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A Round Robin Flow Measurement Testing Program Using Hydrocarbon Liquids: Results for First Phase Testing

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U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
(Formerly National Bureau of Standards)
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National Bureau of Standards became the
National Institute of Standards and Technology
on August 23, 1988, when the Omnibus Trade and
Competitiveness Act was signed. NIST retains
all NBS functions. Its new programs will encourage
improved use of technology by U.S. industry.

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Ernest Ambler, Director

PROGRESS REPORT

FOR

A ROUND ROBIN FLOW MEASUREMENT TESTING PROGRAM USING HYDROCARBON LIQUIDS:

RESULTS FOR FIRST PHASE TESTING

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Chemical Process Metrology Division
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September 1988

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FOREWORD

This program has been carried out under the leadership of the Fluid Flow Group at the National Institute of Standards and Technology (NIST) (formerly, the National Bureau of Standards-NBS) with the joint support of both NIST and the Calibration Coordination Group (CCG) of the Department of Defense (DoD). It is, however, appropriate here to state that significant contributions to this program have been made by the DoD-CCG representatives, by the metrological teams of the Primary Standards Laboratories of the Tri-Services i.e., the Air Force, Army, and Navy, and by the engineering staffs of several of the participating industrial firms and other national standards laboratories.

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ABSTRACT

This report describes the initial phases of an interlaboratory testing program for assessing the fluid flow measurement capabilities of flow calibration laboratories. This program was initiated by the Department of Defense's (DoD) Calibration Coordination Group (CCG) to establish and maintain satisfactory fluid flow measurement processes among DoD laboratories and other industrial and national standards laboratories to which this program has been (and will be) expanded.

This report includes a brief description of the round robin testing procedure and the first round of test results for this initial phase of this program. It also gives the conclusions reached after a group of first round

participants convened in March, 1988 and discussed the test and first round results as collected at the time of the meeting.

INTRODUCTION

Improvements in fluid flow measurements and improvements in the assurance of the measurement results are currently being sought by wide ranges of flow meter manufacturers and users. The custody transfer of scarce fluid resources and the material accountability of valuable fluid products between buyers and sellers demand increasing accuracy in today's marketplaces. The fluid processing industries which have advanced from the "batch" production technology of the past to the more productive continuous processing methods require accurate measurements. This means optimizing productivity through precise fluid controls which, in turn, require equally precise fluid measurements.

Engine (aircraft, auto, etc.) performance testing at high accuracy levels involves commensurate measurement requirements. Thermodynamic state properties are required to specify component conditions and fluid properties; rate measurements of materials (fuel and oxidizer) are critical to accurate engine assessment. Defense department needs in these areas have been appropriately documented, [1-2]*.

Measurement assurance programs (MAPs) are used to provide confidence in the results of the measurement processes. MAPs vary widely. They establish the

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*Square bracketed integers refer to references given below.

desired assurance through the traceability of data, of instruments, or of processes to a higher measurement standard. For example, data can be assured on the basis of the instrument that produced it; an instrument's performance can be assured from having it calibrated in a laboratory; a laboratory can be assured through the facilities and procedures it uses.

Traceability of critical measurements is currently needed in order to properly document the performance - i.e., accuracy or precision levels quoted by instrument vendors or required by instrument users. Definitions for accuracy and precision are given in Appendix 1.

In the case of flow measurement no "identity" standard exists as in other measurement systems such as length or mass where accuracy is simpler to evaluate because systematic errors can be definitively quantified using available "identity" standards. Therefore, in the case of flow measurement, standards have to be derived and the elements and components of these systems can, and should, be appropriately evaluated. Such evaluations produce quantitative results for the precision and accuracy levels for the component measurements that produce the end result - the flow rate measurement. To estimate the systematic error for a flow measurement laboratory, it is most realistic to do this using round robin testing results because all of the lab's routine procedures can be incorporated and evaluated [3-6]. When systematic errors are evaluated in this manner, the laboratory - and the measurement results it produces - can be documented to be appropriately credible.

For the flow measurements made by meter users, traceability can be established in several ways. For example, the actual meter itself can be calibrated in a facility or laboratory for which traceability has been properly established and maintained. This calibration, of course, should be where test conditions are arranged to identically duplicate or to have dynamic similitude to match the operational conditions of meter use. Instrument traceability can also be achieved by proving the complete instrument installation "in-situ" through a transfer standard from a laboratory which has had its traceability established as described below. In these ways, the traceability of this meter's measurements under its conditions of use should be highly assured.

To establish laboratory or facility traceabilities, transfer standards having appropriate operational ranges and performance levels need to be designed and used - i.e., tested to produce the proper quantitative data that is indicative of the routine measurement processes that exist among the measurement laboratories or facilities. Once the desired traceability is established, these tests can be scheduled on a continuing basis to provide the desired measurement assurance over time. The program described below is an example of the types of efforts that need to be carried out to establish realistic traceability of flow measurements.

REALISTIC TRACEABILITY OF FLOW MEASUREMENT LABORATORIES

To establish the realistic traceability for measurement laboratories as described above, a test program must be devised so that:

(1) high confidence can be placed in the artifact package - i.e., the transfer standard meter assembly and the specifics of the test

procedures, check-points, responses to anticipated anomalies, etc.,

(2) the data base produced is adequate to the task of clearly evaluating the significant components of the measurement systems that are involved, and

(3) the algorithm for processing the data produced and the analysis of results are unbiased and clear procedures that are adequate to this task.

Artifact confidence is established via calibration testing over an extended period of time for the kind of conditions that will be used in the round robin. This testing should occur in the initiating laboratory and it should establish a credible background data base for the units being tested. Specifically, high confidence can be attained both in meter performance and in facility operation by calibrating two (2) meters in series according to tightly specified conditions. Pre-testing of these configurations gives expected values for the respective meter factors as well as for the relative performance of the meters - i.e., the ratio of their outputs, [3-6].

Adequacy of the data base is established by specifying the number of repeat calibrations done for each flowrate and meter configuration. These results should produce sufficient data so that statistical significance can be generated to exhibit the quality of measurement performance, such as:

(1) how performance varies for successive calibrations done for the same conditions over short periods of time - i.e., repeatability, and

(2) how performance varies from day to day for conditions that may vary slightly - i.e., reproducibility, [5].

It is recommended here that the data base be generated efficiently and for the expressed purpose of testing laboratory performance. To do this, a minimum number of flowrates are used and numerous tests at each are done. An alternative approach might be to use numerous flowrates and minimal replications at each. However, this alternative approach tends to produce only limited (and perhaps sporadic) data at the specific test points and it tends to place an undesirable emphasis on meter characteristics - as opposed to test laboratory characteristics.

The algorithm for data processing should be well established. This attribute is achieved when it is (has been) used for a number of MAPs for other measurement systems - i.e., the procedures produced by W.J. Youden and co-workers, [7].

By testing in both configurations shown in figure 1 the upstream data and the downstream data, individually, have the statistical independence requirement that is needed to apply the Youden procedures. The "SFC" unit shown in figure 1 is a "specific flow conditioner" placed between the tandem meters, [3-6]. It is intended to isolate the downstream meter from flow profile (or other anomalies) that might exist in the laboratory pipeline that connects to the upstream meter. Thus, the tandem meter configuration affords one the opportunity of generating data, simultaneously, both without and with pipeflow profile effects because downstream meter and upstream meter performances can be analyzed separately. Comparisons can give unique global insights into laboratory pipeflow phenomena without having to measure these distributions.

The types of flowmeters for this type of laboratory testing should be selected according to the experiences of the participating laboratories. This selection should produce the type of meter, the size, manufacture, associated instrumentation, etc. This selection process should be extended to include the fluid conditions, the flowrates, etc. as well as the tolerances to be used in arranging these.

The data generated via the round robin testing program can be analyzed in a number of ways. In what follows, the averaged meter factors are analyzed for each of the flowrates selected and for each of the meter positions. For each of these conditions, plots are produced of the respective meter performance characteristics - i.e., meter factor, discharge coefficient, etc., [3-6]. Individual results, or averages thereof, can be plotted. Each point represents the combined results for both meters when they were tested in each position in each laboratory.

The data processing procedure consists of determining median values for the respective sets of data for the meters. By drawing horizontal and vertical lines through these median points, the plot is divided into four Cartesian quadrants. The origin of this Cartesian system is, according to the available data, the best estimate of the true values of the meter factors for the two meters tested according to the specified conditions, [7]. In the northeast Cartesian quadrant, the data can be considered systematically inaccurate in that points here are each higher than those of the origin. Similarly in the southwest quadrant, points are lower. Thus, the degree to which data produces an elliptical pattern in this plot with its major axis aligned along a northeast to southwest direction is a measure of the systematic off-sets prevailing in the laboratory data.

In the northwest and southeast quadrants the data can be considered inconsistent or random in that one value is low while the other is high. Therefore, the degree to which the data is distributed in a northwest to southeast manner about the median intersection is a measure of the random variation in the laboratory data.

The preferred result-indicating good control of the measurement processes in the participating laboratories-would be to find that the data pattern in these plots is circular. Here, the interpretation would be that the tendency for the data to distribute systematically (northeast to southwest) is similar to the tendency to distribute randomly (northwest to southeast). When the radius of such a circle is acceptably small, the interpretation can be made that the corresponding measurements in these laboratories are in control. The respective levels of uncertainty shown in such graphs can be quantified.

Where, as is usually the case, the two meters are identical, a procedure for quantifying the respective random and systematic levels of the data can be used as follows, [5-7]. A line of slope +1 is drawn through the intersection of medians in figure 2. The data is then projected perpendicular and parallel to this diagonal line. The respective projections are then used to produce "random" and "systematic" standard deviations σ_r and σ_s; as follows

$$\sigma_r = [\frac{1}{M-1} \sum_{i=1}^{M} N_i^2]^{1/2} \tag{1}$$

$$\sigma_s = [\frac{1}{M-1} \sum_{i=1}^{M} P_i^2]^{1/2} \tag{2}$$

where M is the number of points and N_i and P_i are the normal and parallel components of the data projected to the diagonal line. The ratio of these quantities produces the degree of ellipticity of the data:

$$e = \sigma_s / \sigma_r \qquad (3)$$

When the ratio is larger than unity, the interpretation is that systematic variations prevail among the labs; this is quantified by magnitude of e. Analogous conclusions can be drawn for $e < 1$.

If it is pertinent to specify "outliers", it is important to do this on a clear, objective, and quantitative basis. This can be done in a number of ways. For example, it is feasible to select a circular region about the median-intersection point that has a radius of two or three times σ_r. Any points lying beyond such a region could be designated as outliers. Generally, it is found that such designations are not needed in order to initiate "search and repair" efforts in laboratories where conscientious metrologists work.

Depending upon the results obtained for the ellipticity, e, a number of reactions can occur. If e is large and if this is generated by one or more laboratories producing a large σ_s, then the reaction should be to examine the components of their flow measurement processes to find systematic errors, etc. If e is small and if this is generated by one of more laboratories producing a large σ_r, the reaction should be to examine the components of their processes with respect to their precision. If e is near unity but the levels of uncertainty are considered too large, then the appropriate response would be for the labs responsible to search and repair the pertinent components' systematic and random errors.

When such search and repair efforts are completed, the round of tests should be repeated for the same conditions so that improvements can be quantified. Even when such search and repair efforts are not needed, repeat testing should be done on an appropriate schedule to produce the continuous data record desired to substantiate that the realistic traceability established has not diminished in time. When such continuous records are established and maintained to verify laboratory performance in flow measurements, then, at least for the parameters incorporated in the test, appropriate credibility can rightfully be placed in the measurement results from participant laboratories.

TEST PROGRAM

The purpose of this program is to establish realistic fluid flow measurement traceability for the Department of Defense i.e., the Army, Navy, and Air Force laboratories that make the hydrocarbon liquid measurements needed for a range of engine performance tests. To do this; a transfer standard and a test procedure was designed by representatives of these labs and NIST. The transfer standard - the "artifact" - was selected on the bases of the types of devices normally tested by these labs. The fluid and flowrate conditions chosen were based on the routine experience and procedures in these labs. NIST expertise was applied to implement the necessary redundancies and test conditions which experience has shown are required so that high prospects for the success of this program can be expected. The test procedure used in this test is given in Appendix 2.

This test program was arranged to test turbine type flow meters. To insure the integrity of these meters and the validity of the resulting data, two, essentially, identical meters would be tested in series. In this way their relative performance could provide assurance to meter integrity. The flowrate range specified was from 0.5 U.S. gallons per minute (gpm) up to about 200 gpm. Meter sizes included AN-8, AN-16, and AN-32 (in tubing sizes: 0.5 in, 1.0 in, and 2.0 in, respectively). The test fluid was chosen to be the hydrocarbon liquid which is widely used as a calibration material: MIL-C-7024 B-II. This fluid has, for ambient temperature, a density of about 0.75 gm/cc and a kinematic viscosity in the range 1-1.25 centistokes.

As described above, it was decided to use the analyses of variance techniques put forth by W.J. Youden at NIST-Gaithersburg to analyze the data from this program, [3-7]. These analyses require dual sets of data to be produced that are statistically independent of each other and indicative of the testing laboratory's capabilities in generating their "usual product" - i.e., calibration data. To conform with this, the test procedure was set up to test each meter in each tandem position - i.e., the upstream and the downstream position for each of the flowrates tested.

It was agreed by both the representatives from the DoD primary measurement labs and by the NIST flow metrologists that only a few, discretely chosen, flowrates should be used to generate the desired data base. It was also agreed that the flowrates selected for these tests would be arranged according to Reynolds number conditions (i.e., the ratio of turbine frequency to actual fluid kinematic viscosity) based upon the downstream meter. In each of the testing laboratories the kinematic viscosity data was measured according to the laboratory's usual procedures. It was this data that was then used to set the desired flowrates. In this way, a considerable amount of repeat testing could be done in a relatively short time at each flowrate and the resulting statistics could therefore be considered truly indicative of the tested lab's measurement capabilities*. As noted from the test procedure given in the Appendix, each lab is to produce twenty (20) determinations of the meter constants for each meter in each position for each of the two (2) flow rates. To analyze the performance of each of the facilities or laboratories participating in this test, all of the determined meter factors were produced in the manner routinely done in each laboratory. Each of these meter factors was referenced to the standard temperature selected to be 20°C (68°F) using

$$K_o = K\,[1 + 3\alpha(T - T_o)] \qquad (4)$$

where, in compatible units, K is the meter factor in counts per U.S. gallons at the flowing temperature, T and, K_o is the desired meter constant at the reference temperature, T_o. The linear expansion coefficient, α for the meter material (304 stainless steel) is taken to be 9.61×10^{-6} $°F^{-1}$ or 1.726×10^{-5} $°C^{-1}$. No corrections are currently made in this program for pressure effects on meter constants. The pressure levels in the flow conditions specified in

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*The alternative procedure that possibly could have been chosen here would be to calibrate the transfer standards over the full flowrate range of each of the meters. The time required to do this and the way in which to extract the requisite data with which to evaluate the lab's performance is considered to be not as straightforward as in the method chosen.

this program should be sufficiently high* to guard against incipient cavitation anywhere that would affect meter performance.

For each laboratory test, the twenty (20) meter factors, determined as described above, were averaged to produce a single value that would be plotted according to the data analysis procedures given above. In this way, the individual values can be properly interpreted as indicative of the lab's performance.

During the actual test, the groups of five (5) consecutively determined meter constants can be processed to decompose the total variance of these results into specific categories. These five (5) values determined for each of the tandem meters can be used to produce the mean, $\bar{K}$ and the total standard deviation, σ_T as follows:

$$\bar{K} = \frac{1}{M} \left[\sum_{i=1}^{M} K_i \right] \tag{5}$$

$$\sigma_T = \left[\frac{1}{M-1} \sum_{i=1}^{M} (K_i - \bar{K})^2 \right]^{1/2} \tag{6}$$

where M is the number of the data points (5) in each group. The correlation coefficient, r_{12} can be calculated using meter factors determined for the

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*A rule of thumb used at NIST stipulates that the pressure level down stream of the (downstream) meter should be about three (3) times the pressure change across the meter(s) plus the local vapor pressure of the liquid.

upstream meter, K_{1i} and for the corresponding downstream meter factors, K_{2i} via:

$$r_{12} = \frac{\sum_{i=1}^{M} (K_{1i} - \bar{K}_1)(K_{2i} - \bar{K}_2)}{[\sum_{i=1}^{M} (K_{1i} - \bar{K}_1)^2]^{1/2} \; [\sum_{i=1}^{M} (K_{2i} - \bar{K}_2)^2]^{1/2}} \tag{7}$$

The total variance can be decomposed into two categories - one being the part, σ_s which does correlate with the variation in the other meter; the other being that part, σ_r which does not correlate with the variation in the other meter. In the sense that correlated portions of the total variance in each meter influences both meters, this portion of the total variance for each meter may be termed the "system variance", σ_s^2, where

$$\sigma_s^2/\sigma_T^2 = r_{12}^2 \tag{8}$$

Similarly, the uncorrelated portions of the total variance in each meter may be attributed to each individual meter, or

$$\sigma_m^2/\sigma_T^2 = 1 - r_{12}^2 \tag{9}$$

where σ_m^2 is termed the "meter variance". This σ_m value can be used as an indicator that meter condition is as it was in previous testing. When test conditions in a particular laboratory appropriately resemble those conducted in earlier tests, σ_m values can be expected to approximate the previous records. If it should happen that large departures should occur between meter variance and the previous records, it can mean that the meter has become altered in some significant manner - i.e., in turbine meters that the bearings have become damaged. In such a case, it is recommended that the testing program not be continued because the performance of the laboratory would be affected by such a meter condition.

After completion of a round of testing or perhaps even before this, the meters should be tested in the initiating laboratory to confirm that the condition of the meters is satisfactory. In fact, where it is suspected that either the artifact package is susceptible to damage or where the test conditions in one or more participating laboratories is likely to affect meter condition, the "spoke" method of conducting the testing should be used, [6]. In this, the initiating laboratory can be pictured as the "hub" of a wheel and the initial tester. After the test is carried out in each of the participating laboratories, the test is repeated in the initiating lab. This entails a considerable amount of testing at the hub, but if the "before" and "after" data records done at the hub are satisfactorily similar, then it may be concluded that the artifact package was performing properly in between. In such a testing program, the large volume of data produced in the initiating laboratory should not be incorporated into the above described data analysis procedure. Instead, only the data from a single test should be selected. Otherwise the analysis of variance among the participating labs will be inappropriately weighted toward that of the initiating lab.

The "wheel" or "rim" type of round robin testing program can be conducted when the artifact package is sufficiently robust as to not be harmed by the test conditions. In this situation, a single test in the initiating laboratory can be followed by a succession of tests in a large number of participating labs-possibly followed by a final test at the initiating laboratory to confirm that the condition of the artifact package did not change during the round of testing. It is this type of testing that was considered appropriate for the program described herein.

RESULTS

It is not pertinent to include here all the data taken in all the laboratories where this first phase of this program was conducted. Instead, results will be presented in plotted forms. By agreement among the participants, the identity of the participants will not be given other than the technique used to test these small turbine meters and the type of laboratory - namely a DOD lab or an industrial lab or a national standards lab. The letter designations used to plot this data anonymously is given in table 1 which includes the calibration techniques and type of the respective laboratory. This data summary pertains to the fourteen (14) tests shown in table 1.

The temporal sequence in which this set of data was recorded is given in the abscissas of figures 3-6. In all of these plots the ordinate scales give the respective meter factors in counts per U.S. gallon corrected to 20°C (68°F) according as given in equation (4). Each of these time series of meter factors (denoted by serial number - i.e., S/N 37846 or 3082) pertains to a specific configuration - i.e., a specific meter in the upstream position of the tandem arrangement and the other downstream, as listed on the figures and specified in the captions. The "before-and-after" test results conducted at NIST in the same facility are denoted by the letters "A" and "N":

The flowrates used in the test results are:

FLOW	Nominal Flowrate U.S. gpm	Nominal Diametral Reynolds Number
LOW	0.5	3,700
HIGH	1.7	12,800

The results plotted in figure 3 indicated that, in Configuration 1 and at the lower flow, the upstream meter (S/N 37846) has a slightly higher meter factor than the downstream meter (S/N 3082). The figure also shows that the total spread in these results for the S/N 37846 meter is about 0.7% or ± 0.35% from highest to lowest values. For the S/N 3082 meter the spread is about 0.4% or ± 0.2%.

The results shown in figure 4 indicate that, in Configuration 1 and at the higher flow, the upstream meter (S/N 37846) has a slightly higher meter factor than the downstream meter (S/N 3082). The figure also shows that the total spread in these results for the S/N 37846 meter is about 0.5% or ± 0.25% from highest to lowest values for the S/N 3082 meter the spread is about 0.5% or ± 0.25%.

The results shown in figure 5 indicate that, in Configuration 2 and at the lower flow, the downstream meter (S/N 37846) has a slightly higher meter factor than the upstream meter (S/N 3082). The figure also shows that the total spread in these results for the S/N 37846 meter is about 0.5% or ± 0.25%. For the S/N 3082 meter the spread is about 0.4% or ± 0.2%.

The results shown in figure 6 indicate that, in Configuration 2 and at the higher flow, the downstream meter (S/N 37846) has a slightly higher meter factor than the upstream meter (S/N 3082). The figure also shows that the total spread in these results for the S/N 37846 meter is about 0.5% or ± 0.25%. For the S/N 3082 meter the spread is about 0.5% or ± 0.25%.

For the results graphed in figures 3-6, the means and standard deviations of these means are given in table 2. These mean values indicate that there is not a consistent increase in the meter factors when the same meter is changed from the upstream position to the downstream position. If such a change were noted, it could be interpreted that the flow exiting the upstream meter might contain swirl that could impart increased (or decreased) spin to the downstream meter.

Figures 7-10 show the Youden plot results for these tests. Before quantitative analyses are applied to these data sets the "N" values should be excluded because this is data that was done on the same facility at NIST. When this "N" data is excluded from this set of data, the total number of points becomes thirteen (13); for the high flow the data set only totals twelve (12) values because one of the labs ("E") does not normally have flowrate capacity to reach this value.

If, for the results plotted in figure 7, the median values are selected, the median values are:

METER	MEDIAN
S/N 37846	K
S/N 3082	L

It is concluded from these results that the total systematic spread is approximately 0.85% or ± 0.43% and the total random spread is about 0.25% or ± 0.13%. Therefore, the systematic-to-random total spread ratio is about 3:1. If it is estimated that a typical precision from any of these measurement laboratories can be quoted at the level of ± 0.05%, then the systematic spread of these values is about eight (8) times that precision level.

Figure 8 shows the results for the meter when they are in the downstream position at the low flow. The median values are:

METER	MEDIAN
S/N 37846	J
S/N 3082	D

It is again concluded that the systematic-to-random spread ratio is about 3:1. It should be noted that it is characteristic of turbine meters to exhibit more random uncertainty in meter performance at lower flows than at higher flows.

Figure 9 shows the results obtained for the meters when they are in the upstream position flowing the high flowrate. The median values are:

METER	MEDIAN 1	MEDIAN 2
S/N 37846	D	J
S/N 3082	G	G

where the "MEDIAN 1" for these twelve (12) values is chosen as the sixth point from the minimum. The "MEDIAN 2" values is chosen as the sixth value from the maximum. It is noted that no significant differences occur as the result of the different ways of choosing medians. It is concluded that for these high flowrate results that the systematic-to-random spread is about 3:1.

Figure 10 shows the results for these meters in the downstream position for the high flowrate. The median values are:

METER	MEDIAN 1	MEDIAN 2
S/N 37846	D	J
S/N 3082	J	D

Again, no significant differences are found for the medians selected in these two ways. Again, it is concluded that systematic-to-random spread ratio is about 5:1. It is also noted that for these meters in the downstream position and flowing the higher of the two flows that this systematic-to-random spread is the largest among figures 7-10. It is concluded from the data pattern shown in figure 10 that this downstream position and this higher flowrate is best of the four test conditions for: (1) quantifying the minimum random uncertainty for these meters in these test conditions, and (2) estimating the systematic errors for these laboratories during this round of testing. Then, based on data such as shown in figure 10, it is concluded that the differences shown between laboratories are "statistically significant".

CONCLUSIONS

Based upon the specific conditions of the initial phases of this program, it is concluded:

1) that this test procedure is well-suited to produce the credible interlaboratory comparisons desired,
2) that the current results indicate that a number of the participant laboratories should examine the various components of their flowmeter calibration procedures with particular regard for "systematic" errors,
3) that this program is appropriately expanding to include additional U.S. laboratories - both governmental and industrial as well as other national standards laboratories to incorporate different types of calibration facilities,
4) that a repeat round of testing should be carried out to quantify improvements made via the "search-and-repair" efforts suggested in item 2, above, and
5) that the larger meter sizes (AN-16 and AN-32) should be tested in the manner used for the AN 8-4 size described above.

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TABLE 1

POINTS BY TECHNIQUE & LAB TYPE

A	-	Dyn. weigh	-	Gov't
B	-	Volumetric	-	Gov't
C	-	Dyn. weigh	-	DOD
D	-	Volumetric	-	DOD
E	-	Dyn. weigh	-	IND
F	-	Dyn. weigh	-	IND
G	-	Dyn. weigh	-	DOD
H	-	Volumetric	-	IND
I	-	Volumetric	-	IND
J	-	Volumetric	-	DOD
K	-	Volumetric	-	DOD
L	-	Volumetric	-	Gov't
M	-	Dyn. weigh	-	IND
N	-	Dyn. weigh	-	Gov't

TABLE 2: STATISTICAL RESULTS FOR THE MEAN METER FACTORS DETERMINED IN FOURTEEN (14) FACILITIES

CONFIG	FLOW nominal U.S. gals/min	UPSTREAM		DOWNSTREAM	
		$\bar{K}_o$ CTS/GAL	σ CTS/GAL	$\bar{K}_o$ CTS/GAL	σ CTS/GAL
1	0.5	28758.35	70.28	28263.33	45.04
	1.7	28591.45	51.42	28029.07	46.41
2	0.5	28268.10	46.13	28760.80	56.96
	1.7	28031.11	45.06	28595.32	51.13

APPENDIX 1

ACCURACY - The closeness of the agreement - usually expressed as a percentage - between the result of a measurement and the true value of the quantity being measured. Accuracy of flow measurement is defined as the total uncertainty which consists of the sum of the systematic error, or bias, and the precision.

PRECISION - The closeness of the agreement - usually expressed as a percentage - between the results of two or more measurements of the same (or similar) quantity being measured. Precision of flow measurement is defined as the random uncertainty at the 95% confidence level.

a) REPEATABILITY - The closeness of the agreement - usually expressed as a percentage between the results of two or more successive measurements of the same quantity subject to all of the following conditions:

- the same method of measurement,
- the same observer,
- the same measuring instrument,
- the same location,
- the same conditions of use,
- repetition over a short (specified) period of time.

Example: Repeatability expresses "how close duplicate measurement can be made to be."

b) REPRODUCIBILITY - The closeness of the agreement usually expressed as a percentage between the results of two or more measurements of the same (or similar) quantity(s) under changing conditions such as:

- method of measurement
- observer
- measuring instrument
- location
- conditions of use
- time

A valid statement of REPRODUCIBILITY requires specification of the conditions changed.

Example: Reproducibility expresses "how close duplicate measurements normally agree."

APPENDIX 2

NOTE: **In summer 1988, the name of the National Bureau of Standards-NBS was changed to the National Institute of Standards and Technology-NIST. This Test Procedure was produced in early 1987 and therefore "NBS" appears in this original text.**

INTERLABORATORY TURBINE METER TEST PROCEDURE USING HYDROCARBON LIQUID

For:
a) AN 8-4 Turbine Meters, or
b) AN 16 Turbine Meters, or
c) AN 32 Turbine Meters

Read all of this test procedure before handling or testing the NBS turbine meters.

1. After meters arrive at laboratory, they should be inspected visually for any damage incurred in transport from previous lab. Any damage found should be reported immediately (phoned or telexed) to G. E. Mattingly (Phone 301-975-5939; Telex No. 898493 GARC) at NBS and an appropriate course of action arranged.

2. Normal, routine, pretest measurements on the meters, meter tubes, and auxiliary equipment can be made provided they do not alter the meters or the auxiliary devices.

3. The meters with matched adjacent up- and downstream meter tube assemblies are to be tested in tandem so that the electrical connections to the pick-ups are oriented vertically upward. Each meter, with its matched (and marked) meter tube-upstream and downstream sections will be referred to in what follows as a "meter assembly". For the AN-16 meter assembly only, the flow conditioning device is installed in the pipeline so that it separates these two assemblies in the test line and flow through it occurs as indicated by the arrow on it.The upstream meter used initially for each line size is given ,via the serial number, in the table below; also given is the serial number of the meter to be installed, initially in the downstream position.

INITIAL INSTALLATION POSITIONS TABLE

LINE SIZE (AN)	INTERNAL DIAMETER (IN)	UPSTREAM METER SERIAL NUMBER	DOWNSTREAM METER SERIAL NUMBER
8-4	.42	37846	3082
16	.87	7809A0645A2	7809A0645A1
32	1.76	37113	46555

4. The total length of the tandem meter assemblies varies: these lengths are:

    a) AN 8-4 Tandem Turbine Meter Assembly is 27 inches long,
    b) AN 16 Tandem Meter Assembly is 45 3/4 inches long,
    c) AN 32 Tandem Meter Assembly is 48 1/4 inches long.

    After both meters have been assembled as per step 3, they should be mounted into the test line.

5. Normal, routine connection of turbine meter pulse counters should be done for both meters. If it is normal procedure to connect multiple counters to each turbine meter, this may be done. The counters referred to here are those normally used in the Laboratory for these types of calibrations.

6. A ratio counter should be connected to the turbine meters so that a specified frequency ratio can be visually displayed during the test. If at least two turbine meter pulse counters and a ratio counter are not available in any Lab planning to participate in this test, G.E. Mattingly should be contacted via phone above before the round of testing is to begin.

7. Temperature and pressure instrumentation should be installed on, or adjacent to, the meter assemblies in the manner normally done during turbine meter calibrations in the testing laboratory.

8. The test line should be slowly filled with the test liquid, and "run-in" procedures begun. The test liquid should be hydrocarbon fluid MIL-C-7024B, Type II or a close duplicate. Deviations from this fluid should be discussed with G.E. Mattingly in advance of the Lab's test.

9. Where the test fluid can be continuously pumped through the meters this should be done as described below. Where the calibration is done by piston displacement, an adequate number of piston strokes should be done to insure that air is completely purged and equilibrium conditions prevail as is done in the normal routine in the respective laboratory. For continuous pumping it is suggested to use a flow rate, set via the downstream meter, for which the respective pipe line flowrate is given in the following table:

"RUN-IN" FLOWRATE TABLE

LINE SIZE	NOMINAL GPM	NOMINAL Re_D	NOMINAL FREQ/CTSKS	RATIO (KMX/KMN)
8-4	1.7	$1.1X10^{4}$	682.603	1.021640
16	27.8	$6.5X10^{4}$	733.322	1.007727
32	180	$2.8X10^{5}$	811.402	1.037427

10. This "run-in" condition is to continue for fifteen (15) minutes to allow for air to be completely purged from the test line. During this "run-in" period, instrument check-out of any of the systems can be done. Should further zeroing be required during the test, it should be done in some appropriate manner that is normal for the testing laboratory.

11. During these "run-in" conditions, the meter assemblies and associated instrumentation should receive final inspection. Any auxiliary instrumentation normally used in each laboratory for this type of meter test can be added, i.e., densitometry, viscometry, etc. This should be done in the normal, routine manner for the testing laboratory <u>without change to the meter assemblies</u>. If liquid properties are measured by extracting test fluid samples for analysis, or density and viscosity measurements in advance of the test, this should be done in the normal manner.

12. After the "run-in" procedure and pertinent checking of equipment, the test shall begin. The attached Table 1 lists specific conditions. The flow in the test line is adjusted so that according to the downstream meter, the respective pipe line flowrate is given in the following table:

TABLE 1 - LOW FLOWRATE TABLE

LINE SIZE	NOMINAL GPM	NOMINAL Re_D	ACTUAL FREQ/CTSKS	RATIO (KMX/KMN)
8-4	0.5	$3.2X10^{3}$	200.153	1.021797
16	8.8	$2.0X10^{4}$	230.666	1.007957
32	50	$7.8X10^{4}$	225.966	1.036355

and is as stable as routinely expected in the laboratory experience. At this flow condition the ratio of turbine frequencies is required to be within the agreed tolerance of the expected value, i.e., within ± 0.05% of the tabulated value. The next step is <u>not</u> done unless ratio agreement is satisfactory.

13. At this stable flow condition, five individual determinations of the turbine meter factor are made for each meter. At each, the collected fluid weight or volume displacement that is "routine" and convenient with the lab's normal collection or displacement system, the collection or displacement time, the average fluid temperature, and the routinely totaled turbine meter pulses for the two meters are recorded. Turbine meter factors* and frequency to centistoke ratios, i.e., (Reynolds numbers) are calculated in the manner routinely used in the laboratory and the results are tabulated; see NBS results, Attachment 2.

14. After the low flow test is completed the flow in the test line is adjusted so that according to the downstream meter, the respective pipe line Reynolds number (freq/ctsks) is that given in the following table:

TABLE 2 - HIGH FLOWRATE TABLE

LINE SIZE (AN)	NOMINAL GPM	NOMINAL Re_D	ACTUAL FREQ/CTSKS	RATIO (KMX/KMN)
8-4	1.7	1.1×10^4	682.603	1.021640
16	27.8	6.4×10^4	733.322	1.007727
32	180	2.8×10^5	811.402	1.037427

and is as stable as routinely expected in the laboratory experience. At this flow condition, the ratio agreement must be satisfactory, i.e., within ±0.05% of the tabulated value, before the test can progress. When ratio agreement is satisfactory, step 13 is repeated.

15. After this flow test is completed the flow is re-adjusted so that, according to the downstream meter, the pipeline Reynolds number is that given in Table 1 and is as stable as routinely expected in the laboratory experience. At this flow condition,

---

* Should be corrected to 20°C (68°F) to account for thermal expansion effects for turbine meters. The appropriate expansion factor for these meters should be: $1.7298 \times 10^{-5}\,{}^\circ C^{-1}$ or $9.61 \times 10^{-6}\,{}^\circ F^{-1}$

the ratio agreement must be satisfactory, i.e., within ± 0.05 % of the tabulated value before the test can progress. When ratio agreement is satisfactory, steps 13 and 14 are repeated.

16. After the high flow has been tested the second time the results should be plotted. The flow is stopped and the pumps are turned off.

17. After five minutes, the system is turned on and the low flow is stably produced in the pipeline.

18. Steps 12 through 16 are repeated and the results for each meter are determined as stated in Step 15. The Laboratory results are entered into the table, see NBS results.

19. After step 16 is repeated, the flow is stopped, the pipeline drained and the meter assemblies are switched. This places the previous downstream meter assembly in the upstream position and the previous upstream meter assembly in the downstream position. For A-N 16 meters only, the flow conditioner remains between the meter assemblies. The counters are not switched.

20. Steps 8 - 18 are repeated, using the settings and ration criteria given in the "Run-In" Table and Tables 3 and 4, respectively, for the Low and High flowrates.

TABLE 3 -LOW FLOWRATE TABLE - METERS SWITCHED

LINE SIZE (AN)	NOMINAL GPM	NOMINAL Re_D	ACTUAL FREQ/CTSKS	RATIO (KMX/KMN)
8-4	0.5	3.2×10^{3}	200.294	1.021641
16	8.5	2.0×10^{4}	230.574	1.008056
32	50	7.8×10^{4}	226.001	1.037717

TABLE 4- HIGH FLOWRATE TABLE - METERS SWITCHED

LINE SIZE	NOMINAL GPM	NOMINAL Re_D	ACTUAL FREQ/CTSKS	RATIO (KMX/KMN)
8-4	1.7	1.1×10^{4}	693.742	1.021690
16	27.8	6.4×10^{4}	733.167	1.006074
32	180	2.8×10^{5}	811.250	1.039098

21. After the tests are finished, the flow is stopped, the line drained and the meter assemblies are removed from the pipeline and boxed for transport to the next laboratory.

22. Samples of the test fluid are to be taken. Two half liter container samples are to be provided or sent to NBS for density and viscosity analyses.

23. Copies of the raw data and processed results and graphical displays are provided to NBS for subsequent analysis.

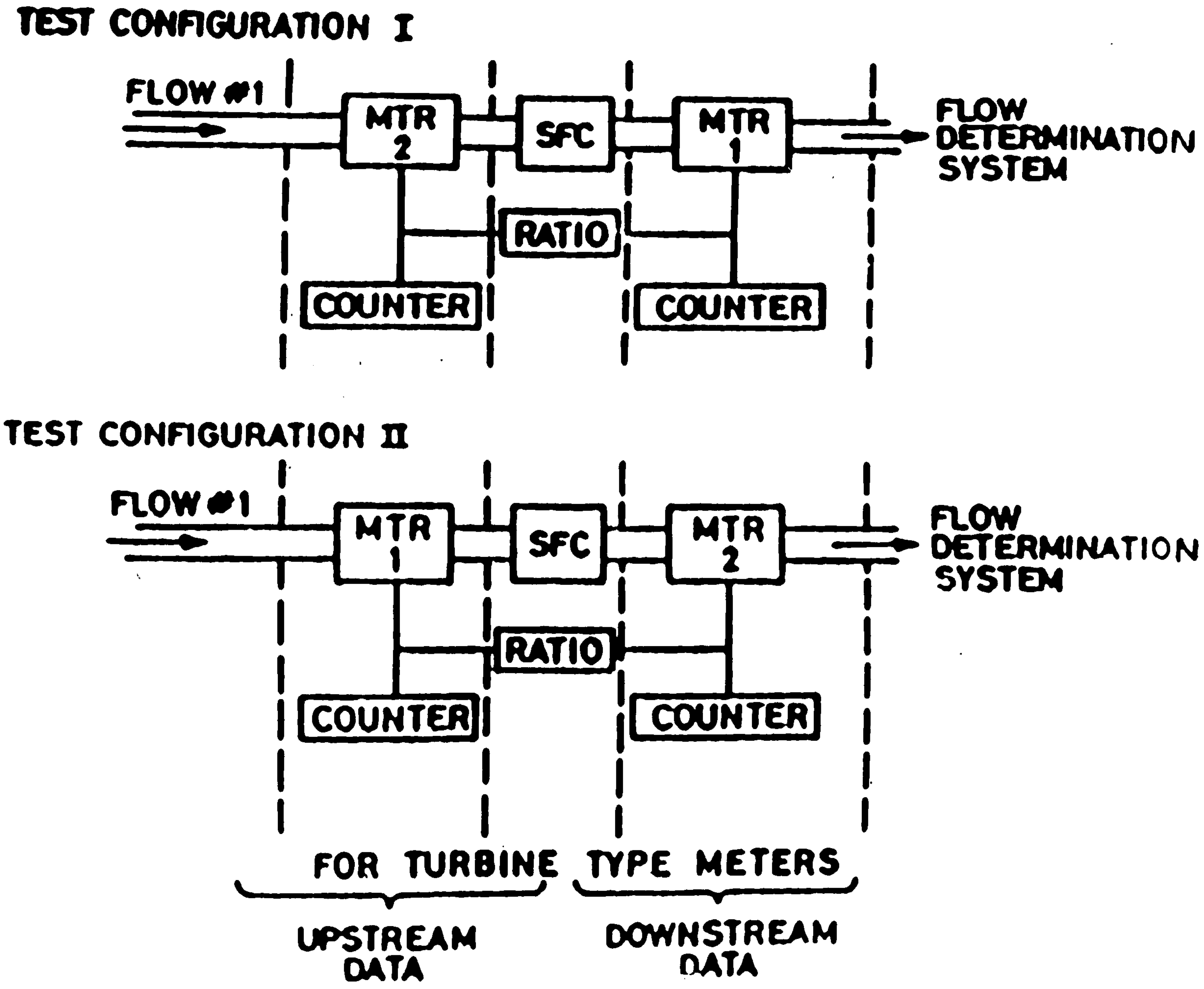

FIGURE 1 SKETCH OF TANDEM TER CONFIGURATIONS

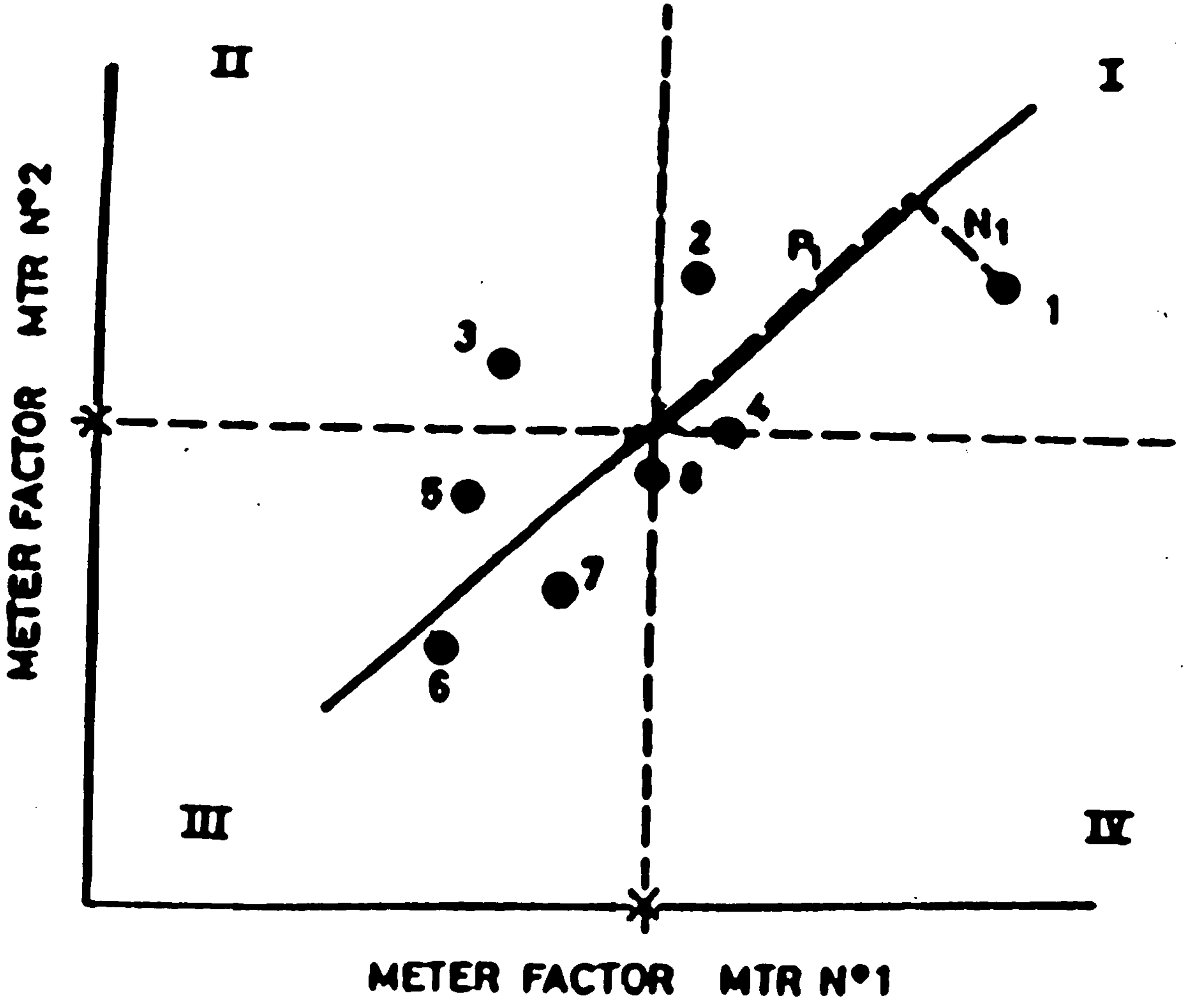

FIGURE 2 ILLUSTRATIVE YOUDEN PLOT

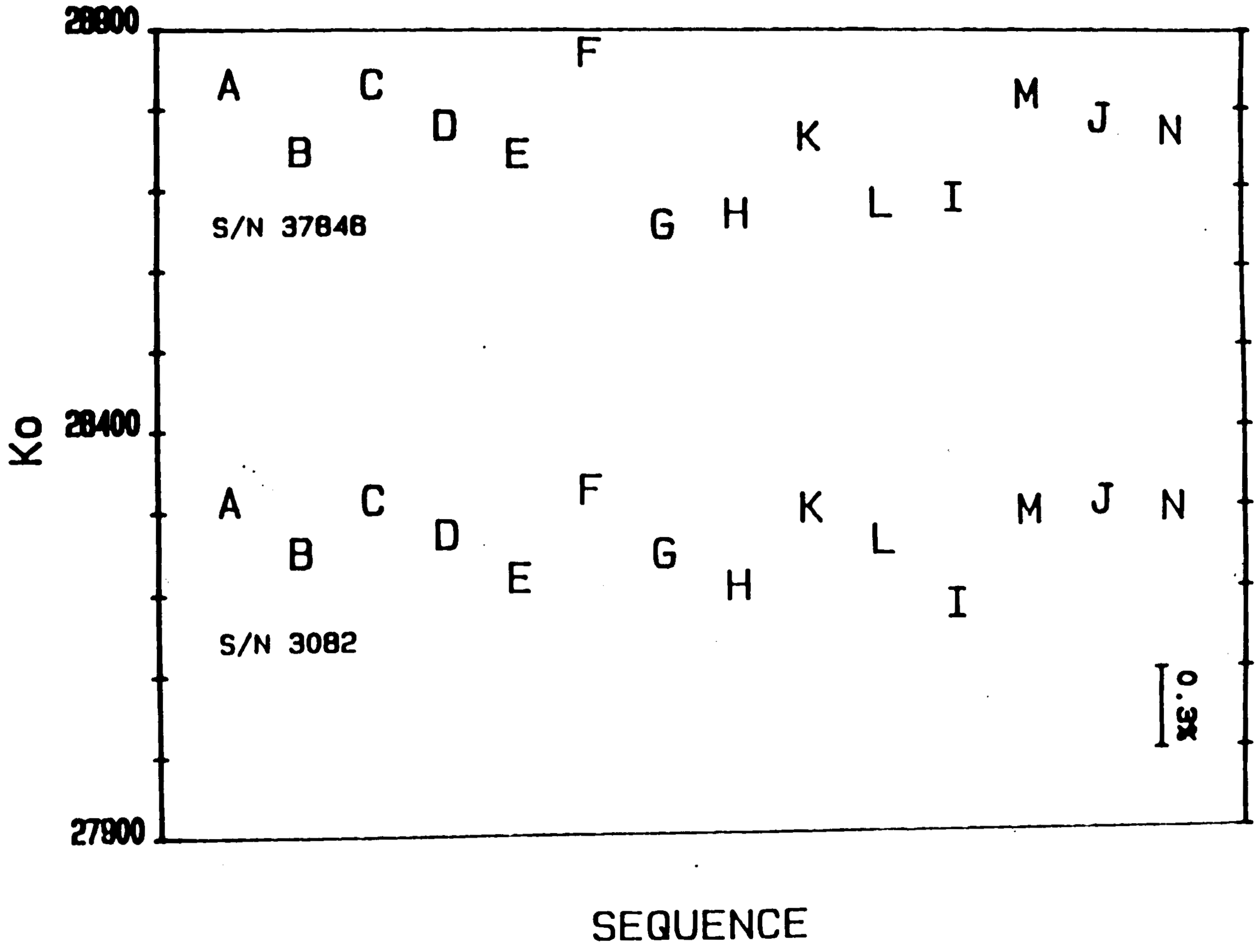

FIGURE 3 DATA SEQUENCE: CONFIGURATION 1-LOW FLOW

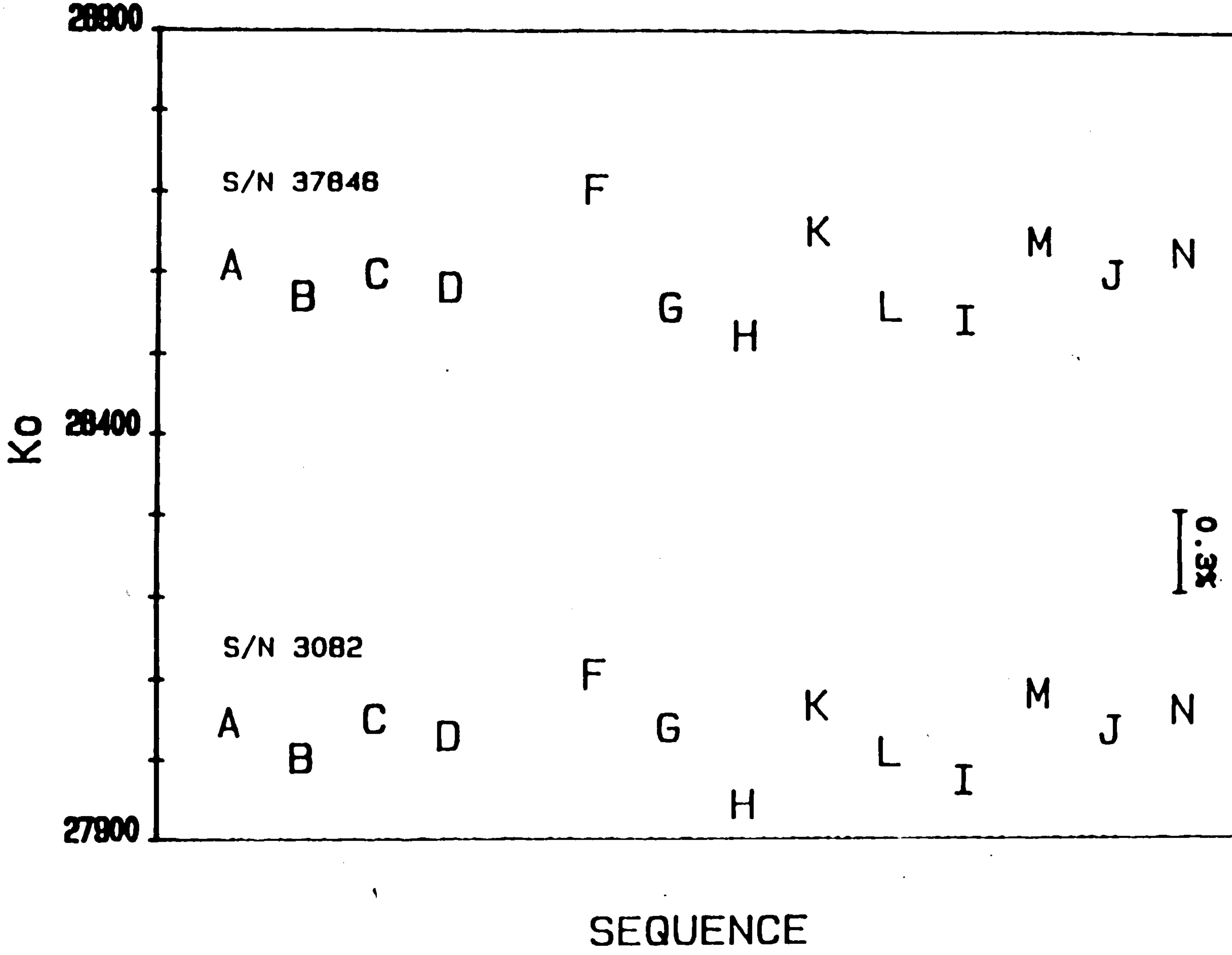

FIGURE 4 DATA SEQUENCE: CONFIGURATION 1-HIGH FLOW

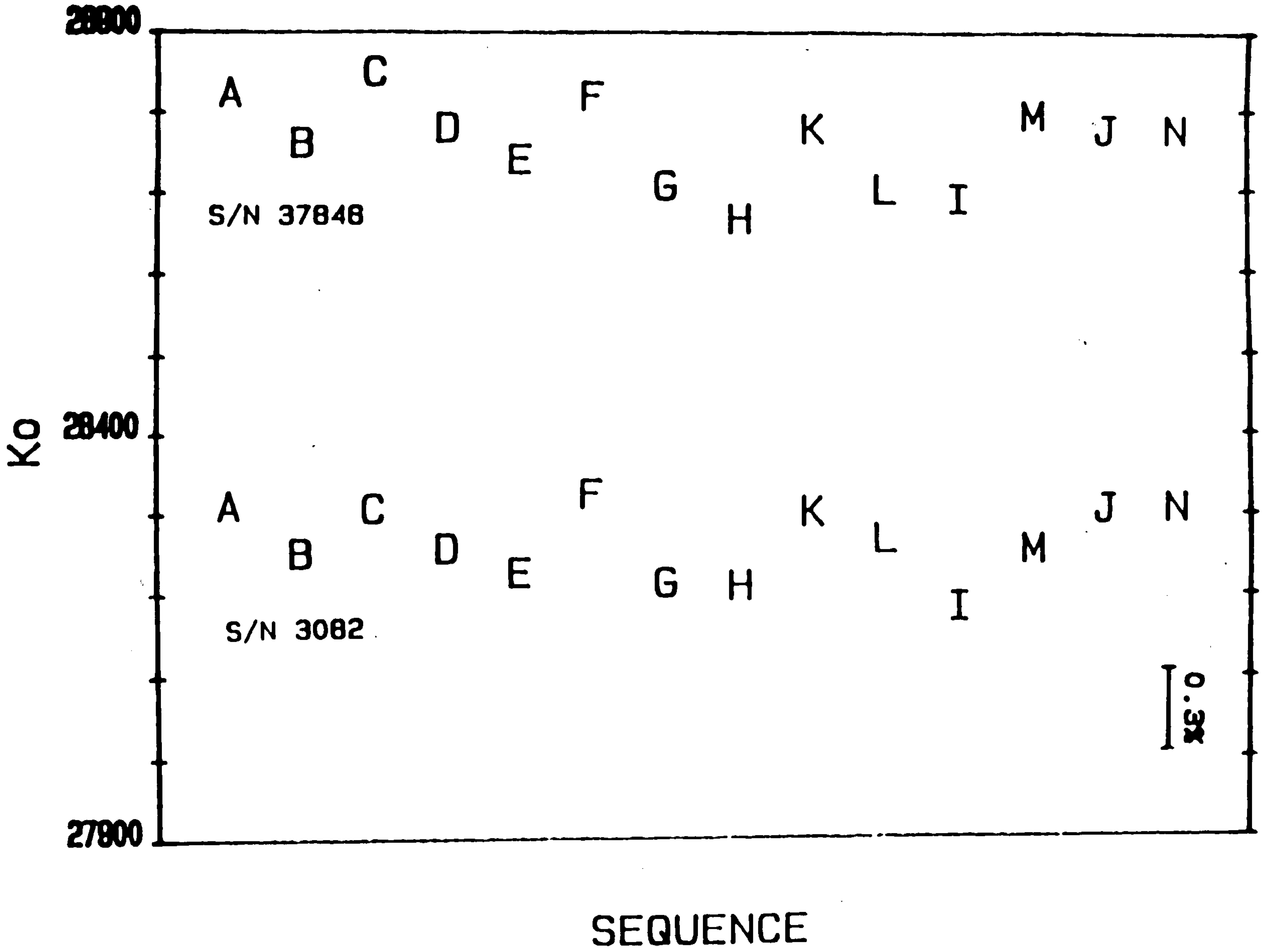

FIGURE 5 DATA SEQUENCE: CONFIGURATION 2-LOW FLOW

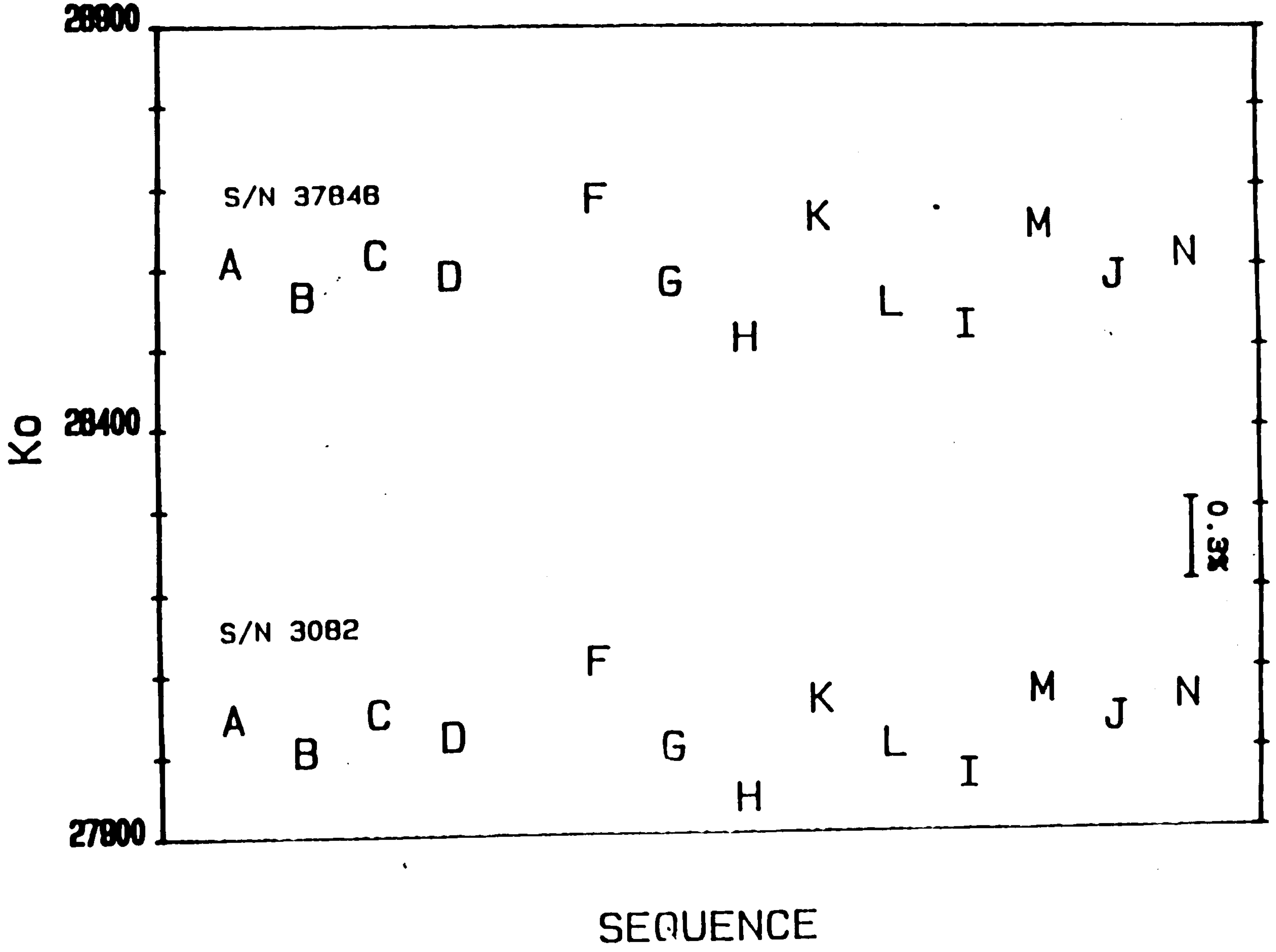

FIGURE 6 DATA SEQUENCE: CONFIGURATION 2-HIGH FLOW

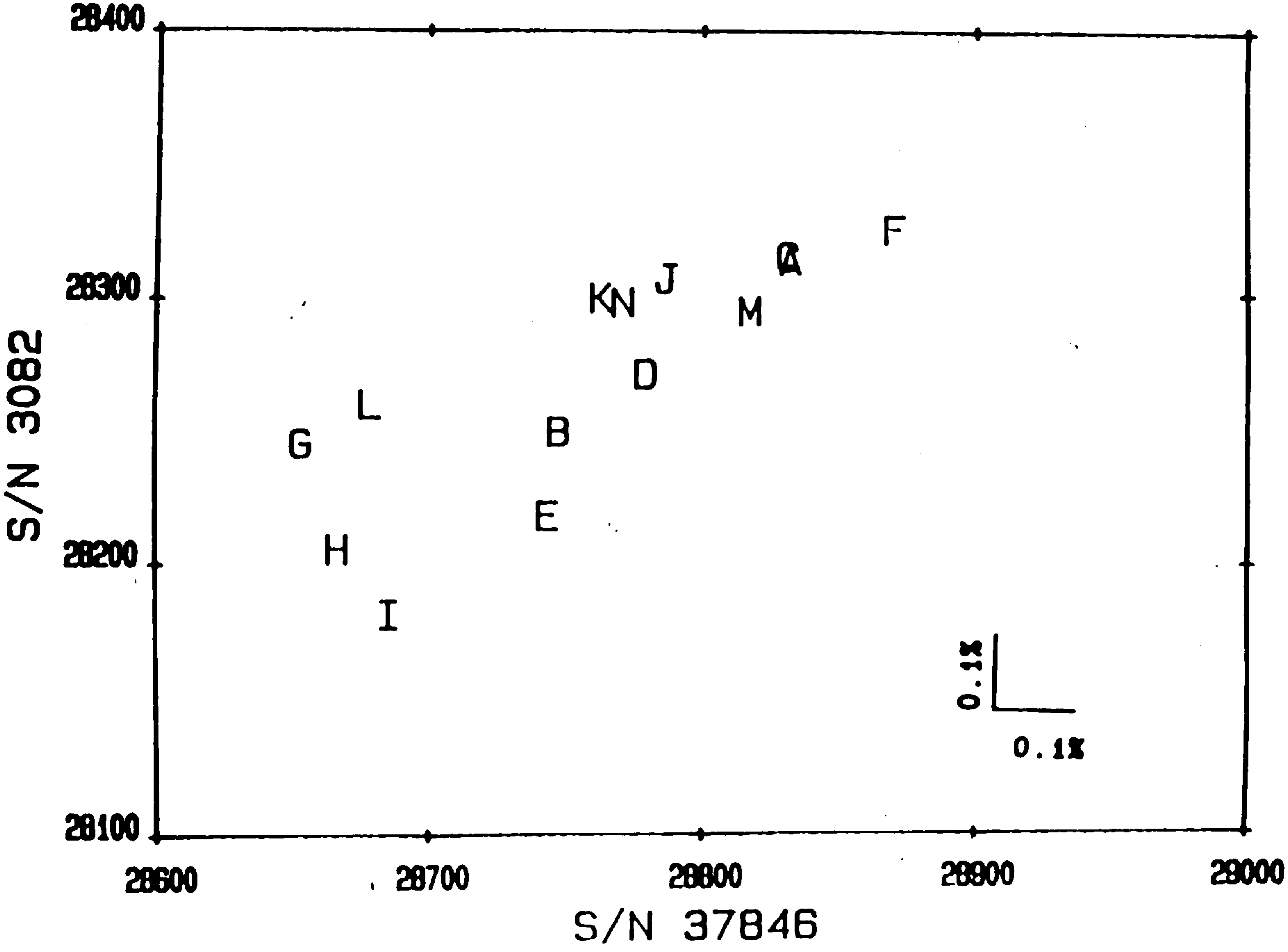

FIGURE 7 YOUDEN PLOT: UPSTREAM METERS-LOW FLOW

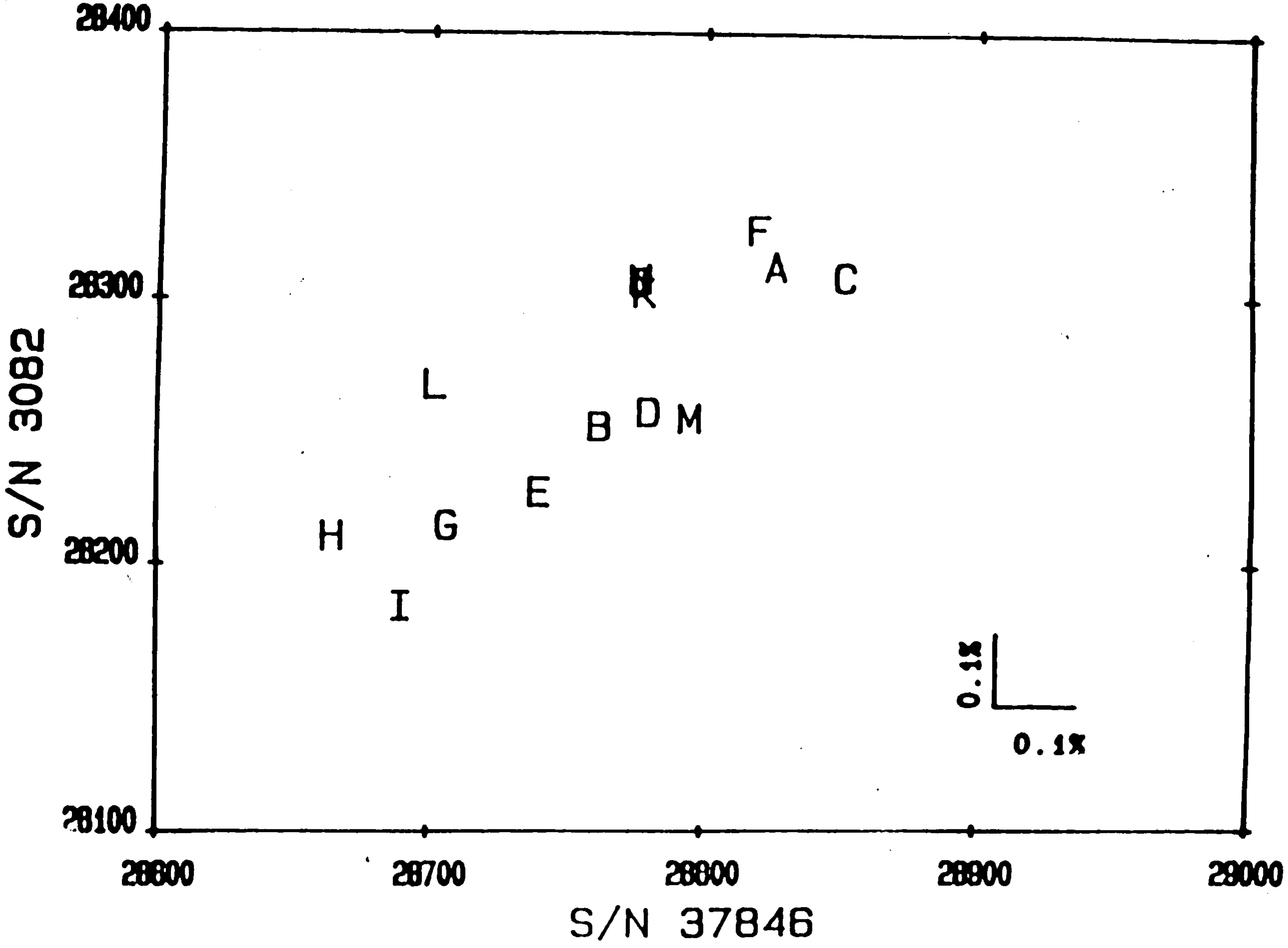

FIGURE 8 YOUDEN PLOT: DOWNSTREAM METERS-LOW FLOW

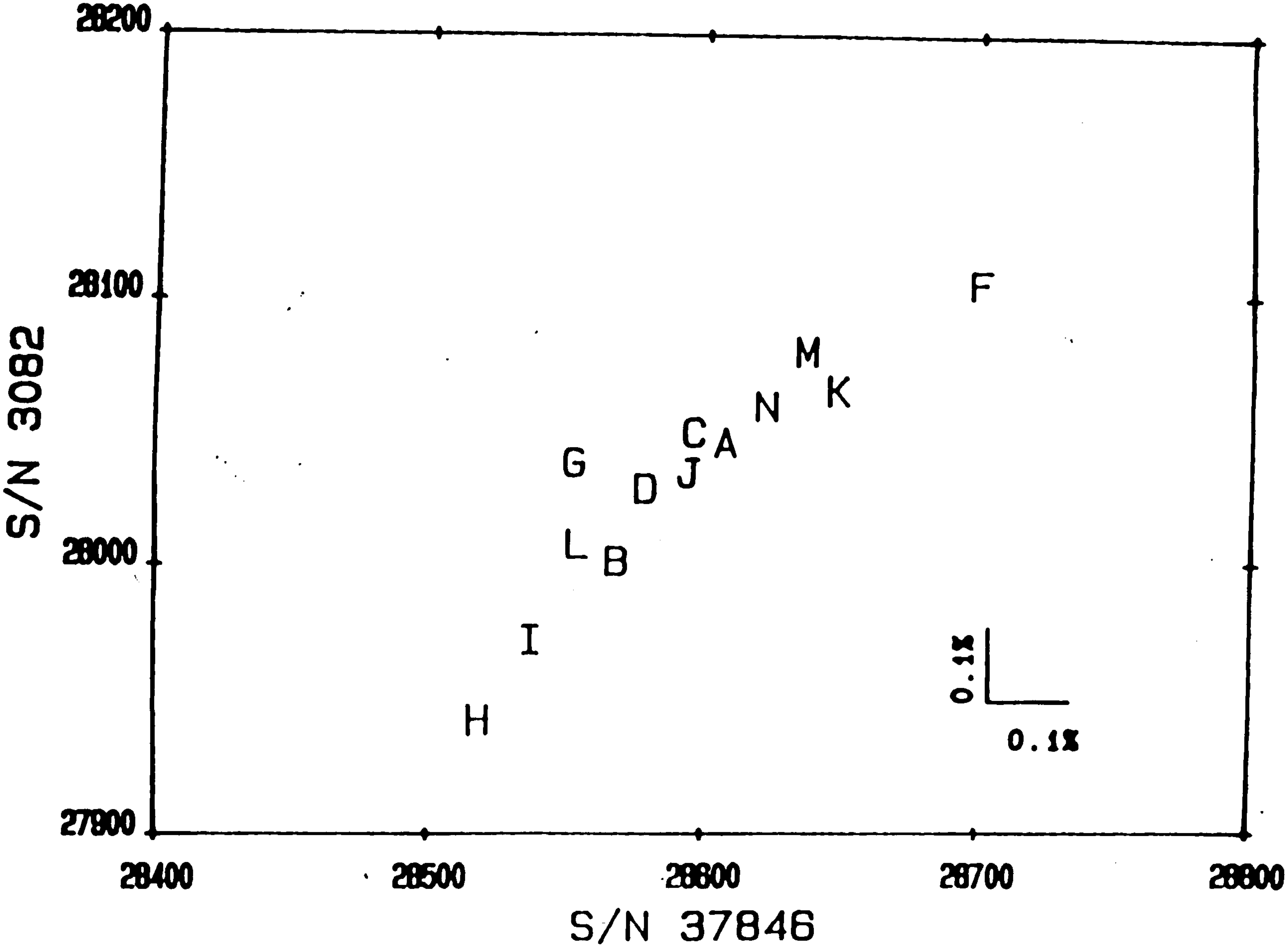

FIGURE 9 YOUDEN PLOT: UPSTREAM METERS-HIGH FLOW

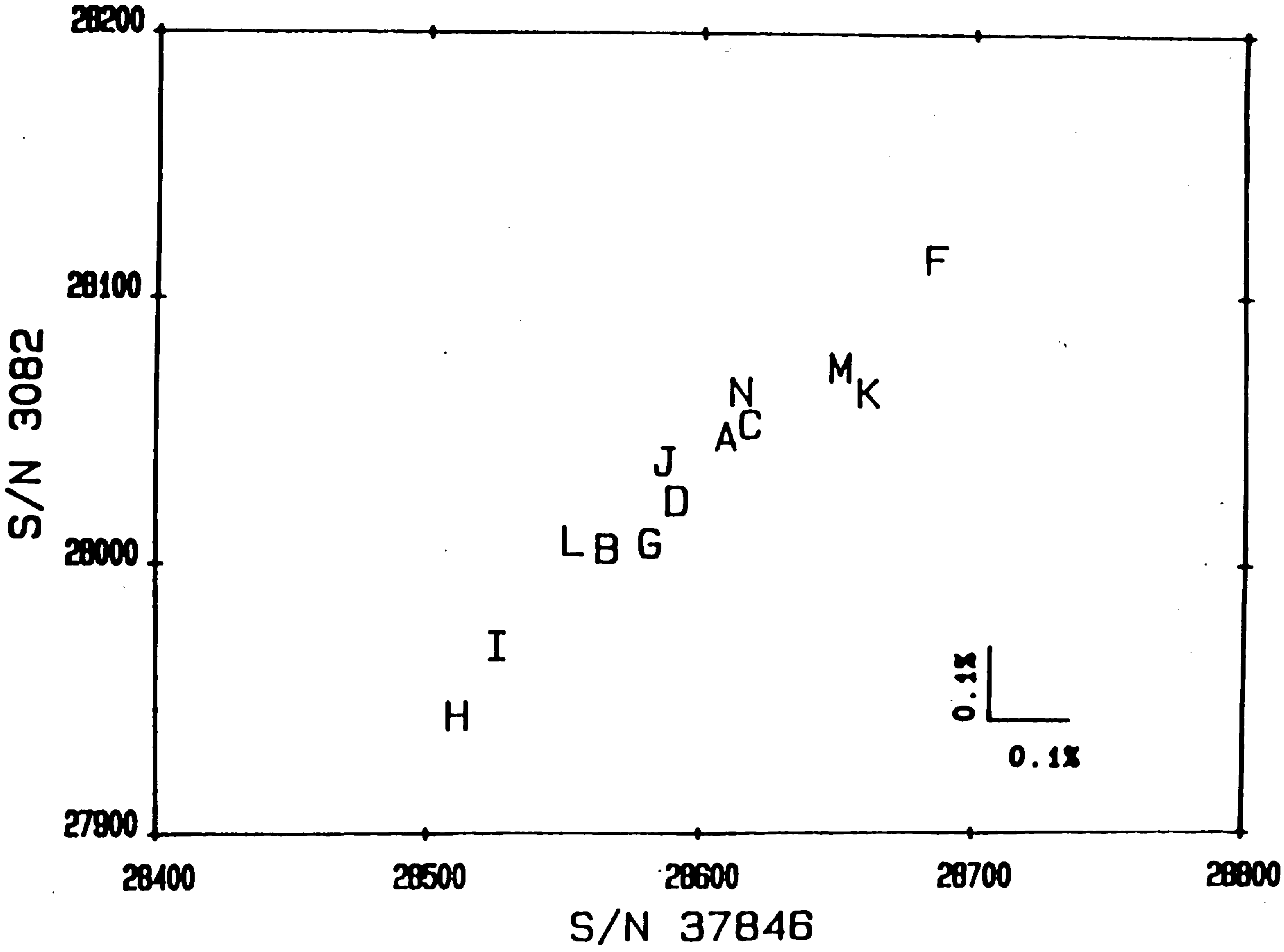

FIGURE 10 YOUDEN PLOT: DOWNSTREAM METERS-HIGH FLOW

SUPPLEMENT

TO

DoD/CCG - NIST ROUND ROBIN FLOW MEASUREMENT TESTING

FOR

HYDROCARBON LIQUIDS

During summer 1988, this round robin testing program was expanded to include the national flow measurement laboratories in Italy and the U.K. The results indicate that good agreement exists among the national laboratories that have participated thus far in this program. This agreement, in turn, indicates that calibration services obtained from these sources should produce data that would compare closely to that from the National Institute of Standards and Technology (NIST) (formerly the National Bureau of Standards (NBS)).

Additionally, the incorporation of these national labs has broadened the range of flow calibration techniques in the group of participants. This range of techniques now includes both volumetric and gravimetric systems. The gravimetric facilities are of both dynamic and static types.

The results of this expanded program are presented graphically on the enclosed eight (8) figures. Figures 1-4 are analogues to figures 3-6 in the main report. Figures 5-8 are analogous to figures 7-10.

Future efforts in this program include round robin tests using the larger meters (AN-16 and AN-32). As well, second round testing using the AN 8-4 meters will be done.

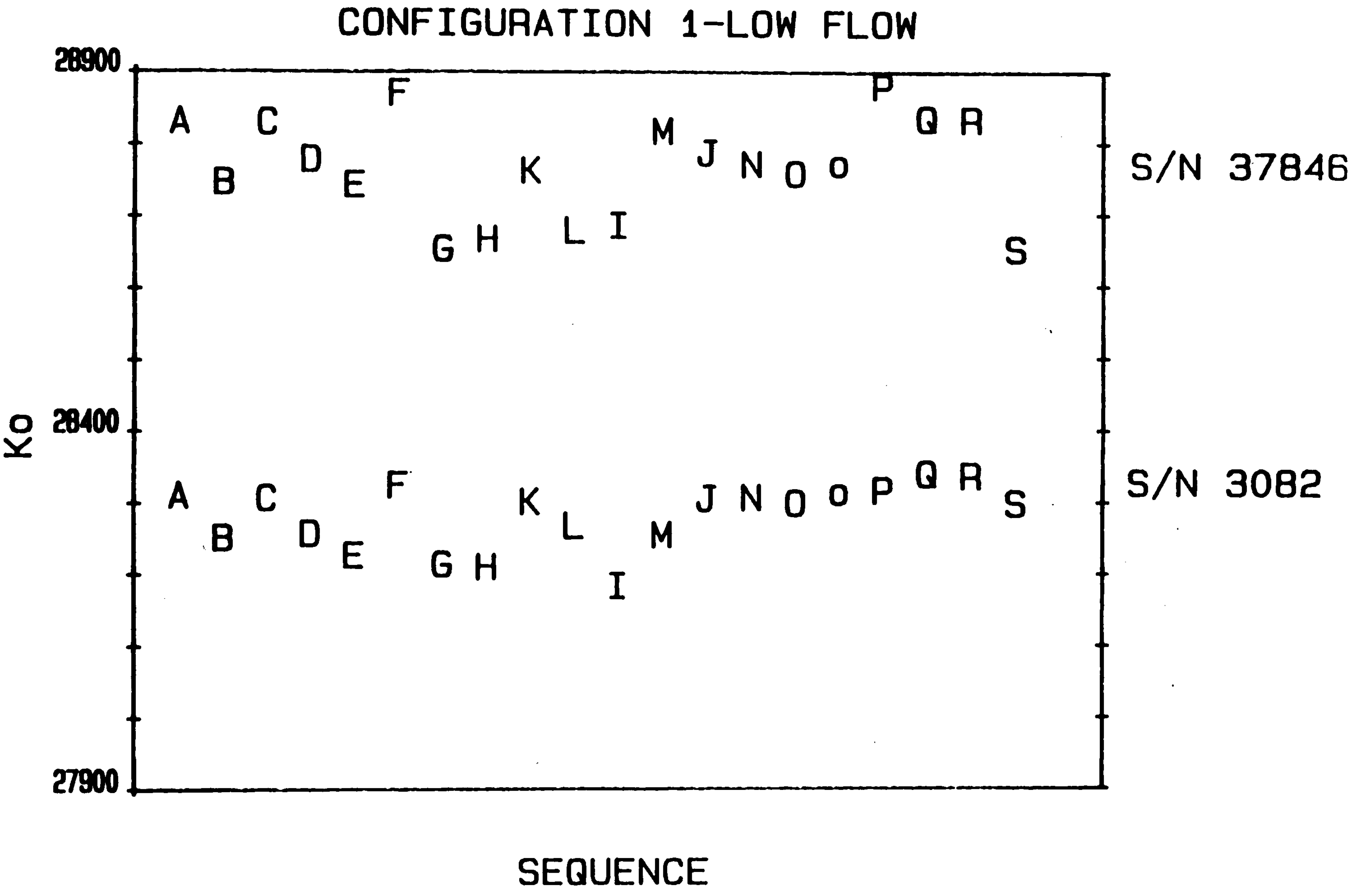

FIGURE 1 DATA SEQUENCE: CONFIGURATION 1-LOW FLOW

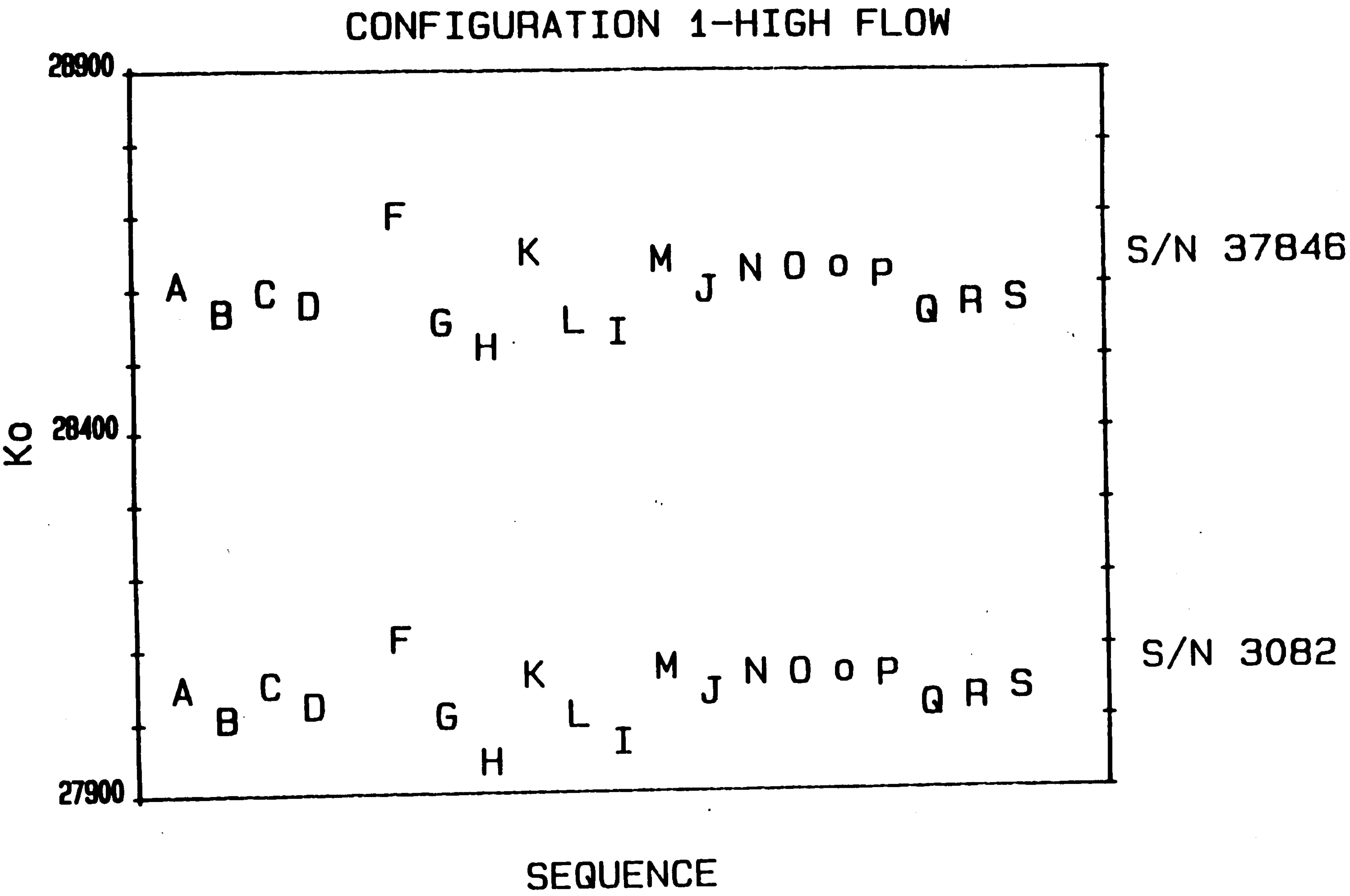

FIGURE 2 DATA SEQUENCE: CONFIGURATION 1-HIGH FLOW

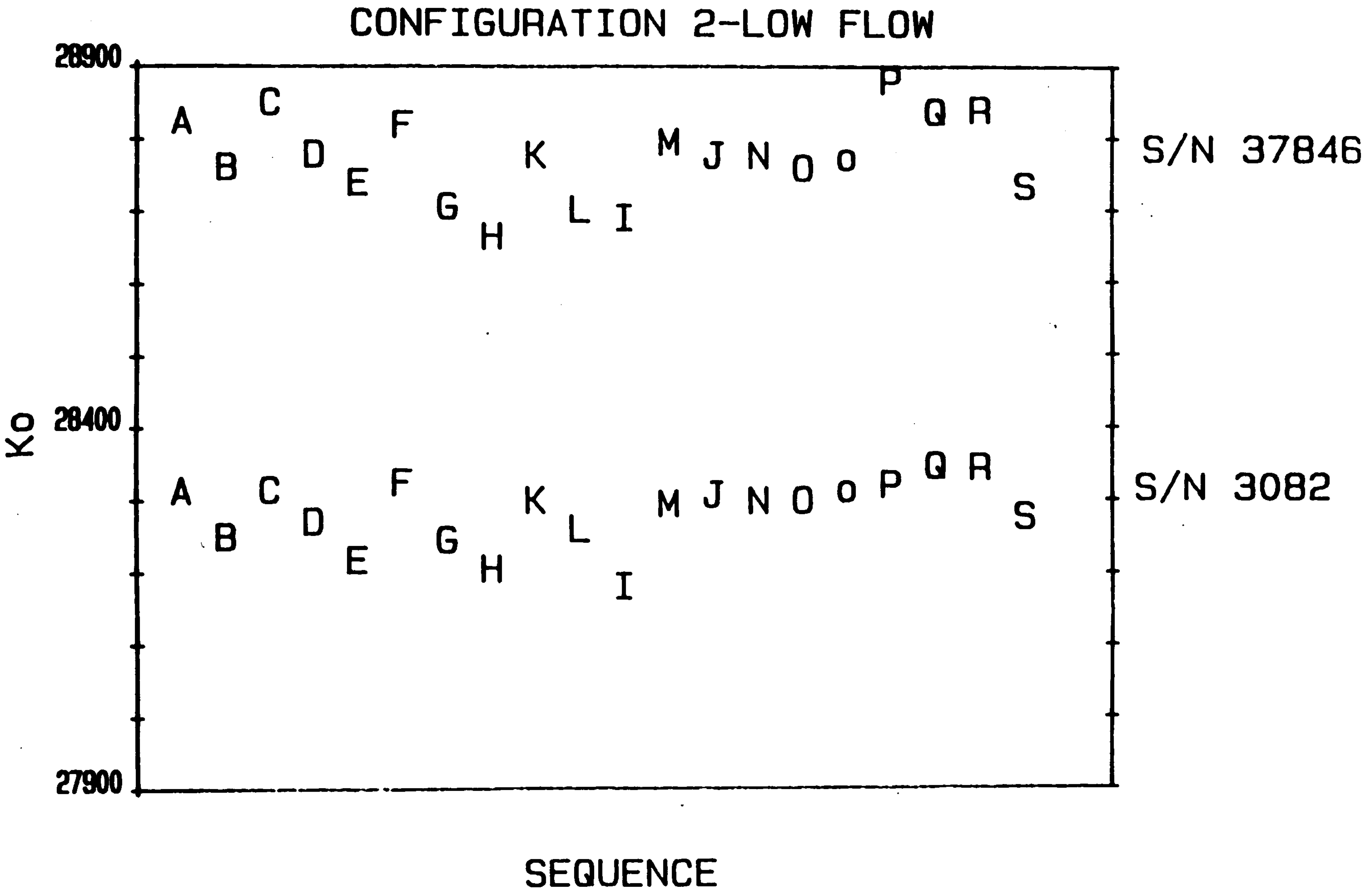

FIGURE 3 DATA SEQUENCE: CONFIGURATION 2-LOW FLOW

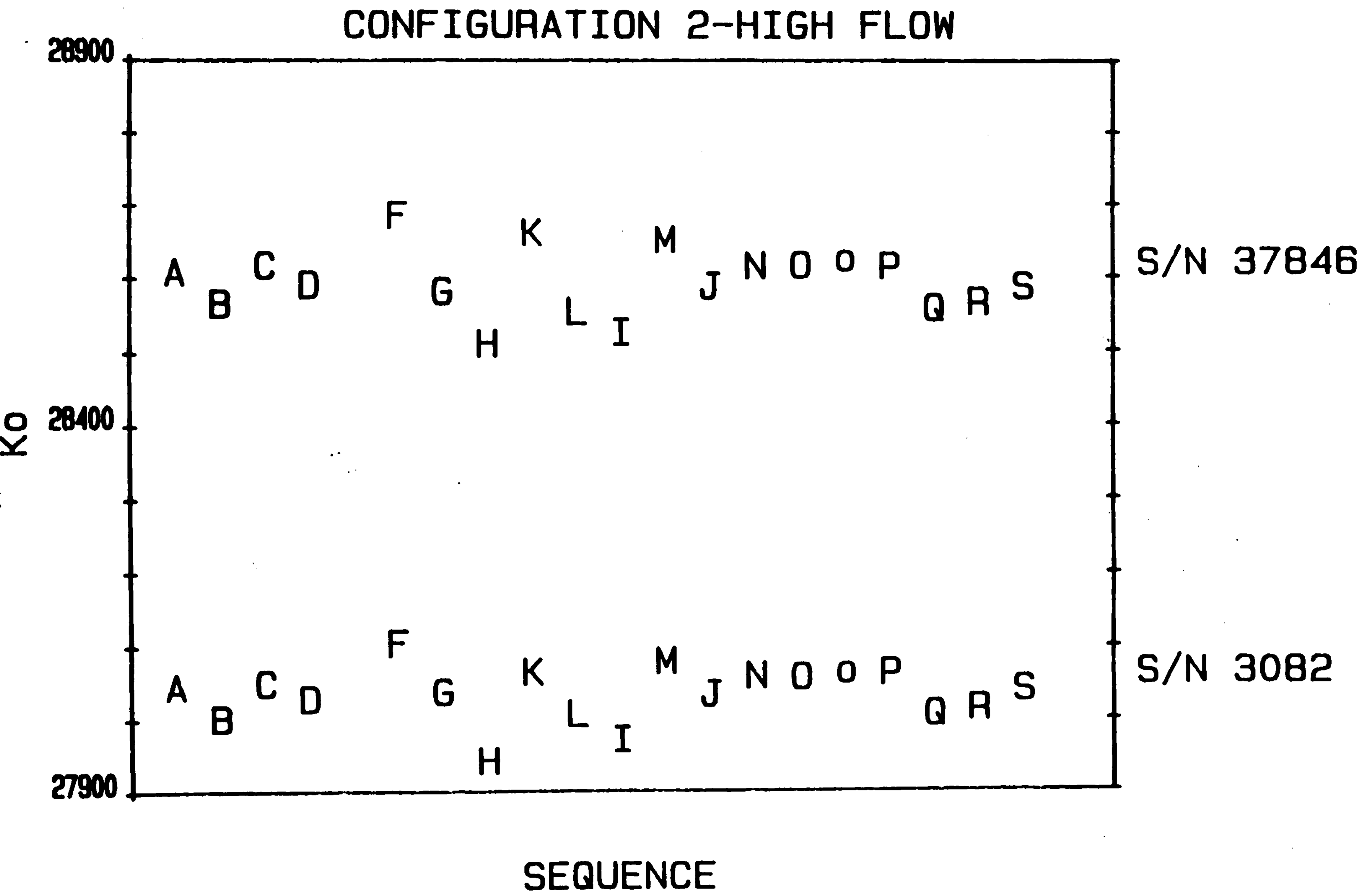

FIGURE 4 DATA SEQUENCE: CONFIGURATION 2-HIGH FLOW

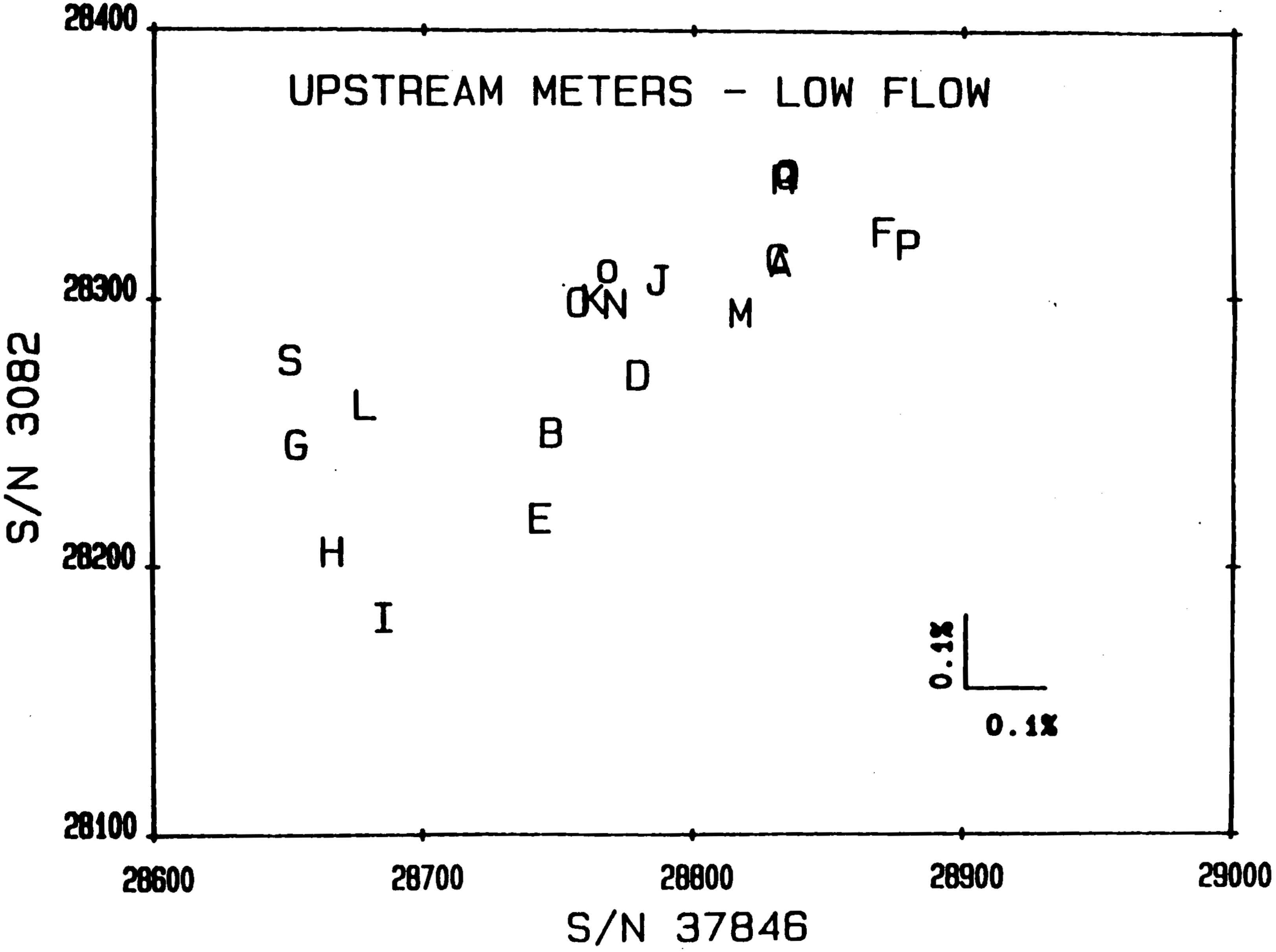

FIGURE 5 YOUDEN PLOT: UPSTREAM METERS-LOW FLOW

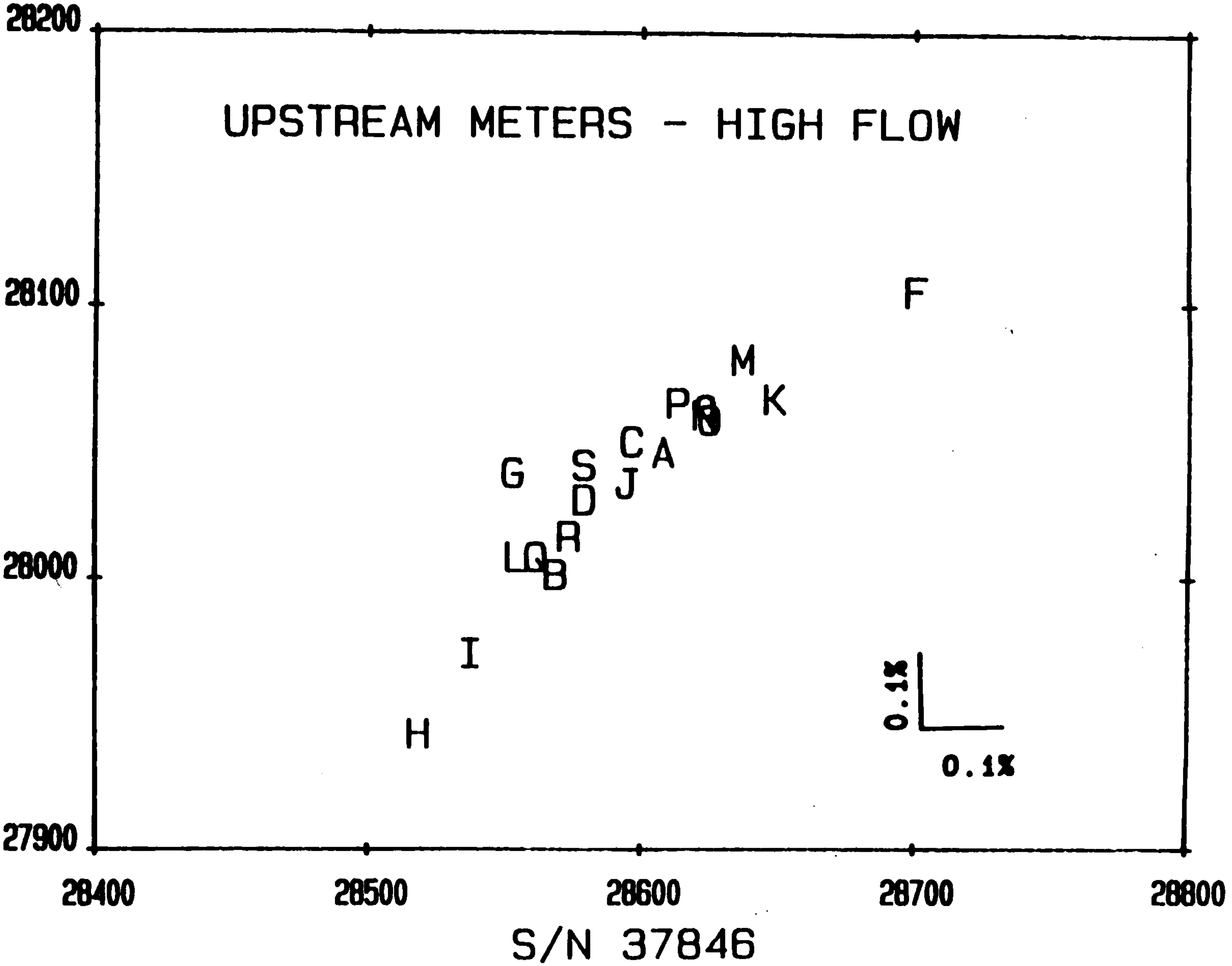

FIGURE 6 YOUDEN PLOT: UPSTREAM METERS-HIGH FLOW

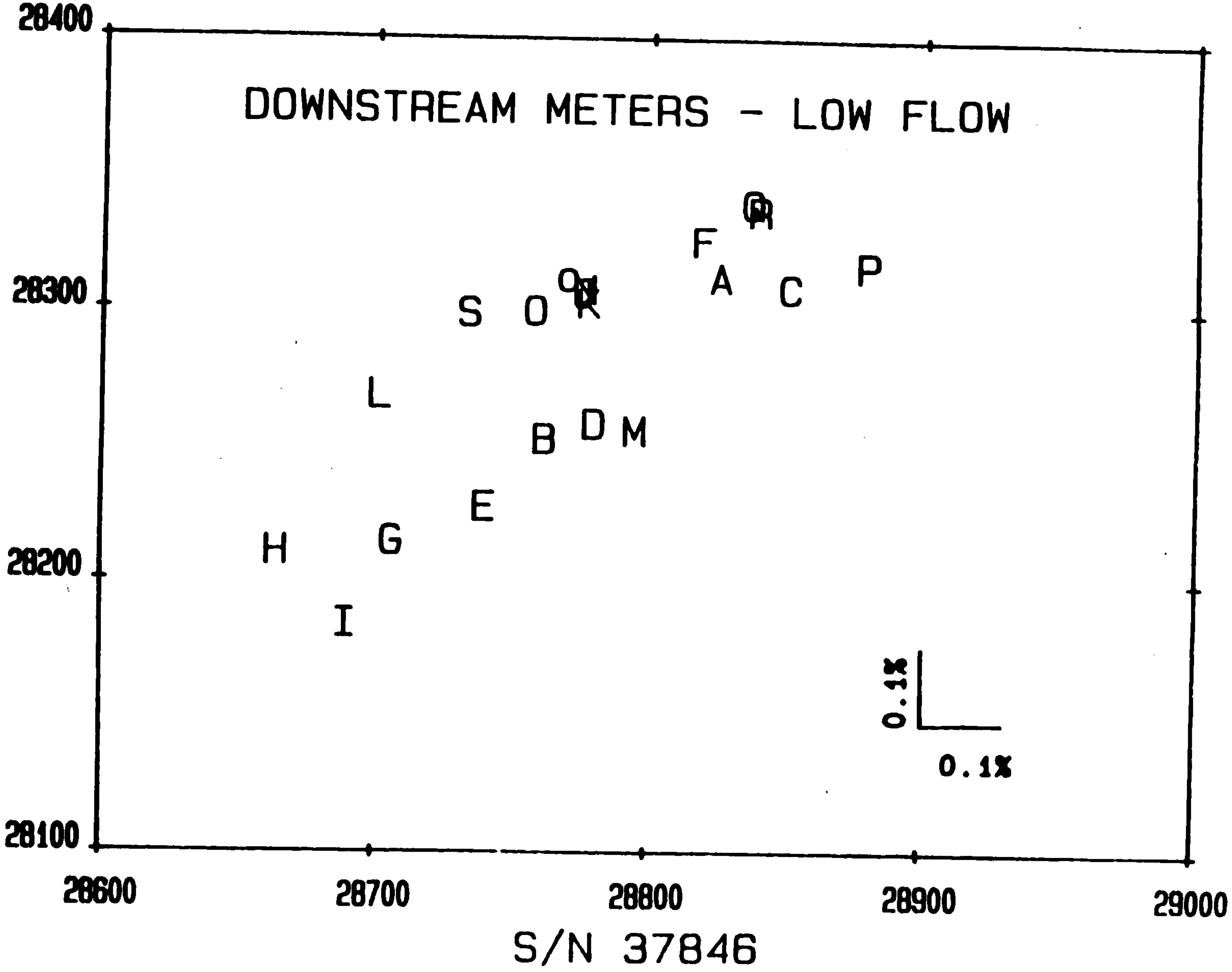

FIGURE 7 YOUDEN PLOT: DOWNSTREAM METERS-LOW FLOW

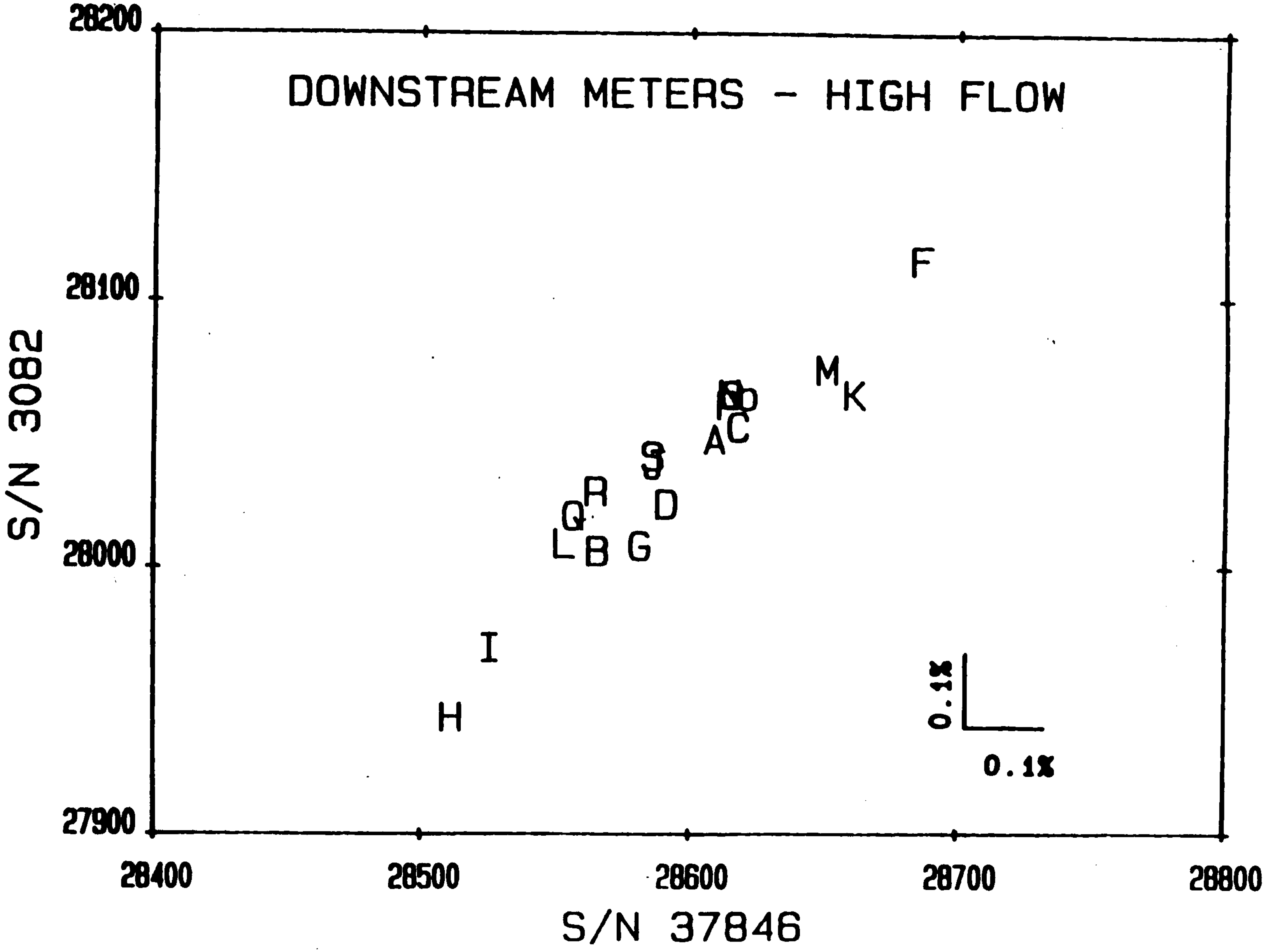

FIGURE 8 YOUDEN PLOT: DOWNSTREAM METERS-HIGH FLOW