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PRESSURE TYPE LIQUID LEVEL GAGES

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PRESSURE TYPE LIQUID LEVEL GAGES

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NBS

U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

CONTENTS

Forward

The Mass, Length and Volume Section of the National Bureau of Standards has traditionally been concerned with volumetric standards. These standards have in turn been utilized by the petroleum industry, either directly or indirectly, to "calibrate" meters. To a somewhat lesser extent, these standards have been used by the dairy industry to "calibrate" tank trucks and storage tanks. Studies over the past few years, in conjunction with the AEC, indicated that such standards may be of use in chemical processing plants, particularly where inventories are important.

Generally speaking, in the development of an industry, solutions to problems are developed which are satisfactory for the moment, but which do not anticipate future changes in requirements. In some instances, development and testing is done by many in unrelated or unrelatable ways. In this way numerous solutions to a particular problem are developed, which are adequate perhaps, but which provide no information as to improvements or limitations of a given technique. At some point in time, it is highly desirable to conduct at least one carefully controlled experiment with these factors in mind. The experiment described in this paper has been done with this express purpose in mind.

This experiment explores the problem of "calibrating" a typical chemical processing plant. While to some extent the problem has been idealized, the information obtained will provide a sound basis for judgment. Factors explored include volumetric and gravimetric "calibration" methods, and the use of a manometer to determine liquid level. It is not necessarily intended that the procedures be adopted by anyone "verbatum". However, because the experiment has been well documented, and because a certain amount of exploratory work has been directed toward the study of limitations, it illustrates the work required to obtain a certain level of performance. It should be clear that if certain factors are omitted, the performance will be degraded. On the other hand, more attention to certain details will result in further improvement. It is specifically recommended that volumetric "calibration" procedures be adopted wherever possible. The degree of detail required is obviously a matter of local judgment.

1. INTRODUCTION

Although a liquid level gauge measures the height of a liquid in a tank, the user ordinarily interprets observations in terms of total volume of liquid present. In the most uncritical cases he may assume constant horizontal cross section area from top to bottom in which case his total volume is a linear function of his "dip-stick" observation. In more critical applications he must determine tank geometry from calibration, and if the tanks have large top-to-bottom dimensions he may have to consider the effects of the compressibility of the liquid on its density. In this latter case he should consider carefully whether his interests lie in knowledge of contained volume or contained mass.

The AEC has long used observations on manometer systems to infer the height of the liquid surface in a tank. Such systems depend upon the fact that the pressure difference, ΔP, between two orifices in a tank, one above and one below the liquid surface, is very nearly proportional to the height, H, of the surface above the immersed orifice; thus

$$H = k \Delta P. \tag{1}$$

Although there are simpler systems of equivalent accuracy, the use of a properly designed manometer system has one outstanding virtue, that is, the high assurance against accidental escape of dangerously radioactive liquid.

It will be shown that k in the foregoing equation is very nearly

$$k = \frac{1}{g(\rho_L - \rho_G)} \tag{1A}$$

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where g is the acceleration of gravity. and ρ_L and ρ_G the densities of the liquid and the gas in the tank. The percentage change in g with H is only $1:10^7$ per foot which is well beyond the capabilities of this type manometer system to detect. Inasmuch as liquids are not perfectly incompressible, ρ_L will vary with H. However, our interests lie in tanks 10 to 20 feet high. and under such circumstances, we are justified in ignoring the few hundred parts per million per atmosphere compressibility of even the most compressible liquids. In some AEC systems, a second manometer (with **both** orifices immersed) is used to obtain a measure of liquid density, and in such cases, this source of uncertainty is partly eliminated. The density of the gas above the liquid surface, ρ_G, is a function of its temperature, gas analysis and pressure.

Manometric systems are very practical ones, and there is a wide selection of apparatus appropriate to their use. The studies reported here were addressed to two questions:

1. What are the ultimate capabilities (accuracy and precision) of such systems?

2. What is the **minimum** calibration effort necessary to achieve such performance?

2. THE EXPERIMENT

Figure 1 shows the details of the experimental set-up. The tank was obtained from an old NBS experiment. After thorough sandblasting it was coated with epoxy on the interior and a foam insulating layer was applied to the exterior. It was equipped with a hook for weighing at the top. Bubble levels (not shown) ware attached in both horizontal orthogonal directions. It was 4 feet in diameter and about 14 1/2 feet from top to bottom. The two liquid levels illustrated show the vertical excursions of the

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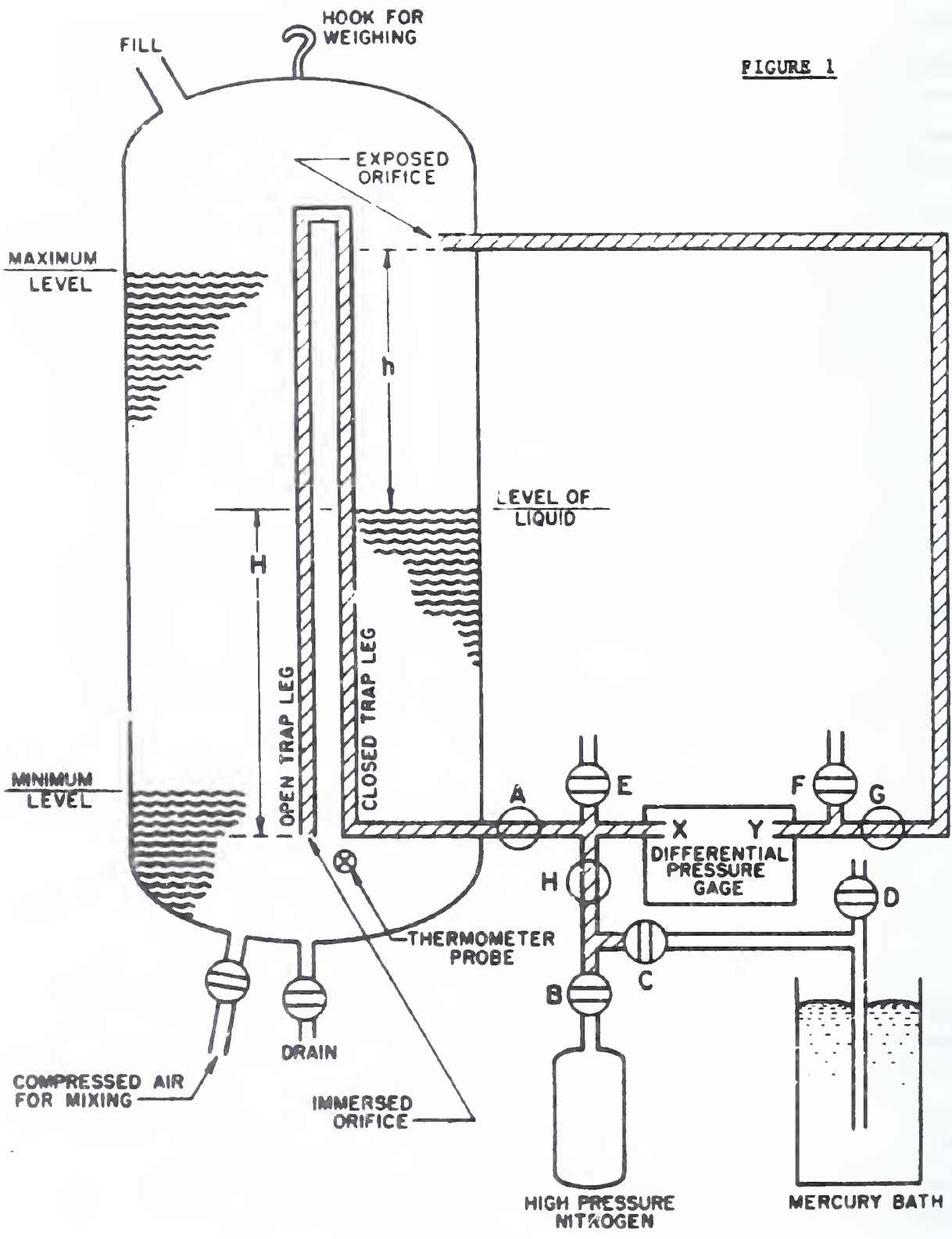
FIGURE 1

surface during the experiment. The lower excursion limit was about one inch above the effective level of the lower orifice. From the bottom to the lower excursion level, the tank contained about 30 gallons (nominal). From the lower to the upper excursion level, it contained 800 gallons (nominal). The pressure system for measurement of ΔP is described in Appendix 1.

The basic experiment consisted of filling the tank in a series of <u>known</u> volumetric increments and recording the height indicated by the manometer system after the addition of each increment. These increments were known because they were poured (dumped) from our standard volumetric vessels. The assumed delivery volumes* of these vessels was based upon several prior calibration experiments in which water was the calibration liquid. This demanded that we use water as a calibration liquid in these filling experiments. The use of water yielded another bonus. By virtue of knowledge of the temperature-density relationship for water, we were able to infer density from a simple temperature measurement, so we avoided the effort required to make independent density measurements on the liquid.

The first increment in each filling experiment was 30 gallons (nominal) from our standard 30 gallon test vessel. This 30 gallons of water "heel" placed the internal liquid surface about an inch above the lower manometer orifice. Following this, eight increments of 100 gallons (nominal) each was added from our 100 gallon standard test vessel. The last (eighth) of the 100 gallon increments raised the liquid surface in the tank to about three inches below the upper manometer orifice.

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*Every standard vessel has two volumetric calibration constants. The "delivery volume" is the volume of water which is poured <u>from</u> the vessel when it is emptied, and the "containment volume" is the volume of water which must be poured <u>into</u> the "dry" vessel to fill it. These two constants are not equal.

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This incremental filling experiment was conducted nine times. In conjunction with three of these filling experiments, the fourth, fifth and sixth, the tank was weighed before filling (when empty) and after the last 100 gallon increment (tank full). The difference between these two weighings gave us an independent measure of the total water poured into the tank during the filling experiments. This provided us with a check on our skill in the conduct of the experiment as well as upon the accuracy of our standard test vessels.

Prior to three of the filling experiments the seventh, eighth and ninth, the internal tank walls were thoroughly dried, and prior o all others, they were thoroughly wetted by water. In e practical situation the tank walls are never either thoroughly wet or thoroughly dry. The differences in the experimental results derived in these tests provides us with the volumetric limits on differences associated with wells of varying degrees of wetness.

It is noted that the filling increments from the standard test vessels were said to be "nominally" 30 or 100 gallons rather than "exactly" 30 or 100 gallons. This is because we have found that the error associated with failure to fill a standard test vessel to e _particular_ level on its neck gauge is significantly greater than the error associated with reading the neck level actually achieved on this gauge. Inasmuch as the experiment is not conducted under thermostat conditions, it is necessary to measure the temperature of the water in the test vessel before it is poured into the tank. After the dump into the tank each volumetric increment is thoroughly mixed with previously dumped increments by compressed air blown into the tank from below. After mixing the (new) temperature of the water in the tank was measured.

The experimental data which must be taken and the various calibration and physical constants which must be available are listed in the following section on Date Reduction.

3.   DATA REDUCTION

The first step in the data reduction is to determine the mass of water in each of the nine dumps, M_1 to M_9. This is obtained from the product of the volume of water in each dump, V_1 to V_9, multiplied by the density of the water in each dump ρ_1 to ρ_9. The volumes are obtained from the calibration coefficients referring to the standard vessel associated with each dump, the neck reading and the water temperature. Subscripts refer to the dump number.

$$V_N = (j_N + N_N k_N)[1 + \beta(T_N - 20)] \qquad [2]$$

where j_N = the vessel volume at the base of the
neck at 20°C

k_N = the volume of each neck division at 20°C

N_N = the neck reading

T_N = the water temperature in the jug prior
to the dump

β = the volumetric coefficient of expansion
(per °C) of the jug

The water density is approximated by a modification of the Taylor-Tilton formula for the density of water which, it is believed, makes it suitable for use with tap water rather than distilled water, and provides density in grams/ cm^3 rather than grams/ml.

$$\rho_N = \left[1 - \frac{(T_N - 3.9863)^2}{508929.2} \times \frac{T_N + 288.9414}{T_N + 68.12963}\right].999973 + \left[Q \times 10^{-6}\right] \qquad [3]$$

where   Q =   the solid impurities (in ppm) in the tap water.
An   adequate   estimate   may be obtained from the
local water company.

After calculation of V_N and ρ_N

$$M_N = V_N \rho_N \qquad\qquad [4]$$

From a table of values of M_1 to M_9 it is possible to devise a
table of values of __total mass__ of water in the tank after each
dump, R_1 to R_9 , by adding the masses of all previous dumps, thus:

$$R_1 = M_1$$

$$R_2 = M_1 + M_2$$

$$R_3 = M_1 + M_2 + M_3 \qquad\qquad [4A]$$

$$R_N = \sum_1^N M_i$$

As stated above, the temperature of water in each dump, T_1 to
T_9, is carefully measured before it is poured out of the standard
into   the   tank.   The experiment is conducted with tap water
(whose temperature varies widely) and the experiment is conducted
in non-thermosteted· spaces. Values of T_1 to T_9 may vary by
several degrees.   When the water is dumped into the tank under
calibration, although the mass is constant, its temperature
changes from T_N to a new value in the tank S_N . This new value,
S_N , is measured by a thermometer __in the tank__ which is observed
after thorough mixing of the water in the tank.

The total volume of water in the tank after each dump, U_1 to
U_9, is calculated from the quotient of total mass, R_1 to R_9 divided

by the (new) density of water in the tank, D_1 to D_9 , associated
with the (new) water temperature, S_N. D_1 to D_9 is calculated
from equation 3 by substituting S_N for T_N, then

$$U_N = \frac{R_N}{D_N}$$

[5]

The volumes U_1 to U_9 refer to the water in the tank from its
bottom to the height of the liquid surface, H_1 to H_9 (which will
be calculated from manometer data). U_1 to U_9 is valid only at
experimental water temperatures S_1 to S_9. It is equally correct
to say that U_1 to U_9 are the volumes of the tank from the bottom
to levels H_1 to H_9 when the tank is at temperatures S_1 to S_9 ,
since the walls of the tank follow the water temperature very
precisely. To find the volume of the tank, W_1 to W_9, at 20°C
from the bottom levels H_1 to H_9

$$W_N = U_N[1 + (2a)(20 - S_N)]$$

[6]

where a is the linear temperature coefficient of expansion of
the tank.

The only calculation remaining is that of the heights of the
liquid surface. Equation 1 shows that we require information on
the density of the liquid and the density of the gas IN ADDITION
TO ΔP. The liquid density, D_N, was calculated above for use in
equation 5. The gas density in grams/cm^3, G_N, is adequately
approximated by

$$G_N = [\frac{464.56 \, p_N - t_N(.085594t_N^2 - 1.8504t_N + 34.47)}{t_N + 273.16}]X10^{-6}$$

[7]

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where t_N = gas temperature

P_N = barometric pressure

r_N = relative humidity

The calculation of heights H_1 to H_9 is made by

$$H_N = \frac{\Delta P_N}{g(D_N - G_N)}$$

[8]

where ΔP is the manometer indication corrected
as necessary to yield dynes/cm^2

g is the local acceleration of gravity

The calibration is a two-column table showing heights of
liquid surface, H_N, alongside associated values of tank volume
at 20°C, W_N. As previously stated the calibration experiment was
conducted nine times. The experimental data, reduced as
described above, is presented in table 1 which shows associated
values of H_N and W_N.

For clarity, the above-described data reduction format is
diagrammed in Figure 2. The figure also indicates a set of appro-
priate and internally consistent units for the various required
data parameters.

4. DISCUSSION OF DATA

In this experiment the primary effort was not in the
calibration of the 830 gallon tank, but, rather to determine the
capabilities of the general type of system which we set-up for
test. Accordingly, the experimental set-up was quite
artificial in terms of a working system. For example, we made
temperature measurements within the tank so that we could

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FIGURE 2

EQN. 4 YIELDS MASS OF WATER IN DUMP (G) ⟶ M

$\sum\limits_{I}^{N} M_i = R_N$ (G) ⟶ R

EQN. 5 YIELDS TOTAL VOLUME OF WATER IN TANK AT TEMP. S (CM³) ⟶ U

EQN. 8 YIELDS HEIGHT OF LIQUID SURFACE IN TANK ABOVE REFERENCE (CM) ⟶ H

EQN. 6 YIELDS VOLUME OF TANK AT 20° C AT SURFACE HEIGHT, H (CM³) ⟶ W

THE COMPLETE CALIBRATION CONSISTS OF A TABULATION OF VALUES OF H ALONGSIDE THE ASSOCIATED VALUES OF W

EQN. 2 YIELDS VOLUME OF WATER IN DUMP AT TEMP. T (CM³) ⟶ V

EQN. 3 YIELDS DENSITY OF WATER IN DUMP (G/CM³) ⟶ ρ

EQN. 3 YIELDS DENSITY OF WATER IN TANK (G/CM³) ⟶ D

EQN. 7 YIELDS AIR DENSITY IN BACK MANOMETER LEG (G/CM³) ⟶ G

D ⟶ G, G ⟶ G, ΔP, g, U, S

j   BASE VOLUME OF STANDARD VESSEL AT 20°C   (CM³)

K VOLUME OF NECK DIVISION (CM³)

β   TEMP. COEF. OF VOLUMETRIC EXP. OF STANDARD   (CM³/CM³/°C)

N NECK READING   (DIVISIONS)

T TEMP. OF WATER IN STANDARD (°C)

Q ESTIMATED SOLID IMPURITIES IN WATER   (P.P.M.)

S TEMP. OF WATER IN TANK AFTER DUMP   (°C)

t_0 GAS TEMPERATURE IN BACK MANOMETER LEG   (°C)

p BAROMETRIC PRESSURE   (MM Hg)

r RELATIVE HUMIDITY   (%)

ΔP CORRECTED MANOMETER READING   (DYNES/CM²)

g LOCAL ACCELERATION OF GRAVITY   (CM/SEC/SEC)

α TEMPERATURE COEF. OF LINEAR EXP. OF TANK   (CM/CM/°C)

calculate the liquid density directly rather than depend upon a second manometer. We selected a very nearly cylindrical tank so that there would be very few discontinuities in our pressure--height curve. We did not use a state-of-the-art weighing system inasmuch as our gravimetric data was intended only as a protection against gross blunders in our volumetric data.

As pointed out previously the tank was weighed immediately before and after each of the 4th, 5th and 6th filling series. The difference between these "tank empty" and "tank full" weighings yields a measure of the true amount of water dumped into the main tank during each filling series. These three values will be different from one another inasmuch as no effort is made to pour in a particular amount of water in each dump. After the ninth dump in each of these three series the temperature of the water in the tank, S_9, was used to calculate the density, D_9, in the tank, which when combined with knowledge of the measured mass of water yielded a calculated volume for the water in the nominally full tank.

This calculated volume was compared to the measured volume U_9, based upon the sum of all nine volumetric incremental dumps in the series. This comparative data is shown below with all volumes reduced to gallons at temperature S_9.

Run No.	Temp °C(S_9)	Volume (Calc.- measured)
4	11.769 °C	0.077 gallons
5	10.673	0.006
6	10.193	0.128

est. std. dev. = 0.072 gallons

= $1:10^4$

We initially felt that we had made a blunder in the gravimetric (that is, weighing) check on the 6th run, and we seriously considered a repeat of this part of the experiment. However, the error bands associated with the volumetric and gravimetric tests overlapped, so we could only conclude that the experiment was valid. Calculation of the uncertainty bands is discussed below.

A. Uncertainty in the Gravimetric Tests.

The uncertainty in a weighing experiment is generally said to be the sum of the uncertainty in the standard weights used in the experiment plus three times the random error of the weighing experiment. The random component is usually ascribed to the random variability in the balance. This variability is ordinarily obtained from the past history of work with the balance, and is judged from the variability in the balance indication of the difference between two loads when compared several times. In the present experiment several observations were made on the difference between the empty tank and a 2500 pound standard weight. Also several observations were made on the difference between the tank "full" and a 10,000 pound standard weight. From these experiments and much previous work with this balance, we estimate its random variability to be about 0.1 pound.

The uncertainty of the standard weights used was about .08 pounds for the 2500 pound weight and 0.1 pounds for the 10000 pound weight. Based on the convention stated above, the uncertainty in the "empty" weight of the tank is about .38 pounds and the "full" weight about .40 pounds. On the difference between weight "empty" and "full" the uncertainty is estimated to be

$$U_{2500} \quad + \quad U_{10000} \quad + \frac{6\sigma}{\sqrt{2}}$$

$$.08 \quad + \quad .10 \quad + .4 \quad = .58 \text{ pounds}$$

which amounts to about .06 gallons.

B. Uncertainty in the Volumetric Tests

The uncertainty in the volumetric transfer value is almost
entirely contained in the uncertainty in the assumed values of
the "delivery" volumes of the two standard vessels (one 100
gallon and one 30 gallon) used in filling the main 830 gallon
tank. This ignores minor or unlikely errors such as evaporation
losses and miscounting of the number of dumps. The uncertainty
in the delivery volume of the standard vessels contains two
significant components:

a) The first component is three times the standard
deviation of the calibration experiment, which is
performed enough times to provide a reliable value of
this standard deviation. Also involved here is the
uncertainty in the standard weights used in the
calibration, however these are small to the extent of
insignificance. The uncertainty in the delivery volume
of the 100 gallon vessel is 1.38 cubic inches and for
the 30 gallon 0.60 inches. Inasmuch as the 100 gallon
vessel was used eight times there is a value of 11.04
cubic inches plus 0.60 for the 30 gallon (used only
once). This component totals up to 11.64 cubic inches
or 0.05 gallon.

b) The second component is the product of the uncertainty
in the temperature coefficient of volumetric expansion
of the standard vessels (about 4 parts per million for
each vessel) multiplied by the difference in
temperature between the calibration experiments (about
20°C) and the average temperature of the experiments of
interest (about 10°C) so the value of this error
component is 4(20 – 10) = 40 parts per million. This
fraction of 830 gallons amounts to .03 gallons.

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The sum of these two components (.05 gallons plus .03 gallons) is 0.08 gallons. The maximum difference between the volumetric and gravimetric experiments occurred in run 6, during which run the difference was 0.128 gallons. If now we look at the sum of the uncertainties associated with these two procedures (0.08 gallons for the volumetric tests PLUS 0.06 gallons for the gravimetric tests totaling 0.14 gallons), we conclude that the observed differences, 0.128 gallons, is smaller than the EXPECTED MAXIMUM VALUE of 0.14 gallons, so that both experiments are valid. A graph of the run 6 data would show the error bands of the two experiments overlapping.

Having concluded that the experimental work was valid, the volumetric data will now be considered in detail. It should be pointed out that two entirely different volumetric experiments were performed -- the first six filling experiments (in which the tank walls were wet) and the last three (in which the tank walls were dry).

Experiments with Wet Walls.

Figures 3, 4 and 5A are plots of the data presented in Table 1. The horizontal axes in each case represent the volume of water in the tank as calculated from the sum of the volumetric increments poured into the tank from our standard vessels. The units are in liters at 20°C. Plotted vertically are the heights in centimeters calculated from the ∆P observations. The dotted lines are not fitted. They are constant slope lines representing the expected rate of height change with volume change, and based upon the assumption of perfectly vertical tank walls (that is, constant cross section area tank).
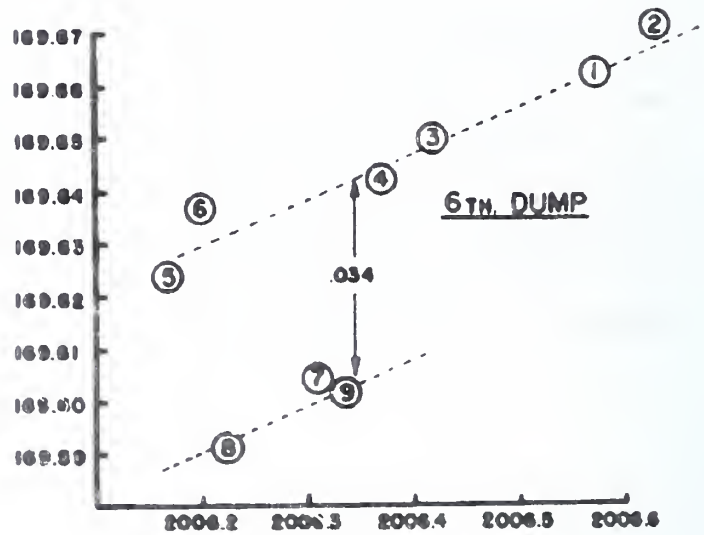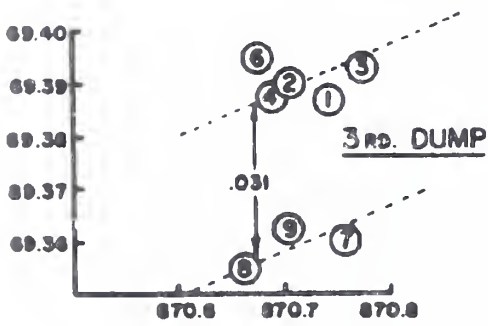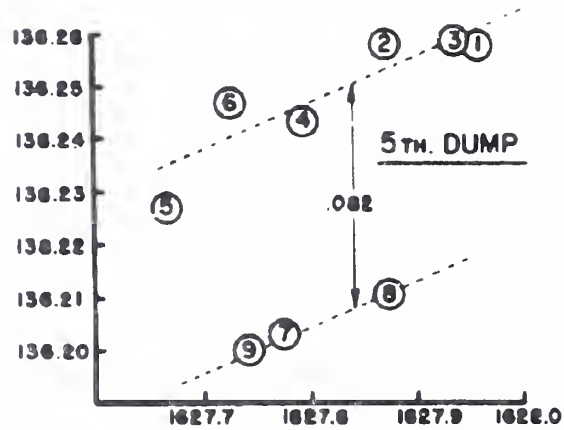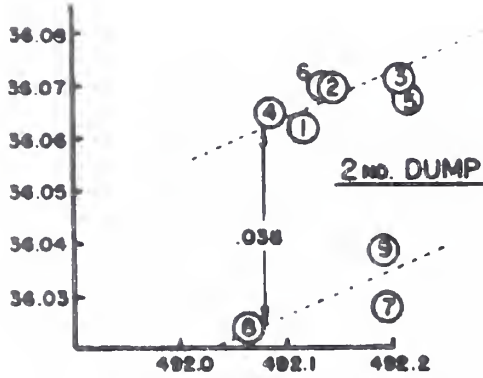
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FIGURE 3

FIGURE 4

7TH. DUMP

8TH. DUMP

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FIGURE 5A

9TH. DUMP

FIGURE 5B

ESTIMATE OF "EXPECTED" DIFFERENCE

DUMPS

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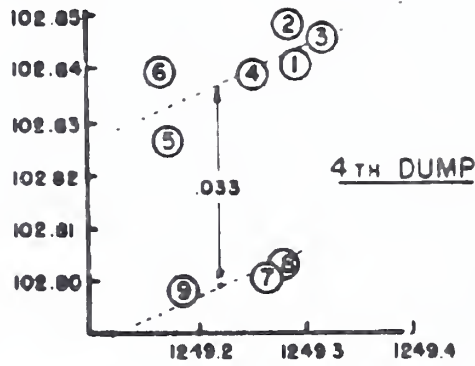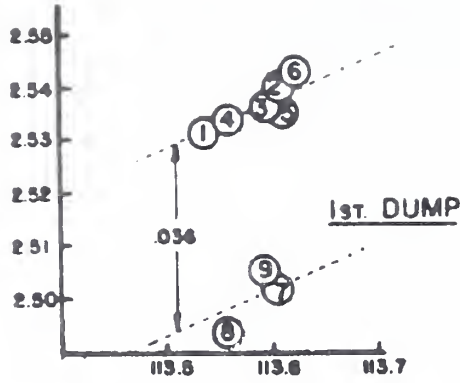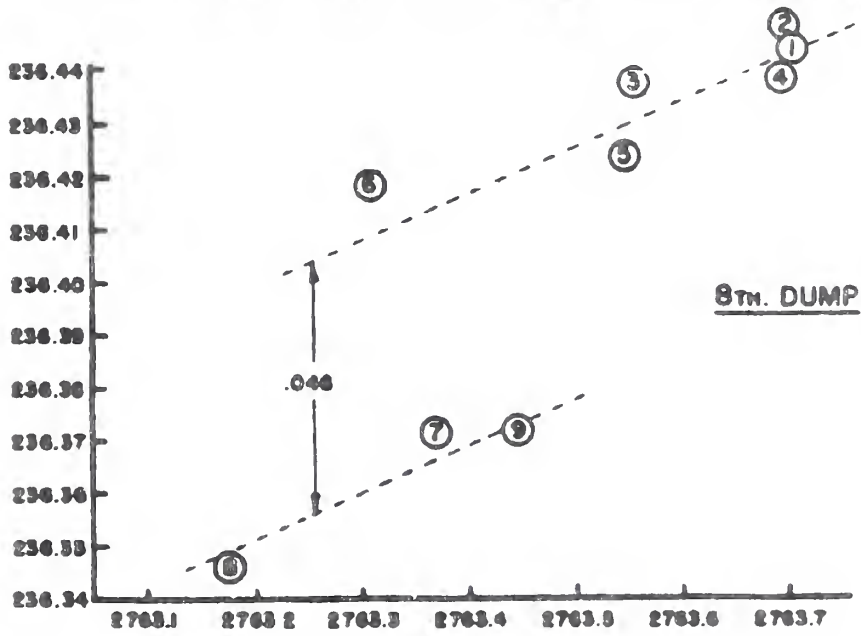
Data from runs I thru VI were used to estimate the standard deviation of a reading of the manometric instrumentation. Straight lines were fitted to sets of six data points for each of the nine dumps, yielding a residual standard deviation of 0.005 cm with 36 degrees of freedom. It is assumed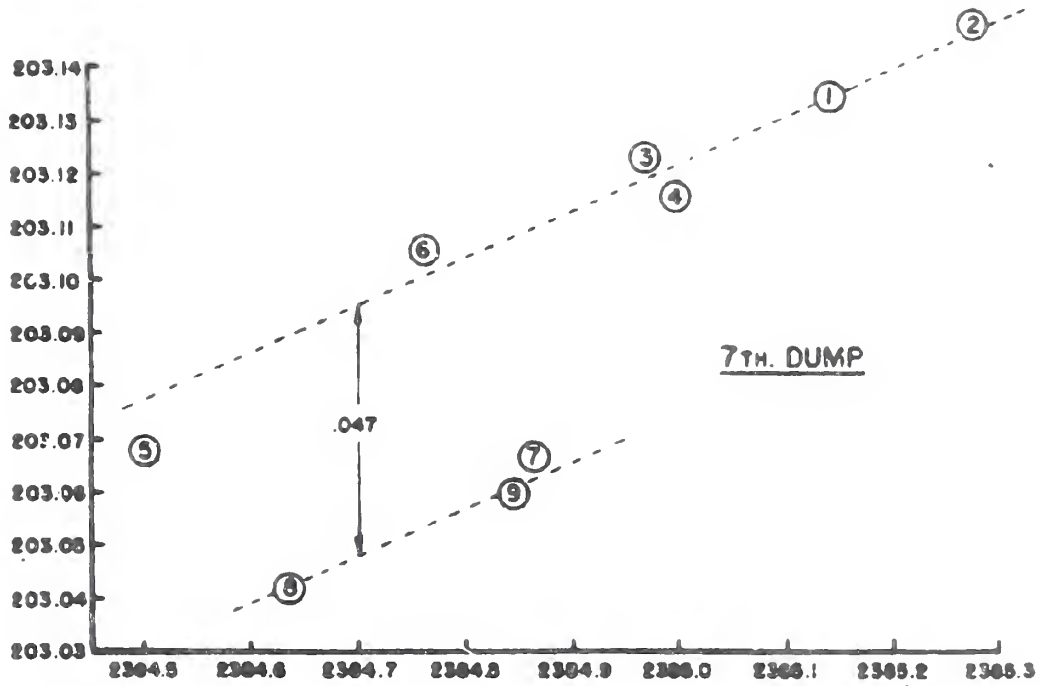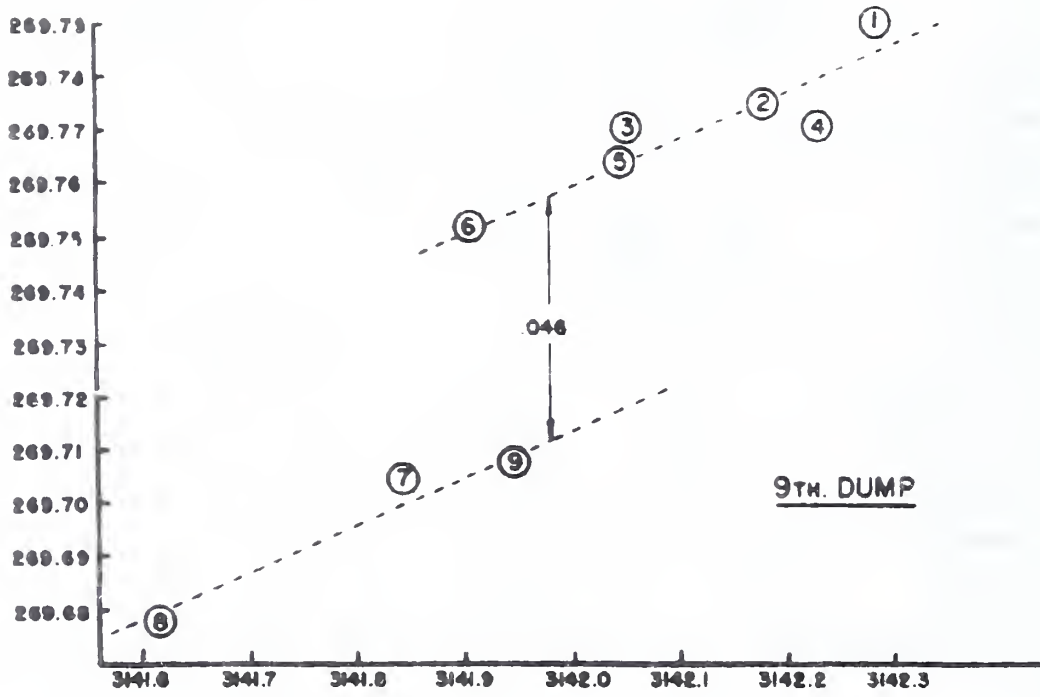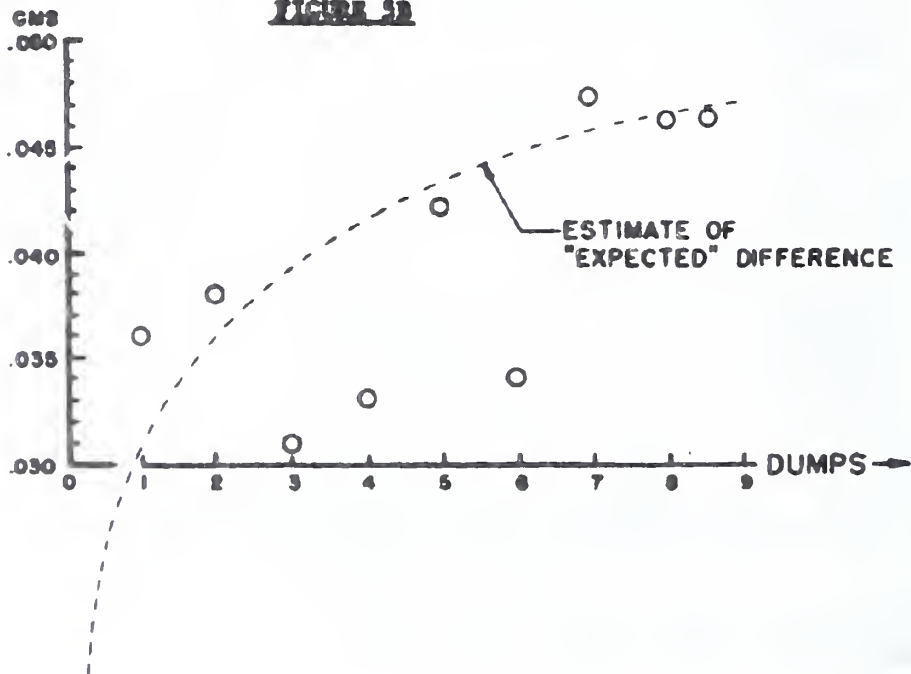 that reading errors are the same at different volume levels, although the data from the first and second dumps showed a smaller scatter.*

The standard deviation of the volume measurements is known by independent experiment to be about 0.004 liters, or equivalently about one-tenth of the estimated standard deviation of the manometer readings. Hence errors from this source may be assumed to be negligible.*

We now look to the observed <u>difference</u> in liquid level height between filling experiments conducted on the tank with internal surfaces initially wet and initially dry. We would expect the observed height to be <u>lower</u> under initially dry conditions than under initially wet conditions. Additionally, we would expect this difference to <u>increase</u> with increasing dumps. Finally, after a fairly long period of time, we would expect that all water initially clinging to the walls would have drained down into the main body of water in the tank, and when this process is complete, we would expect the observed difference in height to remain constant regardless of the number of dumps. An examination of Figure 5B verifies that our observed data follows these expected circumstances. It is noted that during the last three dumps (7th, 8th and 9th) that the height difference is about 0.046 cms which represents a volume difference (the cross section area of the tank is about 1.1 square meters) of about 506 cm^3. This is for a tank of about 800 gallons. For a 100 gallon tank, the difference between "containment" and "delivery" volumes is about 50 cm^3. The ratio of 50:506 is roughly proportional to this volume ratio (100:800) which indicates strongly that there is no gross error in our measurement of the 0.046 height difference between "wet" and "dry" tests.

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*This paragraph by Dr. H.Ku from the NBS Applied Mathematics Div.

Recommendations.

1. The uncertainty in the "delivery volume" of a 100 gallon
   vessel is stated in the report to be .08 cubic inches
   made up of an 0.05 component and an 0.03 component. The
   second component is associated with the uncertainty in
   the coefficient of expansion of the vessel. This
   component could be reduced to near zero by direct meas-
   urement of this coefficient which would reduce the
   uncertainty in a volumetric calibration to that
   associated with a gravimetric calibration.

2. The pressure gage performed admirably well in these
   tests. While it is not suggested that a secondary
   device such as a bourdon tube be used to calibrate a
   primary instrument such as a U-tube manometer, it occurs
   to us that the bourdon instrument might well serve the
   purpose of a portable test instrument to check the
   overall system response of the numerous U tube systems
   already employed by AEC.

3. Although water is almost universally used as a calibra-
   ting fluid, there may be some virtues in using the fluid
   which a tank will be called upon to store in a working
   situation. We believe, without proof, that the delivery
   volume of a standard test vessel would change slightly
   with different fluids, so special calibrations would be
   required on such vessels if they are to be employed in
   large tank calibrations. The parameters of interest are
   probably the tendency of the fluid to cling to the
   vessel wall, viscosity, surface tension and density.
   Inasmuch as the AEC tanks of interest here are used to
   store dangerous fluids, this procedure would be quite
   impractical.

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The volume of a tank as a function of liquid level is a function of tank geometry, which is relatively constant regardless of the contained liquid, and water will more than adequately define tank geometry. This knowledge may be wasted in a working situation, e.g. when the tank is filled with a dangerously radioactive slurry, if the assumptions upon which the measurement system is based are not perfectly achieved. There are two such assumptions:

1. that the density gradients in the contained fluid are insignificantly small after compressed air mixing

2. that the _effective_ vertical distance between the orifices associated with the density measurement manometer is well known.

These two assumptions are subject to experimental verification with only minor modifications to hardware and water calibration procedures, in which a switch to distilled water may be required.

It is our understanding that AEC tanks are equipped with two manometers -- one for measuring contained fluid density (with both orifices immersed) and one for measuring liquid level (with one orifice immersed). If all three immersed orifices are cut to the same geometry and a valve system (external to the tank) can connect any two orifices, immersed or exposed, together into a manometer configuration, it would be possible to obtain _six_ independent manometers. Three of these manometers would have both orifices immersed and would therefore be capable of measuring the contained fluid density, and three would have one orifice exposed and would therefore be capable of measuring liquid level.

The validity of the density measurements is based upon our knowledge of the effective vertical separation of the immersed orifices. In a water calibration situation we can utilize our knowledge of the density of water to determine these effective values. In a working measurement situation we can obtain three values of density and if the immersed orifices are suitably placed (vertically), any differences in calculated values of fluid density can alert the operator to the necessity for additional compressed air mixing. By additional valve manipulation it will be possible to obtain three values of liquid level, the average of which is probably more relia than a single value.

This general technique may be expanded upon by the addition of orifices and improved data handling.

The general working relationship stated in equation 1

$$H = \frac{\Delta P}{g(\rho_L - \rho_G)}$$

is written in slightly different form for the density measuring manometer (s). Thus

$$\rho_L = \frac{P_1}{gH_1}$$

where H_1 is the effective vertical separation of the orifices and P_1 the externally measured pressure difference. When these two equations are combined it is evident that the fluid density, per se, is of little importance, but that the validity of H as a function of ΔP depends almost directly on our skill in measuring H_1 and P_1.

$$\frac{\Delta P}{H} = \frac{P_1}{H_1} - g\rho_G$$

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TABLE I

H (cms)	Volume (liters)		H (cms)	Volume (liters)	
2.5310000	113.534		2.5410000	113.616	
36.0620000	492.136		36.0700000	492.137	
69.3870000	870.744		69.3950000	870.670	
102.8400000	1249.298		102.8390000	1249.170	
136.2570000	1627.960	Run I	136.2470000	1627.721	Run VI
169.6620000	2006.570		169.6370000	2006.198	
203.1340000	2385.145		203.1050000	2384.765	
236.4460000	2763.714		236.4140000	2763.309	
269.7890000	3142.293		269.7520000	3141.909	
2.5400000	113.601		2.5020000	113.605	
36.0700000	492.144		36.0280000	492.191	
69.3900000	870.714		69.3600000	870.751	
102.8480000	1249.289		102.8000000	1249.268	
136.2580000	1627.871	Run II	136.2030000	1627.773	
169.6710000	2006.624		169.6040000	2006.306	Run VII
203.1470000	2385.277		203.0660000	2384.865	
236.4470000	2763.702		236.3710000	2763.370	
269.7750000	3142.218		269.7050000	3141.834	
2.5370000	113.592		2.4940000	113.552	
36.0720000	492.217		36.0240000	492.065	
69.3930000	870.771		69.3550000	870.662	
102.8460000	1249.325		102.8040000	1249.279	
136.2580000	1627.933	Run III	136.2100000	1627.874	Run VIII
169.6500000	2006.418		169.5910000	2006.222	
203.1230000	2384.969		203.0420000	2384.635	
236.4370000	2763.554		236.3460000	2763.174	
269.7700000	3142.055		269.6780000	3141.620	
2.5340000	113.553		2.5060000	113.590	
36.0650000	492.086		36.0390000	492.190	
69.3880000	870.689		69.3630000	870.709	
102.8380000	1249.254		102.7980000	1249.190	
136.2430000	1627.794	Run IV	136.2000000	1627.735	Run IX
169.6420000	2006.368		169.6010000	2006.326	
203.1150000	2384.997		203.0590000	2384.830	
236.4380000	2763.698		236.3710000	2763.443	
269.7700000	3142.226		269.7070000	3141.946	
2.5350000	113.594				
36.0680000	492.222				
69.3960000	870.806				
102.8260000	1249.172				
136.2270000	1627.667	Run V			
169.6240000	2006.167				
203.0670000	2384.500				
236.4240000	2763.543				
269.7640000	3142.045				

APPENDIX 1. THE PRESSURE SYSTEM

Figure 1 is a diagram of our experimental set-up. For clarity, the two measuring legs of the manometer system are cross-hatched. The purpose and use of the non-cross-hatched plumbing will be explained below. The inverted U-trap in the X leg serves to prevent accidental loss of liquid from the tank.

The vertical height of the Y leg is H+h where H is the vertical distance from the immersed orifice in the X leg to the instantaneous position of the liquid surface, and h, from this surface to the exposed orifice. If we assume that the average density of the gas in the Y leg, ρ_G, is equal to that in the tank above the liquid surface, then the significant pressure applied to the X input of the differential pressure gauge is $gH\rho_L + gh\rho_G$ and to the y input, $g(H+h)\rho_G$ where g is the local acceleration of gravity. If the measured pressure difference is ΔP then

$$H = \frac{\Delta P}{g(\rho_L - \rho_G)}$$

and with adequate values of g, ρ_L and ρ_G it is possible to infer the height of the liquid surface in the tank based upon a measurement of ΔP.

The AEC has long used such systems for indicating H in tanks containing dangerously radioactive liquids. It has been customary to use U-tube manometers for indication of ΔP, however we rejected mercury manometers in this service due to their lack of sensitivity. Water manometers are more than an order more sensitive but their large bulk (12 or more feet high depending upon the tank height) and their cost (Mass estimated $6000) led us to select a quartz bourdon tube device manufactured by Ruske.

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This device photo-electrically senses the bourdon tube deflection and (using the photo-electric voltage as an error signal) servos the geneva-gear digital read-out to an appropriate value. The sensitivity of this device lies between mercury and water manometers.

For any value of H, the liquid in the tank will penetrate the open leg of the trap in the X leg. If valve B is cracked open and we allow nitrogen to flow out of its tank, the liquid will be forced out of the open leg and the nitrogen will bubble out of the immersed orifice and rise to the surface of the liquid. Under these circumstances the pressure at X will be higher than that at the orifice by an amount which is a function of the viscosity and volume of gas flowing and system geometry. If the valve B is throttled down to a level at which the gas flow rate is essentially zero, the pressure rise at X (above the orifice pressure) is essentially zero so that the pressure at X is insignificantly different from that at the orifice.

The bourdon tube is an elastic device and, like all such devices, requires exercise before use to stabilize its "zero". This is accomplished by closing valve A and opening C which replaces the orifice immersed in the tank liquid by an orifice immersed in mercury. Inasmuch as the mercury is 13 times as dense as the tank liquid, the depth of the orifice in mercury need be only 1/13 the depth of the tank in order to raise the pressure at X to an amount equivalent to that associated with a "full" tank. To drop the pressure at X to an amount equivalent to an "empty" tank valve D is opened long enough for the bourdon indicator to drop to zero. After a few such cycles, the indicator zero is stabilized (at some value other than zero). To correct this situation valves H and G are closed and E and F opened. This places atmospheric pressure at the bourdon tube level at both X and Y, and the indicator dials are mechanically set to zero.

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After resetting the valves to the position shown in Figure 1 and adjusting B for slow nitrogen flow, the system provided reliable data.

The adjustment of valve B was the subject of considerable study, and we observed the system with B adjusted to provide bubble formation rates of several per second to as slowly as 1/3 bubble per minute. At rapid rates (more than 8/minute)) the liquid surface in the tank is kept in turbulent wave motion at amplitudes of 1/8 inches clearly visible to the naked eye. Inasmuch as the bourdon tube manometer was sensitive to changes in surface height of about 1/100 inch, it was impossible with a turbulent surface to obtain good observations. As the bubble rate was reduced, surface turbulence died down, and at about 8 bubbles per minute the system performed nicely. We found that the pressure pattern with time was about as illustrated in Figure 6. The pressure would commence building up immediately after the loss of a bubble, would then attain a maximum value proportional to H, would then begin to decrease, and after a small retreat from maximum would drop sharply as the bubble broke away from the orifice. We watched the bubble formation in a clear glass container and believe that the decrease in pressure just before breakaway is associated with the horizontal increase in bubble size (and decrease in bubble depth). We did not have a pressure recorder so the curves shown in Figure 6 are highly subjective, but we believe they are representative of true conditions. It is significant that the maximum pressure observed in cycle was quite reproducible, and the data used in the calibration was maximum pressure achieved. We finally settled on 4 bubbles per minute as our "standard" and all calibration data was taken at this bubble rate.

As H changed, the setting of valve B (to obtain a rate of 4/minute) changed, but the proper adjustment was highly proportional to height and we found that we were able to predict
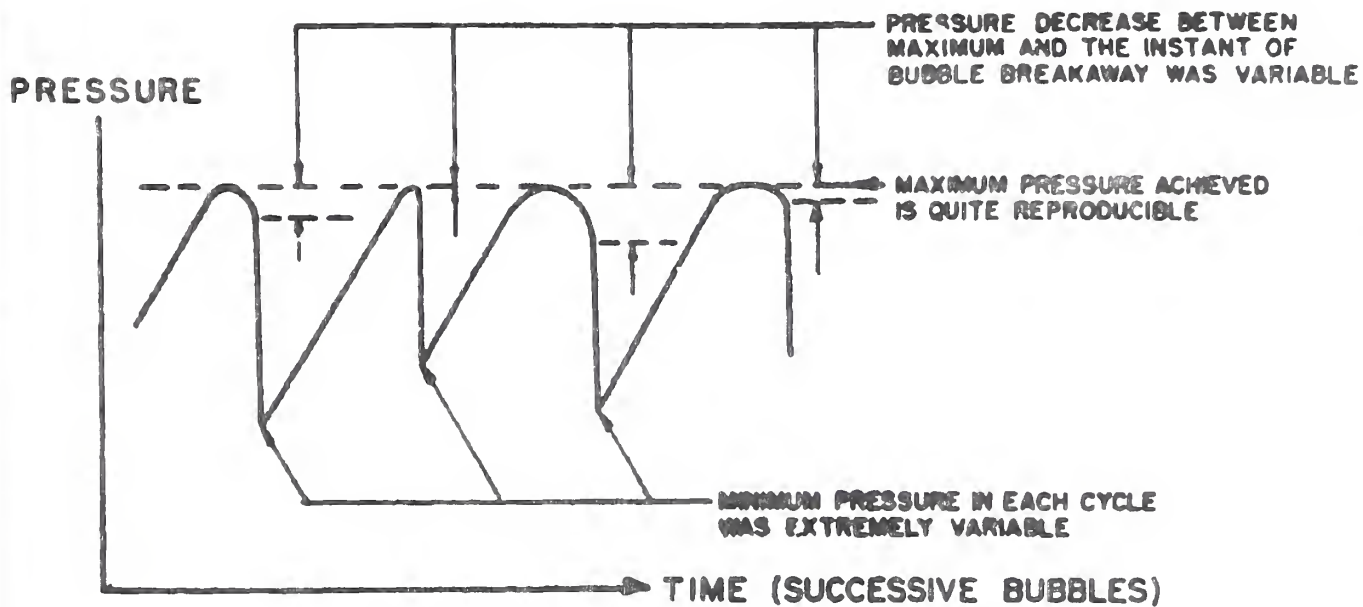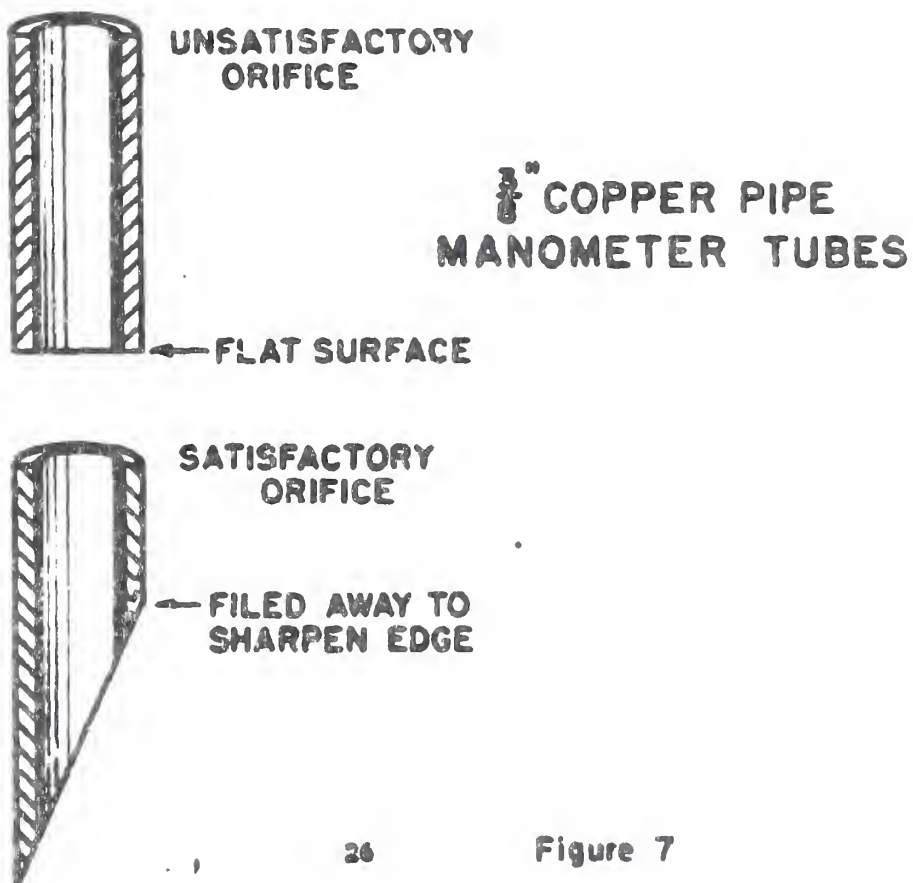
PRESSURE

PRESSURE DECREASE BETWEEN
MAXIMUM AND THE INSTANT OF
BUBBLE BREAKAWAY WAS VARIABLE

MAXIMUM PRESSURE ACHIEVED
IS QUITE REPRODUCIBLE

MINIMUM PRESSURE IN EACH CYCLE
WAS EXTREMELY VARIABLE

TIME (SUCCESSIVE BUBBLES)

Figure 6

UNSATISFACTORY
ORIFICE

$\frac{3}{8}"$ COPPER PIPE
MANOMETER TUBES

FLAT SURFACE

SATISFACTORY
ORIFICE

FILED AWAY TO
SHARPEN EDGE

26   Figure 7

the angular position of the valve stem which would adjust the rate to 4/min.

We also found that the orifice should not contain horizontal flat surfaces, because the decrease in pressure, referred to above, was much greater and much more variable with such surfaces. Figure 7 shows the orifice configuration actually used.

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