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ABSTRACT

At the request of Standard Aero Ltd. (46_PF0_10, LO 6328), a method was devised for calibrating the airflow through the inlet casing of an aircraft gas turbine engine. A rig with a venturi air meter was assembled to mate to the client-supplied inlet casing. Tests were conducted to correlate the flow measured by the venturi (traceable accuracy) to readings from pressure taps installed on casing. Two configurations (with and without inlet screen) were tested. This report provides the documentation for the rig, systems and results, including an uncertainty analysis.

RÉSUMÉ

A la demande de Standard Aero Ltd., une méthode a été imaginée pour étalonner l'écoulement d'air à travers l'entrée qui emballe d'un moteur de la turbine de gaz de l'avion. Un gréement avec un mètre de l'air du venturi a été assemblé pour se marier à l'entrée emballer client-fourni. Les épreuves ont été conduites pour correspondre le courant mesuré par le venturi (exactitude trouvable) à des donneés de pression installées dans l'entrée emballer. Les deux configurations (avec et sans écran de l'entrée) ont été testé. Ce rapport prévoit la documentation du gréement, systèmes et résultats, y compris une analyse de l'incertitude.

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Appendices

AIRFLOW CALIBRATION OF AN ENGINE INLET

1.0 INTRODUCTION

Gas turbine engine airflow is a useful measure of engine performance and health. In particular, the compressor condition is often reflected by changes in the engine airflow at a given compressor speed. However, the measurement of airflow is usually difficult because of the need for special static pressure instrumentation and the effect of local geometry on the readings. In addition, asymmetric flow paths into the flow measuring station may significantly affect the results. A calibration is typically required for all but the most simple axial, axi-symmetric inlets.

NRC/IAR has experience in the measurement of flows with traceable methods. Instrumentation, calibrated venturi meters and a suitably sized blower were used in a comparable installation during a recent icing certification test program. Other inlet sections are available as transfer standards but are not traceable at this time.

Following an initial request from the client, a statement of work and proposal was prepared (Bird, 1998). A contract was established 28/1/98. The client provided a scrap inlet casing for mating duct design and alignment purposes. The instrumented inlet was received on 6/3/98 and returned on 20/3/98.

This report contains a description of the calibration facility, test procedure, the results and the expected uncertainty, with traceability.

2.0 TEST REQUIREMENTS

The PT6 inlet supplied by the client comprised a fairing (PN3016956), an inlet screen (PN 3023695) and a case (PN 3013045). The client requested a calibration of the engine inlet over the range of airflows from 5 and 7.5 pounds mass per second (lbm/s), referenced to standard pressure and temperature. Following the start of the project, the client also requested a calibration without the inlet screen installed.

The flow measurement section provided by the client consisted of four static taps located on the outer annulus of the case, just upstream of the exit flange of the inlet. The inlet as supplied included a manifold to pneumatically average the pressure at the four taps. In addition, a reference pressure was installed on the rear face of the casing.

The calibration was to provide a correlation of the ratio of the averaged static to the reference pressure with airflow measured by an NRC venturi airmeter. The calibration was to include corrections to standard day conditions (pressure and temperature). It is understood that the intended use of the calibration is to compare pre- or post-overhaul engine airflow performance to a known or derived standard.

3.0 TECHNICAL APPROACH

The project required that a duct system be assembled with the client inlet at the inlet, followed by a venturi airmeter of traceable performance and a blower at the outlet. This section describes the rig design, the data acquisition and reduction system and the associated uncertainty analysis.

3.1 Rig Design

A venturi airmeter with a capacity in the required range was selected based on previous experience on a similar installation. A 150 HP blower with a no-load capacity of 18 lbm/s was also available. Ducting was selected based on the geometry of the annular inlet (4.29 inches ID and 6.93 inches OD) and followed general airmeter design guidelines (Miller, 1989):

1) Diffuser expansion angle and diffuser length,
2) Maximum step or mismatch in duct diameter,
3) Length of straight, circular duct upstream of an airflow measurement station, and
4) Length of straight, circular duct downstream of an airflow measurement station.

No allowance was made for the influence of a compressor rotor immediately downstream of the exit flange of the inlet case, as in an actual engine installation. With the calibrated inlet installed in an engine, there may be a bias in the measured airflow that could be a function of gas generator speed. However, while the effect of a rotating stage could not be readily simulated, this bias is expected to be constant from engine to engine.

The rig from the end of the inlet case to the venturi exit plane was approximately 3 meters in length. A cylinder and conical bullet of approximately 1 meter in length were added to extend the inner annulus of the inlet case. The general layout of the completed rig is shown in Figure A1 and in a photograph in Figure 1.

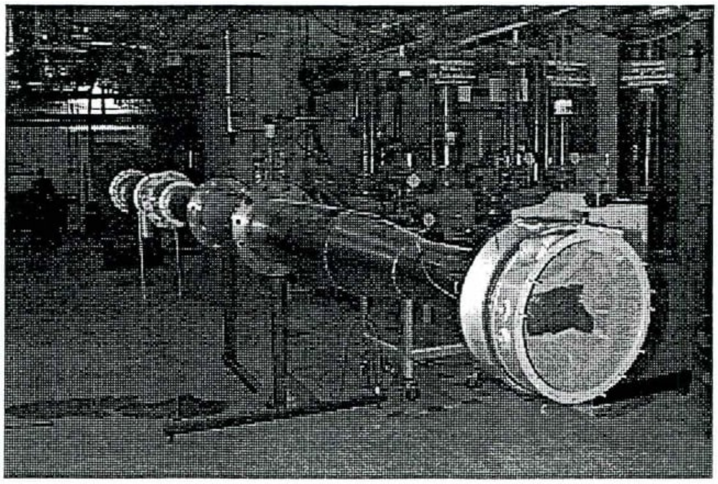


Figure 1. The Flow Calibration Rig with Engine Inlet

3.2 Data Acquisition

The desired result of the calibration was defined to be a plot with relevant curve-fits of the airflow, at standard day conditions, as a function of the static depression at the throat of the inlet. The data acquisition system specification to provide this result is described in this section.

The following input parameters were required to calibrate the inlet airflow:

1) Static pressure at throat of inlet (4 taps pneumatically averaged)
2) Engine carcass static tap as a reference barometric pressure by client,
3) Inlet air temperature (3 thermocouples spaced about the circumference of the inlet screen) (Tair),
4) Total pressure at the inlet of the 12-inch venturi (Pline),
4) Pressure differential across venturi (Dp),
5) Venturi surface temperature for thermal expansion correction (Tbase), and
6) Barometer, ambient pressure in test cell (Pbaro)

The following output parameters were required:

1) Static pressure depression (referenced to barometer) at throat of inlet corrected to standard pressure, Psin/δ where $\delta =$ Pbaro/ 14.696, and
2) Air mass flow corrected to specified reference condition.

3.2.1 General layout

This section provides a general description. Most of the instrumentation was either supplied by the client (inlet statics and case barometer) or was fixed by the venturi manufacturer. Exceptions were the inlet thermocouples added to the screen and a barometer in the room. Refer to Annex A for detailed specifications of the transducers and other equipment.

All pressure measurements were made using Druck PDCR340 series pressure transducers. Barometric pressure was measured using a Druck DPI 140 Digital Pressure Indicator, adjacent to the rig. All temperatures were measured using Thermo Electric T type instrumentation grade thermocouple wire. The reference airflow was measured using a 12-inch ASME low loss venturi that allows the computation of corrected air mass flow as a function of static depression in the throat.

The data acquisition system consisted of the following components: 16 bit A/D Converter with differential input, Pentium 100 MHz running Windows 95, and National Instruments Labview V4.1 for Windows NT/95/3.1. The voltage to temperature conversion equations used in Labview were referenced to NIST Monograph 175.

The instrumentation was calibrated prior to the calibration runs and checked throughout. All pressure transducers were calibrated using Druck model DPI 603 portable calibrator. For each transducer, a multi-point calibration was completed for both increasing and decreasing directions. The calibration of the barometer was verified by checking against a mercury barometer in M-7. Thermocouples were not calibrated but standard manufacturer's specifications were included in the uncertainty analysis (section 3.3).

Initial tests of the rig confirmed reasonably stable operation over the desired airflow range. To account for some variations in the airflow for low flow rates, a scan period of 10 seconds was selected. With a scan rate of 100 points/second, each recorded data point was the average of 1000 reads. These raw data in the form of voltages were processed by the data acquisition program through scaling subroutines to produce data in the desired engineering units for display and storage.

These engineering data were produced in Labview using formula nodes for each channel. All engineering data were written to a spreadsheet file, and processed using Excel 97. For example, all static pressures measured at the inlet were corrected to standard day pressures (14.696 psia) as shown in section 3.2. All curve fits and transfer functions were calculated using 2nd order equations in Excel 97.

The following process (Lambda Square, 1994) was followed to calculate standard cubic feet per minute flow (SCFM), given the venturi geometry (bore diameter, d, beta ratio, b, and flow co-efficient, c, and a fixed specific heat ratio of air, k, of 1.4021:

1) Calculate absolute pressures for Pline and Dp and absolute temperatures for Tbase and Tair;
2) With k and the ratio of absolute pressures, P = (Pline-Dp)/Pline, calculate the gas expansion ratio , Y from individual terms as:

$$Y1 = 1 - b^4$$

$$Y2 = k / (k-1)$$

$$Y3 = P^{2/k}$$

$$Y4 = 1 - P^{(k-1)/k}$$

$$Y5 = 1 - (b^4 P^{2/k})$$

$$Y6 = 1 - P$$

$$Y = \sqrt{((Y1\ Y2\ Y3\ Y4) / (Y5\ Y6))}$$

3) With the nominal flow coefficient of the venturi, c, and the beta ratio, b, calculate the venturi flow coefficient, K:

$$K = c / \sqrt{(1 - b^4)}$$

4) With K, Y, air specific gravity at base conditions (14.7 psia and 60°F), the absolute pressure, Pline, gage Dp, and the absolute temperatures: Tbase and Tair, calculate mass flow in Standard Cubic Feet per Minute (SCFM):

$$Qscfm = 5.9816\, d^2\, K\, Y \sqrt{(27.681\, Dp)} \sqrt{(2.703\, Pline/Tair) / (2.703 \times 14.7 / Tbase)}$$

This SCFM value was then converted to a mass flow, at base conditions (14.7 psia and 60°F), in kilograms or pounds mass per second knowing the density of air at the base conditions:

$$Wc = 5.7931E\text{-}4\ Qscfm,\ [kg/s] \text{ or } 2.2046 \times 5.7931E\text{-}4\ Qscfm\ [lbm/s].$$

Flow data were verified by inputting the manufacturer's venturi test data: line pressure, static pressure depression and temperatures into this flow equation. The output values of flow from this equation agreed with the flow data sheet as supplied with the 12-inch venturi by the manufacturer.

3.2.2 Test procedure

The following procedure was used for each of three separate runs for both of the two configurations (screen and no screen).

1. All pressure transducers were calibrated.

2. The data acquisition program was configured to scan at 100 readings per second for 10 seconds. These 1000 readings were averaged to account for flow variations.

3. All pressure transducers were zeroed prior to each run (by subtracting the pressure offset at zero gage pressure), and were checked for a zero pressure reading after each run.

4. The flow condition for each set of data points was adjusted, and allowed to settle for a minimum of 30 seconds. An on-line 'strip chart' type display of airflow was used to determine the point at which steady-state flow was reached. A minimum of 5 data points per airflow level was taken. Data were taken from 4.0 lbm/s to 7.5 lbm/s in nominally 0.5 lbm/s increments. A minimum of three runs was taken for each inlet configuration.

A repeat of the first test was conducted at the end of the complete test series. The intent was to confirm that there had been no long term drift during the duration of the tests.

Such a drift, if present, would only introduce a bias between the results of the screen and no-screen configuration.

3.3 Uncertainty Analysis

The intent of this uncertainty analysis is to provide an estimate of the expected uncertainty in the value read from the calibration curve or associated curve-fit. This uncertainty is the largest error reasonably expected. This estimate is made up of the systematic and random errors in each of the measurement and calculation processes for each of the desired parameters. In particular, the auditing of the error sources extends right back to the appropriate national standard to ensure traceability. It is this traceability that allows comparisons with internal and external data sets.

The uncertainty analysis begins with the elemental error audit to estimate the error in the measurement parameters:

a) Psin, the static pressure depression in the client airmeter,
b) Pbaro, the barometric pressure in the test area,
c) Pline, venturi inlet total pressure,
d) Dp, differential depression at venturi throat relative to Pline,
e) Tair, air temperature at inlet screen,
f) Tbase, venturi case temperature used for thermal growth corrections to venturi area,
g) Flow equation parameters: gas expansion factor, bore diameter, pipe diameter, flow coefficient, and air density.

Estimates were prepared for two nominal flow conditions: low- 4.5 lbm/s and high- 7.4 lbm/s. Flow equation parameters were estimated with methods provided in Hall (1989) for the particular venturi. The following elemental error sources were considered, with the specifications of Appendix A, in the estimation of the bias and precision errors for the first six parameters:

1) Data acquisition resolution: a precision error of 0.3 counts corresponding to 0.93 μV and calculated as a percentage of reading for each millivolt input signal,
2) Data acquisition relative accuracy: a bias error in producing a digital output corresponding to the high level voltage resulting from the amplification of the millivolt signals (gain of 100), assuming an average of 100 reads. The estimated bias from the data acquisition card supplier was 72.3 μV which was converted to a percent of reading for each amplified signal output.
3) Thermocouple cold reference junction accuracy: a bias error corresponding to a 1K error for the thermistor system.
4) Thermocouple error: a bias error for the manufacturer's special limits of error on Type T wire, 0.5 K. The conversion of millivolt measurements to temperature is

done using high order polynomials. Typically, the look-up errors are negligible, of the order of 0.04 K.

5) Absolute measurement of barometric pressure: a bias error based on the verification of the electronic barometer against a mercury barometer, resulting in an estimate of 0.03%.

6) Calibration curve-fits for the Psin, Pline, and Dp: Multi-point calibrations were conducted for each transducer and second order curve-fits were calculated using EXCEL. The average curve-fit errors for the relevant range of data were estimated as bias errors of: 0.24% for Psin, 0.16% for Pline and 0.36% for Dp.

The resulting elemental error estimates are shown in Table 1. Estimates of uncertainties in the flow equation parameters were prepared from the methods in Miller (1989). These estimates are based on the area ratio of the venturi and the measured pressures. The largest contributor is the bias error in the flow coefficient for the venturi, i.e. one percent of reading. The gas expansion factor biases were estimated at 0.19% and 0.63% for the low and high flow conditions, respectively.

Table 1: Elemental Error Estimates

Elemental Measurement	Low Flow ~4.5 lbm/s Estimated error [% of reading]		High Flow ~7.4 lbm/s Estimated error [% of reading]	
	Bias	Precision	Bias	Precision
Psin	0.28	0.008	0.28	0.003
Pbaro	0.03	-	0.03	-
Pline	0.48	0.12	0.21	0.004
Dp	0.29	0.01	0.37	0.003
Tair	0.37	0.08	0.37	0.08
Tbase	0.38	0.08	0.38	0.08

These elemental errors can then be propagated to the performance parameters of interest: corrected inlet static depression (dependent parameter for the desired calibration) and corrected airflow (independent calibration parameter). The error estimate for the first parameter can be calculated from the Psin and the Pbaro estimates. This uncertainty was estimated as:

1) Low flow: bias of 0.28%, precision of 0.008%, and overall uncertainty of 0.30%;
2) High flow: bias of 0.28%, precision of 0.003%, and overall uncertainty of 0.29%.

The airflow measured by the venturi has an associated uncertainty that has been estimated by the methods of Hall (1989) incorporating the elemental errors for the parameters in the previous list a-g. The resulting estimates for the data with the screen installed are:

1) Low flow: bias of 1.03%, precision of 0.010%,and overall uncertainty of 1.05;
2) High flow: bias of 1.20%, precision of 0.0089%and overall uncertainty of 1.2%.

The use of the curve-fit of the corrected airflow as a function of corrected static depression (Appendix B) incurs errors of two types: the direct error in estimating the venturi airflow (y-axis) and the uncertainty in the independent parameter (x-axis). This latter contribution has been estimated from the slope of the curves at the low and high flow points for the screen-installed configuration data. The bias contributions are 0.42% and 1.17%, respectively. The precision contribution is estimated as 0.012% for both flow conditions.

The root-sum-square combination of these contributions and those for airflow, a) and b) immediately above, yield the estimated uncertainty in the corrected airflow data read from the client inlet casing airflow calibration curves (for the screen-installed configuration), as a percent of reading:

1) Low flow: bias of 1.22%, precision of 0.016%,and overall uncertainty of 1.25%;
2) High flow: bias of 1.67%, precision of 0.015%and overall uncertainty of 1.70%.

4.0 RESULTS

Plots have been prepared for three multi-point runs of each configuration: 193 points in runs 1,2, and 3 for the inlet screen removed (Figure 1, Appendix B) and 141 points for runs 5,6, and 8 for the inlet screen installed (Figure 2, Appendix B). The good repeatability of these data permitted the preparation of curvefits of the airflow data to the measured static depression data (both parameters corrected to standard day conditions). EXCEL data files are to be provided on disk as an attachment to this report: corrected static pressure depression, Psin and corrected airflow, Wc. The following transfer functions represent the best fit curve of the three runs for each inlet configuration, calculated using 2nd order equations in Excel 97.

a) Inlet with screen:

$$Wc = -0.102739\,(Psin/\delta)^2 - 1.658301\,Psin/\delta + 2.288427$$

b) Inlet without screen:

$$Wc = -0.109963\,(Psin/\delta)^2 - 1.667567\,Psin/\delta + 2.412273$$

where:

Psin is the measured average static pressure depression from barometric pressure corrected to standard barometer, in psia, and

Wc is the mass flow at base conditions (14.7 psia and 60°F), in lbm/s.

As expected, the inlet configuration with the screen installed has a lower flow capacity than for the configuration without a screen. The large data sets allowed the actual scatter in the curve-fits to be estimated for comparison with the estimated uncertainties at the end of section 3.3. The standard error of the estimate, a measure of the scatter in the curve-fit was calculated from the data. For the inlet screen installed, this scatter was 0.80% and for the configuration with the screen removed the scatter was 0.57%. These values suggest that the estimates in section 3 are reasonable and should be retained for use.

5.0 CONCLUSIONS AND RECOMMENDATIONS

a) An airflow calibration has been prepared for two configurations of the client inlet casing. A blower simulated the induction of air by the engine but no allowance was made for the presence of the compressor rotor immediately downstream of the plane of the client-installed static taps.

b) The calibrations are based on three separate runs and the data comprise between 140 and 190 individual data points for nominal flows between 4.5 and 7.5 lbm/s. The calibrations are presented in the form of second order polynomials with dependent and independent parameters corrected to standard day pressure and temperature conditions.

c) Uncertainty estimates have been included to allow the use of these calibration curves. Uncertainties were estimated at 1.25 to 1.70 percent depending on the flow. These estimates have been checked against the scatter observed in the measured data and are considered valid for use.

d) Uncertainties associated with client measurement systems and transducers must be combined with these uncertainties to yield uncertainties for data measured in the client facility.

e) With the inlet installed on an engine, flow data derived from these calibrations may have biases associated with the presence of a compressor rotor immediately downstream from the client-installed static pressure taps on the inlet. However, these biases are expected to remain fixed for back to back tests.

6.0 REFERENCES

Abernethy, R.B., et al., Thompson, J.W., Jr. 1973. Revised 1980. Handbook, Uncertainty in Gas Turbine Measurements. Engine Test Facility, Arnold Engineering Development Center, Air Force Systems Command, Arnold AFS, TN.

Bird, J.W. 1998. Proposal for Airflow Calibration, Letter to Standard Aero Ltd. 20/1/98

Lambda Square. 1994. Air and Gas Flow (Low Loss Venturi Meter), Ref. # TM-400, dated 12/8/94, Bayshore, NY.

Miller, R.W. 1989. Flow Measurement Engineering Handbook. 2nd Edition., McGraw-Hill.

Appendix A: Instrumentation Specification

Analog to Digital Converter:

National Instruments AT-MIO-16X.
- 16 Bit ADC Configured for 8 channels differential input.
- Board was configured for bipolar operation (-10 VDC to +10 VDC)
- On-board PGIA was configured to amplify all low level (< =100 mV) signals.
- Resolution @ gain of 100: on -10 to 10 volts is 3.1μV for one bit
- Relative accuracy for averaged samples at gain 100: 72.3 μV.

Thermocouple Processing:

Extension grade T-type thermocouple wire: specification error 0.5 K.
SCB-68 connector block with thermistor cold junction sensor: 10 mv/°C sensitivity, with accuracy: 1K.
High order polynomial using NIST monograph 175 for conversion from millivolts to temperature. Look up error, typically 0.04 K assumed negligible.

Pressure Calibrator:

Druck model DPI 603 portable calibrator S/N 603581711
Specifications: Range: -15 to +30 psig.
Combined non-linearity, hysteresis and repeatability: ± 0.075 % full scale
Actual calibration deviations of 0.001 to 0.006 psid were applied corresponding to 0.1 to 0.45% of reading.
Date of calibration: 03 Nov.1997

Static Pressure Transducer @ Inlet:

Druck PDCR340 series, S/N298465
Range: 2.5 psid
Supply: 12VDC
Sensitivity: 21.847 mV/ 12 V
Non-linearity & hysteresis: ±0.1% Best straight line

Total Pressure Transducer @ venturi inlet:

Druck PDCR340 series, S/N 281868
Range: 1.0 psid
Supply: 12VDC
Sensitivity: 19.397 mV/ 12 V
Non-linearity & hysteresis: ±0.1% Best straight line

Differential Pressure across venturi:

Druck PDCR340 series, S/N 281872
Range: 1.0 psid

Supply: 12VDC
Sensitivity: 19.602 mV/ 12 V
Non-linearity & hysteresis: ±0.1% best straight line.

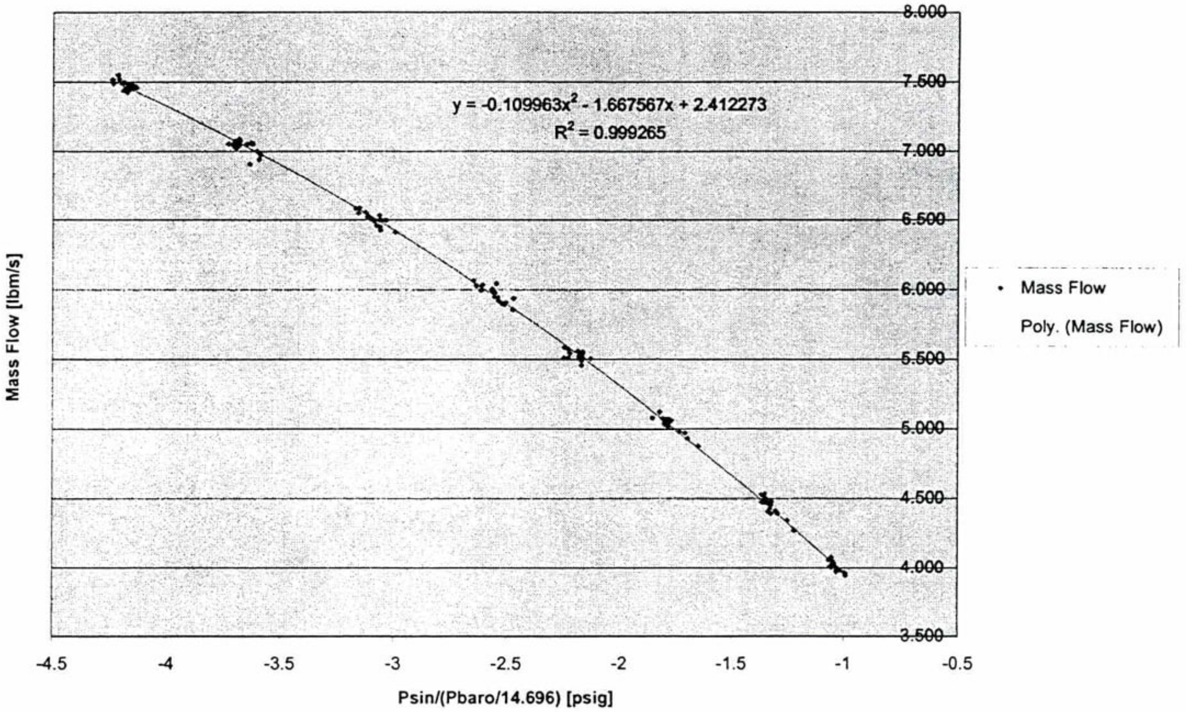
Barometer:
Druck DPI 140 Digital Pressure Indicator S/N 140053011
Range: 11.5000 - 17.000 psia
Nominal accuracy: ± .01% F.S. but 0.03% against mercury barometer
Supply: 110 VAC

Airflow Measurement:
Instrument: 12-Inch ASME Lo-Loss Venturi.
Flow Range: 0 - 8.8 lbm/s
Accuracy: Discharge coefficient ± 1% of full scale
Manufacturer: Lambda Square Inc. Bay Shore NY U.S.A.

Appendix B: Test Results

12-Mar-98

Figure 1: Mass Flow vs. DeltaP (inlet screen removed)



Appendix B: Test Results (cont'd)

Figure 2: Mass Flow vs. DeltaP (inlet screen installed)