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PRESSURE CALIBRATION;

FACTORS THAT YOU CAN'T IGNORE

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ABSTRACT

With the never-ending focus on performance and efficiency, companies are establishing that the final optimized results are usually a mix of the environment, operation and equipment design.

To get the best out of any piece of equipment or system, it has been shown that small differences in the sensor inputs can have a major impact on the final system efficiency.

This, in turn, has put increased focus on the "accuracy" of input sensors. In the case of pressure sensors, the procedure used to calibrate a sensor can have varying final results on the performance of the calibrated sensor.

This paper will highlight the factors that affect the performance of a deadweight tester. As well, differences will be detailed between different types of calibrators: deadweight testers, automatic digital pressure controllers and digital pressure standards.

DEFINITION OF PRESSURE

Pressure is not a basic unit of measure such as seconds, amps or mass but a derived unit (see figure 1).

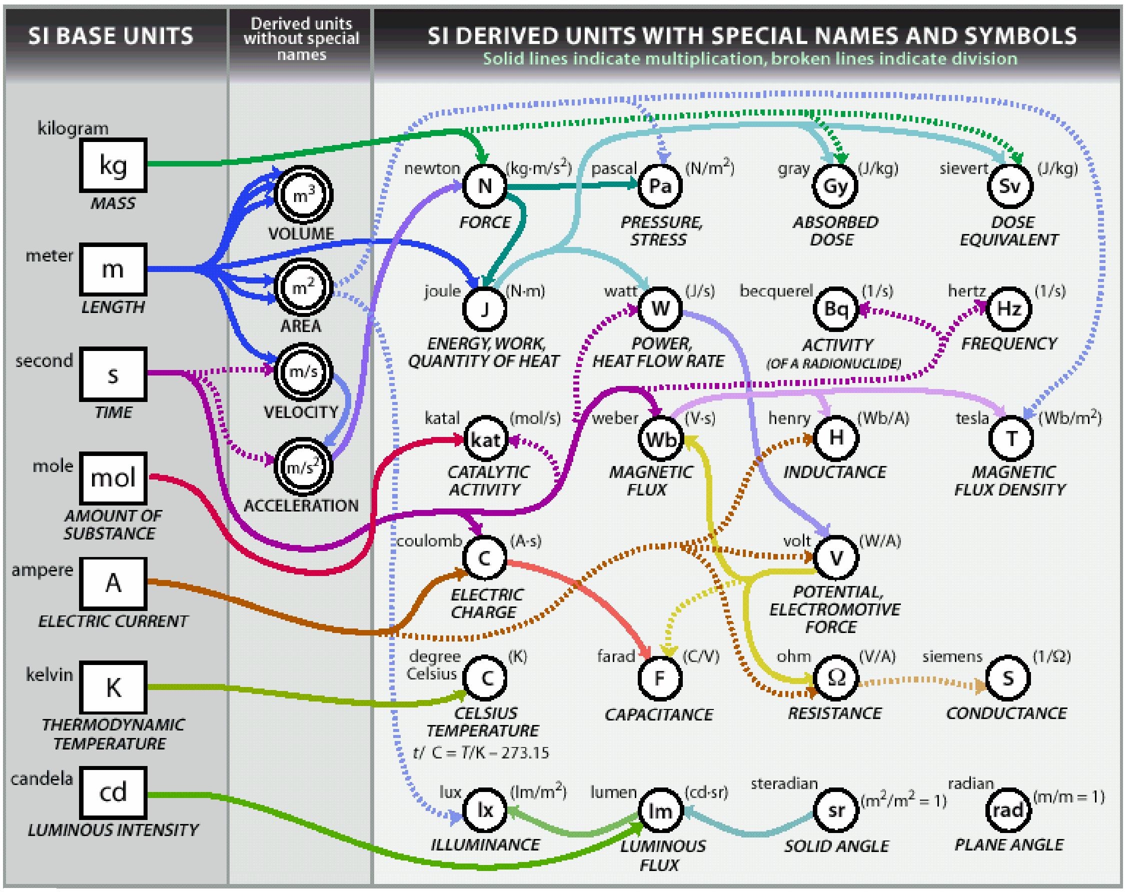

Figure 1: SI Base Units and Derived Units

From the figure above, it can be seen that Pressure is a combination of Force and Area or simply stated; Pressure = Force / Area

In the old English system, pressure units were pounds per square inch, which although an intuitive measure of pressure, leads to many misunderstandings when using a deadweight tester (DWT).

For example, there are many different factors that influence the Force factor:

- Mass load
- Surface tension
- Local gravity
- Air buoyancy
- Attitude (level)

To demonstrate the many factors that influence pressure, we will continue with the English units, psi, and the use of a DWT to produce that pressure. DWT's, sometimes called piston gauges or deadweight gauges, in their most basic form, is a device consisting of a series of "weights" pushing on a piston of a known area. The force that balances this downward force is the pressure given in the units of pounds per square inch.

Since commercial DWT's are available with a total uncertainty of 10 PPM or 0.0010% of reading, there are several factors that we must understand and compensate for in order to achieve this level of uncertainty. To ignore them is to increase the total uncertainty of the pressure produced by a factor of 10.

To understand the different factors that affect our basic formula, let us first look back at the force component. In our example, the force is created by a series of mass pieces or weights on the piston.

Since Force = Mass X Acceleration, the Force is created by the masses being accelerated in the downward direction by the gravitational attraction of the earth.

The standard value for gravity is given as 980.665 cm / sec^2. However, the actual value is a function of where the DWT or mass set is on the earth's surface. Since the earth is not a perfect sphere but is really a “squashed” ball at the poles to the extent that there is a 22 km difference between the equator and the poles. The standard value of gravity is based on latitude 45°.

Even knowing what your latitude position is, you cannot interpolate the value of gravity to any degree of certainty because of anomalies in the earth’s surface; large buildings, subsurface rifts or large mineral deposits. All have an effect on the gravity.

Typically, there is either a public and/or private organization that can determine what the value of gravity is at any location. Within Canada, the federal government has a Gravity Standards Officer, Geodetic Survey Division, Natural Resources Canada.

Lest you think that since you have a known gravity value within 50 KM of your location and that your gravity value should be “close” enough, consider the following example in the greater Montreal area:

Dorval Airport	980.629 cm/sec^2
Mont Royal	980.619 cm/sec^2
Concordia University	980.624 cm/sec^2
Mirabel Airport	980.634 cm/sec^2

When you calculate the difference from the standard gravity value of 980.665 cm/sec^2, there is a significant difference:

Dorval Airport	$1 - \frac{(980.629)}{(980.665)} = 0.000037 = 37$ PPM
Mount Royal	$1 - \frac{(980.619)}{(980.665)} = 0.000047 = 47$ PPM
Concordia University	$1 - \frac{(980.624)}{(980.665)} = 0.000042 = 42$ PPM
Mirabel Airport	$1 - \frac{(980.635)}{(980.665)} = 0.000031 = 31$ PPM

Aside from the large deviation from the standard gravity value, there is an 11 PPM difference just between Concordia University and Mirabel Airport.

In Canada, gravity surveys can be obtained with uncertainty values of ≤ 1 PPM (0.0001%).

AIR BUOYANCY

The effect of air buoyancy on the mass set is based on Archimedes' Principle of Buoyancy;

> "The weight of an object submerged in a fluid is diminished by the weight
> of the fluid displaced."

This Principle is one of only several discoveries by Archimedes, a Greek mathematician that lived from 287 BC to about 211 BC in Syracuse, Sicily. Although a mathematician, he developed several other objects such as the Archimedes Screw. He is considered, by some, to be one the one of the greatest mathematicians of all time, beside Isaac Newton (1643-1727) and Carl Fredrich Gauss (1777-1855).

The effect of air buoyancy on a mass set can be best shown by balancing two masses of different but known specific gravity. Consider the case where we balance a mass of 1 Kgm Brass (8.4 gms/cm^3) against an Aluminum mass (2.7 gm/cm^3). In air, the balance is perfectly level.

However, if each mass was enclosed in a chamber and the air was removed, it would result in the balance tipping towards the aluminum mass. This is because the greater volume of the aluminum no longer displaces an equal volume of air, or no longer has the buoyancy of air as an offset, and hence an imbalance occurs.

It is now necessary to apply a correction factor to offset the "floating" effects of the mass set in air. In order to apply a correction factor, we will need to know both the air density and the mass.

MASS SET

If we first set out to determine the volume of the mass set, we find that there are three different methods for calculating the volume;

1. Dimensional
2. Calculated
3. Apparent Mass

Dimensional although the most direct is fraught with practical limitations when you consider the complexity and size of the modern mass set with a variety of “dimples” and different shapes within one mass.

A calculated value is based on knowing the density and mass of the object. Once again, the reality is that the mass set can be very complex and in some cases consist of different materials. Combined with the uncertainty of knowing the exact specific gravity of each material, the calculated value still leaves too much uncertainty for high precision mass sets.

Apparent mass sidesteps all the dimensional and calculated deficiencies and simply compares the mass set to a known mass set to a given density at standard environmental conditions.

Apparent mass simplifies the process by reporting all of the mass values referenced to a single, common density in the presence of air at standard conditions.

The benefits to using “apparent mass” are;

1) It is not necessary to determine the mass under vacuum conditions
2) You do not have to make a buoyancy correction for each individual mass piece.

Thus by summing all of the apparent mass values together, a single buoyancy correction can be applied to the entire mass load.

The apparent mass method was initially referenced to Brass mass of 8.4 g/cm^3 and more frequently now to Stainless Steel mass of 8.0 g/cm3.

AIR DENSITY

Now that we can determine the volume of the mass set, the next part is to determine the ambient air density. Air density is a function of;

Air Temperature (T) °C
Relative Humidity (U)% RH
Barometric Pressure (P) mmHg

The exact formula being;

$$\rho_{air} = \frac{(0.0004646*(P-4990221.6*U*e^{(-5315.56/273.15 + T)}))}{(273.15 + T)}$$

Fortunately, today’s technology allows us to measure, with an electronic sensor, the ambient air density with an uncertainty of 0.9 PPM. Calculations will show that as long as T is within ±1.5°C, P is ±0.25kPa and U is ±15% RH, then the uncertainty will be 0.9 PPM.

ATTITUDE

The effect of gravity on the mass load is based on a downward force. In our case, the assumption is a true vertical force. When the force is not vertical, the force acting along the axis is reduced by the cosine of the angle of deviation from vertical.

In other words;

$$F = ma (\cos \Theta)$$

The error due to the piston not being vertical or the deadweight tester platform not being horizontal can quickly become significant.

To illustrate;

Cosine Θ (minutes of arc)	Error PPM	
1	0.022	(0.000002%)
5	1.1	(0.00011%)
15	9.5	(0.00095%)
60 (1 degree)	152	(0.015%)
120	609	(0.061%)

Fortunately, the simple "bulls eye" level found on most DWT platforms is accurate to within 5 minutes of arc. However, it is surprising the number of installations that don't even bother to level the DWT.

At this point, the Pressure = Force / Area has developed to;

$$P = \cos \Theta \, \Sigma \, ma \, [1- \rho_{air} / p_m]$$

Where ρ_{air} = ambient air density
ρ_{ref} = reference air density

PISTON EFFECTIVE AREA

The next variable to consider is the actual area being exposed to the pressure. The two primary factors that influence the piston area are distortion and temperature.

If we examine distortion in more detail, we find that it is affected by piston/cylinder design (simple, re-entrant or controlled clearance) and the material used in the P/C.

The Simple Piston / Cylinder design is very effective for low pressure (see figure 2) but as pressure increases, the walls of the cylinder are forced apart. At some point, the sink rate is so high as to make the DWT operation not practical.

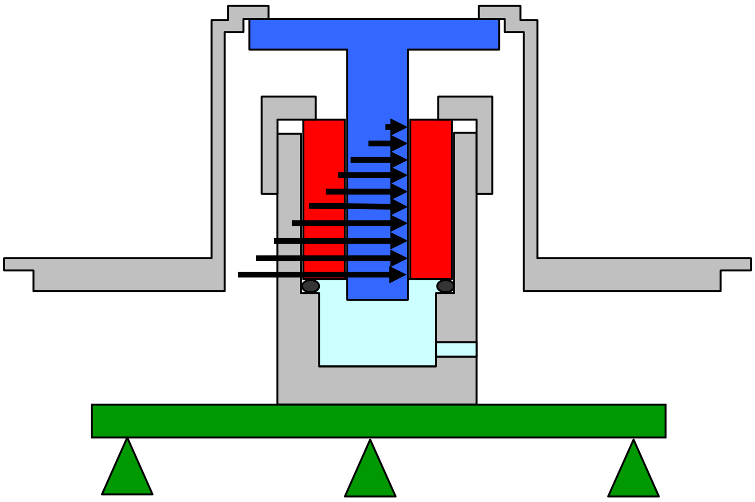

Figure 2: Simple Piston / Cylinder showing pressure gradient on cylinder

In order to reduce the pressure gradient along the cylinder, the “O” ring is moved higher up the cylinder so that the pressure can act on both sides of the cylinder. This design is called the Re-entrant Piston / Cylinder design and although more complex, becomes more effective at reducing the effects of higher pressure on the cylinder.(see figure 3)

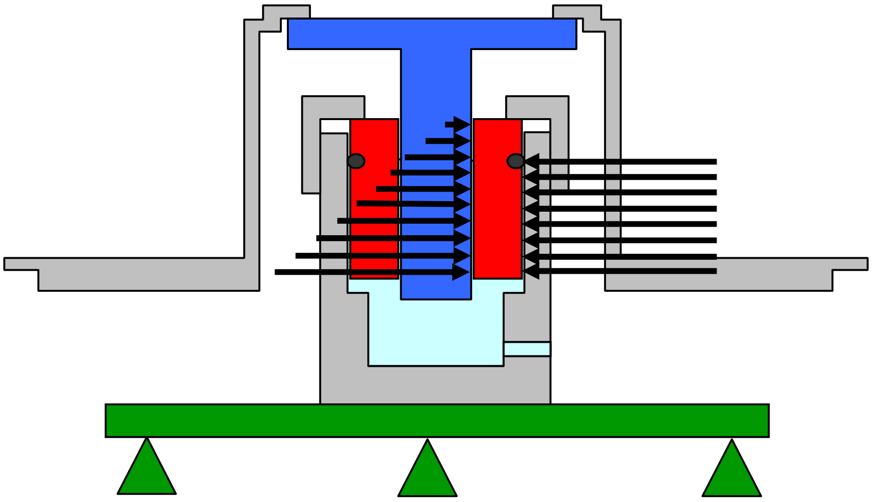

Figure 3: Re-entrant Piston / Cylinder showing pressure gradient on cylinder

The Controlled Clearance P/C design is of academic interest only since this design is typically reserved for research and for extremely high pressures, e.g. 150,000 psi. The intent of the design is to vary the jacket pressure till the sink rate is constant. This is a very complex and time consuming process and not practical in commercial applications.

TEMPERATURE

In order to control the distortion in the P/C, we have shown how P/C design attempts to minimize this distortion. The other major factor is the temperature of the pressure media and the effect that it has on the P/C. The change in temperature is due the energy being put into the media as the pressure increases. The faster the pressure is raised, the faster the temperature raises and distorts the P/C. In order to minimize the temperature effects, operational procedures can definitely help. Increase the pressure slowly and not in single large steps, i.e. Zero to 10,000 psi.

The other factor that can help is the selection of material for the P/C. The thermal coefficient of expansion for piston cylinder materials is well known and a brief look at the chart in figure 4 will explain why tungsten carbide, although difficult to machine, is used for its low thermal coefficient.

Thermal Coefficient of Expansion for Piston Cylinder Materials;

Piston	Cylinder	Coefficient
Steel	Bronze	30 ppm/°C
Steel	Steel	24 ppm/°C
Steel	WC	15 ppm/°C
WC	WC	9.1 ppm/°C

WC = Tungsten Carbide

Figure 4: Thermal Coefficient of Expansion for Piston Cylinder Materials

The effective area formula now becomes;

$Ae = Ao\ (1+b.P+b_2P^2)\ [1+C(t-tr)]$

that corrects for the effect of deformation and temperatures different from our standard conditions.

OTHER PRESSURE INFLUENCES

Other operating influences that must be considered are;

- Pressure gradients
- Reference plan
- Reference Pressure
- Adiabatic effects
- Others
    - Leaks

- Vibration
- Air drafts
- Magnetism
- Static electricity
- Rotation

PRESSURE GRADIENT

Pressure gradient or “head” must be compensated for when the Device Under Test (DUT) is not at the same level as the DWT.

This is important in a Hydraulic DWT and not as important for a Pneumatic DWT. From a practical point of view, typically hydraulic head is 0.03 psi per inch of difference, whereas pneumatic head for Nitrogen is approximately 0.000043 psi per inch of difference. Obviously, it is far more important factor in a hydraulic DWT.

The formula for correction would be;

$P_1 = P_2 + (P_f - P_a)$ x h x g./ar

Where P_1 = DWT Pressure

P_2 = DUT Pressure

P_f = density of compressed fluid (liquid or gas)

Pa = density of ambient air

h = vertical difference between the DUT and DWT

g_1 = local gravity

ar = gravity standard

It should be noted that the pneumatic error could become significant if the DWT pressure is very high (due to the compressibility of gas). For example, the error for Nitrogen at 15,000 psi is 0.02

psi per inch of difference. However, for hydraulic fluids, the added error from ambient to 15,000 psi is less than 0.001 psi per inch.

If at all possible, your calibration bench should be set up such that the DWT and the DUT are at the same level. This one operational procedure can simplify and reduce possible height reading errors as well as save time in making the different height measurements.

PRESSURE EQUATION USING A DWT

From our initial P = F/A, we have developed a formula, due to the various contributing factors, of;

$$P = \frac{\cos o\ E\ ma\ [1-P\ air/pm]}{Ao(1+b_1P_1+b_2P^2)\ [1+C(t-tr]} + P_{fh} + P_{ref}$$

All of this is by way of trying to establish the “Total Uncertainty” of the pressure produced. “Total Uncertainty” can be defined as; “our ability to define the “total uncertainty” of the system is dependent upon our ability to identify, measure and correct each parameter which influences the physical pressure measurement.”

TOTAL UNCERTAINTY ANALYSIS

The following is a typical uncertainty analysis.

Error Source	Uncertainty (ppm)	Effective
Area (From Cal. Report)	14.0	
Mass (From Cal. Report)	3.7	
Temperature (0.14°C)	1.3	
Temperature Coefficient (5%)	0.3	
Pressure Head (+/- 0.5 cm)	1.0	
N_2 Density Coefficient (5%)	1.6	
Level (5 min.)	1.1	
Float Position (0.02 cm)	0.02	
Local Gravity (1 mgal)	1.0	
Buoyancy (1.5°C, 0.25 kpa,15%RH)	0.9	
(K=2) Total (rss)	14.7 ppm	

WHAT IF VARIABLES ARE LEFT UNCORRECTED

Consider the following example where a 0.01% accurate DWT is used without compensating for any of the variables.

	PPM	%
Accuracy (at std. Conditions)	100	.01
Buoyancy	140	.014
Level (Off by 1 degree)	152	.0152
Distortion	300	.03
Temperature	120	.012
Head (12" Hydraulic Fluid)	300	.03
Gravity (Calgary)	86	.0086
Total Additive	1198	0.12%
Total RSS	504	0.05%

To demonstrate the dramatic effect that gravity has on the total uncertainty, if we were in Houston, the error due to gravity is 1,400 PPM, which has the following effect;

Total Additive	2512	0.25%
Total RSS	1486	0.15%

One additional point worth stressing is the total uncertainty method displayed is typical of North America and recognized by both NIST and National Research Council as an acceptable method of calculating uncertainty. It is of interest that the probability factor is K = 2 or Sigma = 2. In other words, 95% of the cases will fall within the standard statistical "Bell Curve".

In Europe, some companies will state their uncertainties for K = 1 or 68% of the cases. To bring these figures to North American standards, you need only multiply the total uncertainty by a factor of two.

DIGITAL PRESSURE CONTROLLERS

Digital pressure controllers have produced the most advances in precision pressure technology. Indeed, in some cases, some controllers now have surpassed DWTs in total uncertainty.

Digital pressure controllers will produce a precise pressure based on a pressure set point being entered through a numeric keypad or via a communication port such as RS232 or IEEE 488. This pressure will then be maintained automatically.

Pressure controllers can be provided for full scale ranges of 1 psi or less to 40,000 psi full scale range.

However, a side by side comparison to DWTs is not easily achieved. Whereas DWTs provide a value for the total uncertainty of the pressure produced, controllers provide only bits and pieces of the final uncertainty value.

To start with, controllers typically use an electronic sensor as the pressure reference standard.

Based on the pressure imposed, the sensor will provide an electrical signal output that is representative of the imposed pressure.

Whereas digital pressure controllers are not affected by gravity and air density (for most sensors), the sensor is affected by temperature, drift, linearity, hysteresis, repeatability and calibration.

The controller output has an additional variable of control stability or ability to remain at set point. Although not directly related to accuracy, it is an operational factor to be considered.

Most manufacturers promote the “precision” of the controller. However, this is not the total uncertainty of the controller.

The precision figure typically includes linearity, hysteresis, repeatability and an operational temperature range. Missing is drift over time and the calibration error passed from the actual calibrator that calibrated the pressure sensor.

All manufacturers tend to omit the calibration error based on the logic that the "precision" value is what the controller (sensor) is capable of. However, since the manufacturer can't control what the user may use to calibrate the sensor, they do not provide a total figure in bold. I say in bold because to their credit, the value of drift and calibrator error is generally found somewhere on the controller data sheet along with a total error figure based on a fixed time period, i.e. six months or typically one year.

A user can calculate the total error by collecting the values for:

- linearity, hysteresis, repeatability
- temperature effects
- drift
- calibration error

and doing on RSS (Square Root of the Sum of the Squares) of the variables.

DIGITAL PRESSURE INDICATORS

The total accuracy of the pressure sensor, as stated before under digital pressure controllers is:

- linearity, hysteresis, repeatability
- temperature
- drift

The RSS of these values will provide a total error figure.

DIGITAL PRESSURE INDICATOR ACCURACY STATEMENTS

Accuracy statements are now stated in terms of % Full Scale or % of Reading with different variations on each.

Percent of Full Scale is the accuracy based on full scale or total pressure range. For the following examples, we will use 100 psi as the full scale range.

An example of +/- 0.25% FS accuracy would be ±0.25% FS of 100 psi. or ±0.25 psi throughout the entire range of 0 to 100 psi.

TRIPLE SCALE

However, some manufacturers can provide a triple scale of a pressure range, which is more “accurate” than just % of FS.

For example triple scale of 100 psi could be scale #1 = 0 – 30 psi, scale #2 = 0 – 60 psi and scale #3 = 0 – 100 psi.

The end user now has an accuracy of ±0.25% of each scale. For example, a pressure of 50 psi now has an accuracy of 0.25% of 60 or 0.15 psi instead of 0.25 psi on the single scale.

A further variation could be two sensors each with a triple scale, such that a 100 psi range would have 0-10 psi sensor and a 0-100 psi sensor, but each sensor has a triple scale.

Our example could then become six scales:

	Scale 1	Scale 2	Scale 3
Sensor 1	0 – 3	0 – 6	0 - 10 psi
Sensor 2	0 – 30	0 – 60	0 – 100 psi

Each scale would have an “accuracy” of ±0.25%.

A word of caution, manufacturers tend to hide the fact that when switching scales, you should (must) return to zero pressure. Failure to do so would result in offset errors being introduced.

% OF READING

Indicators are now available that state accuracy as % of reading which provides the user with the best possible accuracy statement.

Be aware of variations within this statement. Some manufacturers, state accuracy as % of reading from, for example, 20% to 100% FS.

In other words, from 20% to 100%, the error is ±0.25% of the reading between 20 psi and 100 psi. Below 20 psi, the error is fixed, that is ±0.05 psi from 0 to 20 psi.

When no range is specified over the % of reading statement, then there must be an additive error. Typically “X” % of FS is added to the % of Reading error. This must be since it is not possible to have “X”% of Reading where the reading is “zero”.

TRACEABILITY

Manufacturers, as a back-up to their claims of performance, typically note that their statement of accuracy has an unbroken link of traceability back to their country’s bureau of standards. In the USA, this is NIST and in Canada, it is the NRC, Bureau of Standards.

This statement is not given lightly for the integrity and reputation of the manufacturer is directly invoked. It is the user's guarantee that the manufacturer can back up their statement of "accuracy", under the specified conditions, to an independent standards body. It is the responsibility of the user to find the "standard conditions" and how it relates to the user's ambient conditions. From this information, the user can now make an informed evaluation of all the factors that will affect his pressure calibration.

SUMMARY

There are many factors that influence the uncertainty of a DWT. Some factors are quite dramatic; gravity, attitude being two of the most noticeable. However, if the user understands the basic principles behind the operation of the DWT then they can operate the DWT to their optimum design specifications. If they don't or simply ignore the various factors, then we have shown that the pressure produced can have an error 5 to 15 times the rating of the DWT.

Similarly with Digital Pressure Controllers, manufacturer's data sheets have all the information, albeit not always obvious, but it is left to the user to understand what the implications are to the final statement of uncertainty. We have shown that the highly touted "Precision" figure is but one part of the overall uncertainty equation.

Digital pressure indicators have such a wide variety of accuracy statements presented to the user that, once again, it is up to the end user to look beyond just the "number" and understand what the "number" really means.

As always, regardless of the product used, the end user must take the effort to understand the product being presented to them. The information is there; to ignore it, is at the user's own peril.

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