WHITE PAPER

AN EXPLANATION OF THE DG-1000 ACCURACY SPECIFICATIONS

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Introduction:

The purpose of this document is to explain the details of the accuracy specifications for the DG-1000 Digital Pressure and Flow Gauge, and how the overall uncertainty of the gauge was determined.

TEC
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CONTENTS

SECTION 2

BACKGROUND

Manufacturers of measuring instruments publish accuracy specifications to give users an idea of how accurately the instrument is capable of measuring a particular value. However, how these specifications are determined may vary widely from one manufacturer to another. The specifications of one manufacturer may be applicable only under conditions almost identical to those in the calibration laboratory, while another manufacturer's specifications may be applicable under a wide variety of conditions where the instrument is expected to be used; this results in an "apples to oranges" comparison that is not useful to users of the instrument.

This paper will clarify how The Energy Conservatory has determined the published accuracy specifications of the DG-1000. It can also be used to estimate uncertainty for using the instrument under specific conditions.

SECTION 3

METHODOLOGY

The Energy Conservatory has based the accuracy specification on **JCGM 100:2008** Evaluation of measurement data – Guide to the expression of uncertainty in measurement (hereafter called the "JCGM Standard"). The same standard is published as **ISO/IEC Guide 98-3**. Both documents are based on **Guide to the Expression of Uncertainty in Measurement (GUM):1995**, with only minor corrections.

This standard uses statistical methods to combine various components that contribute to the overall uncertainty of a measurement. Generally, the process is as follows:

1. Determine whether each component is "Type A" or "Type B", based on the data available to estimate the uncertainty, according to the definitions given in section 2.3 of the JCGM standard.
2. Determine the probability distribution of each component, based on the data available.
3. Normalize each component to a standard uncertainty value by dividing the uncertainty value by the divisor that is appropriate for the distribution determined in step 2.
4. Combine all of the standard uncertainty components to calculate the combined standard uncertainty. This is done using equation (10) in section 5.1.2 of the JCGM standard.

The combined standard uncertainty has a coverage factor $k=1$, by definition, meaning that the level of confidence p is 68.3%. This means that the "true" value would have only a 68.3% chance of being within the standard uncertainty. A higher level of confidence is generally more useful to people making measurements, so an expanded uncertainty with a coverage factor $k=2$, is used to give a higher level of confidence p of 95.5%. The accuracy specifications used by TEC are based on 95.45% level of confidence, or $k=2$. This is consistent with the industry practice of specifying uncertainty with a confidence of 95% or greater, $k=2$ or greater.

COMPONENTS OF UNCERTAINTY

The major components that contribute to the overall uncertainty are:

- Pressure reference, the uncertainty of the pressure reference used to calibrate the gauge
- Standard uncertainty of the gauge, how much the gauge typically varies from the pressure reference, including linearity, repeatability, and hysteresis.
- Temperature effect on the sensor, the effect of temperature changes on the gauge's measurement
- Drift of the sensor over time, how much the gauge's sensor changes over time, between calibrations
- Each of these components will be discussed and explained in the following sections.

4.1 PRESSURE REFERENCE (TYPE B)

The Energy Conservatory uses Mensor Series 6100 digital pressure transducers as the reference pressure for calibrating pressure gauges. They are calibrated annually and have a published uncertainty of 0.01% of full scale, with the following definition from the manufacturer:

The accuracy is defined by the total measurement uncertainty, which is expressed with the coverage factor (k = 2) and includes the following factors: the intrinsic performance of the instrument, the measurement uncertainty of the reference instrument, long-term stability, influence of ambient conditions, drift and temperature effects over the compensated range during a periodic zero point adjustment.

This means that the published specification is applicable over a range of conditions even wider than those found in TEC's laboratory.

At low pressures, however, the uncertainty will not depend on the manufacturer's specification since TEC's practice is to zero the pressure reference at the beginning and end of each gauge calibration. This is done by applying zero pressure for 1 second, and recording the average of 30 readings during this second. This average is then subtracted from all readings during calibration. Therefore uncertainty of the pressure reference at zero pressure depends only on how much the zero value varies during the calibration process. The variability of the readings of the Mensor pressure reference is recorded for each calibration, and was analyzed to find the standard deviation of the readings at zero pressure. Table 1 gives the standard deviation of the reading at zero for each of the two Mensor transducers; this is also the standard uncertainty.

This means that the published specification is applicable over a range of conditions even wider than those found in TEC's laboratory.

Data from the annual calibrations of each of the pressure reference transducers provides sufficient statistical data to establish a standard uncertainty at 500 Pa. The standard uncertainty at this pressure is comprised of 3 components: the standard uncertainty of Mensor's calibration standard, the standard deviation of the calibration points from that standard, and the effect of the autozero on the accuracy at other pressures. The first 2 of these come from the annual calibration reports received from Mensor. The third effect accounts for the fact that the small adjustments made to the reading at zero pressure will shift the readings at 500 Pa slightly. The standard deviation of this shift is equal to the standard uncertainty at 0 Pa.

The standard uncertainty at pressures between 0 Pa and 500 Pa is assumed to increase linearly with pressure. This assumption is consistent with the direction given in section 4.3.1 of the JCGM standard for evaluation of Type B standard uncertainties.

Nothing in TEC's many years of experience suggests any major nonlinearity or discontinuity of the behavior of these sensors between 0 and 500 Pa.

Mensor Serial Number at 500 Pa (Pascals)	Standard Uncertainty at 0 Pa (Pascals)	Standard Uncertainty
821773	0.0147	0.0464
821774	0.0118	0.0505

Table 1

At pressures greater than 500 Pa, the manufacturer's uncertainty specification is used for convenience, even though it may be an overestimate when compared with the uncertainty under 500 Pa. It is evident from the calculations of combined uncertainty that the Mensor pressure reference at pressures over 500 Pa has a negligible effect on the overall combined uncertainty. Compare Figure 1, and Figure 3.

4.2 STANDARD UNCERTAINTY OF THE GAUGE (TYPE A)

This value was determined from the calibration data of a sample of DG-1000 gauges. After each gauge has been calibrated and the calibration coefficients have been entered into the gauge's memory, pressure is again applied and the gauge readings are again compared to the reference pressure to verify that it meets specifications. TEC verifies that 100% of gauges exceeds the specifications at laboratory conditions at all points for all new gauges and recalibrations. The test is comprised of 10 points of positive pressure and 10 points of negative pressure. For each of these "points" the digital output from the gauge is recorded (as is done with TEC Log or TEC Tite software) and averaged for 5 seconds.

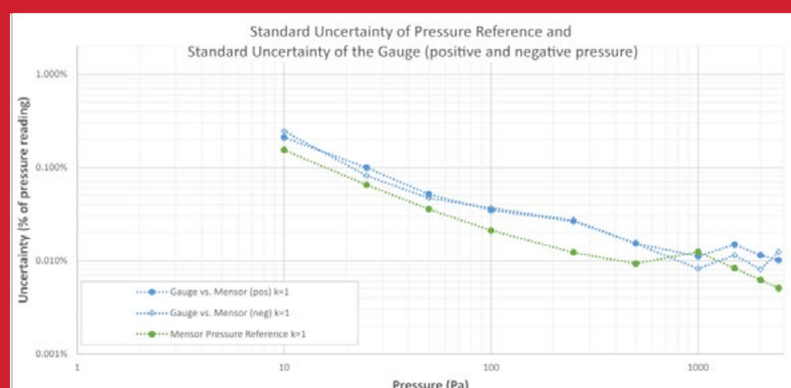

Figure 1

The difference between the readings from the gauge and pressure reference is recorded for each gauge in the sample. The standard deviation for the sample is then calculated, giving the standard uncertainty of the gauge. The standard uncertainty at each pressure is shown as a percent of pressure reading in the graph in Figure 1. The results are shown on a log-log plot, which makes it much easier to compare the respective errors across the pressure range.

4.3 TEMPERATURE EFFECT ON THE SENSOR (TYPE B)

The MEMS pressure sensor inside each gauge is affected by temperature. The manufacturer of the sensor specifies a temperature effect on the pressure reading in terms of microvolts of the output signal. We have calculated the equivalent effect as a percent of the pressure reading. This effect is 0.0678% of pressure reading per degree C, or .0372% of reading per degree F.

Since the manufacturer does not give any information about the confidence interval of the temperature specification, we assume a rectangular probability distribution as explained in section 4.3.7 of the JCGM standard. Following equation 7 in the same section gives a probability divisor of 1.732, and results in the standard uncertainty values shown in Table 2.

Conditions	Temperature Range	Standard Uncertainty
Laboratory	67 – 77 °F (19.4 – 25.0 °C)	0.107 % of reading
Typical Use	54 – 90 °F (12.2 – 32.3 °C)	0.193 % of reading

Table 2

4.4 SENSOR DRIFT OVER TIME (TYPE A)

The best estimate that TEC has for the sensor drift over time comes from recalibration of over 2500 model DG-700 pressure gauges. The data comprises over 5000 sensors ranging from a few days to over 6 years since the previous calibration. The sensors in the DG-1000 are a very similar model made by the same manufacturer as the sensors in the DG-700. TEC's recalibration data far surpasses any data the manufacturer has for either sensor. This data is shown in Figure 2.

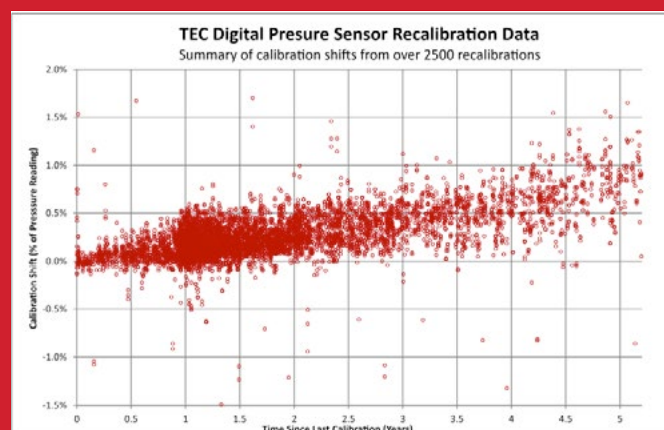

Figure 2

It is clear from the graph that the drift has both a random and systematic component. After 1 year, some sensors have drifted positive and some have drifted negative. However more gauges have drifted positive, and this trend increases over time. We have therefore modeled both the random and systematic components of the drift over time.

Although section 3.2.4 of the JCGM Standard assumes systematic components of error have been corrected, this is impractical for our application. Therefore, we follow the guidance in section F.2.4.5 and will add the uncorrected error arithmetically to the expanded uncertainty values.

Conditions	Time Since Previous Calibration	Standard Uncertainty (Random Component)	Uncorrected Systematic Error
Laboratory	0.33 years (4 months)	0.108 % of reading	+ 0.067%
Typical Use	2 years	0.120 % of reading	+ 0.282%

Table 3

COMBINED STANDARD UNCERTAINTY AND EXPANDED UNCERTAINTY

In the absence of any data to the contrary, each of the four components of the uncertainty is assumed to be independent of the others, and may therefore be combined using Equation 10, in section 5.1.2 of the JCGM standard. This calculation is done for two separate sets of conditions that were indicated above in table 2 and table 3 of this paper as "Laboratory" and "Typical Use" conditions. The more tightly controlled conditions are called "Laboratory" conditions, but in reality they are easily achieved by anyone wanting to take advantage of the higher accuracy.

In order to provide a more useful depiction of the uncertainty an Expanded Uncertainty (U) is calculated from the Combined Standard Uncertainty (uc). This is done by simply multiplying the chosen coverage factor (k=2) by the Combined Standard Uncertainty. This gives a 95% level of confidence for the uncertainty.

As mentioned in section 5.4 above, since the sensor drift over time has a random and a systematic component, we have added the systematic component to the expanded uncertainty to indicate the maximum error that may be expected (with 95% confidence). It should be noted that this maximum error would only occur in the positive direction, since the systematic error is positive. In the negative direction, the maximum error would be smaller. For convenience and clarity, the accuracy specification is stated symmetrically, even though this is an overstatement of the probable error.

5.1 LABORATORY CONDITIONS

Laboratory Conditions include a temperature range of 67 – 77 °F (19.4 – 25.0 °C) and 4 months between calibrations. Under these conditions, Table 4 shows the calculations at the 10 pressures used in a typical DG-1000 calibration.

The more tightly controlled conditions are called "Laboratory" conditions, but in reality they are easily achieved by anyone wanting to take advantage of the higher accuracy.

Combined Uncertainty Calculations at Laboratory Conditions

Pressure (Pa)	Pressure Reference	Gauge Standard Uncertainty	Temp. Effect	Sensor Drift (Random)	Combined Standard Uncertainty	Expanded Uncertainty k=2 (95%)	Sensor Drift (Systematic)	Exp. Unc. + Systematic Drift
10	0.153%	0.228%	0.107%	0.108%	0.314%	0.628%	0.067%	0.695%
25	0.065%	0.091%	0.107%	0.108%	0.189%	0.378%	0.067%	0.445%
50	0.036%	0.049%	0.107%	0.108%	0.164%	0.328%	0.067%	0.395%
100	0.021%	0.036%	0.107%	0.108%	0.158%	0.316%	0.067%	0.383%
250	0.012%	0.027%	0.107%	0.108%	0.155%	0.310%	0.067%	0.377%
500	0.009%	0.015%	0.107%	0.108%	0.153%	0.307%	0.067%	0.374%
1000	0.012%	0.010%	0.107%	0.108%	0.153%	0.306%	0.067%	0.373%
1500	0.008%	0.013%	0.107%	0.108%	0.153%	0.306%	0.067%	0.373%
2000	0.006%	0.010%	0.107%	0.108%	0.153%	0.306%	0.067%	0.373%
2450	0.005%	0.011%	0.107%	0.108%	0.153%	0.306%	0.067%	0.373%

Table 4

5.2 TYPICAL USE CONDITIONS

We assumed that most gauges are used between 54 – 90 °F (12.2 – 32.3 °C), and that they follow TEC's recommended 2 year interval for calibration. Table 5 shows the combined uncertainty calculations at the 10 pressures used in a typical DG-1000 calibration.

Combined Uncertainty Calculations at Typical Use Conditions

Pressure (Pa)	Pressure Reference	Gauge Standard Uncertainty	Temp. Effect	Sensor Drift (Random)	Combined Standard Uncertainty	Expanded Uncertainty k=2 (95%)	Sensor Drift (Systematic)	Exp. Unc. + Systematic Drift
10	0.153%	0.228%	0.193%	0.120%	0.357%	0.713%	0.282%	0.995%
25	0.065%	0.091%	0.193%	0.120%	0.254%	0.507%	0.282%	0.789%
50	0.036%	0.049%	0.193%	0.120%	0.236%	0.471%	0.282%	0.753%
100	0.021%	0.036%	0.193%	0.120%	0.231%	0.463%	0.282%	0.745%
250	0.012%	0.027%	0.193%	0.120%	0.230%	0.459%	0.282%	0.741%
500	0.009%	0.015%	0.193%	0.120%	0.228%	0.457%	0.282%	0.739%
1000	0.012%	0.010%	0.193%	0.120%	0.228%	0.456%	0.282%	0.738%
1500	0.008%	0.013%	0.193%	0.120%	0.228%	0.456%	0.282%	0.738%
2000	0.006%	0.010%	0.193%	0.120%	0.228%	0.456%	0.282%	0.738%
2450	0.005%	0.011%	0.193%	0.120%	0.228%	0.456%	0.282%	0.738%

Table 5

5.3 UNCERTAINTY AND ACCURACY SPECIFICATIONS

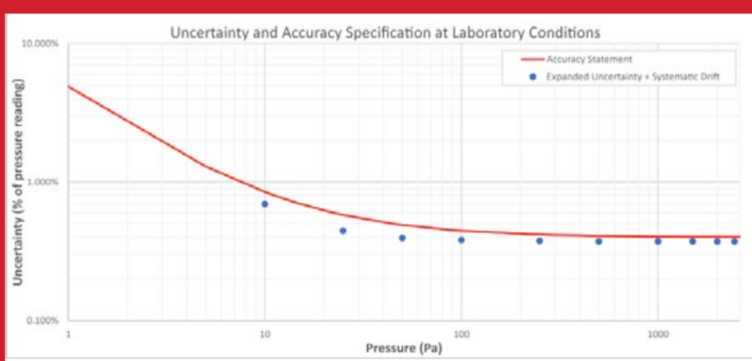

Figure 3

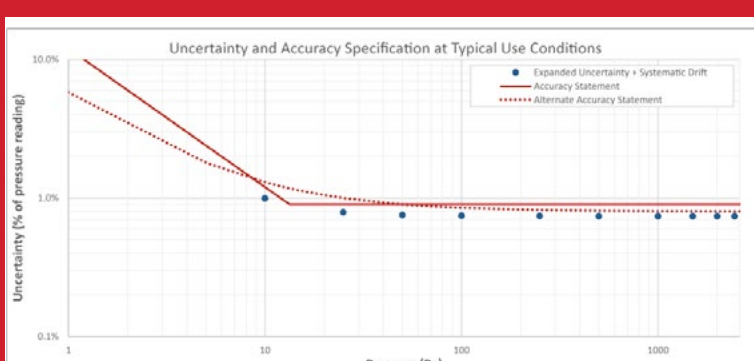

Figure 4

Once the uncertainty has been quantified, we use the data points to determine an accuracy specification that will be published in our literature. It is not practical to present all of the individual points shown in Table 4 or Table 5 so we simplify the information into a more concise statement.

5.3.1 At Laboratory Conditions

At laboratory conditions, the accuracy statement is as follows:

± 0.4% of pressure reading ± 0.045 Pa

Figure 3 shows how the accuracy statement compares to the uncertainty calculations it is based on.

5.3.2 At Typical Use Conditions

At typical use conditions, the published accuracy statement is as follows:

± 0.9% of pressure reading or 0.12 Pa, whichever is greater

SECTION 4

Figure 4 shows how the accuracy statement compares to the uncertainty calculations it is based on.

Figure 4 also includes an alternate statement that may be used to predict performance of the DG-1000.
The alternate Statement is: **± 0.8% of pressure reading ± 0.05 Pa**
This statement is slightly more complicated since the two parts must be added together, but it is a more consistent representation of the gauge's true performance, since the uncertainty data does not contain a "sharp corner" like the published statement does. Users of the gauge may use either statement that meets their needs; the results are not dramatically different.

SECTION 6

CONCLUSION

The uncertainty of the DG-1000 pressure gauge was analyzed in accordance with JCGM 100:2008. The analysis includes all effects that are known and can be quantified by research or practical testing. Under both laboratory and typical use conditions, the results of this analysis are presented with a coverage factor of 2 (k=2), which results in a 95% level of confidence. The published specifications are shown in a graphical comparison with the uncertainty analysis.

For more information visit www.energyconservatory.com

SECTION 7

REFERENCES

1. *JCGM 100:2008 Evaluation of measurement data – Guide to the expression of uncertainty in measurement*, Joint Committee for Guides in Metrology

Note: This standard is available as a free download at: **http://www.bipm.org/en/publications/guides/**

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