'96-1

NORTH AMERICAN INTER-LABORATORY FLOW MEASUREMENT TESTING PROGRAM

Umesh Karnik, NOVA Research & Technology Corporation, Calgary, CANADA.
Edgar B. Bowles, Jr., Southwest Research Institute, San Antonio, Texas, USA.
Jan Bosio, Statoil/Kärstø Metering & Technology Laboratory, Haugesund, NORWAY.
Steve Caldwell, Colorado Engineering Experiment Station Inc., Nunn, Colorado, USA.

ABSTRACT

An inter-laboratory flow measurement testing program has been established for the purpose of benchmarking individual North American facilities relative to each other and to other flow facilities in Europe. The North American laboratories involved are Colorado Engineering Experiment Station, Inc. (CEESI) in Nunn, Colorado, USA; the Gas Research Institute (GRI) Metering Research Facility (MRF) at Southwest Research Institute (SwRI) in San Antonio, Texas, U.S.A; and the NOVA Gas Dynamic Test Facility near Calgary, Alberta, Canada. Also, the Kärstø Metering & Technology Laboratory (K-Lab) in Haugesund, Norway, is directly participating in some of the North American round robin testing.

The initial inter-laboratory comparison tests involve two critical flow venturi nozzles: a NOVA nozzle (with a throat diameter of 10 mm) and a K-Lab nozzle (with a throat diameter of 23.3 mm). Tests have been conducted for a variety of compressible fluids using primary and secondary methods of flow reference. Results from both nozzles are presented for the three North American facilities and K-Lab. Test results, with the NOVA nozzle, from the National Engineering Laboratory (NEL) in Scotland are also included. Results for both nozzles indicate that, at a comparable Reynolds number, the facilities agree to within ±0.2%. Results also suggest that the uncertainty in C* may be negligible. Future North American inter-laboratory comparison plans include testing of the Groupe Européen de Recherches Gazières (GERG) G-650 tandem turbine meter transfer standard package and the EUROMET critical flow nozzle. The NOVA nozzle is also to be tested at Ruhrgas in Germany and at the Korean Research Institute of Standards and Science (KRISS) in Korea.

1.0 INTRODUCTION

In North America and elsewhere around the world, natural gas is more commonly being bought and sold as a commodity. The gas is typically bought and sold more than once between the time it is produced at the wellhead and delivered to the end user. Because large amounts of gas are involved in these transactions and the financial stakes are high, a premium is placed on accurate measurement of the gas passing through each custody transfer point along the way. As an example, the NOVA transmission and distribution system (which is only one component of the gas transportation network in North America) transports approximately $1X10^{11}$ cubic meters (or 4 trillion cubic feet) of natural gas per year.[1] Thus, the cost associated with measurement uncertainties and errors in this one system can be quite significant, and increases proportionately with increased trade.

To ensure the highest level of flow meter performance, gas producers and transport companies either flow calibrate their meters (e.g., turbine and ultrasonic flow meters) or design and build their meters according to accepted industry standards (e.g., orifice meters). In the latter case, flow meter calibrations may still be necessary, particularly when custody transfer disputes must be resolved. When flow calibrations are deemed appropriate, such tests are typically performed at facilities proven to have acceptable limits on measurement uncertainty and repeatability. At present, there are several flow calibration laboratories around the world that claim to meet these stringent performance requirements.

Mass and time can independently be measured very accurately and each can be referenced to an accepted standard. However, in the absence of a flow standard, one way of confirming that calibration laboratories can achieve acceptable measurement accuracy levels is to conduct inter-laboratory comparison tests. These inter-laboratory comparisons, or round-robin tests, involve the flow calibration of a single test artifact, such as a sonic nozzle, tandem turbine meters or other flow element, under similar test conditions at each facility. The results from the participating labs are then compared to ensure that the labs are in reasonably close agreement and that the customers of these facilities are provided with the best estimate of the true mass flow rate. Apart from providing the best estimate of the true mass flow rate, a round-robin test allows the facilities involved to identify and correct problems. Such tests must be repeated periodically so that the laboratories can preserve their measurement integrity.

Recently, several European flow calibration laboratories participated in a round-robin test of two twin-turbine meter packages conducted under the auspices of GERG (Technical monographic, 1993),. This paper presents the results of similar tests performed at CEESI, the GRI MRF, NOVA and K-Lab involving two sonic nozzles. The participating North American labs are now also testing one of the GERG twin-turbine meter packages. There is also a possibility that in the near future, these same labs will test a sonic nozzle previously tested by the EUROMET consortium.

2.0 DESCRIPTION OF FACILITIES

A comparison of the facilities that have participated in the current inter-laboratory comparison is shown in Table 1. The facilities have a similar theme i.e. measure the mass flow rate as accurately as possible. For the measurement of mass, NOVA, GRI MRF and K-Lab use a weigh tank/scale manufactured by Wöhwa as the primary device. CEESI on the other hand uses a volumetric method to measure the mass. All facilities use high accuracy timers to evaluate the mass flow. Usually, the primary method is used in conjunction with a bank of sonic nozzles for flow stability. The nozzle bank used at GRIMRF and K-Lab is designed as a binary system. Nozzles with different throat diameters are used and can be choked in various combinations to obtain the chosen mass flow. The NOVA system is different in this regard. The nozzles in the nozzle bank are all identical and thus the flow rate can be increased in equal steps with the opening of each nozzle. CEESI does not have a bank of sonic nozzles, but uses a CEESI standard nozzle appropriate for the test. The facilities compare well with regards to calibration techniques and instrumentation for pressure, temperature, gas composition (CEESI uses air) and other parameters necessary for mass flow measurement.

The following sections provide a description of the individual facilities.

2.1 Colorado Engineering Experiment Station Inc.

A simplified operational schematic is contained in Figure 1. Air can flow out of one of two pressure vessels, they are identified as "calibration" and "supply". For the calibration vessel there is a known relationship between volume and pressure; at atmospheric pressure the volume is approximately 8.5 m^3. The maximum pressure in the test section ranges between 7 and 70bar. The vessel is instrumented for the measurement of pressure and temperature (P_3 and T_3) hence the mass of air within the vessel can be determined. The supply vessel is a series of tanks with total volume of approximately 312m^3 and maximum pressure capability of 170bar. The pressure vessel providing air flow to test section can be selected based on the position of a three way valve (V_2).

A pair of critical flow nozzles are installed in the test in series, one is the unit under test, the other is a CEESI standard used as a calibration check. The availability of a particular CEESI standard nozzle determines the installation details, the downstream unit must have the larger throat diameter of the two. A control valve (V_3) is located at the test section inlet to provide for flow control. Each nozzle is provided with pressure and temperature measurements (P_1, T_1, P_2 and T_2).

When the air expands as it flows through the system, the temperature will drop. If cool air flows through a warm pipe an air temperature measurement will be subjected to errors due to conductive and radiative heat transfer. To reduce such errors heat exchangers are installed downstream of each control valve, they are not shown in Figure 1. The heat exchangers are designed to maintain the air flow at ambient room temperature.

The mass flow is measured on the basis of measured pressure and temperature (P_3 & T_3) and knowing the volume of air in the calibration vessel. The uncorrected average mass flow rate is defined as the change of mass within the calibration vessel divided by the elapsed time. A small correction must be made to account for the air contained within the pipes and fittings that connect the calibration vessel and test section. The uncertainty in mass flow rate is estimated to be 0.1% at a 95% confidence level. Additional details regarding the operation and uncertainty of the present and a similar system are given by Arnberg and Britton (1971) and Kegel (1995).

The volume and maximum pressure of the calibration vessel limit the maximum flow rate to a value of approximately 4.0 kg/s. In order to obtain data at higher values of mass flow rate a CEESI nozzle is used as a calibration standard. The relationship between Re and C_d is determined based on the work of Smith and Matz (1962), Strattford (1964) and Arnberg, Britton and Seidl (1974). The uncertainty in the resulting mass flow rate is estimated to be 0.5% at a 95% confidence level (Kegel, 1994).

2.2 Gas Research Institute Metering Research Facility

The Gas Research Institute Metering Research Facility is operated by Southwest Research Institute and is located on the grounds of SwRI in San Antonio, Texas, U.S.A. The GRI MRF consists of three separate flow facilities: a High Pressure Loop (HPL), a Low Pressure Loop (LPL) and a Distribution Test Stand (DTS). All three flow facilities use either dry natural gas or nitrogen as the test medium. The HPL is the largest of the three flow systems and has the highest rated flow capacity and line pressure. The LPL is similar in configuration to the HPL, but is smaller in scale and operates at lower flow rates and line pressures. Both the HPL and LPL are closed-loop, continuous-flow facilities. The DTS is the smallest of the three flow systems at the MRF and is configured as a blowdown system. The inter-lab tests described herein were performed only in the HPL and LPL. The operating parameters for the HPL and LPL are included in Table 1.

Each MRF flow facility has a primary calibration system specifically sized for its range of operation. These primary mass flow standards are gravimetric systems. The HPL and LPL gravimetric systems both feature gyroscopic force balances that are believed to be the most sensitive weighing systems available for this application. The capacity of the HPL weigh scale is 1,000 kilograms. The total uncertainty of the HPL scale is ±0.021 kilogram or ±0.0021 percent of full scale. The total estimated uncertainty in the measured mass flow rate for the HPL primary calibration system is ±0.02 to ±0.04% at a 95% confidence level. The capacity of the LPL weigh scale is 155 kilograms. The total uncertainty of the LPL weigh scale is ±0.010 kilogram or ±0.006 percent of full scale. The total estimated uncertainty in the measured mass flow rate for the LPL primary calibration system is ±0.01 to ±0.04% at a 95% confidence level. The weigh scales are calibrated using Class F mass standards traceable to the National Institute of Standards and Technology (NIST) of the United States.

As noted above, both the HPL and LPL are re-circulating flow loops. When a primary flow calibration is performed using either of these flow loops, gas flow from the re-circulating portion of the loop is diverted to the primary calibration system weigh tank. Gas is collected in the weigh tank during a precisely measured time interval. The weight of the gas collected is then accurately measured and the mass flow rate is determined. In order to maintain constant flow conditions in the test section of either the HPL or LPL during a primary calibration run, gas must be added to the re-circulating portion of the loop at the same rate that it is diverted to the weigh tank. Therefore, both the HPL and LPL are fitted with gas storage bottles that are used to supply makeup gas to the test loop at the same rate gas is diverted to the weigh tank. Special, fast-acting hydraulically-powered diverter valves in both the HPL and LPL are used to control the flow of gas to the weigh tank and from the makeup bottles. The weigh tank diverter valves have a switching time of 50 milliseconds. A schematic of the basic HPL primary calibration system is provided in Figure 2. The configuration of the LPL is similar to that of the HPL, although the weigh tank, piping, control valves, and flow elements are of smaller capacity.

The primary calibration systems in the three MRF flow facilities are used to routinely calibrate secondary or transfer flow calibration standards. For the HPL and LPL, the secondary standards consist of ASME/ANSI MFC-7M critical flow nozzles and industrial turbine meters. The estimated total uncertainty in sonic nozzles calibrated using the primary standards is less than ±0.2%.

To determine test gas composition, the MRF has a fully-automated, laboratory-grade Hewlett-Packard Model 5890 Series II gas chromatograph (GC) that has been modified to perform an extended C_{10+} hydrocarbon analysis through capillary column separation and flame ionization detection (FID), in conjunction with packed column separation and thermal conductivity detection (TCD) of inorganic compounds. The packed columns are arranged to separate oxygen from nitrogen to allow for the verification of complete loop purges.

With regard to the measurement accuracy of the MRF GC, the precision limit for a high-quality methane sample was measured as ±0.04 mole-percent (95 percent confidence). Gas density and gas properties are calculated using the composition data and the detail characterization method in American Gas Association Report No. 8 ("Development of Improved Capabilities for Computation of Gas Supercompressibility Factors and Other Properties," 1985).

The mass flow rate is determined from a combination of the mass collected in the weigh tank, the measured valve diversion time and corrections to account for mass storage in the interconnect piping between the nozzles and the weigh tank (Park, et al., 1995). The nozzle discharge coefficient is calculated from the ratio of the theoretical mass flow rate to that of the weigh tank system. The theoretical mass flow rate is based on the measured gas composition, plenum temperature and pressure, and is calculated by the SUPERZ program (Savidge, 1989) which incorporates A.G.A.-8 density calculations and additional thermodynamic equations of state to determine the critical flow at the nozzle throat.

Additional details about the MRF can be found in a GRI report by Johnson, et al. (1992) whereas information about MRF measurement uncertainties can be found in papers by Behring (1994) and Park, et al. (1995).

2.3 Kärstø Metering and Technology Laboratory

K-Lab, standing for Kärstø Metering & Technology Laboratory, is a test and calibration laboratory owned by Statoil, located in Norway, operating in natural gas in the pressure range 1 MPa to 15 MPa, in a closed loop mode, with a gravimetric primary calibration system installed on a by-pass to the test line, as shown on Figure 3. The primary calibration system is the basics in the traceability chain for calibrations at K-Lab. The facility is traceable to the *Bureau international des Poids & Mesures* (BIPM). K-Lab is accredited by the National Measurement service and has a quality system in accordance with EN-45001 and ISO/IEC Guide 25.

The primary calibration system, shown on Figure 4, consists of a 3" diverter valve with a closing time less than 30 ms enabling the gas to be filled into a 5.5 m^3 spherical tank installed on a gyroscopic force balance. The amount of gas to be filled into the tank may vary between approximately 40 kg and 600 kg depending on the operating pressure with a corresponding filling time between 40 and 400 sec.

The discharge coefficient, C_d, of the sonic nozzle is calculated using the general equation from ISO-9300. The critical flow function, C*, is computed from SONFLOW, a specially developed software for calculation of thermodynamic and dynamic properties of natural gas (Weberg, 1988)

The calibrations took place at stagnation temperatures of approximately 37° C and in the pressure range, 2 MPa to 10 MPa, corresponding to Reynolds from 3×10^{6} to 2×10^{7}. The 2σ, on the discharge coefficient; C_d , is less than ±0.2%.

2.4 NOVA Gas Dynamic Test Facility

The NOVA Gas Dynamic Test Facility has been described in several publications in the past (Studzinski et al, 1994 and Williamson et al. ,1995). A sketch of the layout of the test facility is shown in Figure 5. and details of the nozzle bank/gravimetric prover are shown in Figure 6. The facility test loop draws natural gas from the mainline by means of a Solar compressor. This gas, after flowing through the test loop, is then re-injected back into the mainline. Thus, the static pressure and temperature are governed by prevailing conditions in the mainline and there is no need for a cooling system to maintain temperature stability. The static pressure is typically around 6000 kPa and the total flow that can potentially be measured with the 24 sonic nozzles is around 23kg/s. However, with the current compressor, only 14 nozzles can be choked resulting in a capacity of around 13kg/s.

The NOVA meter prover consists of a bank of 24 identical (10mm throat diameter) sonic nozzles and a gravimetric component which includes a Wöhwa gyroscopic scale and a $3.2m^3$ spherical pressure vessel. Gas flow from one nozzle is directed to the gravimetric component where the mass flow for that one nozzle is determined by measurement of mass and time. The total pipe mass flow is thus equal to the mass flow of the diversion nozzle multiplied by the number of choked nozzles. This process eliminates the effect of gas composition on the uncertainty of the discharge coefficient. This method is unique and differs from methods used in other facilities. The overall uncertainty, in mass flow, for such a mode of operation, as evaluated by Williamson et al. (1995) is between 0.13% and 0.16% depending on the number of nozzles being choked. This mode of operation is time-consuming and limits the number of tests that can be conducted on a given day.

The prover can also be operated by using the nozzle bank alone. For example, a historical discharge coefficient can be obtained for the diversion nozzle using the gravimetric component. Since all nozzles are manufactured to be identical, this can be assumed to be the discharge coefficient for all the nozzles. Thus, the total flow can be measured by knowing the number of nozzles being choked. This mode of operation allows more tests to be conducted in a given day. However, the uncertainty associated with such a procedure was rated to be 0.25%

assuming negligible uncertainty in C^* (see Williamson et al., 1995). Majority of the uncertainty is attributed assumption that all the nozzles are identical. The possible variations in the nozzle diameters and discharge coefficients have since been quantified and thus, the uncertainty in using the procedure of the nozzle bank alone is be reduced to less than 0.2%.

The test facility is also equipped with a 102.26mm orifice meter located downstream of a 76D honed, unflanged section of pipe. This meter serves as a secondary method of calibration. Further, the facility includes an 202.7mm orifice meter run located in ideal flow conditions which can also be used as a secondary transfer standard.

Instrumentation includes smart pressure and temperature transmitters for measuring the static pressures, differential pressures and temperatures. The pressure transmitters (±0.1% and better) are calibrated by means of a dead weight tester whereas the temperature transmitters (±0.1deg.C) are calibrated with a dry block calibrator using a NIST traceable high precision platinum RTD as a reference. Gas composition was measured by using a Daniel gas chromatograph.

3.0 EXPERIMENTAL RESULTS

3.1 The NOVA Nozzle

The 10mm NOVA nozzle (shown in Figure 7) is a nozzle from the NOVA meter prover sonic nozzle bank. The design of this nozzle is unlike that described in conventional standards. There exists an intentional step change in the diameter at the throat. This step prevents the possibility of downstream disturbances propagating upstream through the boundary layer to the nozzle throat. Thus, the discharge coefficient curve for this nozzle may differ from those resulting from the use of conventional nozzle geometries.

At the NOVA facility, the NOVA nozzle was placed in the diversion slot of the nozzle bank and was calibrated with the weigh scale at a typical throat Reynolds Number of around $1x10^7$. This nozzle was calibrated in air by NEL and CEESI. The former using a primary standard and the latter using a primary and secondary standard. Calibrations by K-Lab were performed with natural gas using a primary standard. At the GRI MRF, calibrations were performed with nitrogen and natural gas in the LPL and with natural gas in the HPL with a primary standard as the reference.

Results of tests are shown in Table 2. and Figure 8. The results indicate that data from GRIMRF, K-Lab and NEL are in good agreement but differ from the 1994 CEESI/NOVA data by around 0.2% at a Reynolds number of $1x10^7$. Considering the time interval between the calibrations, the nozzle was re-calibrated by CEESI and NOVA in September 1996. CEESI were able to obtain one primary calibration whereas NOVA obtained 6 calibration points. For the data collected in 1996, the agreement between all facilities is well within ±0.1%. The 1994 calibrations fall within the ±0.2% bounds of the 1996 calibrations.

3.2 The K-LAB Nozzle

The K-Lab nozzle is a 23.293mm toroidal nozzle built in accordance with the requirements of ISO-9300 and is shown in Figure 9. Results of calibrating this nozzle are shown in Table 3. and Figure 10.

At the NOVA Facility, this nozzle was calibrated in location A, shown in Figure 5, downstream of the proving device. Since the design of the facility does not permit the choking of nozzles in series, a transfer standard is used in the calibration of the K-Lab nozzle. This secondary calibration was performed by using a 202.7mm orifice meter placed in ideal flow conditions using a β-ratio of 0.3132. The calibration of the orifice meter was performed on the same day as the calibration of the K-Lab nozzle. The meter factor for the orifice meter had a 2σ=0.05%. The resulting calibration of the nozzle (12 points) at a throat Reynolds number of around 24×10^6 is around 0.9972±0.1%. In the case of the other facilities the GRI MRF utilized the HPL using natural gas and K-Lab also performed the calibrations with natural gas. Both facilities used primary standards for the reference. CEESI performed the calibrations with air using primary and secondary standards.

It is clear from Table 3. and Figure 10 that the agreement between the facilities, at a Reynolds number of 24×10^6 , is excellent (within ±0.1%). The entire curve is fitted with a 2nd order regression curve and except for a few outliers, all the data falls within ±0.2% of this curve. The K-Lab data are well represented by the "offset" curve from ISO 9300. The data are within the ±0.5% limits of ISO9300.

4.0 DISCUSSION AND CONCLUSIONS

For the NOVA nozzle, recent calibrations of the GRI MRF, K-Lab and NEL measured a discharge coefficient which is 0.2% greater than that measured in the 1994 calibrations by NOVA and CEESI at a throat Reynolds number of 1×10^7. In general, inter-laboratory comparisons that agree to within ±0.2% are considered to be excellent. The GERG program (1993), for example, which consisted of several European laboratories, reported an agreement to within ±0.25%.

The 0.2% difference in the case of the NOVA nozzle could possibly be explained by the observation that the calibrations of NOVA and CEESI were performed in 1994 and those of GRI MRF, NEL and K-Lab were performed in late 1995 and early 1996. Therefore, the NOVA nozzle was re-calibrated at the CEESI and NOVA facilities. Recalibration of the nozzle at the NOVA (6 points) and CEESI (1 point) facilities indicates that the nozzle discharge coefficient has indeed changed. The 1996 data for all facilities now agree to within ±0.1% of the mean value of the discharge coefficient.

The reasons for the change in discharge coefficient is unknown. Although there was some damage to the external diameter at the inlet, there was no significant damage on the inlet surface or the throat of the nozzle. In the case of the NOVA facility, calibrations on another identical nozzle over the past 2 years have resulted in data that are within ±0.1% of the mean. Thus, there does not appear to be a plausible reason for the shift in discharge coefficient. In any event, an agreement to within ±0.2% between facilities is excellent. This experience (variations with time interval) only emphasizes the need for frequent inter-laboratory calibrations.

The inter-laboratory agreement seen with measurements taken with nitrogen, air and natural gas as the fluids suggests that the uncertainty in C^* is not as severe as previously thought (Studzinski et al., 1988 and Erdal et al., 1992). This observation was also made by Williamson et al. (1995), but, it was thought to be pre-mature since data existed from only two facilities (NOVA and CEESI). However, with the present data in hand from several facilities using fluids such as air, nitrogen and natural gas and two different artifacts, this belief could in fact be a reality. One may be tempted to make a stronger statement that the uncertainty in C^* is negligible.

Conclusions from this program can be summarized as follows :

1. Within the stated measurement uncertainty and repeatability of the participating facilities, the agreement (within ±0.2% of the mean) between the facilities involved in the present tests is excellent.
2. The agreement between the facilities for various test fluids (air, natural gas and nitrogen) and two separate artifacts, suggests that the uncertainty in C^* is negligible.

It is recommended that this program be continued so that the quality of the facilities can be maintained and variances in measurements can be minimized. Future plans include the testing of the EUROMET nozzle and the 150mm GERG turbine meter transfer standard package at the three North American facilities and the testing of the NOVA nozzle by Ruhrgas (Germany) and KRISS (Korea).

5.0 ACKNOWLEDGMENTS

The authors would like to acknowledge the contributions of Tom Kegel in the preparation of the description of the CEESI facility. The support of NOVA Gas Transmission Limited and GRI and their permission to publish this document is also acknowledged.

6.0 REFERENCES

1. "Development of Improved Capabilities for Computation of Gas Supercompressibility Factors and Other Properties," A.G.A. Report No. 8, American Gas Association, Arlington, Virginia, USA, 1985.
2. "Natural Gas Critical Mass Flow Computations". Weberg, Trond, Thesis. The Norwegian Institute of Technology 1988. ISBN 82-7119-074-1
3. GERG Technical Monograph, 1993, "Intercomparison Exercise of High Pressure Test Facilities within GERG", also presented at the 3rd International Symposium on Fluid Flow Measurement, San Antonio.
4. Arnberg, B.T. and Britton, C.L., 1991, "Two Primary Methods of Proving Gas Flow Meters", Symposium on Flow : Its Measurement and Control in Science and Industry.
5. Arnberg, B.T., Britton, C.L. and Seidl, W.F., 1974, "Discharge Coefficient Correlations for Circular-Arc Venturi Flowmeters at Critical (Sonic) Flow", ASME Journal of Fluids Engineering.
6. Kegel, T., 1994, "Uncertainty Analysis of a Compressible Flowmeter Calibration Process", ASME Forum on Fluid Flow Measurement Uncertainty.
7. Kegel, T., 1995, "Uncertainty Analysis of a Volumetric Primary Standard for Compressible Flow Measurement", 3rd International Symposium on Fluid Flow Measurement, San Antonio.
8. Smith, R.E. and Matz, R.J., 1962, "A Theoretical Method of Determining Discharge Coefficients for Venturis Operating at Critical Flow Conditions", ASME Journal of Basic Engineering.
9. Strattford, B.S., 1964, "The Calculation of the Discharge Coefficient of Profiled Choked Nozzles and the Optimum Profile for Absolute Air Flow Measurement", Journal of the Royal Aeronautical Society.

10. Studzinski, W., Williamson, I.D., Jungowski, W, Botros, K.K., Sawchuk, B.D. and Strom, V. "Nova's Gravimetric Meter Prover and Sonic Nozzle Facility", CGA Gas Measurement School, Banff, Alberta (1994).

11. Williamson, I.D., Sawchuk, B.D. and Karnik, U. "The NOVA Meter Prover", 3rd International Symposium of Fluid Flow Measurement, San Antonio, USA (1995).

12. Studzinski, W., Weiss, M.H. and Botros, K.K. "Critical Flow Factor for Natural Gas", 2nd International Conference on Flow Measurement, London, U.K., 1988.

13. Erdal, A., Cabrol, J.F., Bosio, J., Thomassen, D. and Weberg, T. "Analysis of Calibration data from K-Lab for prediction of sonic nozzle discharge coefficients and critical flow functions" Proceedings of 11th International Conference on Offshore Mechanics and Arctic Engineering, Calgary, 1992, VolA. Part A, pp39-45.

14. Park, J.T., Behring II, K.A. and Grimley, T. A., 1995, "Uncertainty Estimates for the Gravimetric Primary Flow Standards of the MRF," Proceedings of the 3rd International Symposium on Fluid Flow Measurement, San Antonio.

15. Savidge, J., 1989, "SUPERZ Extended Thermodynamic Properties Computer Program," Gas Research Institute.

16. Johnson, J.E., Bowles, Jr., E.B., Buckingham, J.C., Harrell, P.J., McKee, R.J. and Sparks, C.R., 1992, "Metering Research Facility Design," Topical Report (July 1987-December 1990), Gas Research Institute Report No. GRI-91/0251, March 1992.

17. Behring II, K.A., 1994, "Application of Uncertainty Analysis in the GRI Metering Research Facility," American Society of Mechanical Engineers Winter Annual Meeting, Chicago, IL, November 6-11, 1994.

Facility	Primary Standard	Fluid	Operating Pressure kPa	Facility Flow Capacity Kg/s	Uncertainty in Mass Flow	Secondary Standards
NOVA	Gravimetric Wöhwa Scale	Natural Gas	≈6000	primary : 1 secondary : 23	primary:±0.16% secondary:±0.25%	Nozzles, Orifice, Turbin
GRIMRF LPL	Gravimetric Wöhwa Scale	Nitrogen Natural Gas	140 to 1450	primary : 1.9 secondary : 2.4	primary:±0.04% secondary:±0.2%	Nozzles, Orifice, Turbin
GRIMRF HPL	Gravimetric Wöhwa Scale	Nitrogen Natural Gas	1035 to 8275	primary : 29 secondary : 44	primary:±0.04% secondary:±0.2%	Nozzles, Orifice, Turbin
CEESI	Gravimetric and Volumetric	Air, other gases & gas mixtures	Atm. to 9500	primary : 8 secondary :100	primary:±0.1% secondary:±0.5%	Sonic Nozzles
K-Lab	Gravimetric Wöhwa Scale	Nitrogen Natural Gas	2000 to15000	0.2 to 78	±0.3%	Sonic Nozzles Turbine

Table 1. Comparison of Facilities

Facility	Throat Reynolds No.	C_d	Deviation from Regression	Date of Calibration	Fluid
NOVA	$\approx 10x10^6$	0.9903	-0.21%	Jul-Nov '94	Natural Gas
	$\approx 10x10^6$	0.9920	-0.04%	Sept. 1996	Natural Gas
CEESI (eqn.)	$10x10^6$	0.9902	-0.22%	April 1994	Air
	$8.6x10^6$	0.9919	-0.05%	Sept. 1996	Air
SwRI	$\approx 10x10^6$	0.9925	0.01%	Sept. 1995	Natural Gas Nitrogen
NEL	$\approx 10x10^6$	0.9920	-0.04%	March 1996	Air
K-Lab	$\approx 10x10^6$	0.9926	0.02%	July 1996	Natural Gas
Regression Average	$10x10^6$	0.9924			

Table 2. Interfacility Comparisons of Calibrations of NOVA Nozzle

Facility	C_d	Deviation from Regression	Date of Calibration	Fluid
NOVA	0.9972	-0.01%	Jan. 1996	Natural Gas
CEESI	0.9982	0.09%	April 1996	Air
SwRI	0.9966	-0.06%	June 1996	Natural Gas Nitrogen
K-Lab	0.9970	-0.03%	Sept. 1996	Natural Gas
Regression Average	0.9973			

Table 3. Interfacility Comparisons of Calibrations of K-Lab Nozzle at a throat Reynolds Number of $24x10^6$.

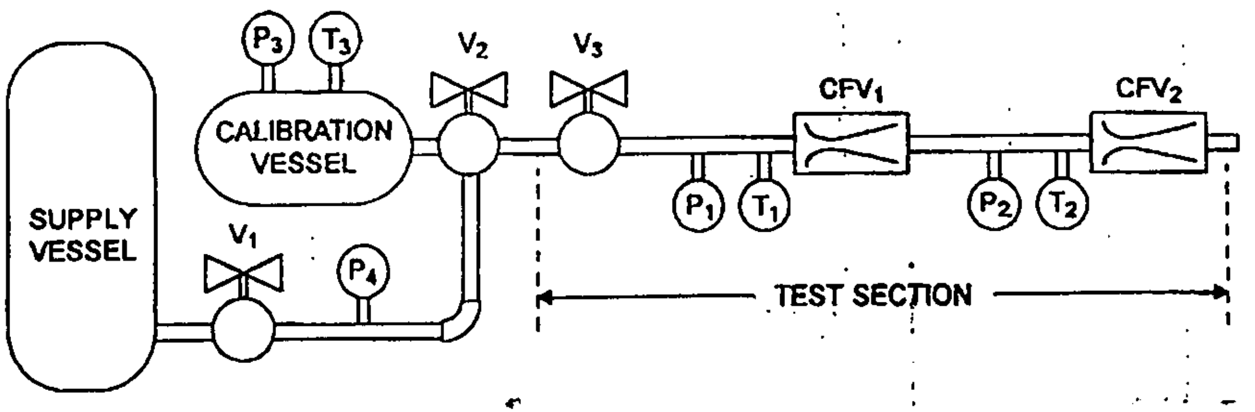
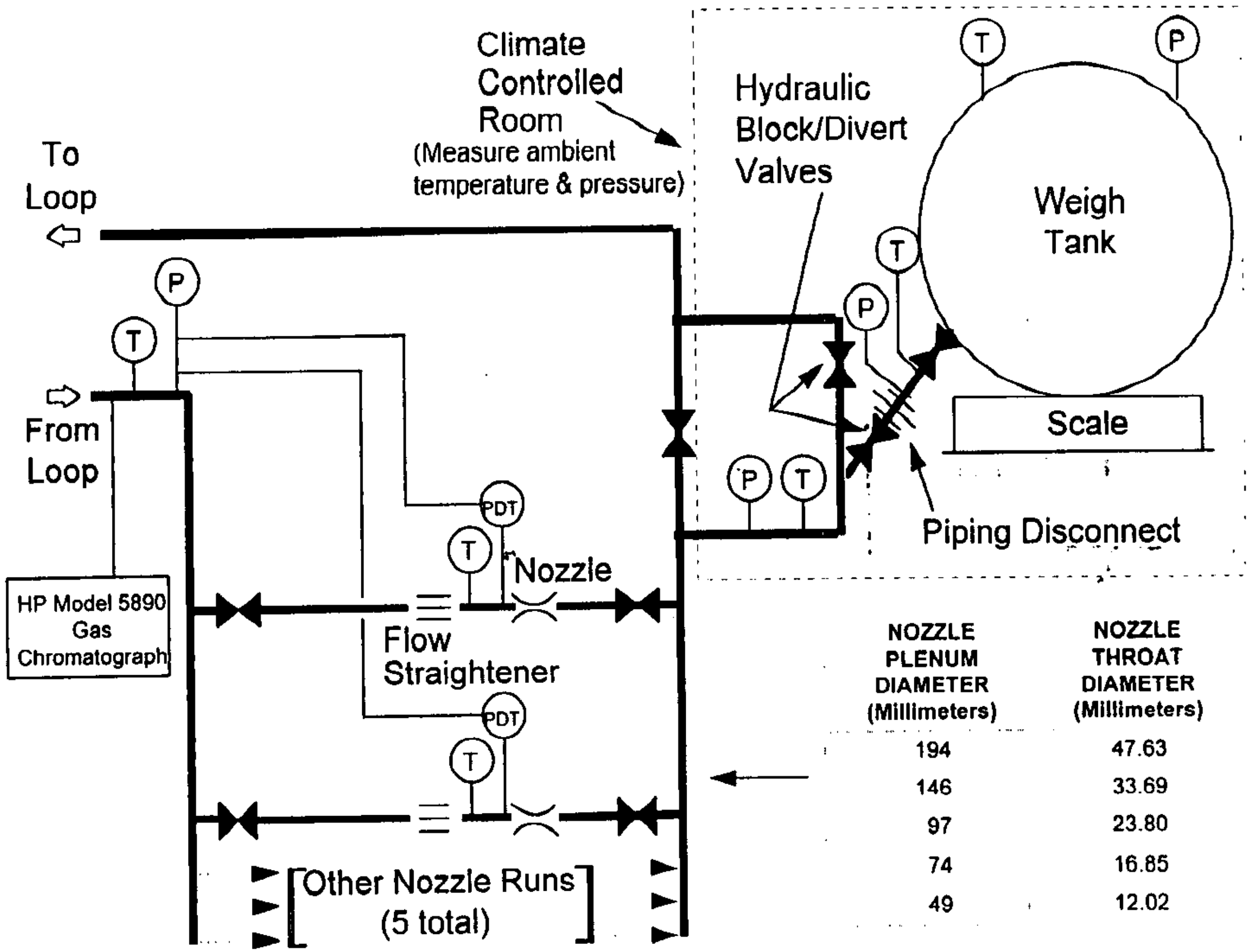


Figure 1. Operational Sketch for the CEESI Facility



NOZZLE PLENUM DIAMETER (Millimeters)	NOZZLE THROAT DIAMETER (Millimeters)
194	47.63
146	33.69
97	23.80
74	16.85
49	12.02

Figure 2. GRI Metering Research Facility Schematic of the High Pressure Loop (HPL) Weigh Tank System.

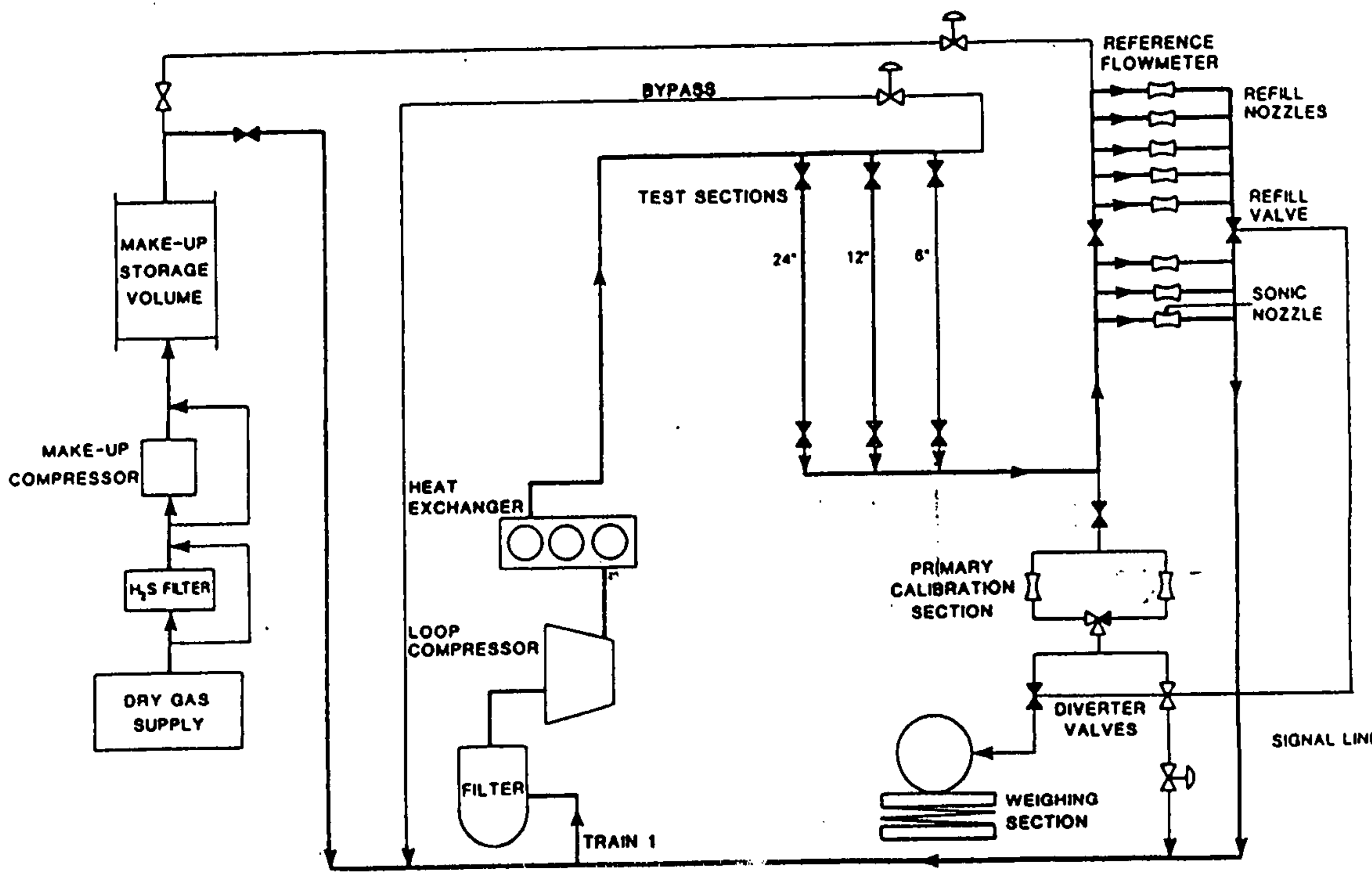


Figure 3. Schematic Layout of K-Lab Test Loop

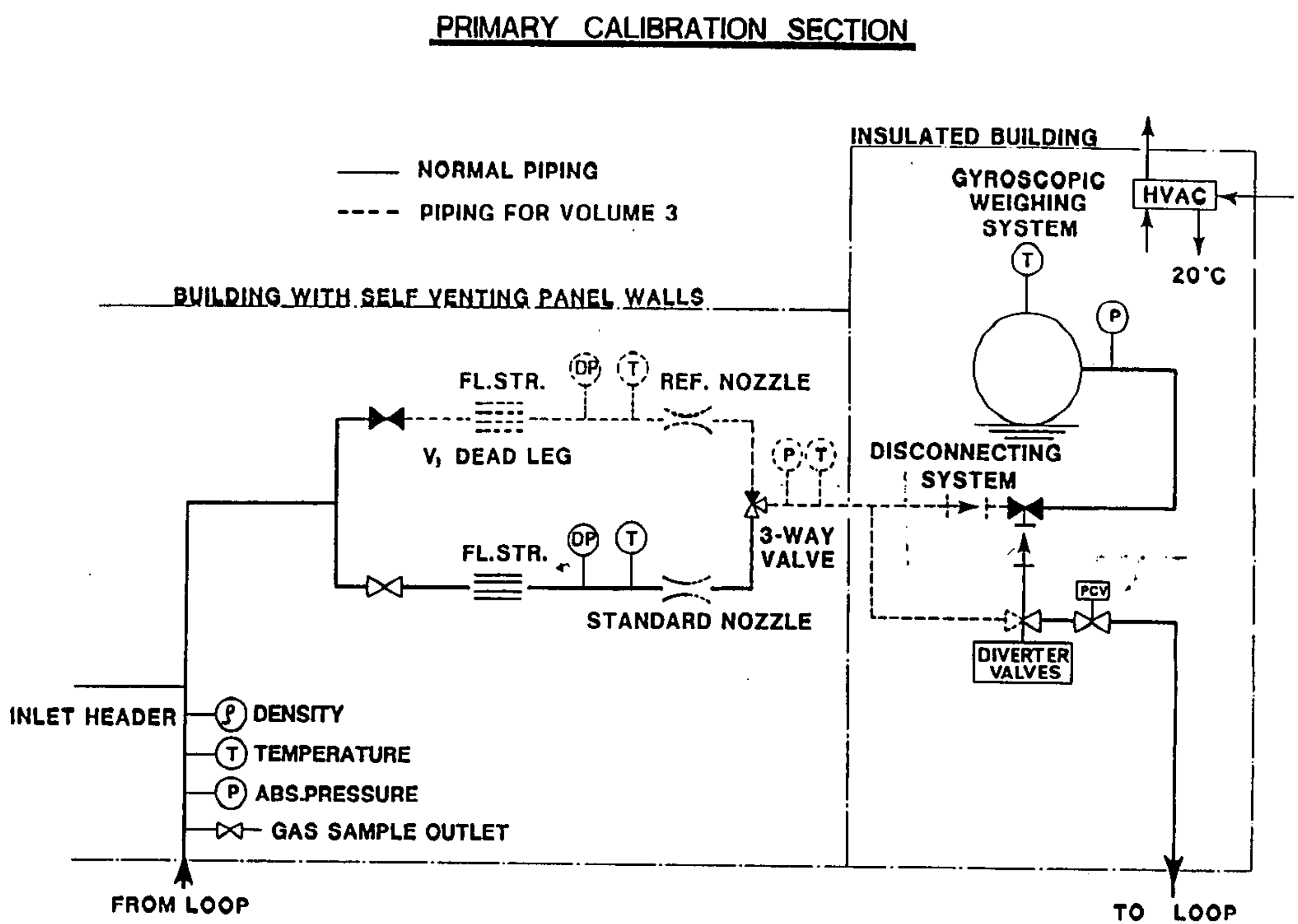


Figure 4. K-Lab Primary Calibration Section

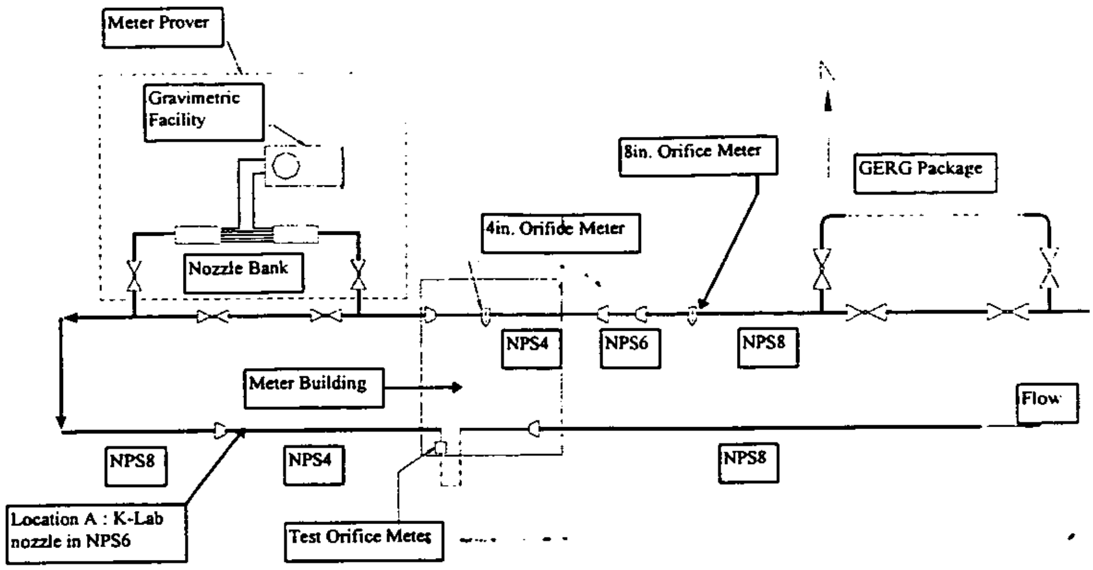


Figure 5. Schematic Layout of the Test Facility

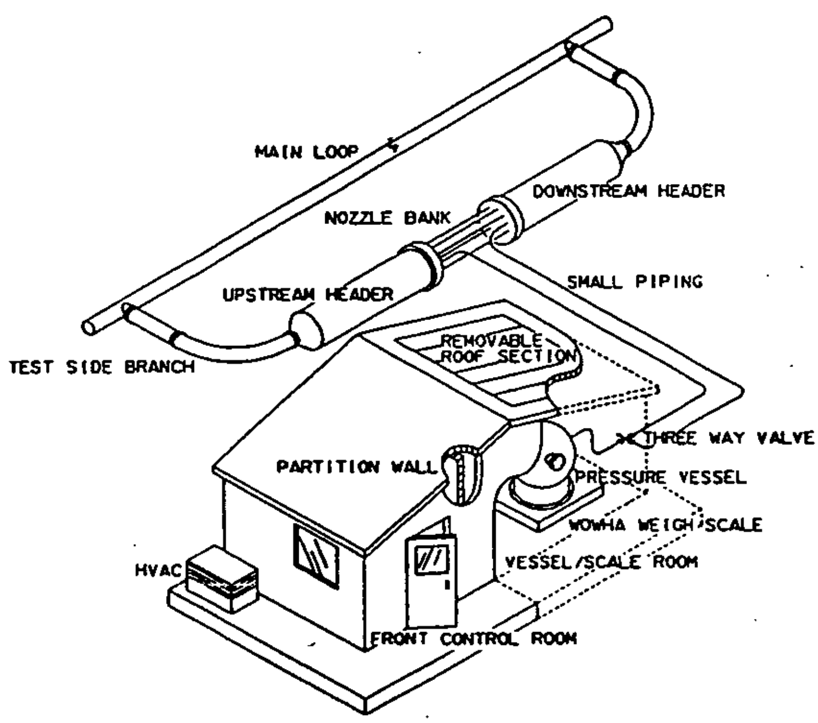


Figure 6. Components of the NOVA Meter Prover

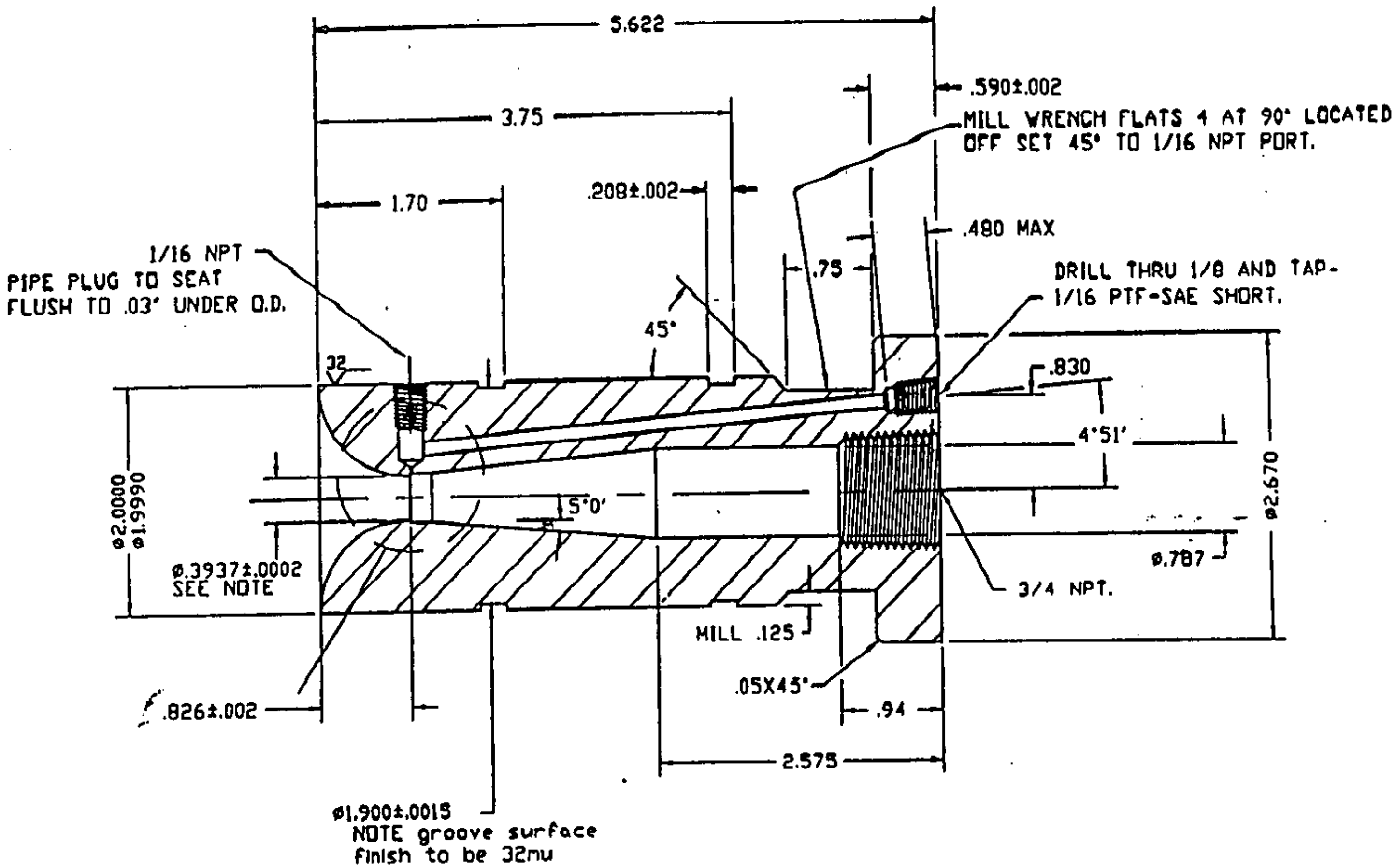


Figure 7. The NOVA Nozzle

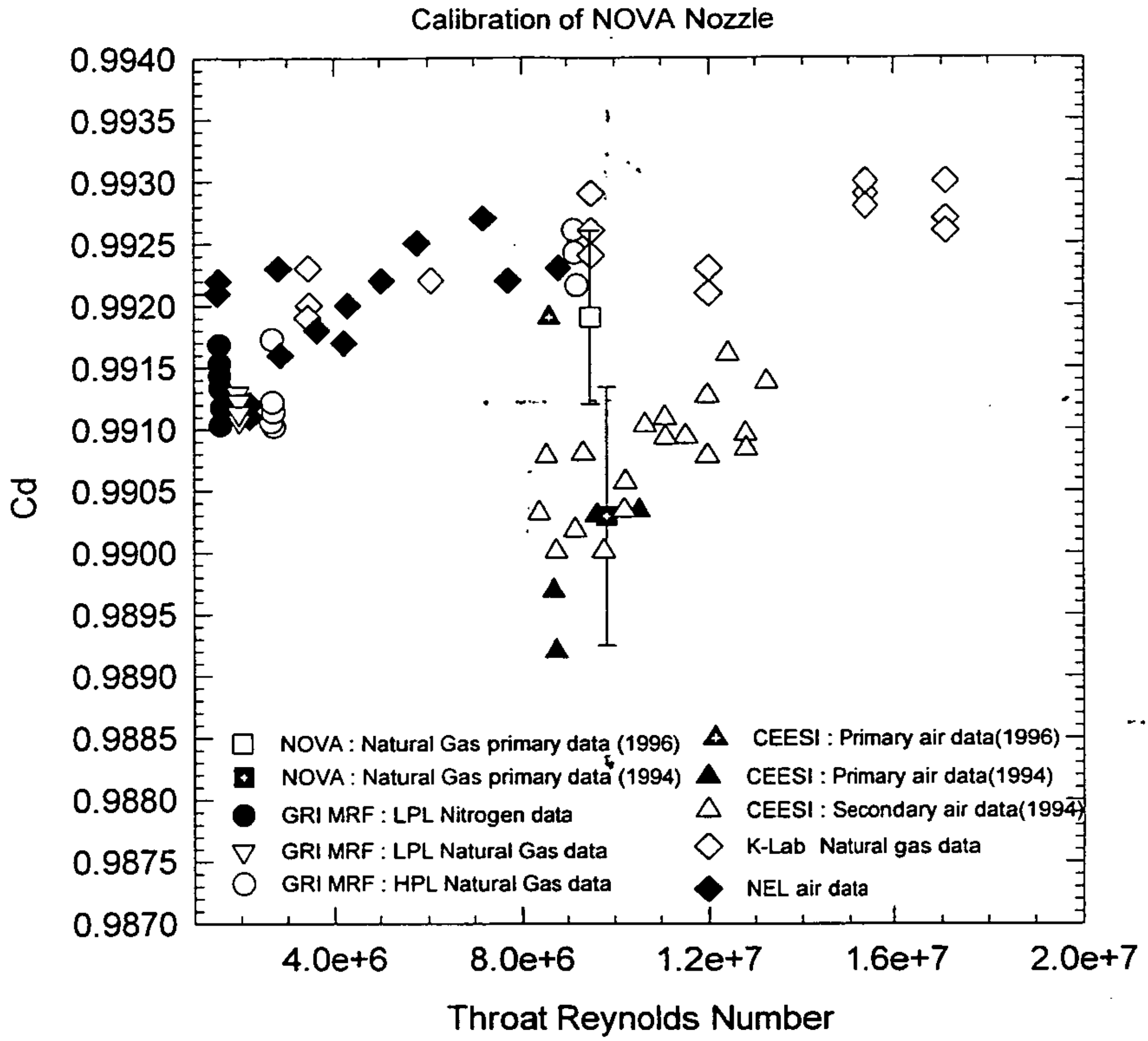


Figure 8. Calibration of NOVA Nozzle

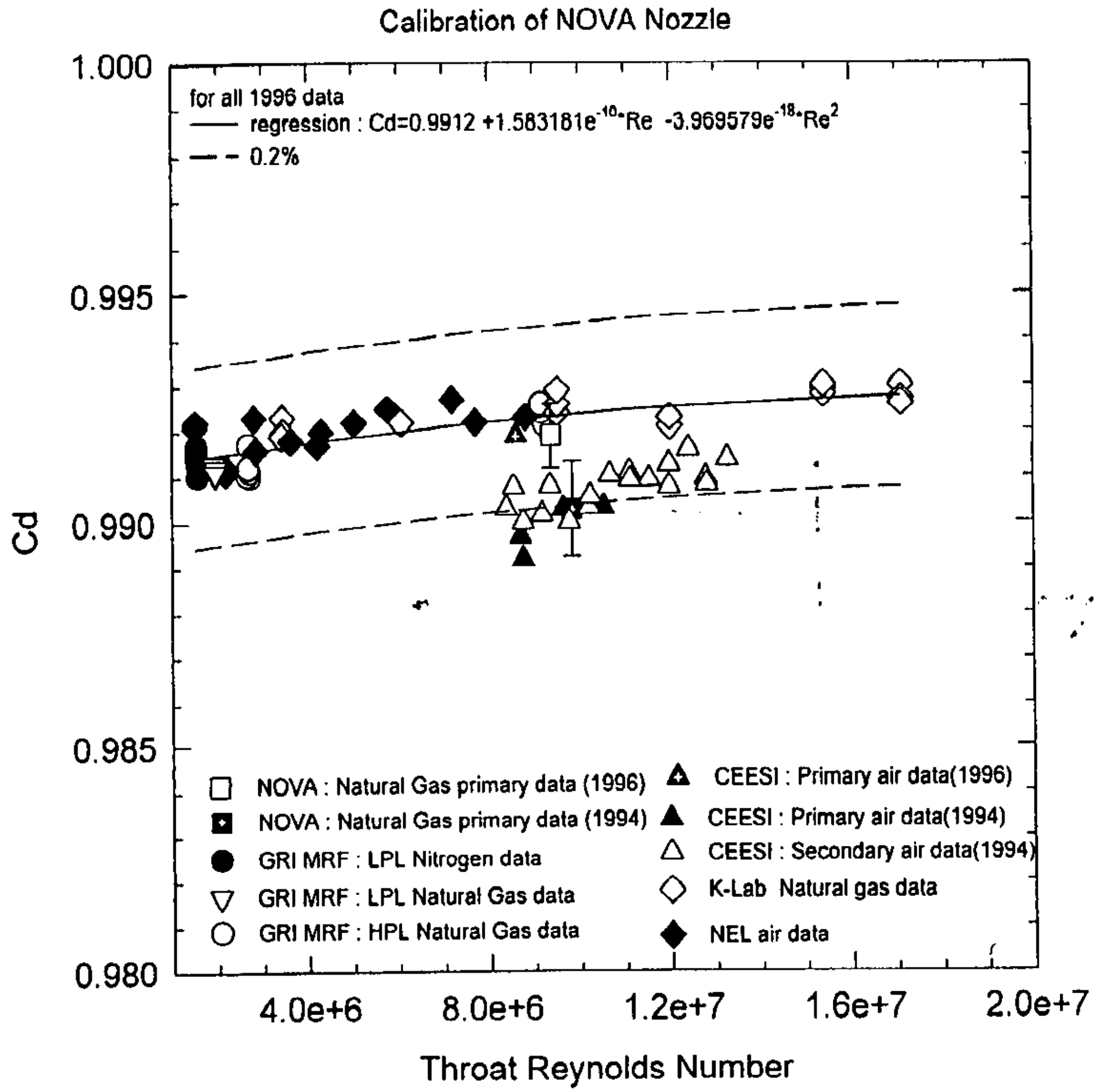


Figure 8. Calibration of NOVA Nozzle

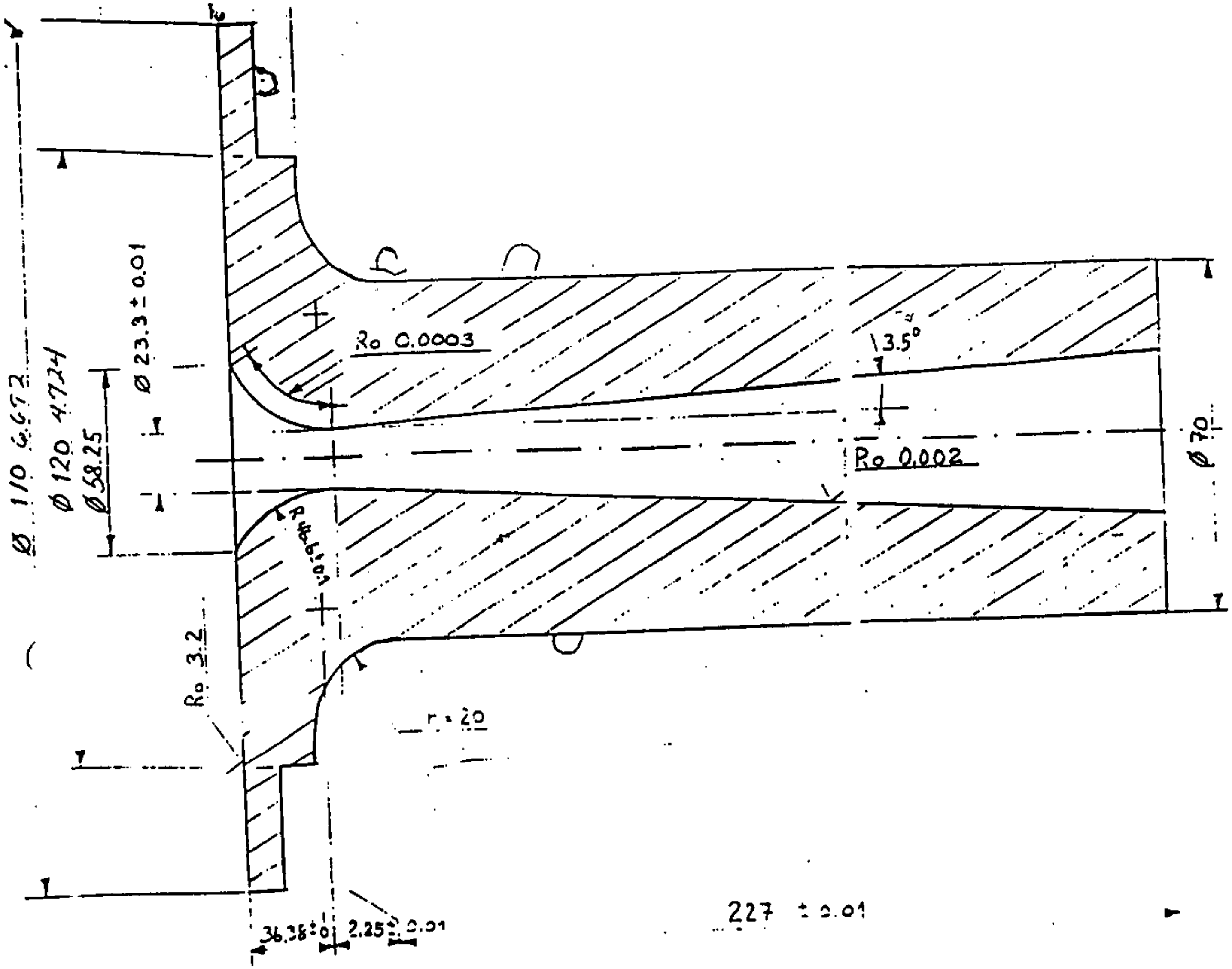


Figure 9. The K-Lab Nozzle

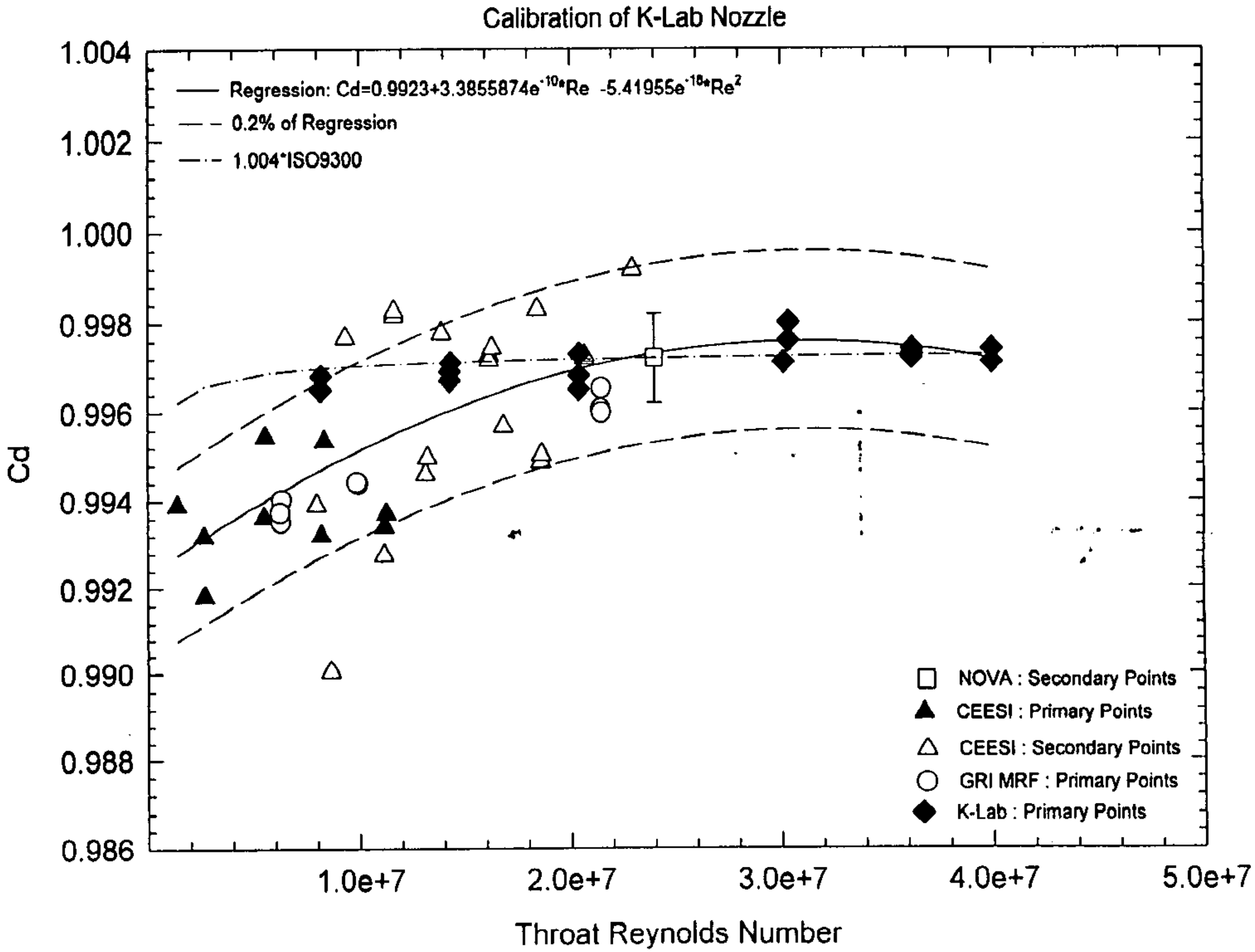


Figure 10. Calibration of K-Lab Nozzle