Cruising through the pressure transmitter selection process:
Technology tradeoffs, application pitfalls, and cost-benefit evaluation

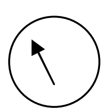
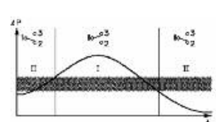
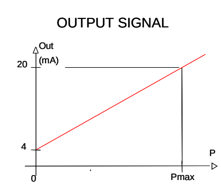
The extent of automation in both mobile and stationary applications is increasing dramatically. As the efficient management of machines and systems becomes more and more dependent on integral electronic controls, there will be an increasing demand for sensors and transmitters. Advances in electronic controls will allow some very attractive features to be offered, and corresponding greater benefits derived, all at competitive costs; but care must be taken to select the best transmitter for the application.

The proliferation of pressure transmitters you encounter today in the marketplace can be overwhelming. Increasingly, transmitter manufacturers seek to differentiate their products by promoting features that may be commonplace. To make the right choice, it is important to know the operating conditions and performance requirements of the target application, and to separate critical and non-critical specs, knowing which features are essential, and which are "nice to have."

Aside from technical aspects of transmitter selection, it is important to evaluate the company that will supply the products. Can they deliver a product consistently on time, and consistently at a quality level that will meet expectations?

From switch function to transmitter signals

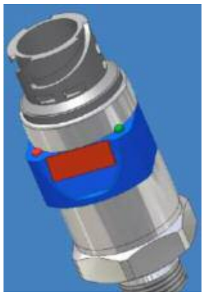
Mechanical gauges and electromechanical pressure switches will still be with us for years to come, but their future is challenged by the quickening pace of electronic integration. Transmitters offer several advantages, but they do require electronics for signal interpretation.

Gauge	Switch	Transmitter and Electronics
		
Monitor	***Alarm + Regulate***	***Monitor + Alarm + Regulate***

Types of pressure monitoring and control devices and their capabilities.

More than one type of these products may be found on a given piece of equipment.
. *Switches* for shut down and safety;
. *Transmitters and electronics* for monitoring and process control;
. *Gauges* for display.

Numerous manufacturers have developed compact, low-cost products that combine monitoring, switching, and transmitter output functions.



Function integration gives us pressure transmitters with built-in switch function and display. The switch function may be achieved by using NPN or PNP open collector transistor outputs or a micro-switch. Although these controls have a limitation on the electrical load that can be handled, the limits will not normally be a problem when using the integrated products in combination with electronic controllers. Some of the advantages of the integrated solution, compared with an electro-mechanical switch, are capabilities for a wider adjustment of the differentia and for increased setting accuracy. Integrated transmitters also enable the use of simpler electronic controls.

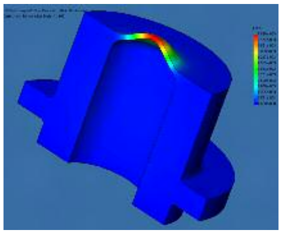
The science behind different technologies

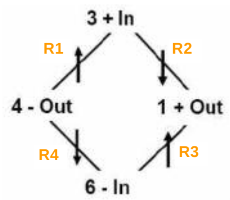
The wide variety of pressure sensing technologies on the market can make it quite difficult for the user to choose the right one for a particular application. To understand and evaluate the strengths and weaknesses of different technologies, the first requirement is some general knowledge about sensing principles.

The two most common principles used in industrial cartridge pressure transmitters are strain gauge Wheatstone bridge sensing and capacitive sensing.

1. Strain gauge Wheatstone bridge sensing
   The strain gauge pressure sensing principle has two crucial elements:

- A force-gathering element (commonly a flexible diaphragm), which converts pressure into a measurable ***strain***.





- ***Gauge*** elements (bridge resistors) that proportionally transform strain into an electric signal by using the Wheatstone bridge principle.

The gauge elements are placed on the flexible diaphragm in such a way that they are stretched or compressed under pressure. The physical change causes a change in resistance and thus a differential output signal that is directly proportional to the applied pressure.

Typical relationships between the gauge resistors in the Wheatstone bridges, diaphragm material, and gauge factors are given in the table below.

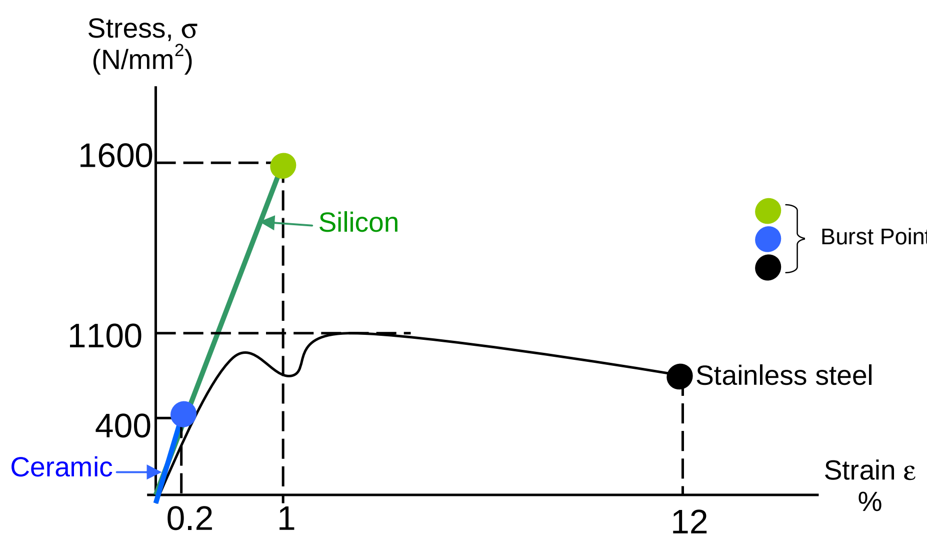
Gauge Resistor / **Diaphragm**	***Thin film metal***	***Thick film paste***	***Piezoresistive semiconductor***
Metal	*Gauge factor: approx. 2		*Gauge factor: approx. 20
Ceramic		*Gauge factor: approx. 10	
Silicon			*Gauge factor: approx. 30

* Gauge factor is a measure of a gauge's sensitivity to changes in strain.

A high signal-to-noise ratio is desirable, so the level of signal should be as high as possible. A simplified expression for the signal level is:

Signal = gauge factor x strain

The graph below shows the relationship between strain (**ε**) and the stress factor (σ) for three diaphragm materials. Ceramic and silicon are normally used in the strain range from 0.05 to 0.1. These limits are chosen in order to have sufficient safety between normal operating pressure and burst pressure. Stainless steel is used in the same range, because of the risk of material deformation that in turn causes zero point shift upon return to normal operating pressure.

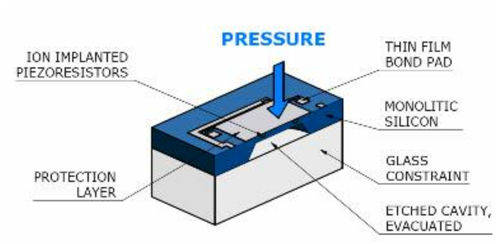


This means that only a small part of the strain range is usable, and therefore a high gauge factor is attractive.

The gauge elements can be bonded onto diaphragms in a number of different ways. Glues, silicon or ceramic fusion, glass bonding, and direct molecular bonding (PECVD or sputtering) are all used.

Thin film

In *sputtering* or *CVD (Chemical Vapor Deposition),* an insulating layer is placed on a metal diaphragm and then thin metal film strain gauge resistors are placed above the insulating layer.



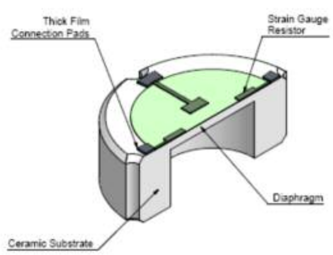
Monolitic piezoresistive semiconductor

A diaphragm is etched into bulk silicon, and piezoresistors are doped into the same material.

Occasionally, these piezoresistive elements are incorporated into oil-filled isolation cells, protecting the strain gauge from corrosive media.

Bonded piezoresistive semiconductor

Individual piezoresistive silicon semiconductor gauges are bonded to the diaphragm using adhesives or glass.



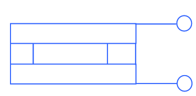
Thick film

Thick film strain gauge resistors are placed onto a ceramic diaphragm using thick film technology.

2. Capacitive sensing

   The principle of capacitive pressure sensing is based on measuring the capacitance between two conductive plates. Under pressure, the plates are forced together, increasing the capacitance in line with applied pressure.

   Capacitive pressure sensors can be of three types: ceramic, constructed by advanced MEMS technology (dies), or build into semi-conductor materials.



   Of the three types, ceramic capacitive technology is the most widely used in industrial applications.

The capacitance of two parallel plates is given by the equation:

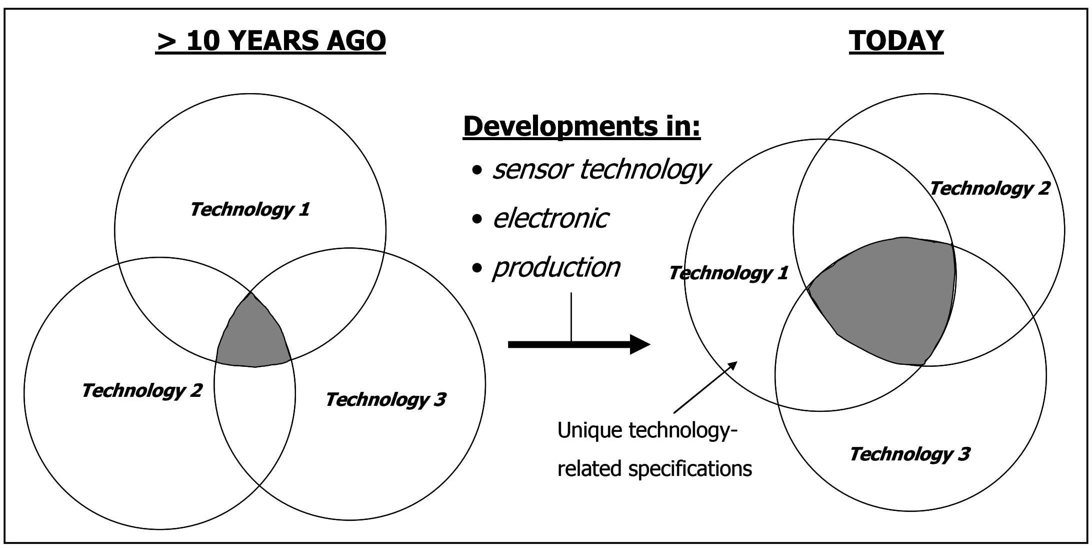
$$C = \mu A/d$$

where μ = dielectric constant of the material between the plates
d = distance between the plates
A = area of the plates

Change in the dielectric constant of the material between the plates may result in error. For that reason, absolute pressure sensors with vacuum between the plates are preferred.

What pressure transmitter technology should I choose for my application?

As a result of the ongoing development of the various sensor technologies and the introduction of digital electronics and advanced production equipment and methods, there is an ever-increasing overlap of specifications between the technologies than there was 10 years ago. This development is to some extent a result of manufacturers having marketed a single technology in the past. In recent years, those same manufacturers have been quite successful in maximizing the capability of products based on their single technology. The result for end users is that there is a much wider choice of sensors that can be used in a given application.



Still, there are characteristics that are unique to each specific technology, difficult and costly, or impossible, to achieve using competing technologies.
Examples of such characteristics include:

- pressure range
- temperature range
- zero displacement due to overpressure
- long term thermal drift both at zero and over span
- ability to measure absolute or gauge pressure

To meet the full range of customer needs today, there appears to be a trend toward sensor manufacturers developing broad product portfolios in order to offer more than one sensor technology.

It is indeed difficult to make a fair judgement about the strengths and weaknesses of pressure transmitter performance characteristics when different technologies are involved. The judgement about whether a specification is strong or weak must be made in light of the specific application's demand.

The table below represents a performance evaluation of the majority of transmitter types on the market today. But individual products are also available in which special measures have been taken to eliminate some of the weaknesses of the product's transmitter type.

	Ceramic capacitive	**Ceramic thick film**	**Thin film**	**Monolitic piezoresistive semiconductor**	**Bonded piezoresistive semiconductor**
Pressure range	0.01 – 60 bar 0.15 – 900 psi	4 – 60 bar 60 – 900 psi	10 – 2000 bar 150 – 30,000 psi	0.1 – 600 bar 1.5 – 8700 psi	5 – 3000 bar 70 – 43,500 psi
Accuracy	++	-	+++	++	+
Operating temperature span	+	+	+++	++	++
Long-term stability	++	+	+++	++	++
Pressure peak resistance	+	+	++	+++	++
Over-pressure safety	++	+	+	+++	++
Burst - pressure safety	++	+	++	++	++
Resistance to shock / vibration	++	++	+++	+++	+++
Hermetical tight pressure port (No seals)	-	-	++	++	+++
Absolute	+++	+	-	+++	-
Gauge	++	++	++	++	++
Low cost	+++	+++	++	++	++

*Typical figures. There are products on the market in which special action has been taken to exceed the range limits shown.

+++ = Very good
++ = Good
+ = Satisfactory
- = Less satisfactory or not applicable

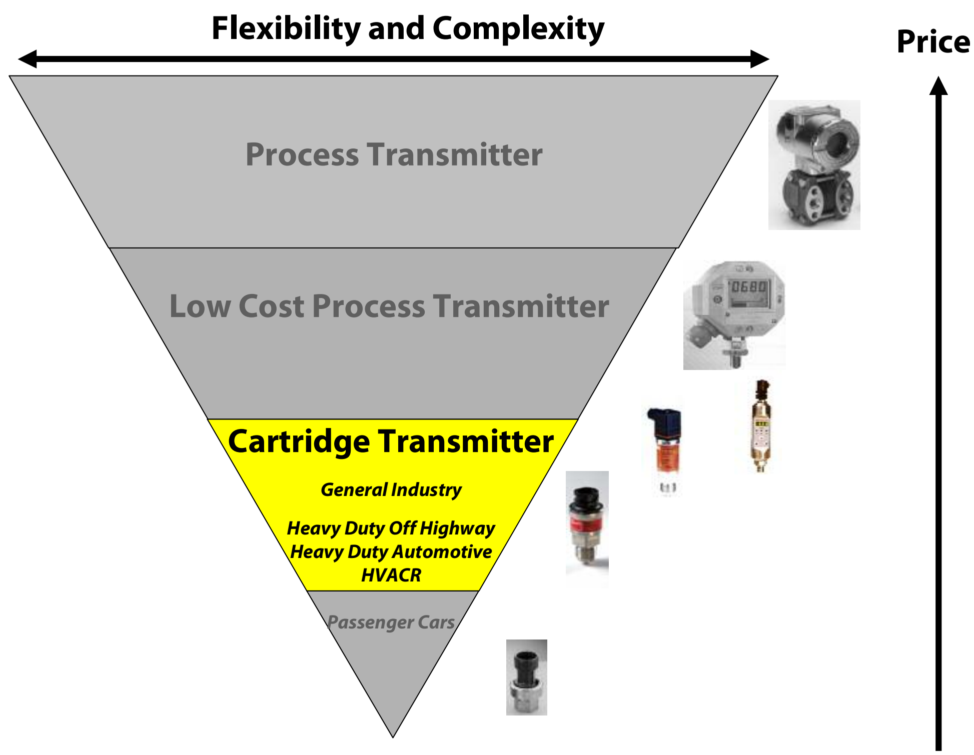
"Cartridge-style" – One of many families

Pressure transmitters used in industrial environments can be divided into families according to their functionality and their complexity. Often, as functionality and flexibility decline, prices decline and market volume increases.

This discussion will focus on "cartridge-style" pressure transmitters used in the following areas of application:

- General Industry
- Heavy Duty Off-Highway
- Heavy Duty Automotive
- Heating, Ventilation, Air-Conditioning and Refrigeration Systems (HVACR)

Below illustration shows how flexibility and complexity relate to various markets, applications, and costs. As the width of the triangle increases, so do flexibility, complexity, and usually costs.

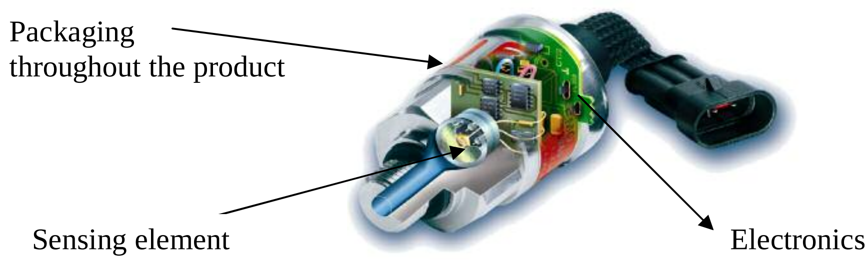


Operating conditions and performance demands

When selecting a sensor for a particular application, it is important to understand the operations conditions that the sensor will be exposed to, and the needed performance!

A typical pressure sensor has three functional elements:

1. The **sensing element** that transforms pressure into an electric signal
2. **Electronic circuitry** to condition and amplify the signal
3. **Packaging**, including the enclosure and the mechanical design throughout the product



The combination of these elements must provide specified performance under the environmental conditions of the specific application. It is therefore important to understand the application, conditions and their influence on the product’s specifications and performance.

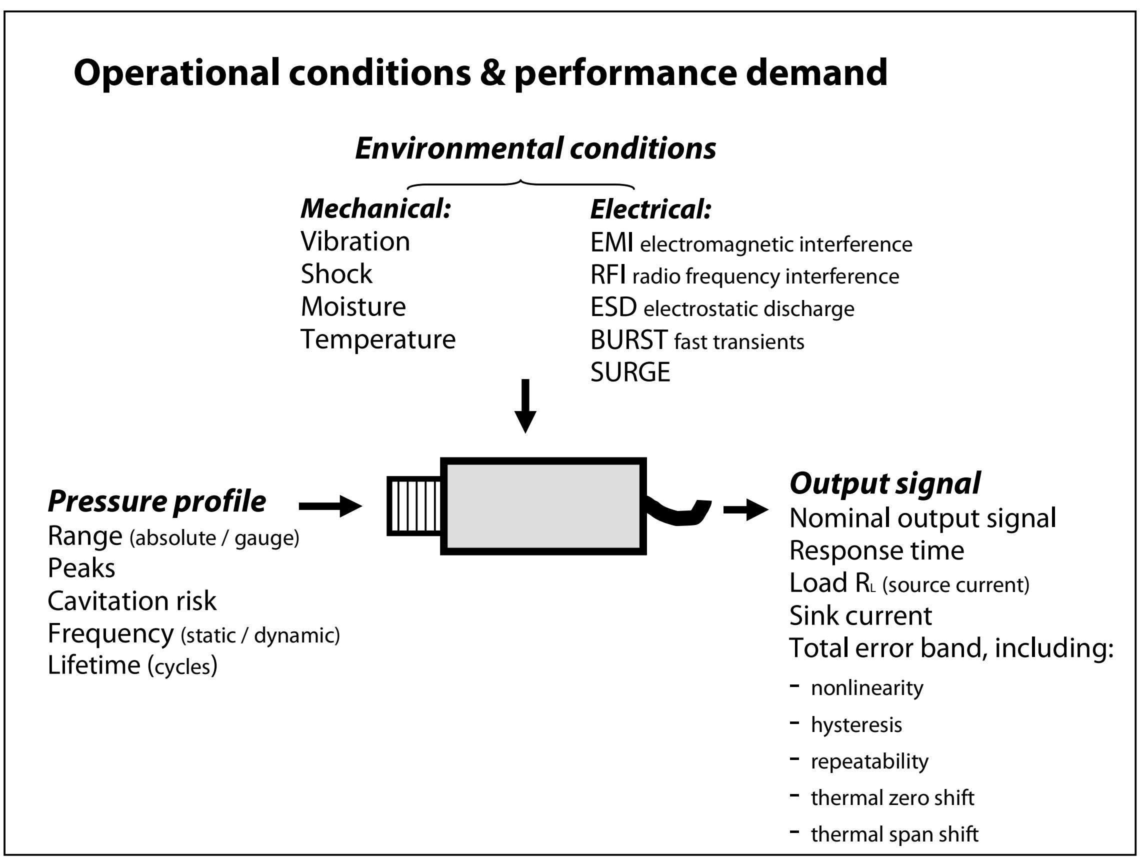


Figure 5. Summary of operating conditions, application requirements, and performance characteristics

Application pitfalls

The pitfalls we present here are encountered not only in these situations, but in many other industrial applications as well.

Material handling applications

Load sensing for tilt control is a typical application for pressure transmitters. The position of the load is often controlled by a hydraulic system. To calculate the tilt risk, pressure on the hydraulic cylinder, boom angle, and load position must all be measured.
In this application there are two demanding conditions under which a pressure transmitter must be able to work.

1. <u>Pressure peaks, liquid hammering, and cavitation.</u>

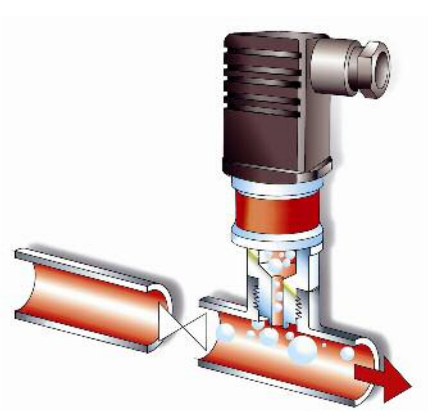
When driving on rough terrain with a load on the forks, the risk of rapid load variation is great. Abrupt load variations can create pressure peaks, liquid hammering, and in some cases life-shortening cavitation.

Liquid hammering occurs where liquid continues its flow in the pipe after a valve has been closed or a pump shut off. A vacuum is built up between the valve or pump, and the liquid returns as a pressure peak or “liquid hammer” on the diaphragm. This pressure peak can cause plastic deformation or even breakage of the measuring diaphragm.

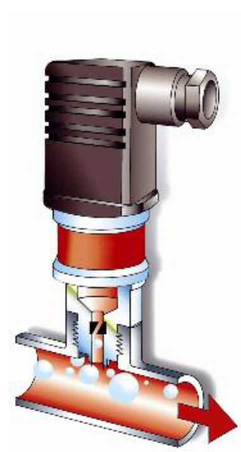
Cavitation occurs where small and mainly empty cavities (“bubbles”) are generated in a fluid and these expand and then rapidly collapse. This will happen when pressure falls below the vapor pressure of the fluid (it is almost the same as the effect that occurs during boiling). A thin sealing diaphragm is especially vulnerable to the asymmetric pressures that result from cavitation.

Depending on the sensing technology used, resistance to damage from liquid hammering, cavitation (or both) can vary. To avoid damage from either, a pulse snubber is recommended.

> *In these applications, one functional element, the sensor element, is challenged. To meet this challenge, carefully evaluate the type of sensor element and consider selecting a transmitter with an integral pulse snubber.*



Without a pulse snubber, cavitation bubbles occur in the transmitter.



With a pulse snubber, no cavitation bubbles occur in the transmitter.

2. Temperature and humidity extremes.

Very often, small forklifts are working under conditions where they experience many temperature changes during a workday. They are driven in and out of buildings, and some are used for picking up and delivering goods in cold storage warehouses.
These extreme cases of temperature and humidity cycles bring specific risks:

a. Moisture entering the encapsulated transmitter, exposing the electronics to damage. *In this case, focus the selection process on the packaging functional element, and specifically on the protective enclosure. If a gauge version is used, make sure that the design for reference to the atmosphere does not subject the transmitter to damage by allowing the entrance of moisture.*

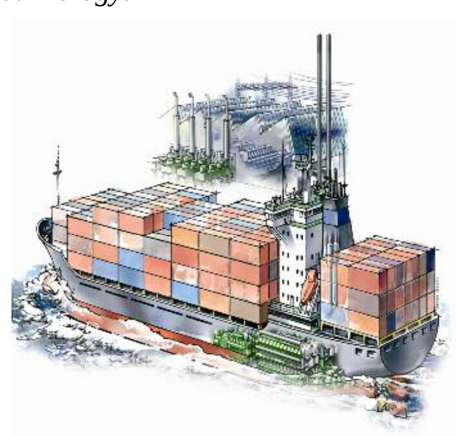
b. Large changes in measurement accuracy. Most transmitters have a thermal error shift affecting both zero point and span. Depending on the manufacturer and the technologies used, the thermal error shift typically varies from 0.1% to 0.6% FS/10°K. Fork lifts picking up goods from cold storage warehouses often run in an environment where the temperature changes from -40°C to 30°C, a span of 70 degrees. Depending on the time spent in the warehouse, and on the transmitter mounting location, such a large temperature change can produce a significant error in the transmitter output signal. (For example, a 20-degree span is equivalent to an error of 0.6 x 2 = 1.2%.)
Here, the important question is: Does the product offer acceptable thermal shift error data?

Construction & forestry equipment

These machines have applications for pressure transmitters on their engines and hydraulic systems. In hydraulic systems applications, you will often find conditions similar to those described above for forklifts. A challenge for products used on rough terrain equipment is to be able to work under extremely difficult mechanical and environmental conditions. The equipment is exposed to weather conditions of every kind and to high levels of moisture, dust, shock and vibration.

The challenge here? Packaging: connector and sealing technology.

Engines (for vessels and power plants)



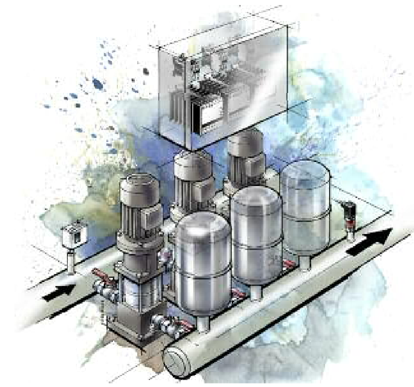
The conditions in these applications are often characterized by temperatures as high as 125°C combined with pronounced vibration. Constant high temperatures for extended periods can result in significant output signal drift, and combined with vibration will be a severe challenge for the product packaging.

Selection for these applications must focus on the need for appropriate sensor technology that has acceptable lo drift data at higher temperatures. For fuel oil applications, choose a transmitter with an integral pulse snubber.

Water booster systems

In this application, transmitters can be subjected to the risk of water hammering and cavitation in two ways. When transmitters are mounted just after a valve, there is exposure whenever the valve closes. The second type of risk arises when a transmitter is placed in a long water line, and hammering and cavitation can occur whenever flow is stopped.

In applications with these risks, selection focus should be on the sensor element and on inclusion of an integral pulse snubber.



Refrigeration systems

Some refrigeration systems operate at low pressure ranges of approximately 1 bar. Refrigeration systems are normally closed systems with no reference to the atmosphere. Given these conditions, you need an absolute or at least a sealed gauge pressure transmitter. If you use a gauge version, you will see errors resulting from one or both of the following:

a. the change in atmospheric pressure, maximum +/- 50 millibar (+/- 1.48 in. Hg)
If a transmitter's full scale range is 1 bar, a change of 50 millibar in atmospheric pressure will result in an error equivalent to 5%.

b. the change in altitude (-100mBar per 1000 meters)
Here, for a 1 bar transmitter, there can be an error equivalent to 10% per 1000m change in attitude. In Denver, a mile above sea level, a transmitter not recalibrated for the altitude would be subject to an error of 16%.

The same effect occurs when using an absolute pressure transmitter to measure level in an open tank system.

Cost-Benefit Evaluation:

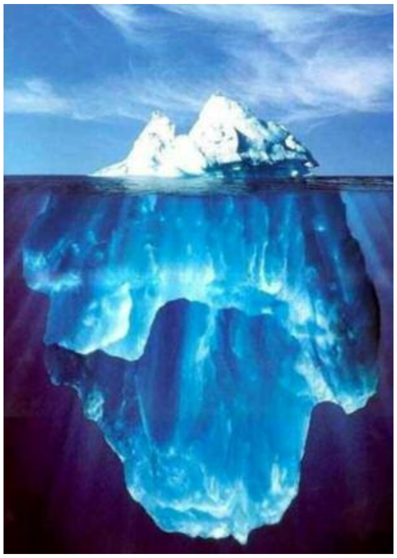
Be a methodical customer
After a thorough technical analysis, an evaluation of the company behind the products will be of great value. End product delivery and quality are very dependent on constantly reliable deliveries of high quality products by suppliers.

In supplier evaluation, follow a methodical course, completing every step:

1. Select some suppliers that you believe are reliable and capable of delivering the products you need. Find suppliers who are interested in serving the application demand, not simply the specification on a blueprint.
2. Audit the company behind the products as to
    a. Tools used during product design, such as
        i. DFMEA (Design Failure Modes and Effect Analysis)
        ii. Lean development
        iii. Availability of test results
    b. Tools used in production, such as
        i. PFMEA (Process Failure Modes and Effect Analysis)
        ii. Process capability tracing (Cpk values) both internally and at suppliers
        iii. Control plans
        iv. Production scrap level in ppm
        v. Level of field complaints in ppm
        vi. Corrective action programs
    c. Support procedures
        i. Logistic setup
        ii. Availability of technical support
        iii. Complaint handling
3. Test the product in the actual application

    It can be difficult to anticipate all operating conditions. Therefore, to avoid any surprises when using the pressure transmitters in running production, run functionality and performance tests on the real application.

Consider the total cost of ownership
A cost-benefit evaluation that focuses primarily on the total cost of ownership is an important part of the selection process.



Product cost

Total cost is also affected by:

- **Application engineering support**: *availability, quality*
- **Logistics:** *supplier location, transportation, inventory, purchasing, administration, etc.*
- **Delivery reliability**
- **Cost of quality** *failure rate, warranty issues*
- **Supplier's willingness to make product modifications**

Product cost
When choosing a product, make sure to specify the application's actual requirements. Select the product with specifications accordingly. Sometimes, "you get what you pay for" applies, but it's also certain that "you will pay for what you ask for." In other words, if you don't know your exact need, you may incur extra costs by choosing a product with specifications beyond what's required by your application.

But what else affects total cost?
As is the case with icebergs, the entire picture is often not immediately apparent. Depending on suppliers, other costs below the surface can be dramatically greater than what appears in the pricelist. It is not only the component price that should govern selection, but rather all costs related to the product.

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