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Error Analysis for Reciprocating Compressor Performance

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ABSTRACT

With our recent history of increased energy costs, "compressor efficiency" has become the byword of many end users of reciprocating gas compressors. This is particularly true for the larger units encountered in the Process Industry or in the Oil and Gas Field Separable Market. This demand for improved efficiency has in turn fostered a need to define the accuracy with which compressor capacity, horsepower, and power economy (BHP/MMSCFD) can be measured. With the object of defining these accuracies in a controlled industrial laboratory environment, the authors review a Closed Loop Compressor Test Facility constructed at their Painted Post Plant. The authors believe this is a timely subject in light of recent society efforts to establish generally accepted methods of specifying error in ASME Performance Test Code work.

INTRODUCTION

In 1979, a gas compressor test facility, named "The Closed Loop," was constructed at the authors' plant in Painted Post, N.Y. The object of the Closed Loop was to satisfy a need for a compressor and valve development test facility. This facility was to combine the flexibility and controlability of a laboratory with conditions and machinery that would be encountered in field operations. It was also our objective to satisfy a need for a test facility that could operate on a variety of gases in a safe environment that conformed to the applicable National Fire Protection Association (NFPA) Codes. The Closed Loop is instrumented to measure horsepower, capacity, heat rejection, cylinder and valve losses, and gas and valve dynamics.

Historically, compressors in the Process Industry and in the Oil and Gas Field Separable Market have been given a +/- 3% brake horsepower, a +/- 3% capacity, and a +/- 6% power economy (BHP/MMSCFD) tolerance on compressor performance predictions. These predictions are determined by the compressor vendor, based on his in-house compressor performance model. The performance programs are usually based part in theory and part in empirical adjustments to laboratory and field test data. Since there is the additional uncertainty of machine-to-machine variations, the accuracy of the test data on any specific machine must be maximized in order to achieve reasonable correlations between performance predictions and the actual performance in the field.

Customer influence is toward reducing the existing +/- 3% horsepower and capacity tolerances. Increasing energy costs have caused customers to place more weight on the difference in efficiency between competitive compressor bids. Customers of the larger machines (1000 HP) tend to treat these performance estimates as absolutes in assigning penalties for efficiency differences between compressor bids. A few percentage points in compressor efficiency difference can be pivotal to a large compressor order.

Since 1979, the accuracy of our performance tests on the Closed Loop has been a constant question that has required review and implementation of system upgrades and procedural changes. The operating costs and the press for laboratory test results in a manufacturing orientated environment do not go hand-in-hand with the time consuming.requirement for accurate calibration procedures and the need for data repetition. Despite this dissidence, we have made continual progress toward increased data accuracy.

With these considerations in mind, the authors have made this analysis of compressor performance test accuracy on the Closed Loop at Painted Post. The subject for this evaluation was a 20.5" x 6" stroke cylinder run at 500 to 1000 rpm compressing nitrogen. The evaluation of accuracy has been confined to brake horsepower, capacity and power economy.

PERSPECTIVE - THE CLOSED LOOP

The Closed Loop facility is divided into two areas, the control room and the compressor room with a 12" double reinforced concrete wall between the two. The control room houses the control and safety panels, instrumentation, services, and the compressor DC drive

(1000 HP between 400 and 1000 rpm) along with its AC to DC power supply. The compressor room is restricted to the compressor, bottles, loop piping and instrumentation sensors that meet the fire and explosion proof criteria of NFPA and DOT. The DC motor in the control room is connected to the compressor in the loop room via a torsionally soft drive train that passes through a gas tight seal in the firewall. Compressor power is measured both by an in-line torque meter and by an electronic indicator with a built-in microprocessor. The loop itself consists of a test compressor, inlet and discharge pulsation bottles, 10" pipe to provide for adequate flow for low pressure tests on large cylinders, gas to air variable speed heat exchanger located outside of the building, receiver-scrubber, an orifice tank and a set of three throttles in parallel to provide system control over a wide range of flows. This system is designed for 1650 psig maximum allowable working pressure. The loop room also contains two charging compressors, a controlled blowdown system, a drain system, an emergency and overpressure blowdown system, and a pneumatic safety and remote control system. These peripherals provide flexibility with a very high level of safety required to meet applicable insurance codes and operator sense of well being. Gas composition is monitored by gas chromatograph. Data is entered, corrected and reduced on an IBM 4341 main frame and graphed on a Tektronics 4312 terminal and plotter.

The dimensions of the Loop encompass single cylinder testing on short stroke, higher speed (4.5" @ 1200 rpm) to long stroke, slower speed machinery (16" @ 320 rpm). Since 1979, tests have been run on helium, natural gas, nitrogen, carbon dioxide and mixtures of these gases. Cylinders have been tested from 0 to 1200 psig inlet pressure, from 20 to 1500 psig discharge pressure and over a pressure ratio of 1.2 to 5.

DEFINITION OF ERROR TERMINOLOGY

The analysis of error in horsepower, capacity and power economy has been guided by two ASME papers on engineering statistics [1], [2] and the Measurement Uncertainty Handbook, Revised 1980 [3]. For detailed support of the error analysis procedure, the authors direct the reader to these publications. Additional reference was made to textual material by R. P.

Numbers in [ ] designate references at the end of this paper.

Benedict [4] and a yet unpublished draft of the ASME PTC 19.1 on Measurement Uncertainty [5] that is in circulation for industrial comment.

In order to place the reader in the proper frame, the following definitions will be made. Precision Index is a statistic that describes the spread of a measurement about the mean of a sample of measurements of a parameter taken from a population of parameter measurements. This statistic is more commonly referred to as the sample standard deviation. Bias Error is the systematic error which is considered to remain constant during a given test. It is the deviation between the sample mean value and the true value of the parameter. Although calibration error is constant during a test, it is treated as a precision error in this analysis since it is a statistic. Also, several variables that are not constant during a test, such as drift and ambient temperature effects on instrumentation, are listed as bias. These errors are based on calculation, observed trends and/or manufacturers specifications. All bias and precision errors are kept separate throughout the calculations. The precision or bias errors for a given measurement have been obtained by taking the square root of the sum of the squares of all independent elemental precision or bias contributions. The degree of freedom for the precision index for a given measurement (dfm) is obtained from:

$$\text{dfm}=\left[\sum_{i=1}^{J}(S_{e_i})^2\right]^2 \Big/ \sum_{i=1}^{J}\left[(S_{e_i})^4/df_i\right] \qquad (1)$$

where Se is the element precision index. Propogation of the errors in the measurement to the result is determined by:

$$\left\{\sum_{i=1}^{J}\left[\left(\frac{\partial r}{\partial X_i}\right)\cdot Y_i\right]^2\right\}^{1/2} \qquad (2)$$

where r = fn (Xi) and Xi is a measured parameter, Yi is the bias or precision index for that parameter and J is the number of parameters included in the result r. The degree of freedom for the precision index propogated to the result (dfr) is:

$$\text{dfr}= \frac{\left[\sum_{i=1}^{J}\left\{\left(\frac{\partial r}{\partial X_i}\right)\cdot S_{m_i}\right\}^2\right]^2}{\sum_{i=1}^{J}\left[\left\{\left(\frac{\partial r}{\partial X_i}\right)\cdot S_{m_i}\right\}^4/df_{m_i}\right]} \qquad (3)$$

where Sm is the measurement precision index. The uncertainty of the results have been stated at 95% coverage of the true value. This is accomplished by taking the square root of the sum of the square of result bias and the square of the product of the result precision and the appropriate Student-t distribution. In this review, we are interested in the accuracy of the results or the deviation of the results from their true value. The term accuracy by this definition then implies a combination of the bias and precision errors in the results as noted above.

UNDER CONSIDERATION

To evaluate the Closed Loop data accuracy, a set of test data from a performance test on a 20.5" X 6" stroke cylinder run on Nitrogen in January 1983 was choosen. The compressor was tested at 54.5 psig inlet pressure, 159 psig discharge pressure (ratio of 2.52) and at speeds of 500, 700, and 1000 rpm. The test condition at 500 rpm was used to illustrate the error analysis procedure. The results at all three speeds are summarized in Table 1. Each one of these data points consist of two identical tests run at different times between the same calibration interval. Each test run consists of three separate recordings of all parameters. All six data recordings have been combined. This approach has the advantage of increasing the data set degrees of freedom. This approach also has the advantage of including within the precision the run-to-run variation.

With respect to instrumentation, all critical readouts are located in a common panel that is maintained at +/- 2°F. The control room varies by +/- 5°F for eight months of the year. The test cell varies by up to 20°F from the temperature at calibration. During the summer months, greater ambient temperature excursions are encountered in both the control room and the test cell. All instrumentation is calibrated before and after each set of tests. When calculating statistics for this combined calibration, the data was refined with the Modified Thompson Tau Outlier Technique per page 71 of reference [5]. The test data is then adjusted for the mean calibration deviation.

A computer program was written to expedite the error analysis. Input to the program include nominal values, bias and precision errors and degrees of freedom. The program generates the required uncertainties and provides step-by-step calculations from input to output. These step-by-step calculations allow tracing of maximum error contributors.

As noted previously, this analysis will consider only brake horsepower, capacity, and power economy (BHP/MMSCFD - brake horsepower per million standard cubic feet per day).

BRAKE HORSEPOWER ERROR ANALYSIS

The brake horsepower is measured by an inline strain gauge type torque transducer with a rotary transformer link. The transducer is mounted between soft, flexible couplings. The meter is located in the control panel. The torque calibration is performed with a leveled, counter-balanced arm with weight hung from a knife edge. The bias that affect the horsepower results follow.

Speed	
- 60 tooth wheel with a one second gate	+/- 1
Weight	
- scale calib. traceable to NBS (570 lbs)	+/- .50
- scale calibration	+/- .25
- minimum scale division	+/- .50
- corrected for gravity and altitude (+.25 lbs)	
Combined weight bias (lbs)	+/- .80
Length	
- six ft. torque arm, machined and doweled on press fit hub with knife edge	+/- .0012
- temperature variation, machining to calib. (+/- 10° (F))	+/- .0004
- leveling error (+/- 1°)	+/- .0009
Combined length bias (ft)	+/- .0016
Torque	
- meter drift (ft-lbs)	+/- 4.0
- smallest subdivision	+/- 1.0
- temp. effect on transducer	+/- 3.3
- temp. effect on readout	+/- 1.5
- contribution to calibration of weight and length. Using equation: Torque = Lgth x Wgt and equation (2): $\{(570*.0016)^2+(6*.8)^2\}^{1/2}$ =	(4) +/- 4.9
Combined bias at meter (ft-lbs)	+/- 7.36

Brake horsepower was obtained from:
BHP = .0001904 x Torque x Speed (5)
and applying equation (2): Bias = .0001904 x $\{(500*7.36)^2+(6*570*1)^2\}^{1/2}$ = +/- .96

Consider the precision errors associated with the 500 rpm data.

Compressor speed (rpm)	500.2
Speed precision index (df=5)	+/- .4

Torque (ft-lbs)	3420.9
precision index (df=5)	+/- 4.1
calib. prec. index (df=12)	+/- 4.5
combined prec. index	+/- 6.1
combined degrees of freedom (1)	15

Brake Horsepower Uncertainty

Brake horsepower (5)	325.78
bias (per above)	+/- 0.96
precision index (2)	+/- .64
degrees of freedom (3)	19
student-t distribution	2.093
BHP uncertainty at 95% coverage	+/- 1.64
BHP percent uncertainty	+/- .50

CAPACITY ERROR ANALYSIS

The mass flow rate is measured with an orifice and orifice meter constructed to ASME standards [6]. These orifices and orifice meter are calibrated together by Alden Research Laboratory, Worcester Polytechnic Institute, Worcester, Mass. This calibration provides orifice flow coefficients with tolerance traceable to NBS. The mass flow rate is converted to inlet capacity by dividing the flow rate by the inlet density. The parameters necessary to calculate the mass flow rate include orifice inlet pressure, measured with a bourdon tube pressure gauge with a mirrored dial, orifice inlet temperature, measured with two iron-constantan thermocouples connected to a digital readout and orifice delta P, measured with a differential pressure transducer connected to a digital readout. The pressure gauge and the differential pressure transducer are calibrated against deadweight testers traceable to NBS. The thermocouples are calibrated in a constant temperature bath against a thermometer, also traceable to NBS.

Capacity Bias Error Analysis

The orifice flow rate was obtained from:

$$\dot{m} = Y*X*F_A*A*K*60 \quad (6)$$

where, $X = (2*g_C*\rho_{oi}*\Delta P*144)^{1/2}$ (7)

Equation (6) was derived from equation 1.5.33, page 54 of reference [6]. The bias that affect the mass flow rate follow.

Orifice Inlet Pressure Gauge	
- calibration minimum division	+/- 1.0
- calibration traceable to NBS	+/- .16

- measurement unsteadiness during runs +/- .5

Combined bias at meter (psi) +/- 1.13

Barometer

- accuracy of a 1/4" ID Fortin type barometer corrected for temperature and gravity [4] +/- .010
- authors' judgement of readability of barometer +/- .015

Combined bias at meter (in. of Hg) +/- .018

Orifice inlet pressure was obtained from:

$P_{oia} = P_{oig} + BAR*.49116$ (8)

and applying equation (2): Bias = $\{(1*1.13)^2 + (1*.49116*.018)^2\}^{1/2}$ = +/- 1.13

Orifice Inlet Temperature

- calibration unsteadiness in bath temperature +/- .2
- calibration traceable to NBS +/- .25
- temperature effect on readout span +/- .005
- temperature effect on readout junction +/- .05
- thermocouple drift, root mean square drift to two instruments, page 70 of reference [3] +/- .25
- heat loss through thermocouple well - negligible due to insulated pipe before and after thermocouples +/- 0

Combined bias at meter (°F) +/- .409

Orifice inlet temperature was obtained from:

$T_{oi} = (T_{oi1} + T_{oi2})/2$ (9)

and applying equation (2): Bias = $\{(1/2*.409)^2 + (1/2*.409)^2\}^{1/2}$ = +/- .289

Also, $T_{oir} = T_{oi} + 459.7$ (10)

Applying equation (2): Bias = $\{(1*.289)^2 + (0*0)^2\}^{1/2}$ = +/- .289

Gas composition, given in Table 2 with other gas data, is measured with a gas chromatograph. The chromatograph yields an accuracy of 2% of area for each gas. The amount of any gas in the composition is defined by the area of the gas divided by the total area, e.g.,

amount of $N_2 = A_{N_2}/(A_{N_2} + A_{O_2} + A_{CH_4})$ (11)

The molecular weight of the mixture was obtained with the data in Table 2 by:

$$MW = MW_{N_2}*A_{N_2}/(A_{N_2} + A_{O_2} + A_{CH_4}) + MW_{O_2}*A_{O_2}/(A_{N_2} + A_{O_2} + A_{CH_4}) + MW_{CH_4}*A_{CH_4}/(A_{N_2} + A_{O_2} + A_{CH_4}) \quad (12)$$

and applying equation (2): Bias =

$$\{(.99473/1*0)^2 + (.01282*.02*.99473)^2 + (.00315/1*0)^2 + (3.9988*.02*.00315)^2 + (.00212/1*0)^2 + (-11.9572*.02*.00212)^2\}^{1/2} = \pm .000621$$

The gas constant bias was obtained from:

$$R = 1545.33/MW \qquad (13)$$

and applying equation (2): Bias =

$$\{(1/28.000*0)^2 + (-1545.33/28.000^2*.000621)^2\}^{1/2} = \pm .00122$$

Gas compressibility in the computerized data reduction process for N_2 uses a generalized compressibility routine. The accuracy of these calculations are referenced to the IUPAC Tables [7], believed by the authors to be the best available data.

Orifice Inlet Compressibility	
- comprss. routine vs. IUPAC	+/- .0011
- accuracy of IUPAC	+/- .001
Combined compressibility bias	+/- .0015

Orifice inlet density was obtained from:

$$\rho_{oi} = 144*P_{oia}/Z_{oi}/R/T_{oir} \qquad (14)$$

and applying equation (2): Bias =

$$\{(144/1.0/55.19/555.895*1.13)^2 + (-144*171.9/1.0^2/55.19/555.895*.0015)^2 + (-144*171.9/1.0/55.19^2/555.895*.00122)^2 + (-144*171.9/1.0/55.19/555.895^2*.289)^2\}^{1/2} = \pm .00546$$

The orifice diameter to orifice pipe diameter ratio, β, has no bias error. The orifice was calibrated with the orifice and orifice meter run, thus the bias is included in the discharge coefficient bias.

Orifice Delta P	
- calibration minimum division	+/- .1
- calibration traceable to NBS	+/- .083
- temperature effect on transducer	+/- .88
- zero shift with pressure on transducer	+/- .21
- temperature effect on readout	+/- .04
- measurement unsteadiness during runs	+/- .5
Combined bias at meter	+/- 1.043

Orifice delta P and orifice delta P bias were converted from "H_2O to psi by multiplying each by .0361 (page 153 of [6]).

The constant pressure specific heat data, given in Table 2, was obtained from page 683 of reference [8] and corrected for temperature from all six runs. The constant pressure specific heat of the mixture was obtained from (12) with C_p substituted for MW and then applying equation (2): Bias =

$$\{(.99473/1*.0043*29.192)^2 + (-.016132*.02*.99473)^2 + (.00315/1*.003*29.4759)^2 + (.26767*.02*.00315)^2 + (.00212/1*.0015*36.3798)^2 + (7.17167*.02*.00212)^2\}^{1/2} = +/- .1249$$

The ratio of specific heats was obtained from:

$$k = Cp/(Cp - 8.31434) \quad (15)$$

and applying equation (2): Bias =

$$\{(-8.31434/(29.2081-8.31434)^2 *.1249)^2 + (29.2081/(29.2081-8.31434)^2 *0)^2\}^{1/2} = +/- .00238$$

The orifice expansion factor was obtained from:

$$Y = 1-(.41 + .35*\beta^4)*\Delta P/P_{bia} /k \quad (16)$$

and applying equation (2): Bias =

$$\{(-1.4*.23075^3*5.818/171.9/1.3979*0)^2 + ((.41 + .35*.23075^4)/171.9/1.3979*.0377)^2 + (-(.41 + .35*.23075^4) *5.818/171.9^2/1.3979*1.13)^2 + (-(.41 + .35*.23075^4) *5.818/171.9 /1.3979^2)^2\}^{1/2} = +/- .000093$$

The variable X was obtained by equation (7) and applying equation (2): Bias =

$$\{(48.1273*(5.818/.8068)^{1/2} *.0054)^2 + (48.1273*(.8068/5.818)^{1/2} *.0377)^2\}^{1/2} = +/- .976$$

The orifice area was obtained from:

$$A = \pi/4*(OD/12) \quad (17)$$

Again, the orifice diameter bias is included in the discharge coefficient bias.

The orifice discharge coefficient was provided by Alden Research Laboratory with an accuracy of +/- .25%. For the 2.625" orifice (500 rpm runs), the discharge coefficient is .5975. For the 3.5" orifice (700 rpm and 1000 rpm runs), the discharge coefficient is 5983. Therefore, the bias of the discharge coefficient is:
Bias = .0025*.5975 = +/- .0015

The nozzle flow coefficient was obtained from:

$$K = C/(1-\beta^4)^{1/2} \quad (18)$$

and applying equation (2): Bias =

$$\{(1/(1-.23075^4)^{1/2}*.0015)^2 + (2*.5975*.23075^3/(1-.23075^4)^{3/2} *0)^2\}^{1/2} = +/- .0015$$

The mass flow rate was obtained by equation (6) and applying equation (2): Bias =

$\{(208.558*1.0005*.03758*.5983*60*.000093)^2 +$
$(.99*1.0005*.03758*.5983*60*.9960)^2 +$
$(.99*208.55*.03758*.5983*60*.00015)^2 +$
$(.99*208.55*1.0005*.5983*60*0)^2 +$
$(.99*208.55*1.0005*.03758*60*.0015)^2\}^{1/2} =$ +/- 1.481

The remaining parameters necessary to calculate the inlet capacity are compressor inlet pressure, measured with a bourdon tube pressure gauge with a mirrored dial, and compressor inlet temperature, measured with two iron-constantan thermocouples connected to a digital readout. The calibration of these instruments follows the same procedure as the orifice instruments.

Compressor Inlet Pressure Gauge	
- calibration minimum division	+/- .2
- calibration traceable to NBS	+/- .16
- measurement unsteadiness during run	+/- .1
Combined bias at meter (psi)	+/- .24

Compressor inlet pressure, P_{cia}, was obtained similar to equation (8) and then applying equation (2): Bias =
$\{(1*.24)^2 + (1*.49116*.018)^2\}^{1/2} =$ +/- .24

Compressor Inlet Temperature	
- calibration unsteadiness in bath temperature	+/- .2
- calibration traceable to NBS	+/- .25
- temp. effect on readout span	+/- .005
- temp. effect on readout junct.	+/- .05
- thermocouple drift, root mean square drift of two instruments, page 70 of reference [3]	+/- .54
- heat loss through thermocouple well - uninsulated pipe, root mean square of two runs	+/- .19
Combined bias at meter (°F)	+/- .657

Compressor inlet temperature, T_{ci}, was obtained similar to equation (9) and then applying equation (2): Bias =
$\{(1/2*.657)^2 + (1/2*.657)^2\}^{1/2} =$ +/- .465

Also, $T_{cir} = T_{ci} + 459.7$ (19)

and applying equation (2): Bias =
$\{(1*.465)^2 + (0*0)^2\}^{1/2} =$ +/- .465

Compressor Inlet Compressibility	
- comprss. routine vs. IUPAC	+/- .0025
- accuracy of IUPAC	+/- .001
Combined compressibility bias	+/- .0027

Compressor inlet density was obtained from:

ρ_{ci} = 144*P_{cia}/Z_{ci}/R/T_{cir} (20)

and applying equation (2): Bias =
$\{(144/1.0018/55.19/550.645*.24)^2$ +
$(-144*68.78/1.0018^2/55.19/550.645*.0027)^2$ +
$(-144*68.78/1.0018/55.19^2/550.645*.00122)^2$ +
$(-144*68.78/1.0018/55.19/550.646^2*.465)^2\}^{1/2}$
= +/- .00146

Compressor inlet capacity was obtained from:
$Q = \dot{m}/\rho_{ci}$ (21)

and applying equation (2): Bias =
$\{(1/.3253*1.481)^2 + (-278.670/.3253^2*.00146)^2\}^{1/2}$
= +/- 5.96

Capacity Precision Error Analysis

Now consider the precision errors associated with the 500 rpm data.

Barometer (" Hg)		29.255
- precision index (df=5)	+/-	.0383
Orifice inlet pressure (psig)		157.55
- precision index (df=5)	+/-	.288
- calib. prec. index (df=31)	+/-	.53
- combined precision index	+/-	.603
- combined degrees of freedom (1)		34
Orifice inlet pressure (psia) (8)		171.90
- precision index (2)	+/-	.6033
- degrees of freedom (3)		34
Orifice inlet temperature #1 (°F)		96.32
- precision index (df=5)	+/-	.746
- calib. prec. index (df=40)	+/-	.12
- combined precision index	+/-	.756
- combined degrees of freedom (1)		5
Orifice inlet temperature #2 (°F)		96.07
- precision index (df=5)	+/-	.736
- calib. prec. index (df=46)	+/-	.17
- combined precision index	+/-	.755
- combined degrees of freedom (1)		6
Ave. orifice inlet temp. (°F) (9)		96.20
- precision index (2)	+/-	.534
- degrees of freedom (3)		10
Ave. orifice inlet temp. (°R) (10)		555.89
- precision index (2)	+/-	.534
- degrees of freedom (3)		10

Orifice inlet density (lbm/ft^3) (14)	.8068
- precision index (2)	+/- .00294
- degrees of freedom (3)	38
orifice delta P (" H_2O)	161.16
- precision index (df=5)	+/- .935
- calib. prec. index (df=22)	+/- .17
- combined precision index	+/- .950
- combined degrees of freedom (1)	5
Orifice delta P (psi)	5.818
- precision index (2)	+/- .0343
- degrees of freedom (3)	5
Orifice expansion factor (16)	.9900
- precision index (2)	+/- .000068
- degrees of freedom (3)	9
The variable X ($lbm/ft^2/sec$) (7)	208.550
- precision index (2)	+/- .7224
- degrees freedom (3)	9
The mass flow rate (lbm/min) (6)	278.67
- precision index (2)	+/- .966
- degrees of freedom (3)	9
Compressor inlet pressure (psig)	54.43
- precision index (df=5)	+/- .163
- calib. prec. index (df=25)	+/- .08
- combined precision index	+/- .182
- combined degrees of freedom (1)	7
Compressor inlet pressure (psia) (8)	68.78
- precision index (2)	+/- .183
- degrees of freedom (3)	7
Compressor inlet temperature #1 (°F)	91.17
- precision index (df=5)	+/- .43
- calib. prec. index (df=41)	+/- .58
- combined precision index	+/- .722
- combined degrees of freedom (1)	28
Compressor inlet temperature #2 (°F)	90.72
- precision index (df=5)	+/- .34
- calib. prec. index (df=41)	+/- .26
- combined precision index	+/- .449
- combined degrees of freedom (1)	11
Ave. compressor inlet temp. (°F) (9)	90.95
- precision index (2)	+/- .4251
- degrees of freedom (3)	39
Ave. compressor inlet temp. (°R) (19)	550.64

- precision index (2)	+/-	.4251
- degrees of freedom (3)		39
Compressor inlet density (lbm/ft^3) (20)		.3253
- precision index (2)	+/-	.0009
- degrees of freedom (3)		8

Capacity Uncertainty

Capacity (acfm) (21)		856.702
- bias (per above)	+/-	5.964
- precision index (2)	+/-	3.800
- degrees of freedom (3)		17
- student-t distribution		2.110
Cap. uncertainty at 95% coverage	+/-	9.993
Cap. percent uncertainty	+/-	1.17

POWER ECONOMY ERROR ANALYSIS

Power economy for the compressor is obtained by converting the measured orifice mass flow rate into a standard flow rate at 14.7 psia, 60 °F in millions of standard cubic feet per day (MMSCFD). This standard flow rate is then divided into the brake horsepower to yield power economy.

Compressibility at standard conditions		
- comprss. routine vs. IUPAC	+/-	.0024
- accuracy of IUPAC	+/-	.001
Combined compressibility bias	+/-	.0026

The standard flow rate was obtained from:

$$\dot{m}_{STD} = .0003535 * \dot{m} * Z_{STD} * R \qquad (22)$$

and applying equation (2): Bias =

$$\{(.0003535*1.0021*55.19*1.481)^2 + (.0003535*278.720*55.19*.0026)^2 + (.0003535*278.720*1.0021*.00122)^2\}^{1/2} = \quad +/- \quad .0322$$

Power economy was obtained from:

$$PE = BHP/\dot{m}_{STD} \qquad (23)$$

and applying equation (2): Bias =

$$\{(1/5.450*.95)^2 + (-325.8/5.450^2*.0322)^2\}^{1/2} = \quad +/- \quad .395$$

Consider the precision errors associated with the 500 rpm data.

Standard mass flow rate (MMSCFD) (22)		5.450
- precision index (2)	+/-	.0189
- degrees of freedom		9

Power economy (BHP/MMSCFD) (23)		59.783
- bias (per above)	+/-	.395
- precision index (2)	+/-	.2378
- degrees of freedom (3)		15
- student t distribution		2.131
PE uncertainty at 95% coverage	+/-	.645
PE percent uncertainty	+/-	1.08

SUMMARY

The uncertainty hoped for prior to this analysis was +/- 1% on capacity, +/- 1% on brake horsepower and +/- 2% on power economy. While the brake horsepower and power economy accuracy levels were met, see Table 1, the capacity did not meet the desired level. Still, the +/- 2% capacity uncertainty is adequate for current objectives in our performance analysis work. Much effort was placed on the instrumentation, its calibration and use to maximize accuracy. Despite this, 95% coverage of the true value for the compressor capacity requires a +/- 2% band on the measured value. The controlability and test accuracy within the laboratory environment far outstrips that achievable in field tests observed by the authors. Compressor performance tests on field installations should be analyzed for error as done herein to determine the uncertainty of the results at 95% coverage in light of the market requirements on compressor performance guarantees.

The computer program used in the analysis proved extremely helpful. The traceability provided by the program showed data acquisition precision errors to be the largest contributors to uncertainty. Uncertainty was most sensitive to differential pressure transducer run-to-run variations. These run-to-run variations in delta P readings were caused by small run-to-run variations in other parameters such as compressor inlet pressure and temperature. The repeatability of the compressor to perform may also have contributed to these run-to-run variations. Generally, within run variations were low. This analysis indicates an increase in the number of runs per test point could improve the precision statistics. The data used for this analysis is 1-1/2 years old. Greater experience and additional controls lead the authors to believe the uncertainty with current data is lower.

The sources of the error analysis procedure used herein were cited under the "Definition of Error Terminology" near the beginning of this paper. The use of the procedure lends credence to the performance test results. The procedure is logical and straightforward. For a unique experiment, its application can be burdensome. For laboratories with dedicated facilities and computer availability, once the error propogation to the results (2) is derived, repeat analysis can readily be added as a test data reduction by-product. The use of such calculations at data sampling time can alert operators to sources of unreliable data. If the ASME Performance Test Code, Instrument and Apparatus Committee number 19.1 adopt a similar form of Measurement Uncertainty Standard [5], the authors' facility will most likely incorporate it as a part of their standard compressor performance data reduction procedure.

Table 1: PERFORMANCE SUMMARY

Speed (rpm)	500.2	700.0	999.7
Bias	1.0	1.0	1.0
Precision	.4	.0	.5
Degrees of freedom	5	5	5
Torque (ft*lbs)	3417.9	3620.9	4035.5
Bias	7.4	7.4	7.4
Precision	6.1	8.6	6.1
Degrees of freedom	15	9	15
Brake horsepower (hp)	325.8	482.6	768.1
Bias	.96	1.20	1.60
Precision	.64	1.15	1.22
Degrees of freedom	19	9	17
Uncertainty	1.6	2.9	3.0
% uncertainty	.5	.6	.4
Barometer (psi)	13.354	14.047	13.991
Bias	.0088	.0088	.0088
Precision	.0188	0	.0619
Degrees of freedom	5	5	5
Orifice inlet pressure (psig)	157.55	156.22	152.29
Bias	1.13	1.13	1.13
Precision	.60	.81	.54
Degrees of freedom	15	9	15
Orifice inlet temp. (°F)	96.20	93.87	91.43
Bias	.2892	.2892	.2892
Precision	.5432	.2775	.6323
Degrees of freedom	11	13	10
Orifice Delta P (psi)	5.818	3.716	8.588
Bias	.0378	.0376	.0378
Precision	.0343	.0531	.1111
Degrees of freedom	5	5	5
Comprs. suct. pressure (psig)	54.43	54.39	54.34
Bias	.24	.24	.24
Precision	.182	.127	.210
Degrees of freedom	8	13	7
Comprs. suct. temp. (°F)	90.95	90.97	90.32
Bias	.4646	.4511	.4476
Precision	.4251	.3700	.4415
Degrees of freedom	39	61	34
Capacity (ACFM)	856.70	1229.90	1836.01
Bias	5.96	9.82	12.13
Precision	3.80	9.58	13.71
Degrees of freedom	17	6	7
Uncertainty	9.99	25.41	34.62
% uncertainty	1.17	2.07	1.89
Power economy (BHP/MMSCFD)	59.78	62.00	66.13
Bias	.40	.47	.39
Precision	.24	.49	.46
Degrees of freedom	14	7	5
Uncertainty	.65	1.25	1.23
% uncertainty	1.08	2.01	1.86

Table 2: GAS COMPOSITION/DATA

Gas	Amount	MW	Cp (J/mol/K)	
N_2	99.473 %	28.013	29.1920	+/- .43%
O_2	0.315 %	31.999	29.4759	+/- .30%
CH_4	0.212 %	16.043	36.3798	+/- .15%

NOMENCLATURE

BAR - barometer reading ("Hg)
g_c - gravitational const. (lbm*ft/lbf/sec)
OD - orifice diameter
P - pressure
T - temperature

Subscripts

a - absolute pressure (psia)
ci - compressor inlet
g - gauge pressure (psig)
oi - orifice inlet
r - absolute temperature (R)
STD - standard
1 - instrument one of multiple instruments
2 - instrument two of multiple instruments

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