White Paper

Ceramic sensors perform well in tough applications

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Executive Summary

The purpose of this article is to facilitate the advantages of selecting ceramic pressure measuring cells in applications where plant operations and maintenance personnel may realize optimum process performance and stability through the use of Ceraphire® pressure sensors. Identify and demonstrate the inherent problems of using metal diaphragm pressure cells particularly in vacuum and chemical service. Bring awareness of enhanced performance and stability in pressure measurement to plant maintenance, quality assurance and operations personnel in order to improve their operations and the bottom line.

About the Author

After 20 years as an outside sales person for a manufacturer’s representative in Florida, John joined Endress+Hauser USA in July, 2008 as the Pressure Product Manager for gauge, absolute, differential and DP flow products. He earned his Bachelors in Business Management from the University of Phoenix.

John has many years experience with Endress+Hauser products and applications. Formally trained in instrument theory and application under the Naval MetCal program, John worked in an NIST Type III calibration lab. He has more than 20 years experience working in pressure measurement. Over the years, he has had many responsibilities including metrology, sales management, and project management and introducing grass roots product technology successfully in existing markets.

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Introduction
The demands on modern power plant engineers and maintenance personnel today are extraordinary. There are more and more expectations on power plant professionals to accomplish greater tasks with fewer resources and personnel. The goals for safety, quality and reliability are outlined by company operating procedures as well as standards set forth by industry organizations such as ISO, ANSI, ISA and IEEE. These standards and goals are expected to be met while at the same time operating budgets have decreased significantly in recent years. These power plant engineers and technicians are finding themselves meeting the goals set forth by management and governing authorities by improving process management and efficiency in the process. Many of these improvements are being done by means of deploying more reliable solutions in the plant and spending fewer hours and days on equipment implementation and maintenance. One of the ways this is being done is by reconsidering how pressure parameters are measured in the process.

Precision and reliability are key concerns when selecting pressure transmitters. Pressure measuring devices that utilize a Ceraphire® ceramic measuring cell rather than an oil filled pressure membrane is one way power plant personnel can increase accuracy, reliability and long term stability. In addition to improved performance, the Ceraphire ceramic cell is more robust than traditional oil filled pressure cells. In many applications the ceramic cell is a better choice for measuring pressure because it has no oil fill fluid and can operate much longer under process conditions where traditional oil filled pressure cells require maintenance on a routine basis. Oil filled pressure transmitters are very delicate instruments and careful consideration must be given to which oil fill is most suitable for the application. In many cases, multiple spares are needed to accommodate the various types of oil fills that are needed in a power plant.

Which oil fill is most suitable for your pressure measuring application, and why does it matter? Traditional pressure measuring cells that utilize a metal isolation diaphragm require an oil fill that surrounds a silicon chip, strain gauge or other signal generator which responds to force and transfers the pressure from the metal isolation diaphragm which is in contact with the process media. This technique is the most common way to measure pressure and is used by virtually every manufacturer in the industry. Pressure is one of the most important variables that are necessary to accurately measure in power generation. A specific example of how important accurate and reliable pressure measurement is in the condenser. Elevated condenser back pressure is one of the most obvious measurable parameters that results in loss of revenue and increased operating cost. Condenser back pressure is directly related to the power output from the steam turbine; excess back pressure equates to reduced efficiency and dollars that are wasted. In order to understand just how important accurate pressure measurement is, one must understand how inaccuracies in the measurement can lead to excess cost. For example, using the Comprehensive Condenser Model Theory (CCMT) on a base loaded condenser for a 525 MW generating unit that has a rise in back pressure of 0.3 inch of HgA, the unit will undergo a rise in heat rate that correlates to a loss of 2.68MW of power or about $770,000 per year. From the gasification process, to the boiler, then the steam turbine, the cooling water, the heat recovery boiler and finally the gas turbine; accurate and reliable pressure measurement is paramount to effective process control.

The oil fill in a traditional pressure transmitter is critical to ensure a uniform exchange of force from the process media to the pressure measuring cell, thus it is critical to the accuracy of the transmitter in the application for which it is applied. When utilizing oil filled pressure cells, there are many process conditions and changes that can interfere with pressure measurements providing false results which can lead to inadequate process control; for example, air bubbles in the measuring cell. Most plant personnel do not realize that a metal diaphragm cell may be filled and calibrated perfectly at the factory but once a vacuum beyond about 40 mbar is pulled on the diaphragm, there may be air trapped inside the diaphragm. This phenomenon is called outgassing and is also commonly referred to as off gassing. Outgassing is the release of absorbed or occluded gases or water vapor contamination under elevated temperatures or vacuum. It is a natural condition of stabilization where materials try to reach equilibrium inside the measuring cell. For similar reasons a new car carries its own aroma for the first several weeks while the materials of construction are meeting equilibrium. These liberated gases are then present in a pressure cell and under normal conditions the operator may never realize unless the measurement cell is being turned down to the low end of the range.

If however, the measuring cell is subjected to vacuum conditions, Boyle’s Law has a propensity to wreak havoc on the metal isolation diaphragm. Boyle’s law states the volume of a gas will vary in exactly the same way the pressure is varied,

\[ V = \frac{C_{BL} P^a}{P} \]

What that means is under high pressure conditions the gas will diffuse into the oil and will likely go unnoticed; conversely when a vacuum occurs on the face of the diaphragm, the gas expands inside the measuring cell creating a positive pressure. Two things happen when the gas expands: one, the transmitter does not measure accurately in this condition because the gas is compressible and proper force is not exerted on the electronic strain gage giving a false measurement and two, the oil is outgassing causing a bubbling effect and exerting pressure inside the measuring cell which is being exerted on the back side of the diaphragm creating a dome effect. This negative pressure causes the diaphragm to take the shape of a dome just like Jiffy Pop popcorn shown in Figure 2. Once this happens, the measuring cell must be replaced, leading to costly repairs and down time.
Over-pressurization and vacuum service are also serious considerations when it comes to the selection of a pressure measuring cell that uses a metal isolation diaphragm. If the process cycles from pressure to vacuum, the metal isolation diaphragm may fatigue which can lead to premature failure. Over-pressurization is commonly combated by forming metal stops directly behind the diaphragm which act as a backstop should the pressure become too great (Figure 7). Although the backstop approach is not a guarantee the diaphragm will not be damaged due to over-pressurization, it greatly reduces the chances of causing significant damage to the diaphragm provided the over pressurization is not excessive. The manufacturer’s specification will usually rate the cell for a maximum allowable pressure.

Chemical compatibility of the metal diaphragm with the process media is another great concern when it comes to the selection of a traditional pressure transmitter. If the proper material is not selected, the process media may damage or destroy the metal diaphragm, rendering the instrument useless which will inevitably lead to costly repairs and down time. Additionally, metal sensors are delicate and must be handled very carefully, ensuring not to even touch the measuring membrane, i.e. one should not touch the membrane at any time. Though the metal isolation diaphragm is prevalent in pressure measurement, Endress+Hauser, a full service instrument supplier in Greenwood Indiana, has been providing ceramic technology for measuring pressure for more than twenty years. Endress+Hauser also manufacturers metal diaphragm sensors and realize there are merits to using them when it is applicable; however, the instrument leader also sees opportunities to help their customers in tough applications where Ceraphire ceramic just makes better sense.

The capacitive Ceraphire ceramic gage and absolute sensor is a dry cell requiring no oil fill and provides a high degree of accuracy and reliability. The measurement cell operates on the principle of capacitance measurement, for which Endress+Hauser has been known for many years. The patented Ceraphire sensor consists of a ceramic body, a ceramic process membrane, a measuring electrode, a reference electrode and a spacer ring. The distance between the membrane and the sensor body is a well defined 40µm. Signal processing, temperature compensation and conditioning is accomplished by an onboard application specific integrated circuit (ASIC) shown in Figure 3. This technique is used for gauge and absolute pressure. Endress+Hauser also offers a differential pressure cell in a ceramic design. The differential ceramic cell has an added benefit which is a self monitoring circuit that will alarm should the ceramic sensor fail. In this simplistic yet innovative design, the pressure measurement is expressed as:

\[ P = \frac{C_p - C_r}{C_p} \]

Cp = Process capacitance  
Cr = Reference capacitance

Endress+Hauser developed a patented process for the Ceraphire ceramic sensors in 1987 and have been deploying them successfully ever since. Ceraphire ceramic sensors are formed of 99.9% aluminum oxide (Al₂O₃) and begin as crystallide particles which are smaller than <400 nm. The forming process uses extremely high pressures and temperatures without the use of sintering aids; the end result is an ultra-
high purity Ceraphire ceramic sensor of the highest quality, the tightest bond and an ultra smooth surface finish of (Ra<0.5µm). Figure 4 illustrates the surface finish of typical ceramic material as compared to Ceraphire by Endress+Hauser.

The Ceraphire ceramic membrane has a microscopic finish which assures that no permeation of small molecules from the process can diffuse in the sensor. The Al₂O₃ sensor has a 10-7 smaller diffusion coefficient than traditional metal diaphragms, which means the process will not permeate in to the cell. Furthermore, the absence of metal and nickel in particular ensures the Ceraphire ceramic sensors are suitable for use in processes where Hydrogen Diffusion can be a problem for metal diaphragm sensors. Traditional metal diaphragm sensors must be conditioned for Hydrogen Diffusion with noble metals such as Gold plating (Au). Gold plated metal isolation diaphragms are very expensive and generally take a long time to procure because they are made to order and the materials are not generally kept on hand by the manufacturer.

The gauge pressure sensor is a vented cell which measures pressure relative to atmospheric conditions by way of a protected vent. The vent is filter protected within the transmitter and allows the sensor to be compensated for atmospheric conditions. Moisture is kept out of the measuring cell with the use of a GORE-TEX® membrane. Just like a GORE-TEX rain coat keeps the wearer dry by keeping the rain out and allowing body heat to dissipate or breathe, the GORE-TEX membrane in the pressure transmitter keeps moisture out. The measuring cell may breathe and be compensated to relative barometric pressure because the air may flow freely through the membrane, but damaging moisture molecules are too large to pass through the membrane so the inside of the sensor remains dry. In the absolute sensor there is no vent. Absolute pressure within the sensor is achieved by evacuation of the measuring cell when the sensor is produced. Figure 5 illustrates the pressure cell where the force is exerted on the bottom of the sensor.

The ceramic pressure measuring cell is insensitive to temperature effects under extreme process conditions. According to the McGraw Hill Sensor Handbook, the typical temperature effects on sensitivity on the ceramic cell are <1% per 100°F Fahrenheit and as much as 12% per 100°F Fahrenheit for silicon metal diaphragm sensors (Soloman, 1998). Although ceramic material can withstand temperatures up to 2,000°C, there are limitations to the electronic components and the gasket material located between ceramic sensor and process connection. The Ceraphire ceramic sensors are fully resistant to temperature shock and will operate up to 150°C or 305°F without affecting the performance or long term stability of the cell.

Vacuum applications are no problem for the Ceraphire ceramic sensors due to the fact the sensor has perfect memory. When pressure or vacuum is introduced to the measuring cell, the sensor deflection responds proportionally and returns to the rest position when the pressure or vacuum is released or the cell returns to atmospheric pressure. The Ceraphire ceramic sensors do not fatigue or bend out of shape as metal will under vacuum conditions. When vacuum is measured in a process, it is the pressure relative to absolute zero that is being measured. At rest the transmitter will be subject to 14.7 psia (sea level) or absolute pressure; when the process is in a vacuum condition, the atmosphere is removed from the process creating a vacuum. Because the Ceraphire ceramic gage and absolute sensor have no oil fill, no bubble effect can occur in the cell which would create a positive pressure in a metal diaphragm pressure cell.

The Ceraphire ceramic sensor is rigorously tested in a helium chamber for a period of 8 weeks at an over-pressure of 10 bar (145 psi). The zero point is measured for deviation before and after the test. This is why Endress+Hauser can guarantee long term stability of the Ceraphire ceramic sensor to be greater than ± 0.05% URL/Year. Conversely, metal diaphragm pressure sensors are limited to a minimum pressure by the oil fill. For example, a silicone oil filled pressure cell may reach 10 mbar absolute while an inert oil filled cell may be rated to 40 mbar. To put that in to perspective, 40 mbar is equivalent to about 1.2 inches of mercury (HG) absolute while the ceramic cell is safe to full vacuum, 30” HG or 0 PSIA.

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A recent application for Ceraphire ceramic sensors is with a leading plastics producer measuring level in vacuum distillation columns which are used throughout the plastic production process. The process materials were various intermediate chemicals that are used in the production of plastics which are brought to temperatures of 220 to 338°F with a head pressure of 4 mmHg and the DP Level ranged from 24” H20 to 100” H20. The application challenges the customer was facing were accuracy problems with traditional metal diaphragm pressure cells. The remote seal metal diaphragm would frequently bulge (Jiffy-Pop) due to boiling of the fill fluid at high temperature and deep vacuum. Redundant metal diaphragm DP transmitters on the same distillation column often differed in level measurement by as much as 30% in a 100” H20 span or less.

The solution was to replace metal diaphragm remote seal DP transmitter with two Cerabar S ceramic absolute pressure transmitters using Ceraphire material. The differential pressure level measurement is now made electronically in the control system using the output from the two absolute pressure transmitters. The results were, two Cerabar S Ceraphire ceramic sensor pressure transmitters provided a more accurate and reliable differential pressure level measurement than the previous metal diaphragm remote seal transmitter. This provided several benefits to the customer:

1. Cost savings from not having to replace remote seal transmitters on a routine basis due to fill fluid boiling.

2. Fewer process interruptions since level measurement is more tightly controlled in the distillation columns.

3. Simplification of instrumentation and control loop since two remote seal DP transmitters and one pressure transmitter (for measuring head pressure) have been replaced by two absolute pressure transmitters (three transmitters with five process connections have been replaced by two transmitters with two process connections).

Figure 6. Cerabar S absolute pressure transmitter mounted on distillation column

Over-pressure is of key concern when selecting a pressure measuring device for any process. Constant over-pressure on the measuring cell or pressure shocks such as water hammer caused by pump starts and valve actuation under normal process conditions can cause fatigue in a metal isolation diaphragm (Figure 7). This constant movement on the diaphragm acts like a sub woofer speaker system that moves in and out as it creates sound. The constant moving in and out with rapid or severe pressure changes can cause weakness over time in a metal diaphragm. These weaknesses lead to instability, zero shift and non linear error over the range of the transmitter; it is particularly important to recognize this in small measuring ranges.

In addition to fatigue which may occur from constant movement of a metal isolation diaphragm, when maximum operating pressure is reached, a metal sensor will begin to bend out of shape. This bending of the diaphragm is permanent and will cause errors in the pressure reading, as well as zero offset. Illustrated in Figure 8 the ceramic sensor will operate consistently and accurately up to as much as 40 times the stated range of the cell without affecting the zero point or the accuracy of the measuring cell.

A major US mining operation was measuring pump discharge pressure on a Raffinate solution (10-20% Sulfuric acid) with a temperature of 80°F and static pressure that ranged from 200 to 500 psig. The engineer was faced with the following challenge: the solvent extraction and electro winning (SX/EW) process used to mine copper ore requires powerful pumps operating at high discharge pressures to pump Raffinate solution to the leach pad. Water hammer is a common occurrence in this process since pumps start and stop frequently and valves open and close quickly to control flow. The metal diaphragm pressure transmitters previously used to measure pump discharge pressure in this application typically lasted only a few weeks before failing. It was critical in this process to measure pressure accurately, and downtime and maintenance were common occurrences because of the overpressure created by water hammer caused the metal diaphragm to flex beyond its elastic limit and fail every few weeks. The customer replaced the metal diaphragm pressure transmitters with Cerabar S Ceraphire ceramic pressure transmitters with excellent results (Figure 9).

The failure rate of the Cerabar S Ceraphire ceramic pressure transmitters in this application is much lower than that of metal diaphragm pressure transmitters. On average, the Cerabar S Ceraphire ceramic pressure transmitters last more than a year, compared to a few weeks for the metal diaphragms. The customer realized several benefits.

Figure 7. Metal isolation diaphragm
1. Significant cost savings from no longer replacing metal diaphragm transmitters every few weeks.
2. More reliable pressure measurements since the ceramic sensor does not fatigue before failure, unlike a metal diaphragm.
3. Reduced process downtime since the ceramic pressure transmitters last much longer than the metal diaphragm transmitters in the application without failing.

Beyond the consideration of the process temperature, diaphragm material and what type of oil the transmitter must be filled with; when it comes time to consider replacement of a pressure transmitter one must consider total performance as well as cost of ownership. Recommended spare parts, calibration interval, chemical compatibility of materials, set up time, reliability, ease of operation, as well as local service are all major factors in the selection of a new transmitter.

A North American integrated steel manufacturer that supplies a range of materials in the automotive, construction and energy markets and has been in business for more than 100 years was faced with a problem using metal diaphragm cells to measure differential pressure in a high temperature location. The problem was the transmitter cabinet location which was above and between two furnaces and it would be costly and time consuming to move the cabinet. The company’s electrical supervisor estimated the ambient temperature between 266° and 284°F (130°- 140°C) when the furnaces were running. Because of the attractive price the customer purchased two of the Ceraphire ceramic differential pressure transmitters and to his delight, the transmitters did not drift at all in the high temperature environment. The manager has since replaced all 12 transmitters on the pre-heat furnace and is replacing pressure transmitters elsewhere in the mill.

What does this mean in dollars and cents? The traditional metal diaphragm sensor is delicate, has limitations in vacuum service, over-pressurization and vibration. Chemical compatibility and Hydrogen Diffusion applications using metal diaphragm pressure cells can lead to using extremely expensive noble metals such as Monel and Gold.

Additionally, cleaning metal diaphragms in dirty or coating applications can be time consuming and risky due to the delicate nature of the metal diaphragm. Because the Ceraphire ceramic sensor technology that is offered by Endress+Hauser is rugged, intelligent and built for industrial applications, combined with the ease of use, long term stability, chemical compatibility and lower purchase price it is easy to understand why Ceraphire is a good alternative to the traditional metal isolation diaphragm sensor.

Since 1987 transmitters using Ceraphire ceramic sensors have been assembled in Greenwood, IN and are installed in all types of pressure measuring applications which have proven the sensors to be rugged and reliable. Three year calibration interval, extremely high proof pressure, vibration immunity and chemical compatibility make for a reliable measurement in the toughest of applications. The Ceraphire ceramic sensors are most suitable for harsh environments, vacuum service and are immune to hydrogen diffusion without the use of expensive exotic materials. The innovative sensor technique, coupled with the smart easy to use electronics, modularity and the HistoROM® memory make this family of pressure measuring instruments a perfect solution for accurate and reliable process variables. Each Ceraphire ceramic pressure cell that is shipped is backed by the reputation for quality and reliability of Endress+Hauser and more than 50 years of know-how and competence in field instrumentation.

The Ceraphire ceramic sensors are also well suited for abrasive process conditions because of the durable material of construction. In addition these sensors are an excellent choice for processes where coating occurs because they can be cleaned with a wire brush or even scraped with a sharp tool with little concern for damaging the ceramic surface. Chemical compatibility is of minor concern when selecting the Ceraphire ceramic sensor due to the resistive nature of the ceramic material. Vibration and pulsating pressure on the gage and absolute sensors is of minimum concern because the sensor has no fill to transmit the vibration from the outside in, as a result the deflection on the sensor only occurs when force is exerted on the outside of the measuring surface. The sensor is also immune to EMI and RFI. The zero and span are non Interactive; the sensor holds calibration reliably time after time.
References


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