215	539.4	500.1
36	1.06	0.35	80.1	48.2	1015	215	539.8	507.9
37	1.06	0.64	80.1	61.4	1015	215	539.8	521.1
38	1.04	0.66	79.3	62.3	1015	215	539.0	522.0
39	1.07	-1.27	80.6	-29.9	1015	215	540.3	429.8

Run	$\frac{P_o}{P_f}$	$\frac{P_o T_f}{P_f T_o}$	$\ln \frac{P_o}{P_f}$	$\ln \frac{T_f P_o}{T_o P_f}$	n
27	4.72	4.27	1.552	1.450	1.070
28	4.72	4.59	1.552	1.522	1.020
30	4.72	4.50	1.552	1.503	1.033
31	4.72	4.56	1.552	1.519	1.022
32	4.72	4.49	1.552	1.500	1.035
33	4.72	4.53	1.552	1.510	1.028
35	4.72	4.38	1.552	1.478	1.050
36	4.72	4.44	1.552	1.490	1.041
37	4.72	4.56	1.552	1.519	1.022
38	4.72	4.56	1.552	1.519	1.022
39	4.72	3.75	1.552	1.321	1.175

Run	t	t^2	$\pi_7 = 1539\ T_o t^2$
27	56.7	3,100	2,540,000,000
28	754.7	568,000	475,000,000,000
29	117.9	13,850	11,550,000,000
30	249.9	62,300	52,000,000,000
31	464.8	215,000	178,500,000,000
32	231.7	53,200	44,400,000,000
33	388.2	150,500	125,300,000,000
35	104.0	10,800	8,950,000,000
36	145.0	21,000	17,450,000,000
37	497.1	246,000	204,000,000,000
38	567.7	322,000	267,000,000,000
39	15.9	252	210,000,000

3.2 Initial pressure = 1200 psig

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o °F_{abs}	T_f °F_{abs}
40	1.14	-0.05	83.6	29.6	1215	248	543.3	489.3
41	1.15	0.13	84.0	38.0	1215	248	543.7	497.7
42	1.12	0.55	82.8	57.3	1215	248	542.5	517.0
43	1.10	0.54	81.9	56.8	1215	248	541.6	516.5
44	1.11	0.44	82.3	52.3	1215	248	542.0	512.0
45	1.02	0.45	78.4	52.7	1215	248	538.1	512.4
46	1.04	0.50	79.3	55.0	1215	248	539.0	514.7
47	1.06	0.66	80.1	62.3	1215	248	539.8	522.0
48	1.14	0.66	83.6	62.3	1215	248	543.3	522.0
49	1.11	0.58	82.3	58.7	1215	248	542.0	518.4
50	1.12	-0.28	82.8	19.9	1215	248	542.5	478.7
51	1.13	-1.33	83.2	-33.0	1215	248	542.9	426.7

Run	$\frac{P_o}{P_f}$	$\frac{P_o T_f}{P_f T_o}$	$\ln \frac{P_o}{P_f}$	$\ln \frac{T_f P_o}{T_o P_f}$	n
40	4.72	4.25	1.552	1.448	1.073
41	4.72	4.33	1.552	1.465	1.060
42	4.72	4.50	1.552	1.504	1.032
43	4.72	4.50	1.552	1.504	1.032
44	4.72	4.45	1.552	1.492	1.040

Run	$\frac{P_o}{P_f}$	$\frac{P_o T_f}{P_f T_o}$	$\ln \frac{P_o}{P_f}$	$\ln \frac{T_f P_o}{T_o P_f}$	n
45	4.72	4.50	1.552	1.504	1.032
46	4.72	4.51	1.552	1.509	1.030
47	4.72	4.56	1.552	1.520	1.022
48	4.72	4.54	1.552	1.511	1.028
49	4.72	4.51	1.552	1.509	1.030
50	4.72	4.16	1.552	1.426	1.090
51	4.72	3.71	1.552	1.310	1.182

Run	t	t^2	$\pi_7 = 1539\ T_o t^2$
40	65.5	4,290	3,580,000,000
41	82.5	6,800	5,680,000,000
42	331.2	109,500	91,500,000,000
43	370.1	137,000	114,000,000,000
44	256.3	65,800	54,900,000,000
45	339.3	115,000	95,300,000,000
46	363.1	131,500	109,000,000,000
47	832.0	691,000	575,000,000,000
48	565.0	319,000	266,000,000,000
49	410.3	168,000	140,000,000,000
50	47.6	2,260	1,885,000,000
51	14.4	207	173,000,000

3.3 Initial pressure = 800 psig

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o $°F_{abs}$	T_f $°F_{abs}$
52	1.00	0.64	77.5	61.4	815	173	537.2	521.1
53	1.02	0.63	78.4	60.9	815	173	538.1	520.6
54	1.04	0.67	79.3	62.7	815	173	539.0	522.4
55	1.02	0.56	78.4	57.8	815	173	538.1	517.5
56	1.08	0.50	81.0	55.0	815	173	540.7	514.7
57	1.09	0.46	81.4	53.2	815	173	541.1	512.9
58	1.08	0.38	81.0	49.5	815	173	540.7	509.2
59	1.08	0.33	81.0	47.2	815	173	540.7	506.9

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o °F$_{abs}$	T_f °F$_{abs}$
60	1.09	0.25	81.4	43.6	815	173	541.1	503.3
61	1.04	0.07	79.3	35.3	815	173	539.0	495.0
62	1.10	-0.14	81.9	25.4	815	173	541.6	485.1
63	1.10	-1.76	81.9	-55.5	815	173	541.6	404.2

Run	$\frac{P_o}{P_f}$	$\frac{P_o T_f}{P_f T_o}$	$\ln \frac{P_o}{P_f}$	$\ln \frac{T_f P_o}{T_o P_f}$	n
52	4.72	4.58	1.552	1.521	1.020
53	4.72	4.58	1.552	1.521	1.020
54	4.72	4.58	1.552	1.521	1.020
55	4.72	4.54	1.552	1.511	1.027
56	4.72	4.49	1.552	1.501	1.034
57	4.72	4.47	1.552	1.498	1.036
58	4.72	4.44	1.552	1.490	1.042
59	4.72	4.42	1.552	1.486	1.045
60	4.72	4.39	1.552	1.479	1.050
61	4.72	4.34	1.552	1.467	1.059
62	4.72	4.23	1.552	1.440	1.078
63	4.72	3.52	1.552	1.260	1.231

Run	t	t^2	$\pi_7 = 1539\ T_o t^2$
52	486.4	236,000	187,000,000,000
53	536.6	288,000	239,000,000,000
54	769.4	591,000	490,000,000,000
55	332.8	110,500	91,500,000,000
56	242.5	58,800	48,900,000,000
57	199.8	40,000	33,400,000,000
58	150.8	22,700	18,900,000,000
59	130.4	17,000	14,200,000,000
60	96.7	9,350	7,790,000,000
61	71.5	5,110	4,240,000,000
62	49.4	2,440	2,030,000,000
63	6.6	44	36,300,000

3.4 Initial pressure = 600 psig

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o °F_{abs}	T_f °F_{abs}
64	1.11	0.80	82.3	68.5	615	130	542.3	528.5
65	1.10	0.84	81.9	70.3	615	130	541.9	530.3
66	1.08	0.76	81.0	66.8	615	130	541.0	526.8
67	1.10	0.78	81.9	67.6	615	130	541.9	527.6
68	1.10	0.82	81.9	69.4	615	130	541.9	529.4
69	1.06	0.61	80.1	60.1	615	130	540.1	520.1
70	1.05	0.60	79.7	59.6	615	130	539.7	519.6
71	1.08	0.64	81.0	61.4	615	130	541.0	521.4
72	1.05	0.72	79.7	65.0	615	130	539.7	525.0
73	1.08	0.39	81.0	50.0	615	130	541.0	510.0
74	1.08	0.09	81.0	36.2	615	130	541.0	496.2
75	1.05	-1.15	79.7	-23.8	615	130	539.7	436.2

Run	$\frac{P_o}{P_f}$	$\frac{P_o T_f}{P_f T_o}$	$\ln \frac{P_o}{P_f}$	$\ln \frac{T_f P_o}{T_o P_f}$	n
64	4.72	4.60	1.552	1.528	1.016
65	4.72	4.62	1.552	1.529	1.015
66	4.72	4.60	1.552	1.528	1.016
67	4.72	4.59	1.552	1.522	1.020
68	4.72	4.61	1.552	1.529	1.015
69	4.72	4.55	1.552	1.515	1.024
70	4.72	4.54	1.552	1.512	1.026
71	4.72	4.55	1.552	1.515	1.024
72	4.72	4.59	1.552	1.522	1.020
73	4.72	4.45	1.552	1.492	1.040
74	4.72	4.33	1.552	1.465	1.060
75	4.72	3.82	1.552	1.340	1.158

Run	t	t^2	$\pi_7 = 1539\ T_o t^2$
64	379.2	144,000	120,000,000,000
65	623.5	389,000	324,000,000,000
66	382.2	146,000	122,000,000,000
67	425.6	181,000	151,000,000,000
68	522.8	274,000	229,000,000,000

Run	t	t^2	$\pi_7 = 1539\ T_o t^2$
69	172.7	29,800	24,800,000,000
70	177.5	31,500	26,200,000,000
71	209.7	44,000	36,600,000,000
72	283.4	80,000	66,400,000,000
73	103.4	10,700	8,910,000,000
74	61.6	3,800	3,160,000,000
75	8.3	69	57,200,000

3.5 Initial pressure = 500 psig

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o °F abs	T_f °F abs
76	1.00	0.68	77.5	63.2	515	109	537.5	523.2
77	1.00	0.71	77.5	64.5	515	109	537.5	524.5
78	0.99	0.72	77.0	65.0	515	109	537.0	525.0
79	0.94	0.74	74.8	65.8	515	109	534.8	525.8
80	0.94	0.55	74.8	57.3	515	109	534.8	517.3
81	0.99	0.58	77.0	58.7	515	109	537.0	518.7
82	0.91	0.54	73.5	56.8	515	109	533.5	516.8
83	0.91	0.55	73.5	57.3	515	109	533.5	517.3
84	0.92	0.59	73.9	59.1	515	109	533.9	519.1
85	0.98	0.28	76.6	45.0	515	109	536.6	505.0
86	0.97	0.35	76.1	48.2	515	109	536.1	508.2
87	1.02	-1.48	78.4	-40.8	515	109	538.4	419.2

Run	$\frac{P_o}{P_f}$	$\frac{P_o T_f}{P_f T_o}$	$\ln \frac{P_o}{P_f}$	$\ln \frac{T_f P_o}{T_o P_f}$	n
76	4.72	4.59	1.552	1.523	1.019
77	4.72	4.60	1.552	1.527	1.017
78	4.72	4.61	1.552	1.529	1.015
79	4.72	4.65	1.552	1.538	1.010
80	4.72	4.57	1.552	1.520	1.021
81	4.72	4.56	1.552	1.519	1.022
82	4.72	4.57	1.552	1.520	1.021
83	4.72	4.58	1.552	1.521	1.020
84	4.72	4.59	1.552	1.523	1.019

Run	$\frac{P_o}{P_f}$	$\frac{P_o T_f}{P_f T_o}$	$\ln \frac{P_o}{P_f}$	$\ln \frac{P_o T_f}{P_f T_o}$	n
85	4.72	4.44	1.552	1.490	1.041
86	4.72	4.47	1.552	1.499	1.035
87	4.72	3.68	1.552	1.303	1.190

Run	t	t^2	$\pi_7 = 1539\ T_o t^2$
76	297.8	88,700	73,400,000,000
77	378.6	143,000	118,000,000,000
78	577.7	334,000	405,000,000,000
79	907.8	823,000	676,000,000,000
80	204.5	41,800	34,400,000,000
81	217.9	47,500	39,200,000,000
82	292.4	85,500	70,100,000,000
83	232.6	54,000	44,300,000,000
84	446.9	199,000	163,000,000,000
85	89.8	8,080	6,660,000,000
86	114.6	13,100	10,800,000,000
87	8.4	71	58,500,000

4. Pressure ratio of 3.00 (ratio of absolute pressures).

4.1 Initial pressure = 900 psig

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o °F$_{abs}$	T_f °F$_{abs}$
88	1.08	0.48	81.0	54.1	915	305	541.0	514.1
89	1.08	0.52	81.0	55.9	915	305	541.0	515.9
90	1.05	0.64	79.7	61.4	915	305	539.7	521.4
91	1.08	0.53	81.0	56.4	915	305	541.0	516.4
92	1.10	0.61	81.9	60.0	915	305	541.9	520.0
93	1.14	0.85	83.6	70.8	915	305	543.6	530.8
94	1.15	0.72	84.0	64.9	915	305	544.0	524.9
95	1.11	0.74	82.3	65.8	915	305	542.3	525.8
96	1.14	0.41	83.6	50.9	915	305	543.6	510.9
97	1.08	0.65	81.0	61.8	915	305	541.0	521.8
98	1.09	-1.02	81.4	-17.4	915	305	541.4	442.6
99	1.05	0.00	79.7	32.0	915	305	539.7	492.0

Run	$\frac{P_o}{P_f}$	$\frac{P_oT_f}{P_fT_o}$	$\ln \frac{P_o}{P_f}$	$\ln \frac{P_oT_f}{P_fT_o}$	n
88	3.00	2.85	1.099	1.047	1.051
89	3.00	2.86	1.099	1.051	1.047
90	3.00	2.90	1.099	1.065	1.032
91	3.00	2.86	1.099	1.051	1.047
92	3.00	2.88	1.099	1.058	1.040
93	3.00	2.97	1.099	1.089	1.010
94	3.00	2.89	1.099	1.061	1.037
95	3.00	2.91	1.099	1.068	1.030
96	3.00	2.87	1.099	1.054	1.042
97	3.00	2.89	1.099	1.061	1.037
98	3.00	2.45	1.099	0.896	1.228
99	3.00	2.53	1.099	0.928	1.186

Run	t	t^2	$\pi_7 = 1539\ T_o t^2$
88	143.1	20,500	11,350,000,000
89	187.7	35,200	29,300,000,000
90	314.9	99,000	82,200,000,000
91	207.3	42,900	35,700,000,000
92	296.8	88,000	73,400,000,000
93	937.9	880,000	735,000,000,000
94	402.8	162,000	139,500,000,000
95	626.4	393,000	328,000,000,000
96	116.5	13,580	11,350,000,000
97	449.3	202,000	168,000,000,000
98	7.0	49	40,800,000
99	47.7	2,275	1,890,000,000

4.2 Initial pressure = 600 psig

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o $°F_{abs}$	T_f $°F_{abs}$
100	1.05	0.39	79.7	50.0	615	205	539.7	510.0
101	1.08	0.45	81.0	52.7	615	205	541.0	512.7
102	1.08	0.48	81.0	54.1	615	205	541.0	514.1
103	1.03	0.53	78.8	56.4	615	205	538.8	516.4
104	1.02	0.56	78.4	57.8	615	205	538.4	517.8

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o °F abs	T_f °F abs
105	1.04	0.65	79.2	61.8	615	205	539.2	521.8
106	1.08	-0.89	81.0	-10.8	615	205	541.0	449.2
107	1.00	0.67	77.5	62.7	615	205	537.5	522.7
108	0.91	0.63	73.4	60.9	615	205	533.4	520.9
109	0.95	0.65	75.2	61.8	615	205	535.2	521.8
110	1.01	0.73	78.0	65.4	615	205	538.0	525.4
111	1.00	0.75	77.5	66.3	615	205	537.5	526.3
112	1.08	-0.73	81.0	- 2.9	615	205	541.0	457.1
113	1.09	0.10	81.4	36.7	615	205	541.4	496.7

Run	$\frac{P_o}{P_f}$	$\frac{P_o T_f}{P_f T_o}$	$\ln \frac{P_o}{P_f}$	$\ln \frac{P_o T_f}{P_f T_o}$	n
100	3.00	2.84	1.099	1.044	1.053
101	3.00	2.84	1.099	1.044	1.053
102	3.00	2.85	1.099	1.048	1.050
103	3.00	2.88	1.099	1.058	1.040
104	3.00	2.89	1.099	1.061	1.037
105	3.00	2.90	1.099	1.065	1.033
106	3.00	2.49	1.099	0.914	1.204
107	3.00	2.92	1.099	1.071	1.027
108	3.00	2.93	1.099	1.075	1.023
109	3.00	2.92	1.099	1.071	1.027
110	3.00	2.93	1.099	1.075	1.023
111	3.00	2.94	1.099	1.079	1.020
112	3.00	2.54	1.099	0.933	1.180
113	3.00	2.75	1.099	1.011	1.088

Run	t	t^2	$\pi_7 = 1539\ T_o t^2$
100	105.1	11,050	9,170,000,000
101	118.9	14,100	11,750,000,000
102	132.7	17,600	14,650,000,000
103	156.4	24,500	20,300,000,000
104	211.0	44,500	36,800,000,000
105	281.7	79,000	65,500,000,000

Run	t	t^2	$\pi_7 = 1539\ T_o t^2$
106	5.4	29	24,300,000
107	353.3	125,000	103,500,000,000
108	384.8	148,000	121,500,000,000
109	476.6	227,000	187,000,000,000
110	753.5	567,000	469,000,000,000
111	520.4	271,000	224,000,000,000
112	20.3	412	343,000,000
113	48.8	2,380	1,985,000,000

4.3 Initial pressure = 1200 psig

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o °F$_{abs}$	T_f °F$_{abs}$
114	1.10	0.76	81.9	66.8	1215	405	541.9	526.8
115	1.06	0.64	80.1	61.4	1215	405	540.1	521.4
116	1.07	0.59	80.6	59.1	1215	405	540.6	519.1
117	1.06	0.60	80.1	59.6	1215	405	540.1	519.6
118	1.06	0.48	80.1	54.1	1215	405	540.1	514.1
119	1.09	0.42	81.4	51.4	1215	405	541.4	511.4
120	1.09	0.38	81.4	49.5	1215	405	541.4	509.5
121	1.07	0.28	80.6	45.0	1215	405	540.6	505.0
122	1.07	0.19	80.6	40.9	1215	405	540.6	500.9
123	1.08	0.11	81.0	37.1	1215	405	541.0	497.1
124	1.08	-0.04	81.0	30.1	1215	405	541.0	490.1
125	1.12	-1.13	82.8	-22.8	1215	405	542.8	437.2

Run	$\frac{P_o}{P_f}$	$\frac{P_o T_f}{P_f T_o}$	$\ln \frac{P_o}{P_f}$	$\ln \frac{P_o T_f}{P_f T_o}$	n
114	3.00	2.92	1.099	1.072	1.026
115	3.00	2.90	1.099	1.065	1.033
116	3.00	2.88	1.099	1.058	1.040
117	3.00	2.88	1.099	1.058	1.040
118	3.00	2.85	1.099	1.048	1.050
119	3.00	2.83	1.099	1.040	1.058
120	3.00	2.82	1.099	1.038	1.060
121	3.00	2.80	1.099	1.030	1.068

Run	$\frac{P_o}{P_f}$	$\frac{P_o T_f}{P_f T_o}$	$\ln \frac{P_o}{P_f}$	$\ln \frac{P_o T_f}{P_f T_o}$	n
122	3.00	2.77	1.099	1.020	1.079
123	3.00	2.76	1.099	1.015	1.084
124	3.00	2.72	1.099	1.000	1.099
125	3.00	2.42	1.099	0.885	1.243

Run	t	t^2	$\pi_7 = 1539\ T_o t^2$
114	720.9	520,000	434,000,000,000
115	446.2	199,000	165,500,000,000
116	300.8	90,000	74,900,000,000
117	386.2	149,000	124,000,000,000
118	234.3	55,000	45,700,000,000
119	187.8	35,300	29,400,000,000
120	154.0	23,700	19,700,000,000
121	125.8	15,800	13,150,000,000
122	96.4	9,290	7,730,000,000
123	77.5	6,000	5,000,000,000
124	52.1	2,710	2,260,000,000
125	4.4	19	16,200,000

5. Pressure ratio of 6.50 (ratio of absolute pressures).

5.1 Initial pressure = 1200 psig

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o °F abs	T_f °F abs
128	1.15	0.70	84.0	64.1	1215	187	544.0	524.1
129	1.12	0.54	82.7	56.8	1215	187	542.7	516.8
130	1.10	0.60	81.9	59.6	1215	187	541.9	519.6
131	1.04	0.40	79.3	50.5	1215	187	539.3	510.5
132	1.02	0.45	78.4	52.7	1215	187	538.4	512.7
133	1.01	0.40	78.0	50.5	1215	187	538.0	510.5
134	1.06	0.38	80.1	49.5	1215	187	540.1	509.5
135	1.07	0.33	80.6	47.2	1215	187	540.6	507.2
136	1.09	0.26	81.4	44.0	1215	187	541.4	504.0
137	1.10	0.22	81.9	42.2	1215	187	541.9	502.2

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o °F_{abs}	T_f °F_{abs}
138	1.10	0.09	81.9	36.2	1215	187	541.9	496.2
139	1.10	-0.20	81.9	22.6	1215	187	541.9	482.6
140	1.11	-2.26	82.3	-82.6	1215	187	542.3	377.4

Run	$\frac{P_o}{P_f}$	$\frac{P_o T_f}{P_f T_o}$	$\ln \frac{P_o}{P_f}$	$\ln \frac{P_o T_f}{P_f T_o}$	n
128	6.50	6.26	1.870	1.834	1.020
129	6.50	6.19	1.870	1.823	1.026
130	6.50	6.23	1.870	1.829	1.023
131	6.50	6.16	1.870	1.818	1.029
132	6.50	6.19	1.870	1.823	1.026
133	6.50	6.17	1.870	1.820	1.028
134	6.50	6.13	1.870	1.813	1.032
135	6.50	6.10	1.870	1.808	1.035
136	6.50	6.05	1.870	1.800	1.039
137	6.50	6.02	1.870	1.795	1.042
138	6.50	5.95	1.870	1.783	1.050
139	6.50	5.79	1.870	1.756	1.066
140	6.50	4.53	1.870	1.510	1.240

Run	t	t^2	$\pi_7 = 1539\ T_o t^2$
128	869.9	758,000	634,000,000,000
129	477.0	228,000	190,500,000,000
130	583.9	340,000	283,500,000,000
131	357.8	128,000	106,200,000,000
132	456.9	209,000	173,000,000,000
133	384.1	147,500	122,000,000,000
134	309.1	95,500	79,400,000,000
135	250.8	62,900	52,300,000,000
136	214.6	46,000	38,400,000,000
137	187.2	35,000	29,200,000,000
138	132.9	17,650	14,700,000,000
139	72.8	5,300	4,420,000,000
140	6.9	48	39,600,000

5.2 Initial pressure = 600 psig

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o °F_{abs}	T_f °F_{abs}
126	0.98	0.25	76.6	43.6	615	95	536.6	503.6
127	0.98	0.59	76.6	59.1	615	95	536.6	519.1
141	1.01	0.62	78.0	60.5	615	95	538.0	520.5
142	1.04	0.68	79.3	63.2	615	95	539.3	523.2
143	1.05	0.77	79.7	67.2	615	95	539.7	527.2
144	1.06	0.74	80.1	65.8	615	95	540.1	525.8
145	1.07	0.72	80.6	65.0	615	95	540.6	525.0
146	1.09	0.56	81.4	57.8	615	95	541.4	517.8
147	1.07	0.50	80.6	55.0	615	95	540.6	515.0
148	1.09	0.34	81.4	47.7	615	95	541.4	507.7
149	1.09	0.28	81.4	45.0	615	95	541.4	505.0
150	1.11	-0.03	82.3	30.6	615	95	542.3	490.6
151	1.11	-2.14	82.3	-76.1	615	95	542.3	383.9

Run	$\frac{P_o}{P_f}$	$\frac{P_o T_f}{P_f T_o}$	$\ln \frac{P_o}{P_f}$	$\ln \frac{P_o T_f}{P_f T_o}$	n
126	6.50	6.09	1.870	1.807	1.036
127	6.50	6.28	1.870	1.837	1.019
141	6.50	6.29	1.870	1.839	1.018
142	6.50	6.30	1.870	1.841	1.017
143	6.50	6.35	1.870	1.848	1.012
144	6.50	6.33	1.870	1.845	1.014
145	6.50	6.31	1.870	1.842	1.016
146	6.50	6.21	1.870	1.826	1.025
147	6.50	6.19	1.870	1.823	1.027
148	6.50	6.09	1.870	1.807	1.036
149	6.50	6.06	1.870	1.802	1.039
150	6.50	5.89	1.870	1.773	1.055
151	6.50	4.60	1.870	1.526	1.227

Run	t	t^2	$\pi_7 = 1539\ T_o t^2$
126	128.9	16,600	13,700,000,000

Run	t	t^2	$\pi_7 = 1539\ T_o t^2$
127	408.4	166,000	137,000,000,000
141	299.2	89,900	74,400,000,000
142	357.4	127,500	106,000,000,000
143	745.4	555,000	461,000,000,000
144	595.4	355,000	295,000,000,000
145	475.8	226,000	188,000,000,000
146	227.8	51,900	43,200,000,000
147	173.5	30,100	25,100,000,000
148	127.5	16,200	13,500,000,000
149	100.8	10,150	8,460,000,000
150	54.6	2,990	2,490,000,000
151	5.4	29	24,400,000

5.3 Initial pressure = 900 psig

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o °F_{abs}	T_f °F_{abs}
152	1.08	0.74	81.0	65.8	915	141	541.0	525.8
153	1.15	0.78	84.0	67.6	915	141	544.0	527.6
154	1.13	0.75	83.2	66.3	915	141	543.2	526.3
155	1.15	0.67	84.0	62.7	915	141	544.0	522.7
156	1.16	0.69	84.9	63.6	915	141	544.9	523.6
157	1.16	0.67	84.9	62.7	915	141	544.9	522.7
158	1.16	0.61	84.9	60.0	915	141	544.9	520.0
159	1.16	0.64	84.9	61.4	915	141	544.9	521.4
160	1.17	0.51	85.1	55.5	915	141	545.1	515.5
161	1.17	0.39	85.1	50.0	915	141	545.1	510.0
162	1.17	0.25	85.1	43.6	915	141	545.1	503.6
163	1.17	-0.30	85.1	17.9	915	141	545.1	477.9
164	1.18	-2.40	85.3	-90.2	915	141	545.3	369.8

Run	$\frac{P_o}{P_f}$	$\frac{P_o T_f}{P_f T_o}$	$\ln \frac{P_o}{P_f}$	$\ln \frac{P_o T_f}{P_f T_o}$	n
152	6.50	6.32	1.870	1.844	1.013
153	6.50	6.30	1.870	1.841	1.016

Run	$\frac{P_o}{P_f}$	$\frac{P_o T_f}{P_f T_o}$	$\ln \frac{P_o}{P_f}$	$\ln \frac{P_o T_f}{P_f T_o}$	n
154	6.50	6.30	1.870	1.841	1.016
155	6.50	6.25	1.870	1.833	1.020
156	6.50	6.25	1.870	1.833	1.020
157	6.50	6.24	1.870	1.831	1.021
158	6.50	6.21	1.870	1.826	1.024
159	6.50	6.23	1.870	1.829	1.022
160	6.50	6.15	1.870	1.816	1.030
161	6.50	6.09	1.870	1.807	1.036
162	6.50	6.00	1.870	1.792	1.043
163	6.50	5.70	1.870	1.740	1.075
164	6.50	4.41	1.870	1.484	1.260

Run	t	t^2	$\pi_7 = 1539\ T_o t^2$
152	520.1	270,000	225,000,000,000
153	672.8	452,000	378,000,000,000
154	567.7	322,000	269,000,000,000
155	397.2	158,000	132,200,000,000
156	441.2	199,500	163,000,000,000
157	401.9	161,500	135,500,000,000
158	265.5	70,500	59,000,000,000
159	292.2	85,300	71,400,000,000
160	205.4	42,100	35,300,000,000
161	162.1	26,300	22,050,000,000
162	103.7	10,750	9,010,000,000
163	56.6	3,200	2,685,000,000
164	5.2	27	22,700,000

CALCULATIONS - SMALL TANK
CHARGING

6. Pressure ratio of 4.72 (ratio of absolute pressures).

6.1 Final pressure = 600 psig

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o °F abs	T_f °F abs
165	1.09	2.61	81.4	145.9	130	615	541.4	605.9
166	1.10	2.44	81.9	138.8	130	615	541.9	598.8
167	1.10	1.50	81.9	99.3	130	615	541.9	559.3
168	1.04	1.72	79.3	108.7	130	615	539.3	568.7
169	1.04	1.55	79.3	101.4	130	615	539.3	561.4
170	1.09	1.50	81.4	99.3	130	615	541.4	559.3
171	1.10	1.44	81.9	96.7	130	615	541.9	556.7
172	1.10	1.40	81.9	94.9	130	615	541.9	554.9
173	1.08	1.78	81.0	111.3	130	615	541.0	571.3
174	1.10	1.45	81.9	97.1	130	615	541.9	557.1

Run	$\frac{P_f}{P_o}$	$\frac{P_f T_o}{P_o T_f}$	$\ln \frac{P_f}{P_o}$	$\ln \frac{P_f T_o}{P_o T_f}$	n
165	4.72	4.22	1.552	1.437	1.081
166	4.72	4.27	1.552	1.452	1.069
167	4.72	4.58	1.552	1.522	1.020
168	4.72	4.48	1.552	1.500	1.035
169	4.72	4.53	1.552	1.511	1.028
170	4.72	4.57	1.552	1.520	1.021
171	4.72	4.60	1.552	1.526	1.018
172	4.72	4.61	1.552	1.528	1.016
173	4.72	4.47	1.552	1.497	1.039
174	4.72	4.59	1.552	1.524	1.019

Run	t	t^2	$\pi_7 = 1539\ T_o t^2$
165	17.2	296	247,000,000
166	18.8	354	295,000,000
167	203.0	41,200	34,400,000,000
168	89.2	7,970	6,620,000,000

Run	t	t^2	$\pi_7 = 1539\ T_o t^2$
169	162.8	26,500	22,000,000,000
170	254.9	65,000	54,200,000,000
171	301.2	90,600	75,600,000,000
172	441.6	195,000	162,800,000,000
173	87.4	7,630	6,350,000,000
174	295.2	87,000	72,600,000,000

6.2 **Final pressure = 1000 psig**

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o °F abs	T_f °F abs
175	1.10	1.48	81.9	98.4	215	1015	541.9	558.4
176	1.09	1.55	81.4	101.4	215	1015	541.4	561.4
177	1.08	1.50	81.0	99.3	215	1015	541.0	559.3
178	1.07	1.43	80.6	96.2	215	1015	540.6	556.2
179	1.05	1.42	79.7	95.8	215	1015	539.7	555.8
180	0.99	1.35	77.0	92.8	215	1015	537.0	552.8
181	0.97	1.55	76.1	101.4	215	1015	536.1	561.4
182	0.99	1.54	77.0	101.0	215	1015	537.0	561.0
183	1.00	1.45	77.5	97.1	215	1015	537.5	557.1
184	0.98	1.55	76.6	101.4	215	1015	536.6	561.4
185	1.01	1.72	78.0	108.7	215	1015	538.0	568.7
186	1.01	2.15	78.0	126.8	215	1015	538.0	586.8

Run	$\frac{P_f}{P_o}$	$\frac{P_f T_o}{P_o T_f}$	$\ln \frac{P_f}{P_o}$	$\ln \frac{P_f T_o}{P_o T_f}$	n
175	4.72	4.59	1.552	1.524	1.018
176	4.72	4.55	1.552	1.515	1.025
177	4.72	4.57	1.552	1.520	1.021
178	4.72	4.59	1.552	1.524	1.018
179	4.72	4.59	1.552	1.524	1.018
180	4.72	4.59	1.552	1.524	1.018
181	4.72	4.51	1.552	1.506	1.031
182	4.72	4.51	1.552	1.506	1.031

Run	$\frac{P_f}{P_o}$	$\frac{P_f T_o}{P_o T_f}$	$\ln \frac{P_f}{P_o}$	$\ln \frac{P_f T_o}{P_o T_f}$	n
183	4.72	4.55	1.552	1.515	1.025
184	4.72	4.51	1.552	1.506	1.031
185	4.72	4.47	1.552	1.497	1.037
186	4.72	4.33	1.552	1.466	1.060

Run	t	t^2	$\pi_7 = 1539\ T_o t^2$
175	484.9	235,000	196,000,000,000
176	313.2	98,000	81,600,000,000
177	340.1	115,500	96,200,000,000
178	630.5	397,000	330,000,000,000
179	370.2	137,000	114,000,000,000
180	447.2	200,000	165,500,000,000
181	171.1	29,300	24,200,000,000
182	170.4	29,000	24,000,000,000
183	271.4	73,600	60,900,000,000
184	161.1	26,000	21,500,000,000
185	104.4	10,900	9,030,000,000
186	37.8	1,430	1,180,000,000

7. Pressure ratio of 3.00 (ratio of absolute pressures)

7.1 Final pressure = 600 psig

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o °F_{abs}	T_f °F_{abs}
187	1.09	1.41	81.4	95.4	205	615	541.4	555.4
188	1.10	1.38	81.9	94.1	205	615	541.9	554.1
189	1.09	1.33	81.4	91.9	205	615	541.4	551.9
190	1.08	1.28	81.0	89.7	205	615	541.0	549.7
191	1.10	1.26	81.9	88.8	205	615	541.9	548.8
192	1.05	1.35	79.7	92.8	205	615	539.7	552.8
193	1.07	1.50	80.6	99.3	205	615	540.6	559.3
194	1.07	1.44	80.6	96.7	205	615	540.6	556.7
195	1.07	1.68	80.6	107.0	205	615	540.6	567.0
196	1.07	1.65	80.6	105.7	205	615	540.6	565.7

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o °F abs	T_f °F abs
197	1.08	1.89	81.0	115.8	205	615	541.0	575.8
198	1.08	2.25	81.0	131.0	205	615	541.0	591.0

Run	$\frac{P_f}{P_o}$	$\frac{P_f T_o}{P_o T_f}$	$\ln \frac{P_f}{P_o}$	$\ln \frac{P_f T_o}{P_o T_f}$	n
187	3.00	2.92	1.099	1.072	1.025
188	3.00	2.94	1.099	1.078	1.020
189	3.00	2.94	1.099	1.078	1.020
190	3.00	2.95	1.099	1.082	1.015
191	3.00	2.96	1.099	1.082	1.015
192	3.00	2.93	1.099	1.075	1.022
193	3.00	2.90	1.099	1.065	1.032
194	3.00	2.92	1.099	1.072	1.025
195	3.00	2.86	1.099	1.051	1.045
196	3.00	2.87	1.099	1.054	1.042
197	3.00	2.82	1.099	1.037	1.061
198	3.00	2.75	1.099	1.012	1.086

Run	t	t^2	$\pi_7 = 1539\ T_o t^2$
187	255.3	65,000	54,100,000,000
188	347.8	121,000	101,000,000,000
189	423.2	179,000	149,000,000,000
190	688.8	474,000	394,000,000,000
191	552.5	305,000	254,000,000,000
192	325.0	105,500	87,500,000,000
193	186.3	34,700	28,900,000,000
194	214.4	46,000	38,300,000,000
195	96.6	9,330	7,760,000,000
196	110.0	12,100	10,100,000,000
197	50.4	2,540	2,115,000,000
198	23.6	558	465,000,000

7.2 Final pressure = 1200 psig

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o °F abs	T_f °F abs
199	1.10	1.50	81.9	99.3	405	1215	541.9	559.3
200	1.06	1.45	80.1	97.1	405	1215	540.1	557.1
201	1.01	1.36	78.0	93.2	405	1215	538.0	553.2
202	1.01	1.44	78.0	96.7	405	1215	538.0	556.7
203	1.00	1.39	77.5	94.6	405	1215	537.5	554.6
204	0.99	1.31	77.0	91.0	405	1215	538.0	553.2
205	0.96	1.60	75.7	103.6	405	1215	535.7	563.6
206	0.97	1.55	76.1	101.4	405	1215	536.1	561.4
207	0.97	1.50	76.1	99.3	405	1215	536.1	559.3
208	0.98	1.80	76.6	112.1	405	1215	536.6	572.1
209	0.99	1.96	77.0	118.8	405	1215	537.0	578.8
210	1.00	2.65	77.5	147.5	405	1215	537.5	607.5

Run	$\frac{P_f}{P_o}$	$\frac{P_f T_o}{P_o T_f}$	$\ln \frac{P_f}{P_o}$	$\ln \frac{P_f T_o}{P_o T_f}$	n
199	3.00	2.91	1.099	1.068	1.030
200	3.00	2.91	1.099	1.068	1.030
201	3.00	2.92	1.099	1.072	1.025
202	3.00	2.90	1.099	1.065	1.032
203	3.00	2.91	1.099	1.068	1.030
204	3.00	2.92	1.099	1.072	1.025
205	3.00	2.86	1.099	1.051	1.046
206	3.00	2.86	1.099	1.051	1.046
207	3.00	2.88	1.099	1.058	1.039
208	3.00	2.81	1.099	1.033	1.063
209	3.00	2.78	1.099	1.022	1.074
210	3.00	2.65	1.099	0.975	1.128

Run	t	t^2	$\pi_7 = 1539\ T_o t^2$
199	314.0	98,600	82,300,000,000
200	386.6	149,500	124,000,000,000
201	516.6	267,000	221,000,000,000

Run	t	t^2	$\pi_7 = 1539\ T_o t^2$
202	314.2	98,700	81,600,000,000
203	455.3	207,000	171,000,000,000
204	637.6	335,000	335,000,000,000
205	142.4	20,300	16,700,000,000
206	107.2	29,000	23,900,000,000
207	223.4	49,900	41,200,000,000
208	85.7	7,350	6,060,000,000
209	63.0	3,960	3,270,000,000
210	13.9	193	193,000,000

8. Pressure ratio of 6.50 (ratio of absolute pressures).

8.1 Final pressure = 1200 psig

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o °F abs	T_f °F abs
211	1.00	1.44	77.5	96.7	187	1215	537.5	556.7
212	1.00	1.37	77.5	93.6	187	1215	537.5	553.6
213	0.98	1.49	76.6	98.8	187	1215	536.6	558.8
214	0.98	1.45	76.6	97.1	187	1215	536.6	557.1
215	0.98	1.39	76.6	94.5	187	1215	536.6	554.5
216	0.95	1.70	75.2	107.9	187	1215	535.2	567.9
217	1.00	1.68	77.5	107.0	187	1215	537.5	567.0
218	0.96	1.63	75.7	104.9	187	1215	535.7	564.9
219	0.95	1.48	75.2	98.4	187	1215	535.2	558.4
220	0.94	1.50	74.8	99.3	187	1215	534.8	559.3
221	0.91	1.77	73.4	110.9	187	1215	533.4	570.9
222	0.97	1.90	76.1	116.3	187	1215	536.1	576.3
223	0.95	2.02	75.2	121.3	187	1215	525.2	581.3
224	1.00	2.36	77.5	135.5	187	1215	537.5	595.5

Run	$\frac{P_f}{P_o}$	$\frac{P_f T_o}{P_o T_f}$	$\ln \frac{P_f}{P_o}$	$\ln \frac{P_f T_o}{P_o T_f}$	n
211	6.50	6.27	1.872	1.836	1.019
212	6.50	6.31	1.872	1.842	1.016
213	6.50	6.25	1.872	1.833	1.021

Run	$\frac{P_f}{P_o}$	$\frac{P_f T_o}{P_o T_f}$	$\ln \frac{P_f}{P_o}$	$\ln \frac{P_f T_o}{P_o T_f}$	n
214	6.50	6.26	1.872	1.834	1.020
215	6.50	6.29	1.872	1.839	1.018
216	6.50	6.13	1.872	1.813	1.032
217	6.50	6.16	1.872	1.818	1.030
218	6.50	6.17	1.872	1.820	1.028
219	6.50	6.24	1.872	1.831	1.022
220	6.50	6.22	1.872	1.828	1.023
221	6.50	6.06	1.872	1.802	1.039
222	6.50	6.05	1.872	1.800	1.040
223	6.50	5.99	1.872	1.790	1.046
224	6.50	5.86	1.872	1.768	1.059

Run	t	t^2	$\pi_7 = 1539\ T_o t^2$
211	506.1	256,000	212,000,000,000
212	804.0	647,000	535,000,000,000
213	406.8	165,000	136,000,000,000
214	453.0	205,000	169,000,000,000
215	650.5	424,000	350,000,000,000
216	162.5	26,400	21,700,000,000
217	178.8	32,000	26,500,000,000
218	207.8	43,200	35,600,000,000
219	310.1	96,000	79,100,000,000
220	242.3	58,800	48,400,000,000
221	110.6	12,200	10,000,000,000
222	84.0	7,060	5 ,830,000,000
223	65.6	4,300	3,540,000,000
224	32.2	1,000	860,000,000

8.2 Final pressure = 600 psig

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o °F abs	T_f °F abs
225	0.99	1.42	77.0	95.8	95	615	537.0	555.8
226	0.99	1.32	77.0	91.4	95	615	537.0	551.4
227	0.97	1.43	76.1	96.2	95	615	536.1	556.2

Run	T_o mv	T_f mv	T_o °F	T_f °F	P_o psia	P_f psia	T_o °F$_{abs}$	T_f °F$_{abs}$
228	0.96	1.30	75.7	90.6	95	615	535.7	550.6
229	0.93	1.23	74.3	87.5	95	615	534.3	547.5
230	0.92	1.16	73.9	84.5	95	615	533.9	544.5
231	0.95	1.22	75.2	87.1	95	615	535.2	547.1
232	0.95	1.22	75.2	87.1	95	615	535.2	547.1
233	0.96	1.18	75.7	85.3	95	615	535.7	545.3
234	0.91	1.24	73.4	88.0	95	615	533.4	548.0
235	0.91	2.00	73.4	120.5	95	615	533.4	580.5
236	0.92	1.93	73.9	117.5	95	615	533.9	577.5
237	1.03	1.85	78.8	114.2	95	615	538.8	574.2
238	1.06	1.56	80.1	101.8	95	615	540.1	561.8
239	1.06	1.66	80.1	106.2	95	615	540.1	566.2
240	1.10	2.26	81.9	131.4	95	615	541.9	591.4

Run	$\frac{P_f}{P_o}$	$\frac{P_f T_o}{P_o T_f}$	$\ln \frac{P_f}{P_o}$	$\ln \frac{P_f T_o}{P_o T_f}$	n
225	6.50	6.28	1.872	1.837	1.020
226	6.50	6.33	1.872	1.845	1.014
227	6.50	6.26	1.872	1.834	1.019
228	6.50	6.33	1.872	1.845	1.014
229	6.50	6.34	1.872	1.874	1.013
230	6.50	6.36	1.872	1.850	1.012
231	6.50	6.36	1.872	1.850	1.012
232	6.50	6.36	1.872	1.850	1.012
233	6.50	6.39	1.872	1.855	1.010
234	6.50	6.32	1.872	1.844	1.015
235	6.50	5.96	1.872	1.785	1.049
236	6.50	6.00	1.872	1.792	1.044
237	6.50	6.10	1.827	1.808	1.036
238	6.50	6.25	1.872	1.833	1.021
239	6.50	6.20	1.872	1.825	1.026
240	6.50	5.95	1.872	1.783	1.050

Run	t	t^2	$\pi_7 = 1539\ T \cdot t^2$
225	223.9	50,000	41,300,000,000
226	344.4	119,000	98,300,000,000
227	241.8	58,500	48,300,000,000
228	290.3	84,000	69,300,000,000
229	378.6	143,000	117,500,000,000
230	586.4	344,000	282,000,000,000
231	377.3	142,000	117,000,000,000
232	416.6	174,000	143,000,000,000
233	582.6	340,000	280,000,000,000
234	359.1	129,000	106,000,000,000
235	43.5	1,890	1,550,000,000
236	49.6	2,460	2,020,000,000
237	84.1	7,080	5,860,000,000
238	168.4	28,400	23,600,000,000
239	120.6	14,500	12,050,000,000
240	31.5	990	825,000,000

Calculation of the overall coefficient of heat transfer.

Assumptions: On slow runs (any run over three minutes) the temperature of the air in the tank and of the wall of the tank reach a steady state soon after the start of the run and remain at or near these temperatures for the remainder of the run.

Assume that there is enough mixing inside the tank for the thermocouple reading to be a true average reading of the temperature inside the tank.

Assume: $T_s = T_{\text{ambient air}} - T_{\text{wall steady state}}$

$= T_{\text{steady state room temp.}} - T_{\text{average wall during run}}$

$= T_o - T_{\text{wall av.}}$

$T_U = T_{\text{ambient air}} - T_{\text{steady state inside tank during run}}$

$= T_o - T_f$

Heat flow from ambient air to wall of tank:

$$q_s = h_s A_t T_s$$

Heat flow from ambient air to air inside tank:

$$q_U = U A_t T_U$$

For steady state heat flow q_s must $= q_U$

Therefore: $h_s A_t T_s = U A_t T_U$

$$U = h_s \frac{T_s}{T_U}$$

From Heat Transmission by McAdams, page 241, eq. 18)

$$h_s = 0.27 \left(\frac{T_s}{D_o}\right)^{0.25} \qquad D_o = \text{diam. in feet}$$

Calculation of U for the Large Tank:

$$D_o = \frac{\text{Circumference}}{\pi} = \frac{29.5}{12 \times \pi} = 0.793 \text{ foot}$$

Run	T_o °F	T_f °F	$4T_1$ mv	$4T_2$ mv	$4T_3$ mv	T_1 mv	T_2 mv	T_3 mv
1	77.4	32.0	2.36	2.56	2.85	0.590	0.640	0.713
9	77.0	53.5	2.72	2.93	3.18	0.680	0.733	0.795
21	75.2	52.7	2.39	2.67	2.87	0.598	0.668	0.718
26	76.7	43.9	2.72	3.15	3.44	0.680	0.788	0.860

$$T_{\text{wall av.}} = T_w = \frac{T_1 + T_2 + T_3}{3}$$

Run	T_1 °F	T_2 °F	T_3 °F	$3T_w$ °F	T_w °F	T_s °F	T_U °F	$\frac{T_s}{T_U}$
1	59.1	61.4	64.6	185.1	61.7	15.7	45.4	0.346
9	63.2	65.5	68.3	197.0	65.7	11.3	23.5	0.481
21	59.5	62.6	64.9	187.0	62.4	12.8	22.5	0.569
26	63.2	68.0	71.2	202.4	67.5	9.2	32.9	0.280

Run	$\frac{T_s}{0.793}$	$\left(\frac{T_s}{0.793}\right)^{0.25}$	h BTU/hr ft²	U °F
1	19.8	2.11	0.570	0.197
9	14.3	1.94	0.524	0.252
21	16.2	2.01	0.543	0.309
26	11.6	1.85	0.500	0.140

Calculation of U for the Small Tank:

$$D_o = \frac{\text{Circumference}}{\pi} = \frac{14.5}{12 \times \pi} = 0.385 \text{ foot}$$

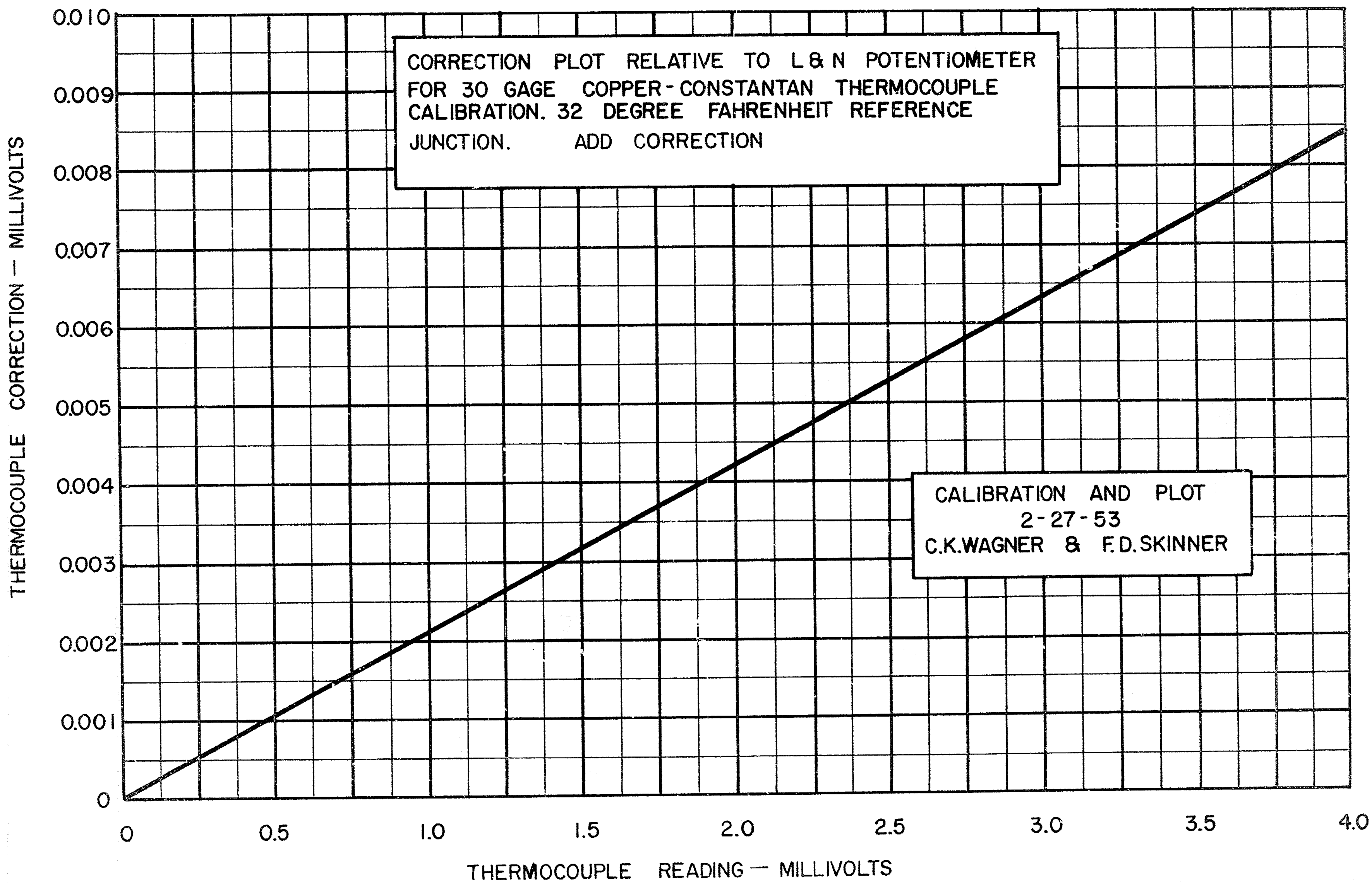
$$T_{\text{wall av.}} = T_w = \frac{T_1 + T_2}{2}$$

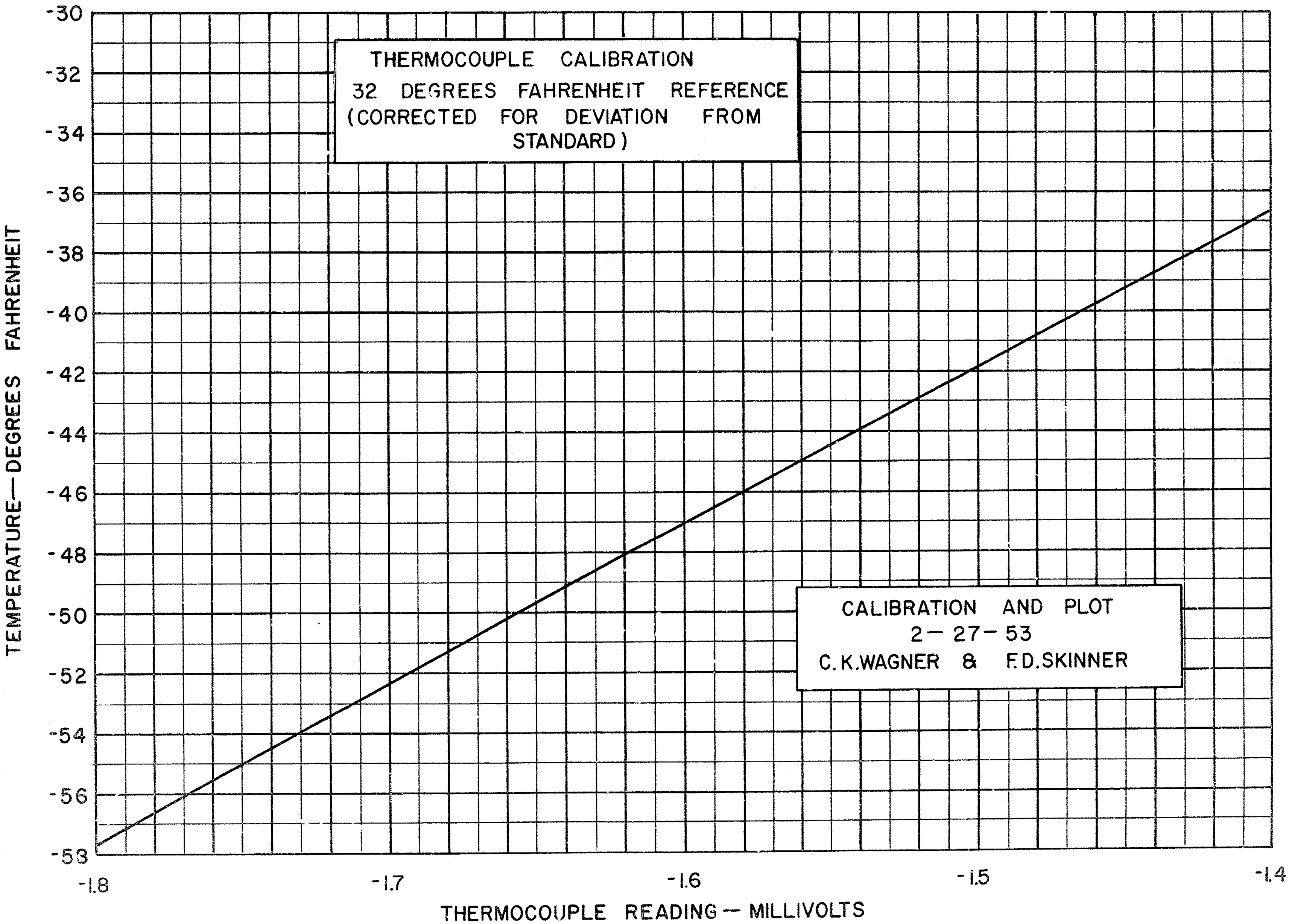
Run	T_o °F	T_f °F	$4T_1$ mv	$4T_2$ mv	T_1 mv	T_2 mv	T_1 °F	T_2 °F
33	80.6	59.1	3.12	3.58	0.780	0.895	67.6	72.8
53	78.4	60.9	3.00	3.34	0.750	0.835	66.3	70.1
49	82.3	58.7	3.06	3.55	0.765	0.888	67.0	72.5
79	74.8	65.8	3.30	3.52	0.825	0.880	69.7	72.2
72	79.7	65.0	3.42	3.97	0.855	0.992	71.0	77.1
145	80.6	65.0	3.44	3.78	0.860	0.945	71.2	75.0
153	84.0	67.6	3.34	3.61	0.835	0.903	70.1	73.2
90	79.7	61.4	3.24	3.68	0.810	0.920	69.0	73.9
129	82.7	56.8	3.09	3.44	0.773	0.860	67.3	71.2
114	81.9	66.8	3.40	3.57	0.850	0.893	70.8	72.7
109	75.2	61.8	3.12	3.45	0.780	0.863	67.6	71.4

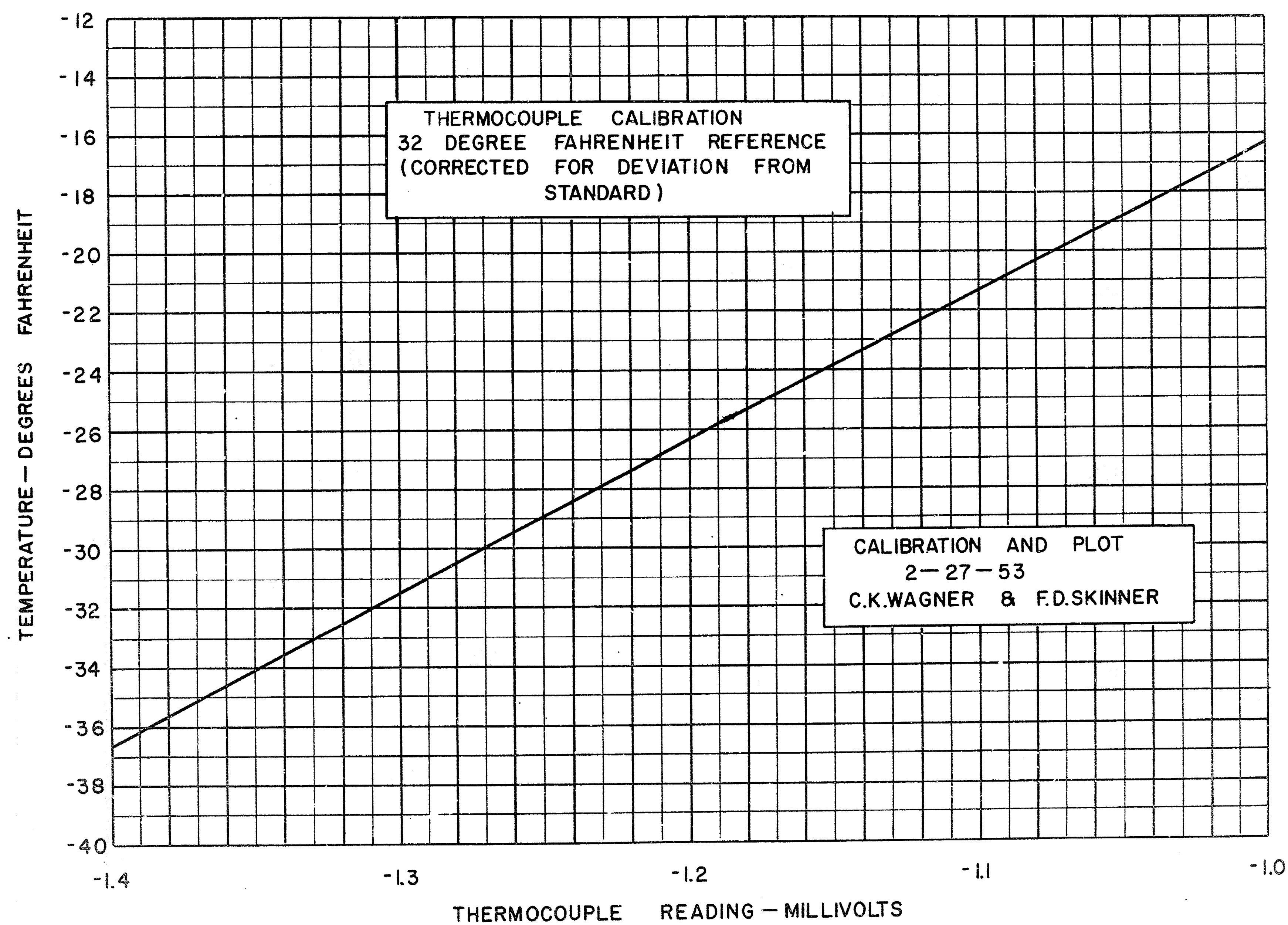
Run	$2T_W$ °F	T_W °F	T_s °F	T_U mv	$\frac{T_s}{T_U}$	$\frac{T_s}{0.385}$	$(\frac{T_s}{0.385})^{0.25}$
33	140.4	70.2	10.4	21.5	0.484	27.0	2.28
53	136.4	68.2	10.2	17.5	0.583	26.5	2.27
49	139.5	69.8	12.5	23.6	0.530	32.5	2.39
79	141.9	71.0	3.8	9.0	0.423	9.9	1.77
72	148.1	74.0	5.7	14.7	0.388	14.8	1.96
145	146.2	73.1	7.5	15.6	0.481	19.5	2.10
153	143.3	71.7	12.3	16.4	0.750	32.0	2.38
90	142.9	71.5	8.2	18.3	0.448	21.3	2.15
129	138.5	69.3	13.4	25.9	0.518	34.8	2.43
114	143.5	71.8	10.1	15.1	0.669	26.3	2.27
109	139.0	69.5	5.7	13.4	0.425	14.8	1.96

Run	h BTU/hr ft^2 °F	U	Run	h BTU/hr ft^2 °F	U
33	0.615	0.297	153	0.643	0.482
53	0.612	0.357	90	0.580	0.260
49	0.645	0.342	129	0.655	0.339
79	0.478	0.202	114	0.613	0.410
72	0.529	0.205	109	0.529	0.225
145	0.567	0.273			

APPENDIX III


CORRECTION PLOT RELATIVE TO L & N POTENTIOMETER FOR 30 GAGE COPPER-CONSTANTAN THERMOCOUPLE CALIBRATION. 32 DEGREE FAHRENHEIT REFERENCE JUNCTION. ADD CORRECTION
CALIBRATION AND PLOT
2-27-53
C.K.WAGNER & F.D.SKINNER
THERMOCOUPLE CORRECTION — MILLIVOLTS
0.010
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
THERMOCOUPLE READING — MILLIVOLTS


THERMOCOUPLE CALIBRATION
32 DEGREES FAHRENHEIT REFERENCE
(CORRECTED FOR DEVIATION FROM STANDARD)
CALIBRATION AND PLOT
2-27-53
C.K.WAGNER & F.D.SKINNER
TEMPERATURE—DEGREES FAHRENHEIT
-30
-32
-34
-36
-38
-40
-42
-44
-46
-48
-50
-52
-54
-56
-58
-1.8
-1.7
-1.6
-1.5
-1.4
THERMOCOUPLE READING—MILLIVOLTS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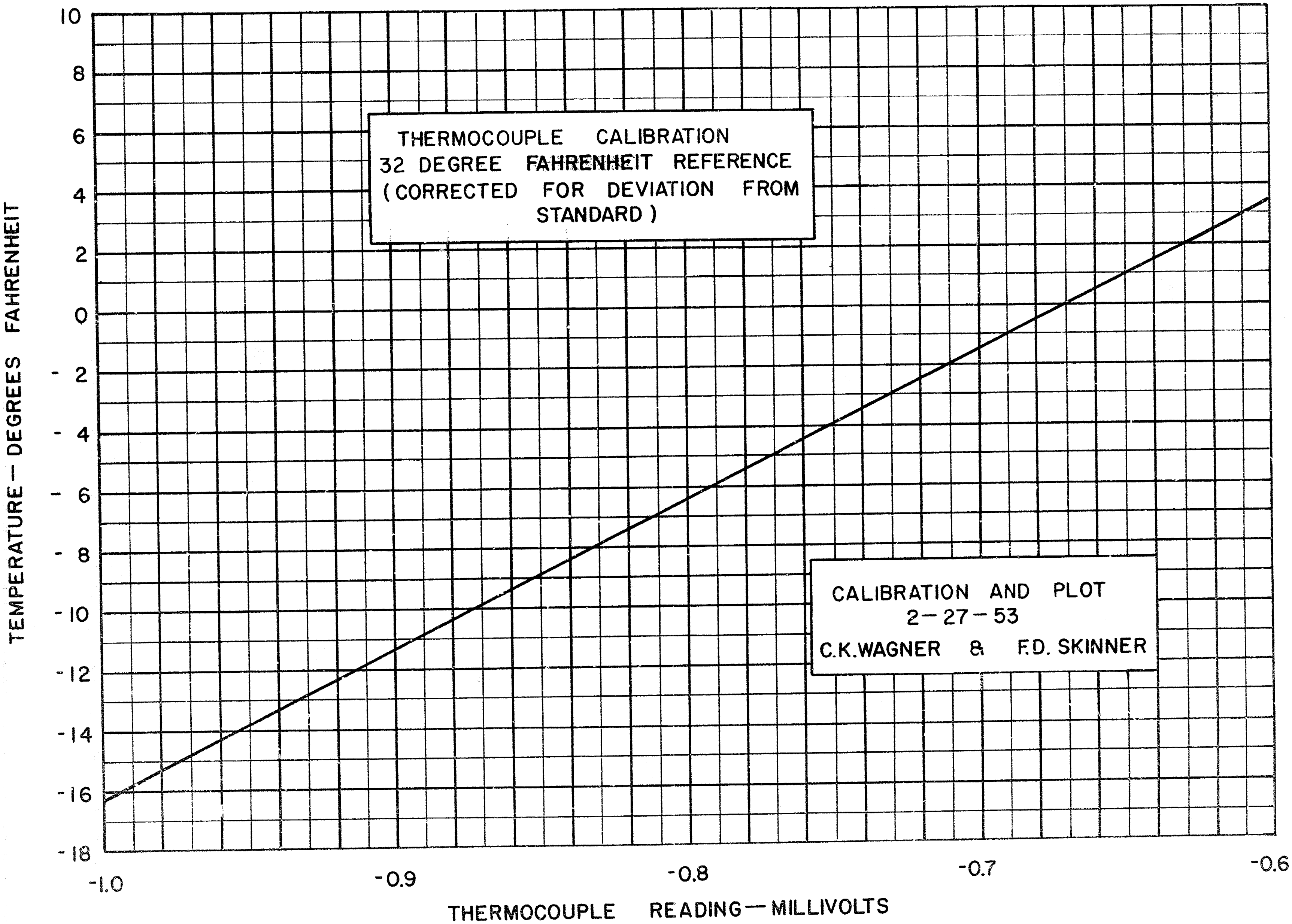
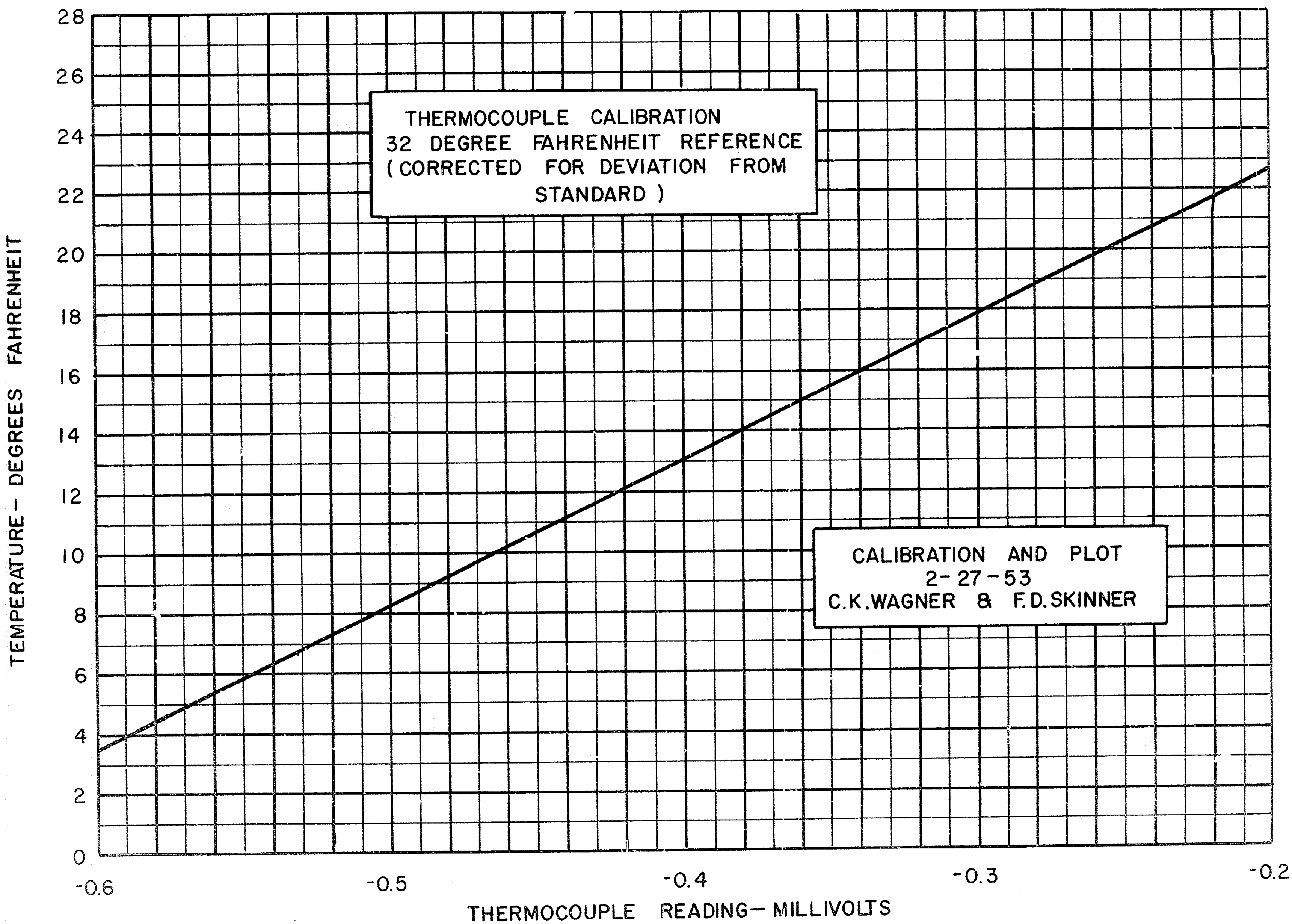
(CORRECTED FOR DEVIATION FROM
STANDARD)
CALIBRATION AND PLOT
2—27—53
C.K.WAGNER & F.D.SKINNER
TEMPERATURE — DEGREES FAHRENHEIT
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
-32
-34
-36
-38
-40
-1.4
-1.3
-1.2
-1.1
-1.0
THERMOCOUPLE READING — MILLIVOLTS


THERMOCOUPLE CALIBRATION
32 DEGREE FAHRENHEIT REFERENCE
(CORRECTED FOR DEVIATION FROM STANDARD)
CALIBRATION AND PLOT
2-27-53
C.K.WAGNER & F.D. SKINNER
TEMPERATURE — DEGREES FAHRENHEIT
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-1.0
-0.9
-0.8
-0.7
-0.6
THERMOCOUPLE READING — MILLIVOLTS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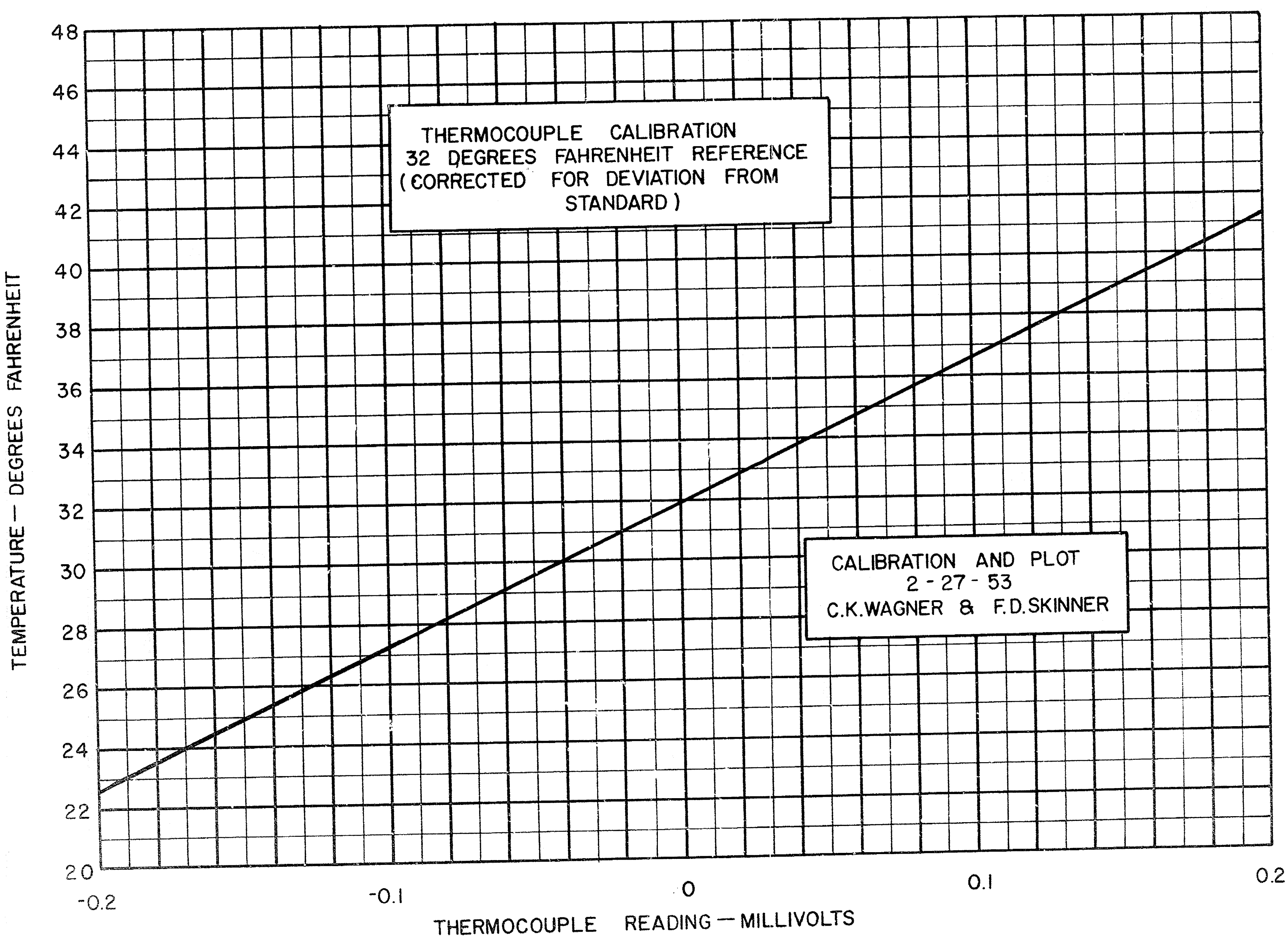
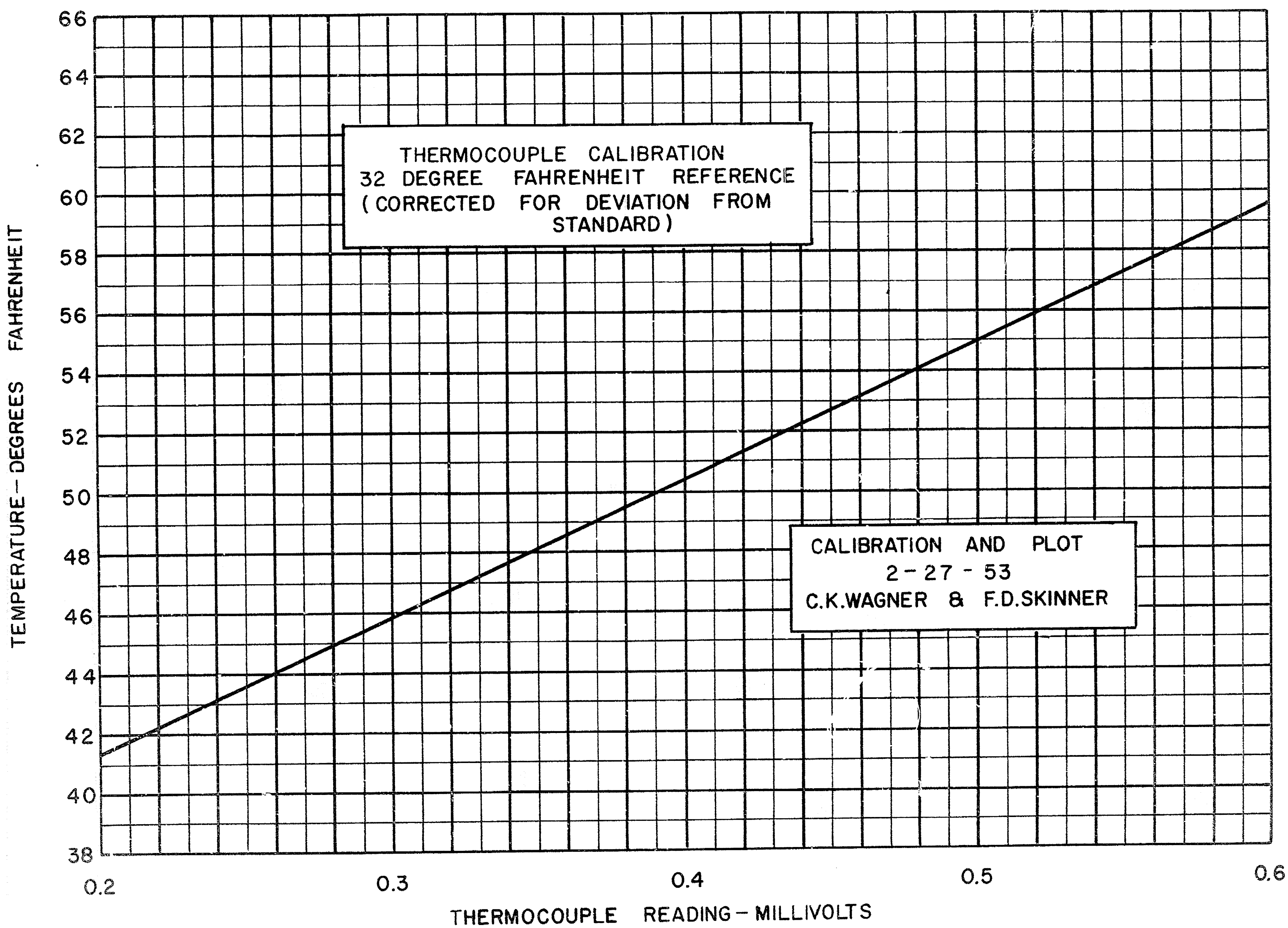
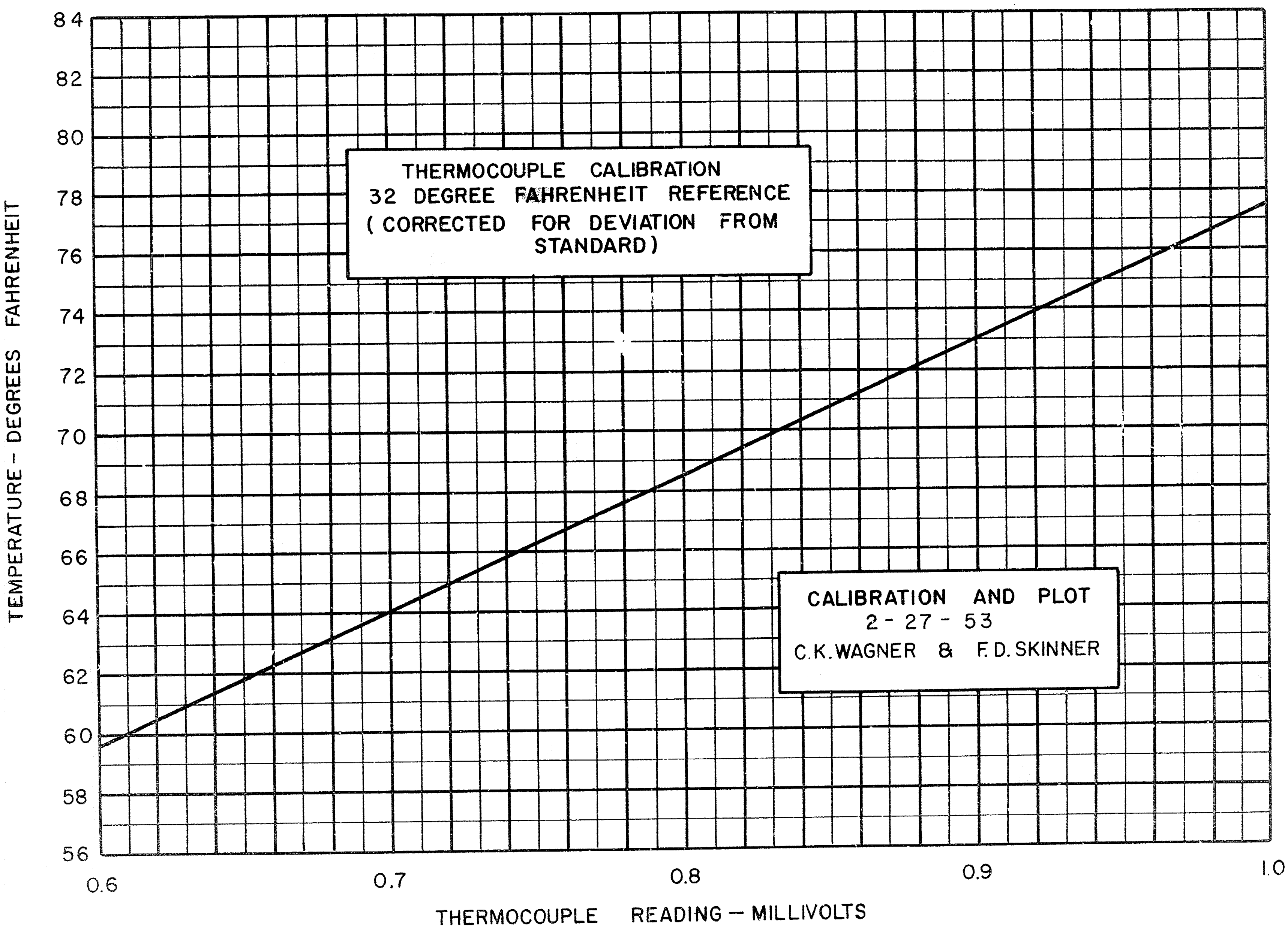
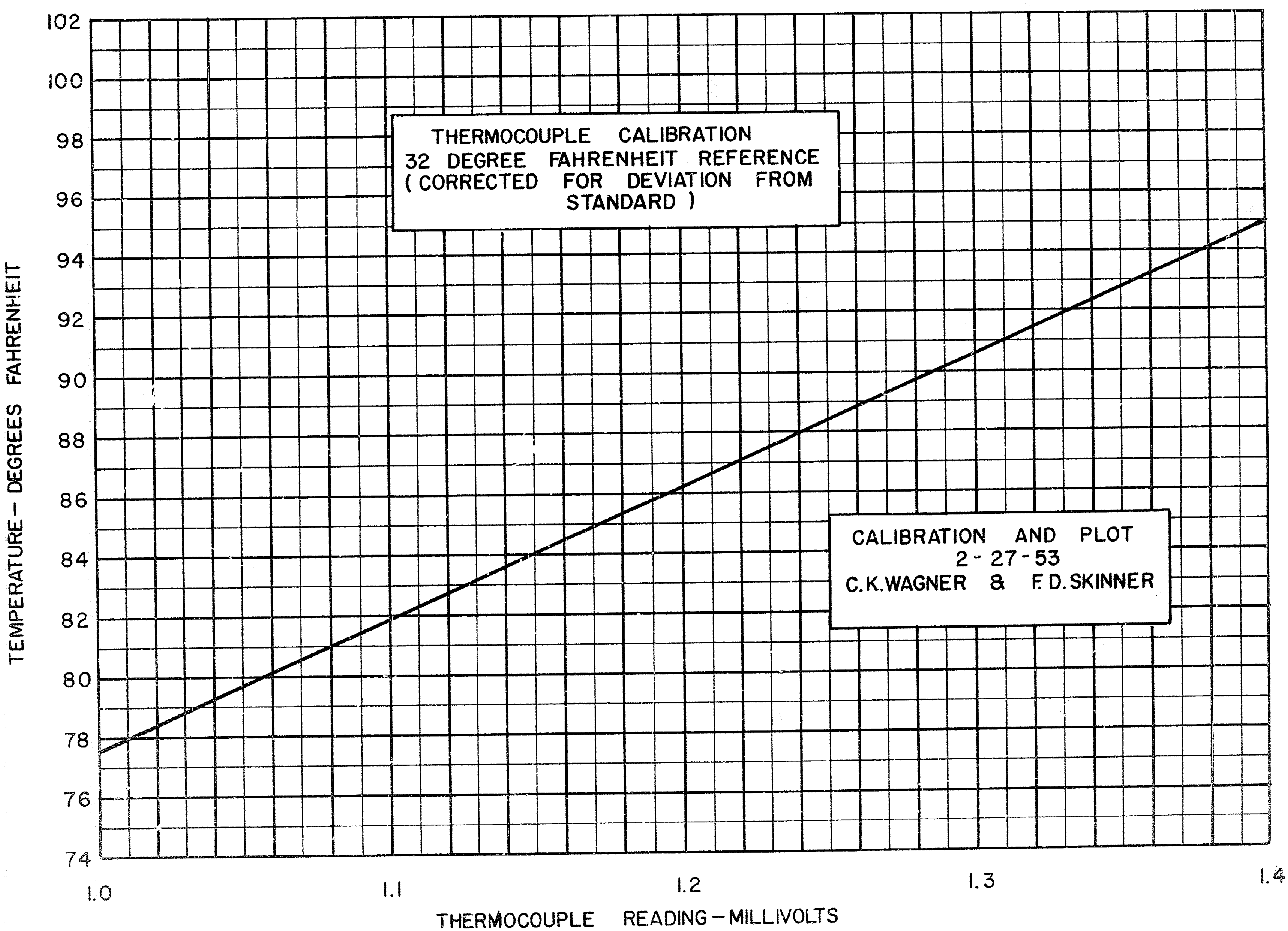
32 DEGREE FAHRENHEIT REFERENCE
(CORRECTED FOR DEVIATION FROM STANDARD)
CALIBRATION AND PLOT
2-27-53
C.K.WAGNER & F.D.SKINNER
TEMPERATURE - DEGREES FAHRENHEIT
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
-0.6
-0.5
-0.4
-0.3
-0.2
THERMOCOUPLE READING - MILLIVOLTS


THERMOCOUPLE CALIBRATION
32 DEGREES FAHRENHEIT REFERENCE
(CORRECTED FOR DEVIATION FROM STANDARD)
CALIBRATION AND PLOT
2 - 27 - 53
C.K.WAGNER & F.D.SKINNER
TEMPERATURE — DEGREES FAHRENHEIT
48
46
44
42
40
38
36
34
32
30
28
26
24
22
20
-0.2
-0.1
0
0.1
0.2
THERMOCOUPLE READING — MILLIVOLTS

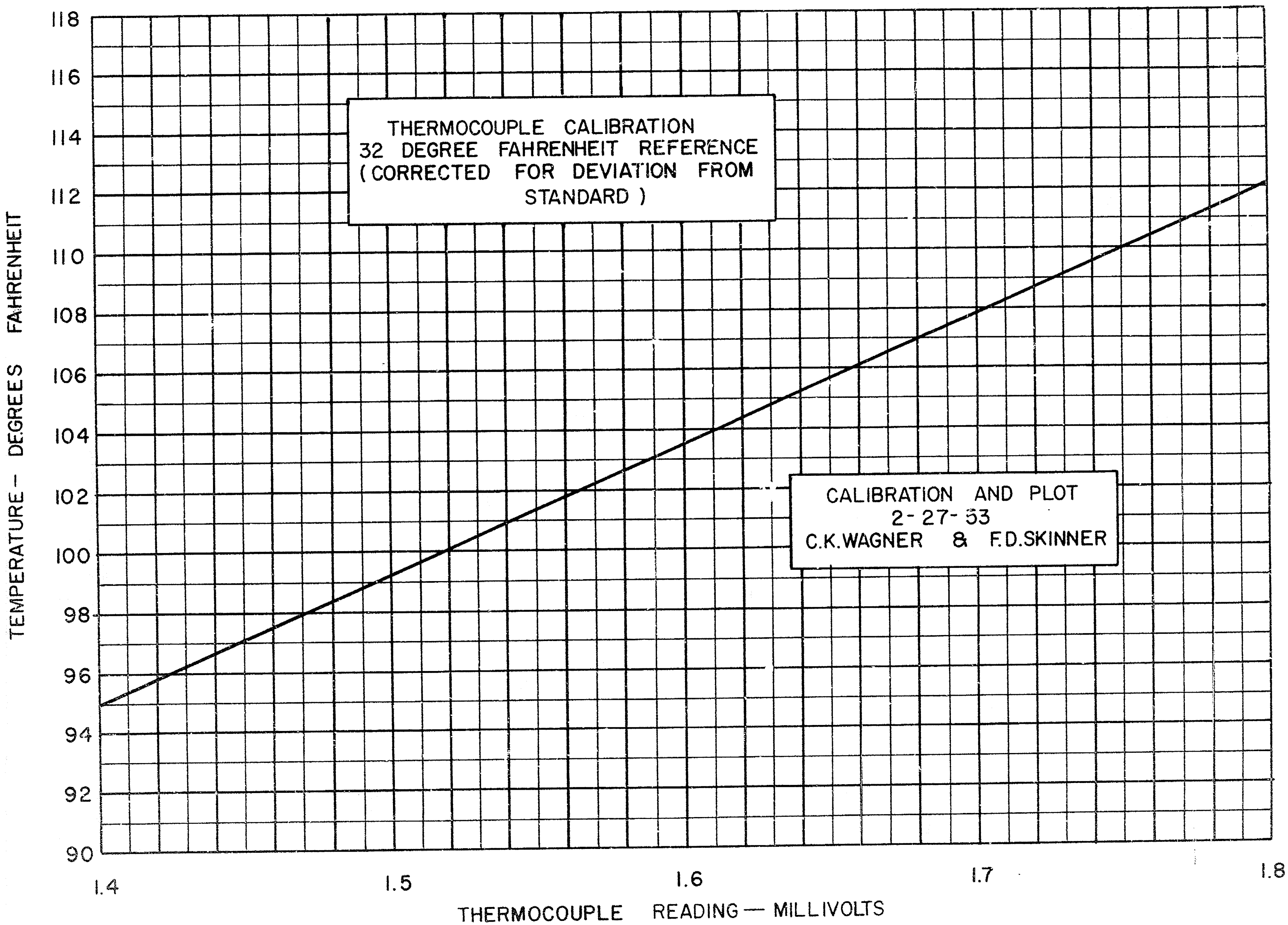


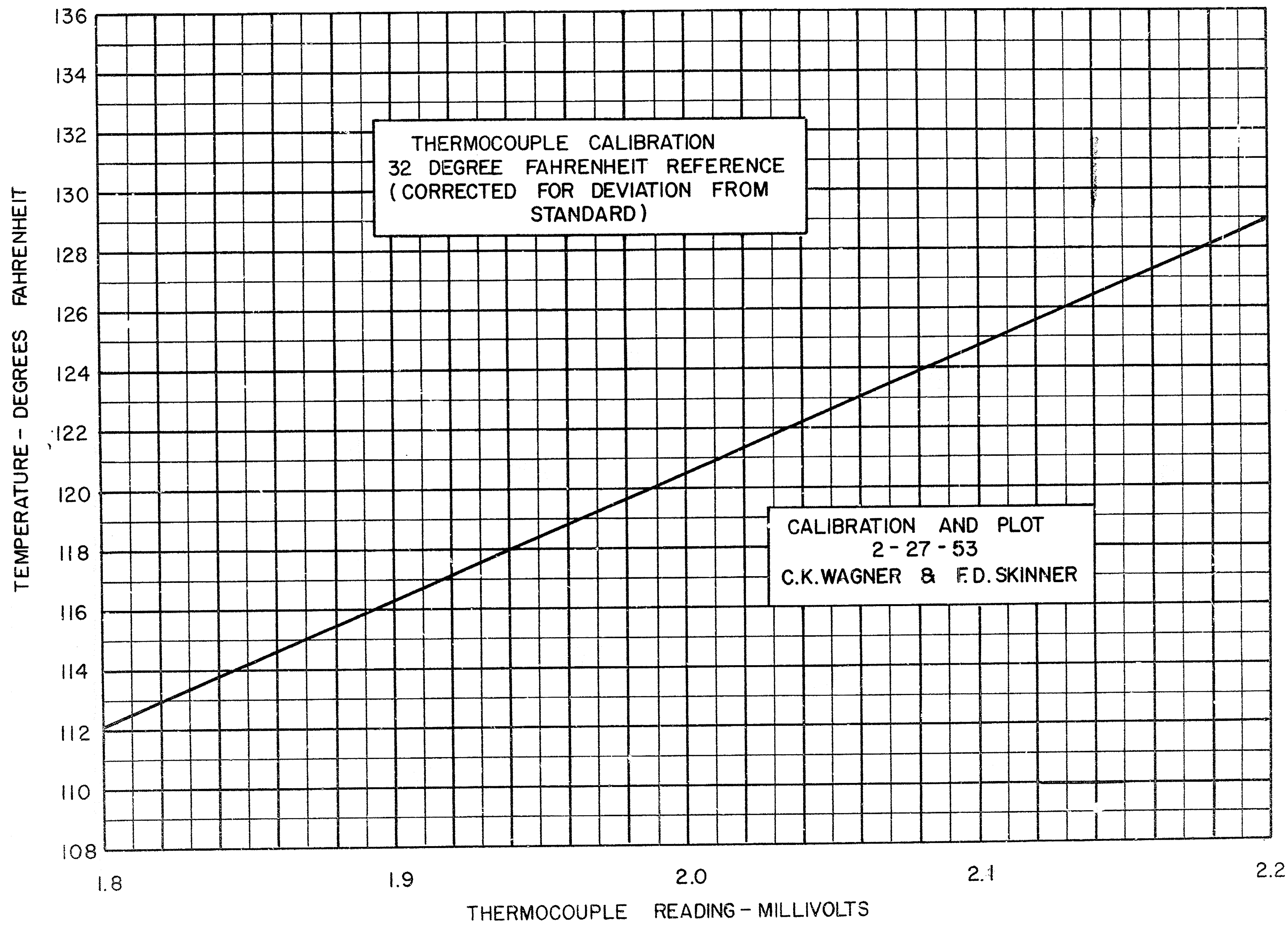
THERMOCOUPLE CALIBRATION
32 DEGREE FAHRENHEIT REFERENCE
(CORRECTED FOR DEVIATION FROM STANDARD)
CALIBRATION AND PLOT
2-27-53
C.K.WAGNER & F.D.SKINNER
TEMPERATURE - DEGREES FAHRENHEIT
THERMOCOUPLE READING - MILLIVOLTS
66
64
62
60
58
56
54
52
50
48
46
44
42
40
38
0.2
0.3
0.4
0.5
0.6

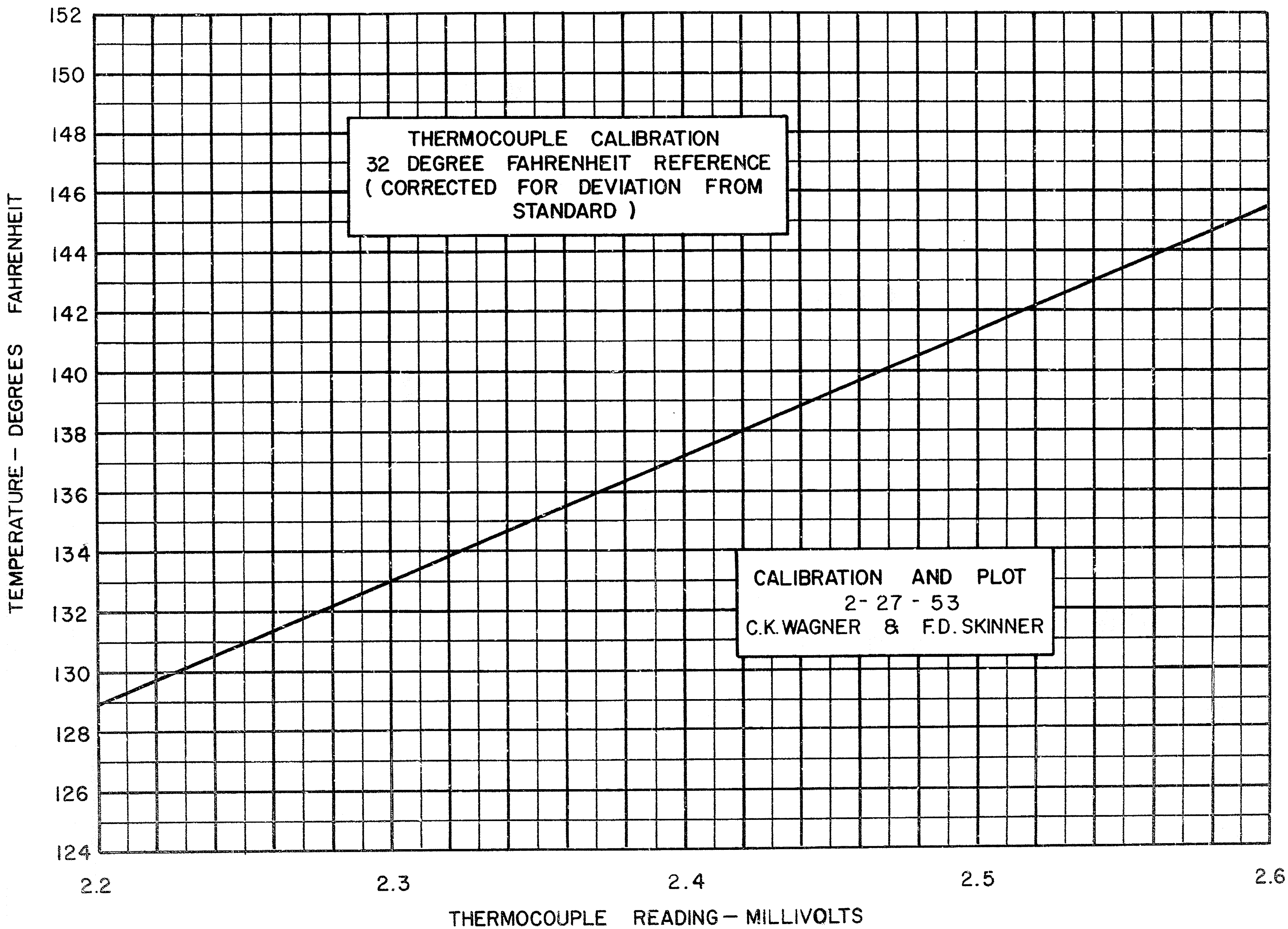

THERMOCOUPLE CALIBRATION
32 DEGREE FAHRENHEIT REFERENCE
(CORRECTED FOR DEVIATION FROM STANDARD)
CALIBRATION AND PLOT
2 - 27 - 53
C.K. WAGNER & F.D. SKINNER
84
82
80
78
76
74
72
70
68
66
64
62
60
58
56
TEMPERATURE - DEGREES FAHRENHEIT
0.6
0.7
0.8
0.9
1.0
THERMOCOUPLE READING — MILLIVOLTS

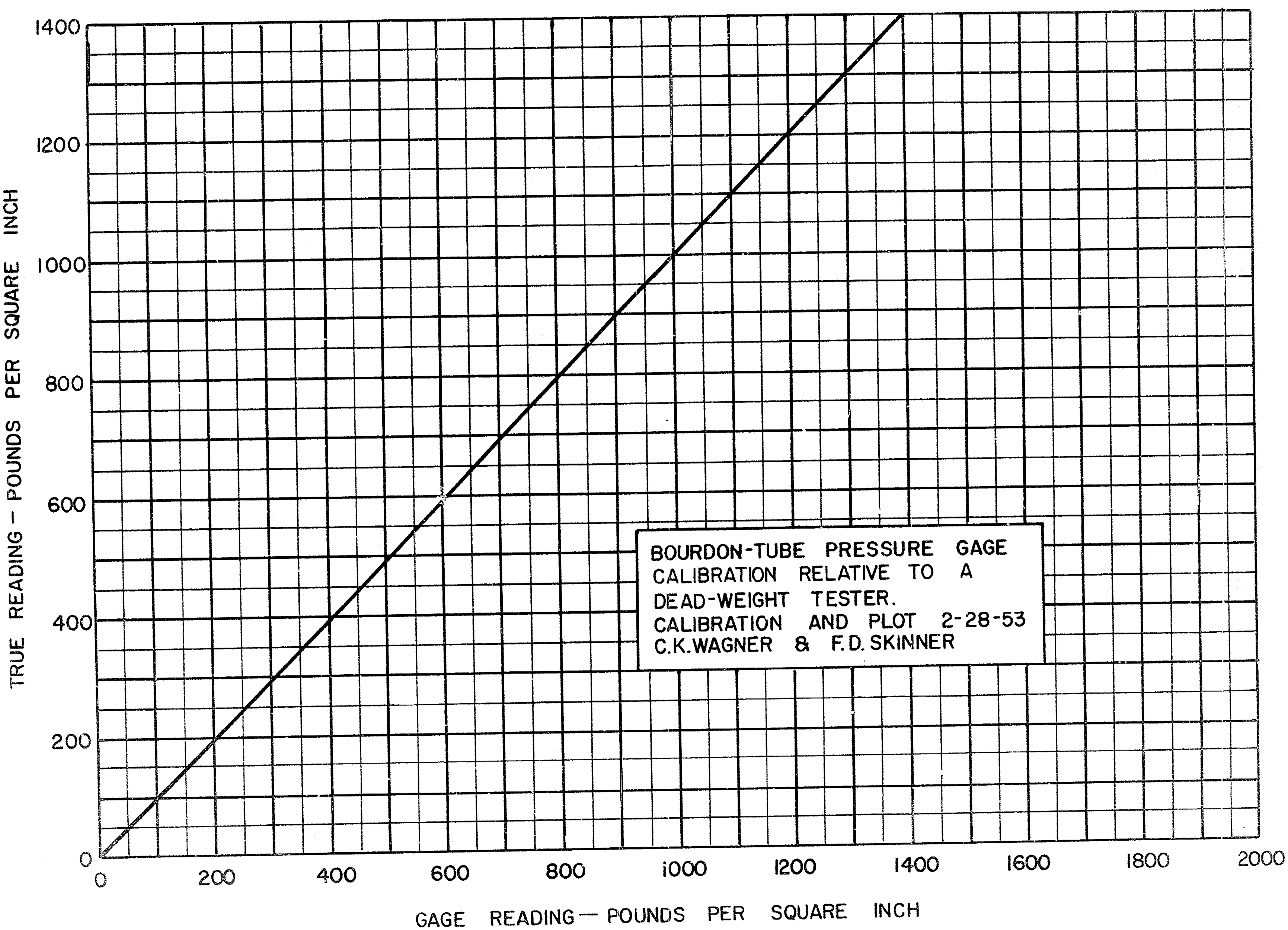


THERMOCOUPLE CALIBRATION
32 DEGREE FAHRENHEIT REFERENCE
(CORRECTED FOR DEVIATION FROM STANDARD)
CALIBRATION AND PLOT
2-27-53
C.K.WAGNER & F.D.SKINNER
102
100
98
96
94
92
90
88
86
84
82
80
78
76
74
TEMPERATURE - DEGREES FAHRENHEIT
1.0
1.1
1.2
1.3
1.4
THERMOCOUPLE READING - MILLIVOLTS


THERMOCOUPLE CALIBRATION
32 DEGREE FAHRENHEIT REFERENCE
(CORRECTED FOR DEVIATION FROM STANDARD)
CALIBRATION AND PLOT
2-27-53
C.K.WAGNER & F.D.SKINNER
TEMPERATURE - DEGREES FAHRENHEIT
118
116
114
112
110
108
106
104
102
100
98
96
94
92
90
1.4
1.5
1.6
1.7
1.8
THERMOCOUPLE READING — MILLIVOLTS


THERMOCOUPLE CALIBRATION
32 DEGREE FAHRENHEIT REFERENCE
(CORRECTED FOR DEVIATION FROM STANDARD)
CALIBRATION AND PLOT
2-27-53
C.K. WAGNER & F.D. SKINNER
TEMPERATURE - DEGREES FAHRENHEIT
136
134
132
130
128
126
124
122
120
118
116
114
112
110
108
1.8
1.9
2.0
2.1
2.2
THERMOCOUPLE READING - MILLIVOLTS


THERMOCOUPLE CALIBRATION
32 DEGREE FAHRENHEIT REFERENCE
(CORRECTED FOR DEVIATION FROM STANDARD)
CALIBRATION AND PLOT
2-27-53
C.K. WAGNER & F.D. SKINNER
TEMPERATURE - DEGREES FAHRENHEIT
152
150
148
146
144
142
140
138
136
134
132
130
128
126
124
2.2
2.3
2.4
2.5
2.6
THERMOCOUPLE READING — MILLIVOLTS


TRUE READING – POUNDS PER SQUARE INCH
GAGE READING — POUNDS PER SQUARE INCH
0
200
400
600
800
1000
1200
1400
1600
1800
2000
BOURDON-TUBE PRESSURE GAGE
CALIBRATION RELATIVE TO A
DEAD-WEIGHT TESTER.
CALIBRATION AND PLOT 2-28-53
C.K. WAGNER & F.D. SKINNER