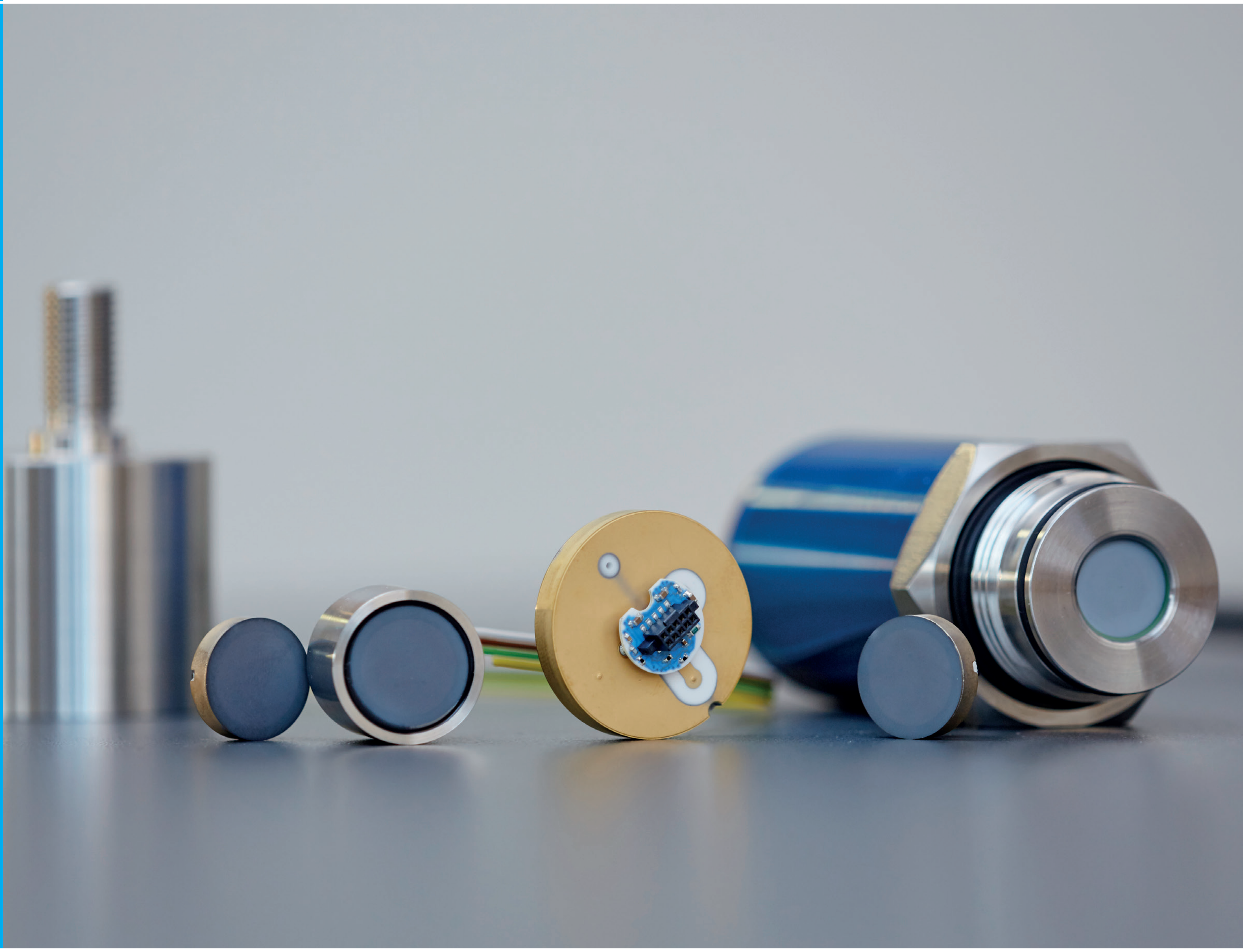
Achieving High Performance Pressure Sensing with Small Ceramic Based Capacitance Sensors



Register

By Dr. Jorge Andres Diaz

University Professor and Sensor Characterization & Development Expert
Head of Sensor Characterization Lab. (SCL) CICANUM. University of Costa Rica.

About the author:
Dr. Diaz is a University Professor focused on sensor design & instrumentation and is the head of the Sensor Characterization Laboratory. He achieved his Ph.D. at the University of Minnesota and has become an international expert in gas concentration, flow and pressure sensing characterization as well as instrument development. He has served as a NASA collaborator on more than 20 projects related to in situ sampling, evaluation and optimization of portable systems for different earth and space applications and has worked for 22 years as new product development and sensor engineering consultant for the semiconductor industry, holding several patents and awards.

1 Introduction

When we talk about high performance in pressure sensing, we sometimes imagine large and bulky pressure sensors with space or military development backgrounds. Those easily cost thousands of dollars for a single transducer. That is true for applications where very high accuracy (typical less than 0.1% FS, 1% RD and precise temperature compensation (< 0.001%/oC) is needed to provide an accurate and repeatable signal that is stable over time. I have been involved in space, atmospheric and earth application projects **(Ref 1, 2, 3)** where a single pressure sensor with such specs can cost several thousand dollars. An amount which is paid without hesitation by customers who need unique and custom-made instruments that require such precision.
But, can such performance be obtained from a small ceramic sensor costing relatively small price? My first reaction was: no, it is impossible. I have worked with pressure sensors for more than 20 years and designed custom pressure sensors for specific harsh environment applications **(Ref 4)**. So, I'm familiar with what is possible to achieve with small ceramic based pressure sensors and what is not. Whether they are using capacitive or piezo resistive technologies, there are intrinsic limitations to high performance. **(Ref 5)** This was the challenge when I was asked to evaluate a new family of pressure sensors from a well-known European company specialized on industrial measuring instrumentation. How accurate and stable can these small sensors perform? The present article describes the results.

2 Pressure Sensor

The Ceracore USC30 is a small pressure sensor designed for absolute and gauge pressure measurement **(Ref 6,7,8,9).** According to the manufacturer, its capacitive ceramic 99.9% pure Al_2O_3 measuring cell introduces new designs and new digital capabilities achieving high overpressure and abrasion resistance. It also has diminished mounting effects, claiming better performance, stability, accuracy, temperature compensation and providing a more flexible adaption to different applications than its previous versions.

Figure #1: Ceracore USC30: Capacitive High-Performance Pressure Sensor

To confirm these claims, we tested the small 17.5mm OD sensor version with 0-4bar gauge pressure range, which is one of the most widely used versions of this sensor. Per request, the sensors were calibrated for 0-4.5bar and 10-65°C.

Table #1 describes the technical characteristics of the selected sensor: This capacitance sensor is manufactured exclusively at the Endress+Hauser facility in Maulburg located in southwest Germany, near to the French and Swiss border. Today, Endress+Hauser in Maulburg is a leading producer of instruments, sensors, components and services for level measurement, pressure and differential pressure measurement as well as inventory management solutions.

Table #1 Ceracore USC30 Technical Information

Design size:	17.5 mm external diameter
Ambient/process temperature:	-40 to +125°C
Storage temperature:	-40 to +125°C
Electrostatic discharge (ESD):	± 2kV
Operating voltage:	2.9 to 5.5V
Material:	99.9% Al_2O_3
Power consumption:	< 1.6mA
Analog output signal:	Ratiometric or absolute
Digital interface:	UART or SPI
Pressure signal:	24bit
Temperature signal (optional):	16bit
Measuring rate:	1.25 to 160ms
Nominal gauge pressure ranges:	-100 to 100mbar / -10 to 10kPa / -1.5 to 1.5psi
	-200 to 200mbar / -20 to 20kPa /-3 to 3psi
	-400 to 400mbar / -40 to 40kPa /-6 to 6psi
	-1 to 1bar / -100 to 100kPa /-15 to 15psi
	-1 to 2bar /-100 to 200kPa /-15 to 30psi
	-1 to 4bar /-100 to 400kPa /-15 to 60psi (selected)
	-1 to 10bar / -0.1 to 1MPa / -15 to 150psi
	-1 to 20bar / -0.1 to 2MPa / -15 to 300psi
	-1 to 40bar / -0.1 to 4MPa / -15 to 600psi
	-1 to 100bar / -0.1 to 10MPa / -15 to 1500psi
Nominal absolute pressure ranges:	0 to 100mbar / 10kPa / 1.5psi
	0 to 200mbar / 20kPa / 3psi
	0 to 400mbar / 40kPa / 6psi
	0 to 1bar / 100kPa / 15psi
	0 to 2bar / 200kPa / 30psi
	0 to 4bar / 400kPa / 60psi
	0 to 10bar / 1MPa / 150psi
	0 to 20bar / 2MPa / 300psi
	0 to 40bar / 4MPa / 600psi
	0 to 40bar / 4MPa / 600psi

3 Testing

To determine the sensor performance, a batch of 20 sensors were exposed to a series of different pressures and temperatures mounted on a metal manifold **(Ref 10)**. Their compensated output is then compared to a reference pressure meter with a pressure range of 0 to 200psi and ±0.01% Reading Error Accuracy Spec and a reference temperature meter with -50 to 200°C range, ±0.1°C Accuracy Spec.

The sensors provided by the manufacturer are already pressure and temperature calibrated from 10-65°C and 0-65psi operating pressure range which is a customization of the options stated on the technical information. The determination of the sensor accuracy is just the exercise to compare the sensor pressure output with the reference meter at each temperature. As shown in Figure #2,9 pressure points per temperature at 5 different temperatures are used to determine accuracy in the temperature range selected plus 3 cycles at room temperature are used to determine repeatability, therefore a total of 9 temperature steps were used for this characterization.

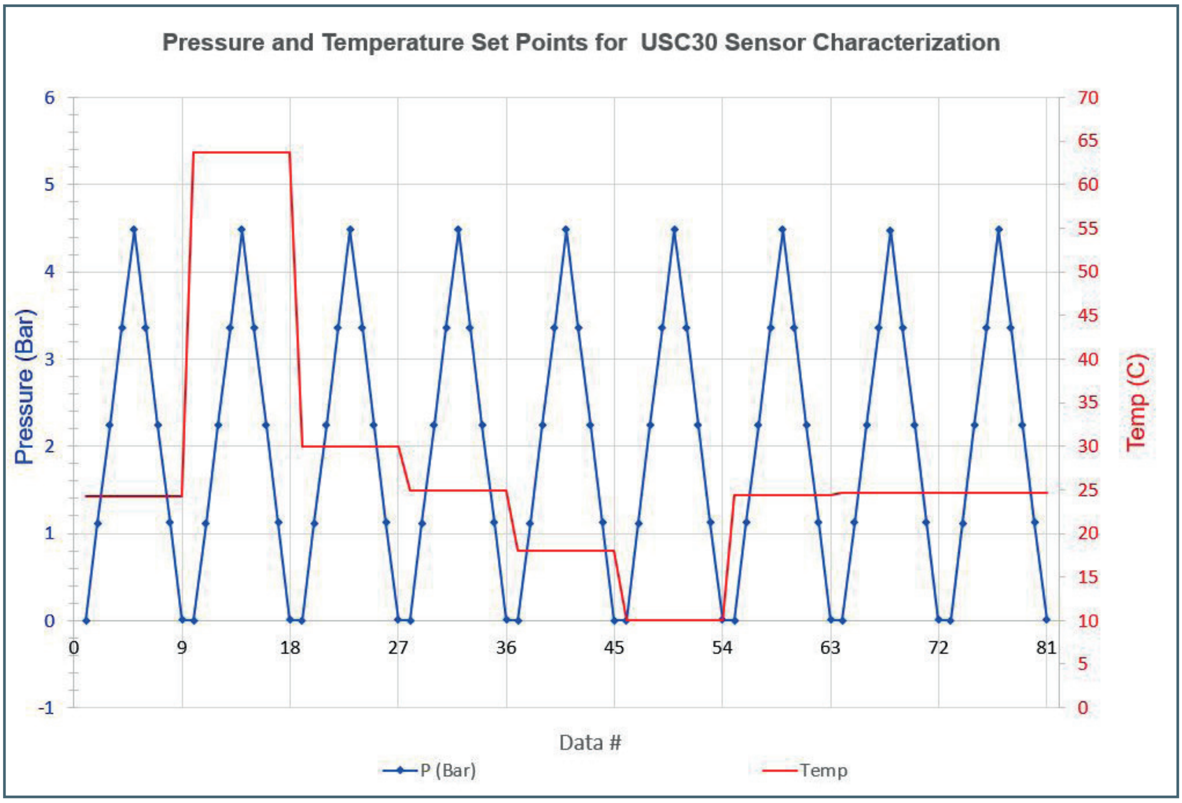


Figure #2: Pressure and Temperature Verification Sequence

4 Results

For any pressure sensor, accuracy can be specified as a percentage of full scale error (% FS):

$$\% \text{ FS Error} = [(\text{P Sensor} - \text{P Ref}) / \text{FS Sensor}] \times 100 \qquad (1)$$

For standard small ceramic pressure sensors, the typical accuracy error specified for most sensors is ±1% FS error at room temperature. Some automobile industry pressure sensors can even specify 3% or even 5% FS accuracy error. In my experience **“High performance”** on a pressure transducer can be considered when it has an accuracy specification below 0.1% FS error over the specified temperature range. Figure #3 shows the test results of the 20 USC30 sensors plotted as a % FS error for all temperatures tested. To visualize better the performance of the sensors each plot is referenced against Standard industry specifications (±1% FS error) and zoomed into High Performance specifications (±0.1% FS error) as plotted in Figure #4.

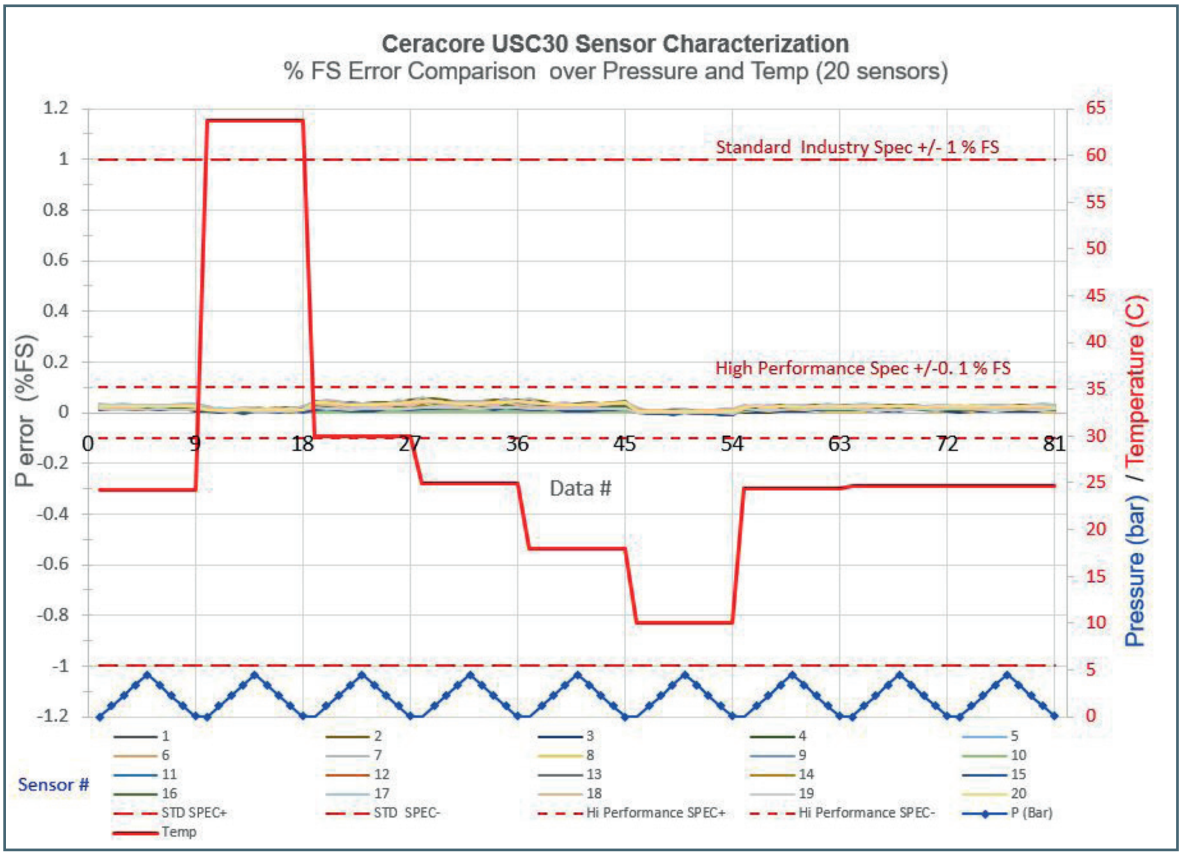


Figure #3: Pressure and Temp Verification Result (%FS%) for 20 Ceracore USC30 Sensors

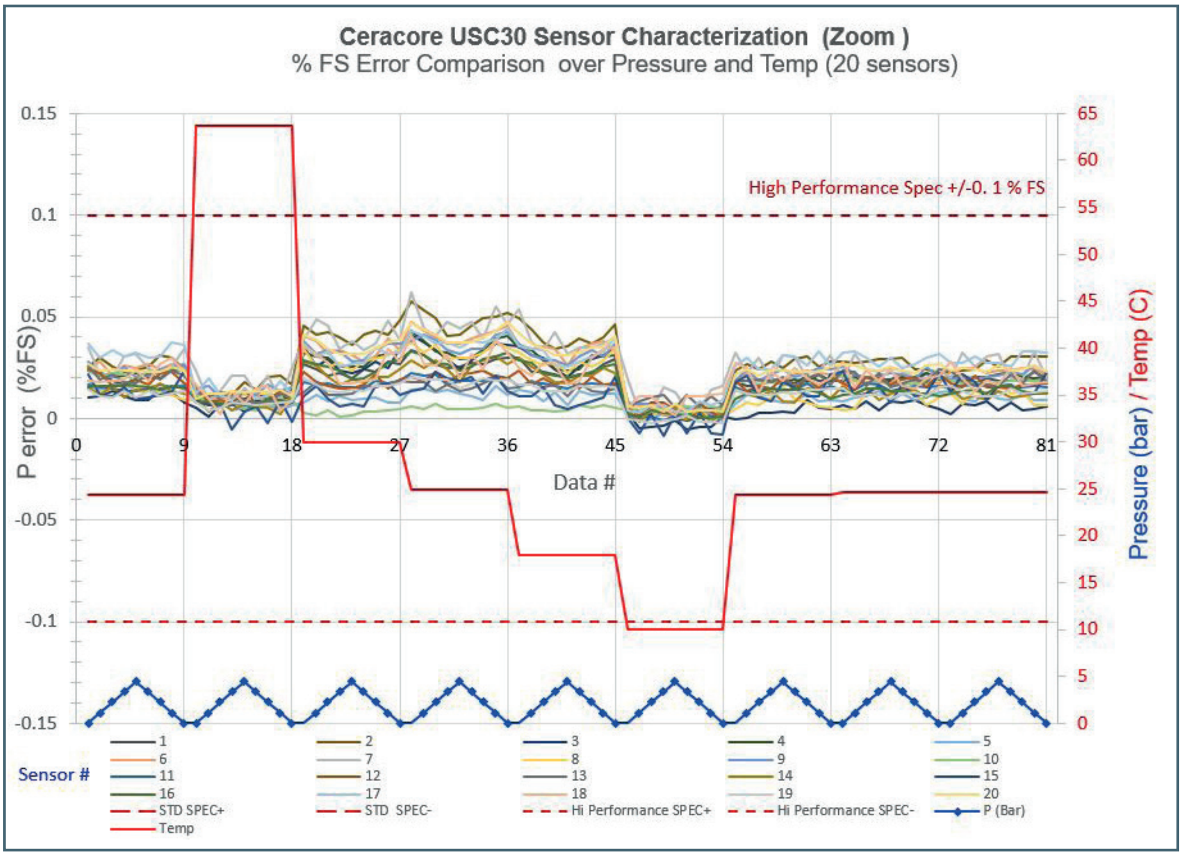
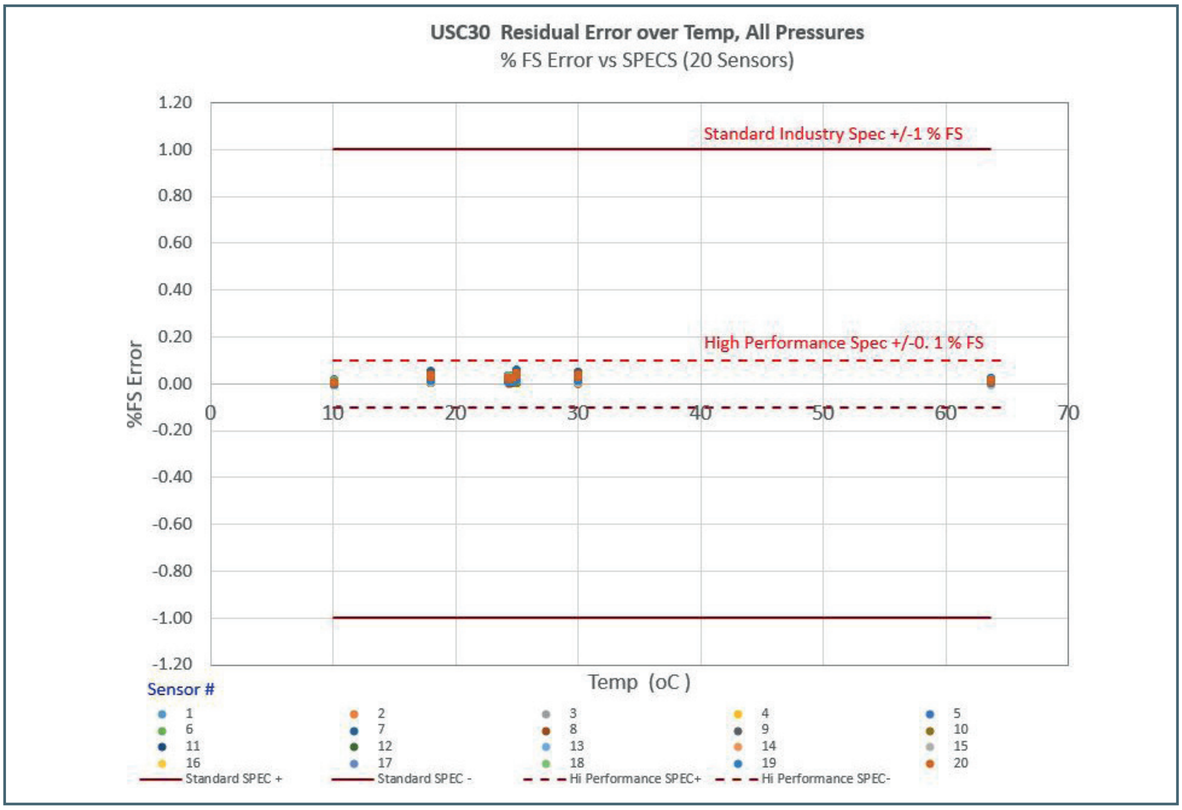


Figure #4: Pressure and Temperature Verification Result for 20 Ceracore USC30 Sensors. Zoomed in accuracy plotted in % FS.

To visualize temperature and pressure effects independently, the % FS error is plotted as a function of Pressure on Figure #5 and Temperature on Figure #6. Zoomed in %FS error graphs for each parameter are plotted for all 20 sensors in the bottom graphs.



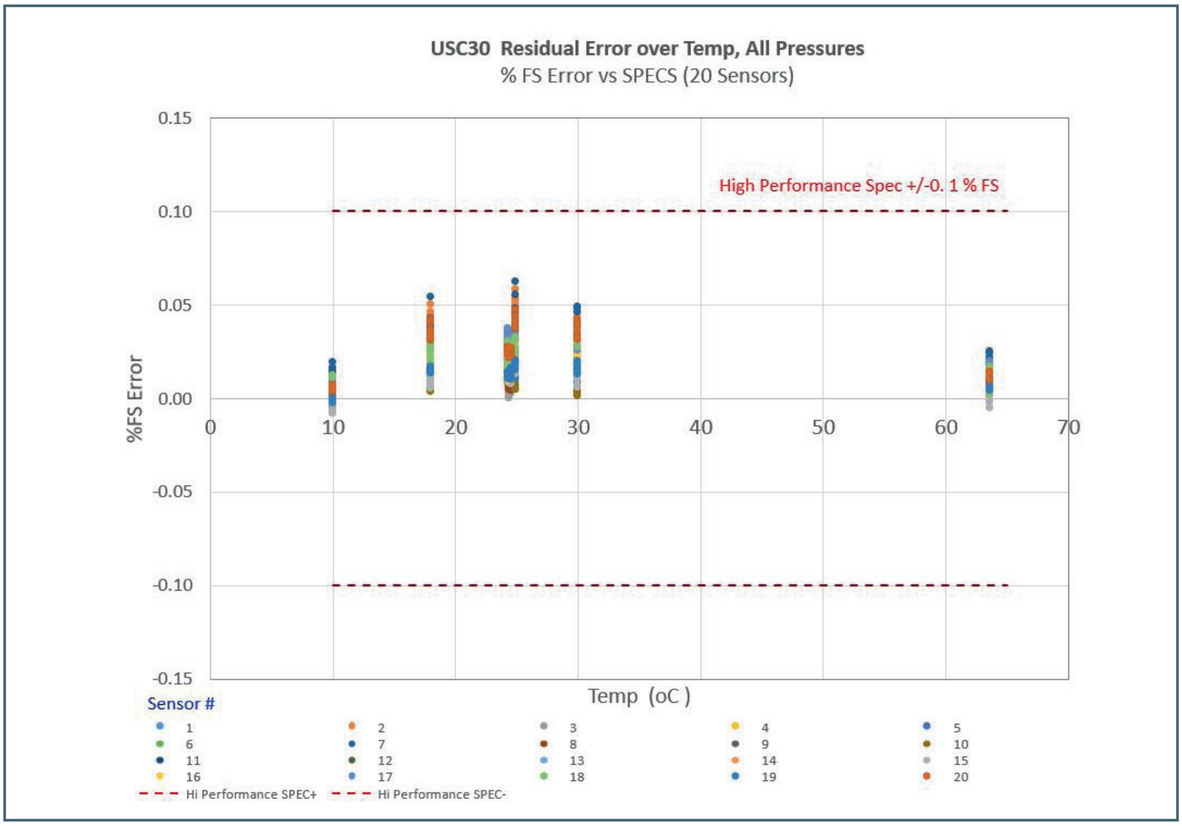
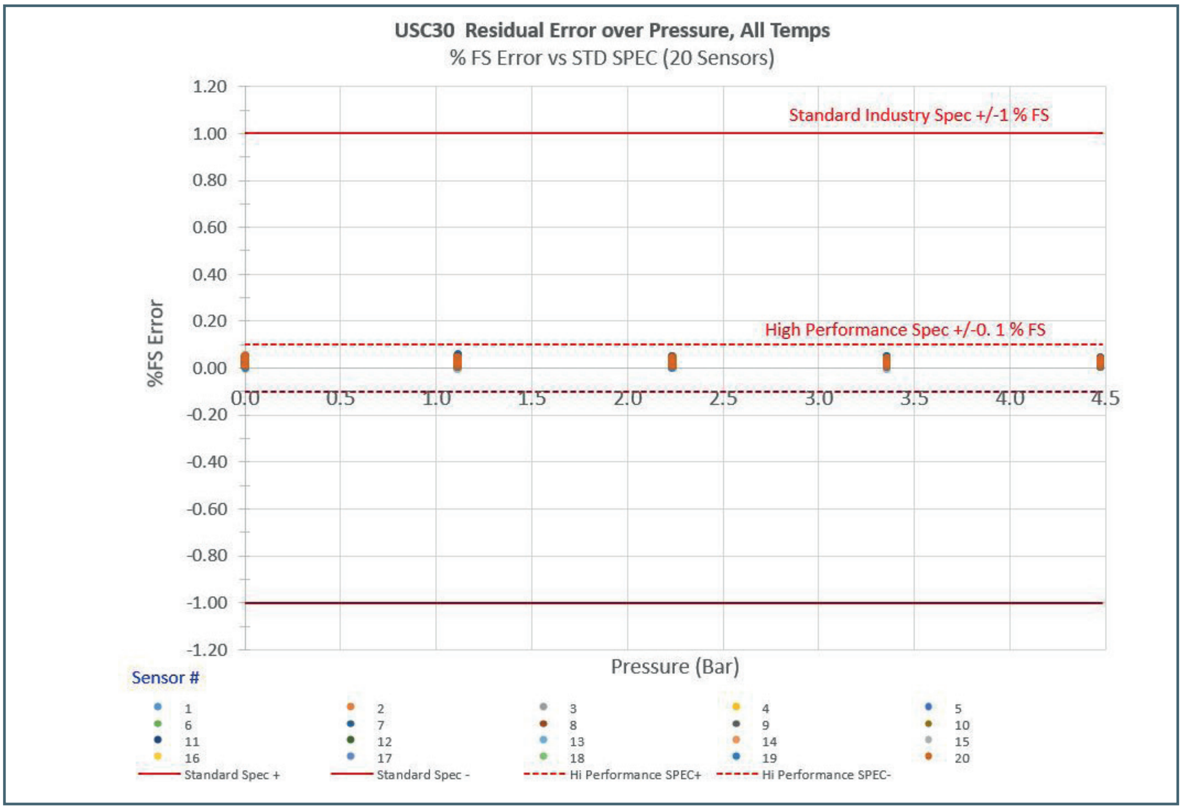


Figure #5: Pressure Effects of USC30 Sensors. % FS Error vs Pressure for all Sensors. (Zoom in on Y Axis for bottom Plot)



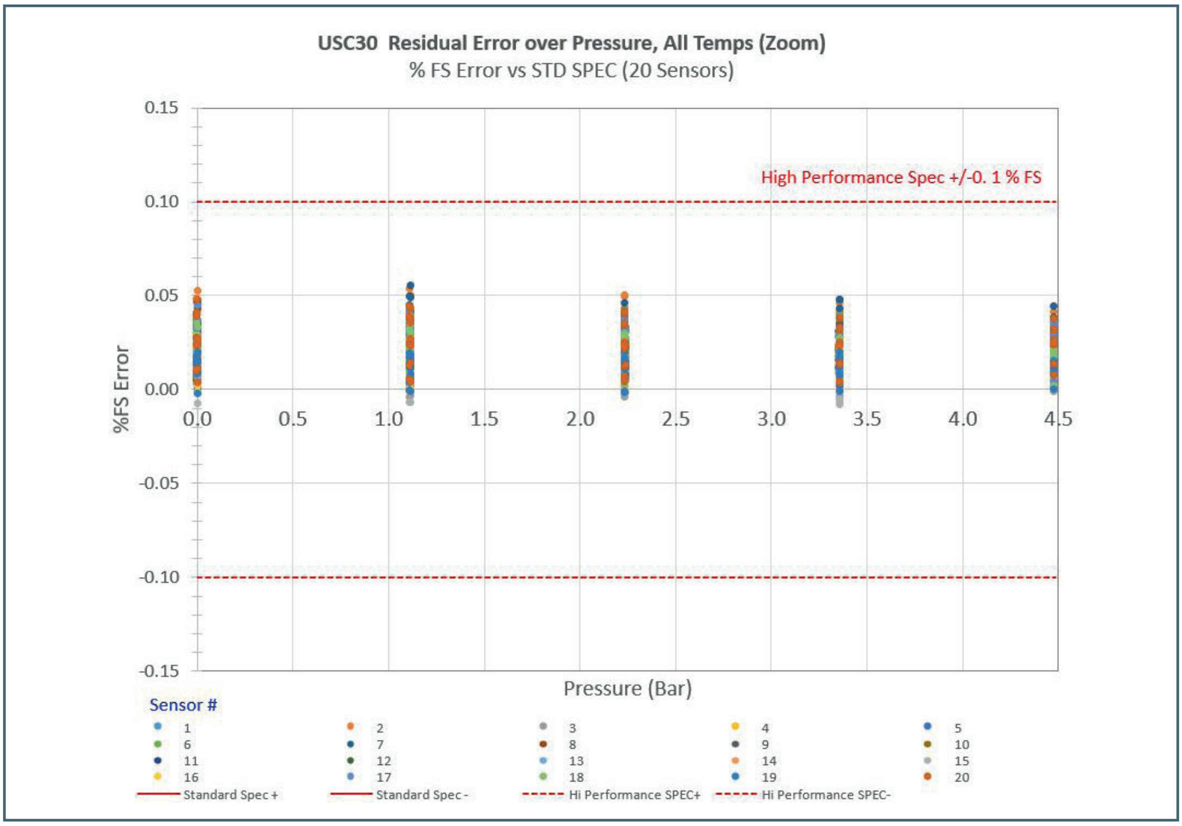


Figure #6: Temperature Effects of USC30 Sensors. % FS Error vs Temperature for all Sensors. (Zoom in on Y Axis for bottom Plot)

The testing of the 20 Ceracore USC30 sensors yields a very remarkable result. The maximum error for all sensors is just **0.062% FS error**. In comparison with the typical industrial specification, this is **16 times** better than any standard pressure transducer specified at 1% FS and **1.6 times** better than the threshold for high performance set to 0.1% FS. Figure #7 shows a summary of the max accuracy error measured among the 20 sensors, the repeatability at room temperature for the same batch, and the max individual accuracy error for each sensor compared with the STD SPEC and high performance threshold.

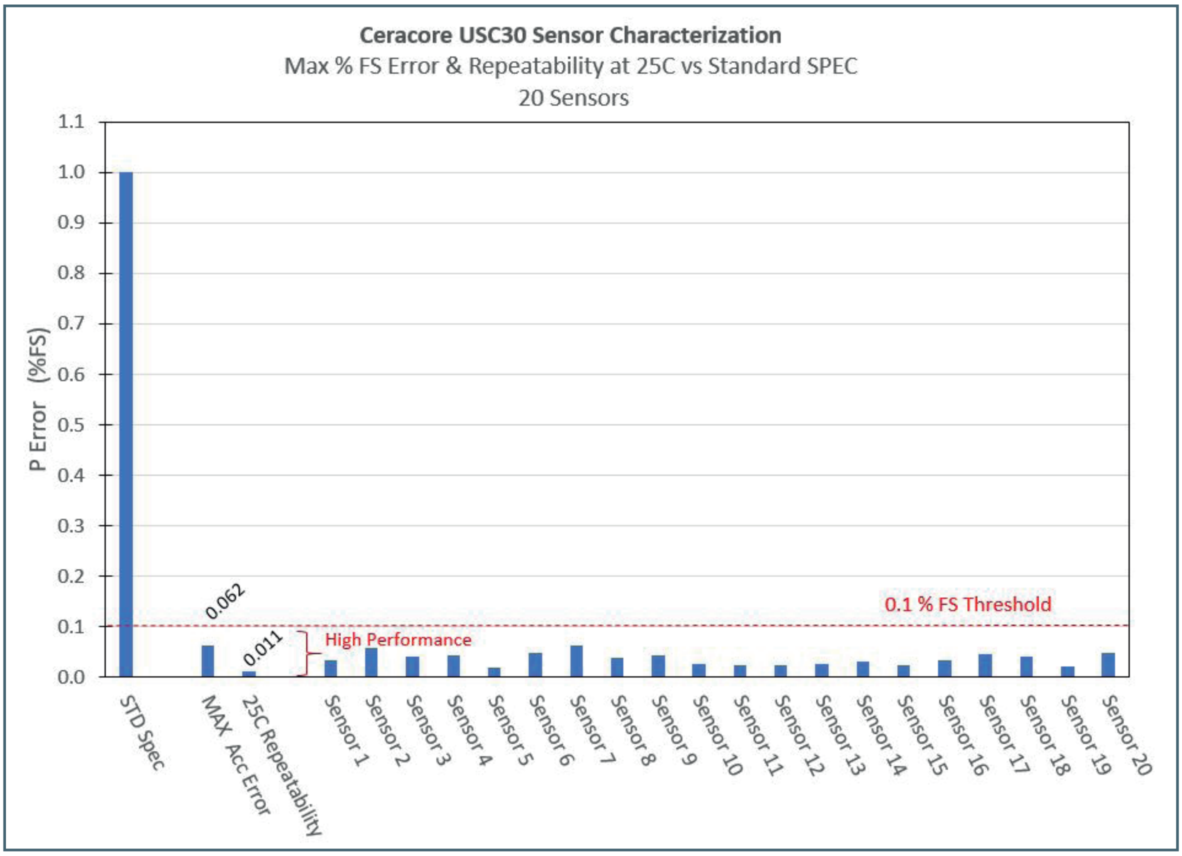


Figure #7: Summary of all Sensors. Max % FS error accuracy @ all temps and repeatability at 25°C

A good % FS pressure transducer can maintain pressure readings within specification over the full range of the device but is particularly better at higher pressures than lower pressures. There are many applications were this type of behavior is not enough: the performance needs to be similar at each set pressure, so another way to specify accuracy is percentage of Set Point or Reading (%RD) which assures the pressure sensor will be able to read accurately within the specification in the same way at any given pressure. (Zero pressure set point is taken out of this characterization since the division by zero is undetermined).

For more accurate pressure transducers, accuracy is specified as a percentage of reading or set point

$$\% \text{ RD Error} = [(\text{P Sensor} - \text{P Ref}) / \text{P Ref}] \times 100 \qquad (2)$$

It is typical to find small pressure transducers with specified accuracy of 5% RD or even 1% RD. Similar to % FS sensors and their characterization, a sensor with below 1% RD error can be considered a **High Performance** sensor. Figure #8 shows the same test results of the 20 USC30 sensors but this time plotted as a % RD error for all temperatures and all pressure excluding the zero pressure set points.

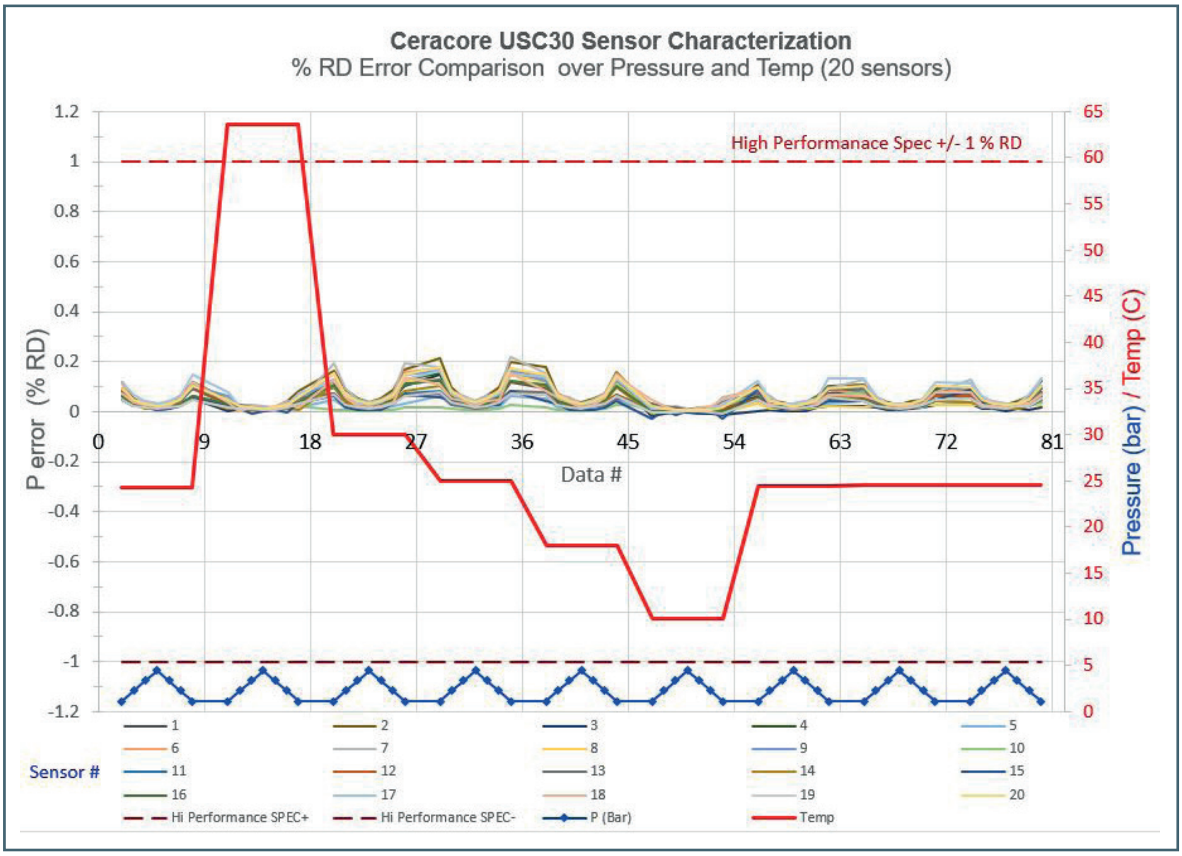


Figure #8: Pressure and Temp Verification Result (% RD Error) for 20 Ceracore USC30 Sensors

As we did with % FS plots, to visualize temperature and pressure effects independently, the % RD error is plotted as a function of Pressure on Figure #9 and Temperature on Figure #10.

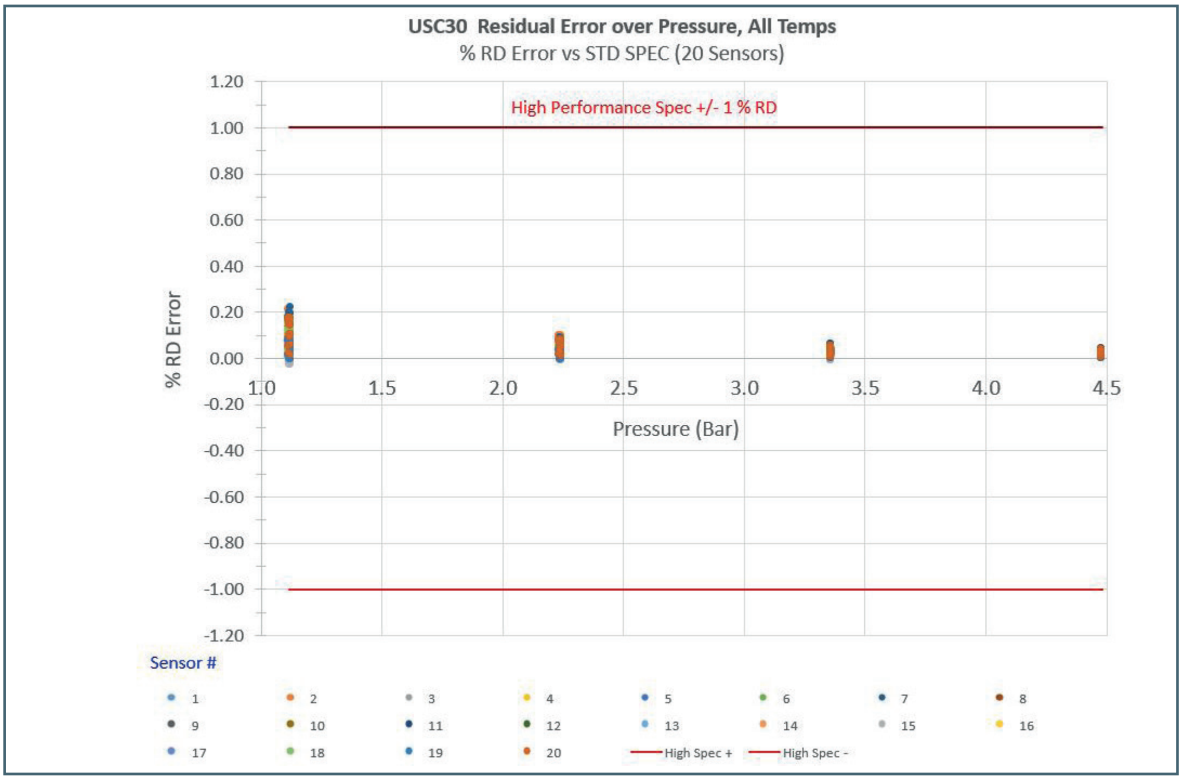


Figure #9: Pressure Effects of USC30 Sensors. % RD Error vs Pressure for all Sensors

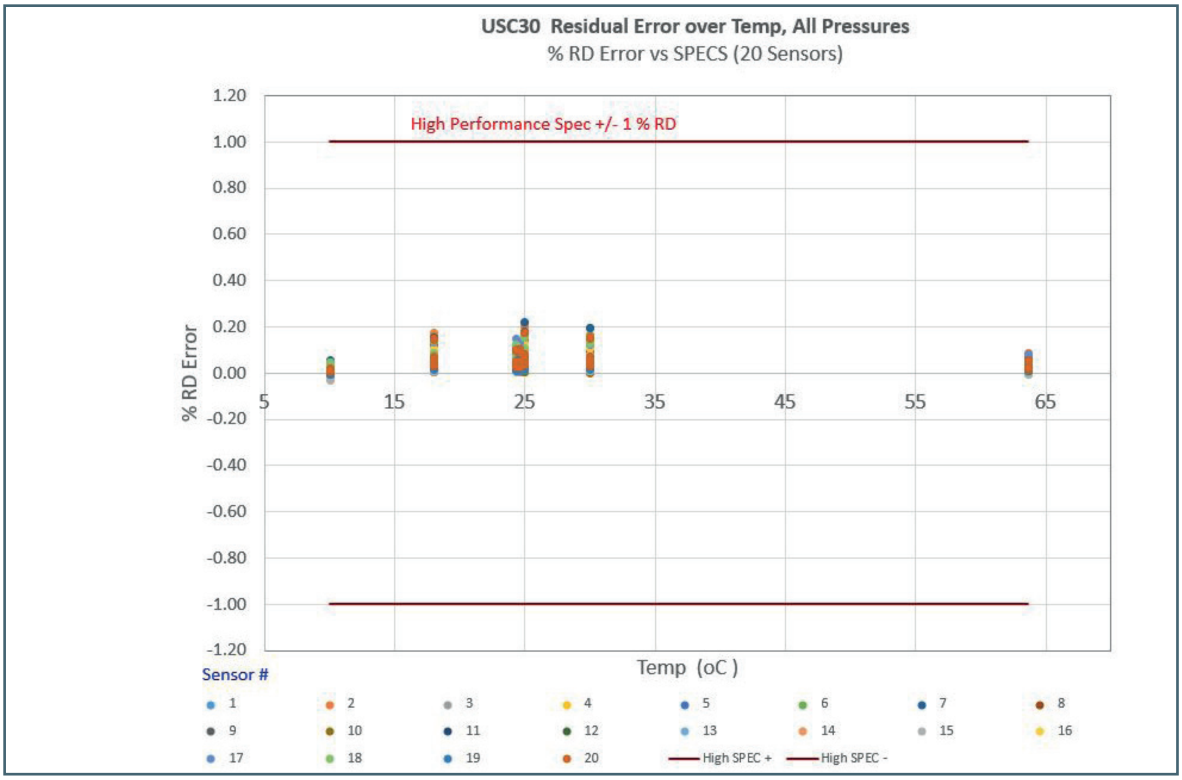


Figure #10: Temperature Effects of USC30 Sensors. % RD Error vs Temperature for all Sensors

Figure #11 shows the results for the testing of the 20 sensors plotted as % RD error. As with the % FS error results, the graph shows the remarkable advantages of the small Ceracore USC30 pressure sensor. The maximum reading accuracy error is **0.22% RD** error for all temperatures tested, which is **4.5 times** better than the target high-performance pressure transducer specified as 1% RD accuracy. The repeatability at 25°C measured among sensors is 0.037% RD, which is 27 times better than the required threshold for high performance.

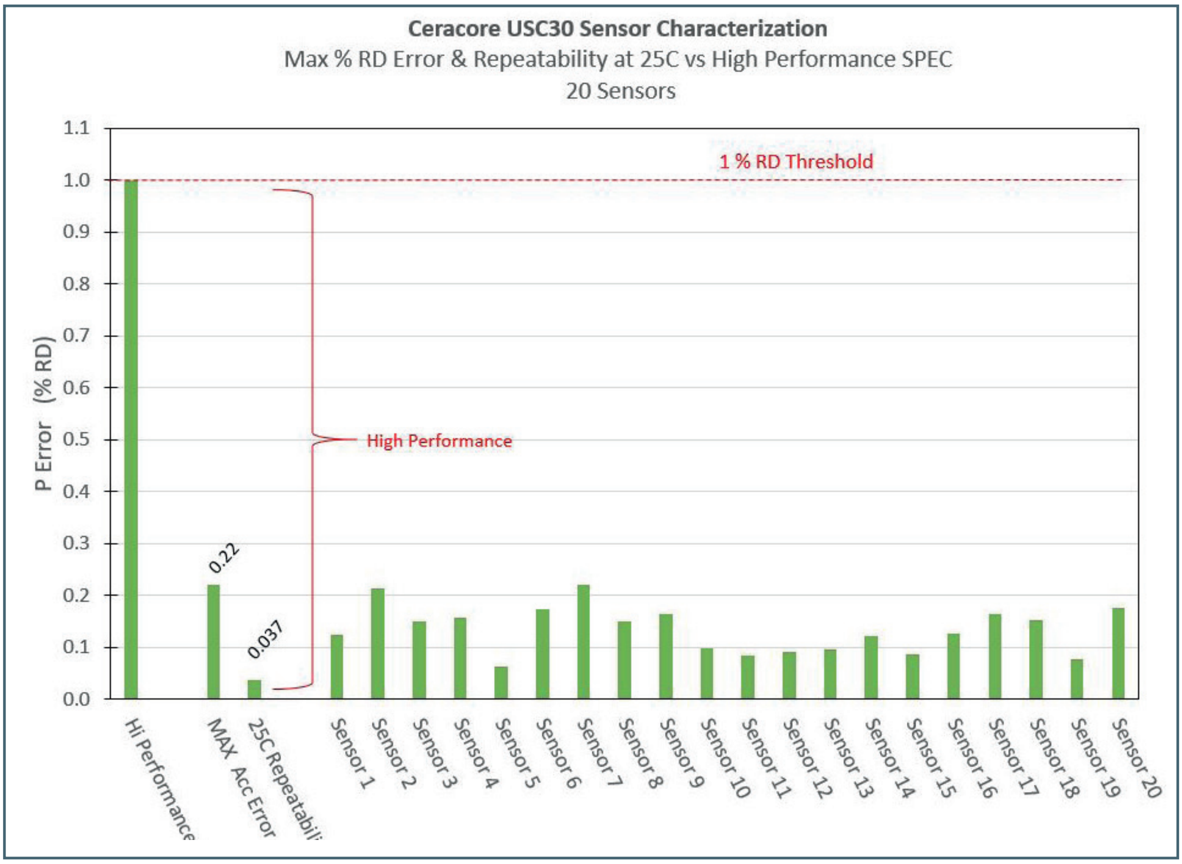


Figure #11: Standard Pressure Sensor Accuracy vs Ceracore USC30 Accuracy plotted as % RD

The final parameters of this study were temperature performance and repeatability at room temperature. Temperature performance can be defined with calculating Temperature Compensation Coefficient (or TCC) which assumes a linear behavior between temperature and accuracy error. The lower this number the less susceptible the sensor is to temperature effects. A typical number for TCC with high- or very high-performance sensors is < 0.001% error change / oC.

For the 20 sensors USC30 lot tested, we obtained the following TCCs:

> TCC (%FS) = 0.000088% FS error change/ °C which is **11 times** lower than the **High-Performance** target.

For repeatability on %FS, we calculated the max-min error at the same test point within the 3 final cycles at room temperature, this provided the following results than can also be visualized on Figure #11:

> Max. Repeatability at 25°C (% FS) = 0.037% FS error which is **27 times** higher than the **High-Performance** target.

All these results point in the direction of a very stable capacitive pressure sensor that can compete with high performance (< 0.1% FS Error Spec) and (<1% RD Error Spec).

5 Conclusions

If we consider the typical specifications offered in the market today by the manufacturers of pressure sensors for both OEM or transducer pressure sensing applications (1% FS), the results obtained in this study by testing the Ceracore USC30 sensors are far and beyond what is expected for a small OEM ceramic pressure sensor at reasonable pricing. The average performance in accuracy and repeatability is within the ranges of high performance (< 0.1% FS, < 1% RD). These values are typical of larger, heavier, bulkier and more expensive pressure transducers. The correct materials, the precise process, the proper calibration method, the appropriate electronic board for signal conditioning and the implementation of higher order temperature and pressure compensation algorithms, all add up to generate a pressure sensor that outperforms any small ceramic pressure sensor available today in the market.

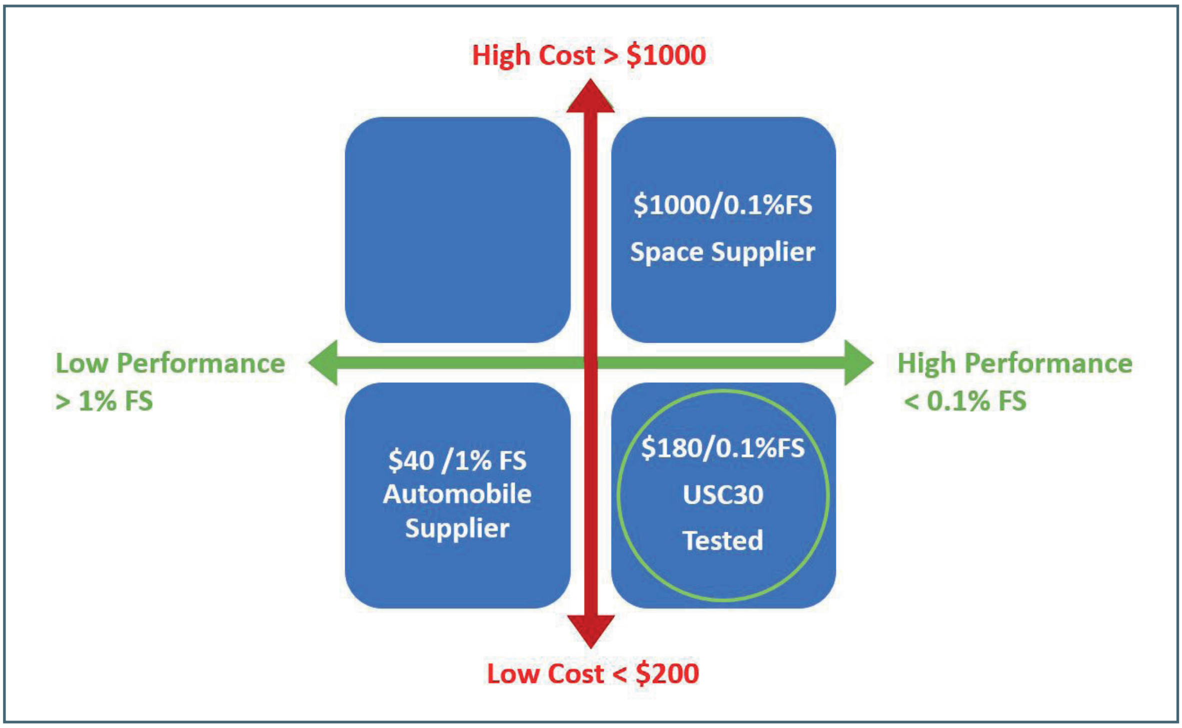


Figure #12: Performance to price ratio study

In an environment where mass production and miniaturization is driving the process industry and the need for better and better sensors is required at a lower and lower cost, it is necessary to focus on both the performance of the sensors (accuracy, repeatability, temperature compensation, drift) and its cost in large quantities. This is where a sensor like the Ceracore USC30 recently developed by Endress+Hauser will play an important role on bridging the gap between very high performance and low cost enabling applications that were not possible before. Either because it was too expensive to integrate the right temperature compensated pressure sensor, or performance was too low because of the allocated build of materials budget.
I hope this article can be used as a guideline to select the right sensor for your application.

References:

1. Paper: J Am Soc Mass Spectrom (JASMS). **Evaluation of small mass spectrometer systems for permanent gas analysis.** 13 Aug 2002:1004-12. Arkin CR, Griffin TP, Ottens AK, Diaz JA, Follistein DW, Adams FW, Helms WR
2. Paper: J Am Soc Mass Spectrom (JASMS). **Unmanned aerial mass spectrometer systems for in-situ volcanic plume analysis,** 15 Jan 2015. Diaz J.A., Pieri D., Wright K., Sorensen P., Kline-Shoder R., Arkin CR., Fladeland M., Bland G., Buongiorno M.F., Ramirez C., Corrales E., Alan A., Alegria O., Diaz D. and Linick J
3. Paper: Bulletin of the American Meteorological Society (BAMS) **Ozonesonde Quality Assurance: The JOSIE-SHADOZ (2017) Experience.** Sept 2018. Thompson, A. M.,..., **Diaz J.A.**, et al
4. US Patent #6612175B1. **Sensor usable in ultra pure and highly corrosive environments** Jul 20, 2000. NT International Inc/ Current: Entegris Inc. Tom Peterson, Jorge Andres Diaz, Gerald R. Cucci.
5. Sensor Expo and Conference Proceedings. **Capacitive Ceramic Pressure Sensors** June 7, 2012. Christopher Proios.
6. US Patent # 9958350. **Capacitive, ceramic pressure-measuring cell and method for the production thereof.** May 1, 2018. Endress+Hauser GmbH+Co. KG. Nils Ponath, Andreas Rossberg
7. US Patent # 9931717. **Assembly having at least two ceramic bodies joined with one another, especially a pressure measuring cell, and method for joining ceramic bodies by means of an active hard solder, or braze.** April 3, 2018. Endress+Hauser GmbH+CO. KG. Andreas Rossberg, Elke Schmidt, Markus Rettenmayr, Peter Siegmund
8. US Patent # 8966989. **Capacitive ceramic pressure measuring cell and pressure sensor with such a pressure measuring cell.** March 3, 2015. Endress+Hauser GmbH+Co. KG. Ulfert Drewes, Thomas Uehlin, Elke Schmidt, Andreas Rossberg
9. US Patent # 8104353. **Capacitive pressure sensor.** January 31, 2012. Endress+Hauser GmbH+Co. KG. Ulfert Drewes, Frank Hegner, Andreas Rossberg, Elke Schmidt, Sabine Stolle, Christel Kretschmar, Melanie Hentsche
10. Sensor Expo and Conference Proceedings. **How to find the right high-performance pressure sensor for your application: An independent performance characterization on capacitive ceramic pressure sensors.** June 27, 2012. Jorge A. Diaz

Contact

Dr. Jorge Andres Diaz
Universidad de Costa Rica,
Escuela de Física (School of Physics)
San José, Provincia de San Jose,
Costa Rica

jorge.andres.diaz@gmail.com
www.ucr.academia.edu