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A LABORATORY STUDY OF TURBINE METER UNCERTAINTY

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A series of laboratory tests are conducted to assess, quantitatively, the uncertainties produced in making fluid flow measurements using turbine meters. The patterns of uncertainty are analyzed statistically and remedial modifications are described and evaluated.

Using a tandemly connected pair of conventional turbine meters with recommended meter tubes and straightening vane sections, calibration procedures are performed with a weigh-time reference for the liquid flow. The calibration data are analyzed using a variety of techniques. The results indicate that turbine meter performance can, within the realm of "normal" operating conditions, be perturbed to exceed specified values. Modifications, both to hardware and conventional testing procedures, are described which enhance metering assurance.

Key Words: Accuracy; calibration; flow conditioning; meter performance; perturbations; precision; turbine meter; uncertainty.

1. Introduction

A concerted effort at the National Bureau of Standards (NBS) has been recently directed toward the establishment of Measurement Assurance Programs (MAPs) for flow. The objective of a flow MAP is to quantitatively characterize the flow measurement process. It is <u>not</u> to force everyone into state-of-the-art measurements but rather to establish techniques and procedures which will provide assurance, at all levels of measurement, that the results are adequate for the intended purpose [1,2,3,4][1].

[1]Figures in brackets indicate the literature references at the end of this paper.

Throughout the flow metering industry and practice, turbine meters have earned a considerable reputation for their precision and reliability. The advantages and disadvantages of using turbine meters to measure fluid flow are widely known and well documented [5,6,7,8,9,10,11,12].

The advantages include:

(1) A characteristic performance which exhibits a small range of variability over wide flow rate ranges. For normal fluids, this characteristic can be reduced to a single descriptor using dimensionless parameters.

(2) A pulsed output which is readily digitized. The resolution is limited only by the least count.

(3) Rotor bearing designs which have evolved to enable reliable performance over extended periods.

(4) Relative insensitivity to minor variations in streamwise velocity profile, due to the fact that the multi-bladed rotor and hub completely fill the flow cross-sectional area.

(5) Very rapid response characteristics.

In light of these advantages, turbine meters are widely used in aircraft applications, petroleum metering and other industrial areas where the user's flow measurement needs are critical. Turbine meters are not without their disadvantages, however. For example:

(1) The flowing fluid and any materials in it must not impair the rotor bearing or the rotor and blade geometry.

(2) The meter is susceptible to the effects of swirl in the inlet pipe flow and radical variations in the streamwise velocity profile have been known to cause variations in performance characteristics.

In view of these respective advantages and disadvantages, turbine meters have been selected for the initial phases of the flow MAP program. The present tests focus on turbine meter performance in water flows in medium pipe sizes.

2. Experimental Study

The experiments were carried out in the large, water calibration facilities of the Fluid Meters Section of the National Bureau of Standards. Shown in Figure 1, these facilities consist of a 60,000 gal. ($\sim 230 m^3$) sump from which water is pumped by means of one or more submerged pumps. For the present tests, the water then flows through filters and straight lengths of PVC pipe to the test sections where the meters under test are located. The flow is either bypassed to the sump or diverted into a collection tank positioned on a scale. The correspondence between the meter indication and the collected volume of water is determined from a static weighing of the water delivered in a measured time interval. More details on this system and procedure can be found in [13].

In the present experiments, pairs of turbine meters are tested in tandem. These turbine meters are commercially available, 4 in. (∿ 10cm) internal diameter meters, each of which is equipped with a matched meter tube. These meter tubes have both upstream and downstream sections. The upstream sections are fitted with flow straighteners consisting of tube bundles sized and located according to AGA/ASME recommendations [6-7]. This upstream meter tube section is bolted to its respective meter by means of pinned flanges to assure repeatable, aligned joints. The assembled meter and matched meter tube sections shall be referred to, in what follows, as a matched unit.

The present tests were confined to measurements at two flow rates set to achieve Reynolds numbers of 1.2×10^5 and 6.0×10^5 based on pipe diameter and water temperature. At each flow rate, respectively, given that a certain meter performance criterion (the ratio of meter responses) is satisfied, repeated water collections are performed and the so called "turbine meter constants" are determined in pulses per gallon corrected to 20°C. Initially, five such runs were made at each flow rate. The run-to-run variation obtained indicated that three such collections were adequate, and this change in the test procedure was implemented halfway through the test program.

The meter performance criterion used in this test is based upon a particular ratio of the two turbine meter responses. When this ratio closely approximates an expected value (formulated via averages from many previous tests), it is assumed that both meters are performing "properly" and the test results can be considered credible. Should the ratio criterion not be satisfied, it is assumed that something has impaired the meters - such as an anomalous deposit on a turbine blade. It is assumed that the probability of simultaneous and identical occurrences in both meters affecting each meter's performance in the same manner is negligibly small. Given repeatability of the ratio to within a specified tolerance of the expected value, the test procedure is continued. Otherwise, the meters are back flushed to remove anomalous deposits or the flow is stopped, and the pipeline drained and opened so that the meters can be inspected and cleaned by flushing with alcohol. To date, it has been possible at NBS to return this ratio to an acceptable value with one of these remedies.*

*In view of what follows, the actual value of the ratio may be a characteristic of a given test facility.

The specific procedures used to test the meters are given in Appendix 1. The data produced using this procedure will be referred to as "conventional." With a conventional data base determined, study consists of devising and evaluating a variety of schemes that perturb the meter performance from the conventional values. Once the perturbation effects have been determined, remedial procedures are devised and evaluated which are intended to re-establish conventional meter performance in the presence of perturbations.

The perturbation schemes devised include: (1) vibration effects, (2) radically changing the streamwise velocity profile entering the stream meter tube, and (3) inserting various levels of "swirl" in the inflow to the meter tube. It will be shown below that all of these have some effect on conventional meter performance. Of the three types of perturbations, swirl exerts the most significant perturbation effect.

The types of remedial procedures devised to re-establish conventional meter performance have included: (1) using a third turbine meter, installed upstream of the meters under test, (2) a particular "flow conditioner" installed upstream of the meters under test, and (3) flow conditioner installed ahead of the upstream section of the matched units.

To facilitate interpretation of the results of the present experiment, a list of symbols, shown in Figure 2, has been prepared. Using this list, particular piping configurations are efficiently described in the graphs that follow. It should be noted that the meter tube symbolized denotes both upstream and downstream sections. Thus, the connection of the meter tube with flow straightener and turbine meter symbols from Figure 2 denote the matched unit described above.

The flow straightener is of the tube bundle type containing nineteen tubes having OD = 3/4 in. (1.9 cm), wall thickness 0.049 in. (1.24 mm), and length 10 in. (25.4 cm). The tubes in this bundle are arranged in the scallop pattern and the bundle is centered in the tube by means of spacer lugs. The turbine meters symbolized by the squares are those under test. The different meters are designated by the numbers 1 and 2 placed in the proper square symbol.

The flow conditioner used in these tests is a radial flow filter. As a flow conditioner it is unusual in that it contorts the flow through four right angle turns. Three such turns produce a flow radially toward the pipe centerline. This radial flow is then turned again so that it flows axially out of the device. During the radially inward flow, the fluid passes through a porous element. Although the details of the conditioning mechanisms in this device are presently unknown, it will be seen, in what follows, that they are effective.

The third turbine meter, denoted by the propeller symbol is of the same line size as the meters under test. It has approximately the same angular speed as the test meters.

The swirler consists of a semicircular shaped vane. This is positioned in the pipeline so that its diameter is aligned with the pipe centerline when the vane is parallel to the pipe. The angular position of the vane is adjusted from outside the pipe and can impart swirl to increase or decrease, respectively.

The "out of plane elbows" configuration was specially prepared for this test. It consists of seven straight 4 in. (∿ 10 cm) diameter pipe lengths that are 6 diameters long and six elbows, and represent a "worst case" elbow configuration.

The 2:1 contraction, based upon diameters, was used when the meters were tested in the 8 in. (∿ 20 cm) diameter pipeline. This contraction is produced by two reducers, one 8 in. (∿ 20 cm) to 6 in. (∿ 15 cm) and one 6 in. (∿ 15 cm) to 4 in. (∿ 10 cm).

3. Results for the Low Flow Rate

3.1 Conventional Configuration

A control chart for the performance characteristics of meter 2 for the low flow rate is presented in Figure 3. The piping configuration is symbolically shown as the conventional one having a long, straight pipe length upstream of the tested meter 2. In this figure the error bars shown on either side of the round, darkened circles refer to the ± 3 standard deviation spread from the averages of one set of meter constants. The center of the bars is the average of the set. On the other side of the large, darkened circle is the repeat set performed after the pump is turned off and on again. The large darkened circle is the average of the two set averages. In what follows, the term "repeatability" is used in several ways. By repeatability is meant the percentage within which a subsequent determination of meter constant reproduces a previously determined value. Accordingly, switch off-switch on repeatability refers to two values which are averages of from three to five individual runs that are obtained from performing the presently described test procedure once. As noted from the test procedure, the meter connections to the pipeline remain untouched between these repeated tests thus excluding from causes of variation the alignment of the meter in the pipeline. Analogously, day-to-day repeatability refers, here, to the percentage within which the meter constant averages of all runs performed for a single flow rate and meter position on one particular day are reproduced on another day. Hence, Figure 3 exhibits the degree of switch off-switch on repeatability via the centers of error brackets for a single day as well as that from day-to-day via the differences between the large darkened circles for any two days. The 3 σ limits indicated for all the points are obtained from taking the average and standard deviation of the nine (9) ordinates given by the large, darkened circles. These values are given along the ordinate scale with the standard deviation given in parentheses under the average. It will be with these "conventional" values that the perturbation and remedial effects are compared.

Figure 4 presents the control chart for the ratio values corresponding to the results presented in Figure 3. This ratio is that of meter 2 divided by meter 1 and the graphical notation is identical to that used in Figure 2.

3.2 Perturbation and Remedial Effects

To examine the effects of pipeline vibration on turbine meter performance a controlled vibration source was attached directly to the pipeline. This source imparted a radial oscillation to the upstream section of the meter tube near the inlet. Vibration amplitude and frequency were controlled independently with this source.

The results of the vibration effects are shown in Figure 5. Here, on the left ordinate are the meter constant results plotted as a function of vibration frequency for constant amplitude as shown. The conventional mean results from Figure 3 are shown with 3 σ brackets. The nominal background levels of vibration experienced by the pipeline at these flow rates is 0.010 to 0.020 in. (0.25 to .5 mm) peak-to-peak. On the right ordinate are the corresponding ratio results. These results indicate that, while this imposed vibration causes a decreasing trend in meter constants at the higher frequencies, the variations are well contained within the 3 σ limits about the conventional mean. Similarly, the ratio values obtained show neither a systematic variation with frequency nor any excursion beyond the 3 σ limits. It appears that this particular type of vibration does not significantly influence the performance of these turbine meters at low flow rates.

The range of perturbations imposed by various elements which alter the flow into the meters is shown in the modified Youden Plots[4] presented in Figure 6. Here, the meter constant for upstream meter 2 under test is compared with downstream meter 1. All points for meter 2 include 3 σ bars. Along the right side of the graph is the legend indicating the corresponding piping configurations. It is found that an out of plane elbow configuration produces a small decrease in meter constant. Combinations of elements such as the flow conditioner described earlier and the third turbine meter or the 2:1 contraction and the third meter tend to increase the turbine constant slightly. Each of these perturbations, however, does not cause the turbine constant to deviate beyond the 3 σ limit about the conventional mean value. The effect of the third meter placed upstream of the meters under test is shown to cause an increase in meter constant of about 0.3 percent. The effect of swirl induced by the vane is shown by the extreme values in Figure 6. When the vane induced swirl is in the same direction as turbine rotor rotation, the overspinning effect causes the meter constant to increase 0.4 percent. This demonstrates that a considerable amount of swirl passes through the straightening vane in the meter tube. Reversing the swirl direction is shown to decrease the turbine constant about 0.3 percent. The distribution of vorticity across the flow section was not measured.

Figure 6 can be used to determine the corresponding data for the ratio of meter responses. For any value plotted, dividing the ordinate by the abscissa gives the desired ratio. Therefore, the percentage changes specified above for the meter constants also pertain, nominally, to the ratio values. Also evident from Figure 6 is that the downstream meter unit is relatively unaffected by the perturbations imposed ahead of the upstream meter unit. In fact, for all these perturbations, the variation sustained by the downstream meter is about 0.1 percent. This suggests that the upstream meter unit with its adjacent straightening tubes forms a rather effective flow conditioner. From the range of perturbations imposed on the flow into the test meters, the extreme values, namely those due to vane induced swirl, will now be selected as the basis for evaluating the various remedial schemes devised to reduce the perturbation effects.

In Figure 7 are presented the results obtained when the flow conditioner replaces the upstream section of the matched meter tube. The results plotted refer to three piping configurations: (1) the extreme perturbation effects denoted by the square symbols, (2) the flow conditioner installed with no perturbing effects present, and (3) the conditioner installed in the presence of perturbations. The meter constants, as determined with the conditioner and no perturbations, are found to be lowered approximately 0.15 percent from the conventional mean. This change exceeds the 3 σ limits which correspond to about 0.1 percent. Although not presented here, the velocity profiles at the conditioner exit were measured and found to be more uniform than the "normal" turbulent profile found in these pipes. It is to this alteration in the velocity profile that the shift in meter constant is attributed. In the presence of positive swirl, the flow conditioner is found to dramatically lower the perturbed values which, it is recalled, exceeded the conventional mean by 0.4 percent. For the case of swirl opposite to turbine rotor rotation, the flow conditioned results are found to be highly scattered. Although the details are, as yet, unclear, these results suggest that the outlet flow from this conditioner which directly enters the meters produces unstable performance.

Figure 8 presents results for the remedial effects obtained with the flow conditioner directly upstream of the conventional piping configuration. With flow conditioning, the averaged meter constants with and without the extreme perturbation case of positive swirl are within 0.1 percent of each other. The 3 σ limits are nominally the same with and without perturbations. In view of this set of results, it is concluded that the flow conditioner installed upstream of the conventional meter unit produces the most satisfactory arrangement of the presently devised schemes.

4. Results for the High Flow Rate

The control chart for the No. 2 meter at the high flow rate is shown in Figure 9 where the notation corresponds to that of Figure 3. It is noted in Figure 9, that the switch off-switch on repeatability can be as much as 0.06 percent. The day-to-day repeatability can be as much as 0.12 percent. The ratio of meter responses at the high flow are given in the control chart presented in Figure 10. It is evident from this figure that before precise expected values can be chosen for a flow rate an extensive amount of data must be taken.

The effects of vibration on meter performance at the high flow rate are shown in Figure 11. Here again, as seen above in the results for the low flow, no significant variation is produced by this type of vibration.

The remedial effects produced by the flow conditioner bolted upstream of the conventional piping configuration are shown in Figure 12. Only the extreme perturbation effects due to vane induced swirl in the direction of turbine rotation are shown. This swirl increased meter constants 0.4 percent above conventional values. Vane induced swirl in the opposite direction produced reductions in meter constants which plot off this graph.

The meter constants obtained with the flow conditioner in place, without perturbing effects, indicate that the meter constants are reduced slightly (0.06 percent) in comparison with conventional values. In the presence of vane induced swirl, the flow conditioner was found to eliminate the swirl effects.

5. Conclusions

On the basis of this tightly controlled series of tests at two flow rates, day-to-day repeatability for turbine meter constants over a 10 month period ranges from ± 0.07 to ± 0.12 percent based upon averages of at least six runs. The repeatability obtained during a single day's test when the flow is switched off and then on again ranges from ± 0.03 percent at the low flow to ± 0.06 percent at the high flow rate. The results for the ratio criterion for "proper" meter performance indicate that a 3 σ tolerance is ± 0.1 percent for the low flow and ± 0.18 percent for the high flow. The charateristics of these meters thus enable the investigation of the effects of flow phenomena beyond the "simple" questions of precision and accuracy of weighing, counting, timing, and temperature measurements which comprise overall accuracy estimates.

The effects of various levels of swirl, however, were found to produce the most significant changes in meter constants. These ranged from -0.3 percent to + 0.4 percent. For selected types of perturbations on conventional meter performance, those due to vibration and limited alterations to the streamwise velocity profiles entering the meters produced no significant changes in the values for the meter constants.

Of the various schemes devised to remedy the perturbing effects on meter constants, the most successful was a radial flow conditioner. In the absence of perturbations, this device produced a slight decrease in meter constants which was expected in view of the velocity profile at the exit of the conditioner. In the presence of the most severe perturbations, the flow conditioner was successful in restoring the meter performance to within the 3 σ limits of average conventional values.

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References

[1] Pontius, P. E., Notes on the Fundamentals of Measurement and Measurement as a Production Process, *NBSIR 74-545*, Sept. 1974.

[2] Pontius, P. E., Measurement Assurance Programs - A Case Study: Length Measurements. Part I Long Gage Blocks (5 in. to 20 in.) *NBS Monograph 149*, Nov. 1975.

[3] Pontius, P. E. and Cameron, J. M., Realistic Uncertainties and Mass Measurement Process: An Illustrated Review, *NBS Monograph 103*, Aug. 1967.

[4] Youden, W. J. Graphical Diagnosis of Interlaboratory Test Results, *Industrial Quality Control*, Vol. XV, No. 11, May 1959.

[5] Shafer, M. R., Baker, D. W., and Benson, K. R., The Calibration and Performance of Turbine Type Flow Transducers Operating at Pressure Levels Up to 1400 psig, *NBS Report 9088*, Apr. 1966.

[6] American Gas Association, *Report No. 3. Orifice Metering of Natural Gas*, Arlington, Va, 1972.

[7] Bean, H. S., ed, *Fluid Meters - Their Theory and Application*, ASME, New York, 1971.

[8] Strohmeier, W. O., Turbine Flowmeters, Past, Present, and Future, *Symposium Proceedings: Flow - Its Measurement and Control in Science and Industry*, Vol. I, Part II, Flow Measuring Devices, ISA 1974, pp. 687-693.

[9] Thompson, R. E. and Grey, J., Turbine Flowmeter Performance Model, *Trans ASME*, Dec. 1970, pp. 712-723.

[10] Spencer, E. A., private communication; National Engineering Laboratory, East Kilbride, Glasgow, Great Britain, 1976.

[11] Bellinga, H. and Stronk, H., The Practical Application of Flow Straighteners With Turbine Flow Meters for Gas. *British Fluids Laboratory paper No. 242*.

[12] Rubin, M. Miller, R. W., and Fox, W. G., Driving Torques in a Theoretical Model of a Turbine Meter, *Trans ASME Journal of Basic Engineering,* 1964, Paper No. 64-WA/FM-2

[13] Shafer, M. R. and Ruegg, F., Liquid-Flowmeter Calibration Techniques, *Trans ASME,* Oct. 1958, pp. 1369-1379.

Appendix 1 Test Procedure

1. The meters are bolted to their respective meter tubes with a new gasket inserted in the upstream flange joint of the meter.

2. The meters, with meter tubes, are bolted in tandem with a specified meter (No. 2) in the upstream position: the tandem pair of meters are then bolted into the test section of the pipeline.

3. A "run-in" flow is produced in the pipeline. This flow rate is the higher of the two test flow rates. It is continued for fifteen (15) minutes, during which time the ratio of meter responses is monitored and compared with the expected value.

4. The lower of the two test flow rates is produced in the pipeline. This flow is valved according to a Reynolds number criterion, i.e., a specified ratio of upstream turbine meter frequency in cyc/sec divided by the (temperature dependent) kinematic viscosity of the water in centistokes. The tolerance on the turbine meter frequency is nominally 2 cyc/sec.

5. The ratio of turbine meter frequencies, i.e., that of No. 2 divided by that of No. 1 is monitored. When this is within 0.05 percent of the expected value, the test may proceed. Should this ratio criterion not be satisfied, the following sequence of remedial procedures is suggested. The flow in the pipeline can be increased and decreased repeatedly. If possible a reversed flow in the pipeline, is produced to dislodge particles from the turbine blades. The meters are removed from the pipeline inspected for anomalous deposits or adherents to the internal components, cleaned via a flushing with alcohol and returned to the pipeline.

6. Repeated diversions of the flow into the collection system are performed and the data is processed to produce turbine constants in pulses per gallon corrected to 20°C. Five such "runs" are done.

7. The higher flow rate is produced according to a specified upstream turbine frequency-to-centistoke ratio; the ratio of meter frequencies is monitored. When satisfactory agreement with the expected value is obtained, repeated determinations of meter constants are done.

8. After the high flow meter constants are determined the flow is stopped and the pumps are turned off. After five (5) minutes, the pumps are switched on and the tests at both flow rates are repeated as per steps 4 through 7.

9. When this has been completed, the flow is again stopped, the pumps switched off, the line drained, and the positions of the meters with their matched meter tubes are reversed in the pipelines.

10. Steps 3 through 8 are repeated for this tandem configuration of the meters.

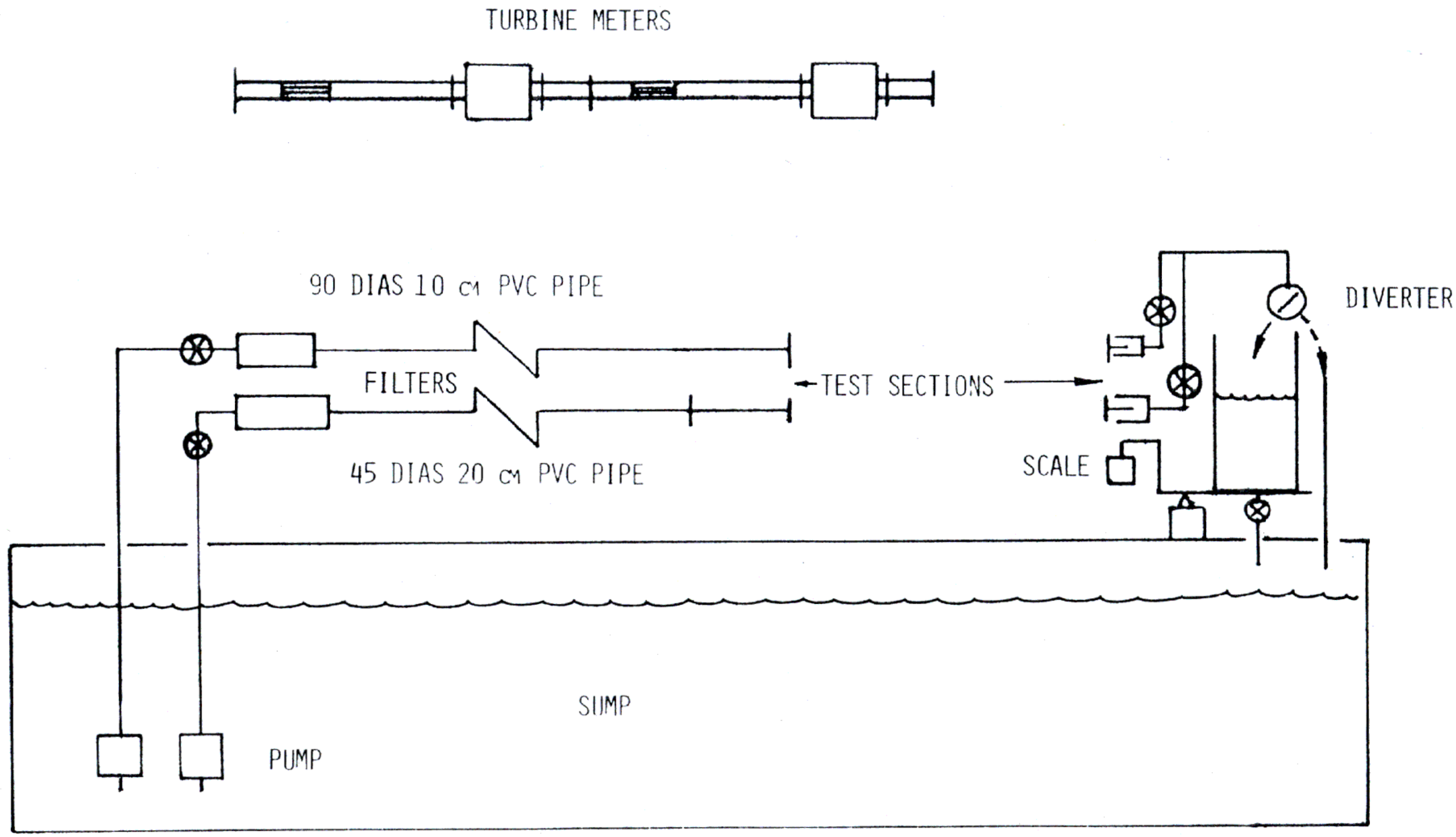
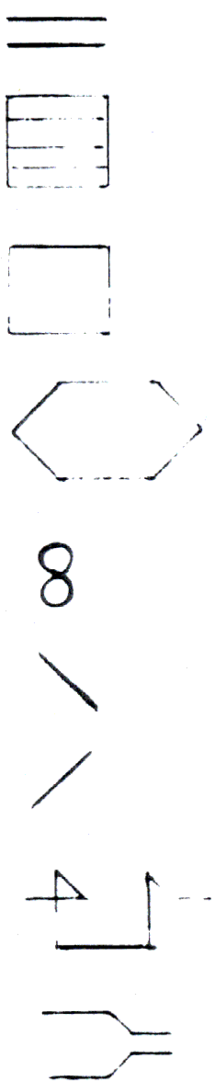


Figure 1. Sketch of Calibration Facilities.

LIST OF SYMBOLS



PIPE

METER TUBE WITH FLOW STRAIGHTENER

TURBINE METER

FLOW CONDITIONER

OTHER TURBINE METER

SWIRLER (+)

SWIRLER (−)

OUT OF PLANE ELBOWS

2 : 1 CONTRACTION

Figure 2. List of Symbols.

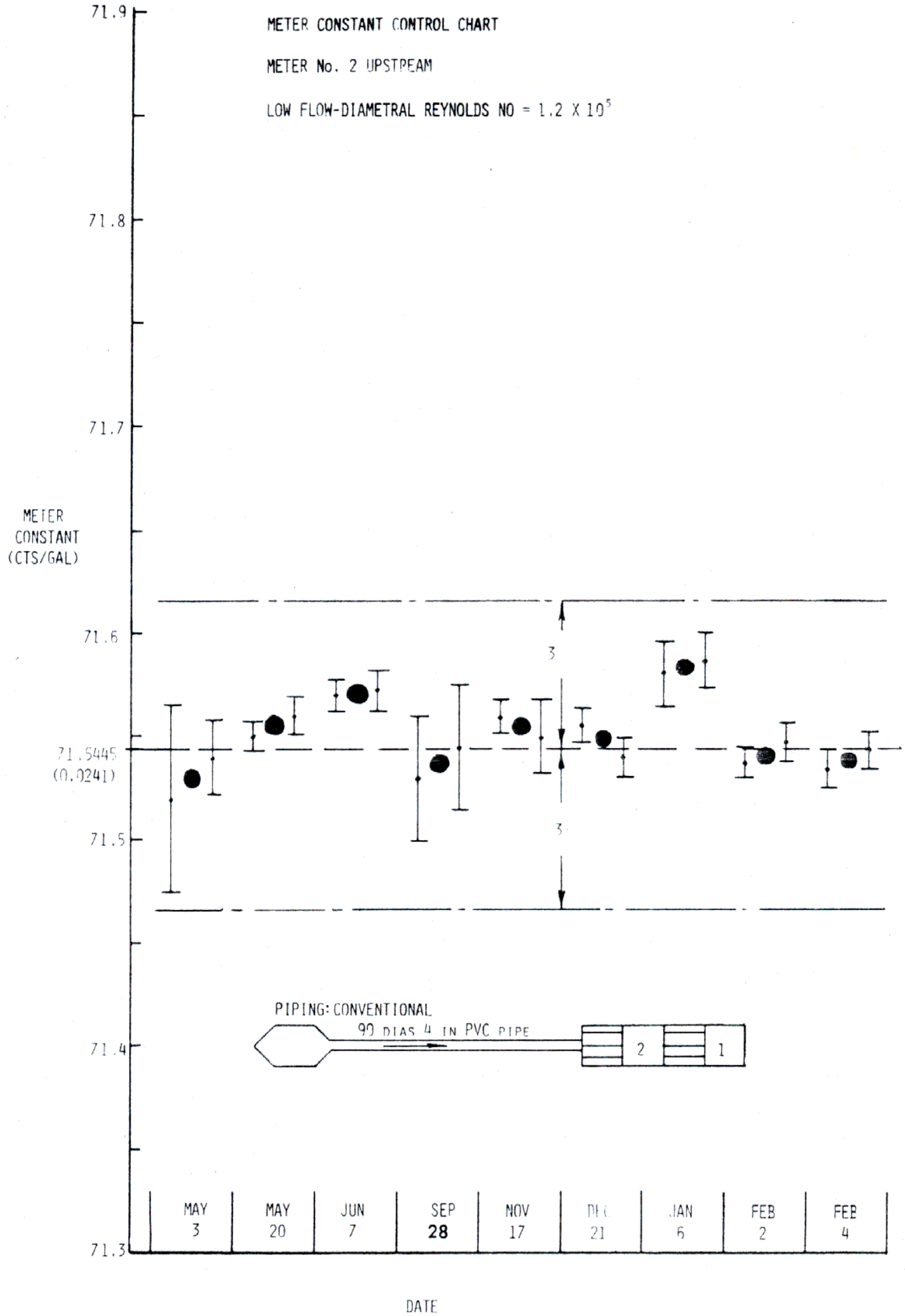


Figure 3. Control Chart for Meter No. 2. Low Flow.

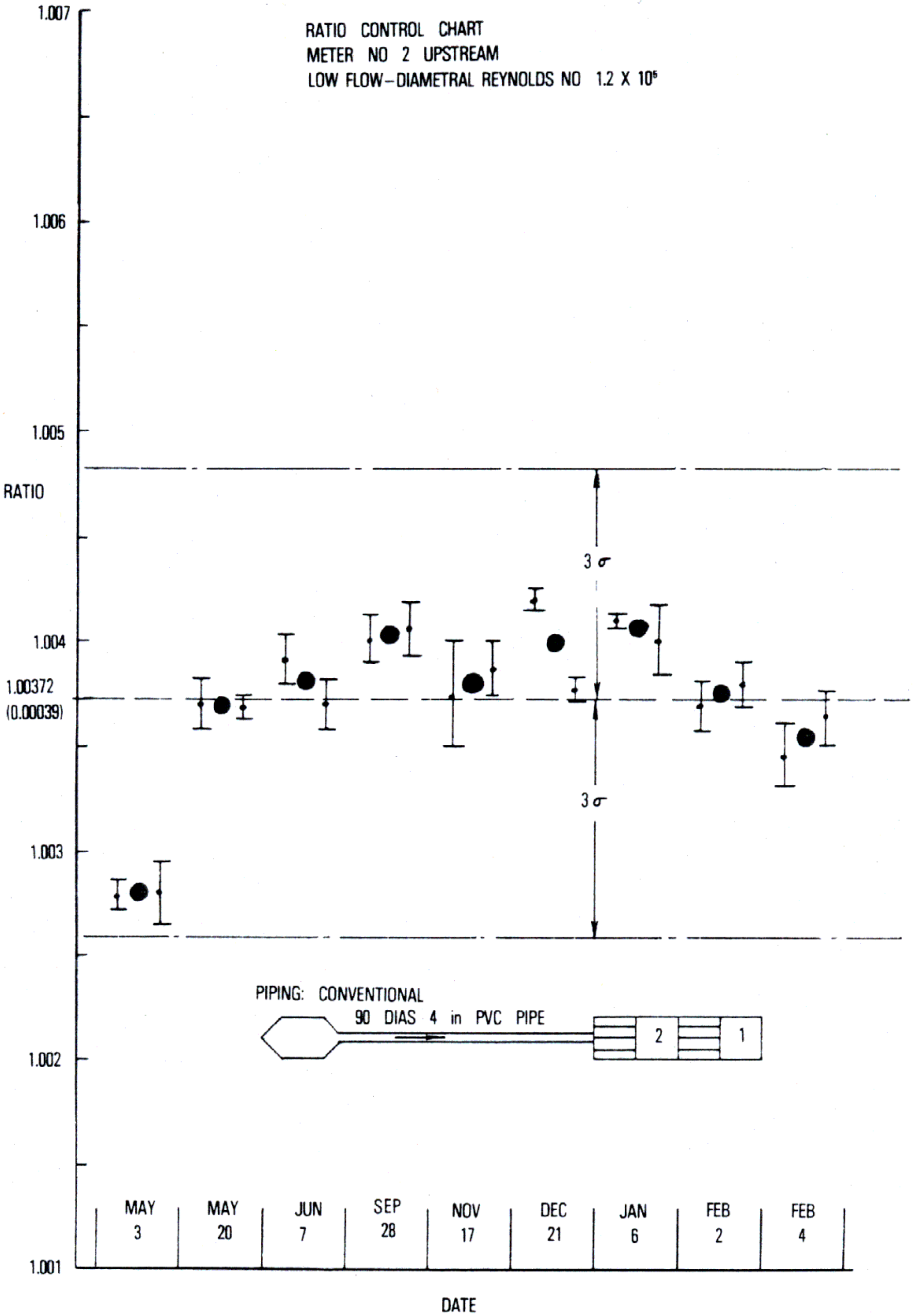


Figure 4. Control Chart for Ratio of Meter Constants. Low Flow.

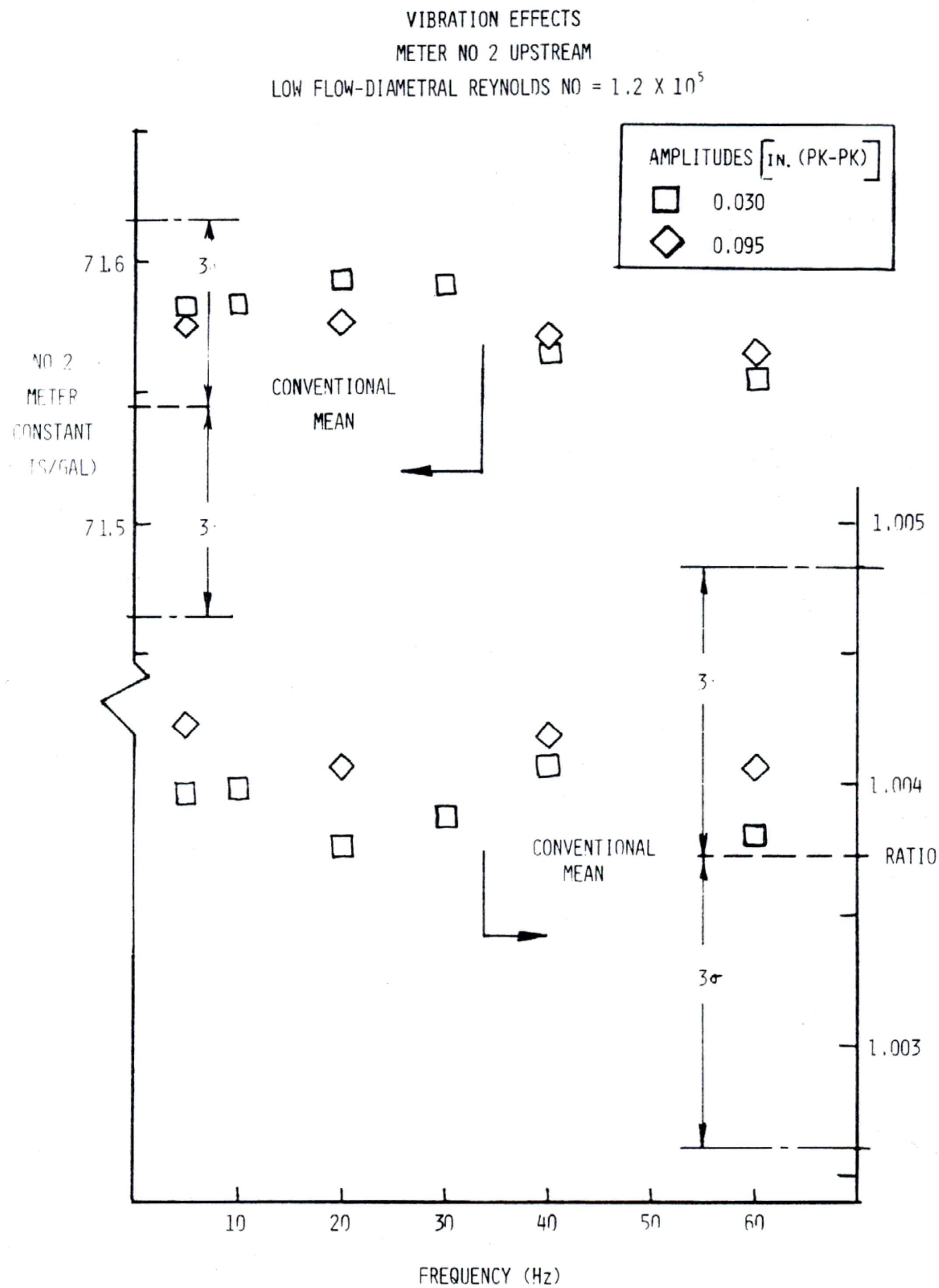


Figure 5. Vibration Effects on Meter No. 2. Low Flow.

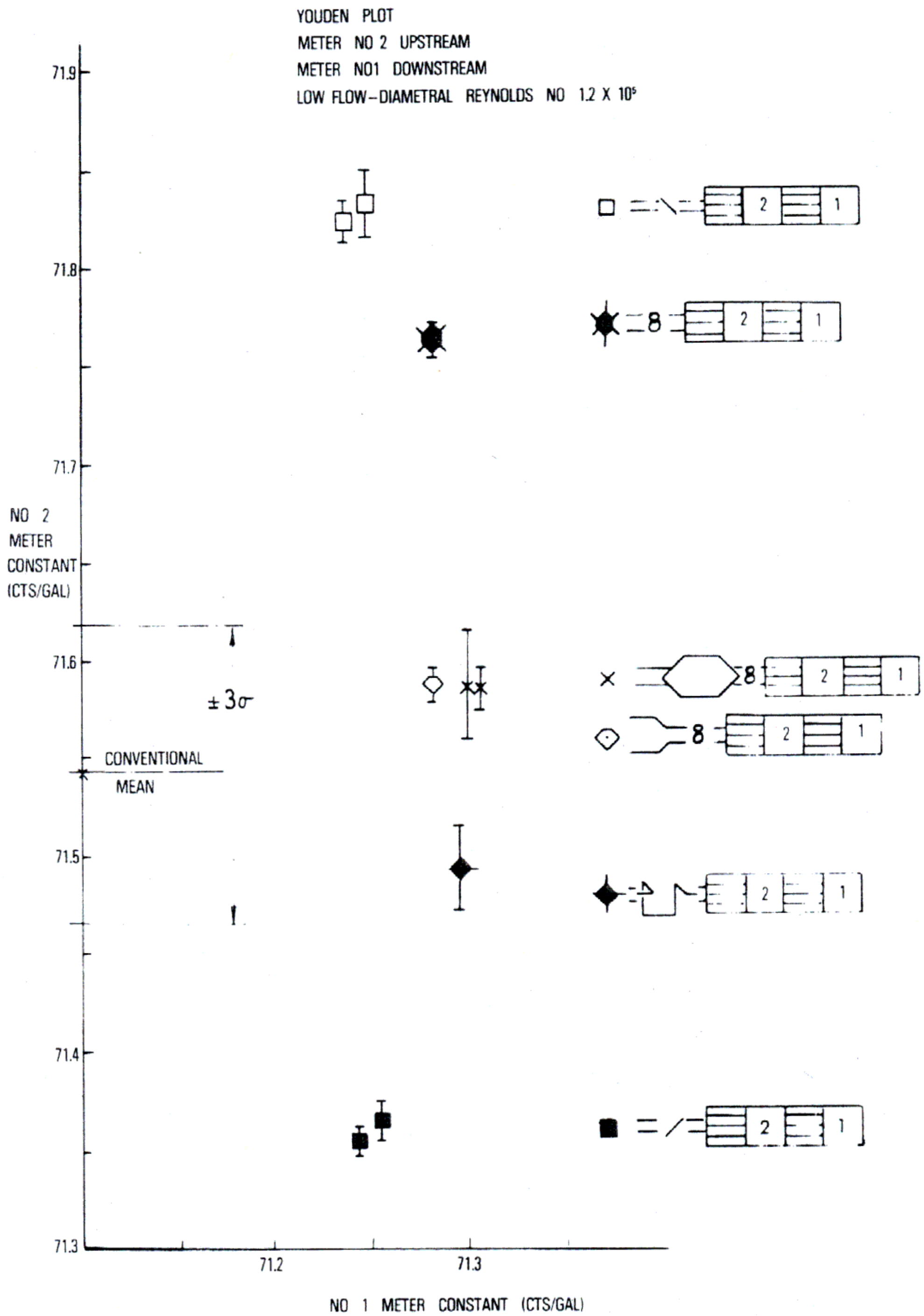


Figure 6. Modified Youden Plot for Perturbation Effects. Low Flow.

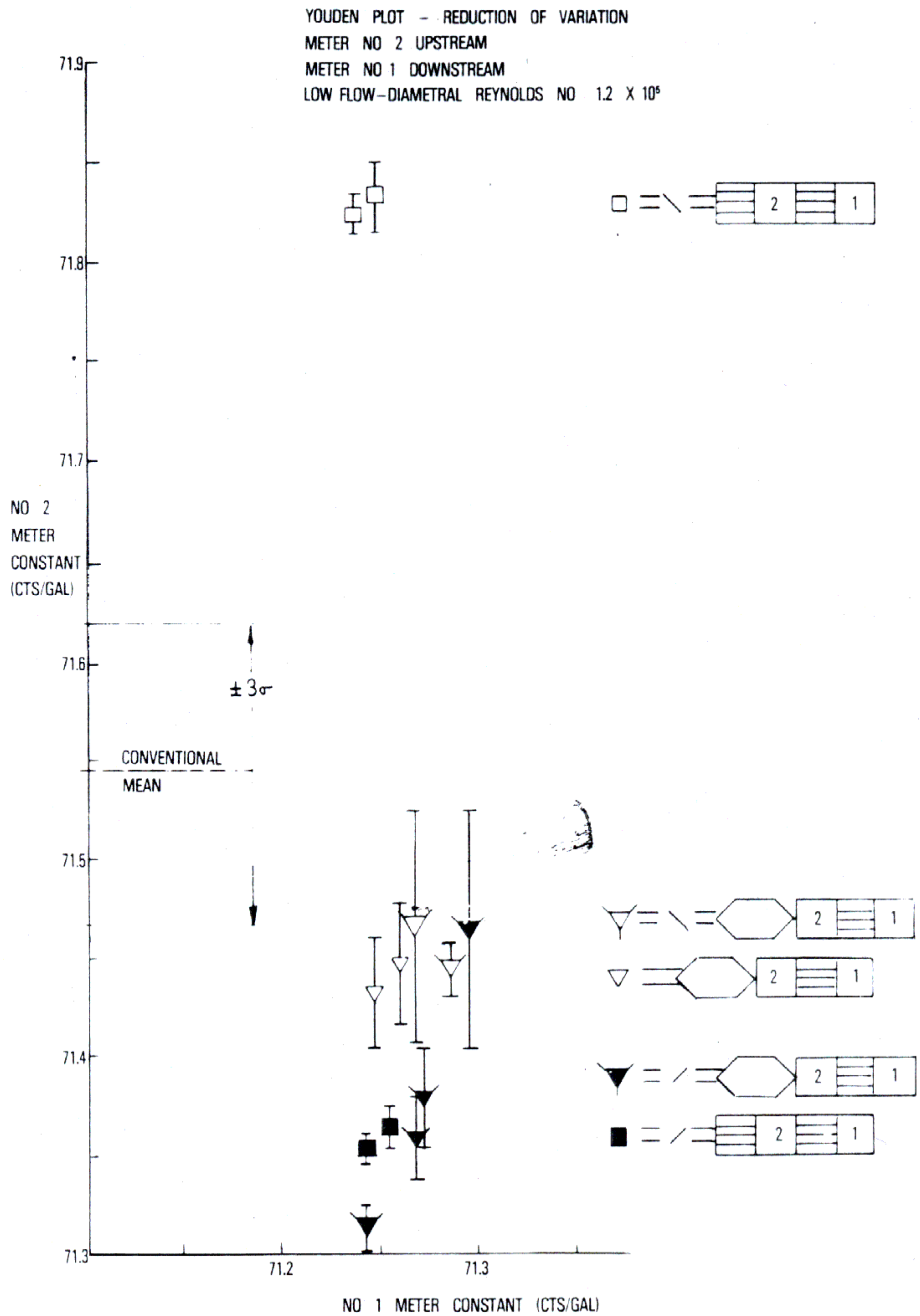


Figure 7. Modified Youden Plot for Remedial Effects Consisting of the Flow Conditioner Bolted Directly to the Meter. Low Flow.

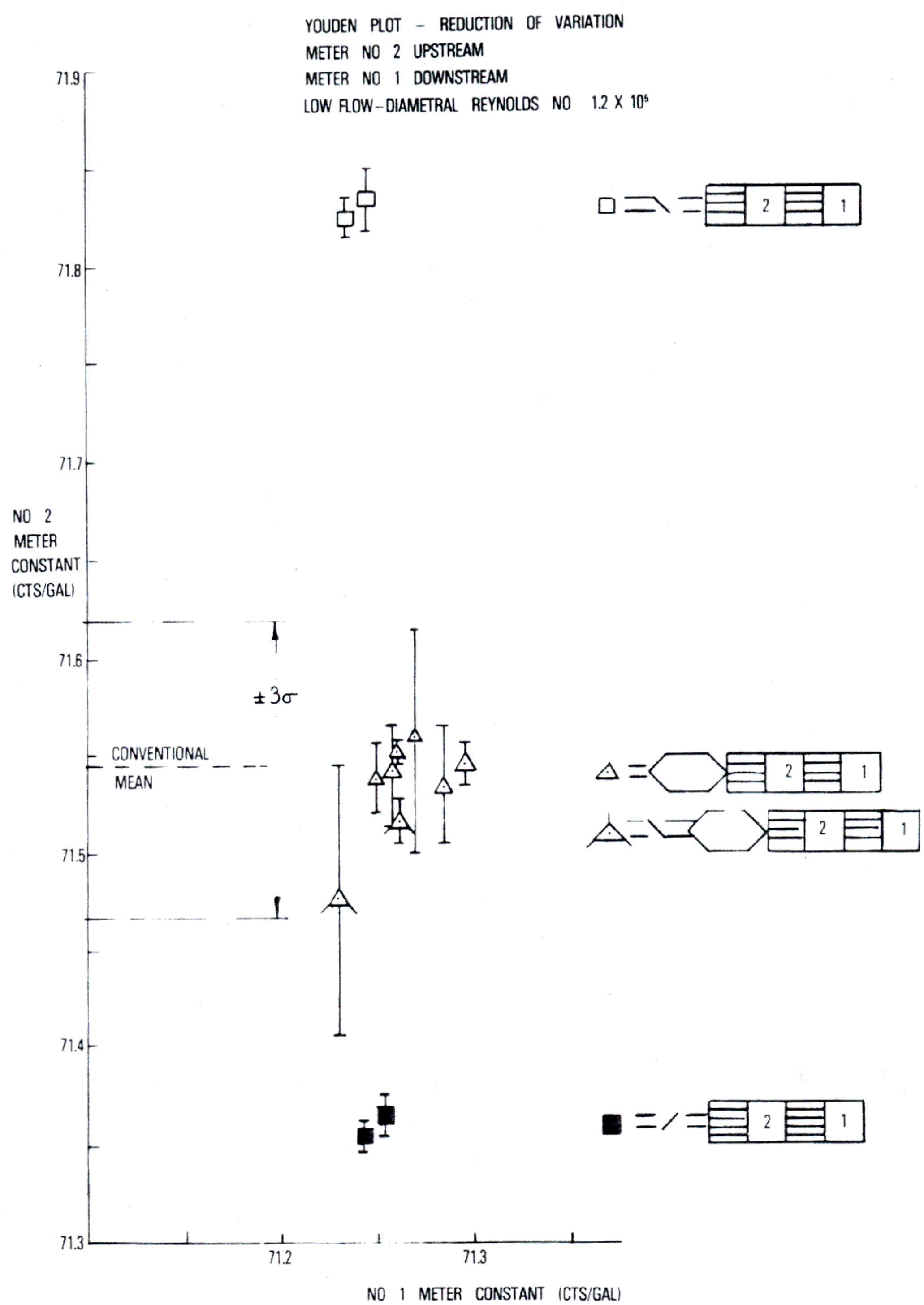


Figure 8. Modified Youden Plot for Remedial Effects Consisting of the Flow Conditioner Bolted Upstream of the Meter Tube Assembly. Low Flow.

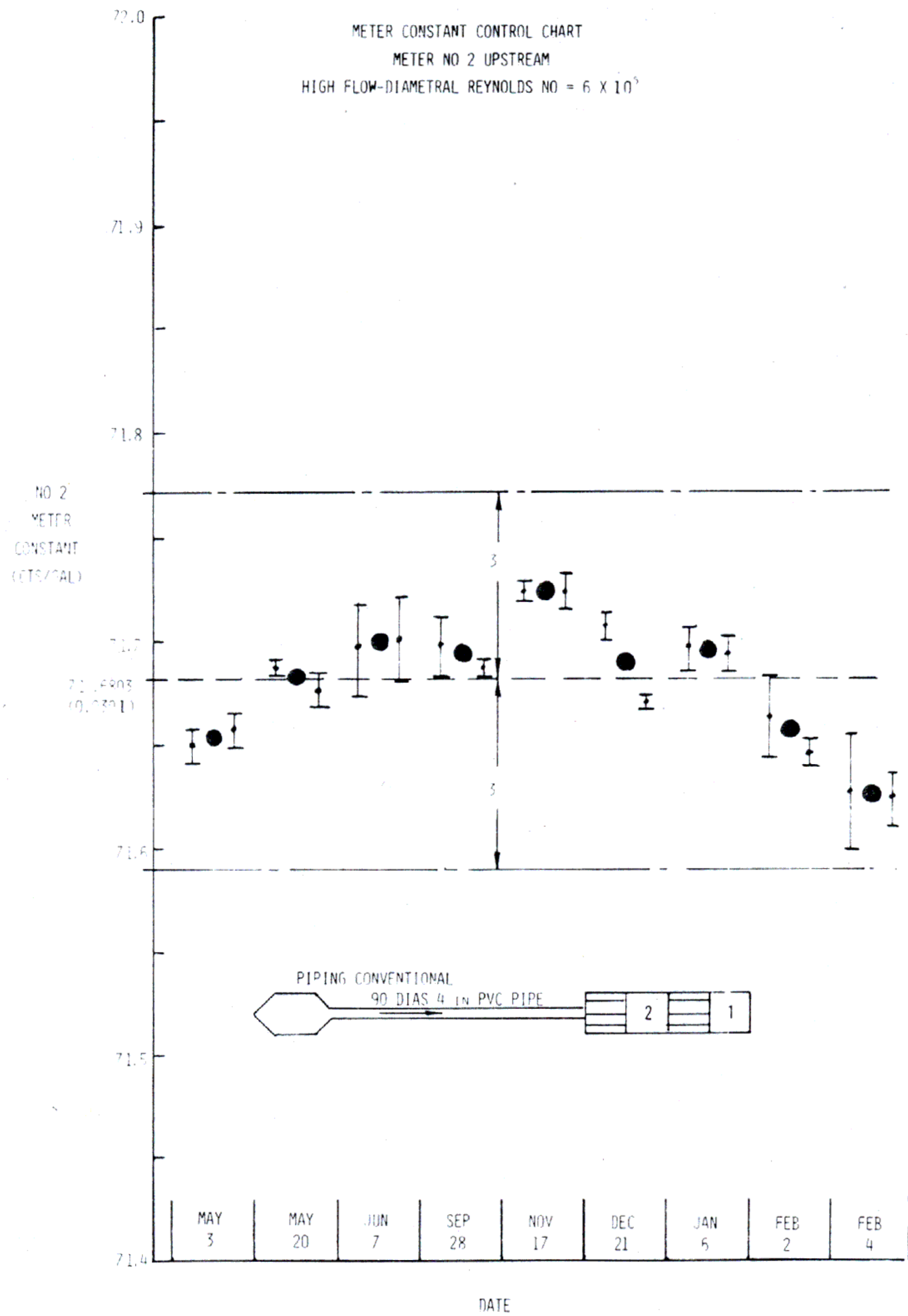


Figure 9. Control Chart for Meter No. 2. High Flow.

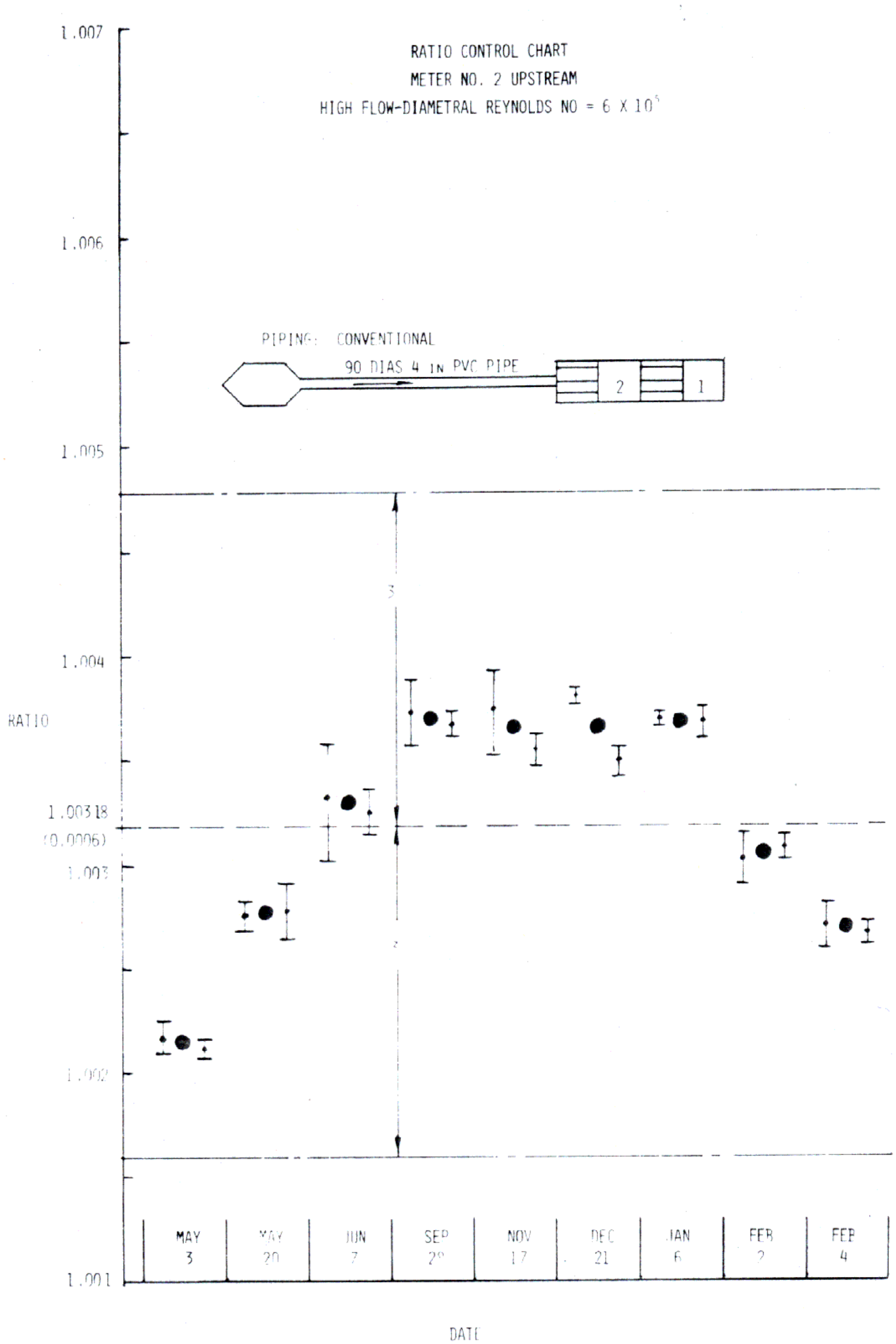


Figure 10. Control Chart for Ratio of Meter Constants. High Flow.

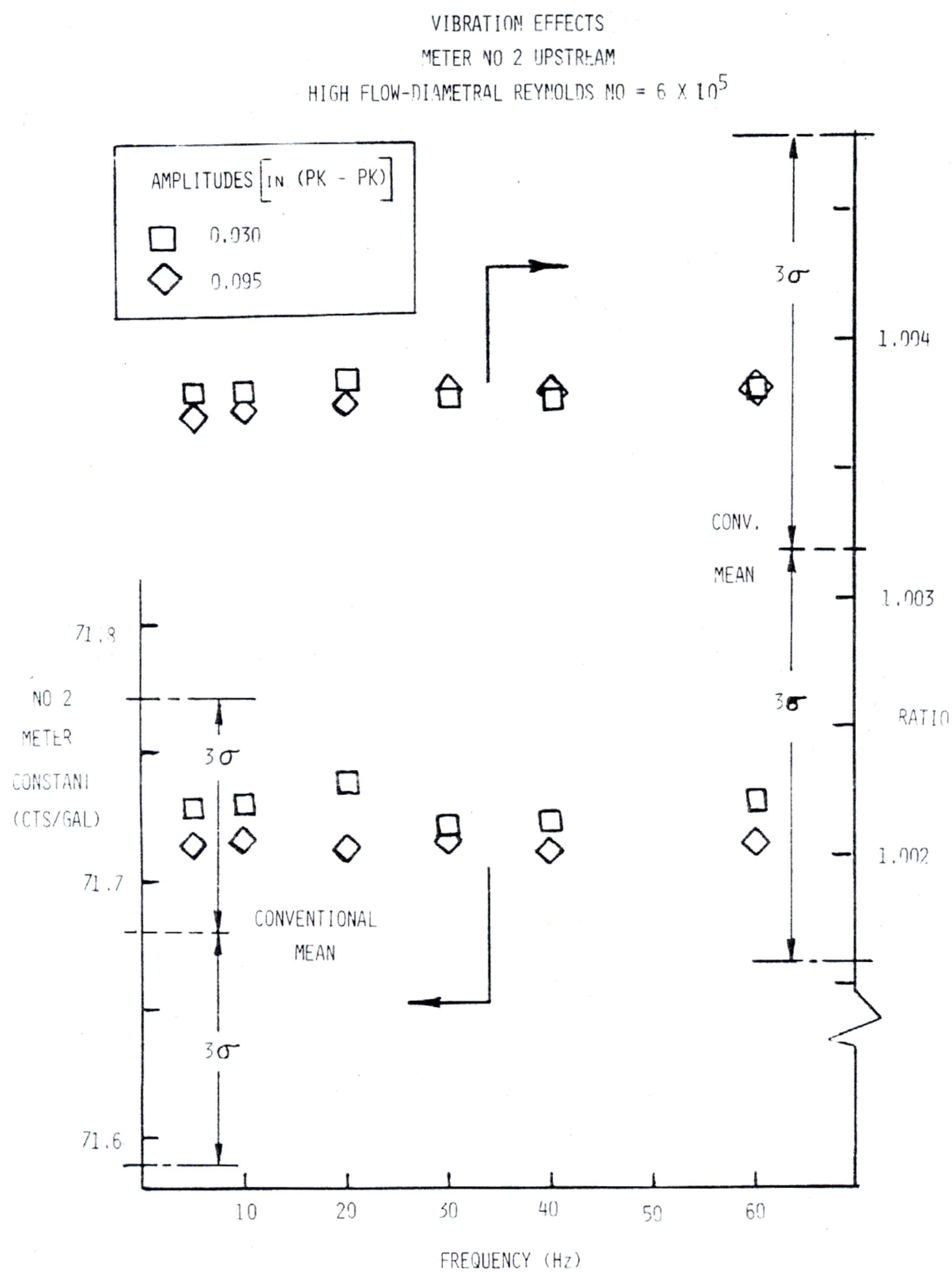


Figure 11. Vibration Effects on Meter No. 2. High Flow.

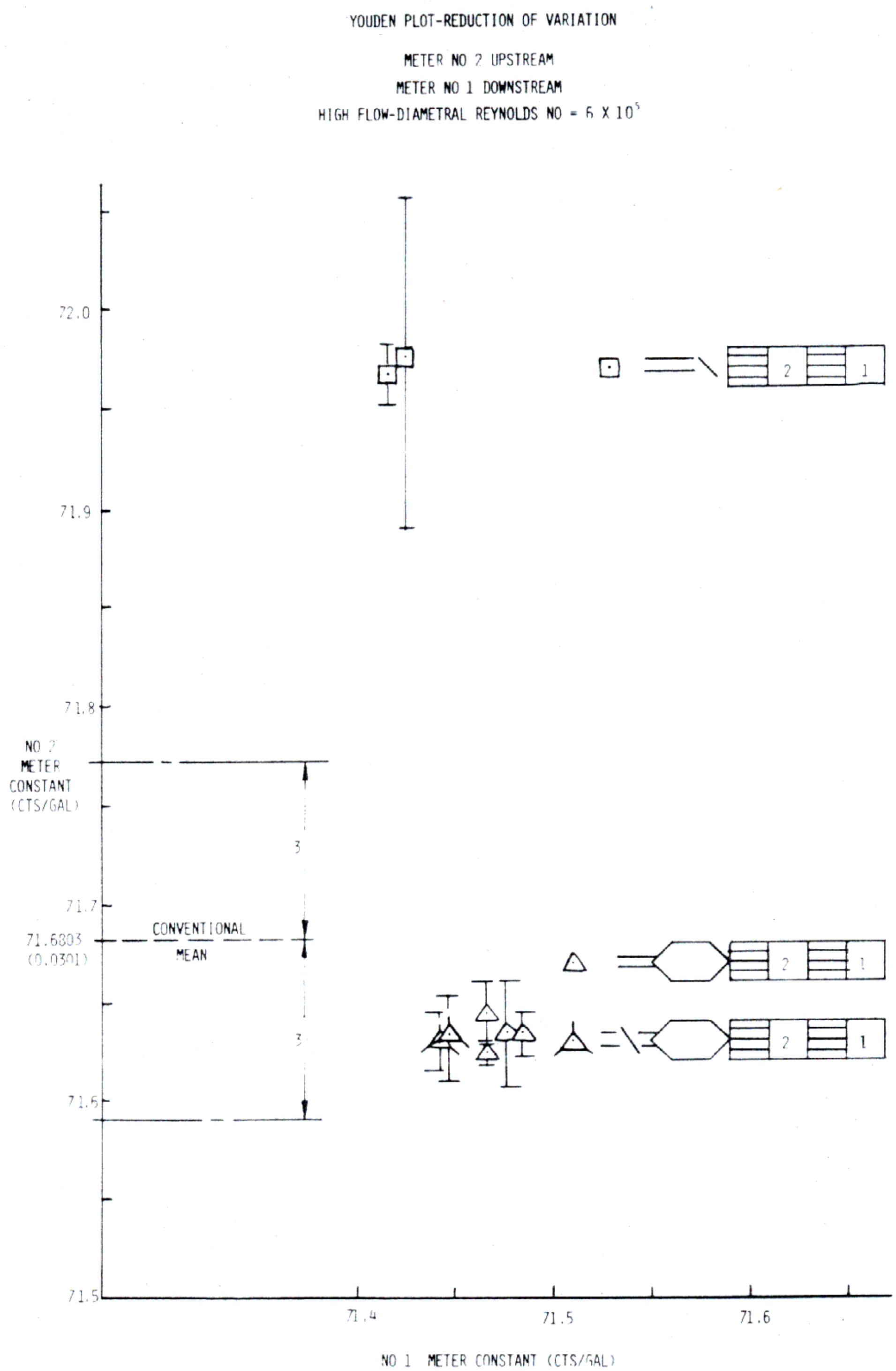


Figure 12. Modified Youden Plot for Remedial Effects Consisting of the Flow Conditioner Bolted Upstream of the Meter Tube Assembly. High Flow.