

Understanding Accuracy Ratings in Melt Pressure Sensors

ABSTRACT

This paper discusses the differences between the two predominantly used rating methods—Best-Fit Straight Line (BFSL) and Terminal Straight Line (TSL)—by which manufacturers of melt pressure sensors express their products’ accuracy and precision. This paper will also briefly discuss the possible systemic effects of unexpected deviations from melt pressure sensor accuracy on extrusion line output.

INTRODUCTION

The graph at right (*Figure 1*) probably looks a little dramatic. However, this is an example of the output level that a melt pressure sensor with a stated accuracy of $\pm 1\%$ of full scale output (FSO) could be delivering to the user’s control system. In the graphical example given, a 5,000 p.s.i. (FSO) melt pressure sensor’s output voltage is nearly 3.9% off from the ideal, or expected, value at 3,500 p.s.i. To most users, this would seem impossible. If you were truly concerned about accuracy your first reaction might be to call the manufacturer and demand a replacement, since, clearly, the sensor is not meeting the specification. Yet most manufacturers could easily defend the behavior of that sensor as being well within the specifications. In fact, the transfer function of the sensor in question could be much worse and still be within a $\pm 1\%$ Best-Fit Straight Line rating.

HOW ACCURATE IS YOUR MELT PRESSURE SENSOR REALLY?

When specifying and purchasing measurement components—sensors—for engineered systems, there can be numerous operating parameters that the system designer may take into account during the decision making process. Quite often, the designer will sacrifice a bit of performance in one parameter to obtain better performance along some other dimension. Occasionally, we might even let a subjectively determined characteristic carry a lot of weight: how “bullet-proof” the product is—its robustness—is one such characteristic. Or sometimes, it comes down to a matter of pure aesthetics.

In most cases though, the system engineer is more concerned with accuracy and precision than any other characteristic. This is especially true when the sensor will be used to generate the error signal in a closed-loop control system. After all, inaccuracy in the error signal can be amplified by system gains, thereby contributing to sub-optimal control performance.

Although accuracy and precision are not necessarily related, they can be quite clearly specified as in this specification from one melt pressure sensor manufacturer’s data sheet:

- Non-linearity:**
 $\pm 0.5\%$ of full scale maximum (BFSL)
- Repeatability:**
Within $\pm 0.1\%$ of full scale maximum

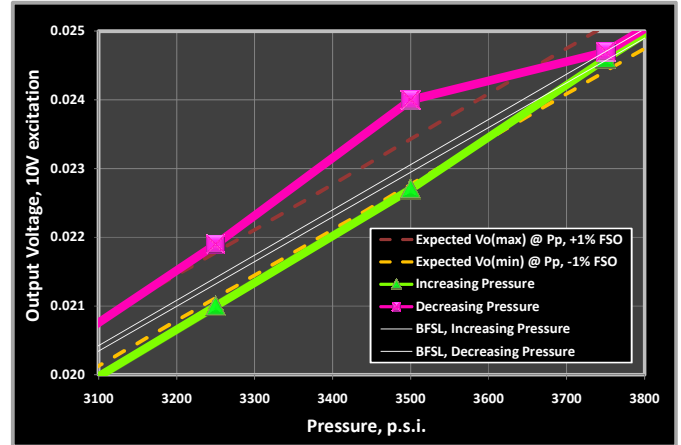


Figure 1

However, that snippet of a specification falls short of telling us everything that we might want to know about that sensor. While it is good to have a non-linearity rating, the specification says nothing about hysteresis. And the repeatability rating is nice, but it doesn’t tell the designer under what operating conditions that rating holds true. (To be fair, elsewhere on the same datasheet, specifications pertaining to drift relative to temperature are given.)

Before we get much further into this discussion on accuracy and precision and their effects on extrusion line performance, there are a few terms for which we should establish working definitions. For technical definitions as they pertain to strain gage based sensors, please refer to ISA-37.1-1975 (R1982), *Electrical Transducer Nomenclature and Terminology*. If you’re interested in a very deep presentation of the subject, a copy of *JCGM 100:2008, Evaluation of Measurement Data — Guide to the Expression of Uncertainty in Measurement* published by Working Group 1 of the Joint Committee for Guides in Metrology is an indispensable addition to the library. This is freely accessible at: http://www.bipm.org/utis/common/documents/jcgm/JCGM_100_2008_E.pdf

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DEFINITIONS

Linearity: as a percentage of full scale output (typically), the degree by which the transfer function of a transducer deviates from a straight line. *E.g.*, a perfect voltage-output pressure transducer will produce an output voltage that is directly proportional to the applied pressure; a doubling of pressure will result in an exact doubling of output voltage within the sensor's range. All real transducers have some non-linearity. For the discussion of rating methods that follows we have created an imaginary and very non-linear transducer—let's call it the iVeNT. *Figure 2* shows its transfer function.

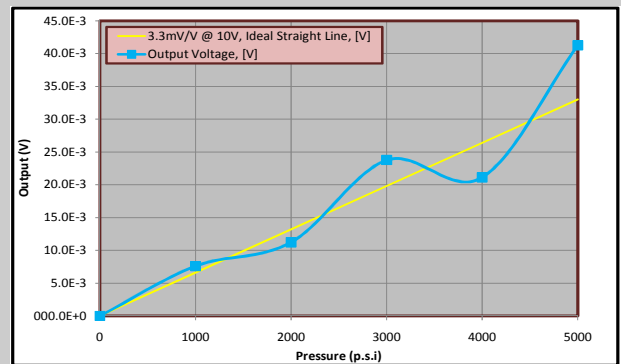


Figure 2

Hysteresis: the tendency of a transducer's output to not change in proportion to a change in the input depending on the starting value and direction of change. In other words, the sensor's output depends on the previous state(s) of the input. *E.g.*, pressure rising to 50% of full scale from 48% of full scale may produce a rising output voltage from 48% to 50% or 2% of the span, whereas pressure falling from 50% of full scale to 48% may produce an output changing from 50% to 49%, or 1% of the span, although falling pressure from 52% to 50% will produce a 2% change at the output. (It's true that settling time will affect apparent hysteresis, but if it takes the sensor 60 seconds to settle to a final value, but you need it to be there in five seconds or less, it's a moot point.) In effect, hysteresis errors exhibit themselves as directionally dependent low pass filters. *Figure 3* shows the transfer function of the iVeNT as shown in *Figure 2*, but now two series of "measured" values are shown: one for rising pressure, and the other for falling pressure.

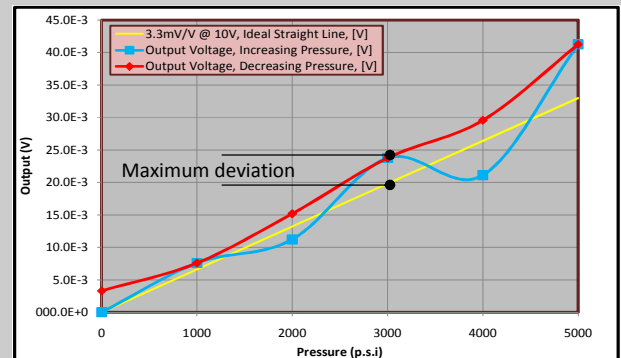


Figure 3

Repeatability: an expression of precision. Either independent of, or dependent on, time and temperature, this is an indication of how close a sensor's output is to previously measured output values for the same input value. As with linearity in pressure transducers, repeatability is expressed as a percentage of full scale output. *Figure 4* shows the transfer functions for the iVeNT collected over three sequences of rising and falling pressure. (To be sure, no one would try to sell a sensor that was this bad!)

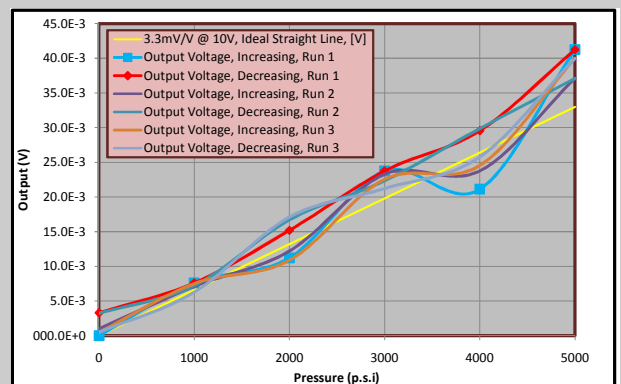


Figure 4

Accuracy: an expression of veracity, or how close the measured value is to an expected value. With regard to pressure transducers, common practice is to express the deviation from the expected output value as a percentage of the full scale output. Deviation from the full scale output results from any combination of measurement imperfections, and is often expressed as a combination of non-linearity, hysteresis, and repeatability since, in practice, it is exceedingly difficult to separate the effects of the various imperfections from one another.

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Other performance parameters that have an effect on melt pressure sensor performance are related to time and temperature. *Short-term drift* (or shift) of the zero point due to temperature change at the diaphragm or due to temperature change of the housing is often specified, although *long-term drift* quite often is not. *Sensitivity shift* is also often specified. In a typical strain gage based sensor, the effect that the aforementioned characteristics will have on performance should result only in an upward shift in the transfer function. *Figure 5* shows the iVeNT at 25°C (77°F) and 250°C (482°F); it's still performing badly here too, showing drift of 0.1%/°C. For high quality sensors, sensitivity shifts should be on the order of a few tenths of a percent per 10°C. *Settling time, response time, and frequency response* of a melt pressure sensor do have an effect on performance, especially when used in a closed loop control system, but these parameters are usually not specified due to the expense associated with obtaining them.

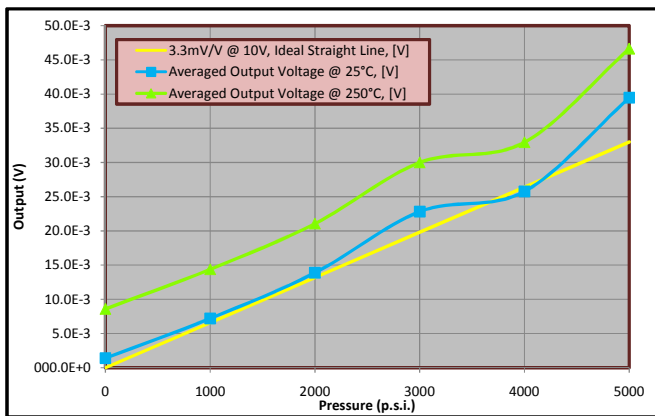


Figure 5

DETERMINING THE BEST LINE OF REFERENCE

Going back to the iVeNT for a moment, one might ask just how accurate this sensor would be, or more important, how would its accuracy be expressed on its datasheet. The answer is that it depends on how we decide to reference the data. (You can have a look at the Appendix to see the data sets that were used to generate the various graphs.) Accuracy in measurement devices can be expressed in many different ways, and the ways in which that information is presented, and what it really means, has been the source of many a heated discussion among technical people ever since the concept of measurement accuracy was created. What we're going to take a look at first is how this sensor's performance would be rated by the BFSL method. Afterwards we'll have a look at what those datasheet numbers would look like if we had used the TSL method.

If we wanted to be brutally frank about the performance of our imaginary sensor here, we could just express the maximum non-linearity as the amount (as a percentage) by which the output deviates from the ideal straight line at its

worst case. On a datasheet this number would look pretty ugly. For our case, the greatest output deviation from an ideal straight line is 8.3mV and the expected full scale output is 33mV, so we would need to say that this sensor is a 25% device. We could make the numbers look a little better if we rated the maximum deviation from the ideal output relative to the actual *full-scale output*, which is the commonly accepted method of rating the imperfections in strain gage based sensors anyway. Now, with the maximum deviation still at 8.3mV, but with the full scale output at 41.3mV, our accuracy can be stated as 20%. Wow, the numbers are starting to look better.

But, we're not done yet, because no one is going to buy a 20% accurate sensor (or even one that's rated +20%/-12.8%) and we would like the iVeNT to be able to put up the best numbers possible on its datasheet. So, since we ran our tests three times so that we could establish repeatability, maybe if we averaged the values from the three tests, that would make our accuracy number look even better. We can make a valid argument for doing it this way since, clearly, we can reasonably expect subsequent tests to produce data somewhere within the range of the previous tests. (But, never quite the same as previous tests; not only is this sensor inaccurate, it's imprecise too.) The transfer function produced by the averaged data for the iVeNT is shown in *Figure 6*. Now, this is starting to look pretty good. So, the number that goes on the datasheet should look a lot better too...and it does. Once again, ref-

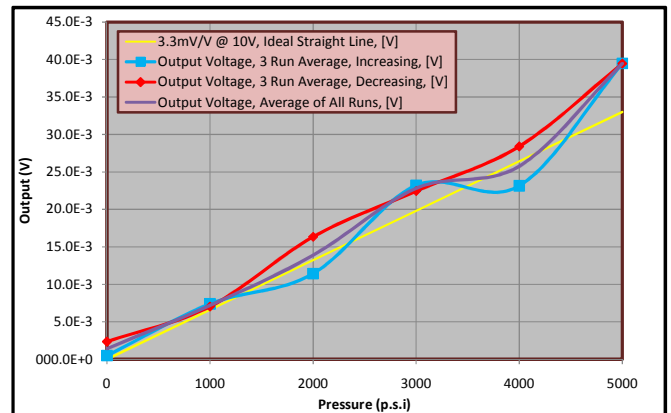


Figure 6

erencing the greatest deviation of the averaged output (6.5mV @ 5,000 p.s.i) relative to the ideal output (33mV @ 5,000p.s.i) as a percentage of the averaged full scale output (39.5mV) we get 16.4%. However, no one is going to buy a sensor with that kind of accuracy even if we say it's +16%/-2%. So, isn't there something we can do to make the numbers on the datasheet look even better?

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The answer is, there is something that can be done. This is a discussion of linearity after all, so let's linearize the averaged transfer function. In other words, let's create a straight line that approximates what we can reasonably expect the transfer function of the iVeNT to average to after an infinite number of data samplings. Fortunately, we live in the 21st century and we can allow a spreadsheet program to do the regression analysis and come up with the straight line in question and tell us what its equation is. *Figure 7* shows the averaged transfer function with its best fitting straight line superimposed as well as the straight line's equation, where x is the pressure applied and y is the output voltage. Next, if we express the deviation of the

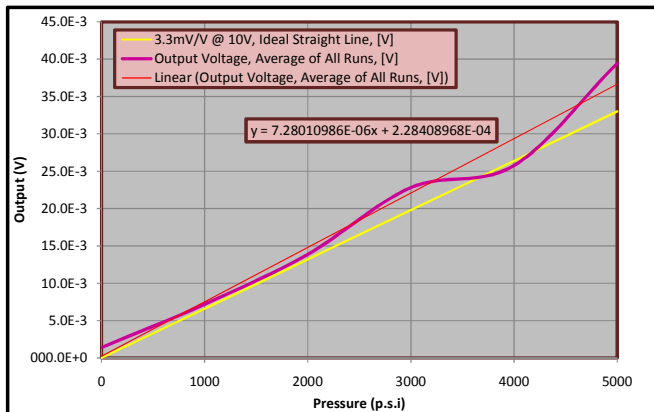


Figure 7

averaged curve from the linearization of that curve relative to the expected output as determined by the best fitting straight line, we'll get a number that looks much nicer on the datasheet. Now, at 4,000 p.s.i. we see our greatest deviation (-3.6mV) from the best fitting straight line relative to the expected full scale output (36.6mV). As a percentage we're now only off by -9.1%! Let's just put the following spec on our datasheet and call it a day:

Accuracy (including linearity, hysteresis, and repeatability):
 $\pm 10\%$ of full scale maximum (BFSL)

You might be inclined to ask whether this is some sort of trick. The answer is that it is not a trick at all. What we just did in that last section is determine the accuracy of the iVeNT by the Best-Fit Straight Line method as outlined in ISA-37.3-1982 (R1995), *Specifications and Tests for Strain Gage Pressure Transducers*. What that says is that you need to collect data for a minimum of six points of rising pressure and five points of falling pressure at 0, 20, 40, 60, 80, and 100% of the rated maximum pressure (if we are concerned with a strain gage pressure transducer). Some people might ask why we would rate a sensor this way, because this clearly does not give us an accurate representation of the sensor's true performance. The answer is that this method does give you an accurate representation of the sensor's average performance over time, which is well and good if that's what you're interested in. However, if

what you're really interested in is the "instantaneous" performance of the transducer then this can cover up some flaws that might concern you.

In the Appendix we've presented some data for a sensor that is rated at $\pm 1\%$ accuracy, and its transfer function is shown in *Figure 8*. If you look at the raw numbers for the curves, you can see that at 1,000 p.s.i. with falling pressure, the output is off by about -6.1% in absolute terms, or -1.2%

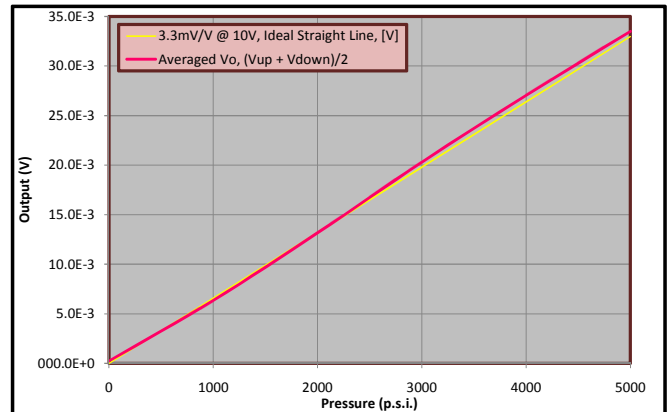


Figure 8

referenced to a perfectly linear transfer function and relative to the expected full scale. Also with falling pressure, at 4,000 p.s.i. the output is off the mark by about 2.4% referenced to an ideal transfer function and relative to the full scale output (expected or actual). If you were trying to use this sensor in a closed loop control system, you wouldn't get the performance you were expecting based on the sensor's stated 1% accuracy. And if you bought a 0.5% or 0.25% sensor that was rated by the BFSL method, you could expect your results to be proportionately as bad.

So, what should you be looking for in accuracy ratings if accuracy is important to you? There are some manufacturers of melt pressure sensors that use a different method to determine their products' accuracy: the Terminal Straight Line (TSL for short) method. In the TSL method, the manufacturer is providing a zero data point and another data point at full scale pressure (the two terminal data points). A straight line is then plotted between those two points to be used as the reference line. The deviation of measured outputs compared with that straight line is then expressed as a percentage of full scale output. If we had rated the iVeNT using the TSL method, we would have had to express the accuracy as +0%/-45% (refer to *Figure 2*, linearity after one pass) or +0%/-15% (refer to *Figure 6*, total accuracy after three rising and three falling passes). In either case the number that goes on the datasheet doesn't look nearly as appealing as the number we came up with using the BFSL method. In fact, the only way we could have made the numbers look worse, would have been to have used the *expected* full scale output voltage as the reference rather than the "measured" full scale output voltage.

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If we had rated our “1%” transducer using the TSL method, we would have referred to it as having $\pm 1.6\%$ accuracy. In fact if we compare the percent error span for the two methods on our “1%” transducer, the BFSL method yields a span of 1.85% whereas the TSL method yields a span of 2.23%, again putting the worst case on the numbers. The upshot of all this is that if accuracy in a melt pressure sensor is truly a concern in your selection criteria, then a sensor that is rated by the TSL method presents a more accurate picture of the sensor’s performance than rating by the BFSL method. What would be even better yet is if your sensor manufacturer rates accuracy by comparing the actual output error to the ideal transfer function—*i.e.*, what *should* the output voltage be for a given input pressure—relative to the expected full scale output.

THE EFFECT OF MELT PRESSURE SENSOR INACCURACY ON EXTRUSION OUTPUT

Quite often, melt pressure sensors are used in extrusion lines to drive indicators for monitoring purposes, or to trigger alarms that signal operators to manually make changes in the line’s operating parameters. In these applications, measurement instrument error may have less effect on the finished product than human error does. However, in an application where rising pressure is supposed to indicate to the line operator that it’s time to change screens, or perhaps decrease screw speed, the combined error effects may result in significant losses over time due to excessive scrap and out of tolerance product. These negative outcomes don’t occur only in manually adjusted lines; they can occur in closed loop controlled extrusion lines as well.

As previously mentioned, in extrusion lines using melt pressure sensors to generate the error signal for closed loop control of the screw, transducer inaccuracies can have serious consequences. First, if we assume that the sensor is exhibiting non-linearities that result in pressures along a linear range to be very non-linearly represented, the resulting control signal will also be generated non-linearly. This may result in surging of screw speed, especially if the sensor is afflicted with a large proportion of hysteresis errors. At the very least, sensor inaccuracy will result in a corresponding error in melt pressure. Previous papers (for example, see <http://www.dynisco.com/literature/Technical%20Articles/ClosedLoop.pdf>) on closed loop control for the extrusion process have shown that small errors in the melt pressure can result in much larger deviations in the mass of the extrudate (*i.e.*, a 1% deviation in melt pressure results in a greater—sometimes much greater—than 1% deviation in extruded mass). Hence, the manufacturer is wasting material, at the least, and perhaps scrapping finished product due to profiles being out of tolerance. In addition to mere tolerance problems of extruded plastics, excessive

pressures at the extruder die are also known to contribute to degradation of the polymer structure, which can lead to premature product failure.

In the end, seemingly small linearity errors in the transfer function of a melt pressure transducer can create large variations in the operating melt pressure of an extrusion line, which ultimately will affect a manufacturer’s bottom line. Understanding the limitations and conditions of the accuracy ratings of melt pressure transducers can help process and maintenance engineers who are responsible for extrusion lines avoid production problems that are directly attributable to real sensor inaccuracies.

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APPENDIX

Data for Figure 2

Pressure, [p.s.i]	3.3mV/V @ 10V, Ideal Straight Line, [V]	Output Voltage, [V]	delta Relative to Ideal Straight Line, [V]	% Error Relative to Ideal Full-Scale Output	% Error Relative to Expected Full-Scale Output	% Error Relative to Actual Full-Scale Output
0	0	0	0	N/A	0.0%	0.0%
1000	0.0066	0.00759	0.00099	15.0%	3.0%	2.4%
2000	0.0132	0.01122	-0.00198	-15.0%	-6.0%	-4.8%
3000	0.0198	0.02376	0.00396	20.0%	12.0%	9.6%
4000	0.0264	0.02112	-0.00528	-20.0%	-16.0%	-12.8%
5000	0.033	0.04125	0.00825	25.0%	25.0%	20.0%

Data for Figure 2 by TSL Method

Pressure, [p.s.i]	Output Voltage, Ideal Straight Line, [V]	Measured Output Voltage, [V]	Terminal Straight Line, 0 and 100% (measured)	% Error relative to TSL and measured FSO	% Error relative to TSL and expected FSO
0	000.0E+0	000.0E+0	0	0.0%	0.0%
1000	6.6E-3	7.6E-3	0.00826	-2.5%	-2.0%
2000	13.2E-3	11.2E-3	0.01652	-20.1%	-16.1%
3000	19.8E-3	23.8E-3	0.02478	-3.9%	-3.1%
4000	26.4E-3	21.1E-3	0.03304	-45.2%	-36.1%
5000	33.0E-3	41.3E-3	0.0413	-0.2%	-0.2%

Data for Figure 3

Pressure, [p.s.i]	3.3mV/V @ 10V, Ideal Straight Line, [V]	Output Voltage, Increasing Pressure, [V]	Output Voltage, Decreasing Pressure, [V]	% Error Relative to Ideal Straight Line, Increasing Pressure	% Error Relative to Expected Full-Scale Output, Increasing Pressure	% Error Relative to Ideal Straight Line, Decreasing Pressure	% Error Relative to Expected Full-Scale Output, Decreasing Pressure
0	000.0E+0	000.0E+0	3.3E-3	N/A	0.0%	N/A	10.0%
1000	6.6E-3	7.6E-3	7.6E-3	15.0%	3.0%	15.0%	3.0%
2000	13.2E-3	11.2E-3	15.2E-3	-15.0%	-6.0%	15.0%	6.0%
3000	19.8E-3	23.8E-3	23.8E-3	20.0%	12.0%	20.0%	12.0%
4000	26.4E-3	21.1E-3	29.6E-3	-20.0%	-16.0%	12.0%	9.6%
5000	33.0E-3	41.3E-3	41.3E-3	25.0%	25.0%	25.0%	25.0%

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Data for Figure 4, Figure 6, and Figure 7

Pressure, [p.s.i]	3.3mV/V @ 10V, Ideal Straight Line, [V]	Output Voltage, Increasing, Run 1	Output Voltage, Decreasing, Run 1	Output Voltage, Increasing, Run 2	Output Voltage, Decreasing, Run 2	Output Voltage, Increasing, Run 3	Output Voltage, Decreasing, Run 3
0	000.0E+0	000.0E+0	3.3E-3	1.0E-3	3.2E-3	500.0E-6	500.0E-6
1000	6.6E-3	7.6E-3	7.6E-3	7.1E-3	7.2E-3	7.5E-3	6.3E-3
2000	13.2E-3	11.2E-3	15.2E-3	12.2E-3	16.7E-3	10.9E-3	17.1E-3
3000	19.8E-3	23.8E-3	23.8E-3	23.3E-3	22.3E-3	22.6E-3	21.2E-3
4000	26.4E-3	21.1E-3	29.6E-3	23.8E-3	29.9E-3	24.6E-3	25.8E-3
5000	33.0E-3	41.3E-3	41.3E-3	37.1E-3	37.1E-3	40.0E-3	40.0E-3

Data for Figure 5

Pressure, [p.s.i]	3.3mV/V @ 10V, Ideal Straight Line, [V]	Averaged Output Voltage @ 25°C, [V]	Averaged Output Voltage @ 250°C, [V]
0	000.0E+0	1.4E-3	8.6E-3
1000	6.6E-3	7.2E-3	14.4E-3
2000	13.2E-3	13.9E-3	21.1E-3
3000	19.8E-3	22.8E-3	30.0E-3
4000	26.4E-3	25.8E-3	33.0E-3
5000	33.0E-3	39.5E-3	46.6E-3

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APPENDIX

Data for Figure 8

Pressure	Increasing Pressure				Decreasing Pressure			
	3.3mV/V @ 10V, Ideal Straight Line, [V]	Output w/ Increasing Pressure [V]	Absolute Error	Error, Referenced to Ideal Straight Line, Relative to Expected FSO	3.3mV/V @ 10V, Ideal Straight Line, [V]	Output w/ Decreasing Pressure [V]	Absolute Error	Error, Referenced to Ideal Straight Line, Relative to Expected FSO
0	000.0E+0	0.00033	∞	1.0%	000.0E+0	0.00016	∞	0.5%
1000	6.6E-3	0.0065	-1.5%	-0.3%	6.6E-3	0.0062	-6.1%	-1.2%
2000	13.2E-3	0.01315	-0.4%	-0.2%	13.2E-3	0.0132	0.0%	0.0%
3000	19.8E-3	0.0202	2.0%	1.2%	19.8E-3	0.0204	3.0%	1.8%
4000	26.4E-3	0.0269	1.9%	1.5%	26.4E-3	0.0272	3.0%	2.4%
5000	33.0E-3	0.0335	1.5%	1.5%	33.0E-3	0.0335	1.5%	1.5%

Pressure [psi]	3.3mV/V @ 10V, Ideal Straight Line, [V]	Averaged V_o , $(V_{up} + V_{down})/2$	Absolute Error	Error, Referenced to Ideal Straight Line , Relative to Expected FSO	Best Fit Straight Line From Test Data	Error, Referenced to BFSL , Relative to BFSL FSO	Terminal Straight Line From Test Data	Error, Referenced to TSL , Relative to TSL FSO
0	000.0E+0	0.000245	∞	0.7%	-51.4E-6	0.9%	245.0E-6	0.0%
1000	6.6E-3	0.00635	-3.79%	-0.8%	6.7E-3	-1.0%	6.9E-3	-1.6%
2000	13.2E-3	0.013175	-0.19%	-0.1%	13.4E-3	-0.7%	13.5E-3	-1.1%
3000	19.8E-3	0.0203	2.53%	1.5%	20.1E-3	0.5%	20.2E-3	0.3%
4000	26.4E-3	0.02705	2.46%	2.0%	26.9E-3	0.6%	26.8E-3	0.6%
5000	33.0E-3	0.0335	1.52%	1.5%	33.6E-3	-0.3%	33.5E-3	0.0%