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by Herbert L. Minkin, Howard F. Hobart, and I. Warshawsky

Lewis Research Center
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SUMMARY

Results of calibration experience with 3/4-inch to 2-inch meters in liquid hydrogen are presented. The calibration factor (pulses per unit volume) below nominal full scale remains constant over only about one-sixth of the flow range obtained with water, although the factor is reproducible over much wider flow ranges. Nonreproducibility is such that the maximum deviation of the factor from its mean value at nominal full scale ranges from 0.5 to more than 1 percent, depending on the history of use; the probable deviation is one-half of the maximum deviation. A 50-percent probability exists that the calibration factor of a meter in liquid hydrogen at full scale can be predicted to within 0.7 percent from the water calibration. A 90-percent probability exists that the prediction can be made to within 1.0 percent if there are prior data on meters of the same design, and to within 1.5 percent if there are no such data; in the latter case, the calibration factor in liquid hydrogen must be assumed to be 0.5 percent higher than the calibration factor in water. The influence of piping conditions and of pressure drop is also discussed.

INTRODUCTION

Development of advanced chemical and nuclear space propulsion systems that use liquid hydrogen as the propellant has relied heavily on the turbine-type flowmeter because of the convenience of installation and use. However, there are few published reports of firsthand experience with volumetric turbine-type meters in liquid-hydrogen service. Some preliminary experience was reported by Burgeson (ref. 1) and Minkin and Hobart (ref. 2, with abbreviated summary in ref. 3). The only extensive reports are by Bucknell (refs. 4 to 6), who reported on meters of the order of 3 inches nominal size, giving data on the relation between water and liquid-hydrogen calibrations, linearity, and reproducibility.

Data obtained with 3/4-inch to 2-inch (nominal size) meters are presented herein that provide some insight into the linear range obtainable in liquid hydrogen, the relation between linear range and pressure drop, the extent to which a water calibration may be used to predict the liquid-hydrogen calibration, the effect of meter orientation, and the stability of calibration. The meters tested were in two groups:

Group I: *Fifteen* $1\frac{1}{2}$*-inch meters from three manufacturers,* which were purchased under identical performance specifications and were tested repeatedly to determine the reproducibility of their calibrations, as well as other characteristics.

Group II: More than 20 meters in a variety of sizes and types, calibrated as a routine service to various NASA research programs that used these meters for liquid-hydrogen flow measurement. These meters were generally calibrated only once.

All liquid-hydrogen runs were made in the facility described in reference 2. Some minor modifications in the instrumentation of this facility have been made since 1961 to achieve slight improvements in accuracy.

SYMBOLS

C	calibration factor, pulses per unit volume
C_h	calibration factor in horizontal position
C_m	asymptote of calibration factor
C_{m,H_2O}	value of C_m in water
C_{m,LH_2}	value of C_m in liquid hydrogen
C_{nfs}	calibration factor at nominal full-scale flow rate
ΔC_{nfs}	peak-to-peak change in C_{nfs}
C_v	calibration factor in vertical position
D	nominal tube diameter
e_p	probable error
e_σ	rms error
N	pulse rate
N_{nfs}	nominal full-scale pulse rate
N_r	reference pulse rate
N_{995}	pulse rate at $C = 0.995\ C_m$
N_{980}	pulse rate at $C = 0.980\ C_m$
$N_{0.5\ psi}$	pulse rate at $\Delta p = 0.5$ psi

$N_{2\ psi}$	pulse rate at $\Delta p = 2$ psi
$N_{7\ psi}$	pulse rate at $\Delta p = 7$ psi
Δp	pressure drop across meter
v	linear velocity through meter at blades
ρ	density

TERMINOLOGY

The calibration factor C of a turbine-type meter denotes the pulses generated per unit volume of fluid passing through the meter. When this factor is plotted against the frequency N of pulses generated, a typical calibration of a meter in liquid hydrogen has the appearance shown in figure 1. The volume flow rate corresponding to any indicated frequency N is the quotient N/C.

The approach to the horizontal asymptote indicates that bearing friction and magnetic drag have become negligible compared with hydrodynamic torque. The asymptotic value of C is denoted as C_m. As rotor speed drops, bearing friction becomes influential in reducing the value of C.

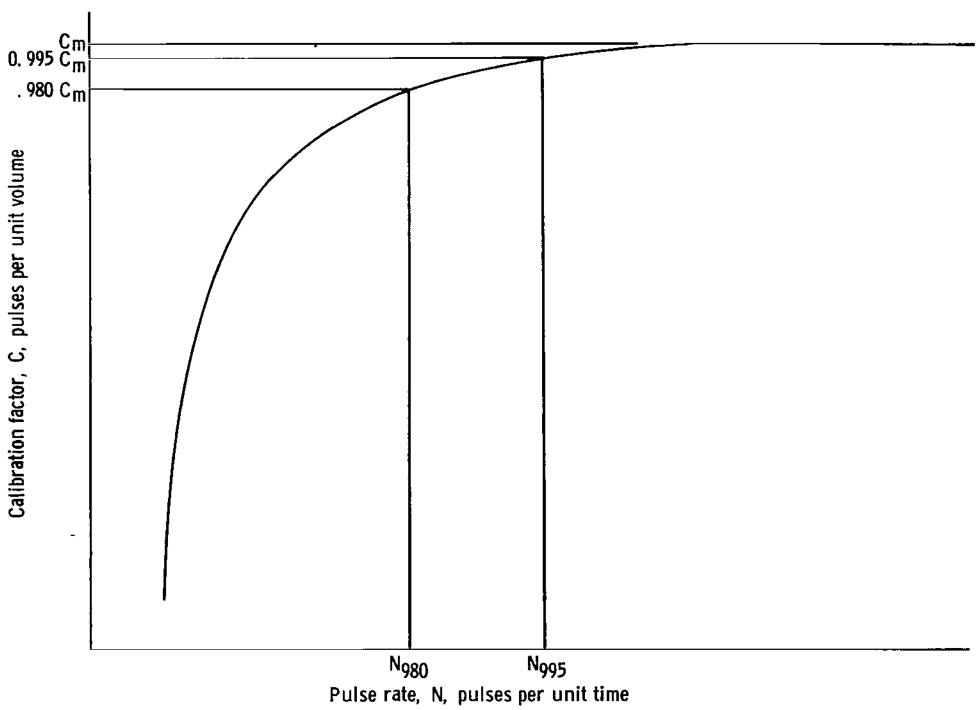


Figure 1. - Representative calibration of meter in liquid hydrogen.

In references 2 and 3, the lower limit of the useful range of the meter was taken arbitrarily as the value N_{995} of N for which $C = 0.995\ C_m$. Later experience shows that this value is poorly definable because of variations in meter calibration and that a less equivocal value of N for use in describing liquid-hydrogen meter performance is N_{980}, for which $C = 0.980\ C_m$. The value N_{980} is used because the slope of the calibration curve at this value of C is sufficiently high so that the intercept with the horizontal line corresponding to $0.980\ C_m$ is definable with acceptably small uncertainty. No implication is intended that N_{980} represents a lower limit of usefulness. The definition of such a lower limit is the privilege of the meter user and will depend on the nature of the application; most users have chosen N_{995} as a lower limit of usefulness, which permits use of a constant calibration factor and obviates referral to a calibration curve.

If the meter is a standard catalog item, the manufacturer generally states the maximum recommended value for N in water or standard-air service. This nominal full-scale pulse rate is denoted as N_{nfs}. The term "linear range" or the term "rangeability" is sometimes applied to the value N_{nfs}/N_{995} or to a similar ratio with a different denominator (e.g., N_{nfs}/N_{990} or N_{nfs}/N_{980}). Such a ratio may represent a figure of merit for the performance of a meter, but the ratio can always be made greater by defining a higher value of the numerator, at the expense of shorter service life and higher pressure drop.

Another method of defining linear range is based on pressure drop. If a meter is intended for use exclusively in liquid hydrogen, it may be operated at a high rotational speed and a correspondingly high pressure drop that nevertheless is acceptably small because it (1) produces an acceptably small load on the bearings, (2) produces an acceptably small overall line pressure loss, and (3) does not produce local pressures near the vapor pressure of the liquid. (The pressure drop in water at the same rotational speed would be prohibitively high.) Thus, in the definition of linear range, it is sometimes convenient to replace N_{nfs} by the N at which a specified pressure drop exists, for example, $N_{0.5\ psi}$, $N_{2\ psi}$, etc.

The measure of statistical dispersion used in this report is the probable error e_p. The probability that an error will be larger than e_p is equal to the probability that an error will be smaller than e_p. The determination of e_p is therefore independent of the form of the error-distribution function. The relation of e_p to the root-mean-square (rms) error e_σ is

$$e_p = 0.67\ e_\sigma \qquad \text{for Gaussian distribution}$$

$$e_p = 0.87\ e_\sigma \qquad \text{for uniform distribution}$$

TABLE I. - PROBABILITY OF EXCEEDING A GIVEN ERROR

Error	Probability, percent	
	Gaussian distribution	Uniform distribution
Probable, e_p	50	50
rms, e_σ	32	42
$1.8\ e_p$	22	10
$1.9\ e_p$	20	5
$2\ e_p$	18	0
$1.73\ e_\sigma$	8.4	0
$2.4\ e_p$	10	--
$2.9\ e_p$	5	--
$2\ e_\sigma$	4.55	--
$3\ e_\sigma$	.27	--

The probability of exceeding an error that is a multiple of e_p does depend on the form of the distribution, as is the case for e_σ and its multiples. The probability of exceeding a given error is indicated in table I for a large sample size and for the indicated error distributions.

Practical experience shows that the maximum error encountered is about twice the probable error. This approximation is adequate because the actual number of data is small and because large errors are invariably discarded, so that the distribution is truncated. Data are often treated as Gaussian because it is mathematically convenient to do so, but the distribution of much of the data reported herein approximated a uniform distribution (the limit of a sharply truncated Gaussian distribution) more closely than a Gaussian distribution.

METERS TESTED

Group I Meters

Group I meters were purchased in groups of five from three manufacturers, with the following specifications: (1) nominal $1\frac{1}{2}$-inch size, (2) AN-flared tube end fittings, (3) upstream straightening vanes, (4) ball-bearing rotor (all meters supplied by the manufacturers had full-complement ball bearings of 440-C stainless steel), (5) approximately 500 pulses per second at nominal full-scale flow rate, (6) nominal full-scale flow rate of 10 liters per second, (7) usability in water or in liquid hydrogen at nominal full-scale flow rate, (8) pressure drop of approximately 7 pounds per square inch at full-scale water flow rate, and (9) $N_{nfs}/N_{990} > 14$ in water. It is important to note that these represent specifications used in 1962 to evaluate stock catalog items. No implication is intended that these represent desirable or recommended specifications; on the contrary, the results reported herein indicate that the preceding set of specifications is not the most desirable one.

Group II Meters

Group II meters ranged in nominal size from 3/4 to 2 inches, generally had AN-flared-tube end fittings in sizes less than 2 inches and flanged end fittings in the 2-inch size, had full-complement ball bearings, and represented five different internal designs. Many of the meters had already been used, with an unrecorded amount and severity of service. A few used meters were defective at the time of receipt; the data reported herein represent only the results after satisfactory repair had been effected.

Criteria for Defective Meter

The fact that an instrument was defective was revealed by at least one of the following criteria:

(1) Values of C_m differing by more than 0.5 percent for two liquid-hydrogen calibrations performed the same day or on successive days without removing the meter from the line or exposing it to the atmosphere

(2) A difference of 1 percent or more between two liquid-hydrogen calibrations, respectively, preceding and following a water calibration

(3) Failure to have approached within 0.3 percent of a clearly defined asymptote when nominal full-scale flow had been reached

(4) Scatter of data in a single calibration that exceeded $e_p = 0.3$ percent

Accumulated experience revealed that a defective meter implied defective bearings. The following crude test for bearing quality correlated well with subsequent results of calibrations: Blow dry air gently into the meter, with just enough velocity to initiate spinning of the rotor; then observe how the rotor comes to rest when blowing ceases. The rotor should decelerate smoothly and finally oscillate with decreasing amplitude about the rest point because of the magnetic coupling between the blade and the pickup coil. Failure to oscillate, that is, a completely aperiodic deceleration, is generally indicative of a defective bearing. This test would not be applicable to a meter that uses a radiofrequency type pickup.

TESTING PROCEDURE

Technique

Calibrations were performed by using the techniques described in reference 2. Salient features of the procedure are that (1) the meter is completely immersed in liquid hydrogen; (2) each datum of a calibration represents an average over a period of 100 seconds or more during which volumetric flow rate is held constant, with momentary random variations not exceeding 2 percent and averaging 0.5 percent; (3) redundant measurements are made as a check on each datum, where primary reliance is placed on the buoyant-

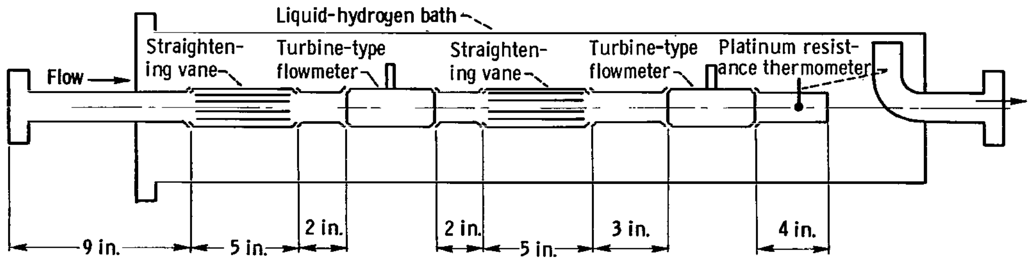


Figure 2. - Representative arrangement of two meters in tandem.

float mass-flow-rate device with platinum resistance thermometers to measure supply-tank and test-section densities, and where secondary checks are made with the liquid-level gages and platinum resistance thermometers.

Figure 2 shows a representative arrangement of apparatus. Unless otherwise noted in this report, all meters were in a horizontal position. Calibrations were generally made with two meters in series and straightening-vane sections ahead of each meter. These sections consisted of bundles of 13 tubes, each 0.3 inch in diameter by 0.010 inch in wall thickness by 5 inches in length.

Calibration System Reproducibility and Accuracy

For those meters that appeared to yield the best reproducibility of calibration, the dispersion of data about any single smoothed calibration curve yielded $e_p = 0.1$ percent of the calibration factor C. This value, therefore, represents the upper bound of the calibration system reproducibility. Figure 3 shows a typical liquid-hydrogen calibration of a good meter.

For all meters tested, the dispersion of the data in any single calibration yielded values of e_p up to 0.25 percent at nominal full-scale flow rate (where the average value is 0.12 percent) and values of e_p up to 0.5 percent at one-fourth of nominal full-scale flow rate (where the average value is 0.2 percent).

Inclusion of the additional uncertainties in true flow rate leads to an estimated probable error in the absolute value of C of 0.25 percent for the upper half of the flow range. This number is necessarily larger than the scatter of data in any single calibration because it includes fixed probable errors of the calibration system (such as the uncertainty in the buoyant-float area to tank area ratio) that do not affect the ability to establish reproducibility. The absolute accuracy of calibration, rather than the reproducibility, is important in comparing a calibration in liquid hydrogen with a calibration in water.

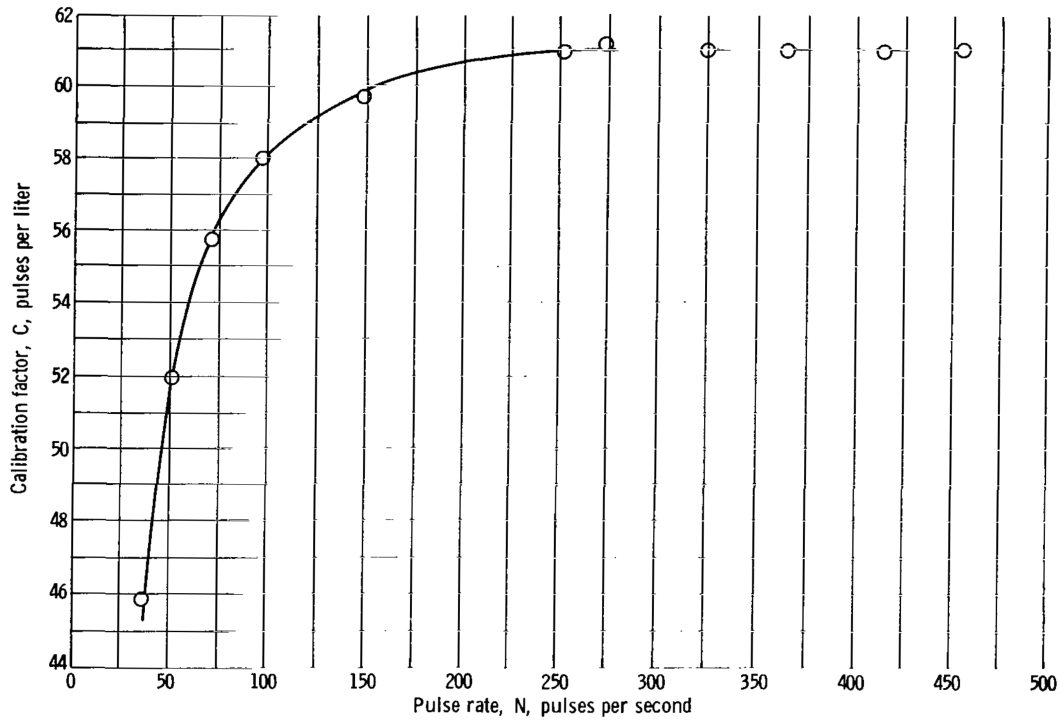


Figure 3. - Typical calibration of good meter.

TESTS AND RESULTS

Group I Meters

Among the Group I meters, one did not run in liquid hydrogen because of inadequate blade clearance (about 0.001 in. at room temperature), although it performed well in water. Another meter of the same type proved to be defective according to the criteria for a defective meter listed earlier in this report. Neither of these meters is reported on.

Reproducibility of calibration factor at nominal full-scale, C_{nfs}. - Table II lists the variation in the value of C_{nfs} encountered over a 1- to 2-year period during which a meter may have been subjected to

(1) Exposure to the atmosphere while in storage for various periods
(2) Calibration in water
(3) Operation in nitrogen gas at about 60 atmospheres pressure
(4) Cleaning by immersion in acetone and subsequent drying in warm air after any of the conditions described in items (1) to (3)

If the meter was in tandem with another, the data on the meter were used in compiling table II only if the meter was in the upstream position, and only if the downstream meter was another Group I meter, or the nozzle described in reference 2. Only those meters are listed in table II for which a sufficient number of calibrations had been made to warrant a meaningful estimate of reproducibility over a long time.

The reproducibility of a meter calibration is better than that represented in table II if the meter is left in the line in an atmosphere of hydrogen or helium gas, or has been exposed to air for only brief periods. Table III compares the greatest change ΔC_{nfs}

TABLE II. - VARIATION IN CALIBRATION FACTOR AT NOMINAL FULL SCALE (C_{nfs}) OVER 2-YEAR PERIOD

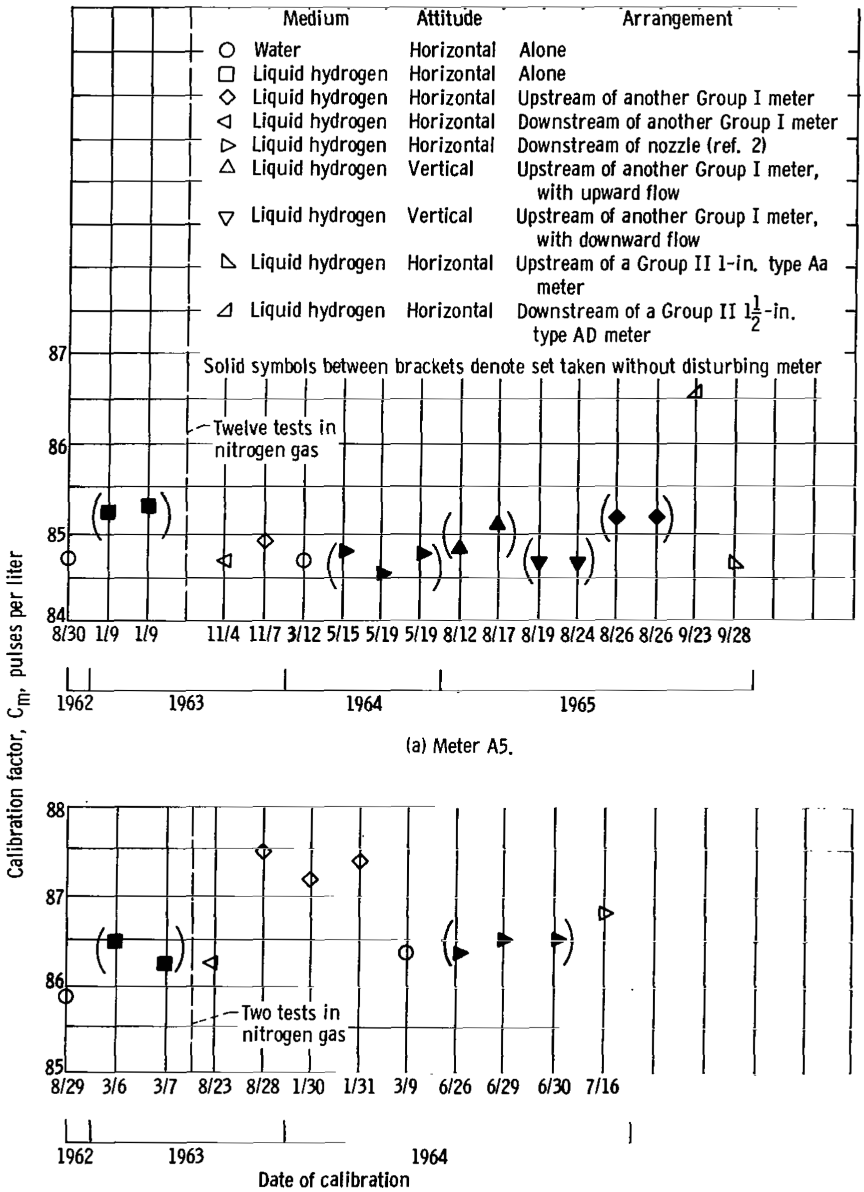
Meter	Number of tests	Maximum deviation of C_{nfs} from mean, percent of mean
A1	5	0.9
A2	2	1.2
A3	3	.2
A4	3	.4
A5	5	.3
Average	--	0.6
B1	4	0.9
B2	4	.5
B5	5	.3
Average	--	0.6
C1	3	0.5
C3	3	.5
Average	--	0.5

TABLE III. - COMPARISON OF SHORT- AND LONG-TERM VALUES OF PEAK-TO-PEAK CHANGE IN CALIBRATION FACTOR AT NOMINAL FULL SCALE

Comparison conditions	ΔC_{nfs}, percent of average C_{nfs}	
	Average value	Highest value
Meter in line or in hydrogen or helium atmosphere, 1 to 8 days	0.3	1.2
Comparable data for a 1- to 2-yr period	1.0	2.5

(highest value of C_{nfs} encountered minus lowest value of C_{nfs} encountered) in C_{nfs} when the meter was calibrated several times under such circumstances over a period of 1 to 8 days, with the value of C_{nfs} encountered over the 1- to 2-year period covered by the data in table II.

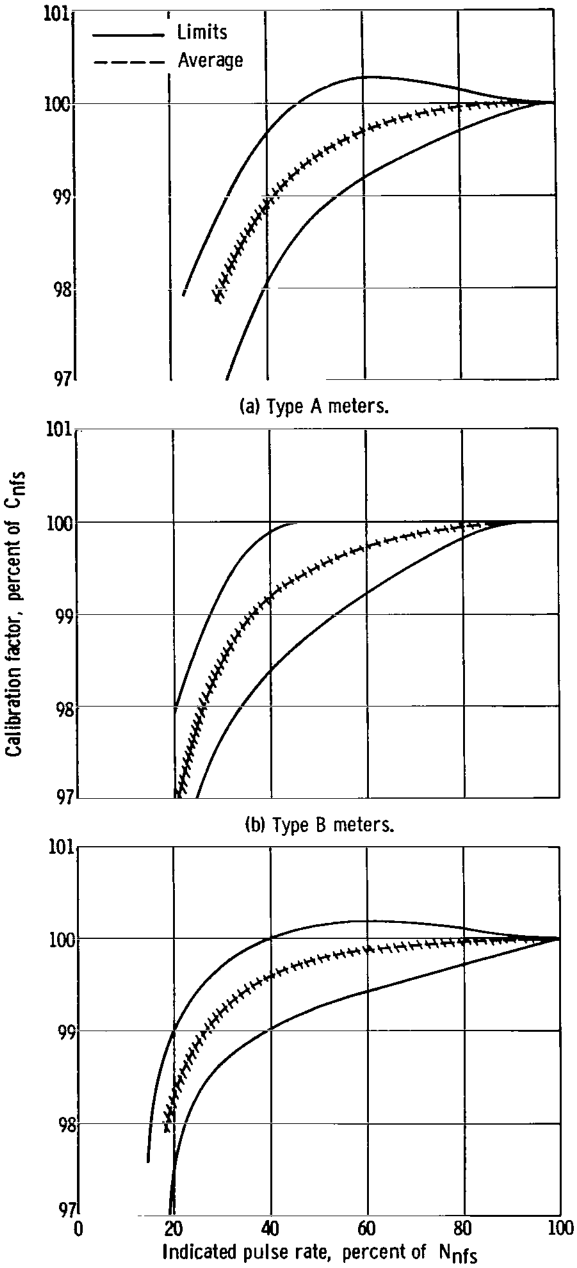
Figure 4(a) shows the chronological history of C_{nfs} for one of the better meters, and figure 4(b) shows a similar history for one of the poorer meters, when the criterion of quality is the reproducibility of C_{nfs} for calibrations in water taken at widely separated times.



(a) Meter A5.

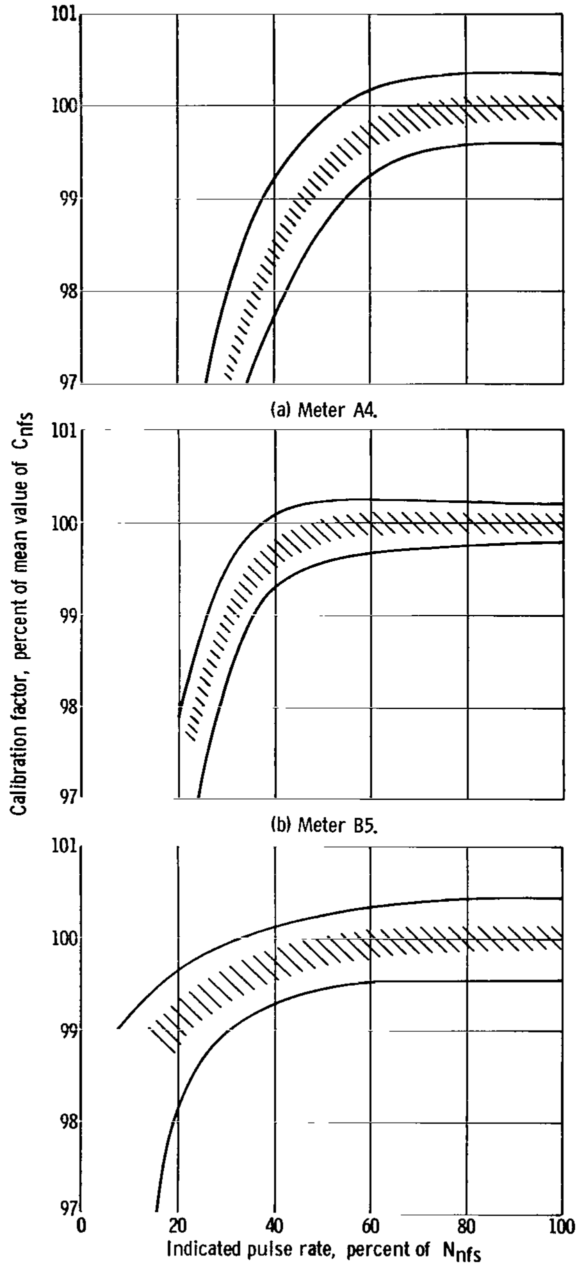
(b) Meter A4.

Figure 4. - Chronology of calibrations.



(c) Type C meters.

Figure 5. - Envelope of calibration-curve shapes of all flowmeters of given type over 2-year period; shaded band is probable error of calibration.



(c) Meter C3.

Figure 6. - Envelope of all calibrations of single meter over 2-year period; shaded band is probable error of calibration facility.

Reproducibility of shape of calibration curve. - The relative shape of the calibration curve of any one meter, as represented by the plot of C/C_{nfs} as a function of N, also varied for the calibrations performed over the 1- or 2-year period. Figure 5 shows the envelope of all such calibration curves of all meters of a given type. The average curve is also shown, as representative of that type of meter. The shaded area represents the uncertainty expected because of the probable error of a single calibration.

The envelope includes only calibrations when the meter was alone or was upstream of another meter of the same size. If calibrations with the meter in the downstream position had been included, there would be no substantial systematic shift in the average curve, and the following changes would result in the envelope:

(1) Type A meters, no change

(2) Type B meters, no change down to 40 percent of N_{nfs}, but the envelope would be 50 percent wider at 30 percent of N_{nfs}, and 100 percent wider at 25 percent of N_{nfs}

(3) Type C meters, no change down to 60 percent of N_{nfs} but the envelope would be about 50 percent wider below 50 percent of N_{nfs}

Reproducibility of calibration curve. - Any change in the calibration curve may be considered as the combination of a change in C_{nfs} and a change in curve shape. Each of these appeared to be independently random; that is, there was no apparent correlation between changes in the absolute value of C_{nfs} and changes in the shape of the graph of C/C_{nfs} as a function of N/N_{nfs}. Figure 6 shows envelopes of all calibrations for each of three meters. Each meter was chosen as representative of its type. The shaded area, which has been drawn around the median of the envelope, represents the average probable error of a single calibration (0.12 percent at N_{nfs} increasing to 0.2 percent at 0.25 N_{nfs}).

Effect of installation stresses. - Calibrations performed after the AN-flare fittings had been progressively tightened with torques of 100, 150, and 200 pound-feet, respectively, showed no systematic shift in the value of C_{nfs} as large as the random variations in C_{nfs} that had otherwise been encountered.

Effects of relative position and orientation. - Calibrations were generally performed with two meters in line and arranged as shown in figure 2 (p. 7). The difference between C_{nfs} for the upstream and downstream locations of a flowmeter is shown in table IV.

One meter from each of two manufacturers was also calibrated in liquid hydrogen in a vertical position. The percentage deviation of the factor C_v from the factor C_h is given in table V for upward and downward directions of flow.

Linear range. - Values of the pulse rate ratio N_{nfs}/N_{980} are given in table VI. This ratio did not always have a constant value from one liquid-hydrogen calibration to another, so that the range of values encountered is listed, as well as the mean value.

TABLE IV. - EFFECT OF RELATIVE POSITION OF TWO GROUP I

METERS IN TANDEM

Meter type	Number of tests	$100\left[\frac{(C_{nfs} \text{ in downstream position}) - (C_{nfs} \text{ in upstream position})}{C_{nfs} \text{ in upstream position}}\right]$	
		Range of values	Average value
A	5	-1.3 to -0.2	-1.0
B	5	-1.3 to 0.8	-.2
C	1	-----------	.4

TABLE V. - EFFECT OF

METER ORIENTATION

Percent of nominal full scale flow rate	Meter type			
	A		C	
	Flow direction			
	Up	Down	Up	Down
	$100\left(\frac{C_v - C_h}{C_h}\right)$			
100	-0.3	-0.6	0	-0.1
30	1.0	1.0	-.3	-.2
25	1.0	1.0	.8	1.3
20	.9	.9	1.3	2.2

TABLE VI. - LINEAR RANGE AS DEFINED BY N_{nfs}/N_{980}

Meter	Pulse rate ratio, N_{nfs}/N_{980}			
	Liquid hydrogen			Water
	Range of values	Mean value	Probable error, e_p, percent	Mean value
A1	2.5 to 3.1	2.9	5	12
A2	2.2 to 3.6	2.7	13	13
A3	2.1 to 2.4	2.3	4	20
A4	2.3 to 3.1	2.8	9	14
A5	3.0 to 4.3	3.5	10	13
Average	---------	2.8	8	14
B1	3.2 to 4.2	3.6	6	23
B2	2.8 to 4.8	3.4	13	28
B3	3.2 to 4.3	3.6	7	>20
B4	3.3 to 4.3	3.8	11	>20
B5	3.3 to 5.0	4.4	10	20
Average	---------	3.8	9	>22
C1	3.7 to 10.0	6.7	17	70
C2	4.3 to 7.1	5.9	14	50
C3	4.8 to 11.1	8.2	24	50
Average	----------	6.9	18	57

TABLE VII. - RATIO OF ASYMPTOTE OF CALIBRATION FACTOR IN WATER TO THAT IN LIQUID HYDROGEN

Meter	Ratio of asymptotes of calibration factor, $C_{m,H_2O}/C_{m,LH_2}$	
	Mean value	Probable error, e_p
A1	0.991	0.006
A2	.995	.012
A3	.972	.010
A4	.984	.005
A5	.995	.003
Average	0.987	0.007
B1	1.001	0.008
B2	.997	.004
B3	1.009	.005
B4	.993	.003
B5	1.005	.003
Average	1.001	0.005
C1	0.995	0.005
C2	.990	.006
C3	1.004	.005
Average	0.996	0.005

Also given is the variation e_p in the mean value that was obtained from several liquid-hydrogen calibrations of the meter. Comparable values of N_{nfs}/N_{980} for water are presented, as well as some grand averages that may be useful in characterizing the particular meter type. Included are data from tests with the meter downstream of another Group I meter, or of a nozzle, as well as with the meter in an upstream location, since there was no significant difference in linear range between upstream and downstream locations of a meter.

Relation to water calibration. - The ratio of C_m, the asymptote of the calibration factor, in water to C_m in liquid hydrogen is presented in table VII for each meter tested. The value of C_{m,H_2O} is generally the mean of two calibrations made an average of 1 year apart. The value of C_{m,LH_2} is the mean of all calibrations, over approximately a 2-year period, in which the meter was alone in the line or was the upstream meter of a tandem pair (with the downstream meter from Group I). The probable errors given include the random scatter of the test data, the probable error of the liquid-hydrogen calibration system (0.25 percent), and the probable error of the water calibration system (0.1 percent).

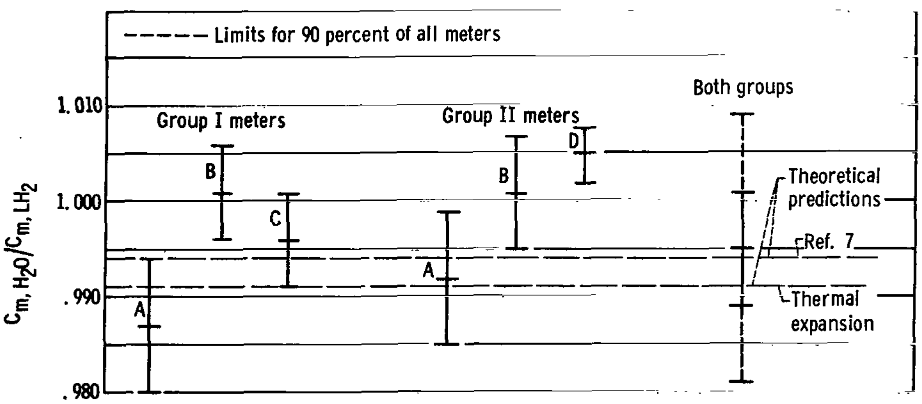


Figure 7. - Mean values of $C_{m,H_2O}/C_{m,LH_2}$ for various meter types and for all meters, and corresponding probable error for single meter.

The theoretical prediction of $C_{m,H_2O}/C_{m,LH_2}$ based on the thermal expansion of the meter materials is 0.991. Reference 7, which allows for blade-tip clearance and boundary-layer effects, predicts 0.994 for all three types of meter. The results are given in table VII and shown graphically in figure 7.

Group II Meters

In the following presentation of results on Group II meters, each "type" designation represents a different mechanical design. In most cases, a meter was merely calibrated twice in liquid hydrogen within a 24-hour period. In a few cases, these calibrations were followed by a calibration in water and then by another calibration in liquid hydrogen. The liquid-hydrogen data presented then represent the average of the several runs, the dispersion among them being small.

Pressure drop. - The empirical relation $\Delta p = 0.4\ \rho v^2 D$, where D is in inches and v is the actual linear liquid velocity through the annulus at the location of the blades, describes the overall pressure drop for 80 percent of all the meters tested. The formula applied well to conventional designs for liquid service. It was in error (high or low) by a factor as high as 2 for meters ordinarily considered as gas-service designs. Such meters are becoming increasingly popular for liquid-hydrogen service because they offer

TABLE VIII. - LINEAR RANGE AND CORRESPONDING ROTOR SPEED AND PRESSURE DROP AT VARIOUS REFERENCE FLOW RATES FOR SEVERAL GROUP II METERS

Meter		Linear range, N_r/N_{980}									
Size, in.	Type	$N_r = N_{nfs}$				$N_r = N_{0.5\ psi}$		$N_r = N_{2\ psi}$		$N_r = N_{7\ psi}$	
		Water	Liquid hydrogen								
		Linear range	Linear range	Rotor speed, rpm	Pressure drop, psi	Linear range	Rotor speed, rpm	Linear range	Rotor speed, rpm	Linear range	Rotor speed, rpm
$\frac{3}{4}$	Aa	10	1.9	9 000	0.5	1.9	9 000	3.8	18 000	7.1	34 000
	Ba	(a)	11 to 20	20 000	38	1.3 to 2.3	2 300	2.6 to 4.6	4 600	4.9 to 8.6	9 000
	Bb	(a)	6.6	15 000	.7	5.7	13 000	11	26 000	21	49 000
	Da	(a)	10	18 000	11	2.2	3 900	4.4	7 800	8.2	15 000
1	Aa	15	2.8	9 000	.5	2.8	9 000	5.6	18 000	10.5	34 000
$1\frac{1}{2}$	Aa	11	3.5	6 000	.7	3.0	5 100	6.0	10 000	11	19 000
2	Aa	13	2.8 to 9.2	4 500	1.0	2.0 to 6.5	3 200	4 to 13	6 400	7.5 to 24	12 000
	Bc	10	3.6	5 000	1.0	2.5	3 500	5.0	7 000	9.4	13 000

[a]Gas-service types.

greater linear range or better reproducibility.

Linear range. - Table VIII gives the values of linear range, defined by

$$\text{Linear range} = \frac{N_r}{N_{980}} = \frac{\text{Reference pulse rate}}{\text{Pulse rate at which } C = 0.980\ C_m}$$

for the following definitions of reference pulse rate:

N_{nfs} nominal full-scale pulse rate for water or standard air, as estimated from manufacturer's literature

$N_{0.5\ psi}$ pulse rate at which pressure drop of liquid hydrogen would be 0.5 psi (pressure drop of water = 7 psi)

$N_{2\ psi}$ pulse rate at which pressure drop of liquid hydrogen would be 2.0 psi (pressure drop of water = 28 psi)

$N_{7\ psi}$ pulse rate at which pressure drop of liquid hydrogen would be 7.0 psi (an equal flow rate of water would be impractical because of excessive pressure drop and excessive bearing load)

A range of values is given for certain meter types when there is a wide variation in the values of linear range for different meters of that type. Table VIII also lists the corresponding rotor speeds for each of the definitions of N_r, the pressure drop that would be obtained in liquid hydrogen at nominal full-scale flow rate, and, where applicable, the linear range in water based on nominal full-scale flow rate.

Relation to water calibration. - The ratio of the asymptotes of the calibration factors in water and liquid hydrogen $C_{m, H_2O}/C_{m, LH_2}$ is given in table IX for the three principal meter types tested. Only type Aa meters were tested in sizes from 3/4 to 2 inches; there was no significant correlation with size. Although "gas-service" meters could not

TABLE IX. - VALUES OF ASYMPTOTES OF CALIBRATION FACTORS

IN WATER AND LIQUID HYDROGEN FOR GROUP II METERS

Meter type	Number of meters	Range of values	Average value	Probable error, e_p (a)
Aa	10	0.982 to 1.010	0.992	0.007
Ba, Bb, Bc	4	0.992 to 1.009	1.001	.006
Da	2	1.005 to 1.005	1.005	.003

[a]Includes probable error of liquid-hydrogen and water calibration facilities.

be run at N_{nfs} in water because of the excessive pressure drop that would have resulted, the determination of C_{m, H_2O} was made readily at a fraction of N_{nfs} because of the large linear range of these meters in water.

The probable errors given in table IX include the random scatter of the data, the probable error of the liquid-hydrogen calibration system (0.25 percent), and the probable error of the water calibration system (0.1 percent). The data in the table are also presented graphically in figure 7.

DISCUSSION AND CONCLUSIONS

Reproducibility

A meter user is interested in the extent to which a meter calibration can be known in any installation, from prior calibrations in laboratory setups. This predictability appears to depend on

(1) The one variable factor within the meter, the rotor bearings

(2) The influence of the meter installation on the angle between the rotor blades and the fluid velocity vector in the vicinity of the rotor, and on the local distribution of this velocity

Table III (p. 9) suggests that a threefold improvement in reproducibility of C_{nfs} may be achievable over a short time interval if the meter is not exposed to room environment between calibrations. The tests were not sufficiently definitive to establish the relative importance of avoiding an oxide-forming environment and avoiding atmospheric dust, nor to indicate the relative importance of the favorable atmosphere and the short time interval. A considerable fraction of the improvement may be attributable to higher short-term accuracy of the calibration facility.

Figure 6 is directed to the following problem: if a single calibration of a meter is given, the probable variation in subsequent calibrations of that same meter is to be predicted. Figure 5 is directed to a different problem: if a typical calibration for a given meter type is given, calibrations of other meters of the same type are to be predicted, assuming that C_{nfs} has been determined for each meter. This latter problem is of practical importance because C_{nfs} is often determinable from water or high-pressure-gas calibrations even when C at $N < N_{nfs}$ is not determinable.

Figure 6 indicates that, despite the variations in curve shapes shown in figure 5, the maximum overall variation in the calibration of any one of the Group I meters used as examples was of the same order as the maximum variation to be expected from the experimental inaccuracies of the calibration facility. The conclusions suggested by this fact are that, for these meters,

(1) An approximately 50-percent probability exists that the calibration of any one meter will be reproducible to better than $e_p = 0.12$ percent at N_{nfs} and to better than $e_p = 0.2$ percent at 0.25 N_{nfs}.

(2) A high probability exists that the calibration of any one meter will be reproducible to $e_p = 0.25$ percent at N_{nfs} and to $e_p = 0.5$ percent at 0.25 N_{nfs}.

Figure 5 (p. 11), which applies to a meter type rather than to a single meter, shows that the calibration-curve shape is much less reproducible among several meters of a given type than is the calibration-curve shape for any one meter.

Linear Range

Table VI (p. 13) clearly indicates that the fourteenfold lower density of hydrogen reduces the linear range by a factor of about 6 on the average. Furthermore, the linear range, when defined in reference to nominal full scale, is shown in tables VI and VIII to be so small that a single, constant calibration factor C over the entire usable range of the meter would provide inadequate accuracy in many applications. Although this condition is inconvenient because it makes necessary the use of a calibration curve, no corresponding loss of accuracy is implied. The random variation in C at one-third of nominal full scale was, on the average, about twice the random variation at full-scale flow. Thus, although C does not remain constant, it often remains adequately reproducible.

Table VI (p. 13) and figure 6 (p. 11) suggest that a small blade-tip clearance improves the linear range, because meter types A, B, and C had progressively smaller clearances. Table VIII (p. 15) shows the desirability of operation at the highest rotational speed permissible, subject to limitations imposed by (1) bearing wear, (2) adequate safety margin over the vapor pressure of the hydrogen, and (3) permissible line pressure loss. The linear range is improved, and there is a corresponding improvement in reproducibility at the higher rotational speeds because the effects of bearing friction become of smaller relative significance.

Table X indicates the increase in linear range that presumably could have been obtained with Group I meters, if they had been operated at higher speed and with higher pressure drop.

Bearing life in these small meters is limited principally by abrasion of the balls in the full-complement bearing design that is necessarily used; the bearings are too small to permit use of nonmetallic retainers. In larger meters, with bearings large enough to accommodate glass-filled Teflon retainers, a relatively high operating speed would be even safer (ref. 8).

TABLE X. - LINEAR RANGE AND CORRESPONDING ROTOR SPEED AND PRESSURE DROP OBTAINABLE AT VARIOUS REFERENCE FLOW RATES WITH GROUP I METERS

Meter type	Linear range, N_r/N_{980}					
	$N_r = N_{nfs} = N_{0.5\ psi}$		$N_r = N_{2\ psi}$		$N_r = N_{7\ psi}$	
	Linear range (a)	Rotor speed, rpm	Linear range	Rotor speed, rpm	Linear range	Rotor speed, rpm
A	2.8	6000	5.6	12 000	10.5	22 500
B	3.8	5000	7.6	10 000	14	19 000
C	6.9	3750	14	7 500	26	14 000

[a]From table VI.

Effect of Upstream Conditions

The results in table IV (p. 13), despite the broad dispersion of individual values, do suggest the existence of a systematic effect for at least one of the meter designs. Where such effect existed, it would be necessary that upstream swirl and radial velocity distribution be thoroughly dissipated before a meter could be assumed to have the same calibration in two different installations. Apparently, the straightening-vane installation shown in figure 2 (p. 7) did not achieve this goal, probably because of inadequate plenum length downstream of the straighteners.

Effect of Orientation

The results in table V (p. 13) show that the difference in calibration factor between vertical and horizontal orientations of the meter is small or negligible at nominal full scale, but may be of the order of 1 percent at about one-fourth of nominal full scale. The difference between upward and downward flow was negligible for one design and significant for another.

Relation to Water Calibration

The conclusions suggested by figure 7, which summarizes data on the ratio $C_{m,H_2O}/C_{m,LH_2}$, and by the original data are as follows:

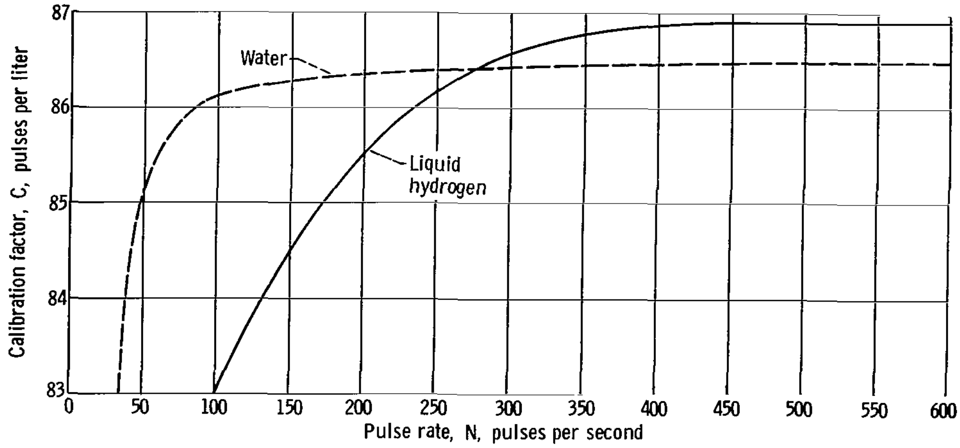


Figure 8. - Comparison of liquid-hydrogen and water calibrations.

(1) The most probable value of the ratio is a characteristic of the meter design.

(2) For the meter types tested, the ratio for any one meter differed from the most probable value for that type by less than 0.7 percent for 50 percent of the meters of that type, and by less than 1.0 percent for 90 percent of the meters of that type.

(3) The experimentally determined most probable value for the various meter types tested differed from the theoretically predicted value of reference 7 by about 0.5 percent on the average, and the maximum disagreement is 1.1 percent.

(4) For all meters tested, regardless of type, the average value of the ratio was 0.995, and the deviation from this ratio for any one meter is less than 0.7 percent for 50 percent of the meters tested and less than 1.5 percent for 90 percent of the meters tested.

(5) The uncertainty of the ratio for any one meter is reduced if there is adequate prior data on meters of that design, but may nevertheless remain sufficiently large to necessitate an actual calibration in liquid hydrogen.

Figures 5 and 6 (p. 11) and tables VI (p. 13) and VIII (p. 15) also indicate that prediction of a meter calibration in liquid hydrogen at flow rates lower than one-third of nominal full scale often cannot be made with acceptable accuracy from the water calibration. The dashed curve in figure 8 shows a water calibration of a typical meter for comparison with the liquid-hydrogen calibration of the same meter. In a companion report (ref. 7) it will be shown that a closer approach to a correct prediction is obtainable by calibration with high-pressure nitrogen.

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