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AN EVALUATION OF SELECTED ANGULAR MOMENTUM, VORTEX SHEDDING AND ORIFICE CRYOGENIC FLOWMETERS

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AN EVALUATION OF SELECTED ANGULAR MOMENTUM, VORTEX SHEDDING AND ORIFICE CRYOGENIC FLOWMETERS

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PREFACE

The comments in this report, the use of descriptive phrases, or the actual performance of the meters do not in any way constitute endorsement either expressed or implied by the National Bureau of Standards.

It is the policy of the National Bureau of Standards to use the International System of Units (SI) in its reports unless this usage would lead to confusion or a lack of understanding. In this report SI units have not been used because it is standard practice in the industry to use English units and the use of SI units would be unduly cumbersome. The following conversions are given so the reader can convert the values in the report if he desires.

$\text{feet}^3 \times 0.028317 = \text{metre}^3$

gallons x 3.7854 = liters

gallons/minute x 0.06309 = liters/second

inches x 0.0254 = metres

pounds x 0.45359 = kilograms

$\text{pounds/inch}^2 \times 6894.757 = \text{pascals}$

The authors wish to thank Dr. Peter Tryon of the NBS Statistical Engineering Laboratory for his assistance in this program. The test schedules he prepared and the assistance in analyzing the data have been invaluable.

CONTENTS

List of Figures

CONTENTS

List of Figures (continued)

List of Tables

CONTENTS

List of Tables (continued)

AN EVALUATION OF SELECTED ANGULAR MOMENTUM, VORTEX SHEDDING AND ORIFICE CRYOGENIC FLOWMETERS

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The National Bureau of Standards (NBS) and the Compressed Gas Association (CGA) have jointly sponsored a research program on cryogenic flow measurement. Cryogenic flowmeters operating on the principles of angular momentum (mass flow), vortex shedding (volume flow), and pressure drop are reported.

The operation and the accuracy of the flow facility is briefly described. The performance of the flowmeters in liquid nitrogen is described by reporting the precision and bias of the meters before and after an 80-hour stability test and by defining the existence of temperature, pressure, flow rate, subcooling, and time order (wear) dependencies.

Meters were evaluated with flow rates ranging from 20 to 210 gpm (0.00126 to 0.0132 m^3/s), pressures ranging from 32 to 112 psia (0.22 to 0.77 MPa), and with temperatures ranging from 72 to 90 K.

Key words: Angular momentum; cryogenic; flow; liquid nitrogen; mass; mass flowmeters; measurement; orifice; volume flowmeters; vortex shedding.

1. Introduction

The National Bureau of Standards and the Compressed Gas Association have jointly sponsored a program of cryogenic flow research. The dynamic gravimetric flow facility at NBS-Boulder has been used to evaluate flowmeters operating on several principles. This report describes the results of the evaluation of an angular momentum direct reading mass flowmeter, a vortex shedding volumetric flowmeter, and an orifice flowmeter. Previous reports have been published on the results of positive displacement meters and turbine meters [Brennan et al., 1971, 1972]. These meters were submitted for testing as a result of joint recommendations of the Compressed Gas Association Committee on Cryogenic Liquid Flowmetering and the National Bureau of Standards, Cryogenics Division. The meters were intended to be representative of those available from industry.

2. Cryogenic Flow Research Facility

The continuous flow loop used in the meter evaluations allows the dynamic gravimetric measurement of liquid nitrogen flow. The continuous flow loop, shown schematically in figure 1, allows the establishment of constant pressures, temperatures, and flow rates over a long period of time. Liquid is pumped out of the catch tank through a heat exchanger where the pump and heat energy are removed. Liquid then passes through the test section, weigh tank, and back to the catch tank. A measurement is taken by closing

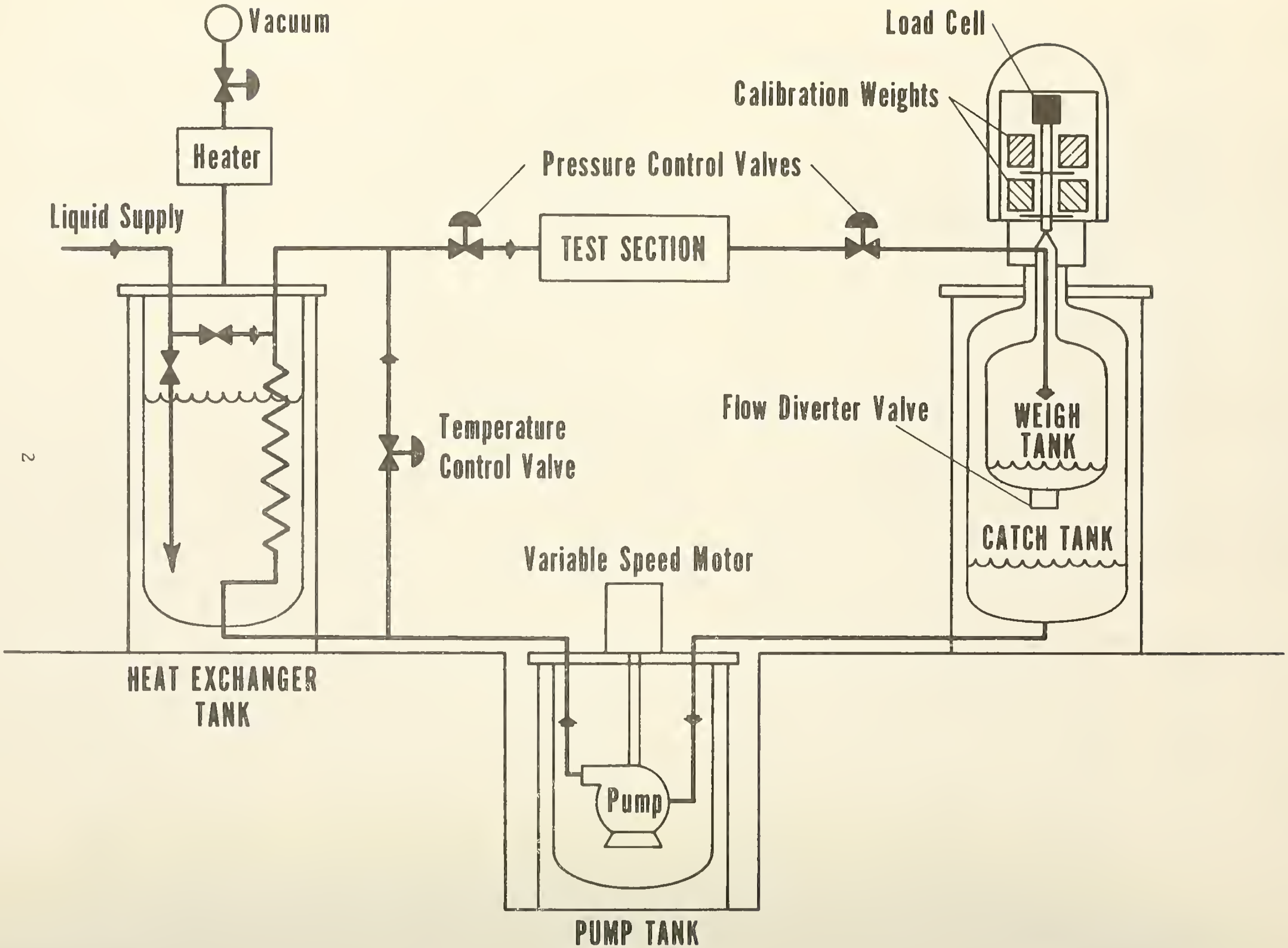

Figure 1. Schematic of Flow Loop.

the flow diverter valve, weighing the fluid that passes through a meter under test located in the test section, recording the meter registration, and timing the test interval. When the tank is filled to a preset level, the flow diverter valve is opened automatically without interrupting the flow. A more complete discussion of the design of the facility is given by Dean et al., [1969].

The principle operating criteria of the flow research facility during the period of these meter evaluations were:

1) Ability to establish and maintain thermal and pressure equilibrium during test.

2) Operation with temperatures ranging from 72 to 90 K and with pressures from 32 to 112 psia (0.22 to 0.77 MPa).

3) Usable weigh tank volume from 50 to 100 gallons (189 to 379 ℓ).

4) Flow rates cover the volume flow range from 20 to 210 gpm (1.26 to 13.2 ℓ/s) [current flow rate limitations of facility].

A detailed description of the accuracy statement for the flow facility has been presented by Dean et al., [1971]. In that report the uncertainty of the measurement of total mass flow was estimated to be ± 0.18 percent. This figure includes an allowance of ± 0.12 percent for known sources of systematic errors, plus an allowance of ± 0.06 percent for random error. The estimated uncertainty due to random error was based on three times the standard deviation calculated from 23 applications of the calibrated weights over a period of three months. An additional uncertainty was specified for total volume flow which was caused by the uncertainty in the thermodynamic properties data. However, when a consistent set of data is used by all meter users this additional uncertainty need not be considered.

Continued analysis of the system has not revealed any reasons for changing the uncertainty values at this time. The random error determination can now be based on many more applications of the calibration weights, but the values are approximately the same as reported by Dean. A revision of the accuracy statement is planned in the near future.

3. Meter Description

Test results are presented for ten meters representing three different manufacturers. In most cases more than one meter of the same size and model was submitted for testing. A brief description of each meter is given in table 1. A detailed description is presented in the appendices.

Table 1. Meter Characteristics

Manufacturer	Meter Designation	Operating Principle	Size in. (cm)	Rated Capacity
1	T, U, FF	Angular Momentum	3 pipe (8.89)	4-32 lb/s
1	BB	Angular Momentum	3 pipe (8.89)	2-16 lb/s
2	W, AA,	Vortex Shedding	$1\frac{1}{2}$ pipe (4.83)	12-120 gpm
2	CC, DD	Vortex Shedding	$1\frac{1}{2}$ tube (3.81)	12-120 gpm
3	X, II	Pressure Drop	1.8 (4.57)	0-25 in. H_2O ΔP

The angular momentum meters are direct reading mass flowmeters while the vortex shedding meters are volumetric meters.

The orifice meters were installed in a piping run with several design features intended to eliminate pressure oscillations characteristic of cryogenic systems.

4. Method of Meter Evaluation

The performance of the meter was evaluated by comparing the amount of liquid registered by the meter over the test interval to the liquid mass accumulated in the weigh tank for a wide range of liquid conditions. The mass of liquid registered by the volumetric meters tested was calculated from the expression:

$$M_R = P \cdot V_K \cdot \rho \tag{1}$$

where

M_R = mass registered by meter (lb)

P = pulses, or meter counts

V_K = volume meter factor (gal/pulse)

ρ = liquid density (lb/gal).

The volumetric meter factor, V_K, is the volume registered by the meter per count. The volume meter factor normally used in this calculation was supplied by the manufacturer. The liquid mass accumulated in the weigh tank is started and terminated on integer meter counts.

The mass of liquid registered by the mass meters tested was calculated from the expression:

$$M_R = P \cdot M_K \tag{2}$$

where

M_K = mass meter factor (lb/pulse).

The mass of liquid registered by the head meter tested was calculated from the expression:

$$M_R = \dot{m}_R \cdot t \tag{3}$$

where

t = test duration (seconds).

The mass flow rate registered by the meter, $\dot{m}_R$, was an average value measured during the test duration. It was calculated from the expression:

$$\dot{m}_R = \alpha A (2g \overline{\Delta P} \rho)^{\frac{1}{2}} \tag{4}$$

where

g = gravitational constant

α = orifice flow coefficient (taken from a standard, not determined experimentally)

A = orifice area (in^2)

$\overline{\Delta P}$ = mean orifice pressure drop (psi)

ρ = fluid density (lb/gal).

The analog ΔP measurement was made compatible with the digital logic system by converting the pressure transducer voltage signal to frequency with a voltage to frequency converter.

The mass registered in all tests was then compared to the mass accumulated in the weigh tank and the percent deviation calculated as follows:

$$\text{percent deviation} = \frac{M_R - M_{NBS}}{M_{NBS}} \cdot 100 \tag{5}$$

where

M_R = mass registered on the meter

M_{NBS} = mass measured by NBS.

The Cryogenic Liquid Flowmetering Committee of the CGA and NBS jointly decided to subject each meter to three types of test. These tests are a rangeability test, a long term stability test, and a boundary test. If the meter has no moving parts, only a rangeability test and a boundary test are run. The reason for emphasizing mechanical stability over thermal and readout stability is that the latter two do not necessarily require a a flow facility. In the interest of conserving time and money, only mechanical stability was tested since it does require a flow facility.

The purpose of the rangeability test is to subject the meter to a variety of conditions and to observe the response of the meter to these conditions. This test was statistically designed so the effect of various factors could be separated. The temperature range explored was from 80 to 90 K in 2.5 K increments. The pressure range was 62 to 112 psia (0.427 to 0.772 MPa) in increments of 12.5 psi (0.086 MPa). Flow rates depended on the meter or flow facility capacity with the flow range being divided into four equal increments if the flow rate range was small. The flow range was divided into twelve equal increments if the range was not small. A typical test schedule is given in Appendix A.

The boundary test was performed with the liquid conditions at the bounds of what the Cryogenic Liquid Flowmetering Committee and NBS judged to be well beyond the normal operating range for most meters and within economic operation of the flow facility. The upper boundary was set at a pressure of 112 psia (0.772 MPa) with the temperature varying from about 72 to 85 K. The lower pressure boundary was set at 32 psia (0.22 MPa) with the temperature ranging from 72 K to a temperature as close to the saturation temperature as could be obtained without excessive cavitation occurring in the meter. The purpose of these bounds was to establish a wide range of liquid subcooling conditions.

An 80-hour stability test was designed to determine the effect of wear on the meter performance. The stability test was run at flow rates near the maximum rated capacity of the meter or the flow facility, whichever was smaller, and at a convenient temperature near 80 K in approximately 8-hour shifts with the meter being allowed to warm up overnight. If the meter had no moving parts, this test was not performed.

A first rangeability test was conducted for each type of meter before the 80-hour stability test, and a second rangeability test was performed at the conclusion of the stability test. The boundary test was performed before the start of the stability test.

5. Data Analysis

The criteria for meter performance are the precision and bias of the meter and the existence of flow rate, temperature, subcooling, pressure and time order (an indication of meter wear) dependencies. The bias is defined as the mean percent deviation from the measured NBS mass for repeated measurements at a specified set of flow conditions. The precision is a measure of the ability of the meter to reproduce the same bias for repeated measurements at the same flow conditions. The precision is reported as three times the standard deviation and, for a meter with no significant dependencies, is calculated from the following expression:

$$3\sigma = 3\left[\frac{\left(\sum_{i=1}^{n} y-a_i\right)^2}{n-1}\right]^{\frac{1}{2}} \tag{6}$$

where

σ = standard deviation (percent)

n = the number of separate measurements over a range of flow conditions

y = mean bias of all n measurements (percent)

a_i = bias of each single measurement (percent).

For a meter that has significant dependencies, the precision is reported as three times the residual standard deviation after the data have been fitted to the mathematical model. The residual standard deviation is the standard deviation computed from the deviations (residuals) of the data points from the fitted curve, whereas the standard deviation is computed from the deviations of the data points from their mean value. The reported bias of the meter was obtained by evaluating the mathematical model at the maximum flow rate of the meter under test at a temperature of 80 K. The bias may also be calculated from the mathematical model for any desired combination of parameters that are within the range of the experimental data.

The mathematical model for a mass flowmeter is:

$$y = \mu + aT + bT^2 + c\dot{m} + d\dot{m}^2 + e\theta \tag{7}$$

where

y = bias in percent

μ = constant

T = temperature in kelvins, K

$\dot{m}$ = mass flow rate in lb/s

θ = time order term.

The coefficients a, b, c, d, and e give an indication of the dependency of the corresponding terms and are given for each rangeability test when they are significant. This model can be used for volumetric meters by substituting the volume flow rate, q, for the mass flow rate terms. Pressure terms are not included in the model since an examination of the data did not indicate a dependency for any of these meters. In the case where terms do not prove to be significant, they were removed from the model. In the majority of cases, reduced linear models have been used.

A subcooling term has not been included in the model since the rangeability test was designed to avoid a subcooling dependency. The subcooling dependency may be seen by examining the boundary test data. Similarly, the effect of wear is best seen by examining the stability test data.

When the meters showed a strong flow rate dependency at the low or high extremes of the flow range, that portion of the data was not fitted to the model. The model then can be considered a mathematical expression of the bias over the useable flow range of each meter. The primary criterion used in determining the significance of each parameter was the residual standard deviation after fitting. If the standard deviation did not change by more than 0. 02, then the parameter was not considered significant.

6. Meter Performance Summary

A meter test record is presented as table 2. The general CGA-NBS Committee policy is to have the manufacturers submit two meters for testing. One of the two is subjected to the first rangeability test, the boundary test, the stability test, and the second rangeability test. The second meter is subjected only to a rangeability test. By then comparing the rangeability tests of the two meters, an insight is gained into the manufacturer's ability to reproduce his meters.

Table 2. Meter Test Record

Manufacturer	Meter	First Range	Boundary	Stability	Second Range
1	T	X	X	X	X
1	U	X			
1	BB	X			
1	FF	X			
2	W	X	X		
2	AA	X			
2	CC	X	X	X	X
2	DD	X			
3	X	X	X		
3	II	X	X		

Meters W, AA, X, and II had no moving parts and were, therefore, not subject to wear in the same sense as the meters with moving elements. For that reason, the stability test and the second rangeability test were not performed.

A detailed description of the meters and their performance is given in the appendices. Wherever possible, meter performance is plotted using a six percent range in deviation. This range was chosen since the tentative code for Cryogenic Liquid Measuring Devices [1972] specifies a maintenance tolerance of + 2 percent and -4 percent. As long as the meters operated normally, all those reported here had sufficient precision over restricted flow ranges to satisfy the tentative code. A summary of the meter performance is given in table 3. The precision reported is three times the residual standard deviation calculated from the data taken during the rangeability test. The precision at the start is calculated from the first rangeability test taken before the stability test, while the precision at the end is calculated from the second rangeability test taken after the stability test. Data used in determining precision were taken from within the indicated flow rate range. The meter bias is reported for each rangeability test and could be reduced to zero with proper selection of meter factor or flow coefficient. The minimum subcooling required for consistent meter performance, as determined in the boundary test, is also reported.

7. Flowmeter Methodology

The accuracy that may be achieved with each of these meters is dependent to some degree on the manner in which they are used. An effort was made during the testing of these meters to observe and record any operational procedure or circumstances that may have a detrimental effect on the accuracy. Those observations are included in the appropriate appendix.

All the meters had varying degrees of restraint placed on the inlet piping configuration by the manufacturer.

Meters T and U were tested with and without a manufacturer supplied flow conditioner at the meter inlet. The reported results are with the flow conditioner installed. Without it these meters overregistered by as much as 2-1/2 percent at the higher flow rates. A change in the inlet piping specification permitted testing meters BB and FF without the flow conditioner.

Several inlet adapters were used for the transition from the flow facility piping to the meter piping on meter W. This was done at the manufacturer's request in an effort to increase the flow rate range. No detectable change in performance was found as a consequence of these piping changes.

Meter X was supplied with a considerable amount of inlet and outlet piping. Meter II was supplied only with an inlet and an outlet straight piping run. Both meters had special pressure tap connections.

Table 3. Meter Performance Summary

Meter Identification	Angular Momentum				Vortex Shedding				Orifice	
	T	U	BB	FF	W	AA	CC	DD	X	II
Precision (3σ) at start, %	≈ ±0.75*	±0.72	±0.93	±0.42	±0.45	±0.54	±0.63	±0.66	±1.50	**
Precision (3σ) at end, %	±0.54	-	-	-	-	-	±0.60	-	-	-
Bias at start, %	≈ +0.2*	+0.56	-0.17	+1.16	-0.48	-0.82	+0.33	+1.21	+2.17	**
Bias at end, %	-0.37	-	-	-	-	-	+0.56	-	-	-
Flow rate range for determining precision	8-22 lb/s (3.6-10 kg/s)	8-22 lb/s (3.6-10 kg/s)	4-16 lb/s (1.8-7.3 kg/s)	5-22 lb/s (2.3-10 kg/s)	20-100 gpm (1.3-6.3 ℓ/s)	20-100 spm (1.3-6.3 ℓ/s)	20-130 gpm (1.3-8.3 ℓ/s)	20-130 gpm (1.3-8.2 ℓ/s)	2.5-7 lb/s (1.1-3.2 kg/s)	
Quantity of liquid metered during stability test	4 773 700 lb (2 165 314 kg)	-	-	-	-	-	448 000 gal (1 696 000 ℓ)	-	-	-
Maximum flow rate	32 lb/s (14.5 kg/s)	32 lb/s (14.5 kg/s)	16 lb/s (7.3 kg/s)	32 lb/s (14.5 kg/s)	120 gpm (7.57 ℓ/s)	120 gpm (7.57 ℓ/s)	120 gpm (7.57 ℓ/s)	120 gpm (7.57 ℓ/s)	≈ 7 lb/s (≈3.2 kg/s)	≈ 7 lb/s (≈ 3.2 kg/s)
Minimum subcooling, K	8	-	-	-	6	-	8	-	-	4

NOTE: This table is a highly condensed summary of the results of an extensive testing program. In this table it has not been possible to present some information that may be important in some applications. For example, some of the meters tested had statistically detectable temperature and flow rate dependencies. These additional details are presented in the appendices of this report.

* Value not exact because of the possibility of a unique problem associated with the test.
** Not determined because test not run according to meter specifications.

8. Reference

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3. J. W. Dean, J. A. Brennan, and D. B. Mann, "Cryogenic Flow Research Facility of the National Bureau of Standards," Advances in Cryogenic Engineering, Vol. 14 (Plenum Press, New York 1969), p. 299.

4. J. W. Dean, J. A. Brennan, D. B. Mann, and C. H. Kneebone, "Cryogenic Flow Research Facility Provisional Accuracy Statement," National Bureau of Standards Technical Note 606 (1971).

5. "Tentative Code Cryogenic Liquid-measuring Devices," National Bureau of Standards, Handbook 44, 4th Edition, 1972 additions.

APPENDIX A. Rangeability Test Plan

The purpose of the rangeability test is to investigate the performance of cryogenic liquid flowmeters when the flowmeters are subjected to the following conditions:

1) Temperature varying from 80 to 90 K.
2) Pressure varying from 50 to 100 psig (0. 427 to 0. 772 MPa).
3) Flow rates from 20 gpm (1. 26 ℓ/s) to the maximum rated capacity in either four or twelve steps.
4) Average barometric pressure of 12. 0 psia (82. 7 kPa).

The liquid density resulting from the chosen pressure and temperature ranges from 6. 7 lb/gal (803 kg/m^3) to 6. 2 lb/gal (743 kg/m^3).

In addition, it is desired to keep the subcooling, which is a function of temperature and pressure, above 8 K.

It is time consuming and inefficient to change the temperature of the flow system, so temperature changes are kept to a minimum. Pressure changes are also kept at a minimum to conserve helium. The flow rate may be changed easily and quickly.

An example of a test plan is presented in table 1A. This particular plan was designed for a meter with a flow range from 20 gpm (1. 26 ℓ/s) to 130 gpm (8. 12 ℓ/s) The flow range has been divided into twelve equal increments in this example; however, a similar plan has been used that divides the flow range into four equal increments. The test draft weight was included as a parameter and was varied as shown in four increments. Points at high temperatures and low pressures are not included because of the subcooling requirement.

The numbers and arrows at the top of each column indicate the sequence in which the columns were executed and the points were taken.

The test plan was then used to generate an operator test schedule which is presented in table 2A. In order to conserve time, the approximate values of these parameters are set and held constant. The actual values are then measured and recorded.

Table 1A. Rangeability Randomized Test Plan

	3↓		5↑		1↓		4↓		2↑	
	Flow Rate gpm	Test Draft lbs	Flow Rate gpm	Test Draft lbs	Flow Rate gpm	Test Draft lbs	Flow Rate gpm	Test Draft lbs	Flow Rate gpm	Test Draft lbs
100	50	460	60	580	30	520	90	520	20	460
	100	580	80	520	110	460	120	400	100	400
							50	580	70	580
									40	460
									130	400
87.5	30	460	20	400	50	520	40	400	80	520
	130	520	130	580	90	400	70	520	120	580
							100	520	60	400
									110	460
									30	400
75	40	400	50	460	120	580	30	580		
	90	460	110	520	20	460	80	460		
					100	580	60	400		
							130	520		
62.5	20	580	70	460	40	460				
	50	400	90	520	80	400				
	100	520	120	460	60	580				
					110	520				
50	30	400	70	520						
	110	580	90	460						
	80	520	130	400						
	60	580	20	520						
	120	400	40	580						
Pressure PSIG / K Temperature	80		82.5		85		87.5		90	

Table 2A. Rangeability Partial Test Schedule

Run Number	Temperature K	Pressure psig	Test Draft lbs	Flow Rate gpm
1	85	100	520	30
2	85	100	460	110
3	85	87.5	520	50
4	85	87.5	400	90
⋮	⋮	⋮	⋮	⋮
56	82.5	87.5	580	130
57	82.5	87.5	400	20
58	82.5	100	520	80
59	82.5	100	580	60

APPENDIX B. Performance of an Angular Momentum Mass Flowmeter (Meters T, U, BB, and FF)

This meter is illustrated in figure 1B. Liquid is admitted to the inlet of the meter through a flow straightener and flows into a rotating member driven through a constant torque clutch by an electric motor. The liquid tends to retard the rotational speed of the rotor in a manner that is inversely proportional to the mass flow rate. Rotor speed is sensed by a magnetic pick up,and the resulting signal is treated electronically to indicate mass flow. Because of the inverse relationship,these meters will tend to overregister when additional drag is introduced into the rotating elements.

The meter supplier's specifications are:

Fluid - liquid oxygen, nitrogen, or argon

Size - 3 inch (7.62 cm) (Inlet)

	T, U, FF	BB
Maximum flow rate	32 lb/s (14.5 kg/s)	16 lb/s (7.3 kg/s)
Minimum flow rate	4 lb/s (1.8 kg/s)	2 lb/s (0.9 kg/s)

Maximum pressure - 350 psig (2.4 MPa)

Accuracy - ± 1% 8-32 lb/s (3.6 - 14.5 kg/s)
± 2% 4-8 lb/s (1.8 - 3.6 kg/s)

Four of these angular momentum mass flowmeters were tested (meters T, U, BB, and FF). Meters T and U were tested both with and without a manufacturer supplied flow conditioner in the inlet piping to the meter. Without the conditioner there was strong tendency to overregister at the higher flow rates. Only results with the flow conditioner installed are included in this report. Meters BB and FF were tested without the flow straightener but with different inlet piping providing more inlet straight section.

Three different methods were used in converting meter output to mass flow. The first method used electronics that provided a readout in ten pound increments. The second method used meter pulses directly, bypassing the electronics. The meter pulses were then converted to mass flow by equation B1:

$$M_R = MF \cdot t^2 / P \tag{B1}$$

where

M_R = mass registered by meter (lb)

MF = meter factor $\left(\frac{\text{lb}}{\text{s}} \cdot \frac{\text{P}}{\text{s}}\right)$

t = time (s)

P = pulses or meter counts.

The third method was the same as the first except new electronics were used in which the output was in 1.5 pound instead of 10 pound increments.

Only the first method was used for collecting the data during the first rangeability test on meter T. In this method the combination of a small test draft and the sampling technique used in the meter electronics might yield results with abnormally large scatter. Since there is the potential for poor meter performance that would be unique to the method of testing, the results from the first rangeability test are not included in this report. It was possible to estimate the meter bias and precision from the data, however, by comparison with a large amount of data obtained on other tests using different methods of collection.

The second method was used for collecting the remainder of the data on meter T as well as the data on meters U and BB. The third method was used for collecting the data on meter FF.

Capacity of the flow facility is approximately 22 lb/s (10 kg/s). Therefore, it was not possible to test the higher capacity meters throughout the manufacturer's stated flow range. Within the range tested, however, the performance of all the meters was similar.

All four meters were subjected to a first rangeability test but only meter T was tested in a boundary test, a stability test, and a second rangeability test.

Meter T

Results of the first rangeability test on meter T are not included here since there was a possibility of poor performance unique to the method of testing.

Results of the boundary test on meter T are shown in figure 2B. Below about 8 K subcooling there is a strong trend toward underregistration at a flow rate of 18 lb/s (8.2 kg/s).

Stability test results are shown in figure 3B. The total amount of liquid registered by the meter during the stability test was 4,773,700 lbs (2,165,314 kg). The average flow rate during this test was about 18 lbs (8.2 kg/s) and no significant dependencies developed.

Results of the second rangeability test are shown in figure 4B. The fit of the mathematical model to these data is given in table 1B. Only flow rates above 8 lb/s were included in the fit.

Table 1B. Fit of Model to Meter T Second Rangeability Test Data for the Flow Rate Range 8-22 lb/s (3.6-10.0 kg/s)

Model $y = 5.9599 - 1.4138\dot{m} + 0.09523\dot{m}^2 - 0.002002\dot{m}^3$
Bias at $\dot{m}$ = 22 lb/s, $y = -0.370\%$
Residual Standard Deviation, $\pm 0.18\%$
Number of Points = 45

Mass flow rate, mass flow rate squared, and the cube of the mass flow rate were found to be significant dependencies for this meter. Meter precision based on three times the residual standard deviation is ± 0.54 percent and the bias is -0.370 percent at a flow rate of 22 lb/s (9.98 kg/s).

The mean bias of these data without fitting them to the model is -0.486 percent. The standard deviation of these data without the model is ±0.24 percent and the precision based on three times the standard deviation is ±0.72 percent.

Meter U

Results of the first rangeability test on meter U are shown in figure 5B. Since flow rates below 8 lb/s (3.6 kg/s) were specified at a different accuracy, flow rates below 8 lb/s were excluded in the fit of the mathematical model to the data. The fit of the mathematical model to the remaining data is given in table 2B.

Table 2B. Fit of Model to Meter U First Rangeability Test Data for the Flow Rate Range 8-22 lb/s (3.6 - 10.08 kg/s)

Model $y = 168.584 - 1.8525\dot{m} + 0.1176\dot{m}^2 - 0.002386\dot{m}^3 - 3.8303T + 0.02307T^2$

Bias at $T = 80$ K and $\dot{m} = 22$ lb/s, $y = +0.565\%$

Residual Standard Deviation = ±0.24%

Number of Points = 42

Temperature, mass flow rate, the square of both of these terms, and the cube of the flow rate are significant dependencies. Meter precision based on three times the residual standard deviation is ±0.72 percent and the bias is + 0.565 percent at a temperature of 80 K and a flow rate of 22 lb/s (9.98 kg/s).

The mean bias of these data without fitting them to the model is -0.675 percent. The standard deviation of these data without the model is ± 0.45 percent and the precision based on three times the standard deviation is ± 1.35 percent.

Meter FF

Results of the first rangeability test on meter FF are shown in figure 6B. The low level cut out in the electronics used with this meter prevented registration below a flow rate of approximately five pounds per second. This fact plus the fact that the shape of the deviation vs. flow rate curve was different than the other meters permitted the use of all the data in the mathematical model. These data were fitted to the model and the results are shown in table 3B.

Table 3B. Fit of Model to Meter FF Rangeability Test Data

Model $y = -3.4815 - 0.1281\dot{m} + 0.008205\dot{m}^2 + 0.04645T$
Bias at $T = 80$ K and $\dot{m} = 21$ lb/s, $y = 1.163\%$
Residual Standard Deviation = $\pm 0.14\%$
Number of Points = 61

Mass flow rate, mass flow rate squared, and temperature were found to be significant dependencies. Meter precision based on three times the residual standard deviation is ± 0. 42 percent and the bias is + 1. 163 percent at a temperature of 80 K and a flow rate of 21 lb/s (9. 52 kg/s).

The mean bias of these data without fitting them to the model is - 0. 407 percent. The standard deviation of these data without the model is ± 0. 52 percent and the precision based on three times the standard deviation is ± 1. 56 percent.

Typical meter pressure drop data for the high range meters are shown in figure 7B. This pressure drop includes the pressure drop across the flow conditioning device in the inlet piping. Pressure drop across the meter alone was approximately half that shown in figure 7B.

Meter BB

Meter BB was similar to meters T, U, and FF but was rated at lower capacity. Externally it was similar in all respects to the larger capacity meters. During some preliminary testing on meter BB there was about a 2 percent shift in the meter factor. The meter was sent back to the manufacturer, but no explanation could be found for the shift. All the test results presented here were obtained after the meter was returned to NBS after the meter factor shift. No similar problems occurred during any of the remainder of the tests.

Results of the first rangeability test on meter BB are shown in figure 8B. These data were obtained by bypassing the electronics and converting the primary meter output to mass flow by equation B1. Only the data between flow rates of 4 and 16 pounds per second were used in fitting to the model. The results of that fitting procedure are shown in table 4B.

Table 4B. Fit of Model to Meter BB Rangeability Test Data for the Flow Rate Range 4-16 lb/s (1.8-7.26 kg/s)

Model $y = -68.7386 - 0.9002\dot{m} + 0.04172\dot{m}^2 + 1.6019T - 0.008728T^2$
Bias at $T = 80$ K and $\dot{m} = 16$ lb/s, $y = -0.169\%$
Residual Standard Deviation = ± 0.31%
Number of Points = 52

Mass flow rate, mass flow rate squared, temperature, and temperature squared were found to be significant dependencies. Meter precision based on three times the residual standard deviation is ± 0.93 percent and the bias is -0.169 percent at a temperature 80 K and a flow rate of 16 lb/s (7.26 kg/s).

The mean bias of these data without fitting them to the model is -0.031 percent. The standard deviation of these data without the model is ±0.78 percent and the precision based on three times the standard deviation is ± 2.34 percent.

Figure 9B shows pressure drop data for meter BB.

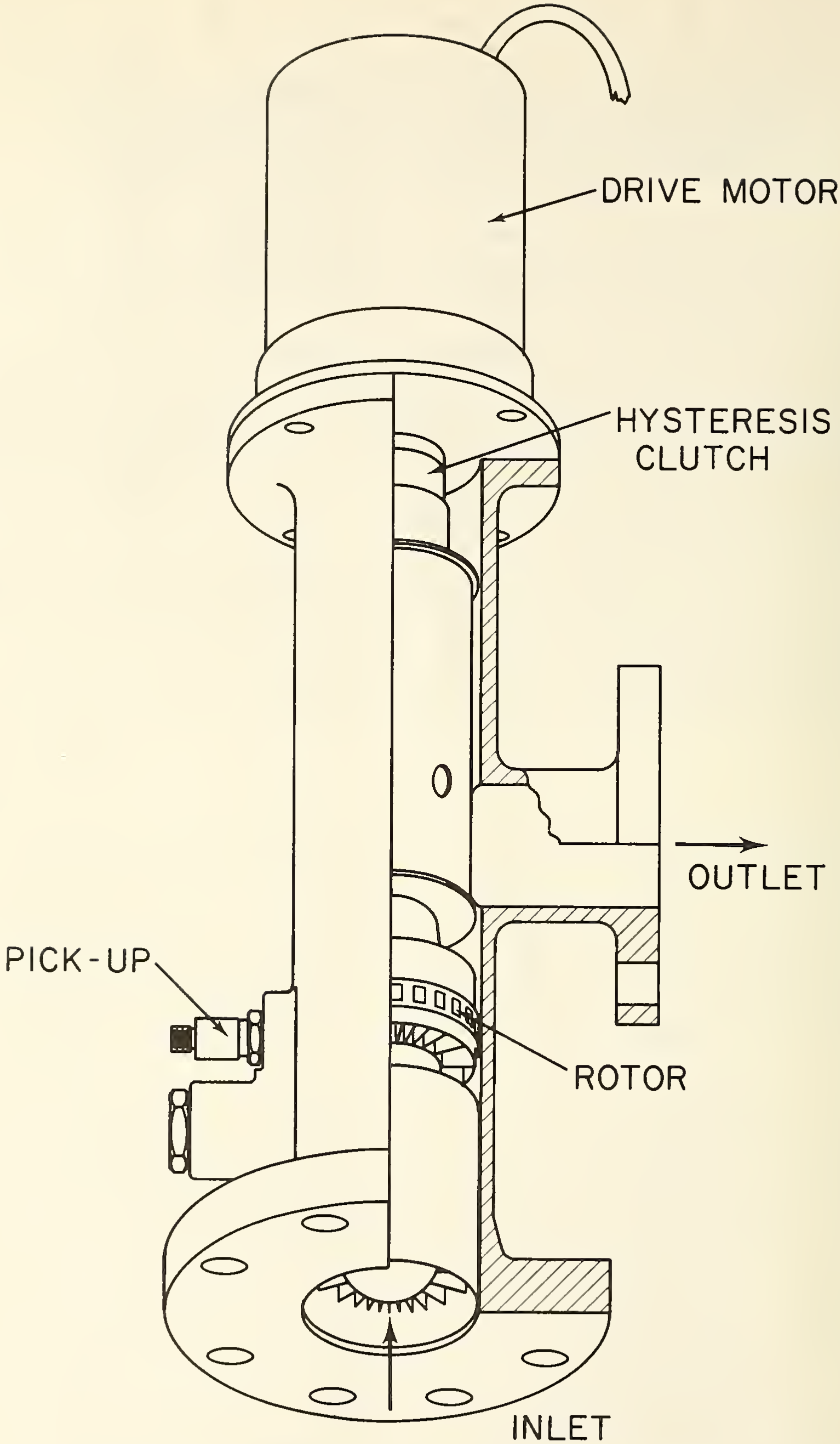

Figure 1B. Schematic of Meters T, U, BB and FF.

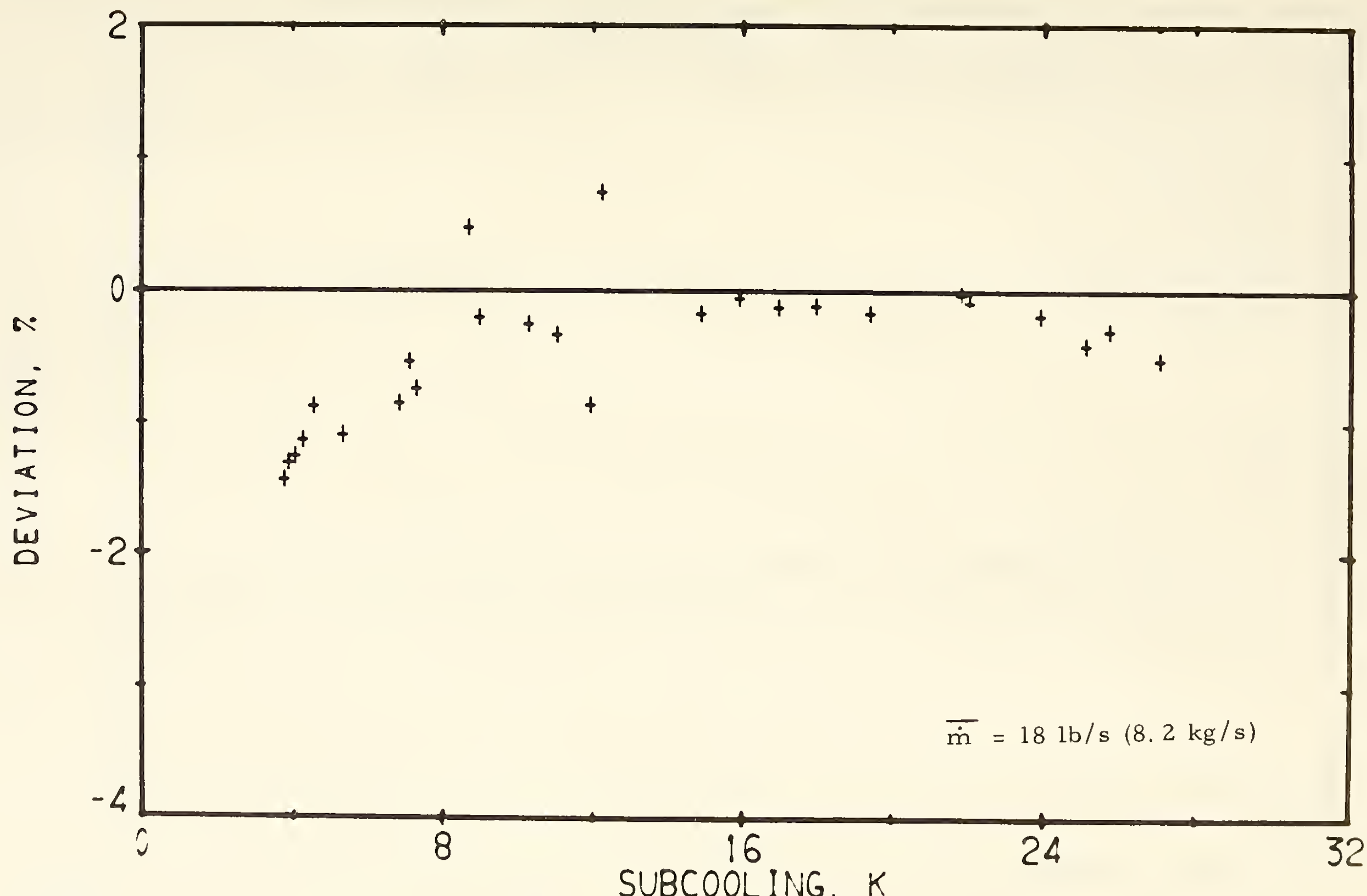

Figure 2B. Meter T, Boundary Test.

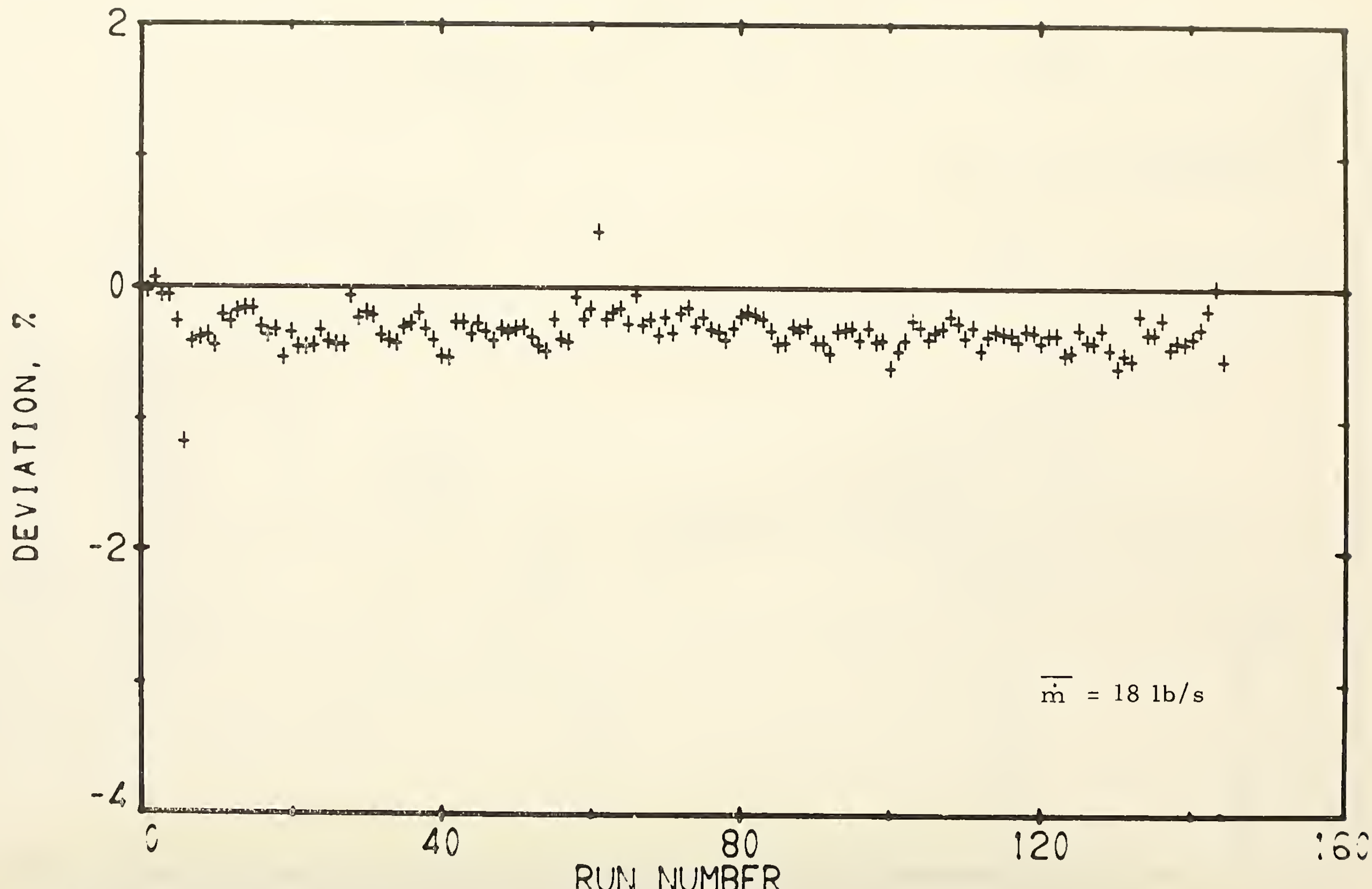

Figure 3B. Meter T, Stability Test.

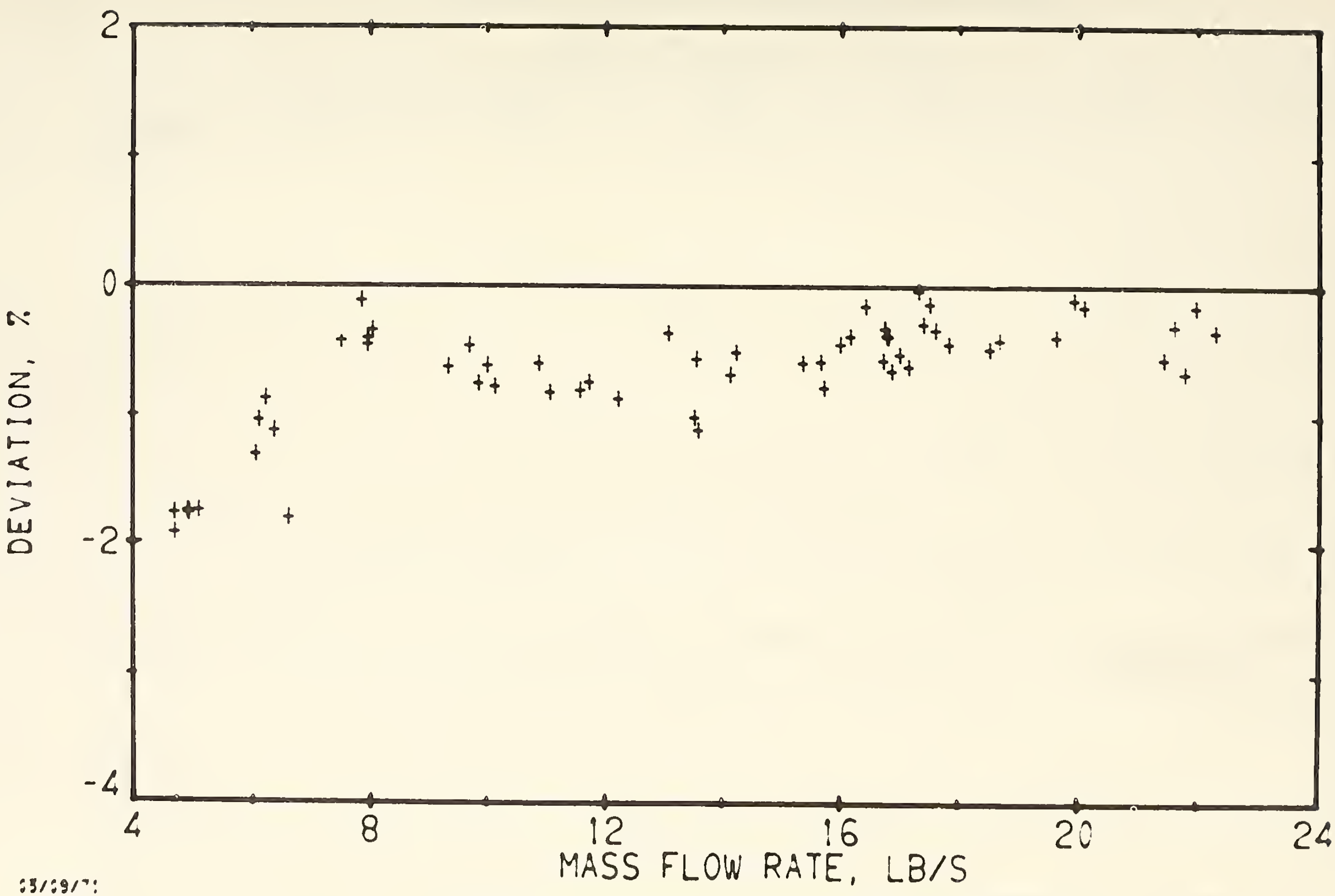

Figure 4B. Meter T, Second Rangeability Test.

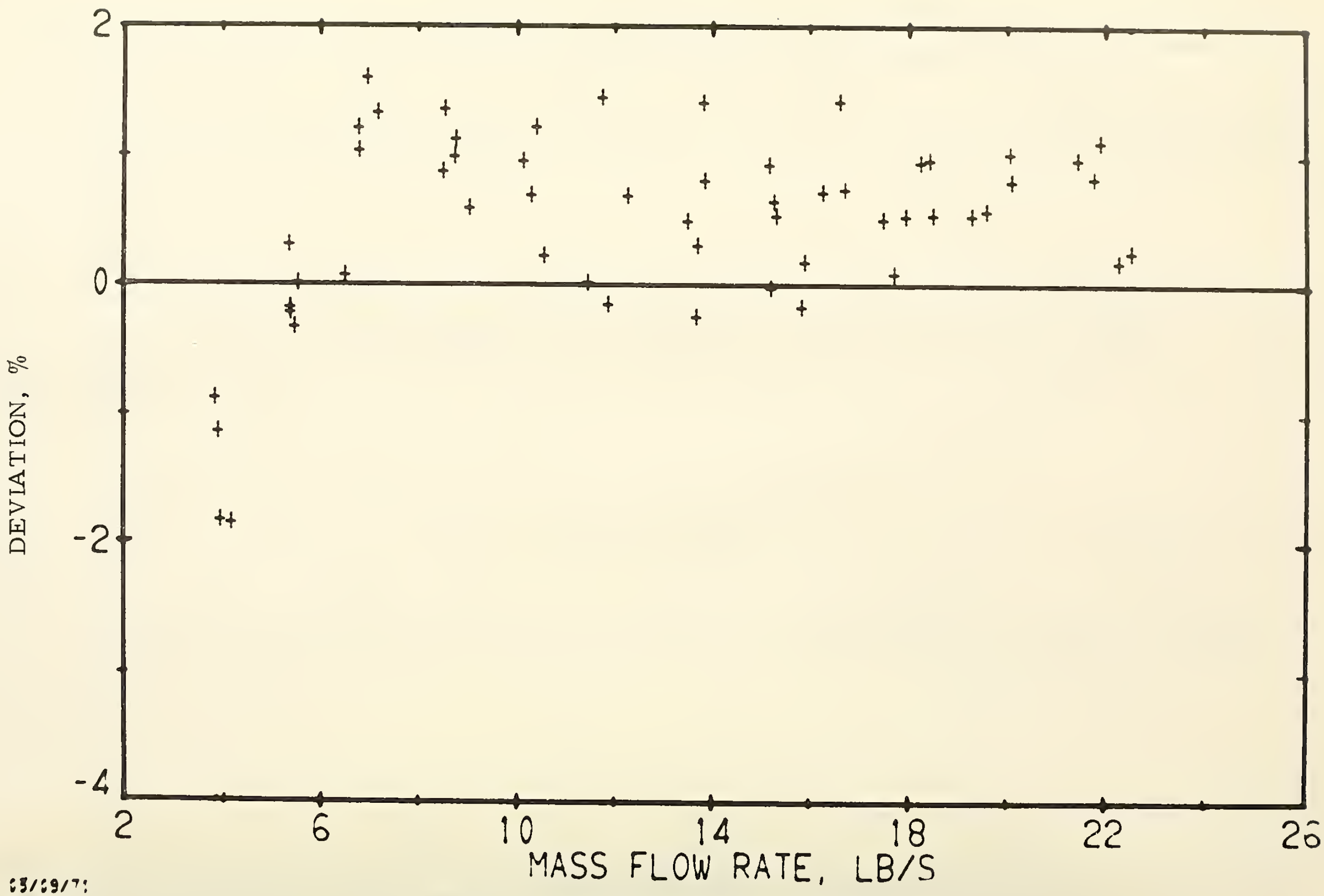

Figure 5B. Meter U, First Rangeability Test.

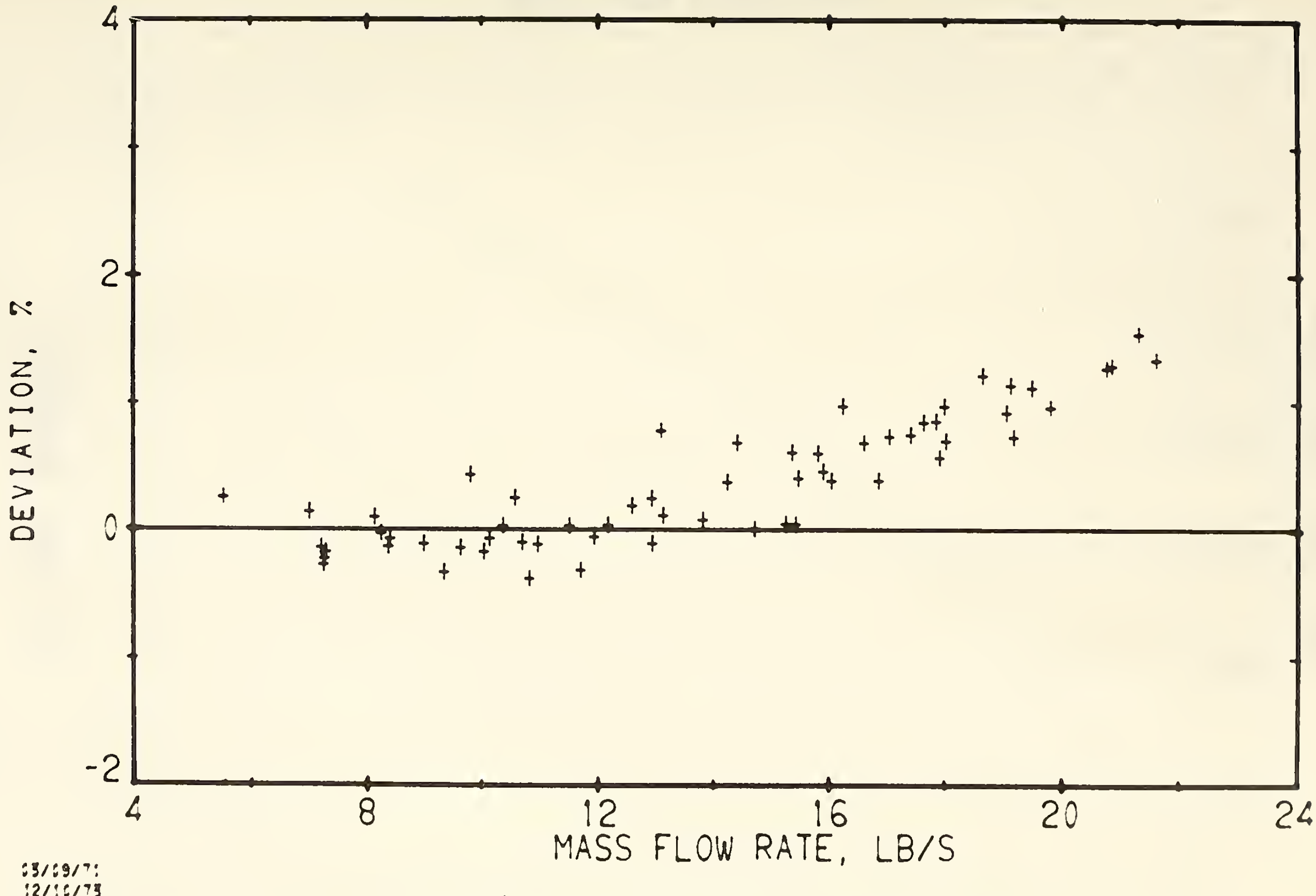

Figure 6B. Meter FF, First Rangeability Test.

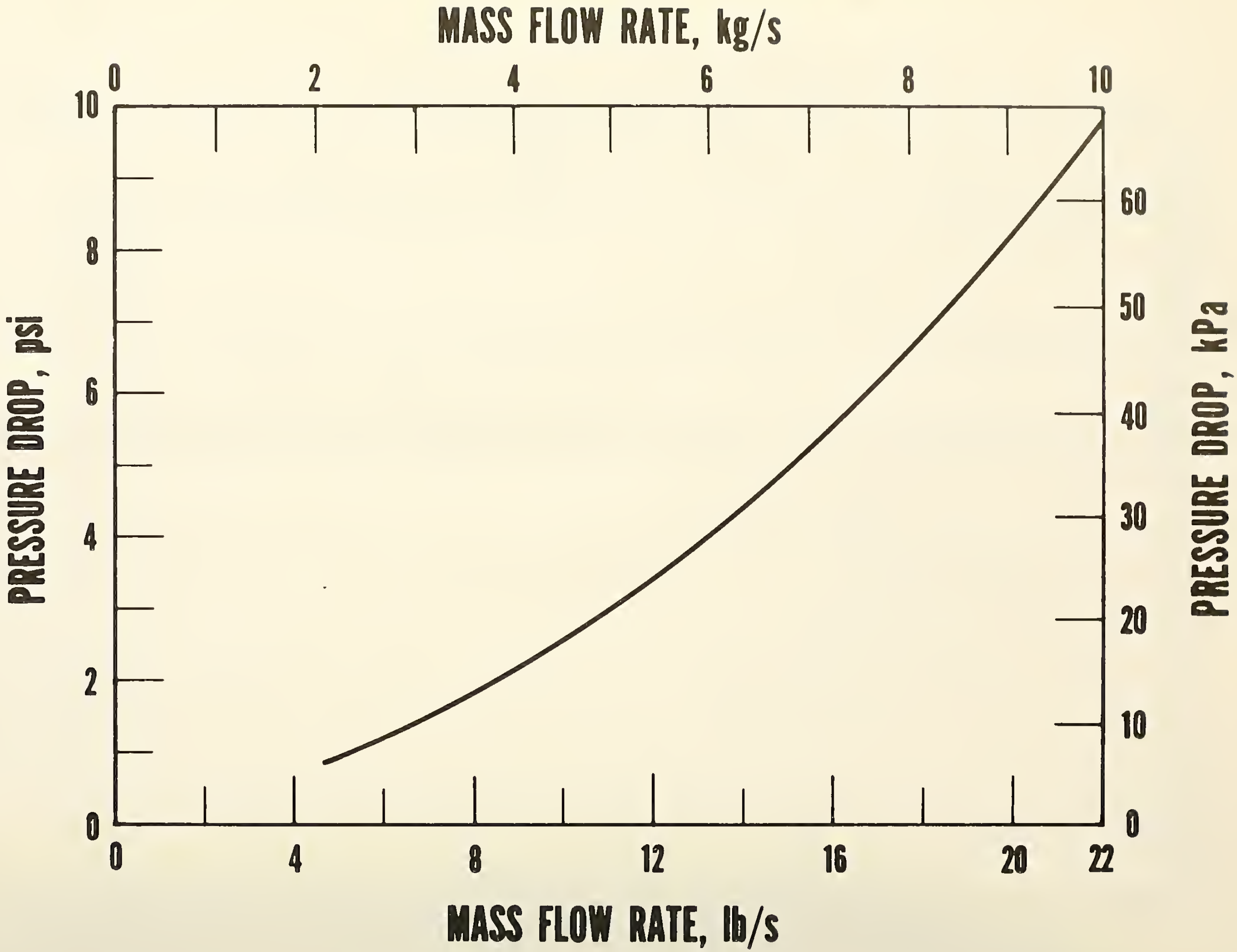

Figure 7B. Meters T and U, Pressure Drop.

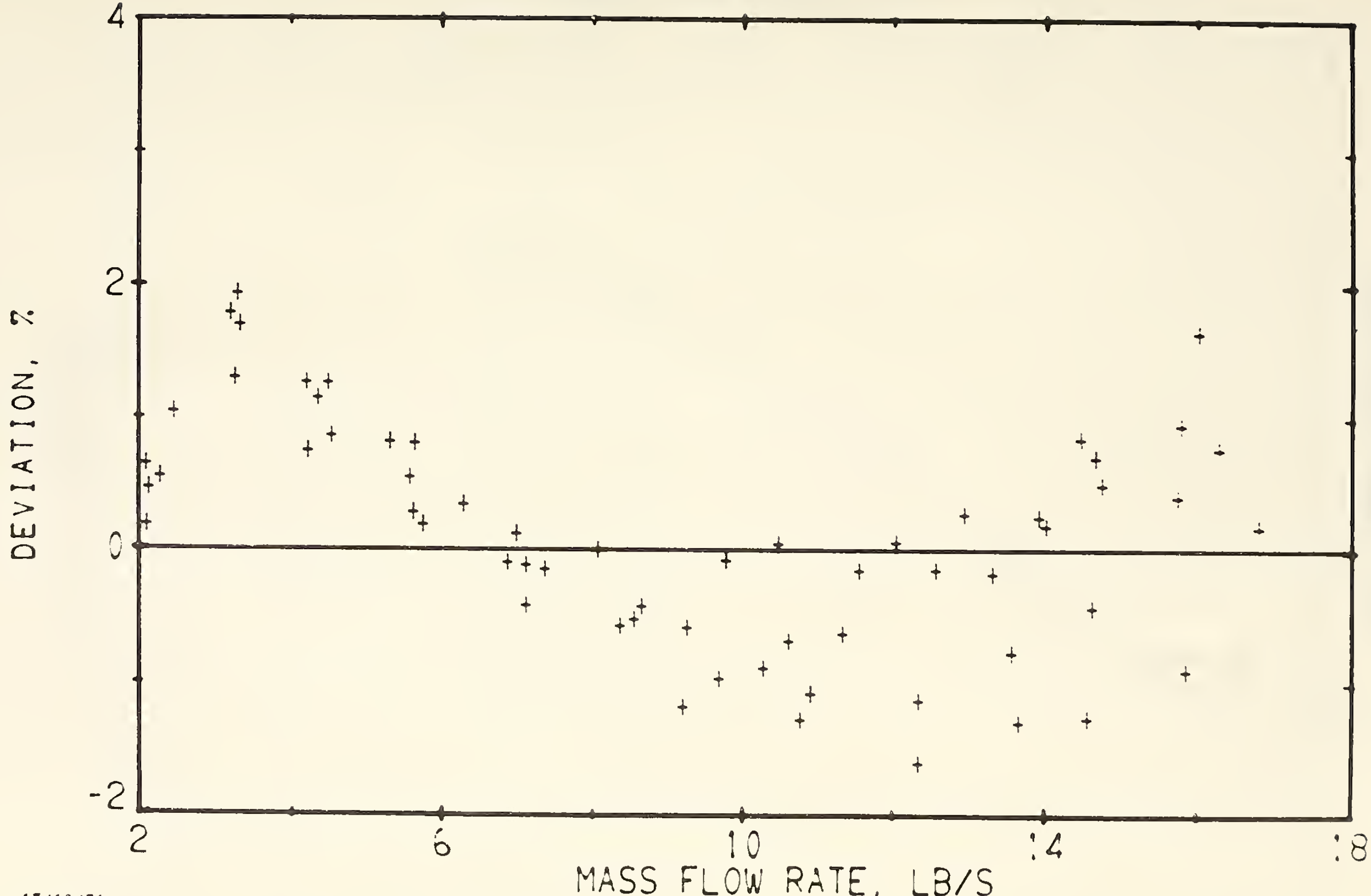

Figure 8B. Meter BB, First Rangeability Test.

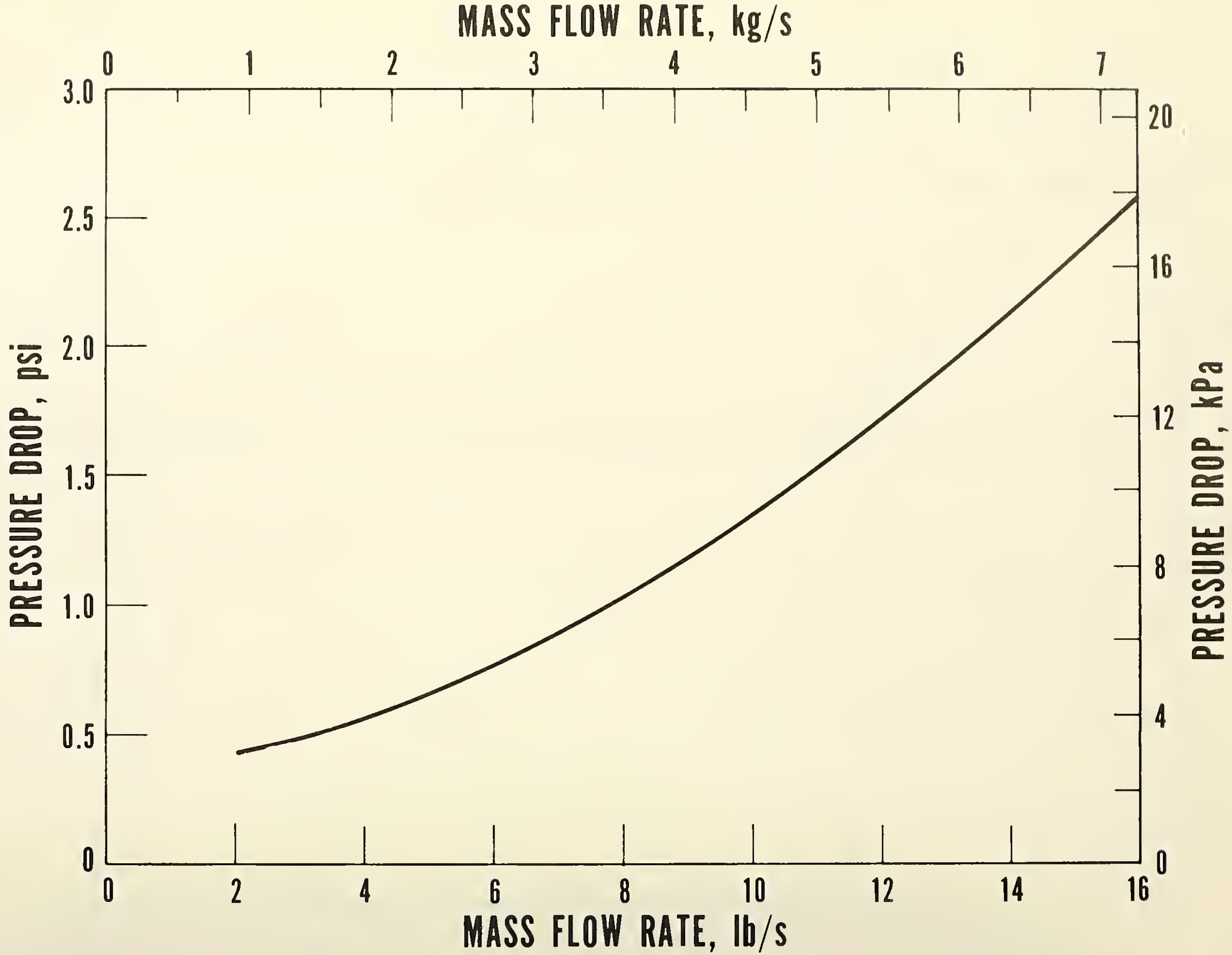

Figure 9B. Meter BB, Pressure Drop.

APPENDIX C. Performance of a Vortex Shedding Meter (Meters W, AA, CC and DD)

These meters are illustrated in figure 1C. The sensing element is in a stationary bluff body located in the flow stream. Vortices generated at the bluff body are shed at a rate that is dependent on the volumetric flow rate. The sensor detects the vortices and generates a signal which is treated electronically to yield a pulse output directly proportional to the volumetric flow rate. Meters CC and DD were made similar to a turbine meter with flared end connections instead of flange connections shown in figure 1C.

The specifications supplied by the meter manufacturer are:

Size - 1-1/2 in (3.81 cm)
Maximum flow rate - 120 gpm (7.57 ℓ/s)
Minimum flow rate - 12 gpm (0.757 ℓ/s)
Working pressure - 150 psi ANSI (1.03 MPa)
Pressure loss - 2.4 velocity heads
Calibration accuracy - ±0.25%
Repeatability - better than ± 0.1%
Linearity - ± 0.5%.

There were two outputs from the electronics supplied with these meters. One output gave one pulse per gallon (0.264 p/ℓ) and was connected to an electric motor driven mechanical register. The second ouptut was an amplified signal at meter frequency. In the work reported here the second output was used because there was a problem with the first output or in the register circuit on two of these meters which manifested itself in a failure to register. No attempt was made to check the performance of the one pulse per gallon output.

Four of the vortex shedding meters were tested. Since there were no moving parts in the meters W or AA, no stability or second rangeability tests were run on either meter. The other two meters did have one moving part, so a stability test and a second rangeability test was run on meter CC. All meters underwent a first rangeability test and meters W and CC also underwent a boundary test.

The moving part in meter CC and DD was a small metallic ball which moved under the influence of the vortex shedding action. The movement of the ball was detected with a magnetic pick-up similar to those used on turbine meters. Primary meter frequency using the metallic ball was approximate half the frequency in meters W and AA in which a temperature sensor was used.

Meter W

Results of the first rangeability test on meter W are shown in figures 2C and 3C. Since the linear range of the meter was less than specified the mathematical model was fitted to the data in the flow rates between 20 and 100 gpm (1.26 - 6.31 ℓ/s). The fit of the model to these data is given in table 1C.

Table 1C. Fit of Model to Meter W First Rangeability Test Data for the Flow Rate Range 20 - 100 gpm (1.26 - 6.31 ℓ/s)

Model $y = -3.7139 + 0.04036T$
Bias at $T = 80$ K, $y = -0.485\%$
Residual Standard Deviation = ± 0.15%
Number of Points = 44

A statistically significant temperature dependency was found. Meter precision based on three times the residual standard deviation is ± 0.45 percent and the bias is -0.485 percent at a temperature of 80 K.

The mean bias of these data without fitting them to the model is - 0.306 percent. The standard deviation of these data without the model is ± 0.21 percent and the precision based on three times the standard deviation is ± 0.63 percent.

Boundary test results are shown in figure 4C. Meter performance changes very abruptly as subcooling is reduced below a critical level. As noted on the figure, the one point not shown is a valid point, and performance was restored by increasing the amount of subcooling a very small amount by increasing the overpressure. Some of the scatter in the data in figure 4C is the result of the temperature and flow rate dependencies of this meter.

Meter AA

Results of the first rangeability test on meter AA are shown in figures 5C and 6C. Since the linear range of this meter was less than specified, the mathematical model was fitted to the data in the flow rates between 20 and 100 gpm (1.26 and 6.31 ℓ/s), the same as meter W. The fit of the model to these data is given in table 2C.

Table 2C. Fit of Model to Meter AA First Rangeability Test Data for the Flow Rate Range 20 - 100 gpm (1.26 - 6.31 ℓ/s)

Model $y = -2.1505 + 0.02604T - 0.007489\,q$
Bias at T = 80 K and q = 100 gpm, y = -0.815%
Residual Standard Deviation = ± 0.18%
Number of Points = 45

Statistically significant dependencies were found in both temperature and volume flow rate. Meter precision based on three times the residual standard deviation is ± 0.54 percent and the bias is - 0.815 percent at a temperature of 80 K and a flow rate of 100 gpm (6.31 ℓ/s).

The mean bias of these data without fitting them to the model is -0.407 percent. The standard deviation of these data without the model is ± 0.28 percent and the precision based on three times the standard deviation is ± 0.84 percent.

Pressure drop data for meters W and AA are shown in figure 7C.

Meter CC

Results of the first rangeability test are shown in figures 8C and 9C. The characteristic shape of the performance curve is quite different from meters W and AA. Pressure drop through the meter and the attached piping was too high to permit testing at flow rates higher than shown in the figures up to that rate; however, no upper flow rate limitation similar to meters W and AA was determined. All of the data were fitted to the flow model and the results are shown in table 3C.

Table 3C. Fit of Model to Meter CC, First Rangeability Test Data

Model $y = -1.5335 + 0.04385q - 0.0002361q^2$
Bias at q = 120 gpm, y = 0.329%
Residual Standard Deviation = ±0.21
Number of Points = 57

Statistically significant dependencies were found in flow rate and flow rate squared. Meter precision based on three times the residual standard deviation is ± 0.63 percent and the bias is 0.329 percent at a flow rate of 120 gpm (7.57 ℓ/s).

The mean bias of these data without fitting them to the model is 0.182 percent.

The standard deviation of these data without the model is ± 0. 49 percent and the precision based on three times the standard deviation is ± 1.47 percent.

Boundary test results are shown in figure 10C. Below 8K subcooling there is a definite tendency toward overregistration.

Results of the stability test are shown in figure 11C. Approximately 448, 000 gallons (1, 696, 000ℓ) were metered during this test; the meter showed no effect from wear.

The second rangeability test results are shown in figure 12C and 13C. The data were fitted to the flow model and the results are shown in table 4C.

Table 4C. Fit of Model to Meter CC, Second Rangeability Test Data

Model $y = -1.1900 + 0.03987q - 0.0002104q^2$
Bias at q = 120 gpm, y = 0. 565%
Residual Standard Deviation = ± 0. 20
Number of Points = 59

This meter had significant dependencies on flow rate and flow rate squared. Meter precision based on three times the residual standard deviation is ± 0. 60 percent and the bias is 0. 565 percent at a flow rate of 120 gpm (7. 57 ℓ/s).

The mean bias of these data without fitting them to the model is 0. 256 percent. The standard deviation of these data without the model is ± 0. 45 percent and the precision based on three times the standard deviation is ± 1. 35 percent.

Meter DD

This meter was subjected to only a rangeability test. Results of this test are shown in figures 14C and 15C. The data were fitted to the flow model and the results are shown in table 5C.

Table 5C. Fit of Model to Meter DD, First Rangeability Test Data

Model $y = -3.5499 + 0.04183q - 0.0002117q^2 + 0.03488T$
Bias at T = 80 K and q = 120 gpm, y = 1. 212%
Residual Standard Deviation = ± 0. 22%
Number of Points = 59

This meter had significant dependencies on flow rate, flow rate squared, and temperatures. Meter precision based on three times the residual standard deviation is ± 0.66 percent and the bias at a flow rate of 120 gpm (7.57 ℓ/s) and a temperature of 80 K is 1.212 percent.

The mean bias of these data without fitting them to the model is 0.980 percent. The standard deviation of these data without fitting them to the model is ± 0.59 percent and the precision based on three times the standard deviation is ± 1.77 percent.

No additional pressure drop data was obtained on meters CC or DD. These two meters were tested installed in a metering run which was supplied with the meters and included two valves. Pressure drop data taken external to the metering run could not yield meaningful meter only pressure drop information.

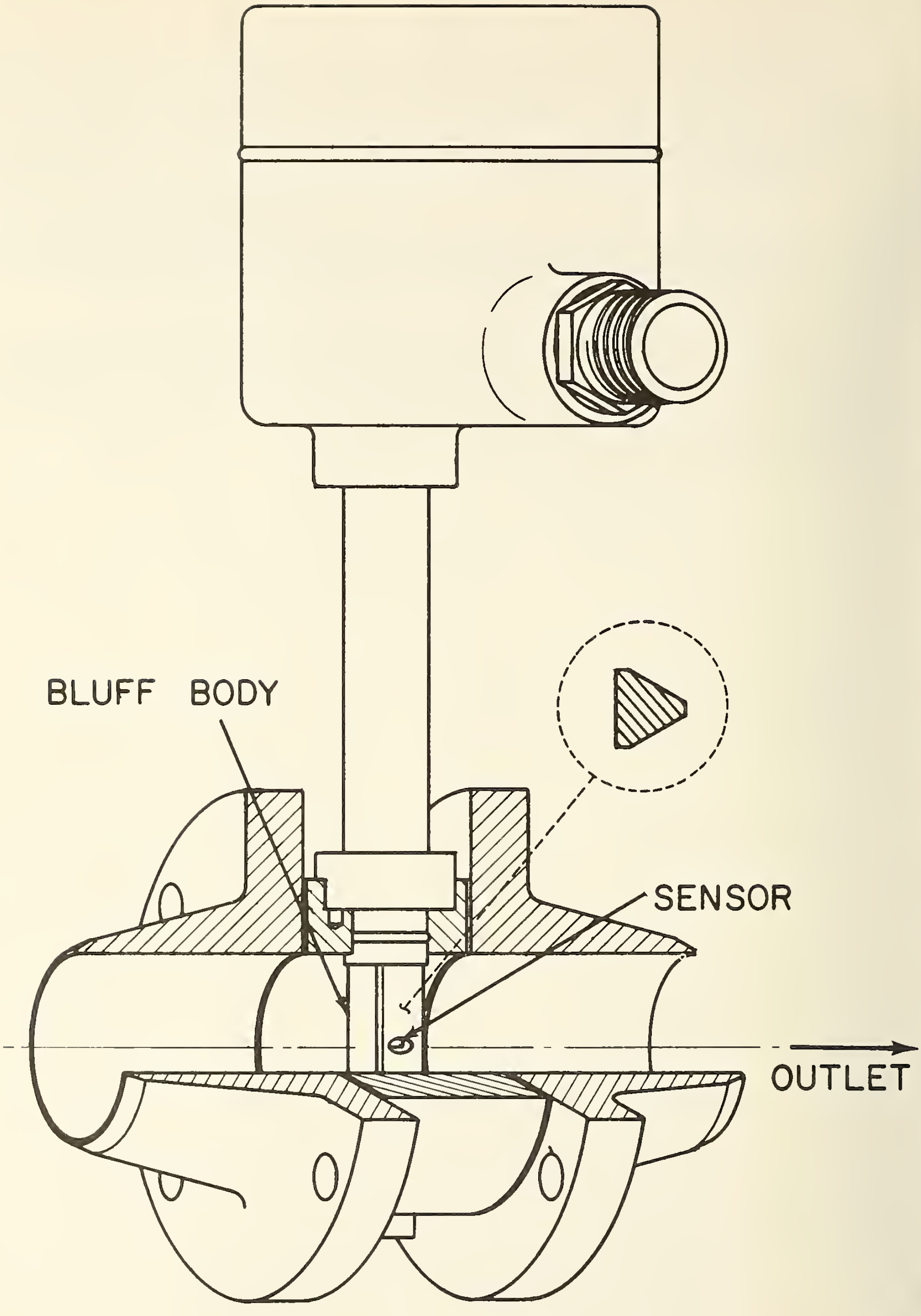

Figure 1C. Schematic of Meters W and AA.

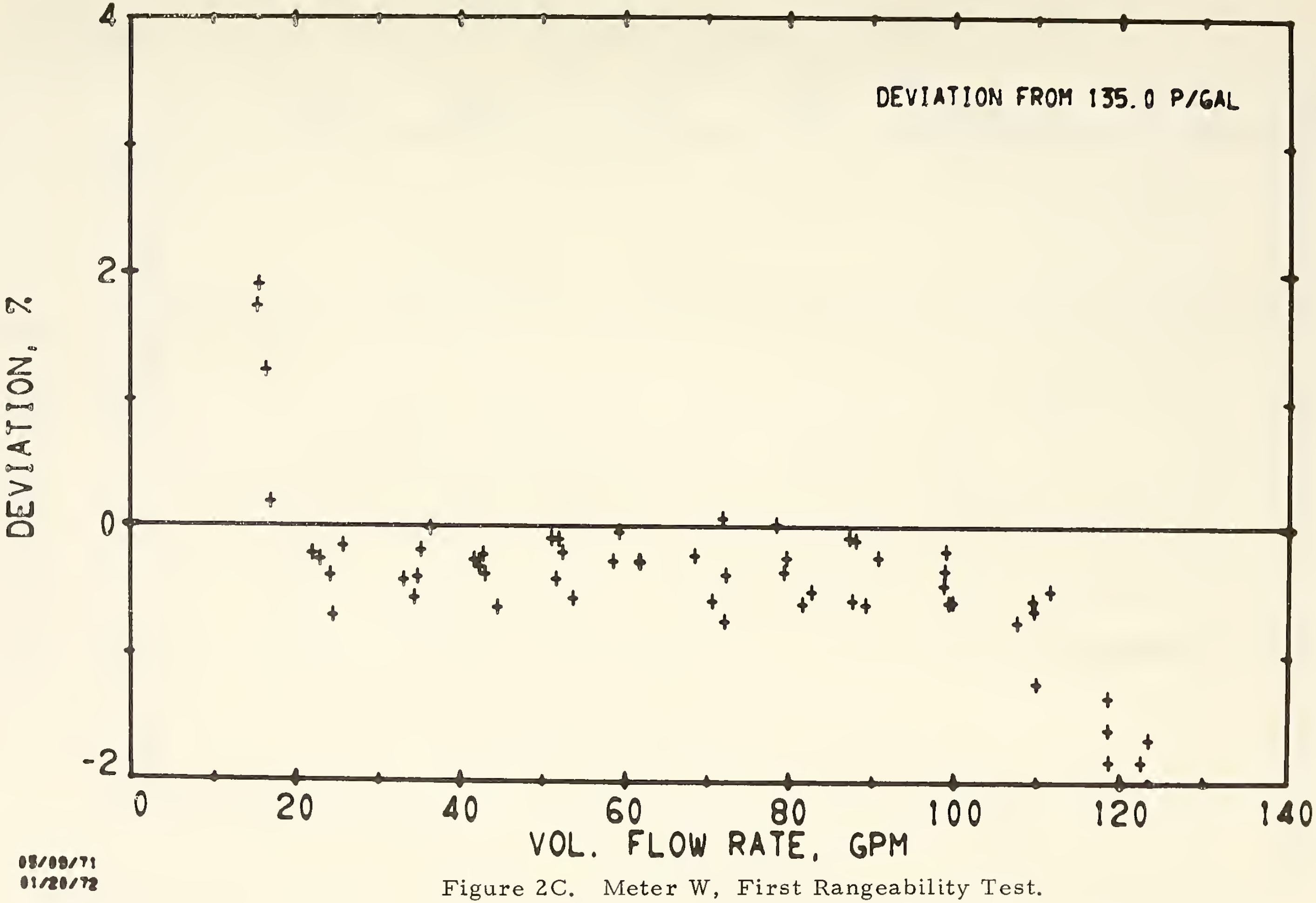

Figure 2C. Meter W, First Rangeability Test.

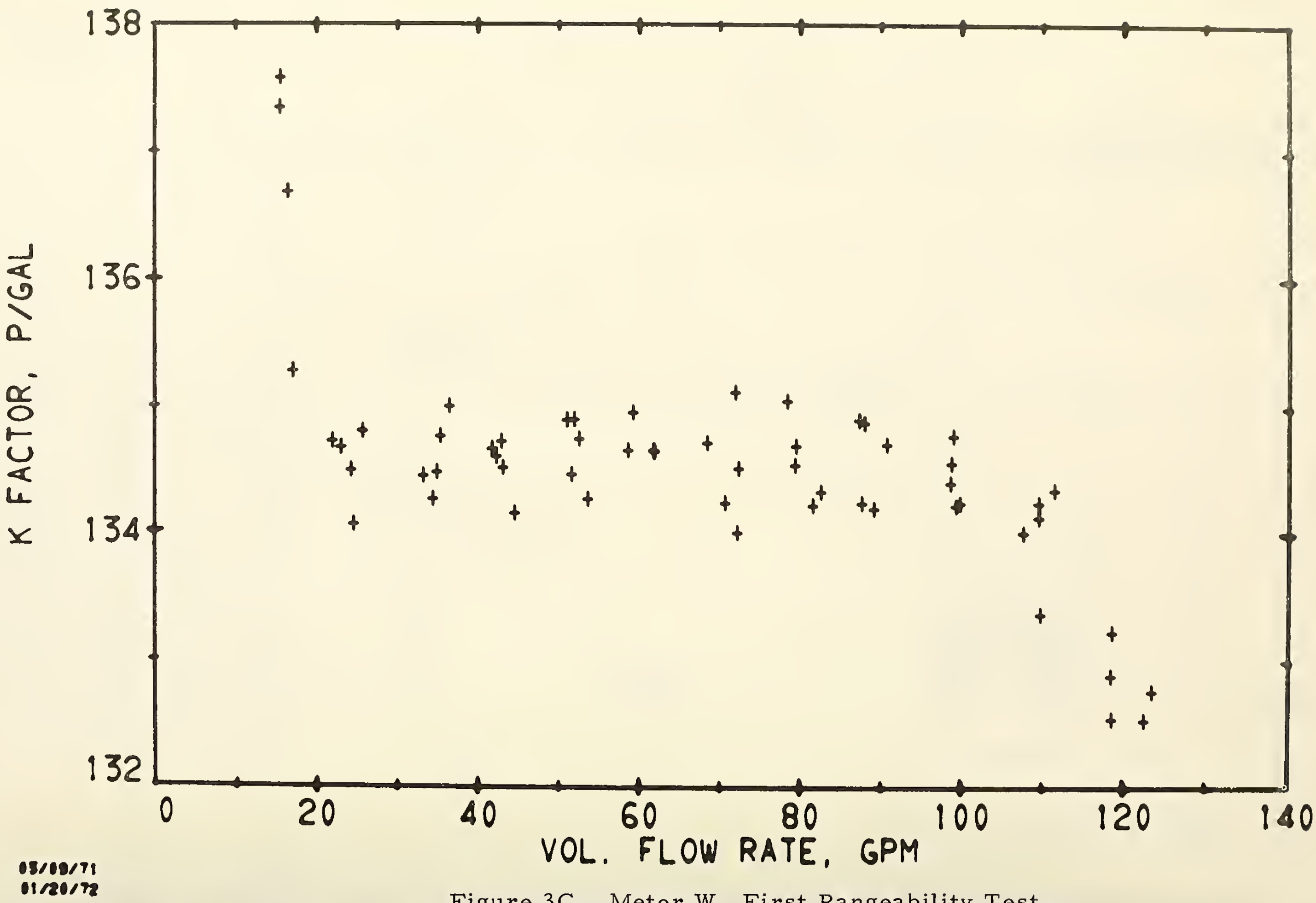

Figure 3C. Meter W, First Rangeability Test.

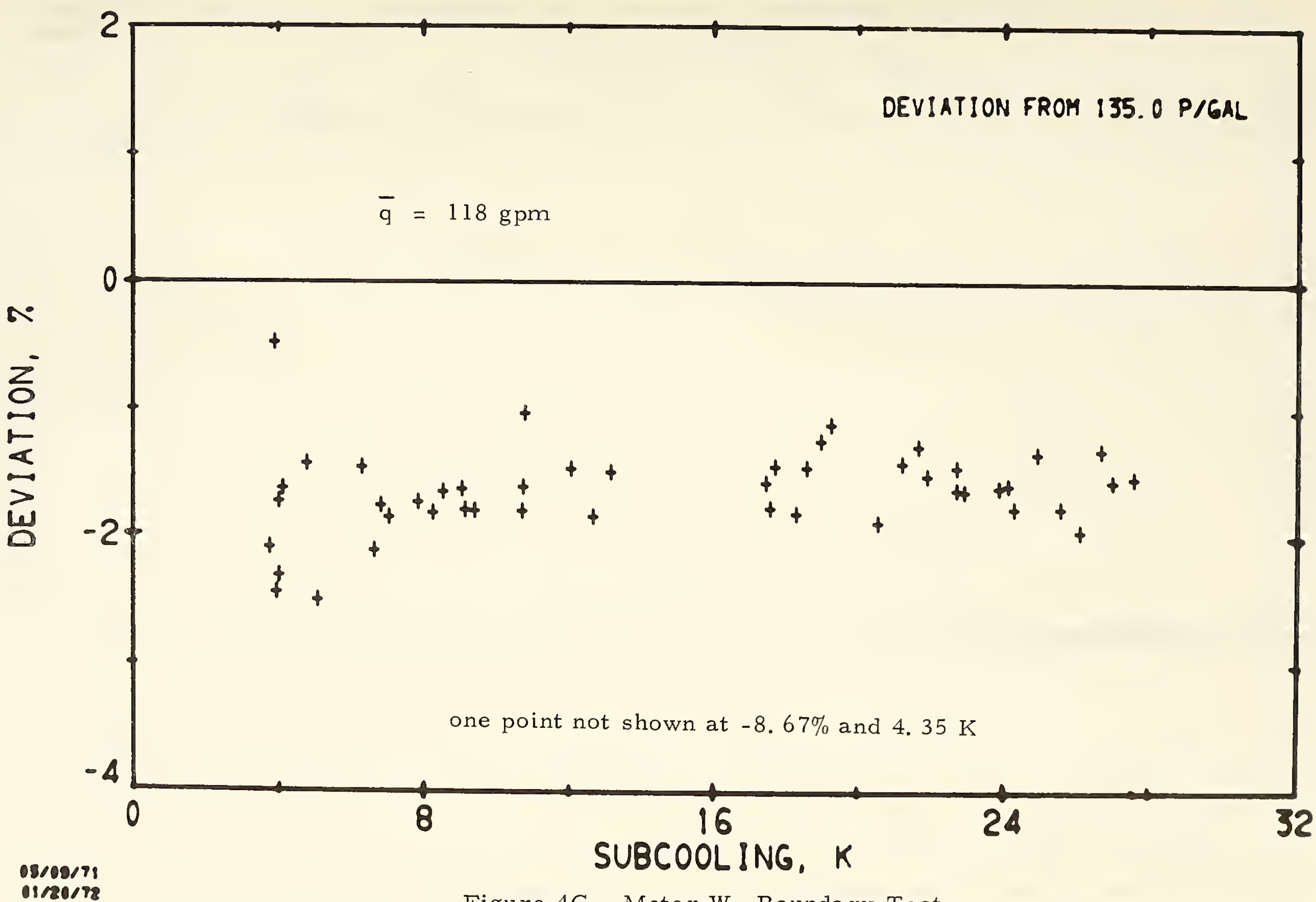

Figure 4C. Meter W, Boundary Test.

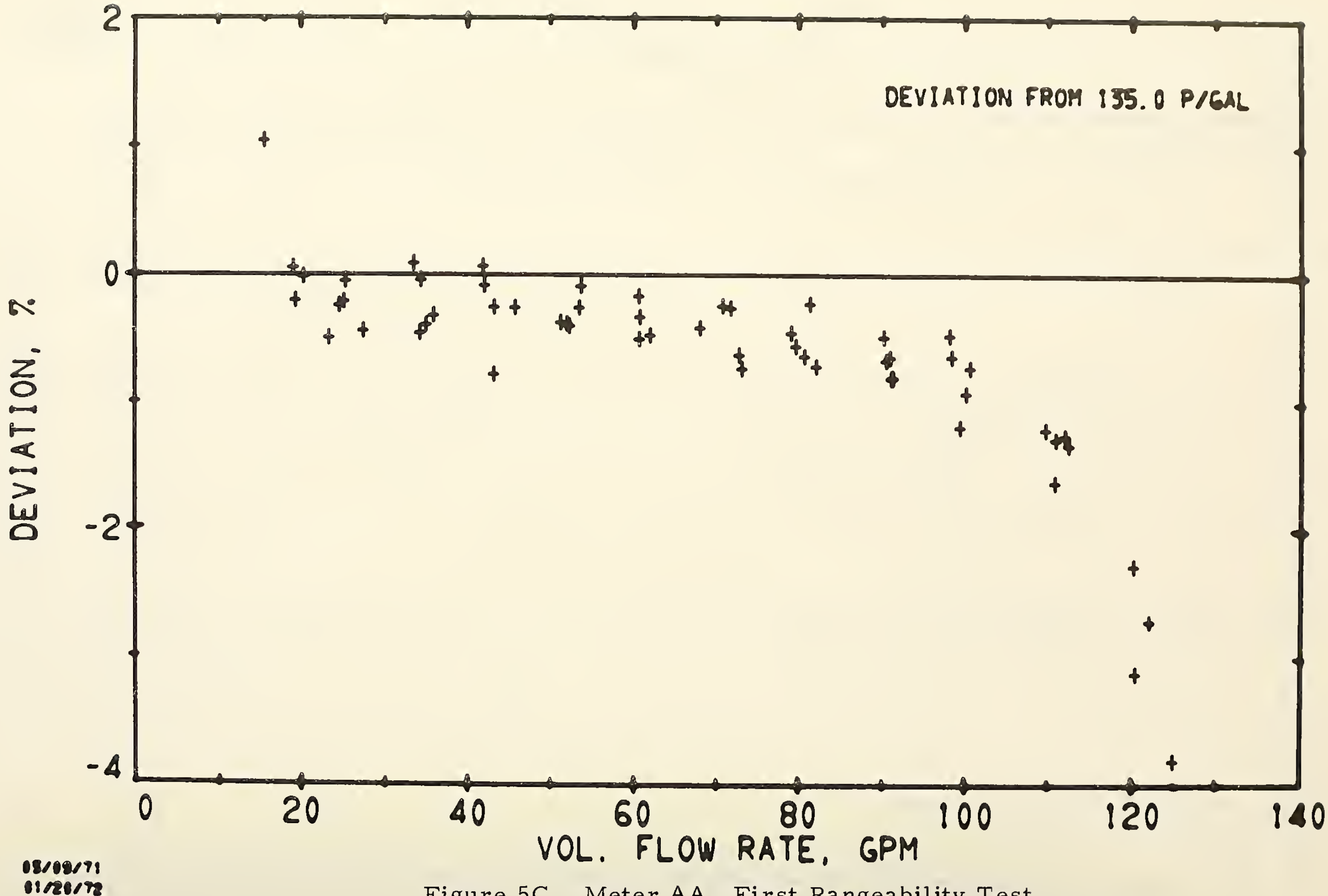

Figure 5C. Meter AA, First Rangeability Test.

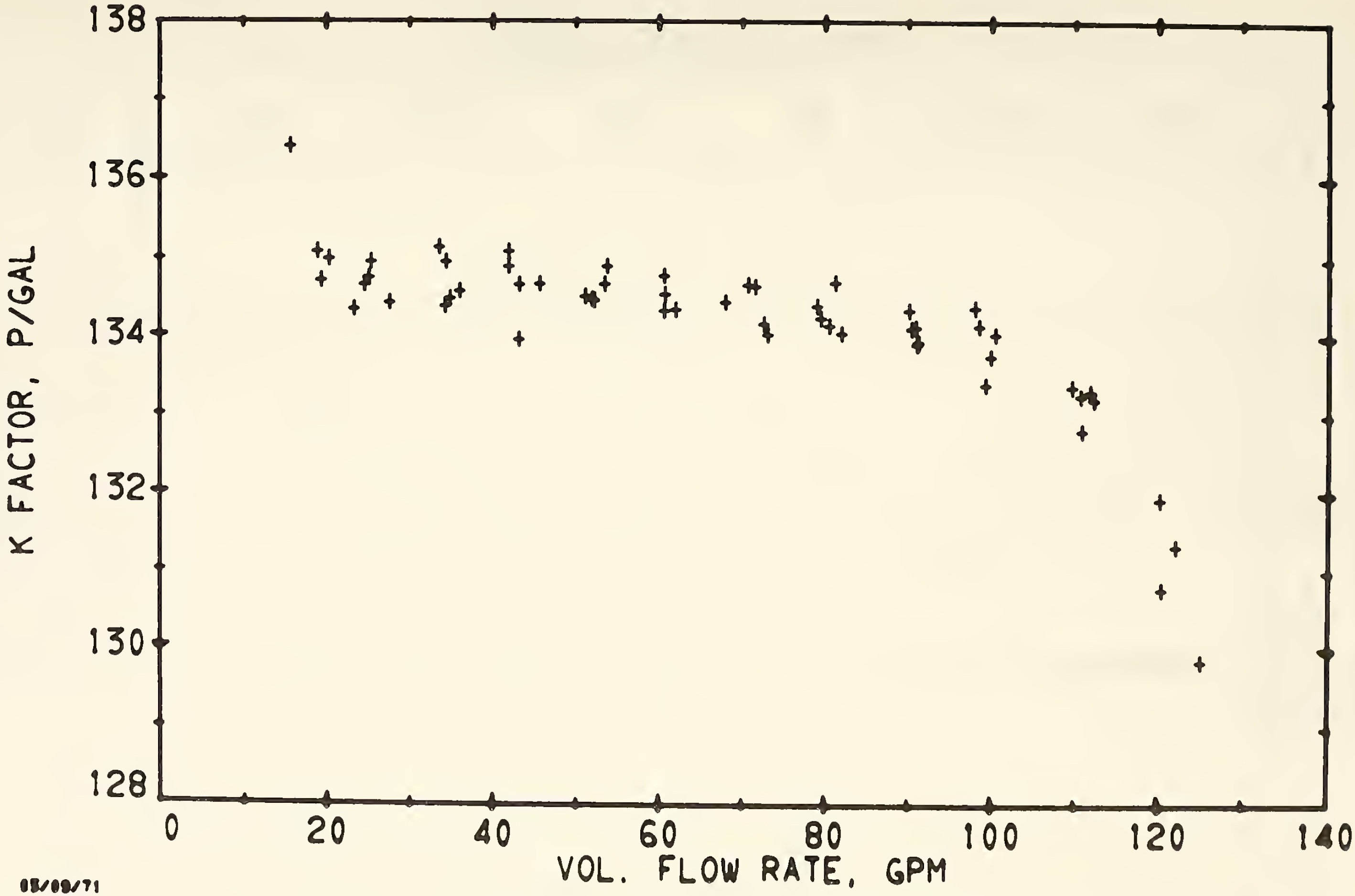

Figure 6C. Meter AA, First Rangeability Test.

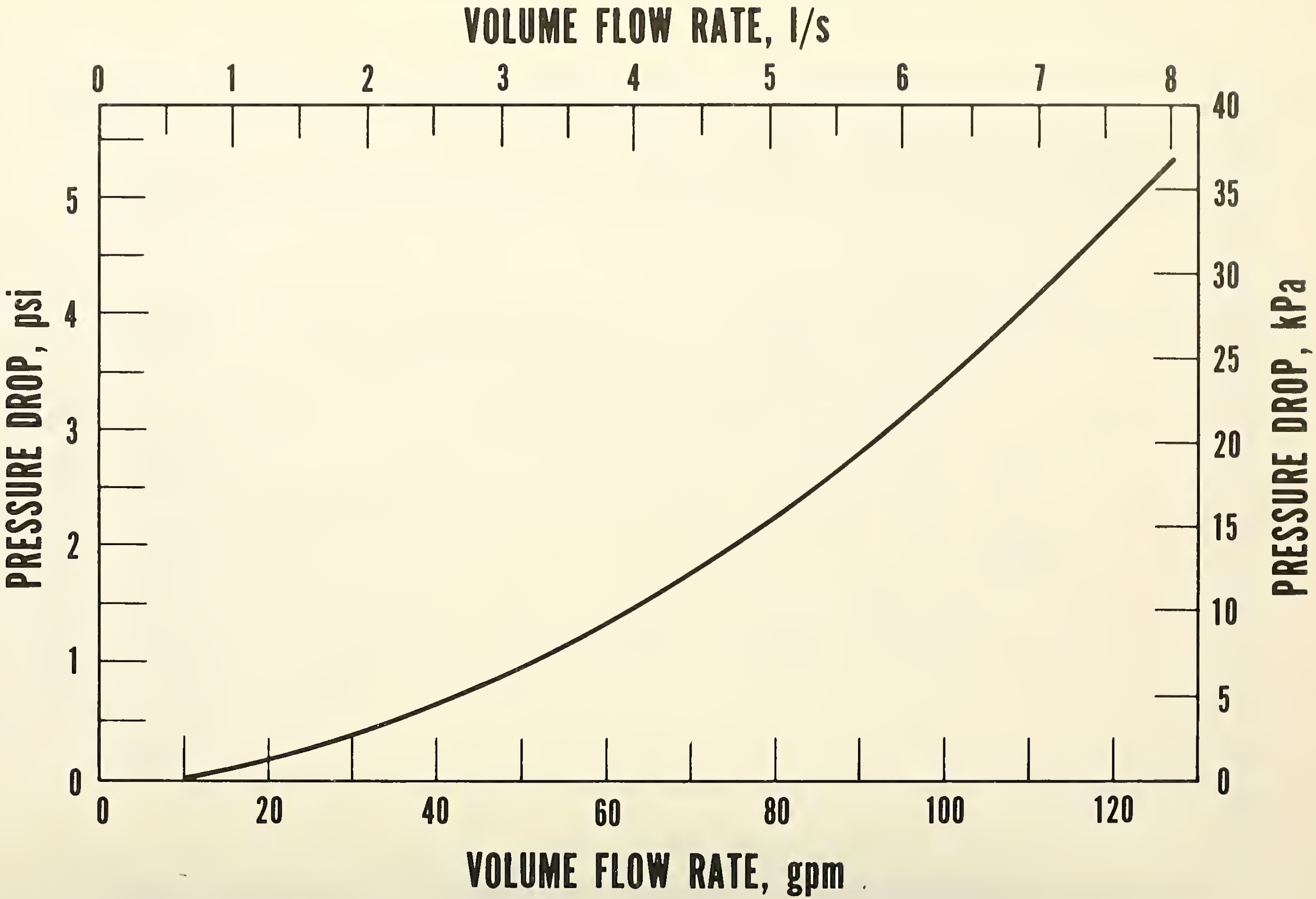

Figure 7C. Meters W and AA, Pressure Drop.

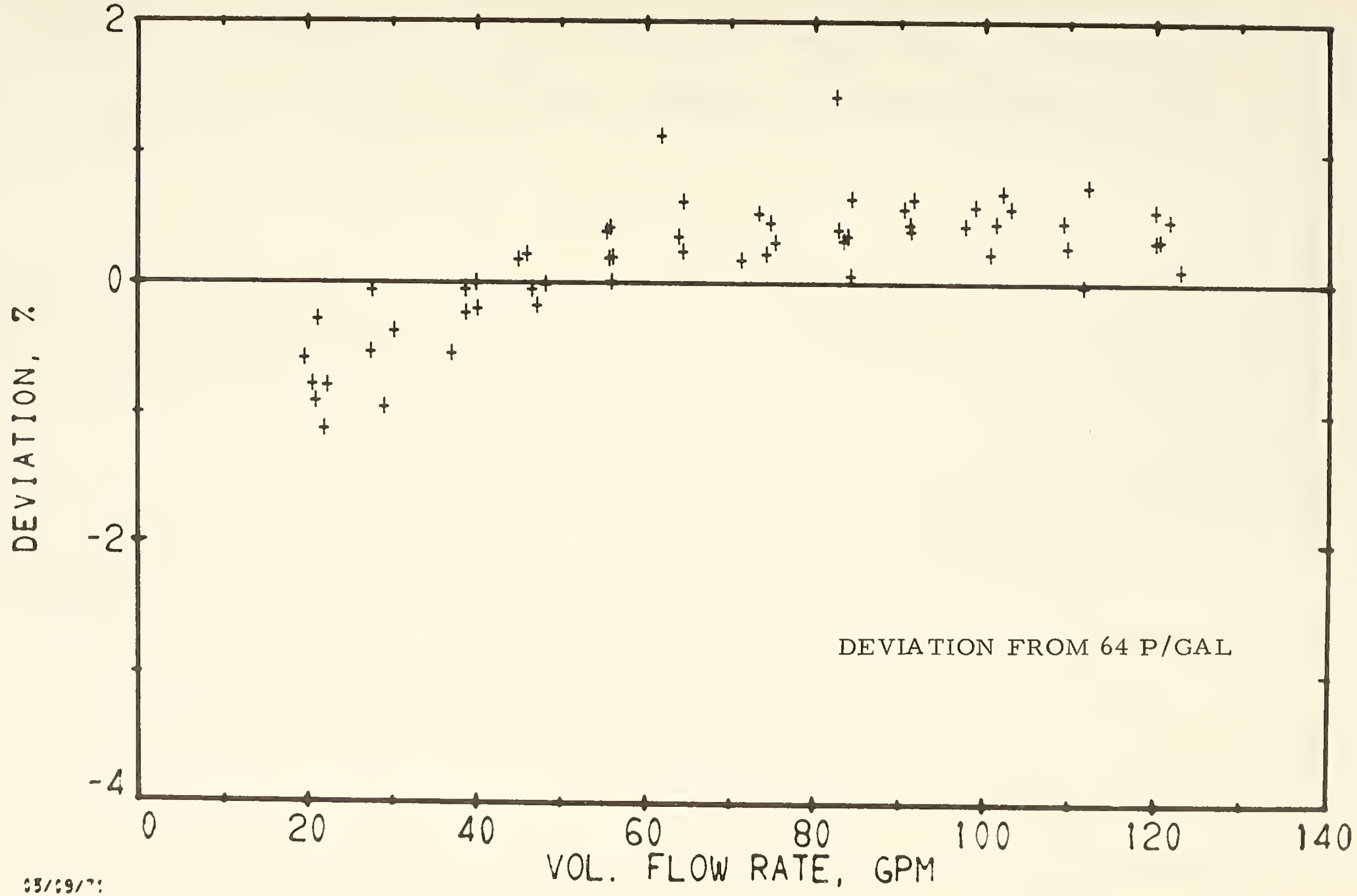

Figure 8C. Meter CC, First Rangeability Test.

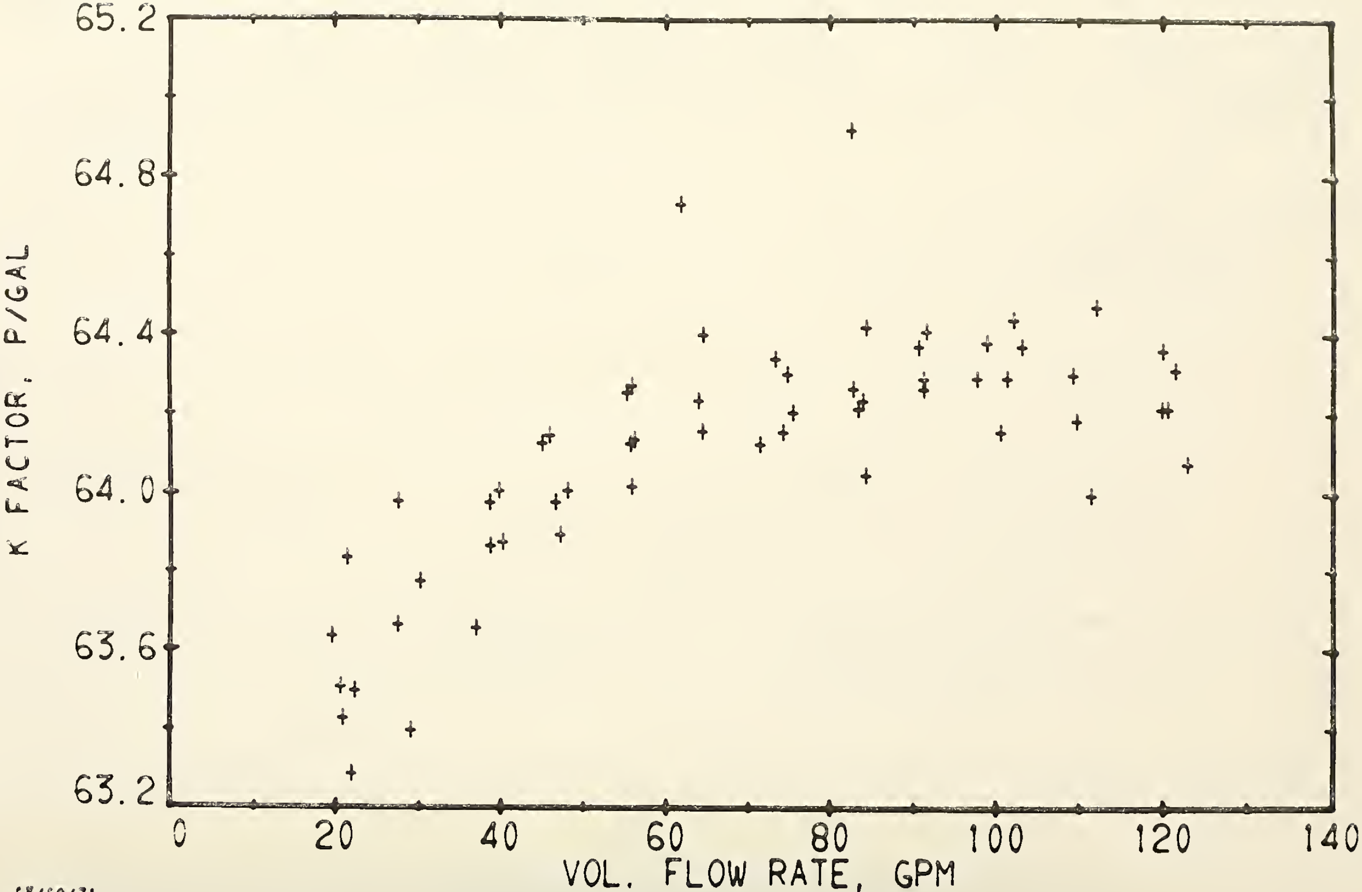

Figure 9C. Meter CC, First Rangeability Test.

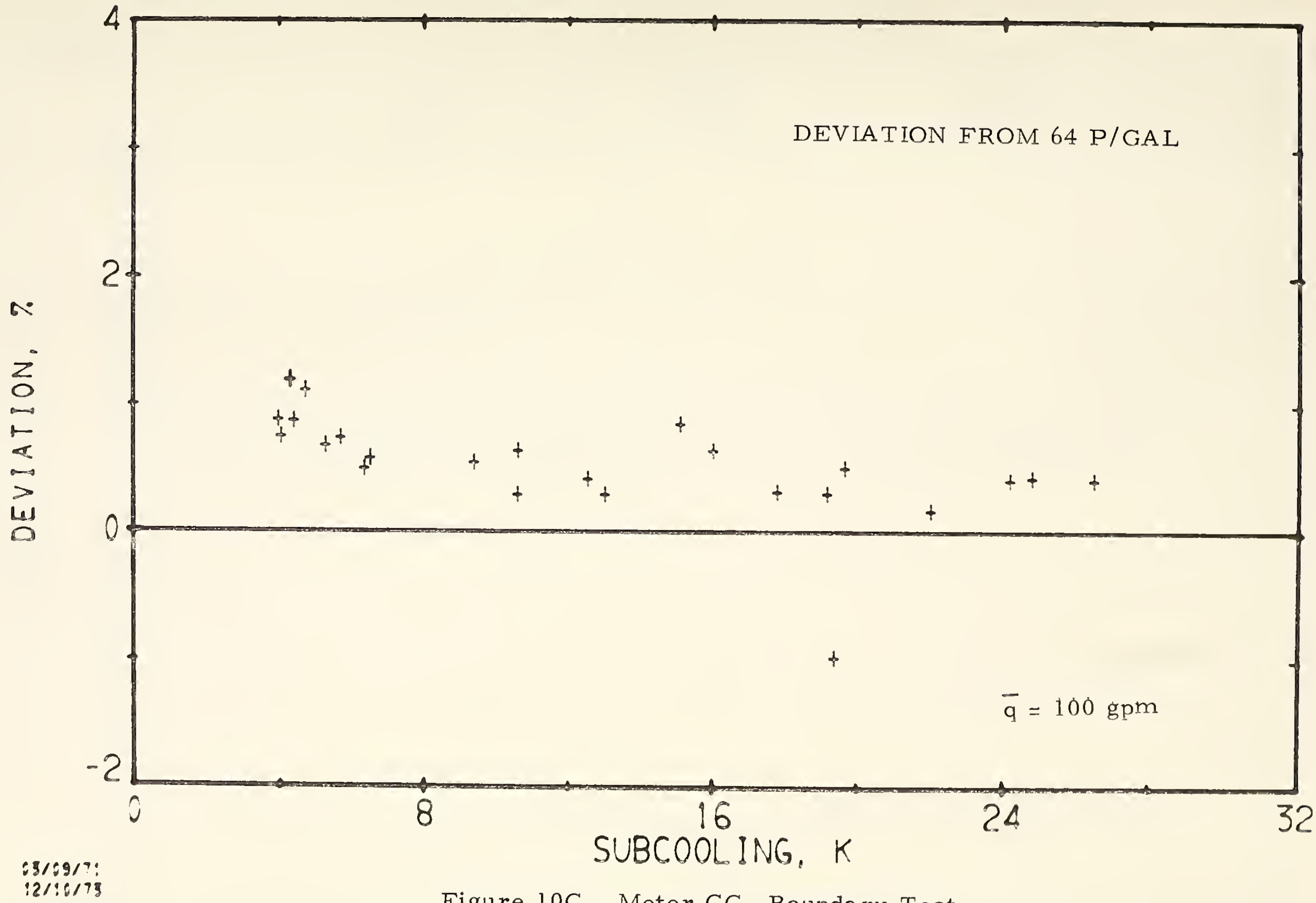

Figure 10C. Meter CC, Boundary Test.

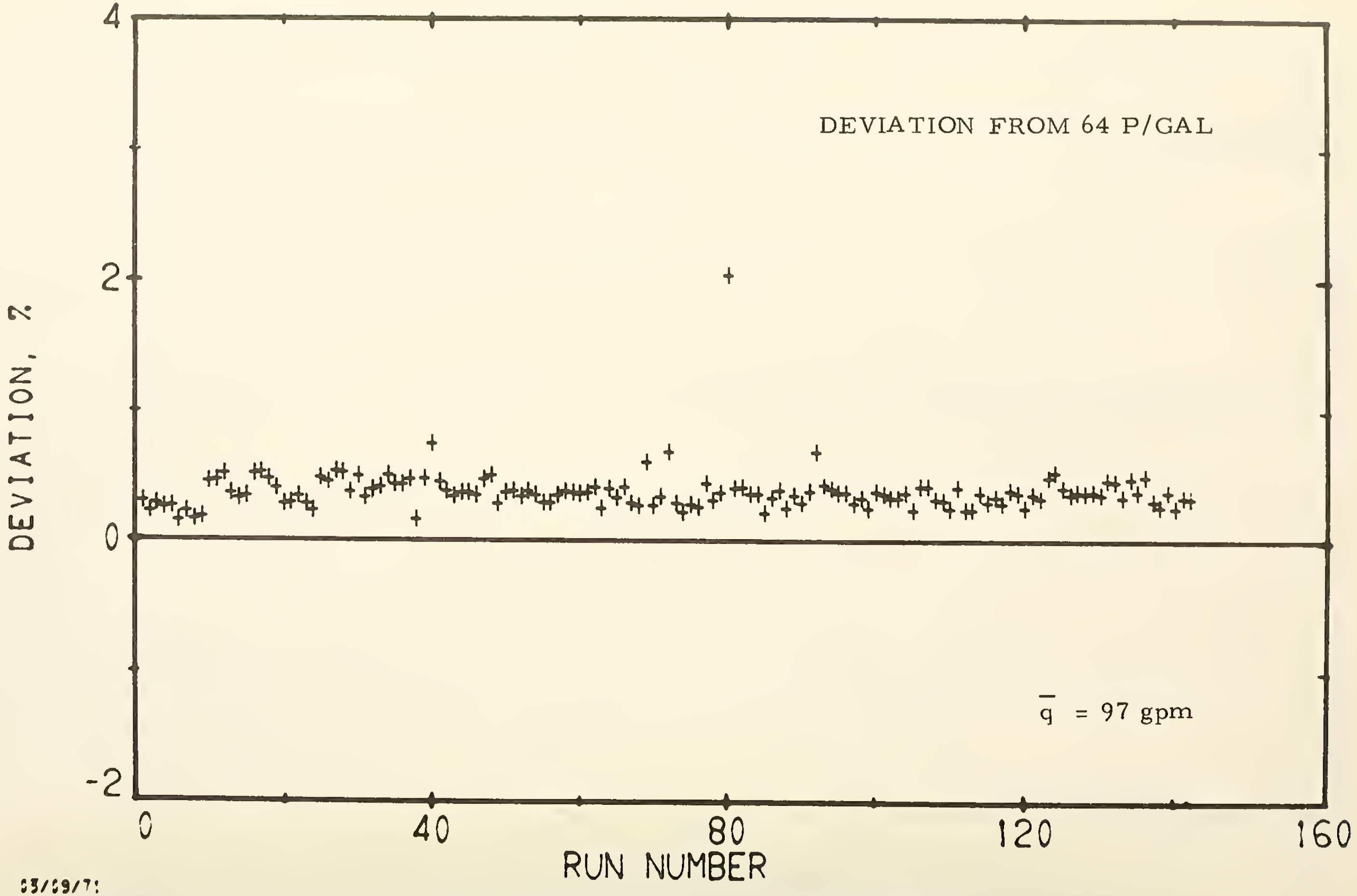

Figure 11C. Meter CC, Stability Test.

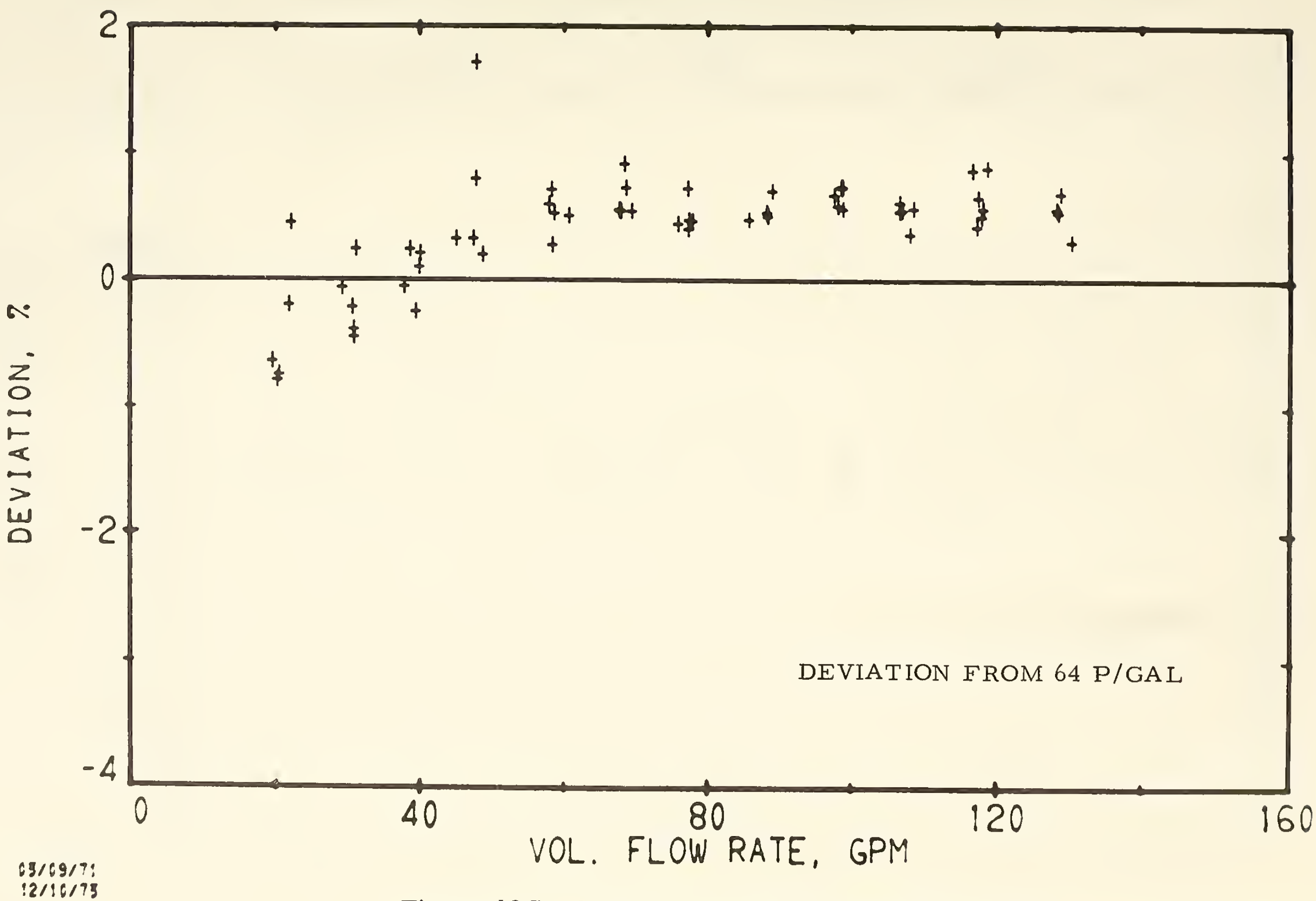

Figure 12C. Meter CC, Second Rangeability Test.

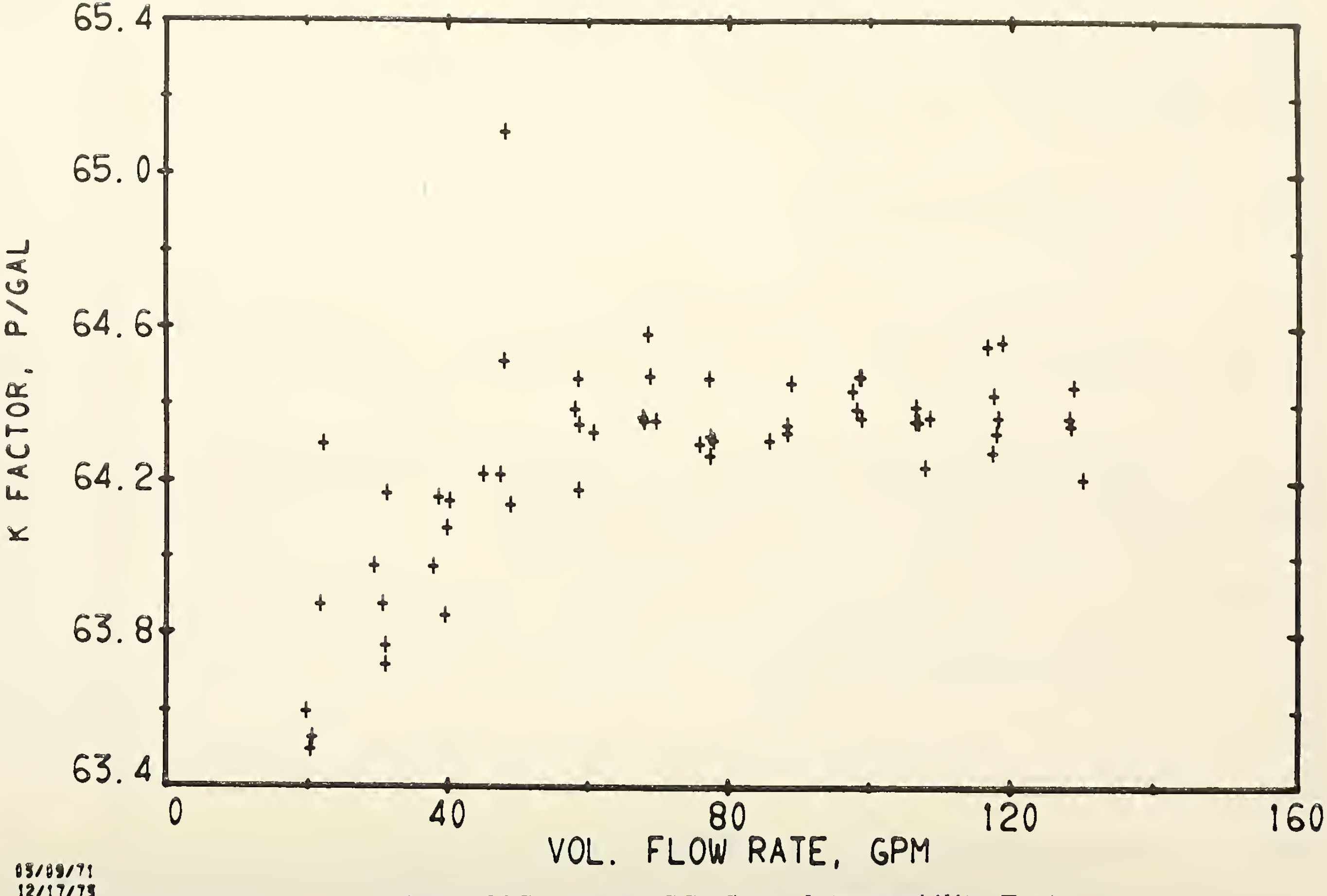

Figure 13C. Meter CC, Second Rangeabilitv Test.

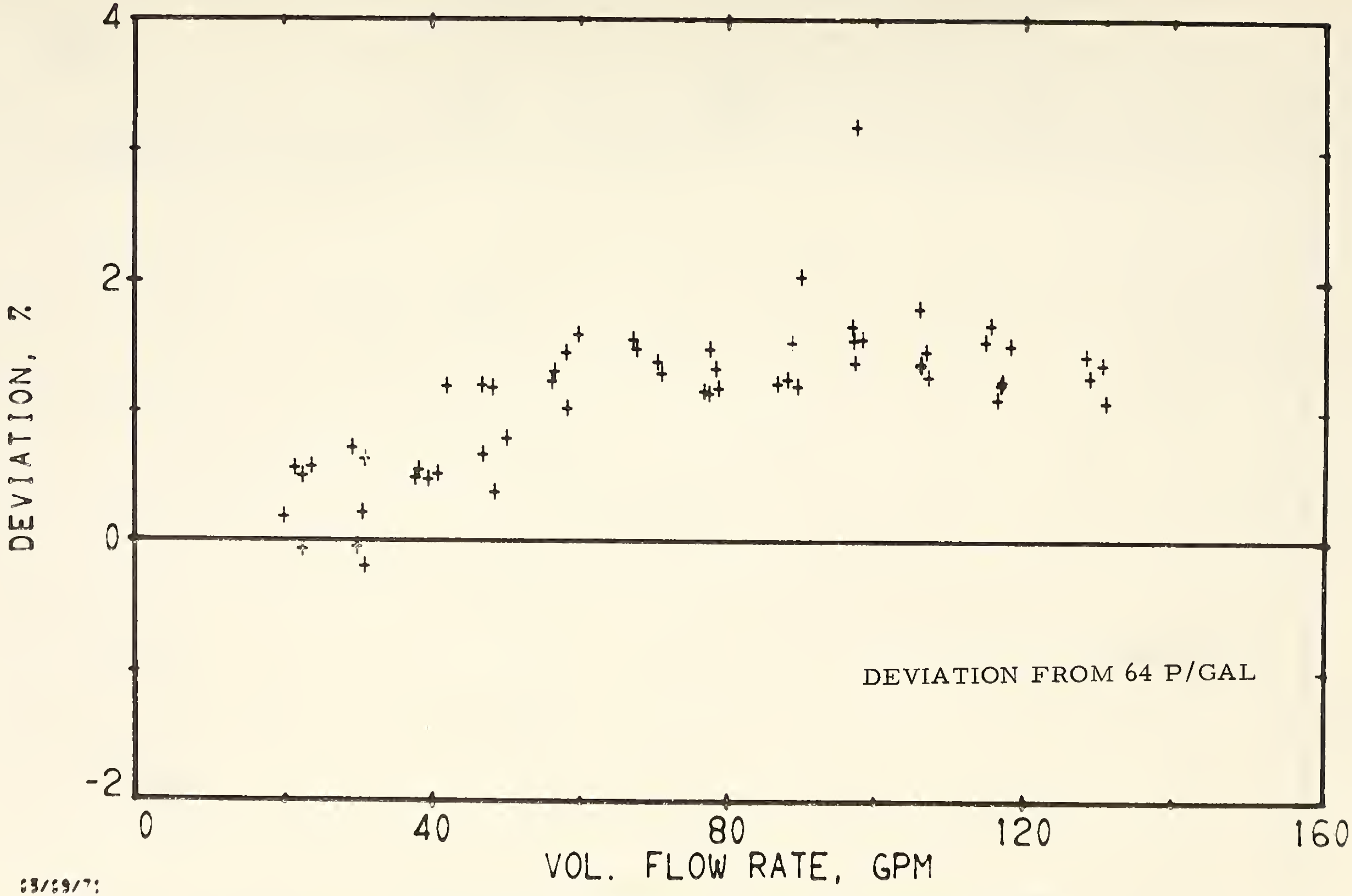

Figure 14C. Meter DD, First Rangeability Test.

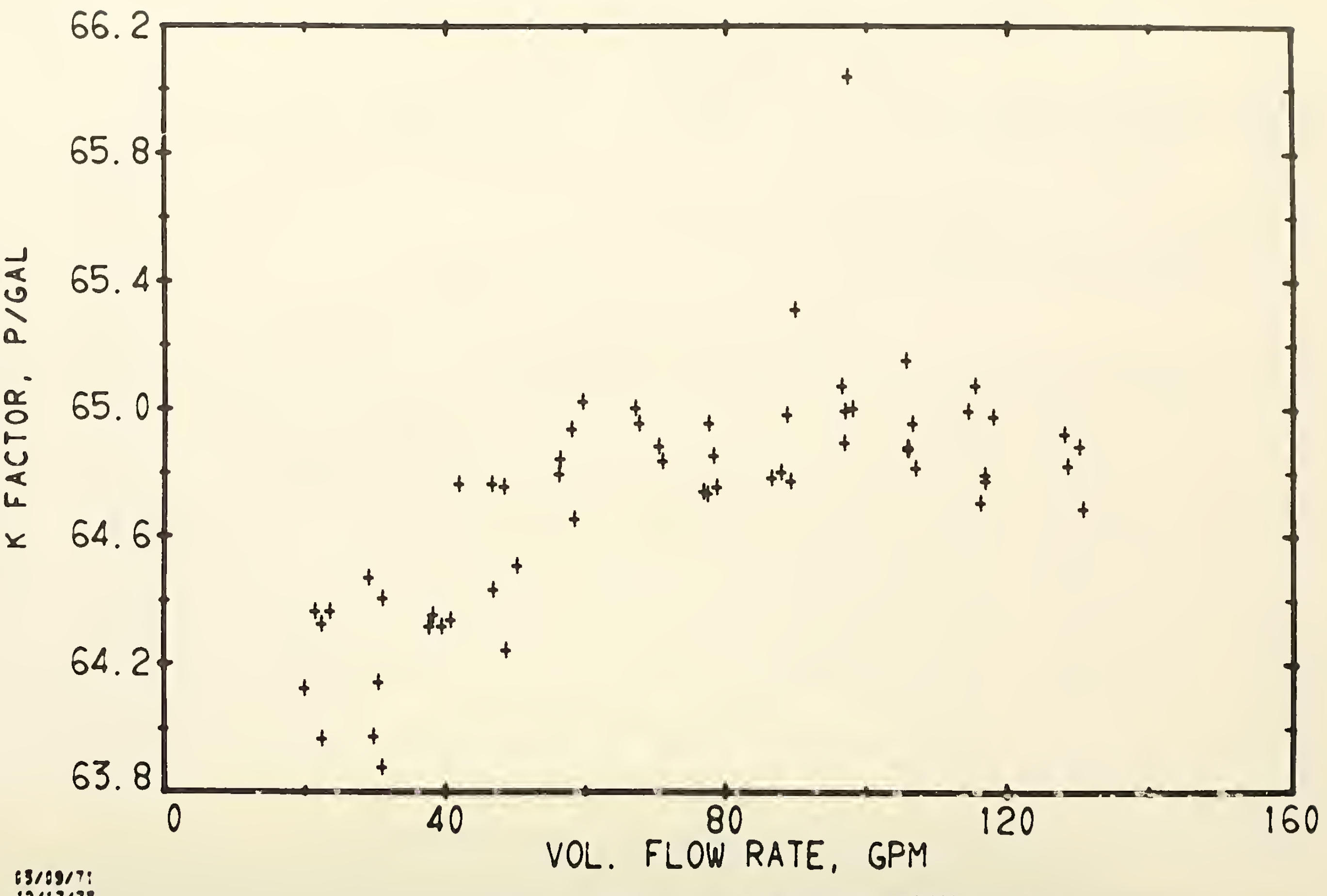

Figure 15C. Meter DD, First Rangeability Test.

APPENDIX D. Performance of an Orifice Meter (Meters X and II)

Meter X is illustrated in figure 1D. Liquid flow in the metering section is indicated by the arrows in the figure. Meter II was similar except that it did not have the external jacket and the flow was straight through. Pressure drop measurements are made with four corner taps which communicate with an annular chamber on each side of the orifice. The pressure tap lines are constructed in a special way in an attempt to eliminate pressure oscillations in the lines. The unique features are indicated in the figure. The degasification lines are used to control the liquid-vapor interface in the annular space. The design goal was to maintain the interface at the entrance to the pressure tap lines which would keep the amount of saturated vapor to a minimum. When the meter is used in a pressurized transfer configuration,the degasification lines are independently connected to the ullage space of the upstream vessel. Since the tests reported here were conducted with a pumped flow system, it was not possible to connect the degasification lines to an appropriate ullage space. Therefore, a consistent test procedure was adopted whereby test conditions were established and then gas from the degasification lines was bled momentarily. The lines were then valved off and the test started after a two minute wait in the tests on meter X and a three minute wait in tests on meter II. The purpose of this procedure was not to try to duplicate any particular set of installation conditions but rather to develop internal consistency in the data.

A differential pressure transducer was used to sense the pressure drop in the tests reported here. The output from the transducer was fed into a voltage to frequency converter in order to make the signal compatible with the logic circuitry used for controlling the test.

The meter supplier's specifications are:

Fluid - liquid nitrogen

Maximum flow rate - 7.66 lbs/s (3.48 kg/s)

Maximum pressure drop - 25 in H_2O (6.2 kPa)

Orifice diameter - meter X: 1.84 in. .(46.65 mm) meter II: 1.80 in. (45.83 mm)

Pipe inside diameter - 3.27 in (83 mm)

Standardized flow coefficient - meter X: 0.6395. Meter II: 0.6650

One of these meters, meter X, was tested based on the manufacturers flow rate limitations. The second meter II was tested extending the flow rate up to a pressure drop of 3 psi (20.7 kPa). The reason the range was extended on the second meter was that there were still some flow oscillations present,and it was felt that these oscillations were affecting the low flow rate results more percentage wise than the high flow rates.

Since these meters had no moving parts and were not supplied with any readout equipment, no stability or second rangeability tests were run.

The reduced precision at the lowest flow rates obtained on these meters may be the result of our method of pressure measurement and the fact that there were still some pressure oscillations present. At the low pressure drops, the oscillation amplitude was a very high percentage of the total measurement. The deviation is calculated from a standardized flow coefficient based on the orifice meter diameter ratio.

Meter X

Results of the first rangeability test are shown in figures 2D, 3D and 4D. The data were fitted to the flow model and results are shown in table 1D.

Table 1D. Fit of Model Meter X First Rangeability Test Data

Model $y = -6.499 + 0.08881T + 0.2083\,\dot{m}$
Bias at $T = 80$ K and $\dot{m} = 7.5$ lbs/s, $y = +2.17\%$
Residual Standard Deviation = ± 0.50%
Number of Points = 58

This meter had statistically significant dependencies in both temperature and mass flow rate. Meter precision based on three times the standard deviation is ± 1.50 percent and the bias is + 2.17 percent at a temperature of 80 K and a flow rate of 7.5 lbs/s (3.4 kg/s).

The mean bias of these data without fitting them to the model is + 2.01 percent. The standard deviation of these data without fitting them to the model is ± 0.66 percent and the precision based on three times the standard deviation is ± 1.98 percent.

Meter pressure drop data are shown in figure 5D.

Meter II

Results of the rangeability test on meter II are shown in figures 6D, 7D, and 8D. Since the test was not performed within the specifications of the manufacturer, the data were not fitted to the mathematical model. The actual pressure measurement instrumentation was not supplied with either this meter or meter X. There is always the possibility that different instrumentation could have reduced the scatter in the data at low flow rates.

Results of the boundary test are shown in figure 9D. No adverse effects were detected even with only approximately 3 K subcooling.

Meter pressure drop data are shown in figure 10D.

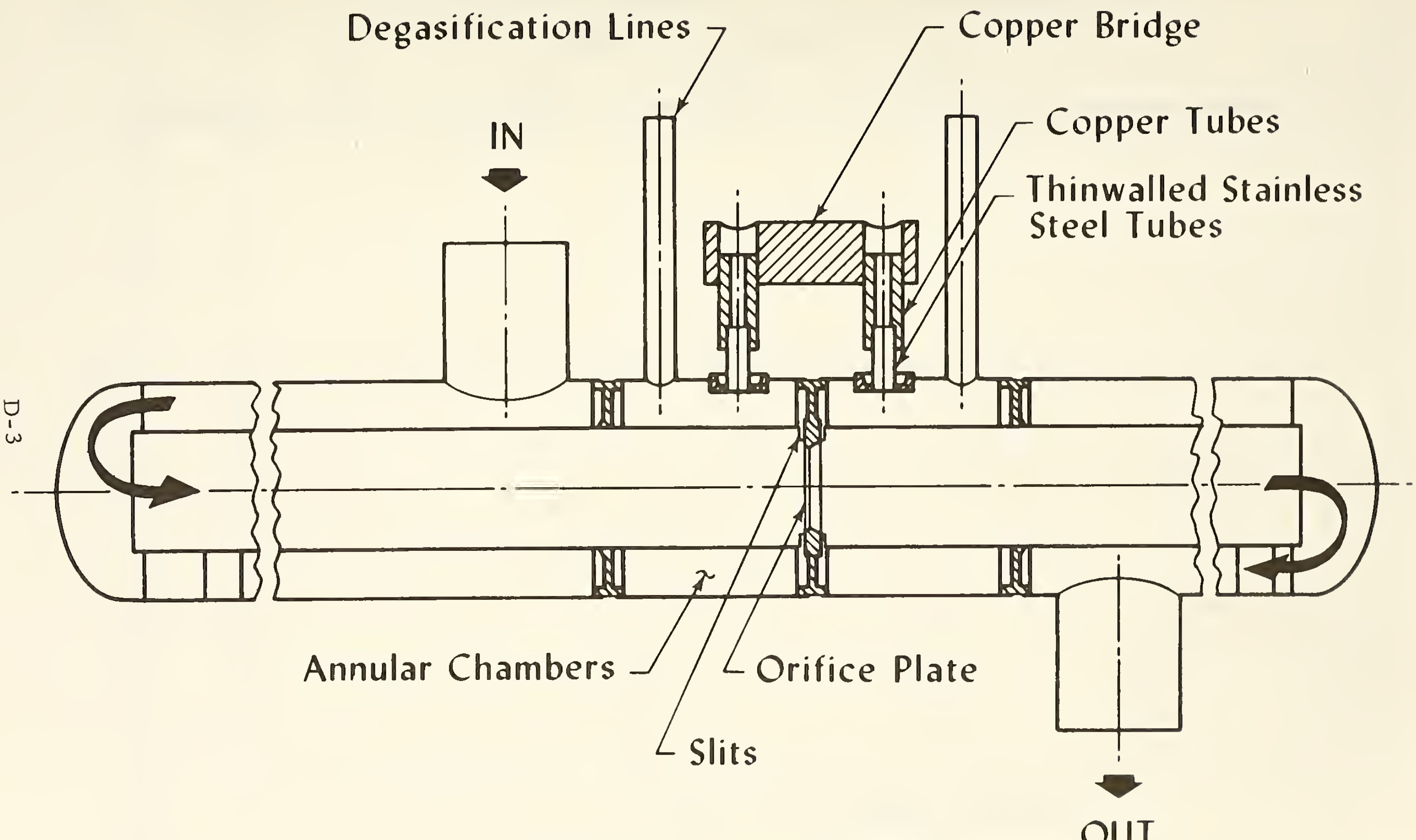

Figure 1D. Schematic of Meter X.

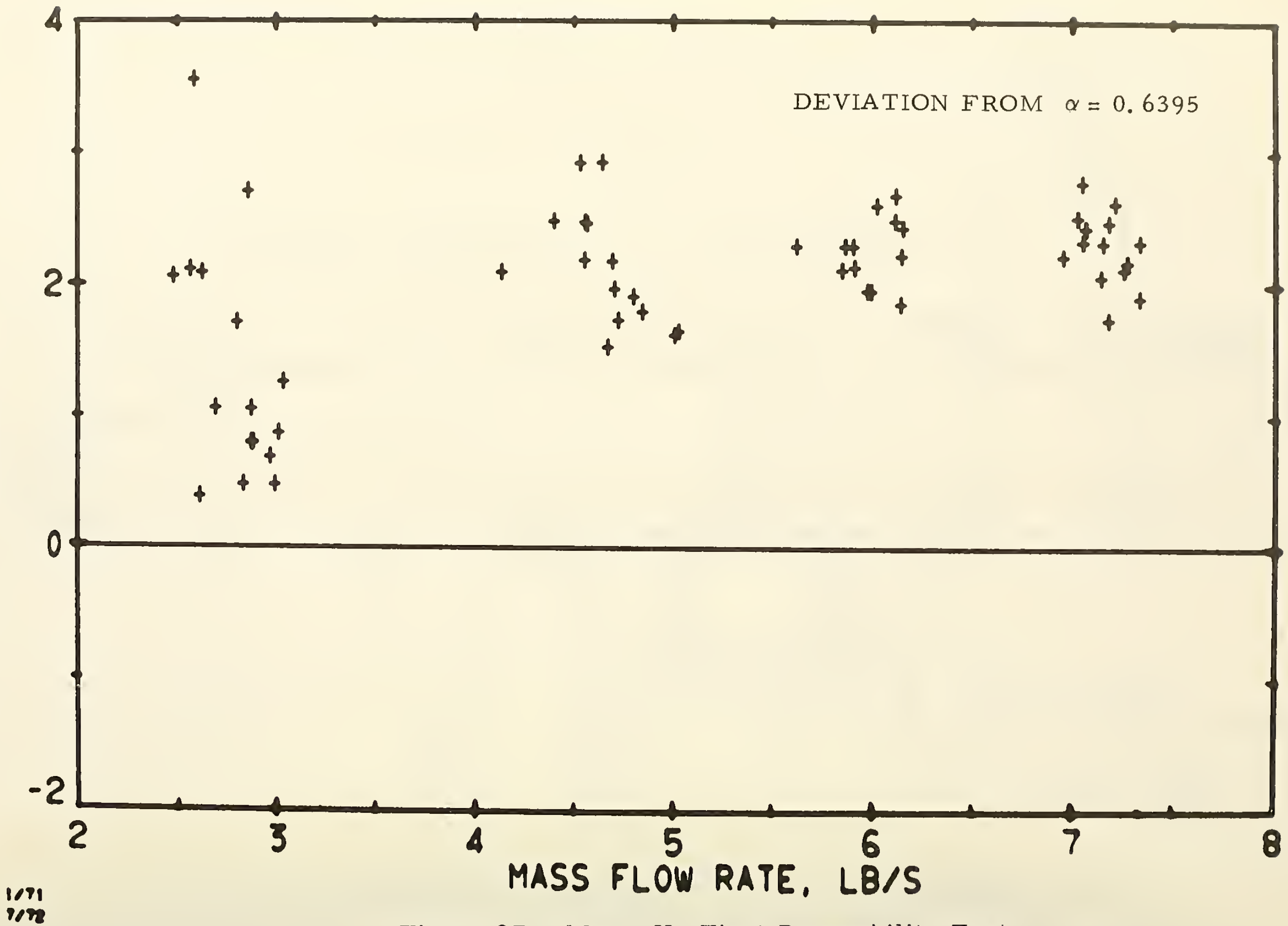

Figure 2D. Meter X, First Rangeability Test.

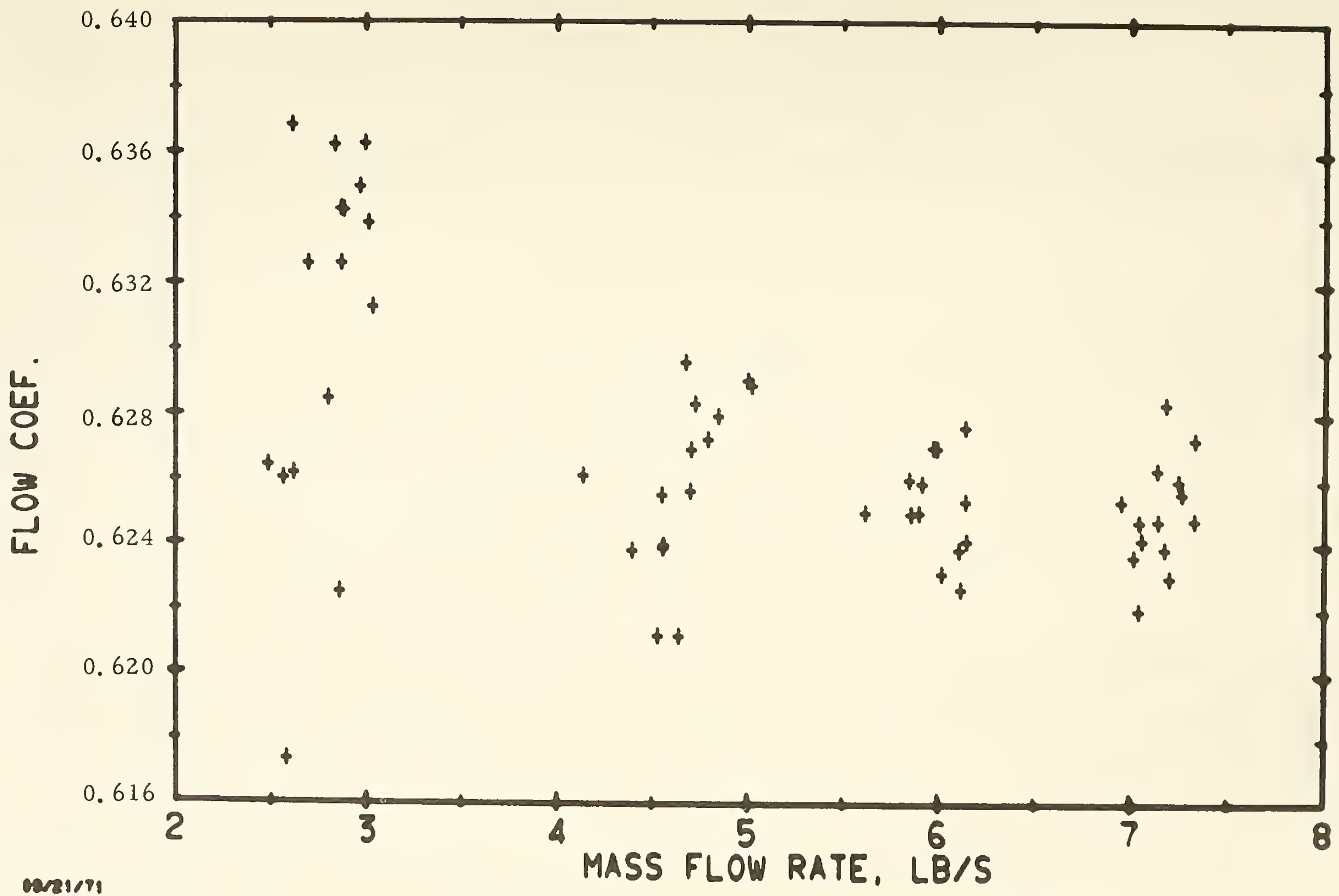

Figure 3D. Meter X, First Rangeability Test.

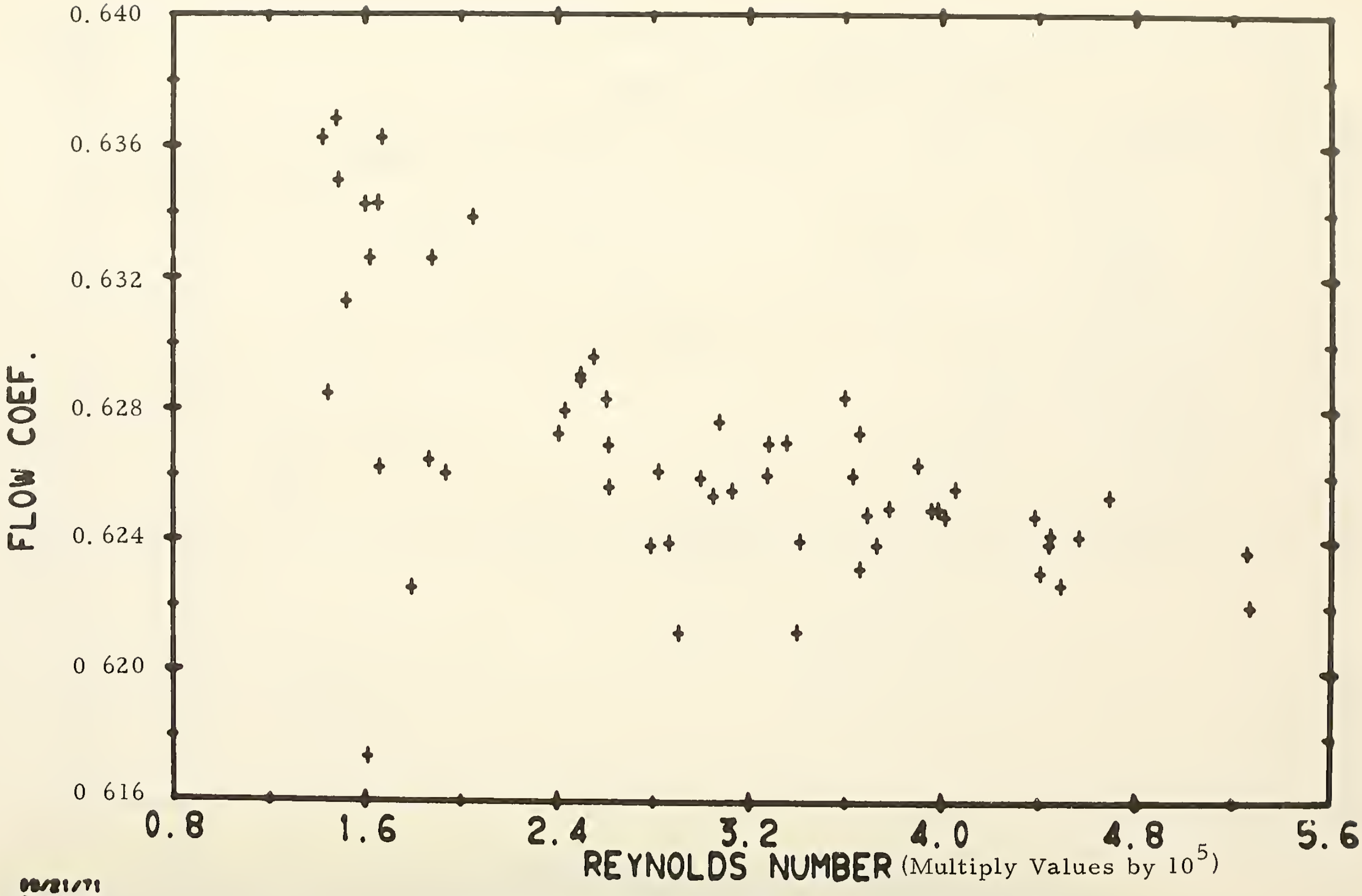

Figure 4D. Meter X, First Rangeability Test.

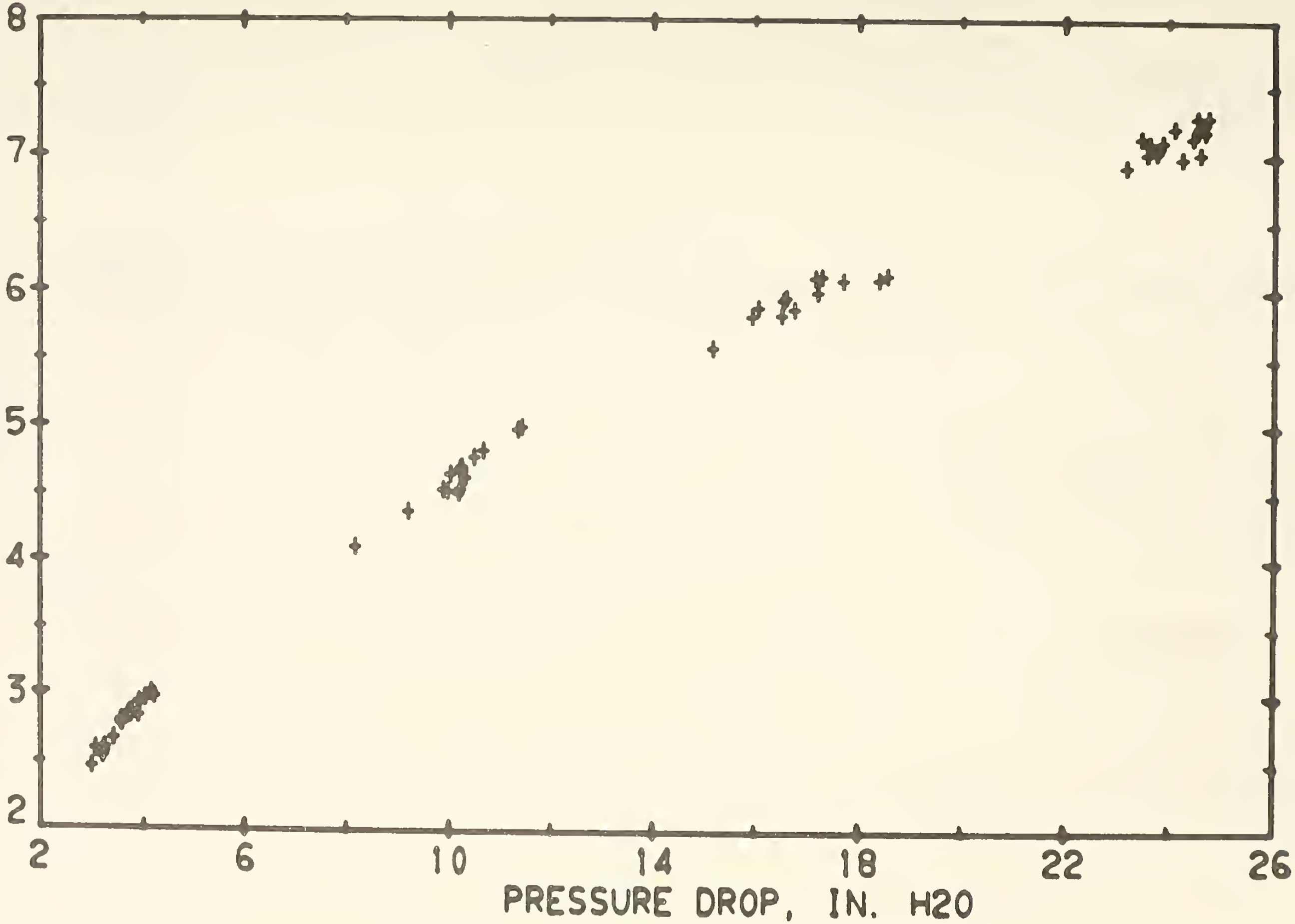

Figure 5D. Meter X, Pressure Drop.

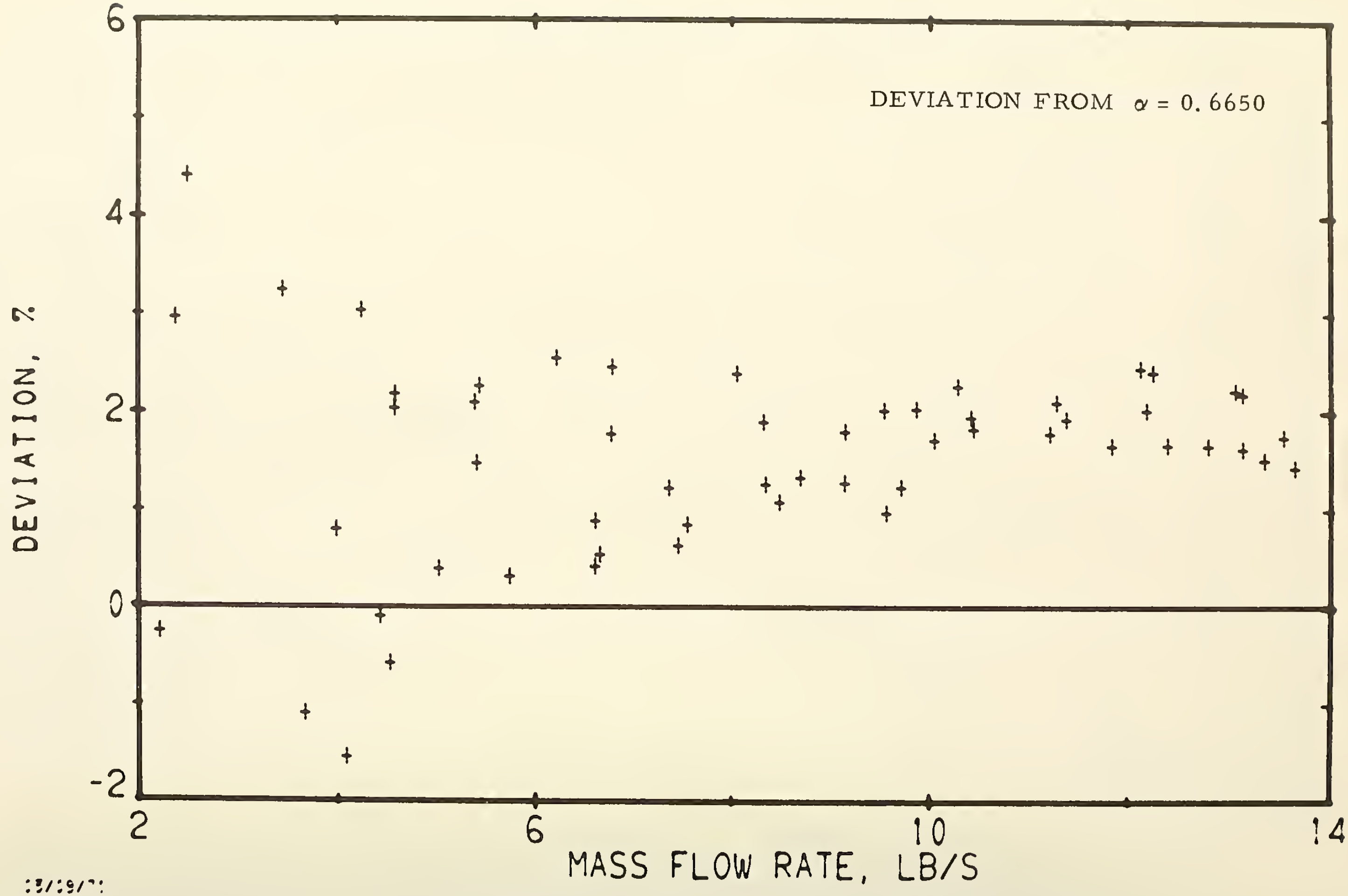

Figure 6D. Meter II, First Rangeability Test.

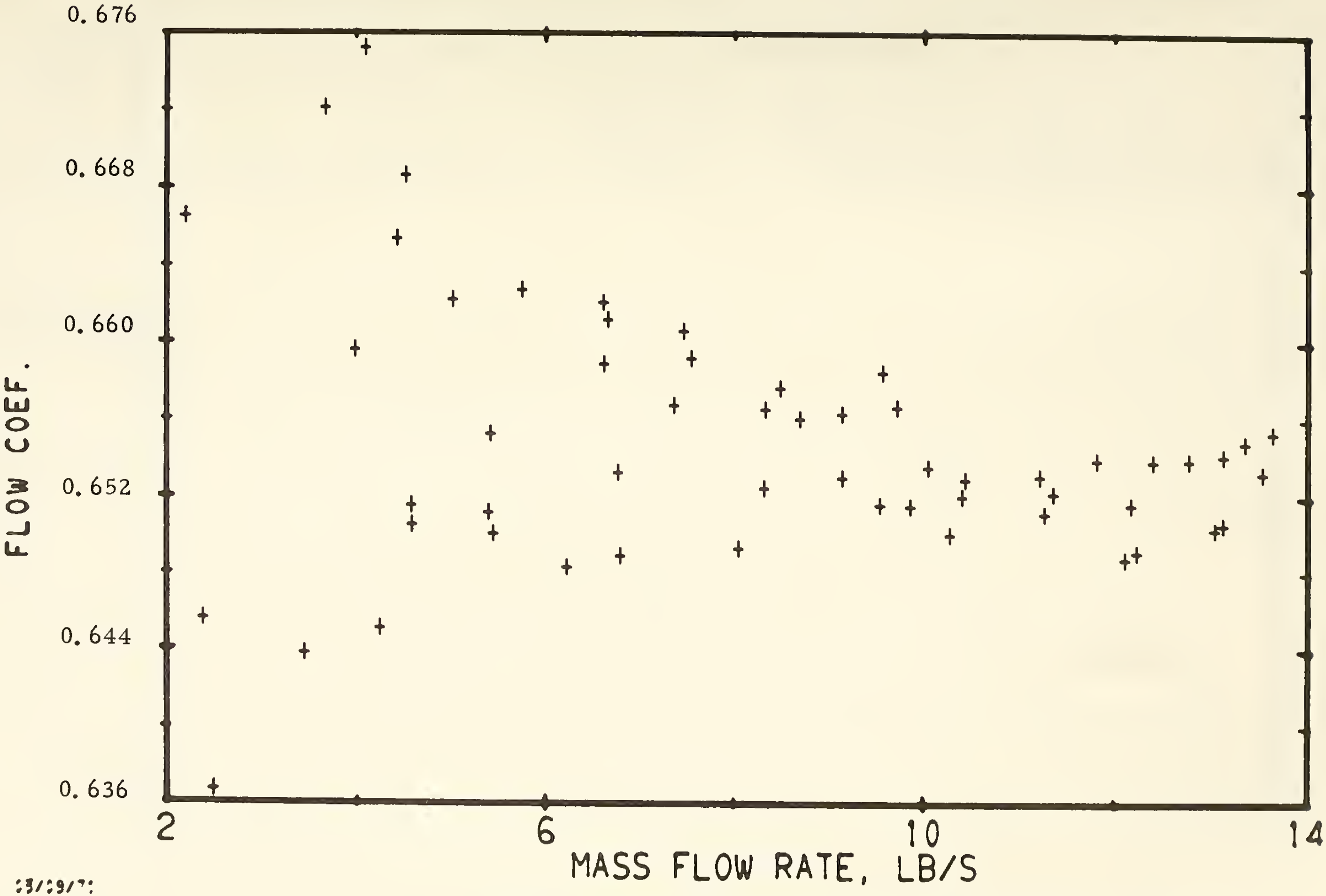

Figure 7D. Meter II, First Rangeability Test.

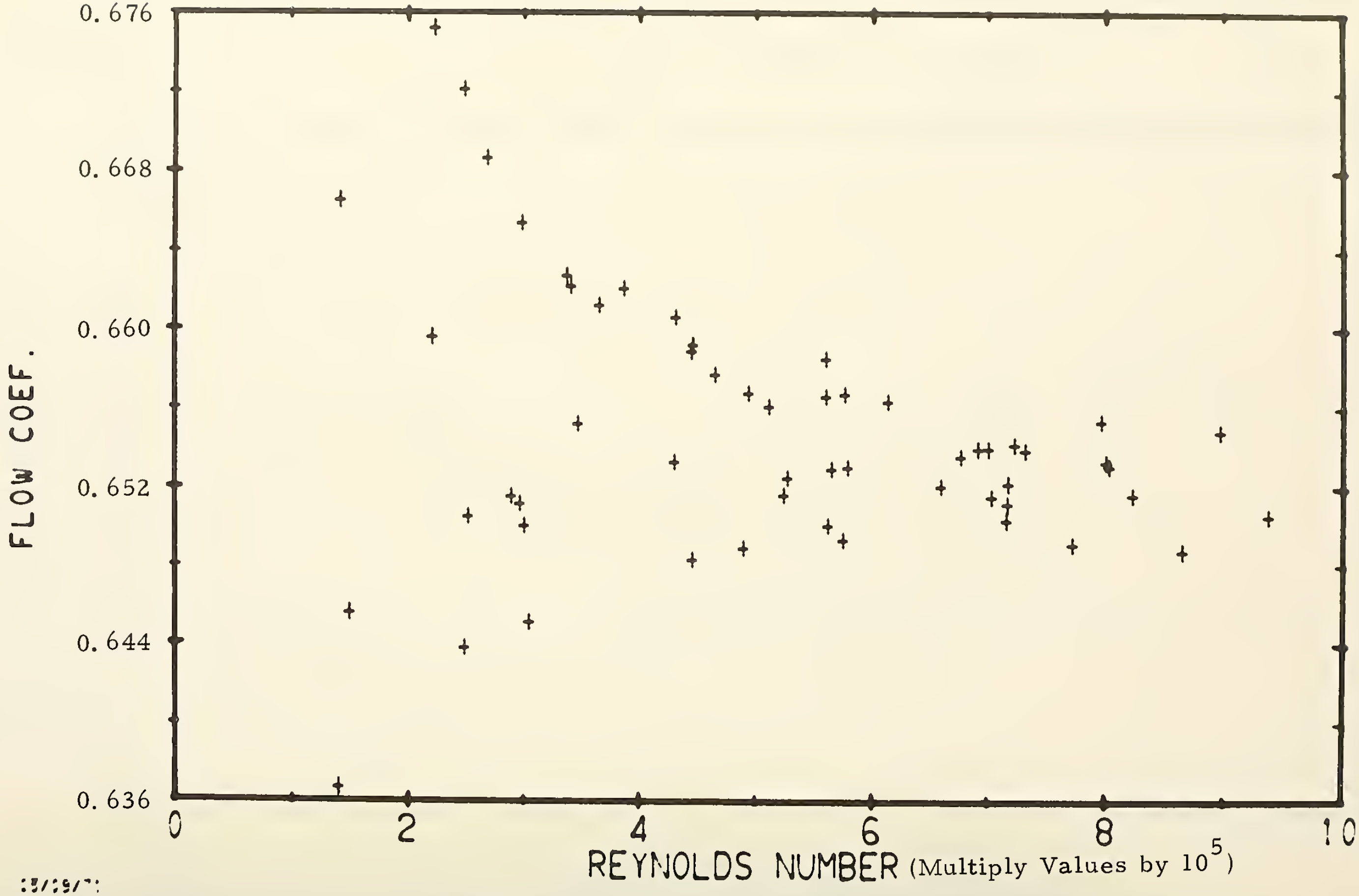

Figure 8D. Meter II, First Rangeability Test.

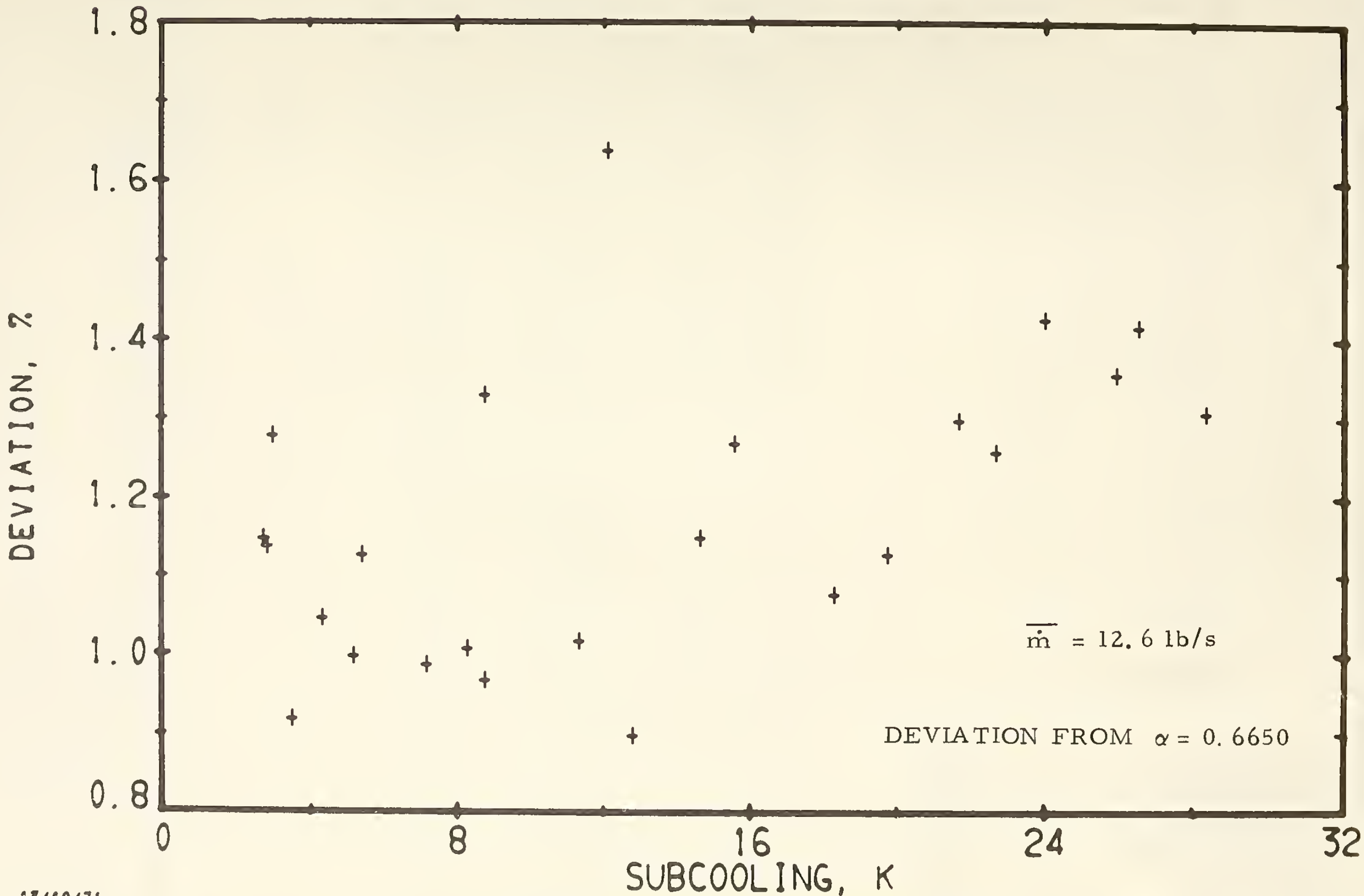

Figure 9D. Meter II, Boundary Test.

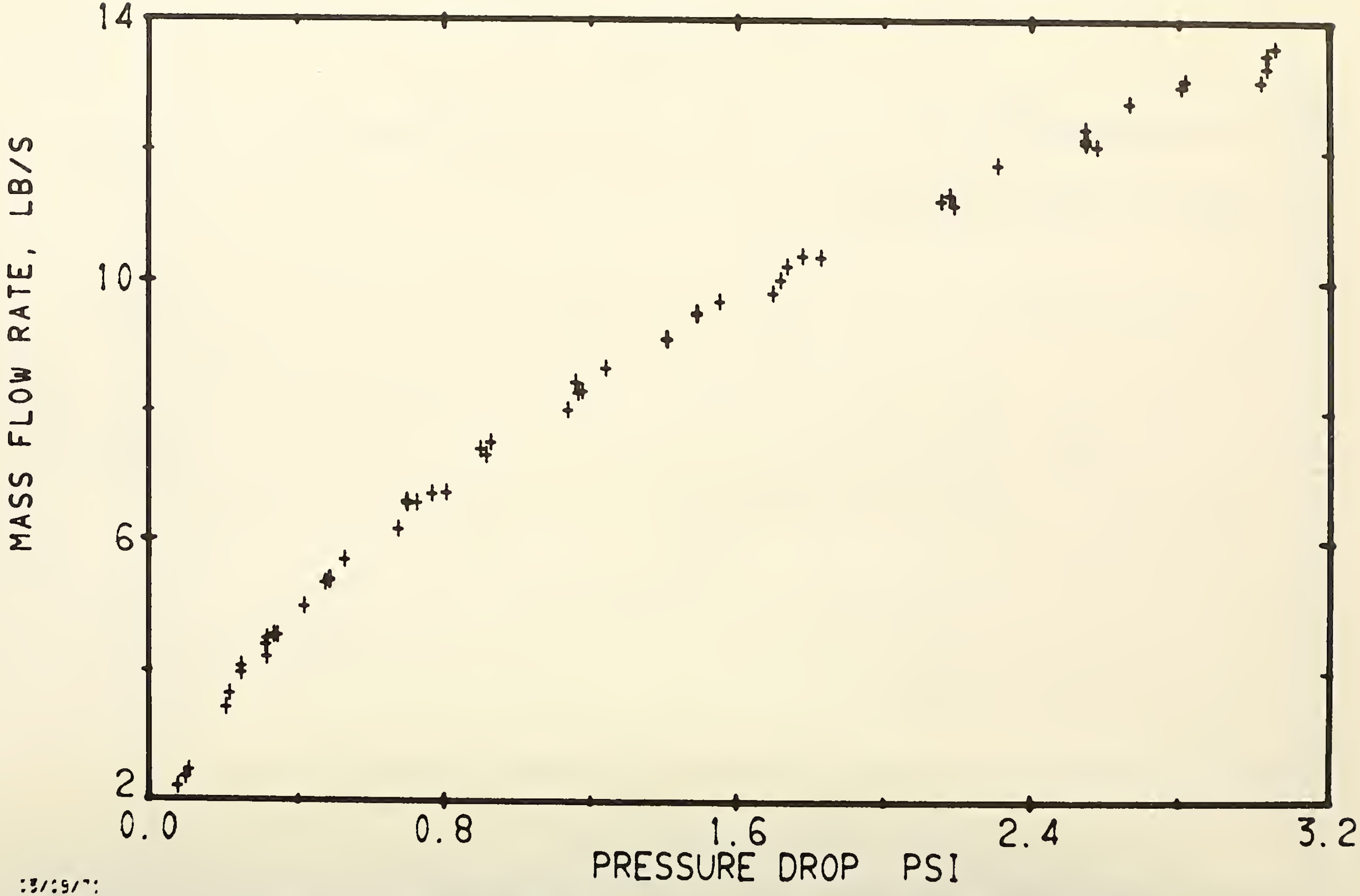

Figure 10D. Meter II, Pressure Drop.

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

The National Bureau of Standards (NBS) and the Compressed Gas Association (CGA) have jointly sponsored a research program on cryogenic flow measurement. Cryogenic flowmeters operating on the principles of angular momentum (mass flow), vortex shedding (volume flow), and pressure drop are reported.

The operation and the accuracy of the flow facility is briefly described. The performance of the flowmeters in liquid nitrogen is described by reporting the precision and bias of the meters before and after an 80-hour stability test and by defining the existence of temperature, pressure, flow rate, subcooling, and time order (wear) dependencies.

Meters were evaluated with flow rates ranging from 20 to 210 gpm (0.00126 to 0.0132 m^3/s), pressures ranging from 32 to 112 psia (0.22 to 0.77 MPa), and with temperatures ranging from 72 to 90 K.

17. KEY WORDS (Alphabetical order, separated by semicolons)
Angular momentum; cryogenic; flow; liquid nitrogen; mass; mass flowmeters; measurement; orifice; volume flowmeters; vortex shedding.

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