UNIVERSITY OF MINNESOTA

ST. ANTHONY FALLS HYDRAULIC LABORATORY

Project Report No. 312

FIELD FLOW TESTING OF SIX LARGE VENTURI METERS

by

Richard L. Voigt, Jr. and Curtis W. Bauers

Prepared for

JAMES M. MONTGOMERY
Consulting Engineers, Inc.
Wayzata, MN

and

THE METROPOLITAN WASTE CONTROL COMMISSION
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TABLE OF CONTENTS

PAGE NO.

Acknowledgement i
List of Figures iii
List of Tables and Photographs iv
Abbreviations v

I. Introduction 1

II. Test Program 4

III. Test Results 11

IV. Conclusions 24

Appendix A A–1
Appendix B A–9

LIST OF FIGURES

Figure No.

1 West side remote meter plan.

2 East side remote meter plan.

3 Typical flow measurement grid for a high flow condition test run, meters M100A and M100B.

4 Typical flow measurement grid for a high flow condition test run, meters M101A, M101B, M102A, and M102B.

5 Typical magnetic current meter measurement cross section with effective areas of two locations denoted.

6 Schematic diagram to visualize the flow situation at meters M102A and M102B.

7 MWCC Computer recorded flows vs. flows measured by SAFHL for meter M100A.

8 MWCC Computer recorded flows vs. flows measured by SAFHL for meter M100B.

9 MWCC Computer recorded flows vs. flows measured by SAFHL for meter M101A.

10 MWCC Computer recorded flows vs. flows measured by SAFHL for meter M101B.

11 JMM DVOM recorded flows vs. flows measured by SAFHL for meter M102A – prior to cleaning.

12 JMM DVOM recorded flows vs. flows measured by SAFHL for meter M102B – prior to cleaning.

13 JMM DVOM recorded flows vs. flows measured by SAFHL for meter M102A – after cleaning.

14 JMM DVOM recorded flows vs. flows measured by SAFHL for meter M102B – after cleaning.

List of Figures (Cont'd)

Figure No.

A–1 Flow channel cross section at insertion mag–meter measurement installation for M100 meters.

A–2 Flow channel cross section at insertion mag–meter measurement installation for M101 meters.

A–3 Flow channel cross section at insertion mag–meter measurement installation for M102 meters.

LIST OF TABLES

Table 1 Summary of Field Data

Table 2 Linear regression equations for Data in Figures 7 through 14.

Table A–1 Summation of Data Taken for Meter M100A.

Table A–2 Summation of Data Taken for Meter M100B.

Table A–3 Summation of Data Taken for Meter M101A.

Table A–4 Summation of Data Taken for Meter M101B.

Table A–5 Summation of Data Taken for Meter M102A prior to cleaning.

Table A–6 Summation of Data Taken for Meter M102B prior to cleaning.

Table A–7 Summation of Data Taken for Meter M102A after cleaning.

Table A–8 Summation of Data Taken for Meter M102B after cleaning.

LIST OF PHOTOS

Photo 1 SAFHL crew preparing for data acquisition.

Photo 2 Magnetic current meter probe mounted on carriage.

ABBREVIATIONS

SAFHL – St. Anthony Falls Hydraulic Laboratory
M100A – Meter A at location 100, 42–inch Venturi
M100B – Meter B at location 100, 42–inch Venturi
M101A – Meter A at location 101, 25–inch Venturi
M101B – Meter B at location 101, 25–inch Venturi
M102A – Meter A at location 102, 25–inch Venturi
M102B – Meter B at location 102, 25–inch Venturi
MWCC – Metropolitan Waste Control Commission
JMM – James M. Montgomery Consulting Engineers, Inc.
DVOM – Digital Volt–Ohm meter
A_m – cross–sectional area of flow at measurement location (in sq. meters)
fps – feet per second
DC – direct current
Q – Total flow
i – meter probe location
V_i – velocity perpendicular to metering cross section at location i
A_i – effective area at location i
C_i – flow coefficient at location i
Col. – column
Q_{SAFHL} – Flow at Venturi measured by St. Anthony Falls Hydraulic Lab using insertion type magnetic current meter
$QVenturi_A$ – Flow measured at Venturi A
$QVenturi_B$ – Flow measured at Venturi B

Abbreviations (Cont'd)

C_A	—	Calibration coefficient for Venturi A
C_B	—	Calibration coefficient for Venturi B
Q_{MWCC}	—	Flow at Venturi measured by regional computer
Q_{JMM}	—	Flow at Venturi measured by DVOM
$M100A_H$	—	Meter 100A at high flow
$M100A_M$	—	Meter 100A at middle range flow
$M101A_L$	—	Meter 100A at low flow
$M102A_{pH}$	—	Meter 102A, prior to cleaning, at high flow
$M102A_{cH}$	—	Meter 102A, after cleaning, at high flow
σ	—	standard deviation
GPM	—	gallons per minute

I. INTRODUCTION

The St. Anthony Falls Hydraulic Laboratory (SAFHL) performed field flow measurement tests for six large Venturi meters (M100A, M100B, M101A, M101B, M102A, M102B) owned and operated by the Metropolitan Waste Control Commission (MWCC), and installed in the 1930's. The MWCC oversees the collection and treatment of sanitary wastewater discharges in the Twin Cities Metropolitan area of Minnesota. The tests were completed as a subcontract to James M. Montgomery Consulting Engineers, Inc. (JMM), of Wayzata, Minnesota, with whom the MWCC had contracted to conduct an overall evaluation of the Venturi meters.

Four of the six Venturi meters (Fig. 1) were located on the west bank of the Mississippi River, just upstream from the Lake Street bridge; two of these meters had throat diameters of 42 inches, with the other two having throat diameters of 25 inches. The two remaining meters (Fig. 2), each with a throat diameter of 25 inches, were located at the Minneapolis–St. Paul border, along the east bank of the Mississippi River.

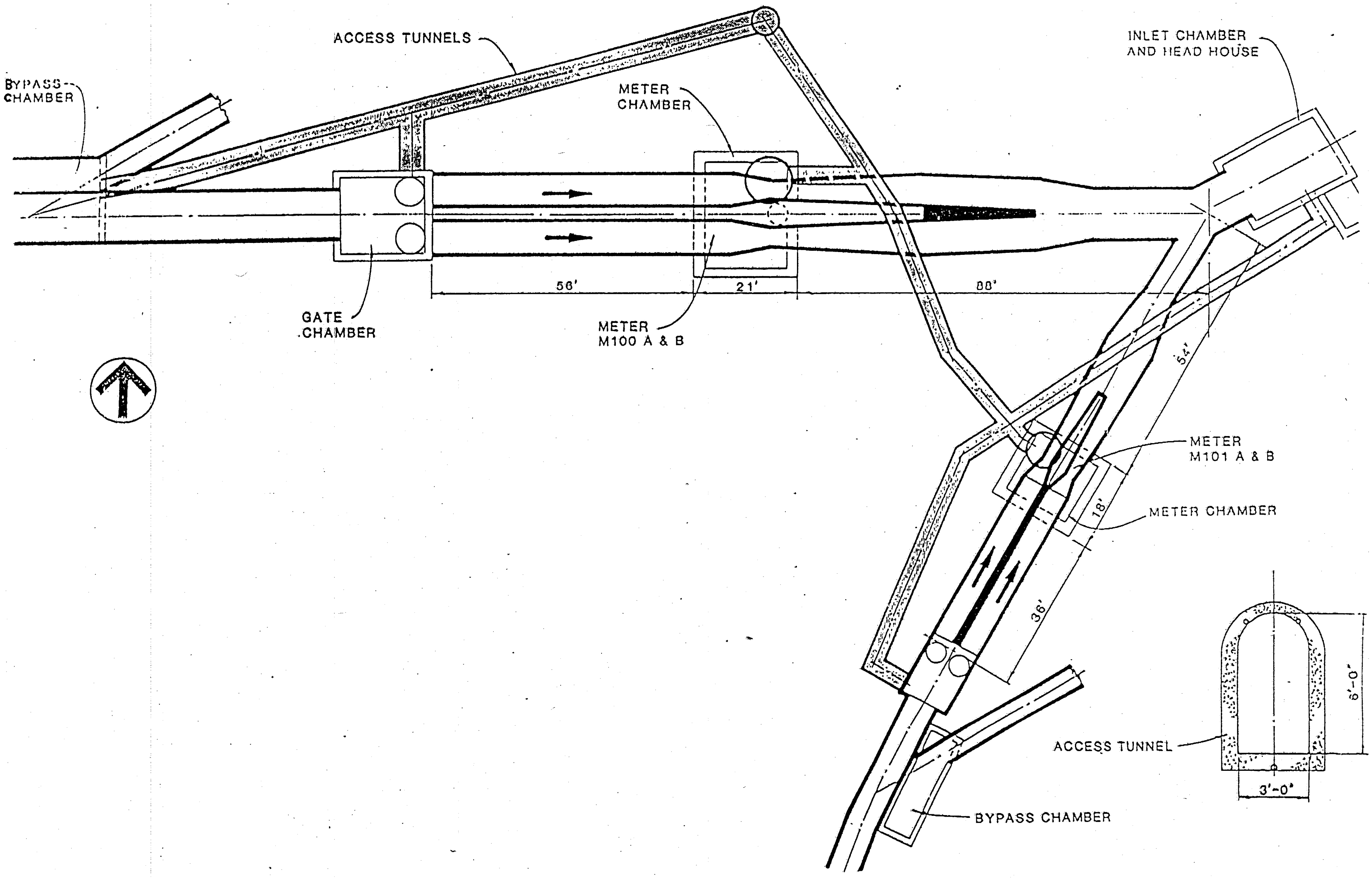

FIGURE 1 WEST SIDE REMOTE METER PLAN

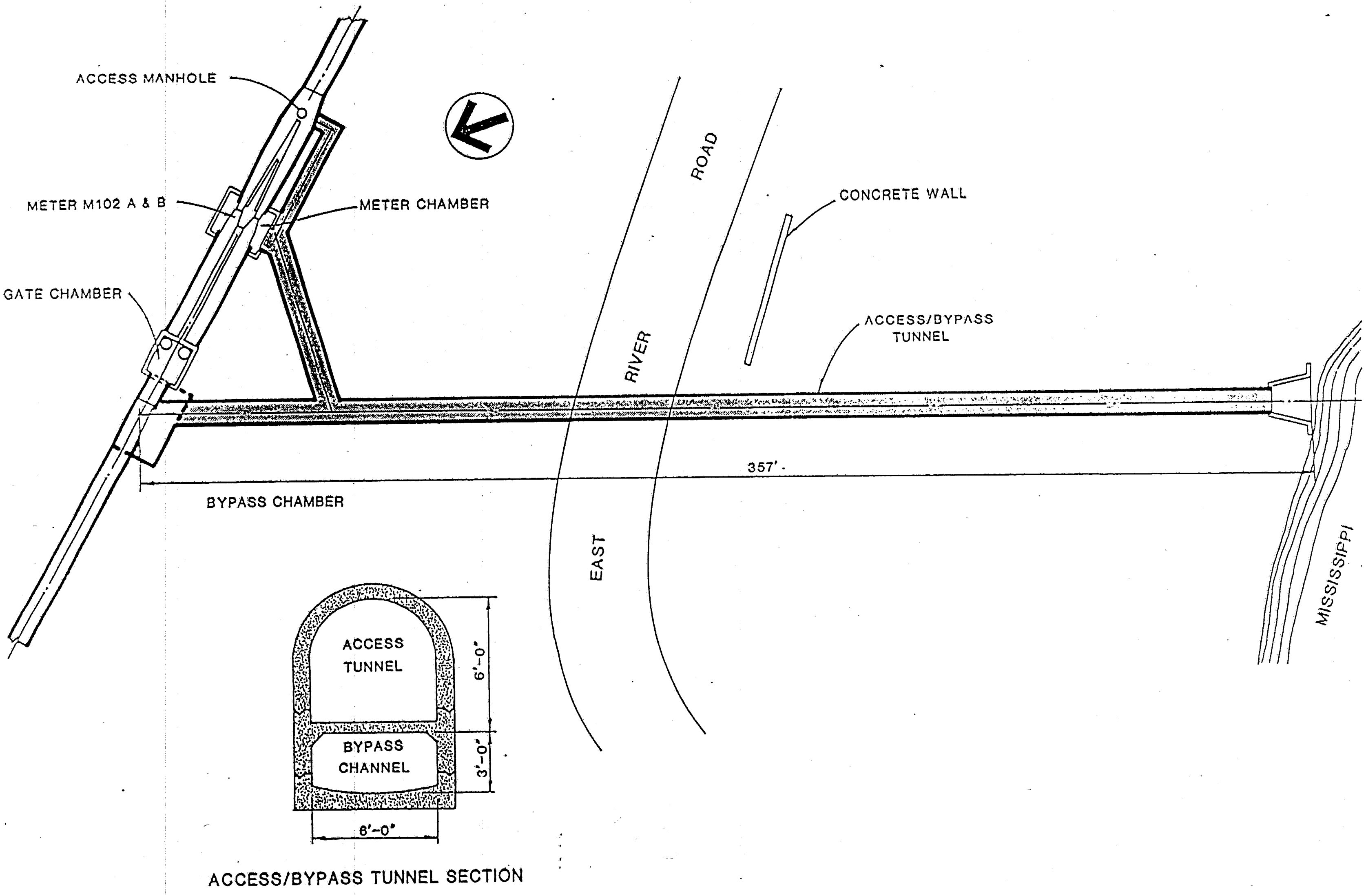

FIGURE 2 EAST SIDE REMOTE METER PLAN

II. TEST PROGRAM

The flow measurement program was developed to assess the flow passing through the Venturi meters in a manner that the time lag between the Venturi and the independently measured flow was minimized. Initial site visits indicated that in the case of each of the three pairs of meters, access to the flow channel was limited to a single gate slot location immediately upstream of the Venturi barrels. Flows at the measurement station were open–channel in nature with the flow varying by a factor in excess of 2 to 1 from the daily high flow to the daily low flow. With a rapid variation of flow rate between the highest and lowest daily flows, it was essential, in order to obtain meaningful results, that the testing be done only at the relatively stabilized times of daily maximum and minimum flows. In addition to the above constraints, much of the region upstream of the meters is still a combined sanitary and storm sewer system, and therefore testing was limited to dry weather periods when runoff was minimized.

A Marsh–McBirney model 511 insertion–type, two–component magnetic current meter was chosen to measure current velocities within the flow as it passed the gate slot. One of the two components of the meter was used to measure the velocity perpendicular to the flow measurement grid, while the other was used to measure any possible cross flow component. For each pair of meters, the M100's, M101's, and M102's, the removal of the obsolete gate and associated operating mechanisms from the gate slot provided an access slot 6 to 9 ft long by 7 to 8 inches in width. Length is defined as the slot dimension transverse to flowing water, while the width is the narrower dimension of the slot parallel to the direction of flow. The gate slots were originally designed to accommodate a gate to divert flow around the Venturi and into the Mississippi River for maintenance purposes. Present day regulations prohibit such diversion, and therefore the gates and gate operating mechanisms were removed to provide access to the slot. Due to higher design discharges, the M100 channel was 9 ft, 6 in., wide as opposed to 6 ft for the M101 and M102 channels. The increased channel size and the corresponding longer gate slot resulted in the development of a sectional rack capable of variable length. Each end of the rack utilized a three–wheeled frame for efficient raising and lowering within the original guidance channels for the gate. The rack was raised and lowered using a steel cable attached to two worm gear hand winches, which were adapted and driven using two 1/2 inch variable–speed reversible drills.

The winches were mounted on a wooden framework designed to straddle the gate slot. The magnetic flow meter probe was mounted on a small, spring–loaded carriage, which moved horizontally along a pair of guidance rails attached to the rack. Since it was important to complete each grid pattern as quickly as possible to ensure that flow changes from start to finish were minimal, the carriage was directed by an 8 ft aluminum bar which enabled sliding along the guidance rails without the need to bring the rack completely out of the gate slot. The guidance rails were designed to allow accurate and rapid positioning of the carriage horizontally at 6-inch intervals. The magnetic probe was mounted on the carriage and positioned approximately two feet below the guidance rails so as not to be affected by any flow disturbances the rack may cause. Vertical positioning of the probe was accomplished by indexing the steel cable at the measurement points, and, with two people operating the drills, adjusting the cable so that the indexing marks reached the appropriate reference point. It was important to raise and lower the rack uniformly in order to prevent binding on the sides of the gate slot, since the length of the rack allowed less than two inches clearance. The tight fit was designed to prevent horizontal displacements of the entire rack from altering the probe location. Photos 1 and 2 show a typical field installation.

The velocity of the flow stream was measured on a grid consisting of either 7 or 9 locations in width by 1 to 3 locations in height. The variation in the horizontal direction was dependent upon the channel width at the measurement cross-section which was: 6 feet for meters 101A, 101B, 102A, and 102B; 9 feet, 6 inches for meters 100A and 100B. The horizontal spacing between grid points utilized only a 6 inch spacing near the sidewalls and a typical spacing of 12 or 18 inches away from the sidewalls. This spacing was used to obtain better resolution of the velocity profile in areas suspected to have a high rate of change with probe position, such as that caused by boundary layer effects near the channel sidewalls. At the same time increased spacing was used away from the side walls because velocity variations were anticipated to be reduced and the increased spacing aided in the speed with which data could be obtained. This allowed test personnel to obtain data as rapidly as possible during a stabilized flow period without sacrificing overall accuracy. The number of locations in the vertical was based on the water depth at the time of measurement. As the channel bottom was usually not horizontal, the bottom row was always a foot or more above the lowest elevation of the bottom of the channel to prevent the curvature of the floor from affecting other rows. The next rows were spaced to split the remaining area roughly equally and conveniently. In the event that the cable was indexed previously, and these marks were reasonably spaced, they were used again to save time, and to avoid confusion with new marks. Most flow depths used two or three rows of points; a fourth row could not be added without the probe becoming covered by debris before data acquisition for a given column was completed. During measurement of M102 low flows, water levels were so low that only one row could be included.

As shown in Figs. 3 and 4, the grids were spaced in a manner that enabled the operators to make a representative assessment of the overall velocity profile. The number of measurement points was based as much as possible on general guidelines of $24 \sqrt[3]{A_m}$, where A_m is the cross-sectional area of the flow at the measurement location in square meters. Each round of testing was done under the field conditions present at the time of testing and therefore subject to minor variations in flow and water surface elevation between similar flow conditions from day to day, sometimes necessitating minor modification of the measurement grid.

6) Compare fluorometer readings and temperatures of samples of C.1.a.5) at times T=0 min., 15 min., 30 min., 45 min., and 60 min. or as determined in part C.1.a.4).

7) The fourth aliquot part will be transported to the MWCC Laboratory for background testing for total organic carbon (TOC), COD, and Chlorine residual (both combined and free available.)

8) Repeat steps C.1.a.1) to 7) with a second sample to verify results.

9) Proceed to subsequent pretest steps if the results of C.1.a.4) or C.1.a.6) above show no significant effect on fluorometer readings for the samples, or that a correction can be made to the readings by filtering or decanting the samples.

b) Temperature Adjustment

1) Collect a 2 gallon sample of wastewater. Split into 2 aliquot parts for separate testing. Use the premix dye solution from step C.1.a.2). Measure the sample temperature.

2) Prepare a group of five parallel samples at 100:1 dilution, wastewater to premix dye solution. Filter or decant the samples as determined in previous steps.

3) Refrigerate two samples to lower the sample temperature by 5° C and 10° C, respectively. Heat two samples to raise the sample temperature by 5° C and 10° C, respectively.

4) Take fluorometer readings and develop a ratio coefficient to adjust readings for temperature.

5) The second aliquot part will be transported to the MWCC Laboratory for background testing for total organic carbon (TOC), COD, and Chlorine residual (both combined and free available.)

6) Repeat steps C.1.b.1) to 5) with a second sample to verify results. Proceed to subsequent pretest steps.

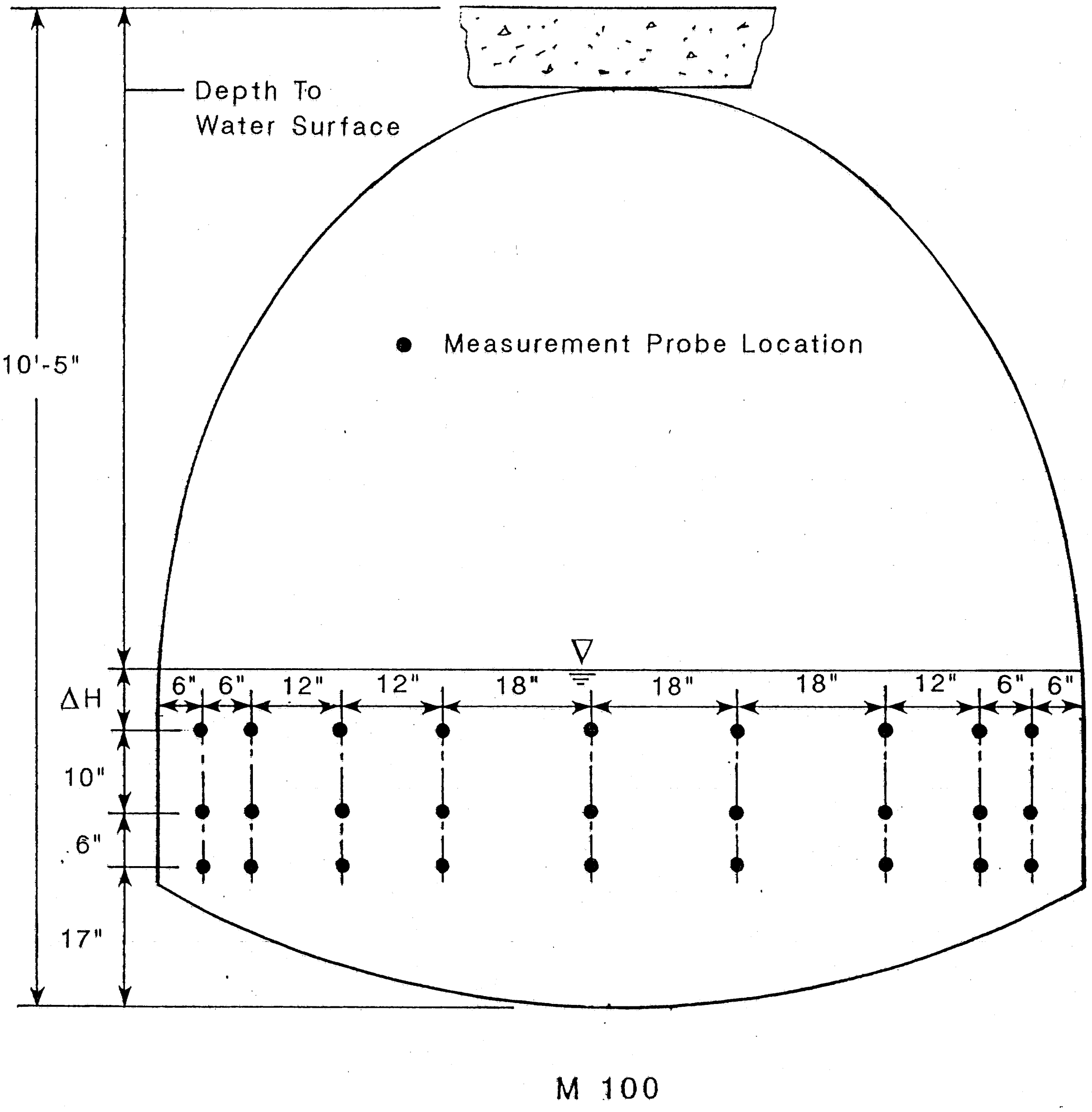

Figure 3 Typical flow measurement grid for a high flow condition test run, meters M100A and M100B.

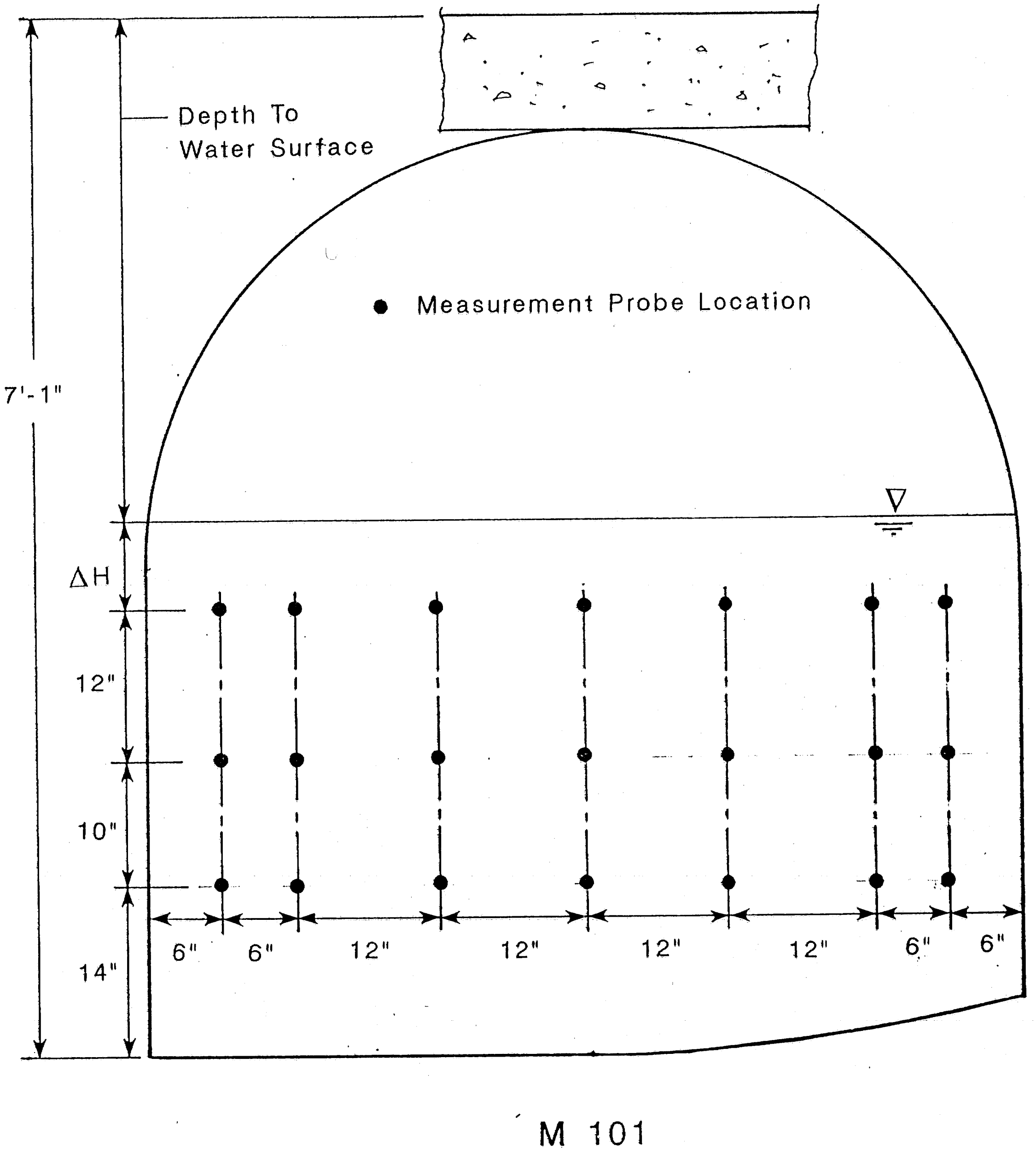

Figure 4 Typical flow measurement grid for a high flow condition test run, meters M101A, M101B, M102A, and M102B.

Prior to the initiation of the field testing program, the insertion mag metering system was calibrated using SAFHL's main channel and associated towing carriage. Calibration involved attaching the probe beneath the carriage and placing the meter control box and the Apple II data acquisition system, with associated support equipment used in the field, on the carriage platform. Calibrations were performed at a series of velocities from 0–8 fps, similar to the velocities expected during the field study. Calibration was done by one technician in charge of mag meter operation riding the carriage, and another staff member in charge of towing carriage operation at the system's control panel. The carriage operates using a DC voltage feedback to maintain a stable velocity after initial acceleration. A stable velocity test length of approximately 65 ft provided sufficient length to calibrate the Marsh–McBirney magmeter. This also allowed for enough unused channel length to provide the necessary distances for the carriage to accelerate to a steady velocity prior to, and smooth deceleration after, each 65 ft test run. After filling the channel to a depth which submerged the probe sufficiently to avoid any surface interference, the probe was towed at the above mentioned velocities. After preliminary runs were completed, the coefficient in the equation used in the computer program which converts a voltage signal to a velocity was adjusted to give a velocity equal to the velocity obtained by the towing carriage. The towing carriage velocity was accurately computed using the specified test length (65 ft) and the time necessary to travel that length. Calibration runs were then repeated with the revised coefficient to verify its accuracy. The entire insertion magmeter data acquisition system was then transferred to the field locations for velocity measurements.

The data acquisition system used was developed to sample the magnetic current meter signal at a rate of approximately 10 samples per second. Pretesting in the field indicated that 80–100 samples were sufficient to provide a representative and repeatable sample, without allowing too much time for debris to accumulate on the probe and alter results.

After obtaining the velocity normal to the measurement grid plane, the velocities were integrated to compute a flow rate using the area velocity method described below.

Typical Computation Procedure – Magnetic Current Meter Weighted Area Average Method (see Figure 5):

$$Q = \Sigma V_i A_i C_i \tag{1}$$

where

Q = total flow in channel

V_i = velocity perpendicular to metering cross section at meter probe location i

A_i = effective area at meter probe location i

C_i = flow coefficient for location i, normally 1. This value reduced to 0.875 between the lowest measurement points and the bottom or the sidemost measurement point and the sidewalls to correct for boundary layer effects presumed to relate to the 1/7 power law which normally exists near a solid boundary.

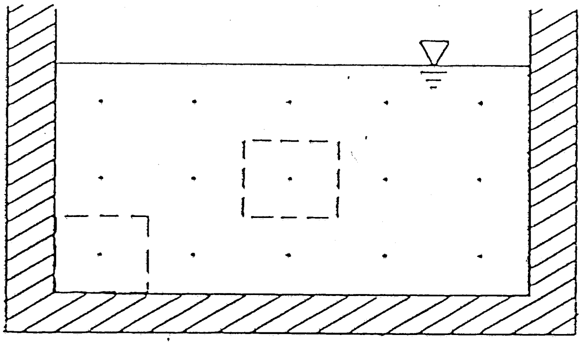

Figure 5
Typical magnetic current meter measurement cross section with effective areas of two locations denoted.

A complete testing program with the tasks necessary for operation of the insertion magmeter is included in Appendix B.

III. TEST RESULTS

Meter calibration data were obtained for each Venturi beginning February 14, 1990, and ending August 28, 1990. For Venturi's 100A and B and 101A and B, both a relatively low or medium flow and a high flow were tested; for Venturi's 102A and B, data were obtained for relatively low, medium, and high flows. The data provided in Table 1 are a summary of the mean calibration coefficients obtained for each particular flow condition. To assure repeatability, a minimum of two runs were taken for all flow tests. A summary of all test runs is provided in Tables A–1 through A–8 in Appendix A.

Considering the complexity involved with access to the measurement locations and the generally difficult working conditions, testing proceeded as well as could be expected. An atypical early March rainstorm dumped 3 inches on the area during a short period of time and caused foam to envelope all testing equipment. All electrical equipment was removed from the tunnel and taken back to St. Anthony Falls Hydraulic Laboratory where it was dried and inspected. No major problems were noted at that time; however, a circuit board on the Marsh–McBirney did short out in July causing the unit to become inoperable and the unit had to be sent to the factory for repairs, and recalibrated in the laboratory's main channel upon its return. Whether or not the storm event had any part in causing this is unknown.

Flow conditions in the channel upstream of the M100A and M100B Venturi were supercritical for low flows with a small hydraulic jump occurring immediately downstream of the measurement location. Probing with a steel measuring rod indicated that the channel bed apparently drops several inches just downstream of the gate slot. The turbulence caused by this change in bed elevation rendered low flow measurement useless, and the times of test measurements were changed to mid–to–late evening to obtain data for a mid–level flow condition. This change appeared to alleviate the problem.

High flows at all locations carried a substantial amount of debris which required that the probe be cleaned at the completion of each vertical traverse. Occasionally, the standard deviation for one of the points in a vertical traverse would be particularly high due to a large amount of debris becoming entangled with the probe. When this happened, the rack would be raised, the probe cleaned, and the vertical traverse re–measured.

It was noted during the measurement of flows for the Venturi meters that, due to the necessity to pass storm water and runoff events because of the combined nature of the system, the meters are substantially oversized for most sanitary flows. This leads to low differential pressures for the meters and inherently less measurement accuracy.

TABLE 1. Summary

Meter	Mean Venturi Indicated Q (GPM)	Mean $\frac{Q_{SAFHL}}{Q_{MWCC}}$	σ $\frac{Q_{SAFHL}}{Q_{MWCC}}$	Number of Test Runs
M100A$_{\mathrm{H}}$	45,327	1.040	0.0275	9
M100A$_{\mathrm{M}}$	37,391	0.958	0.0362	6
M100B$_{\mathrm{H}}$	47,175	1.069	0.0128	2
M100B$_{\mathrm{M}}$	38,687	1.067	0.0143	6
M101A$_{\mathrm{H}}$	21,600	1.119	0.0390	2
M101A$_{\mathrm{L}}$	9,857	1.261	0.0106	3
M101B$_{\mathrm{H}}$	21,189	1.163	0.0489	5
M101B$_{\mathrm{L}}$	10,083	1.305	0.0217	3
M102A$_{\mathrm{pH}}$	20,238	1.202	0.0114	3
M102A$_{\mathrm{pM}}$	15,062	1.111	0.0307	3
M102A$_{\mathrm{pL}}$	8,451	1.134	0.0126	4
M102A$_{\mathrm{cH}}$	14,847	1.073	0.0090	3
M102A$_{\mathrm{cM}}$	11,562	1.066	0.0023	3
M102A$_{\mathrm{cL}}$	10,457	1.111	0.0231	4
M102B$_{\mathrm{pH}}$	19,014	1.187	0.0481	4
M102B$_{\mathrm{pM}}$	15,742	1.168	0.0336	2
M102B$_{\mathrm{pL}}$	8,236	1.144	0.0399	3
M102B$_{\mathrm{cH}}$	13,495	1.150	0.0095	3
M102B$_{\mathrm{cM}}$	10,759	1.097	0.0120	3
M102B$_{\mathrm{cL}}$	9,717	1.162	0.0126	4

Subscript definitions:

H – values computed only for runs of high flow.
M – values computed only for runs of medium flow.
L – values computed only for runs of low flow.
p – values computed for appropriate runs prior to cleaning of the meter.
c – values computed for appropriate runs after cleaning of the meter.

The cross–sectional shape of the channels at the measuring location was obtained from "as–built" drawings #1 (general plan), #3 (Interceptor M–I), and #19 (Interceptor M–H) of the "City of Minneapolis, Plans and Profiles for Intercepting Sewers," and field verified during the testing process. For Venturi 102A and 102B the field measurements repeatedly indicated that the channel was different from that shown on the "as built" drawing number #19, so the field measured x–section was used for flow computations. This happened to agree with the shape of an adjoining tunnel as specified in the "as–built" drawing, number 19, and perhaps this drawing had the channels reversed. The channel cross sections used in the computations are shown in Figs. A–1, A–2, and A–3 of the Appendix.

The data for the M102A and M102B Venturi meters are more complex than the other Venturi meters. For these Venturi, localized conditions prohibited the complete stoppage of flow passing through the "closed" meter. For all other Venturi, complete closure of the gate and subsequent reduction of leakage to, at most, a small, insignificant trickle was possible if 6 – 24 hours time was allowed, during which any leaks plugged with debris prior to flow measurement testing. As best as field test personnel could determine, the leakage through the M102 meters was apparently caused by the use of a rectangular closing gate in a channel whose bottom consisted of an arc. Due to this leakage, we have computed the data using three different methods for use by James M. Montgomery Consulting Engineers and the Metropolitan Waste Control Commission. The first method provides a flow coefficient if the leakage flow is totally ignored (Col. 7) (Tables A–5 through A–8.). The second method (Col. 8) (Tables A–5 through A–8) adds the leakage flow, as indicated by MWCC's regional headquarters computer, to that flowing through the meter being tested (Eq. 2), and the third method (Col. 9) (Tables A–5 through A–8) further refines the data by solving the two equations for two unknowns, a situation that was occurring under testing conditions. (See equations 3 and 4.) Thus, actually correcting the leakage flow, as indicated by the MWCC's regional headquarters computer, by the calibration coefficient (C_A or C_B) determined for the given meter, during the testing program. Figure 6 provides a diagram to further explain the computational procedure.

$$Q_{SAFHL} = Q_{VENTURI_A} + Q_{VENTURI_B}\ [\text{LEAKAGE FLOW}] \qquad (2)$$

$$Q_{SAFHL_A} = C_A\ Q_{VENTURI_A} + C_B\ Q_{VENTURI_B}[\text{LEAKAGE FLOW}] \qquad (3)$$

$$Q_{SAFHL_B} = C_B\ Q_{VENTURI_B} + C_A\ Q_{VENTURI_A}[\text{LEAKAGE FLOW}] \qquad (4)$$

For flow conditions other than low flow, column 9 values are obtained by using Eqs. 3 and 4, depending on the meter being tested, which adjusts the leakage indicated by the MWCC regional computer by the appropriate calibration coefficient determined for that meter under low flow conditions. Note that while the calibration coefficient given above is computed using several methods in an effort to provide as much insight as possible into the data analysis, in all cases it is ultimately defined as Q SAFHL divided by Q MWCC.

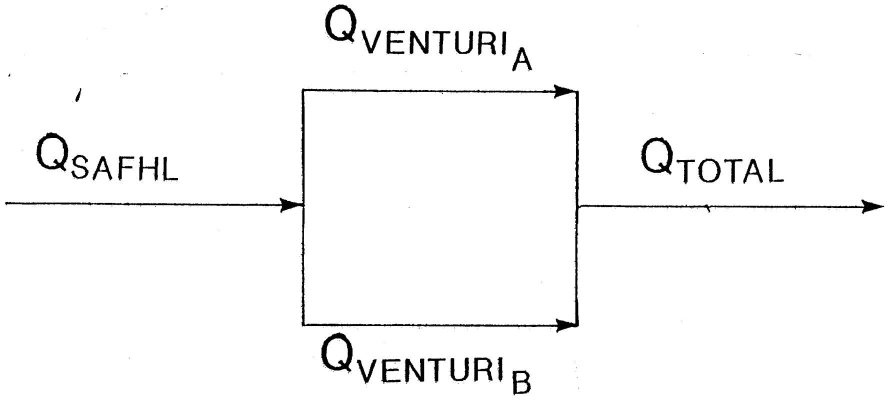

Figure 6
Schematic diagram to visualize the flow situation at meters M102A and M102B.

For some Venturi, a different calibration coefficient is obtained depending on the quantity of flow being metered. Figures 7 through 14 provide a compilation of all valid test runs plotted as Q SAFHL_N vs. Q VENTURI_N, where Q VENTURI is referred to as either Q MWCC or Q JMM depending on the manner in which the Venturi–measured flow was read. Table 2 gives the equations for the linear regression of the data presented in Figures 7 through 14. Earlier runs (all runs for meters M101A, M101B, M100A, and runs M4, M5, and M6 of M100B), and all leakage flows indicated through the M102 meters, refer to the Venturi–measured flow as Q MWCC since the values were obtained from 15–minute averages of the flow as recorded by the MWCC data acquisition computer at the Regional Maintenance Center in Eagan, Minnesota. After test personnel were made aware of the potential for small discrepancies due to the telemetry system, later runs (M1 through M3, and H1 and H2 in M100B), and all test flows through the M102 meters, utilized these data as well; however, computations were based upon values obtained from an on–site digital volt–ohm meter reading of the flow meter signal through the Venturi. This was accomplished by a James M. Montgomery staff member reading a digital volt–ohm meter every minute, thus Q JMM. In this way we were able to get Venturi–measured flow information on a minute by minute basis as well as avoid any possible time or telemetry problems between the actual values at the remote meter site and those obtained in Eagan. Also, individual runs at the M102 meters seldom took as long as fifteen minutes to complete and would therefore be poorly represented by fifteen minute averages of the flow. Thus, whenever available, flow coefficients are based on the on–site readings, or Q JMM, of Venturi–measured flow.

After the completion of the initial testing of the M102 meters, they were inspected and cleaned of accumulated debris which may have affected meter calibration, and then retested. The second phase of the testing of Venturi M102A and M102B indicated that for both Venturi meters the above defined flow coefficient decreased rather markedly after cleaning.

TABLE 2

Equations for the linear regression of data in Figures 7 through 14

Figure 7 –	Meter M100A	$y = 1.40551(x) - 16642.4$
Figure 8 –	Meter M100B	$y = 1.07289(x) - 211.0$
Figure 9 –	Meter M101A	$y = 0.99810(x) + 2595.0$
Figure 10 –	Meter M101B	$y = 1.04127(x) + 2612.3$
Figure 11 –	Meter M102A – Prior to Cleaning	$y = 1.23674(x) - 1110.4$
Figure 12 –	Meter M102B – Prior to Cleaning	$y = 1.20262(x) - 433.5$
Figure 13 –	Meter M102A – After Cleaning	$y = 0.99741(x) + 1054.8$
Figure 14 –	Meter M102B – After Cleaning	$y = 1.15155(x) - 145.9$

$x = Q$ JMM or Q MWCC (in GPM)

$y = Q$ SAFHL (in GPM)

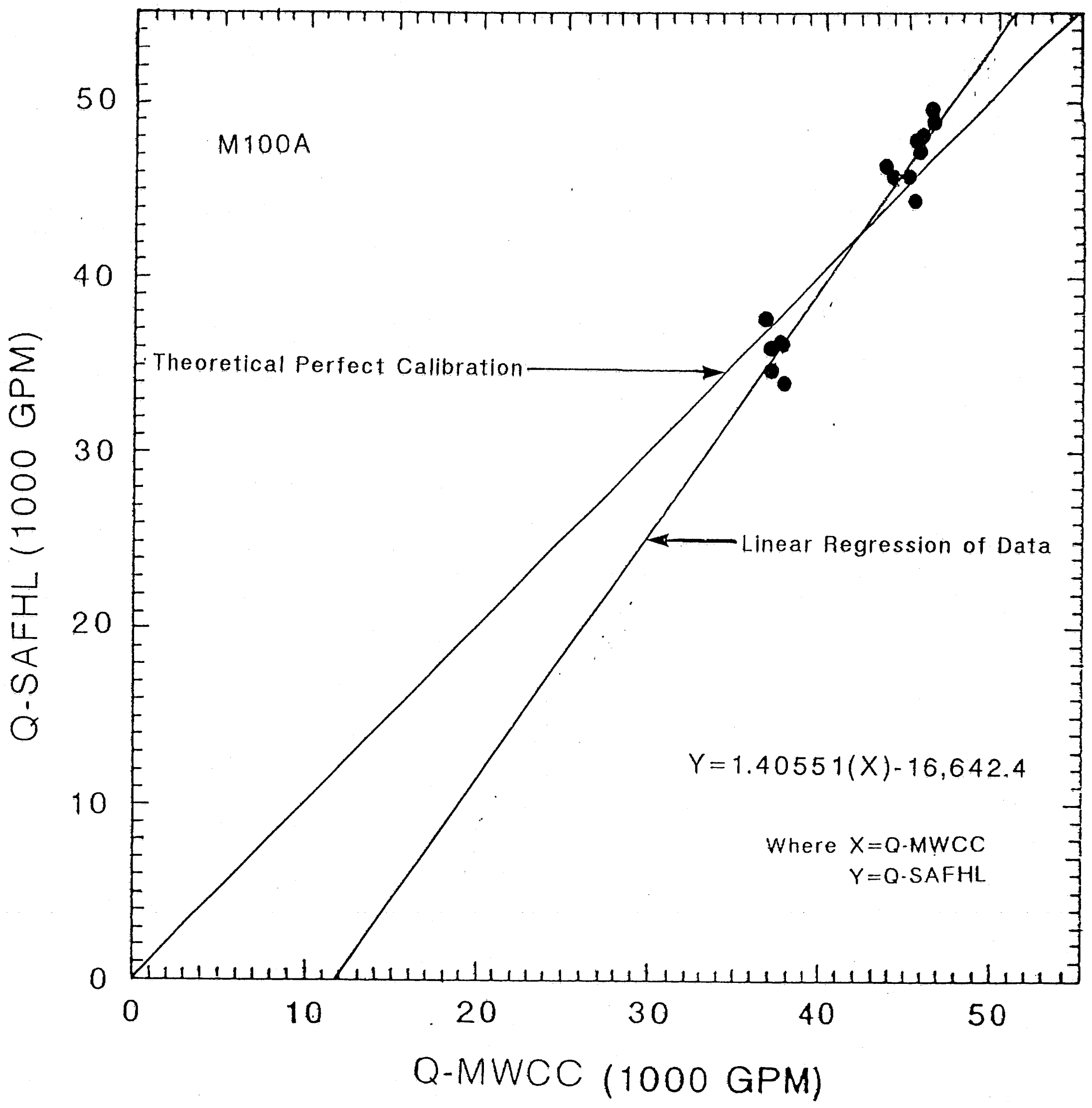

Figure 7 MWCC Computer recorded flows vs flows measured by SAFHL for meter M100A.

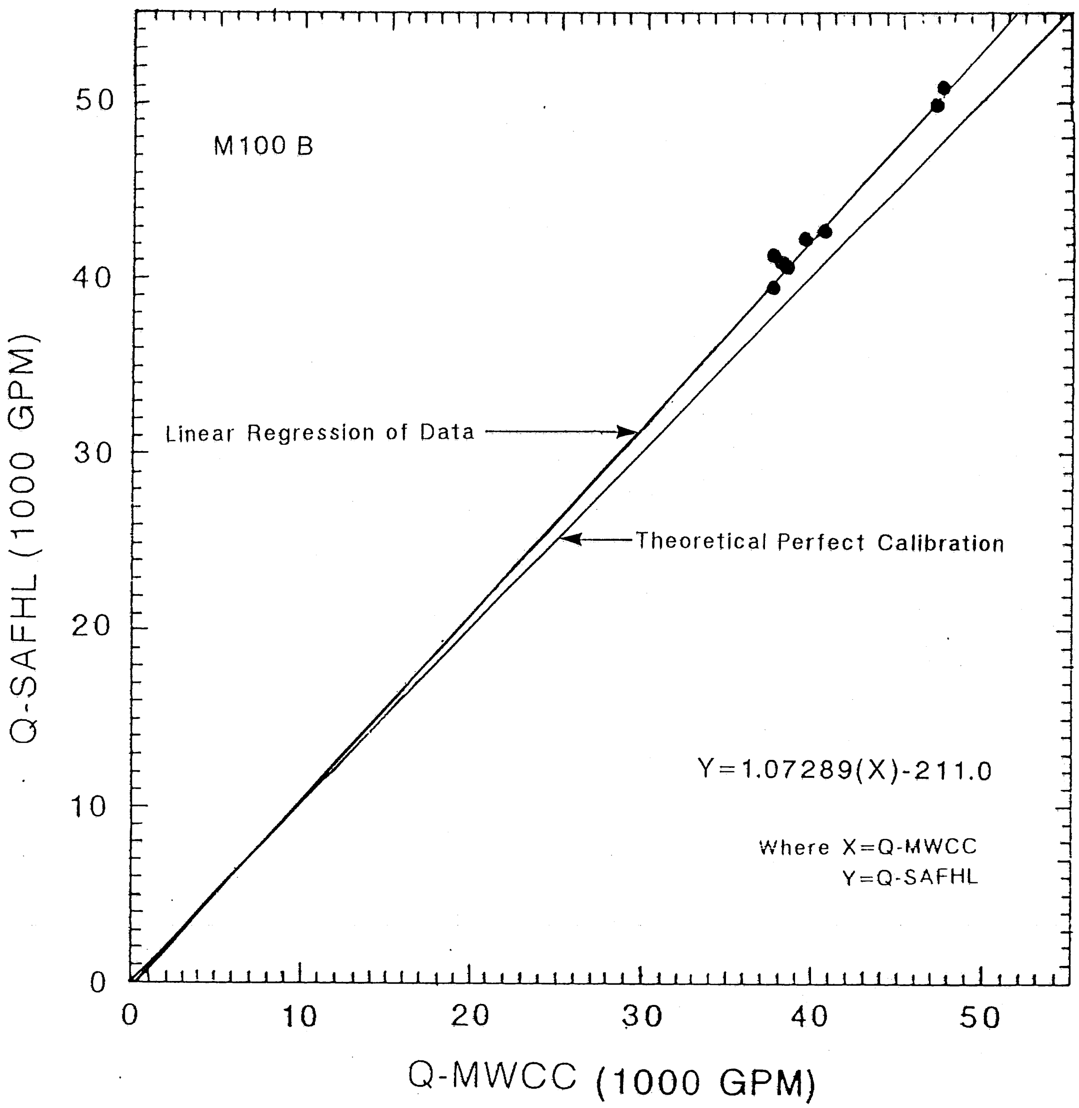

Figure 8 MWCC Computer recorded flows vs flows measured by SAFHL for meter M100B.

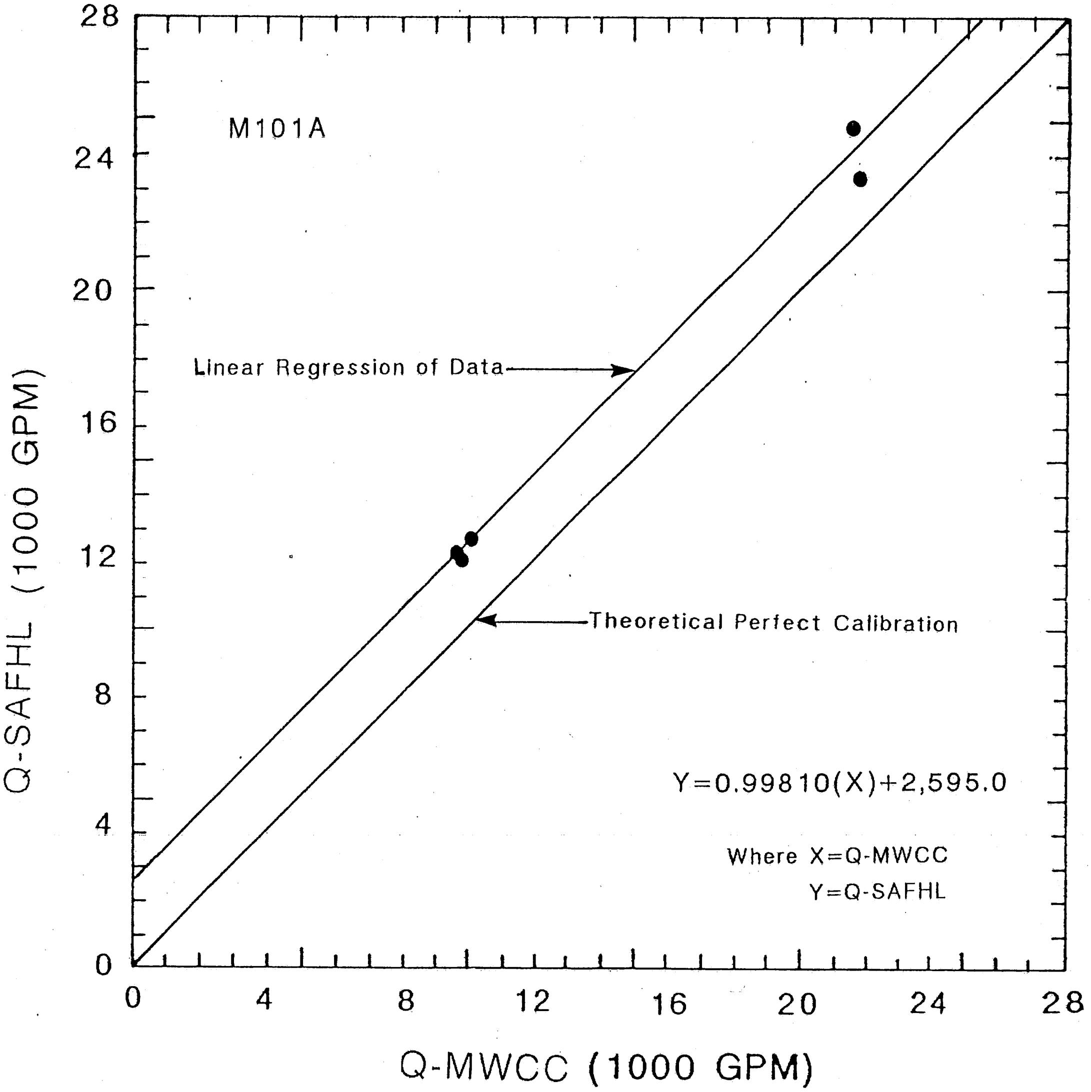

Figure 9 MWCC Computer recorded flows vs flows measured by SAFHL for meter M101A.

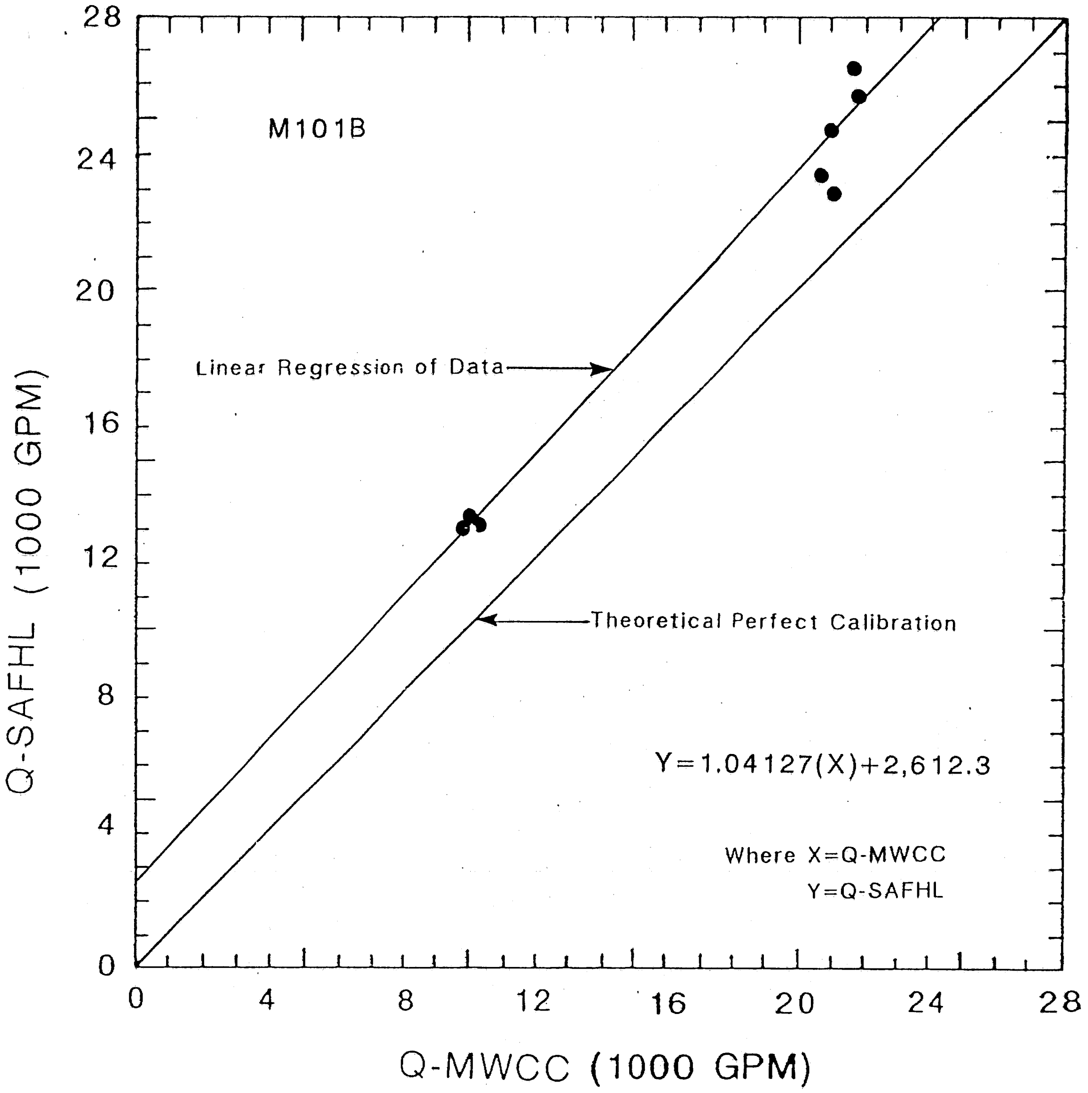

Figure 10 MWCC Computer recorded flows vs flows measured by SAFHL for meter M101B.

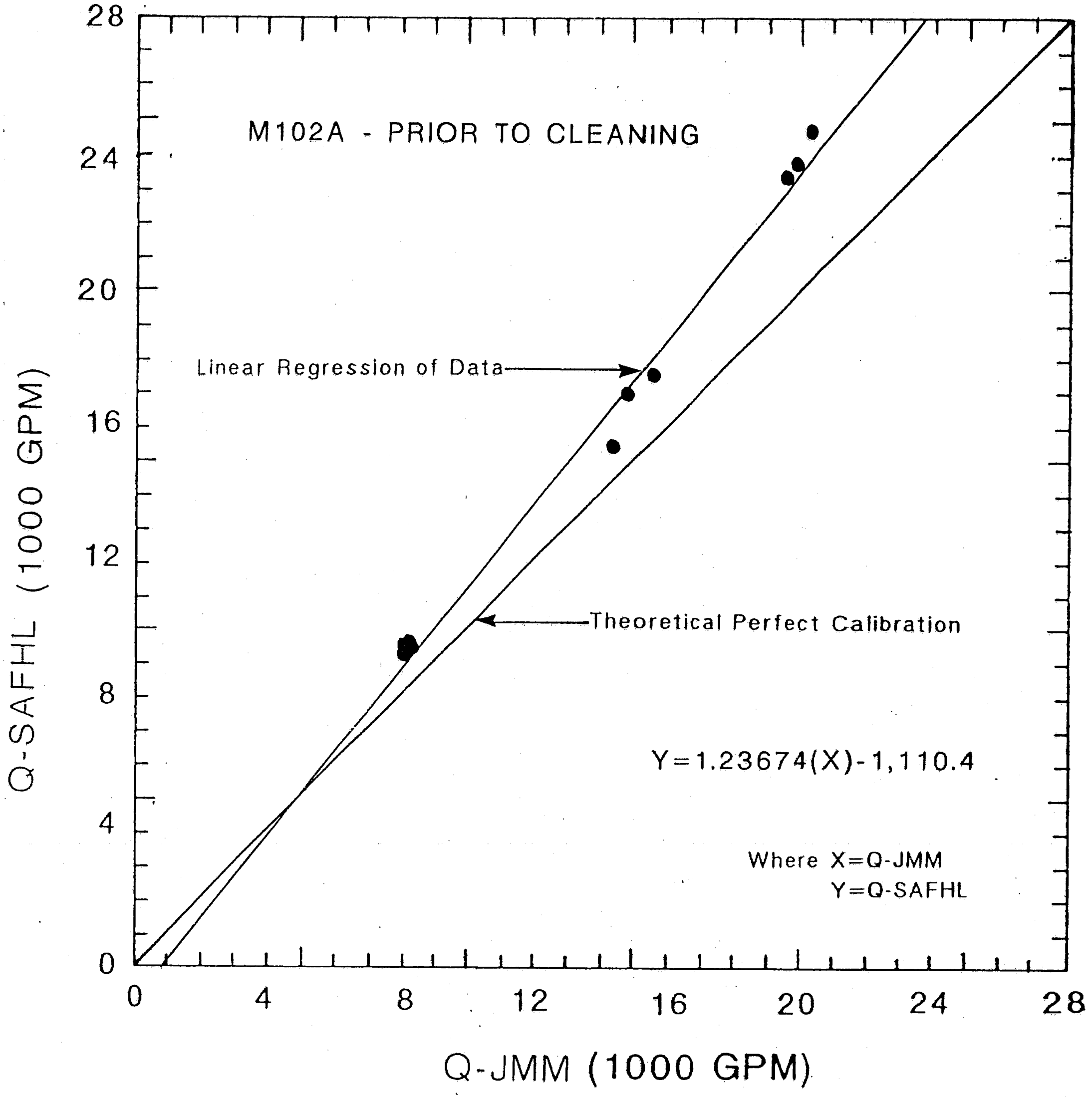

Figure 11 JMM DVOM recorded flows vs flows measured by SAFHL for meter M102A – prior to cleaning.

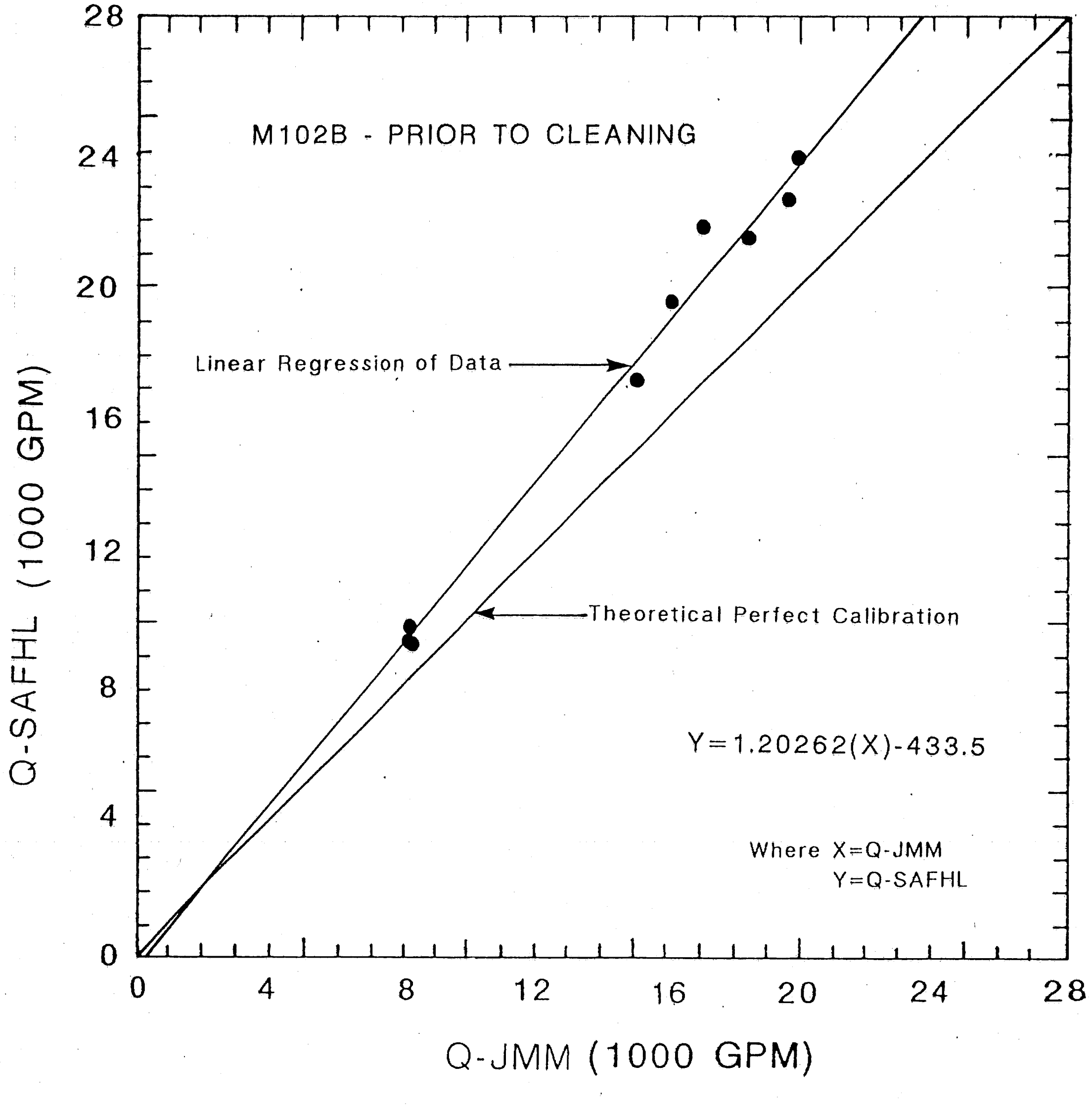

Figure 12 JMM DVOM recorded flows vs flows measured by SAFHL for meter M102B – prior to cleaning.

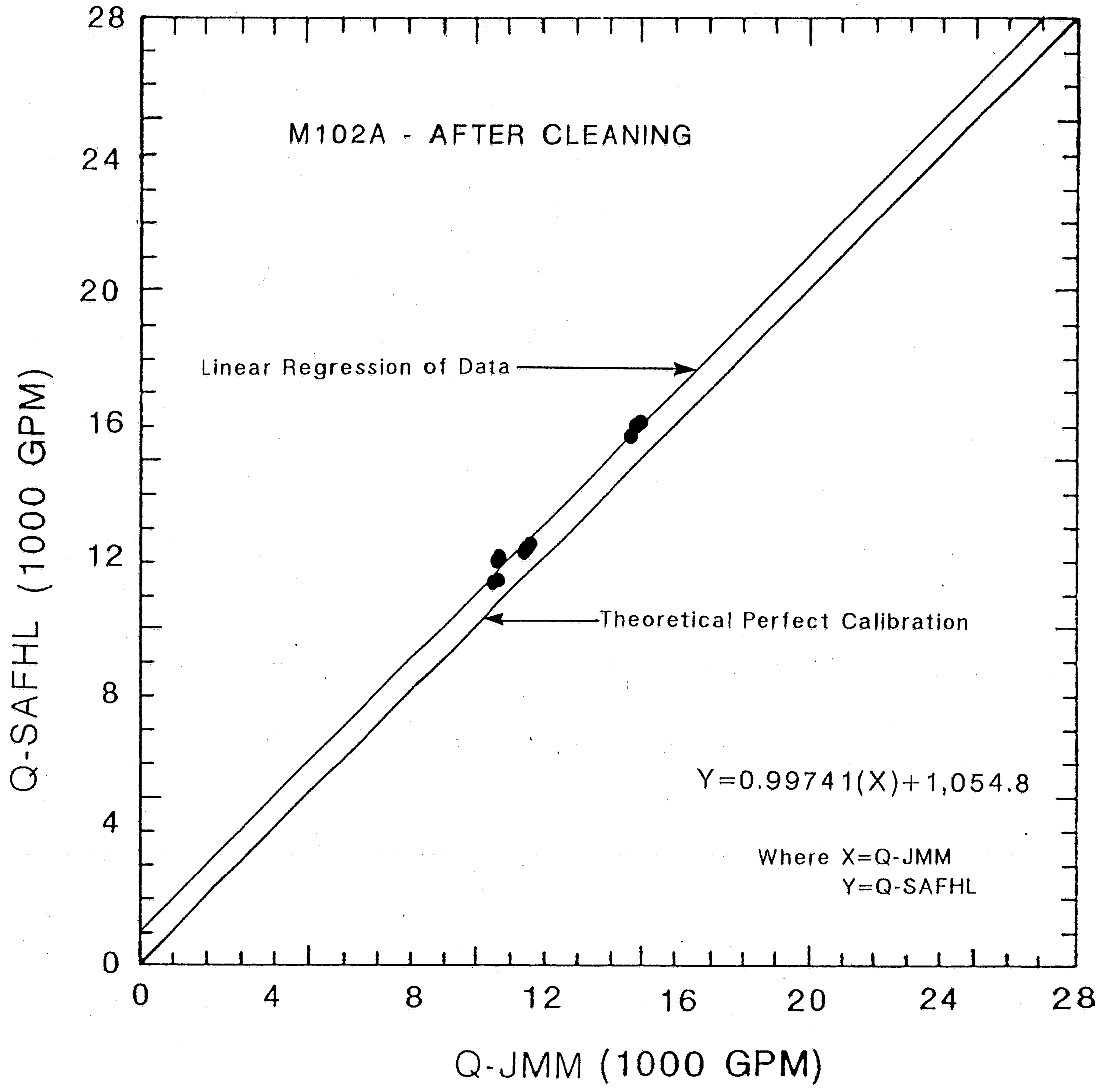

Figure 13 JMM DVOM recorded flows vs flows measured by SAFHL for meter M102A – after cleaning.

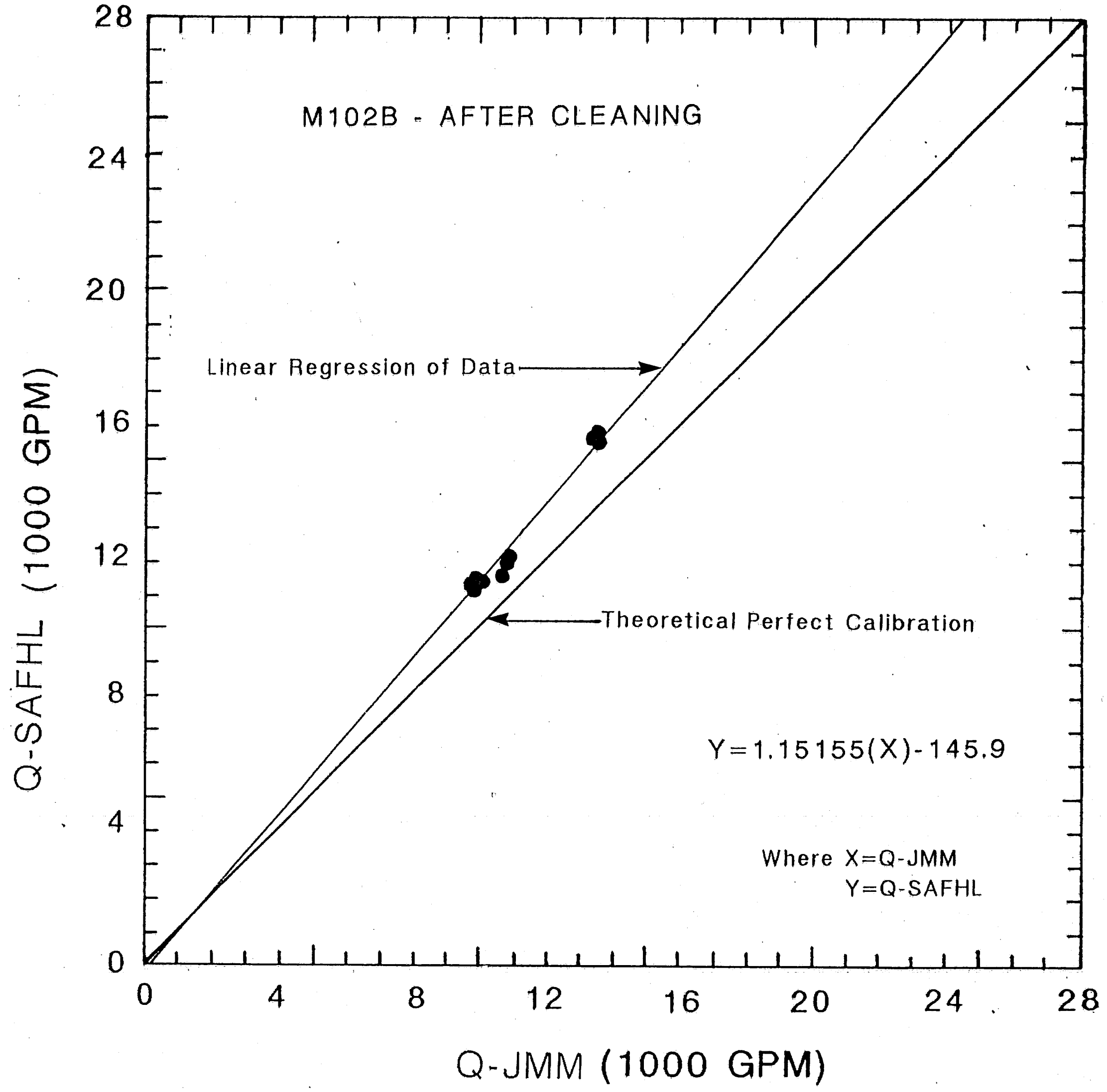

Figure 14 JMM DVOM recorded flows vs flows measured by SAFHL for meter M102B – after cleaning.

IV. CONCLUSIONS

Data obtained during the flow measurement tests can provide a basis for adjusting the instrumentation used to measure the flow passing through each of the Venturi. These data will be incorporated with other information obtained during the study by JMM, and recommendations regarding flow measurement will be provided therein.

APPENDIX A

TABLE A-1

METER M100A

RUN #	SAFHL Q (IN GPM)	MWCC VENTURI Q (IN GPM)	Q-SAFHL ------- Q-MWCC
M1	36316.3	37867	0.9590
M2	36320.0	37843	0.9598
M3	33972.5	37862	0.8973
M4	34699.6	36910	0.9401
M5	36053.8	36935	0.9761
M6	37571.5	36930	1.0174
H1	45668.6	43910	1.0401
H2	46403.0	43840	1.0585
H3	45749.6	45020	1.0162
H4	44194.5	45422	0.9730
H5	47662.7	45734	1.0422
H6	47899.6	45349	1.0562
H7	48127.5	45730	1.0524
H8	48753.3	46550	1.0473
H9	49663.1	46390	1.0706
		MEAN=	1.0071
		ST. DEV.=	0.0507
Q<43,000 GPM		MEAN=0.9583	
(MEDIUM FLOW)		ST. DEV.=.0362	
Q>43,000 GPM		MEAN=1.0396	
(HIGH FLOW)		ST. DEV.=.0275	

TABLE A-2

METER M100B

RUN #	SAFHL Q (IN GPM)	JMM DVOM Q (IN GPM)	MWCC VENTURI Q (IN GPM)	Q-JMM ------ Q-MWCC	Q-SAFHL ------- Q-MWCC
M1	39501.8	37914.0	37860	1.0014	1.0434
M2	40913.5	38190.6	38180	1.0003	1.0716
M3	40919.0	38314.9	38320	0.9999	1.0678
M4	41316.2	NA	37860	NA	1.0913
M5	42266.6	NA	39500	NA	1.0700
M6	42807.6	NA	40400	NA	1.0596
H1	49690.4	47042.1	47050	0.9998	1.0561
H2	51164.1	47301.2	47300	1.0000	1.0817
			MEAN=	1.0003	1.0677
			ST. DEV.=	0.0006	0.0140
	Q<43,000 GPM			MEAN=1.0673	
	(MEDIUM FLOW)			ST. DEV.=.0143	
	Q>43,000 GPM			MEAN=1.0689	
	(HIGH FLOW)			ST. DEV.=.0128	

TABLE A-3

METER M101A

RUN #	SAFHL Q (IN GPM)	MWCC VENTURI Q (IN GPM)	Q-SAFHL / Q-MWCC
L1	12768.5	10100	1.2642
L2	12180.4	9770	1.2467
L3	12338.1	9700	1.2720
H1	23428.5	21700	1.0797
H2	24891.2	21500	1.1577
		MEAN=	1.2041
		ST. DEV.=	0.0744

Q<20,000 GPM (LOW FLOW)	MEAN=1.2610 ST. DEV.=.0106
Q>20,000 GPM (HIGH FLOW)	MEAN=1.1187 ST. DEV.=.0390

TABLE A-4

METER M101B

RUN #	SAFHL Q (IN GPM)	MWCC VENTURI Q (IN GPM)	Q-SAFHL / Q-MWCC
L1	13193.2	10350	1.2747
L2	13292.7	10030	1.3253
L3	12966.9	9868	1.3140
H1	22841.7	21045	1.0854
H2	24776.6	20920	1.1843
H3	23359.9	20600	1.1340
H4	25751.7	21780	1.1824
H5	26528.7	21600	1.2282
		MEAN=	1.216
		ST. DEV.=	0.0799

Q<20,000 GPM (LOW FLOW)	MEAN=1.3047 ST. DEV.=.0217
Q>20,000 GPM (HIGH FLOW)	MEAN=1.1629 ST. DEV.=.0489

TABLE A-5
METER M102A PRIOR TO CLEANING
(ALL Q'S SHOWN IN GALLONS/MINUTE)

RUN #	SAFHL Q	MWCC VENTURI Q	Q-LEAK THRU B DURING A	JMM DVOM Q	Q-JMM ----- Q-MWCC	LEAKAGES IGNORED Q-safhl / Q-jmm	LEAKAGES UNCORRECTED Q-safhl / Q-jmm	LEAKAGES CORRECTED Q-safhl / Q-jmm
L1	9216.2	8150	195	8037.6	0.9862	1.1466	1.1195	1.1157
L2	9539.1	8220	191	8122.9	0.9882	1.1743	1.1474	1.1436
L3	9594.5	8274	187	8147.0	0.9847	1.1777	1.1512	1.1475
L4	9546.5	8392	195	8230.0	0.9807	1.1600	1.1331	1.1294
				LOW FLOW MEAN=	0.9850	1.1647	1.1378	1.1341
				ST. DEV.=	0.0028	.0124	.0125	.0126
M1	15375.4	13798	667	13609.7	0.9864	1.1297	1.0770	1.0698
M2	16971.9	14296	656	14096.0	0.9860	1.2040	1.1505	1.1432
M3	17491.4	15139	630	14881.8	0.9830	1.1754	1.1276	1.1211
				MEDIUM FLOW MEAN=	0.9851	1.1697	1.1184	1.1113
				ST. DEV.=	0.0015	.0306	.0307	.0307
H1	23338.7	19572	296	19136.0	0.9777	1.2196	1.2010	1.1984
H2	23655.6	19910	311	19524.2	0.9806	1.2116	1.1926	1.1899
H3	24707.0	20333	293	19965.3	0.9819	1.2375	1.2196	1.2171
				HIGH FLOW MEAN=	0.9801	1.2229	1.2044	1.2018
				ST. DEV.=	0.0018	.0108	.0113	.0114
				OVERALL MEAN=	0.9835	1.1836	1.1520	1.1476
				OVERALL ST. DEV.=	0.0031	.0323	.0403	.0416

CORRECTIONS BASED ON JMM DVOM LOW FLOW VALUES WHERE C2= 1.1439

TABLE A-6
METER M102B PRIOR TO CLEANING
(ALL Q'S SHOWN IN GALLONS/MINUTE)

RUN #	SAFHL Q	MWCC VENTURI Q	Q-LEAK THRU A DURING B	JMM DVOM Q	Q-JMM ----- Q-MWCC	LEAKAGES IGNORED Q-safhl / Q-jmm	LEAKAGES UNCORRECTED Q-safhl / Q-jmm	LEAKAGES CORRECTED Q-safhl / Q-jmm
L1	9940.8	7385	826	7345.5	0.9947	1.3533	1.2165	1.2003
L2	9336.7	7425	836	7436.7	1.0016	1.2555	1.1286	1.1135
L3	9376.3	7390	847	7427.5	1.0051	1.2624	1.1332	1.1178
				LOW FLOW MEAN=	1.0005	1.2904	1.1594	1.1439
				ST. DEV.=	0.0043	.0446	.0404	.0399
M1	19527.0	15347	836	15301.8	0.9971	1.2761	1.2100	1.2017
M2	17194.8	14230	1070	13941.4	0.9797	1.2334	1.1454	1.1346
				MEDIUM FLOW MEAN=	0.9884	1.2548	1.1777	1.1682
				ST. DEV.=	0.0087	.0214	.0323	.0336
H1	21410.1	17750	1120	17245.8	0.9716	1.2415	1.1658	1.1563
H2	21729.4	16823	858	16214.0	0.9638	1.3402	1.2728	1.2643
H3	23805.6	19223	876	19065.9	0.9918	1.2486	1.1937	1.1868
H4	22466.5	18270	1135	18443.5	1.0095	1.2181	1.1475	1.1387
				HIGH FLOW MEAN=	0.9842	1.2554	1.1950	1.1865
				ST. DEV.=	0.0178	.0507	.0479	.0481
				OVERALL MEAN=	0.9905	1.2699	1.1793	1.1682
				OVERALL ST. DEV.=	0.0147	.0441	.0451	.0464

CORRECTIONS BASED ON JMM DVOM LOW FLOW VALUES WHERE C1= 1.1341

TABLE A-7
METER M102A AFTER CLEANING
(ALL Q'S SHOWN IN GALLONS/MINUTE)

RUN #	SAFHL Q	MWCC VENTURI Q	Q-LEAK THRU B DURING A	JMM DVOM Q	Q-JMM ----- Q-MWCC	LEAKAGES IGNORED Q-safhl / Q-jmm	LEAKAGES UNCORRECTED Q-safhl / Q-jmm	LEAKAGES CORRECTED Q-safhl / Q-jmm
L1	11371.4	9231	1163	9052.9	0.9807	1.2561	1.1131	1.0930
L2	11456.6	9250	1165	9165.4	0.9909	1.2500	1.1090	1.0892
L3	11900.7	9334	1168	9306.5	0.9971	1.2788	1.1362	1.1161
L4	12161.3	9350	1168	9244.6	0.9887	1.3155	1.1679	1.1472
				LOW FLOW MEAN=	0.9894	1.2751	1.1316	1.1114
				ST. DEV.=	0.0059	.0257	.0234	.0231
M1	12321.9	10620	933	10482.0	0.9870	1.1755	1.0794	1.0654
M2	12497.0	10620	953	10581.1	0.9963	1.1811	1.0835	1.0692
M3	12375.6	10620	940	10543.1	0.9928	1.1738	1.0777	1.0637
				MEDIUM FLOW MEAN=	0.9920	1.1768	1.0802	1.0661
				ST. DEV.=	0.0038	.0031	0.0024	.0023
H1	15613.4	13575	1159	13370.3	0.9849	1.1678	1.0746	1.0609
H2	16018.6	13710	1148	13460.4	0.9818	1.1901	1.0965	1.0828
H3	16032.9	13810	1140	13606.1	0.9852	1.1784	1.0873	1.0739
				HIGH FLOW MEAN=	0.9840	1.1788	1.0861	1.0725
				ST. DEV.=	0.0015	.0091	.0090	.0090
				OVERALL MEAN=	0.9885	1.2167	1.1025	1.0861
				OVERALL ST. DEV.=	0.0054	.0506	.0285	.0259

CORRECTIONS BASED ON JMM DVOM LOW FLOW VALUES WHERE C2=1.1615

TABLE A-8
METER M102B AFTER CLEANING
(ALL Q'S SHOWN IN GALLONS/MINUTE)

RUN #	SAFHL Q	MWCC VENTURI Q	Q-LEAK THRU A DURING B	JMM DVOM Q	Q-JMM ----- Q-MWCC	LEAKAGES IGNORED Q-safhl / Q-jmm	LEAKAGES UNCORRECTED Q-safhl / Q-jmm	LEAKAGES CORRECTED Q-safhl / Q-jmm
L1	11374.7	8420	1232	8333.9	0.9898	1.3649	1.1891	1.1723
L2	11162.1	8475	1241	8403.1	0.9915	1.3283	1.1574	1.1410
L3	11474.1	8490	1241	8413.9	0.9910	1.3637	1.1884	1.1716
L4	11399.2	8525	1243	8436.6	0.9896	1.3512	1.1777	1.1610
				LOW FLOW MEAN=	0.9905	1.3520	1.1782	1.1615
				ST. DEV.=	0.0008	.0147	.0128	.0126
M1	11559.9	9510	1163	9408.0	0.9893	1.2287	1.0935	1.0803
M2	11910.8	9610	1153	9513.5	0.9900	1.2520	1.1167	1.1034
M3	12084.4	9690	1152	9629.3	0.9937	1.2550	1.1209	1.1077
				MEDIUM FLOW MEAN=	0.9910	1.2452	1.1104	1.0971
				ST. DEV.=	0.0019	.0118	.0120	.0120
H1	15498.6	12395	1232	12272.0	0.9901	1.2629	1.1477	1.1361
H2	15750.8	12295	1192	12311.1	1.0013	1.2794	1.1665	1.1551
H3	15659.4	12180	1190	12208.9	1.0024	1.2826	1.1687	1.1572
				HIGH FLOW MEAN=	0.9979	1.2750	1.1610	1.1495
				ST. DEV.=	0.0056	.0086	.0094	.0095
				OVERALL MEAN=	0.9929	1.2969	1.1527	1.1386
				OVERALL ST. DEV.=	0.0047	.0481	.0309	.0299

CORRECTIONS BASED ON JMM DVOM LOW FLOW VALUES WHERE C1=1.1115

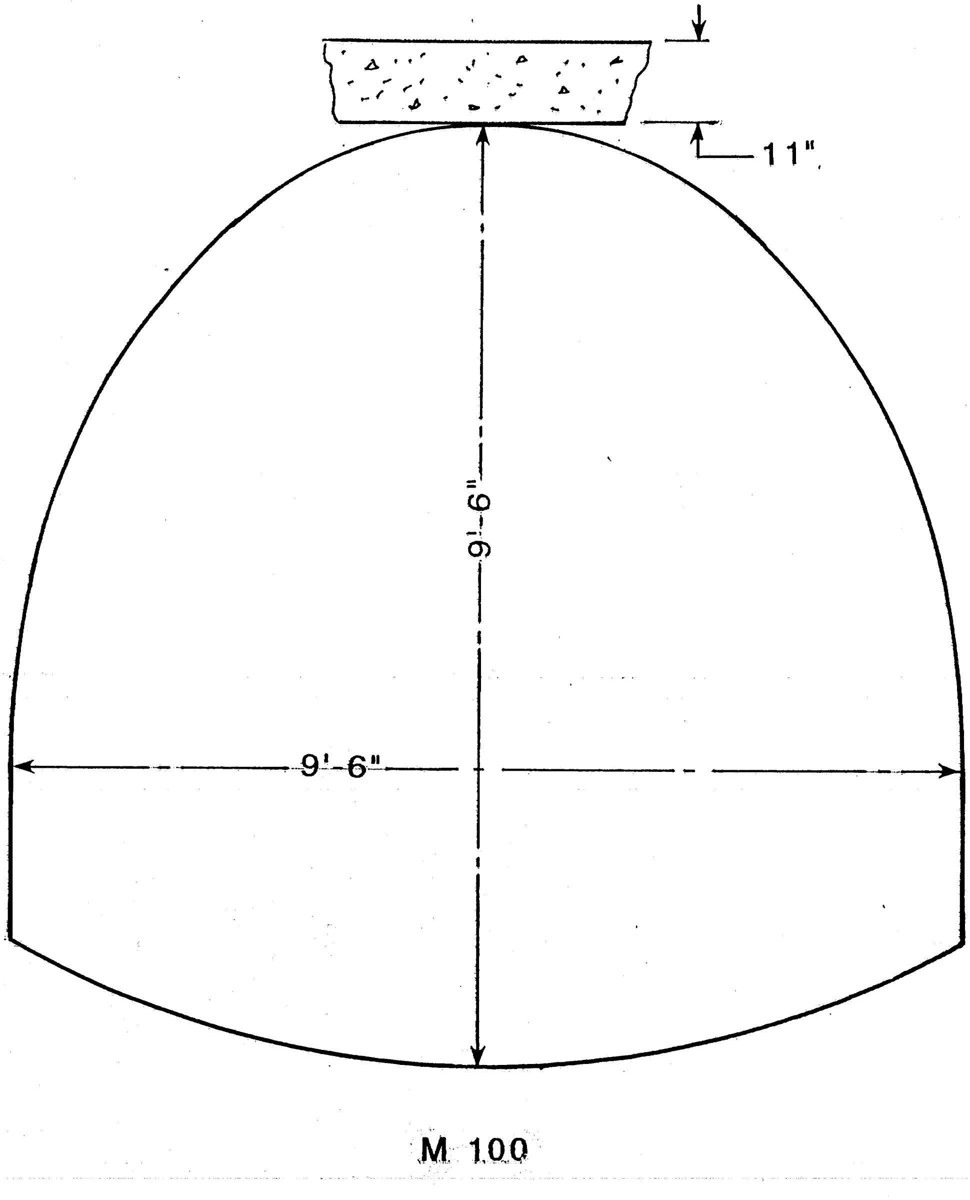

FIGURE A-1 Flow channel cross section at insertion mag meter measurement installation for M100 meters.

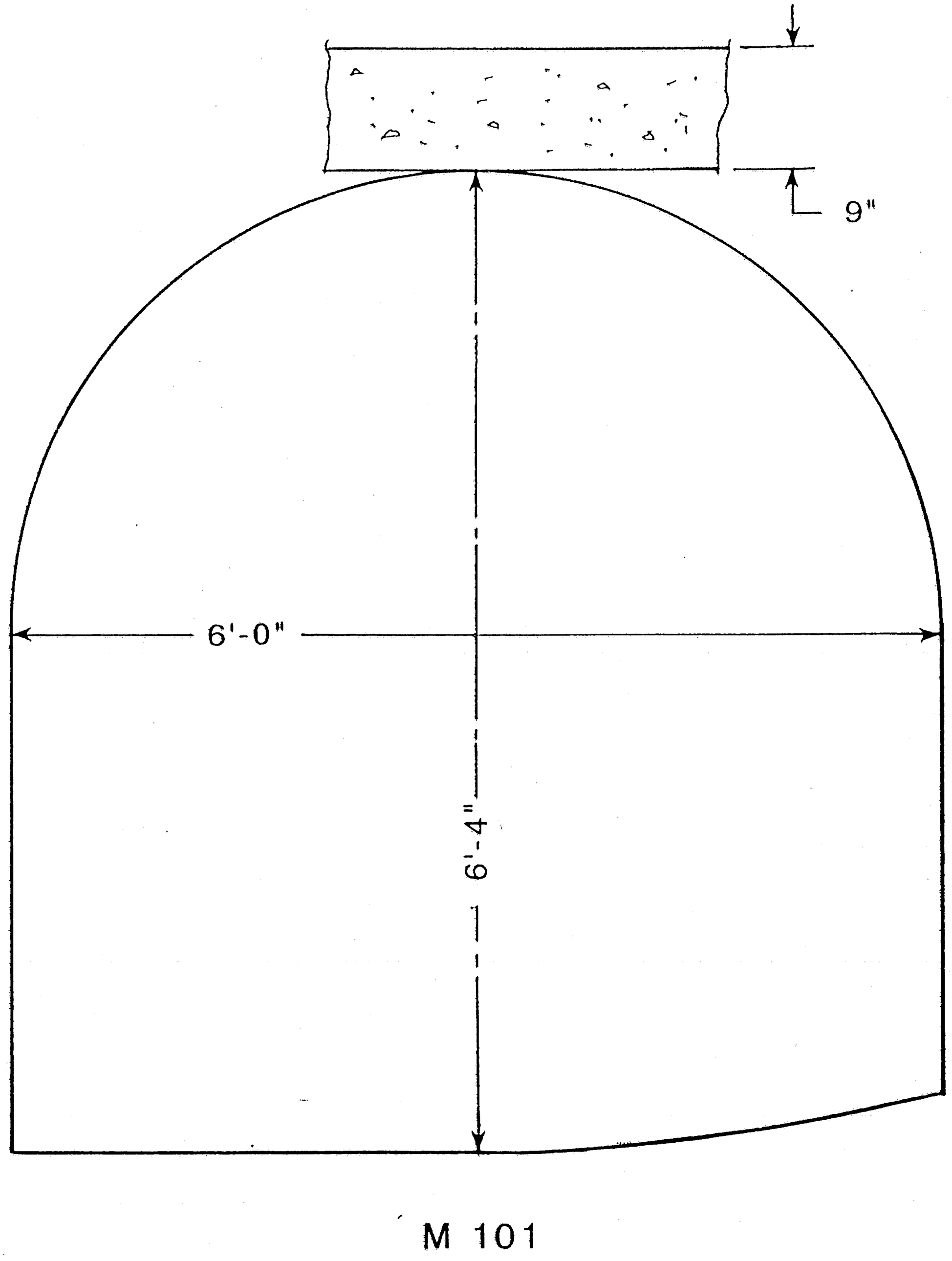

FIGURE A-2 Flow channel cross section at insertion mag meter measurement installation for M101 meters.

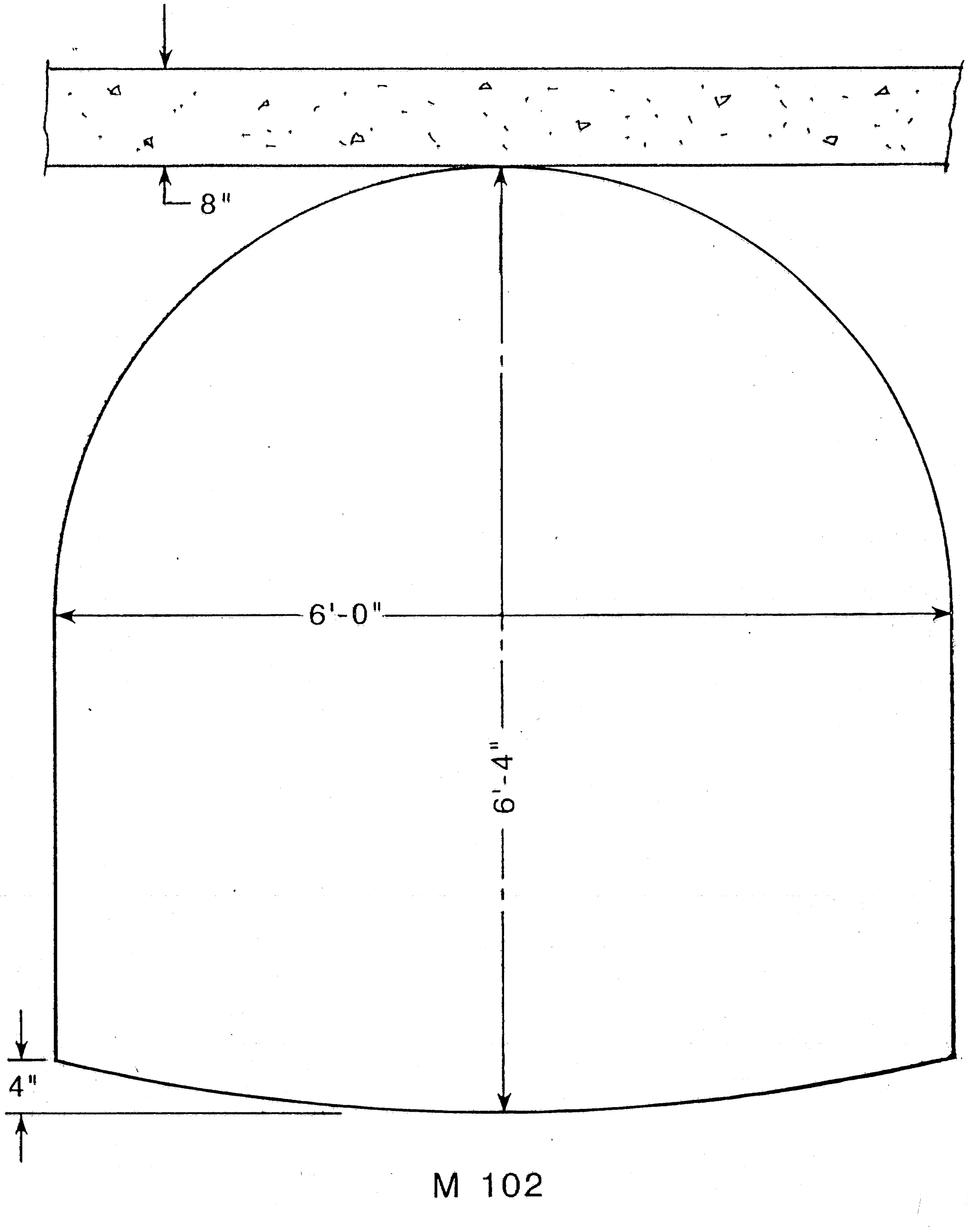

FIGURE A-3 Flow channel cross section at insertion mag meter measurement installation for M102 meters.

APPENDIX B

APPENDIX B

INSERTION MAGMETER DATA ACQUISITION PROCEDURE STEPS

1. Turn on floodlights in the tunnel accessway and at the rack location, and check depth from floor surface to channel water surface using 12 ft tape measure.

2. Unplug the Marsh–McBirney meter which has been charging since previous run.

3. Boot up "Marsh–McBirney Current–Meter Interface" program for velocity determinations.

4. With the rack hanging above the floor, place a pail (rubber) of water under the probe and submerge the meter to take zero velocity readings (taking care not to bang the probe on the side or bottom of the pail). These zeros will later be used as an adjustment to the Marsh–McBirney program readings. Be sure to use at least 200 samples/channel to get the best possible readings.

5. Measure the depth to the water surface again and, as long as there was no significant change, the flow is stable enough to proceed. Record this depth, and the time, on data sheets and determine the appropriate locations of sampling points for this size channel and the water elevation.

6. Very carefully lower the rack into the slot, taking care not to bump the magnetometer probe on the concrete, to the highest appropriate depth.

7. Run the program and record the x & y components of the velocity at that point, as well as the standard deviation of each value. As soon as possible, lower the rack to the next appropriate depth.

8. Again run the program and record the values. If you are not yet on the bottom, proceed to the next appropriate point and run the program again. After recording the final data point (bottom readings) raise the rack completely out of the water and determine whether or not any debris has become entangled with the probe. If so, remove it by brush or by hand. If it is a very considerable amount and there is any drastic change between the last two velocity readings in the column–repeat affected points.

9. Once all points in the column are complete, slide the probe 6" on the rack and repeat steps 6 thru 8. Do this for all columns needed (7 or 9–depending on channel width). Follow the pattern of 6, 12, 12, 12, 12, 6 inches for the 7–column grid and 6, 6, 12, 12, 18, 18, 18, 12, 6, 6 inches for the 9–column grid. See attached sample profiles (Figs. 3 and 4). In low flow cases where there is little problem with debris, you may find it unnecessary to clean the probe before proceeding to the next column.

10. When the grid is complete, raise the rack and again measure the depth from the floor to the water surface in order to determine the water surface elevation. Record the time at this point, the end of the run. Repeat steps 5 thru 10 until the appropriate number of runs have been completed.

11. When all runs are complete, repeat Step 4 to recheck zero. There is usually no change. Minor changes can be taken into account as each run is analyzed. Plug in meter to recharge; cover computer and other electronics to avoid water damage and condensation; and oil winches, cable, and rack to leave in tunnel until the next data acquisition period.

12. Analyze data on the appropriate GW.BASIC program developed by SAFHL (3 versions dependent on grid and channel shape). This program takes the velocity measurements at each grid point, adjusts them by the recorded zero reading, and returns a flow rate for the cross section. This is done by assigning a flow coefficient to each grid point, dependent on the area over which it is measuring (using the 1/7 power law for sidewall effects) and combining all the velocity measurements with their coefficients and the overall channel area to return a composite flow rate, as described in the text of the report.

13. Finally, and most importantly, this newly–computed flow rate must be compared to the flow measured by the Venturi meter being calibrated. To eliminate possible telemetry problems, the Venturi meters were also read on site, using a DVOM rather than relying solely on the remotely recorded values of the MWCC's regional data acquisition computer.