Transducers and Specifications

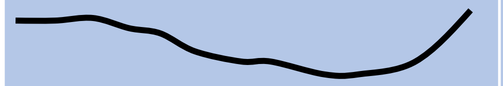
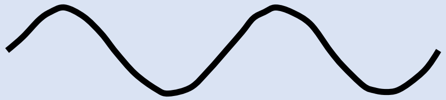
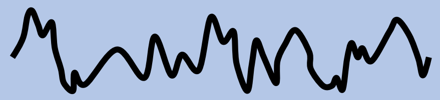
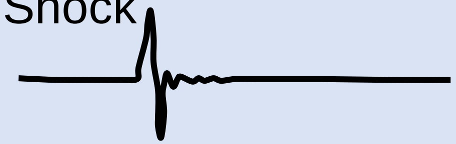
- Accelerometers
- Strain Gages
- Pressure Transducers
- Thermocouples
- Transducer Specifications

Transducers

- Transducers contain a sensing element that responds to a physical phenomena.
- Electronics within the transducer turns the sensing response to an electrical signal.
- The electrical signal may be conditioned within the transducer to a high-level voltage that can be measured by a data acquisition system.
- The transducer must survive and provide quality data in the harsh environment it will be subjected to.
- There are numerous types of transducers available. We will cover the most common types to get an appreciation of the various technologies used.

Accelerometers

- There are a wide range of accelerometers available
- The technology used in each depends upon the type of signal being measured.

Measurement Type	Time Domain	Freq Domain	Other
Simple Motion 	Time plot Maximum Value		
Periodic Vibration 	Peak Amplitude Average Value RMS	Discrete Line Frequency Spectrum	
Random Vibration 		Power Spectral Density	Amplitude Probability Distribution
Shock 	Peak Value Rise Time Duration		

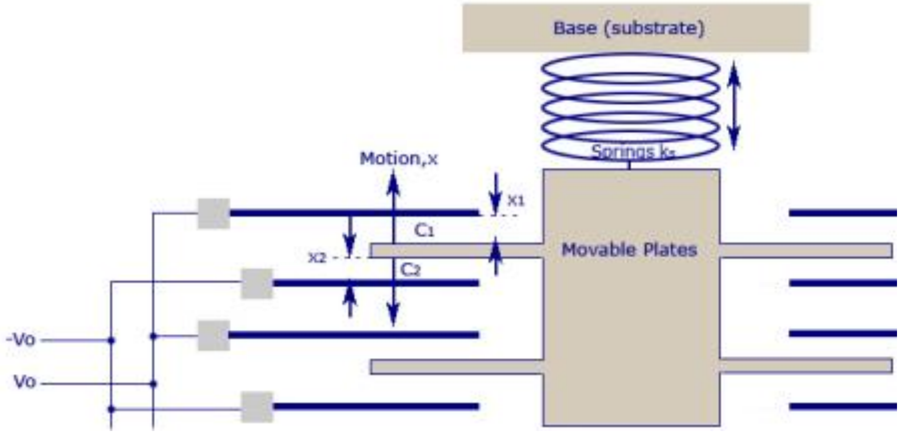
Accelerometers – Variable Capacitance

- Have a DC (steady state) response
- Have high sensitivities to measure small accelerations
- Have a lower frequency response
- Have good temperature stability
- Available in single or tri-axial models

- Variable capacitance accelerometers are good for measuring low frequency vibration, motion and steady state acceleration.

tri-axial

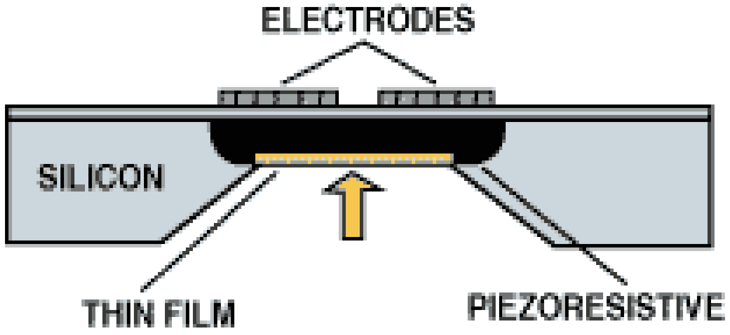
single axis



Accelerometers – Piezo-Resistive

- Have low sensitivity making them desirable for high-G shock measurements.
- Have a wide bandwidth and the frequency response goes down to zero frequency or steady state, so they can measure long duration transients.

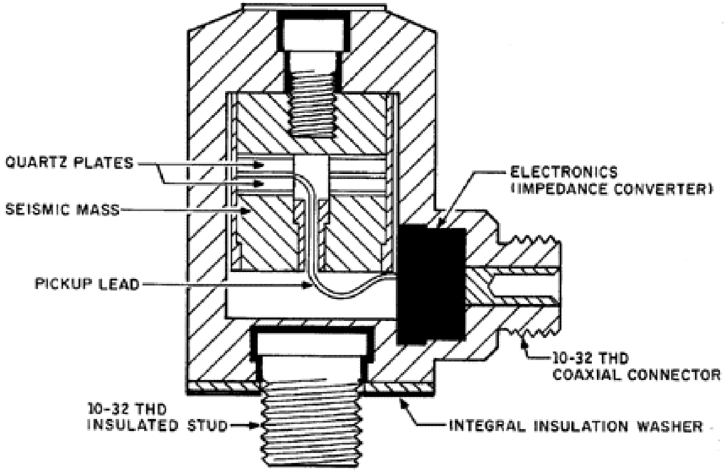
Piezo-resistive accelerometers are used extensively in transportation crash tests. Due to the low sensitivity, they are not used for vibration measurements.



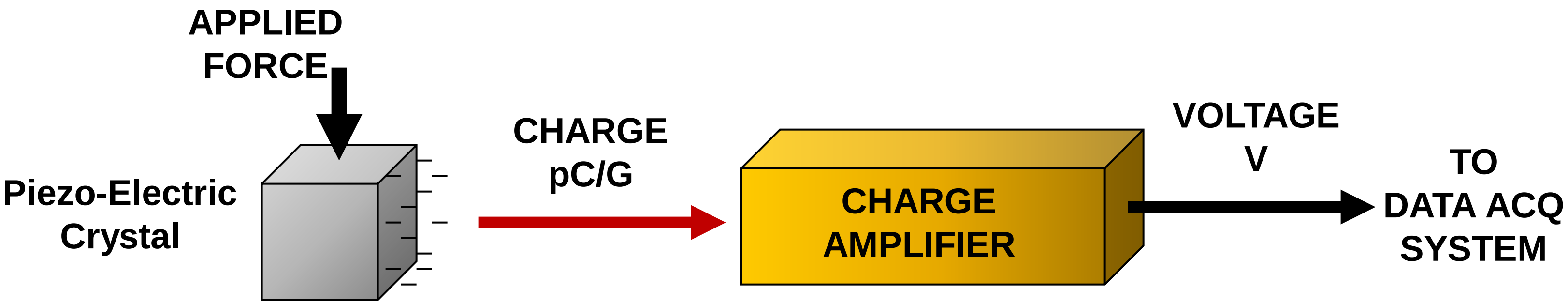
Accelerometers – Piezoelectric

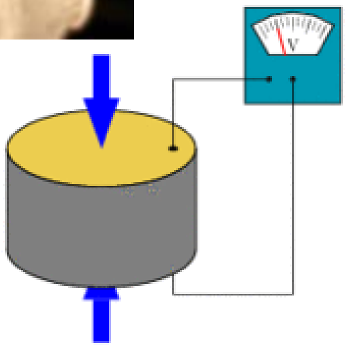
- Have a very wide measurement frequency range (a few Hz to 30 KHz).
- Can measure high G levels .
- Are available in a wide range of sensitivities, weights, sizes and shapes.
- Can be mounted in more volatile environments.

Piezo-electric accelerometers are the most widely used and should be considered for both shock and vibration measurements.



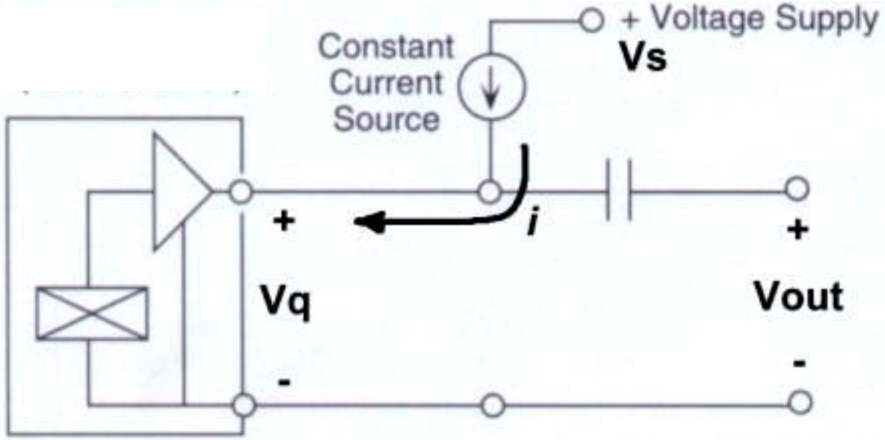
Accelerometers – Piezoelectric





- When a force is applied to the Piezo-electric crystal within the accelerometer, it produces a proportional charge.
- The cable between the accelerometer and charge amplifier is a special, low-capacitance cable.
- The charge amplifier converts the charge in pico-Coulombs (pC) to voltage (V).
- The voltage signal is then conditioned in the data acquisition system.

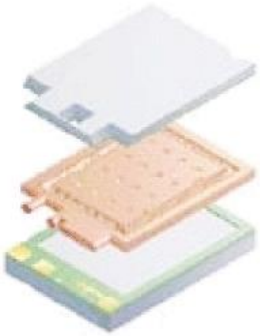
Accelerometers – Constant Current Piezoelectric



- Another piezoelectric type accelerometer for measuring vibration is powered with a constant current source.
- The voltage supply associated with the constant current source is known as the “compliance voltage”.
- This accelerometer has internal electronics, so a charge amplifier is not needed.
- Uses only a shielded twisted pair cable for both signal and power.
- Because of the internal electronics the environment in which it is used must be not as volatile.

Accelerometers – MEMS

- Another source of acceleration measurements are IC packaged accelerometers. The devices come in both through-hole and surface mount packaging. Primarily used in the auto industry, these devices are something to keep in mind where the situation may warrant a small sensor.

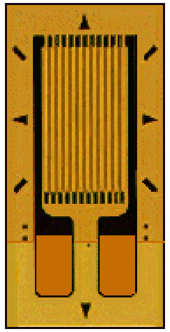


This unit, contains solid state devices measuring accelerations, angular rates, and attitudes which are output to RS-232.

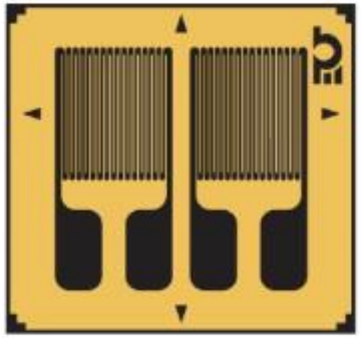
Strain Gages

- Strain gages come in many forms for the various strain and loads measurements being made.

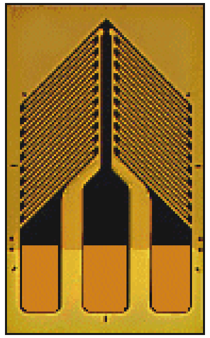
Uniaxial



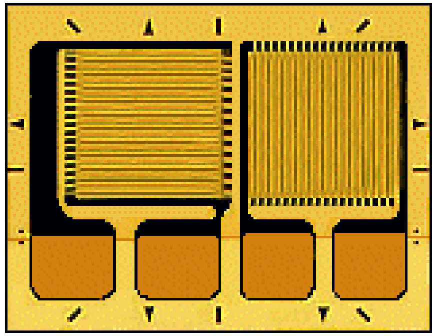
Bending Strain



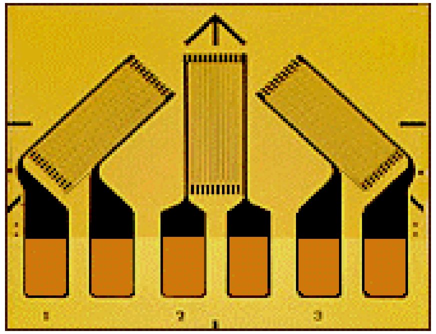
Shear/Torsion



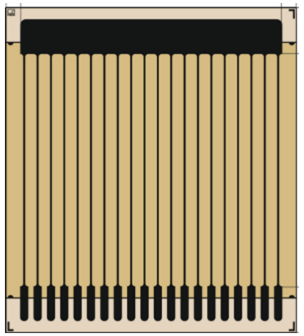
Biaxial Rosette



Three Element Rosette

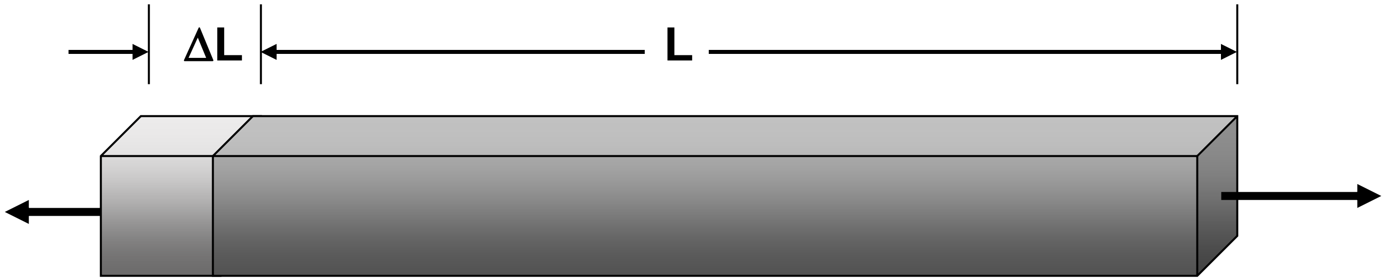


Crack Propagation



Strain Gages – What is Strain?

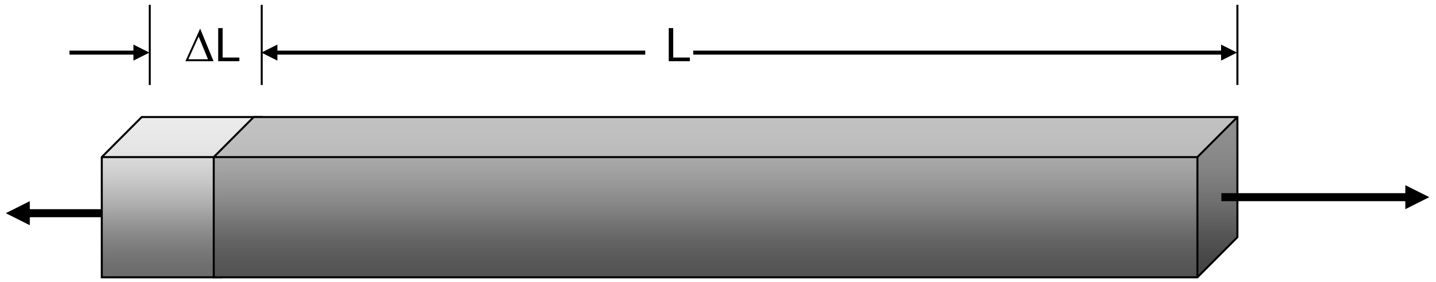
- Strain is defined as the amount of deformation per unit length (in / in, mm / mm) of an object when a load is applied. The quantity is dimensionless, but a unit of strain (Greek letter **ε**) is used. Because the change in length is so small, strain is usually expressed in micro strain (με) or one millionth (10^{-6}) ε.



$$\text{strain} = \left(\frac{\Delta L}{L}\right) \quad (\varepsilon) \quad = \left(\frac{\Delta L}{L}\right) \times 10^{6} \quad (\mu\varepsilon)$$

Strain Gages – What is Strain?

- If a metal rod is originally 3.0000 inches long and it is stretched to a length of 3.0012 inches, what is the amount of micro strains the rod experiences?

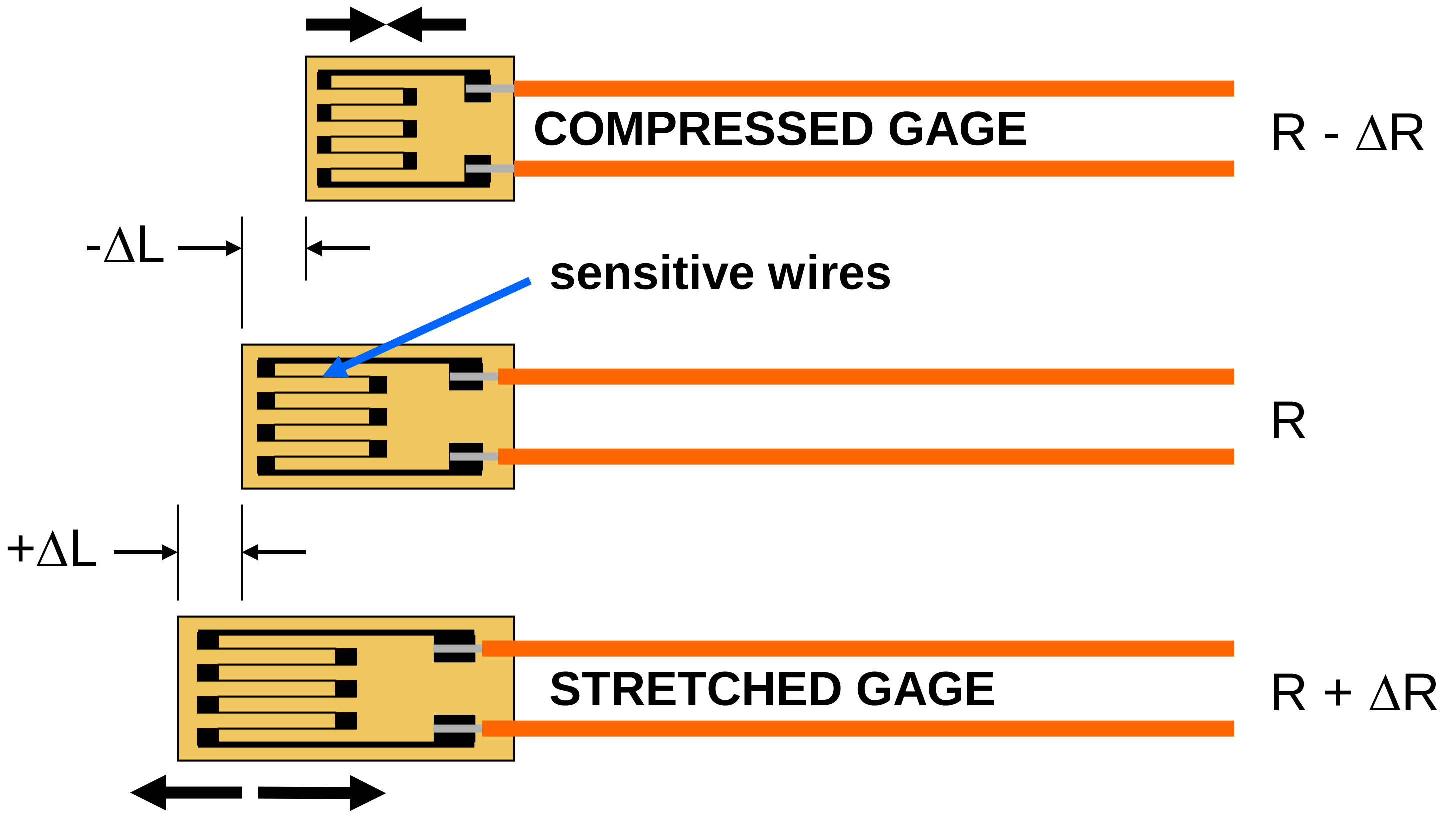


$$\text{strain} = \left(\frac{\Delta L}{L}\right) = \left(\frac{3.0012 - 3.0000}{3.0000}\right) = \left(\frac{0.0012}{3.0000}\right)$$

$$= 0.0004\varepsilon = 0.0004 \times 10^{6}\,\mu\varepsilon = 400\,\mu\varepsilon$$

Strain Gages

- To measure the strain, a strain gage is adhered to the surface. When a strain gage stretches or compresses, the small wires also stretch and compress, causing the resistance of the gage to change proportionally to the change in length.



Strain Gages – Gage Factor

- The relationship between the relative change in resistance and relative change in length is called the Gage Factor (GF). It can be thought of as the "sensitivity" of the gage.

$$GF = \left(\frac{\Delta R}{R}\right) / \left(\frac{\Delta L}{L}\right) = \left(\frac{\Delta R}{R}\right) / strain$$

Rearranging … $\Delta R = GF \times R \times strain$

Strain Gages – Gage Factor

- When a batch of strain gages is manufactured, a sample is taken to determine the Gage Factor. It is usually specified as some nominal value with a corresponding tolerance.

This example illustrates that this particular model of strain gage has a nominal Gage Factor of 2, but can vary as much as ±5% from all the batches of gages the vendor produces.

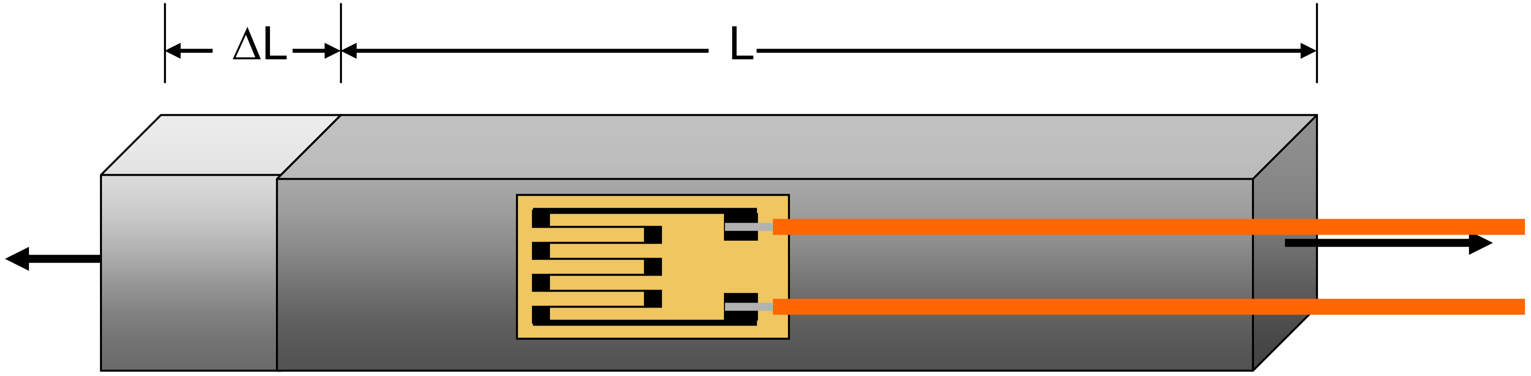
For an individual package from a known batch of gages, the Gage Factor will be specified on the package (2.005) and have a tolerance of only ±1%.

Gage Factor (Actual Value Printed on Each Package)	2.0 ±5%
Gage Factor Tolerance Per Package	1.00%

Think of the Gage Factor as being equivalent to the sensitivity of an accelerometer (mV/G) which is included in their calibration certificate.

Strain Gages – Resistance Change

- For the example we did earlier, we measured 400 $\mu\varepsilon$. The equivalent resistance change of a 350Ω gage with a vendor specified GF of 2.005 would then be:

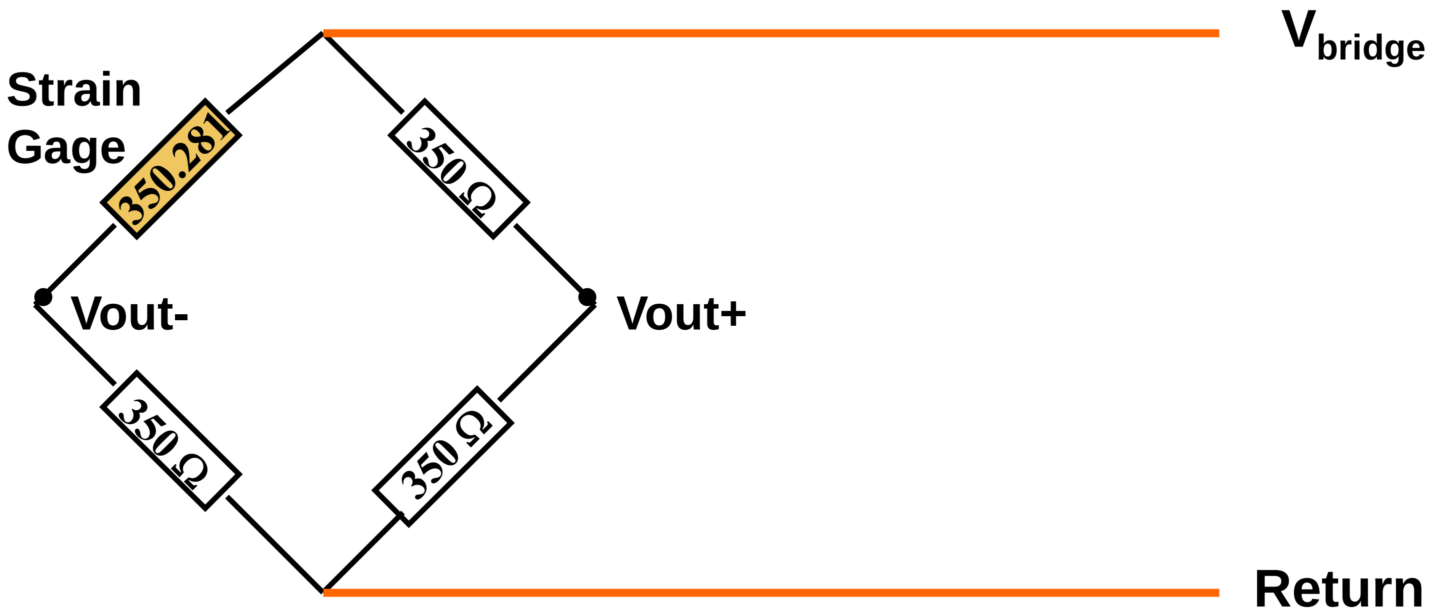


$$\Delta R = GF \times R \times strain$$
$$\Delta R = 2.005 \times 350\Omega \times 400\mu\epsilon$$
$$\Delta R = 0.281\Omega$$

We now have converted the micro strain quantity to its equivalent resistance change by knowing the gage factor for the strain gage.

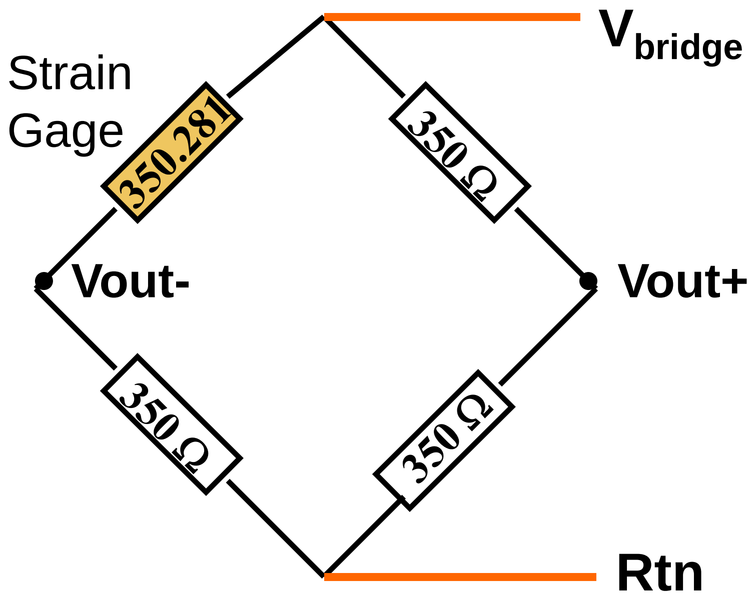
Strain Gages – Wheatstone Bridge

- Data acquisition systems measure a voltage, not a resistance. So using the gage as one of the arms of a Wheatstone bridge, we can now get a voltage proportional to the resistance change which is proportional to the micro strains.
- The configuration shown below only has one *active arm*, so the remaining three resistors are of a fixed value, equal to the nominal strain gage resistance of 350 Ω.



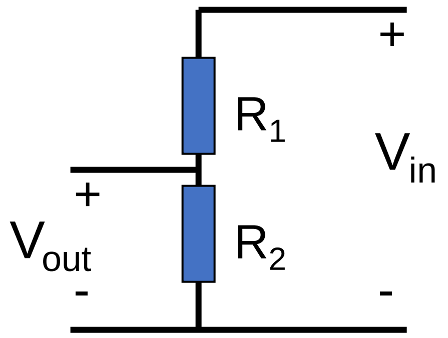
Strain Gages – Wheatstone Bridge Output

- Looking at the left and right pair of resistors as a voltage divider circuit, you can calculate Vout+ and Vout-.



Voltage Divider Law

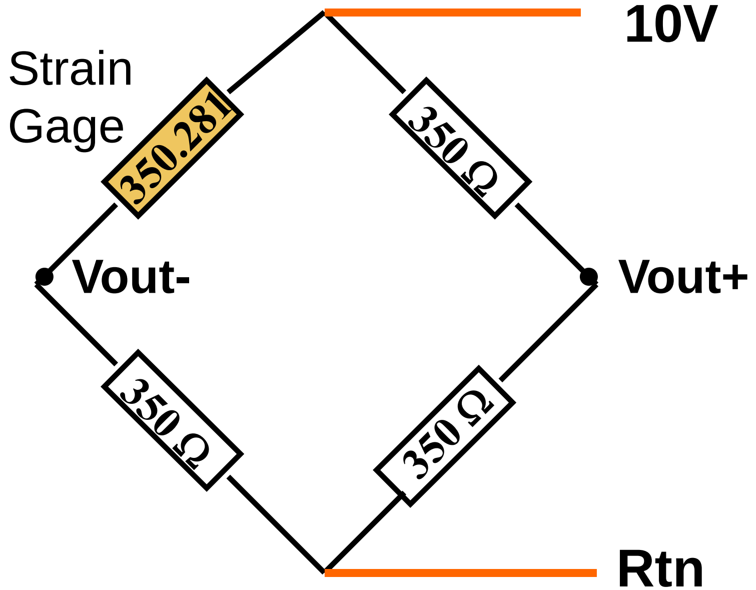
$$V_{out} = \left(\frac{R_2}{R_1 + R_2} \right) V_{in}$$



Strain Gages – Wheatstone Bridge Output

$$V_{out+} = \left(\frac{350}{350+350} \right) 10vdc = \frac{1}{2} 10vdc = 5.000vdc$$

$$V_{out-} = \left(\frac{350}{350.281+350} \right) 10vdc = \frac{350}{700.281} 10vdc = 4.998vdc$$



V_{out} is the difference of the voltages

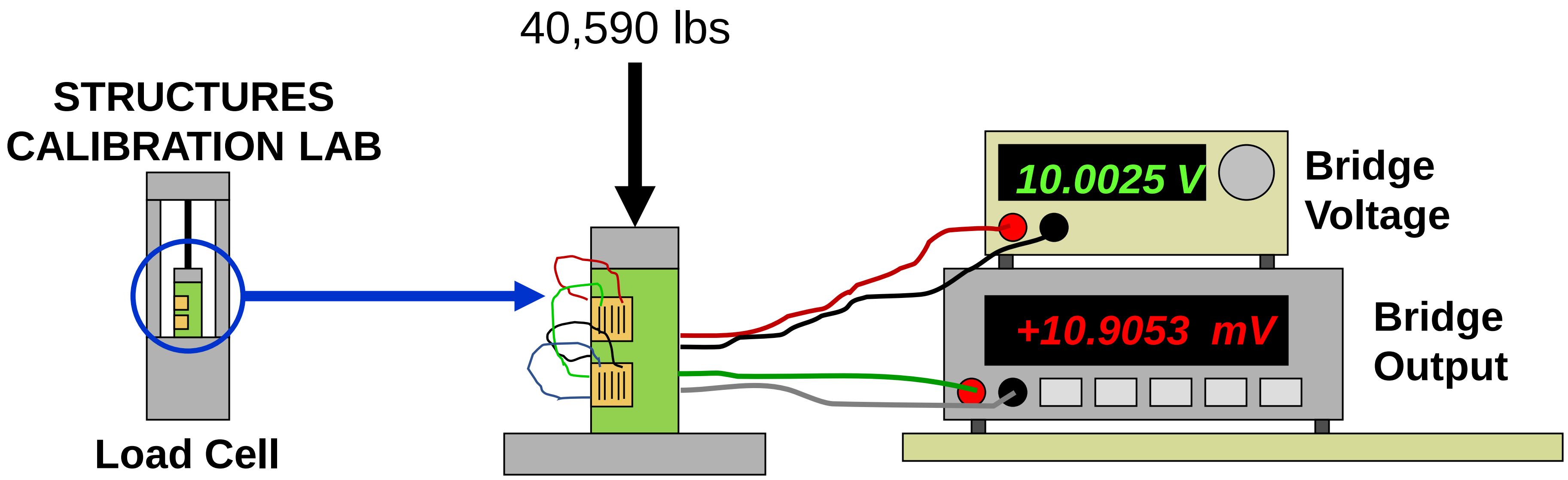
$V_{out} = V_{out+} - V_{out-}$

$V_{out} = 5.000 - 4.998$

$V_{out} = 0.002$ or 2mV

So 400 με
is equivalent to 2 mV

Strain Gages – Reading Force



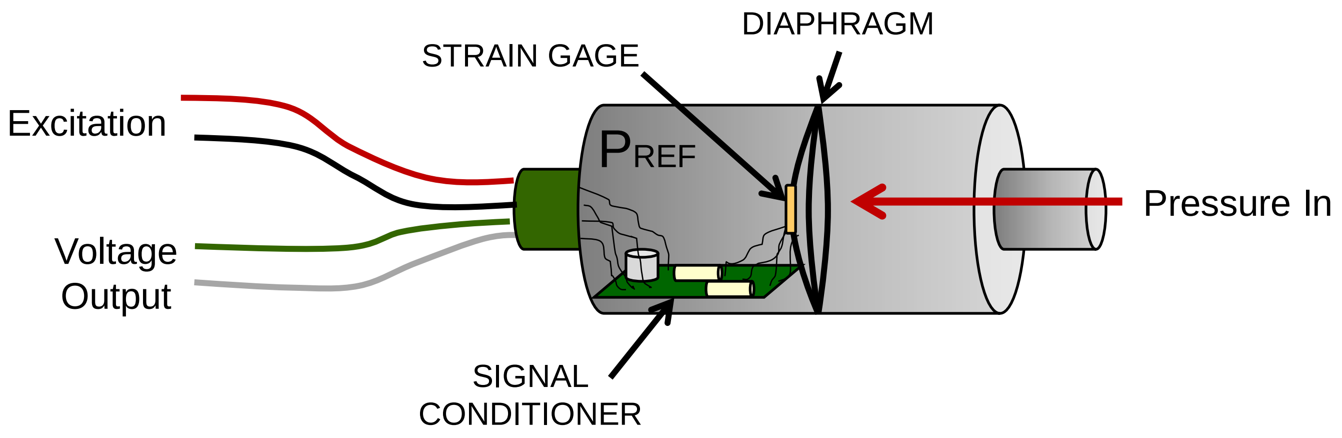
- When a force must be measured, the item with the strain gages installed must be calibrated to get a lbs to mV relationship.

40,590 lbs $\longrightarrow$ +10.9053 mV

Otherwise without a calibration, we would only know $\mu\varepsilon$.

Pressure Transducers

- Pressure is measured by the movement of a sensing element (usually a diaphragm) when pressure is applied.
- The physical movement must be converted to electrical energy using a transducer (in some cases a strain gage).
- Signal conditioning is required to provide a high level voltage output.



Pressure Transducers – Types of Pressure Measurements

- ***<u>Absolute pressure</u>*** is measured relative to a perfect vacuum (0 PSI). An example is atmospheric pressure. A common unit of measure is pounds per square inch, absolute (PSIA).
- ***<u>Differential pressure</u>*** is the difference in pressure between two points of measurement. This is commonly measured in units of pounds per square inch, differential (PSID).

Absolute Pressure Transducer

Has a single pressure port
The reference is 0 PSI

Differential Pressure Transducer

Has two pressure ports
Identify which port is the reference

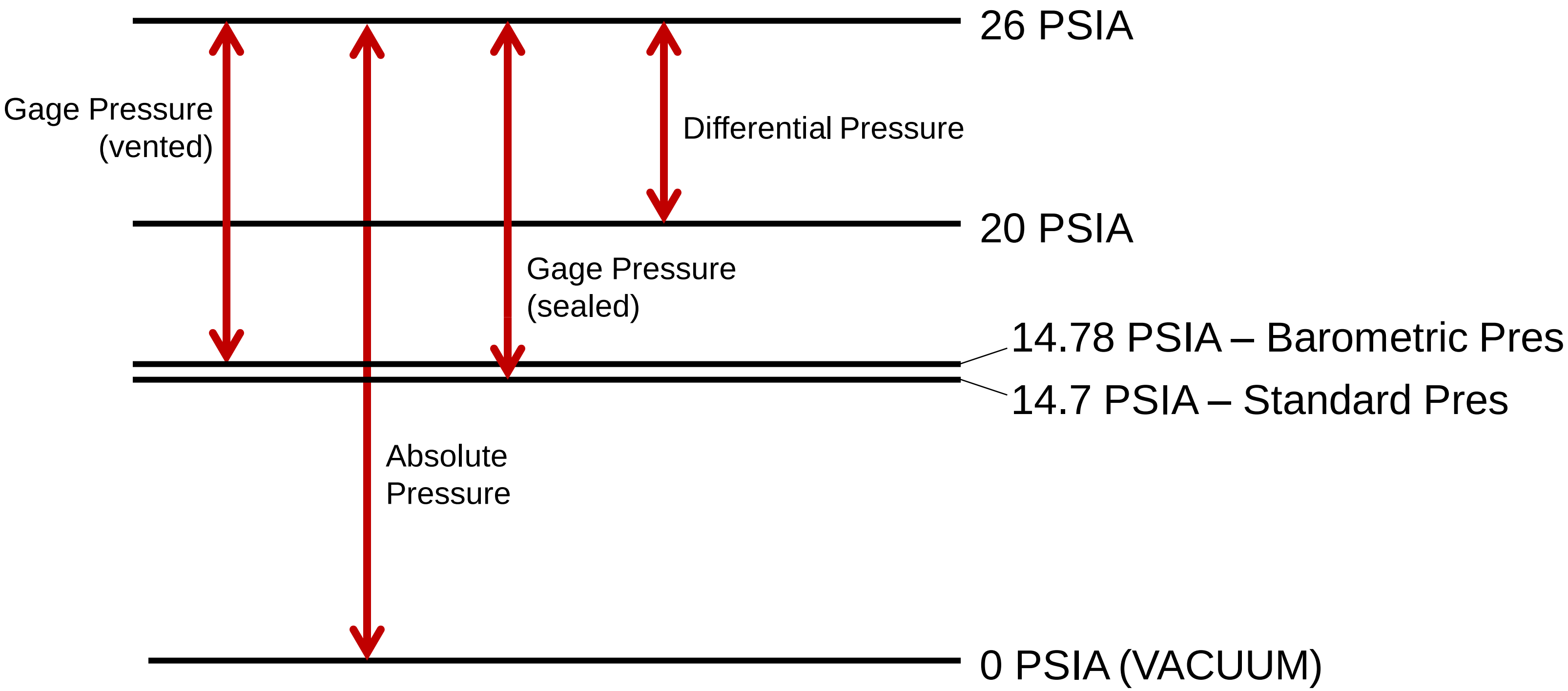
Pressure Transducers – Types of Pressure Measurements

- ***Gauge pressure*** is measured relative to ambient pressure. Common measurement units are pressure per square inch, gauge (PSIG).
    - **Sealed** gage pressure (PSISG) is measured relative to a sealed chamber, pressurized to a standard day pressure (14.7 PSI).
    - **Vented** Gage Pressure (PSIVG) is measured relative to the atmospheric pressure (vented to the outside atmosphere).
- Manufacturers do not always specify if a PSIG transducer is *sealed* or *vented*, so it is best to contact them to be sure.

Gage Pressure Transducer

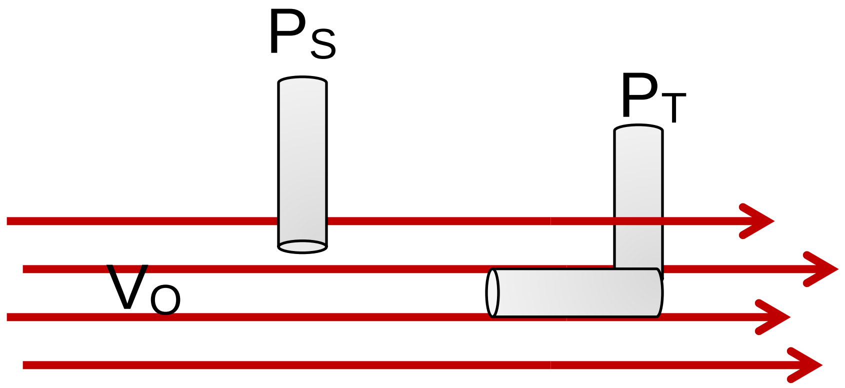
A vented gage pressure transducer can sometimes be identified by a small pin hole in the housing.

Pressure Transducers – Types of Pressure Measurements



Absolute Pressure:	26 PSIA
Gage Pressure (sealed):	11.3 PSISG
Gauge Pressure (vented):	11.22 PSIVG
Differential Pressure:	6 PSID

Pressure Transducers – Pitot-Static Pressure



- The tube facing the flow measures total pressure (P_T)
- The tube normal to the flow measures static pressure (P_S)
- This approach is used on aircraft to measure velocity
- To calculate the derived parameter flow velocity, you need to measure P_T and P_S and use those measurements in the following formula:

$$V_O = \sqrt{\frac{2(P_T - P_S)}{\rho}}$$

ρ = Fluid Density

Pressure Transducers – Pitot-Static Pressure

Static Pressure Port on the aircraft skin

Total Pressure probes on an aircraft

Pressure Transducers – Air Data Computer

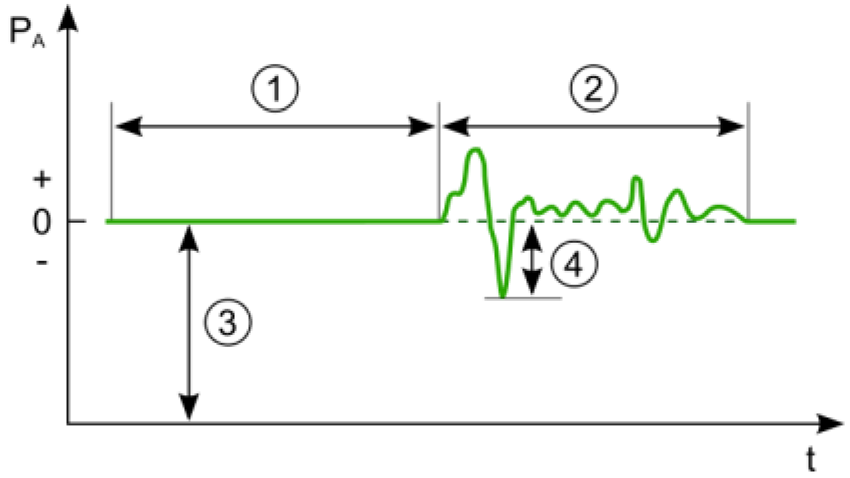
Wing Boom with a pitot-static probe that has both a total and static pressure ports.

The air data computer then calculates airspeed, altitude, and mach number from these pressures.

Total and Static pressure input ports on an Air Data Transducer

Pressure Transducers - Sound Pressure Level

Sound Pressure Level (SPL) or **sound level** is a logarithmic measure of the effective sound pressure of a sound relative to a reference value. It is measured in decibels (dB) above a standard reference level. The standard reference sound pressure in air or other gases is 20 µPa RMS.



1) Silence
2) Audible sound
3) Atmospheric pressure
4) Instantaneous sound pressure

$$\text{SPL (dB)} = 20\log\frac{P}{P_{REF}}$$

P_{REF} = 20 µPa (RMS) or 2.9E-9 PSI (RMS)

This is the threshold of hearing at 1 KHz.

Pressure Transducers - Sound Pressure Level

- Sound Pressure Levels measured in dB can have deceiving magnitudes.
- The threshold of pain is at 140 dB.
- 170 dB is the equivalent of just under 1 PSIA RMS.
- Note that every 20 dB is a pressure factor of 10.

	dB	PSIA(RMS)	PSIA(PEAK)
	170	0.9171	1.297
	160	2.900E-1	4.101E-1
	150	9.171E-2	1.297E-1
Jet Engine @ 75ft	140	2.900E-2	4.101E-2
	130	9.171E-3	1.297E-2
	120	2.900E-3	4.101E-3
	110	9.171E-4	1.297E-3
Jackhammer	100	2.900E-4	4.101E-4
Average Street Traffic	90	9.171E-5	1.297E-4
	80	2.900E-5	4.101E-5
	70	9.171E-6	1.297E-5
	60	2.900E-6	4.101E-6
Conversational Speech	50	9.171E-7	1.297E-6

Pressure Transducers - Microphones

- A microphone is basically an absolute pressure transducer with EU ranges and frequency responses for audio or acoustic signals.

Pressure Transducers – Microphones

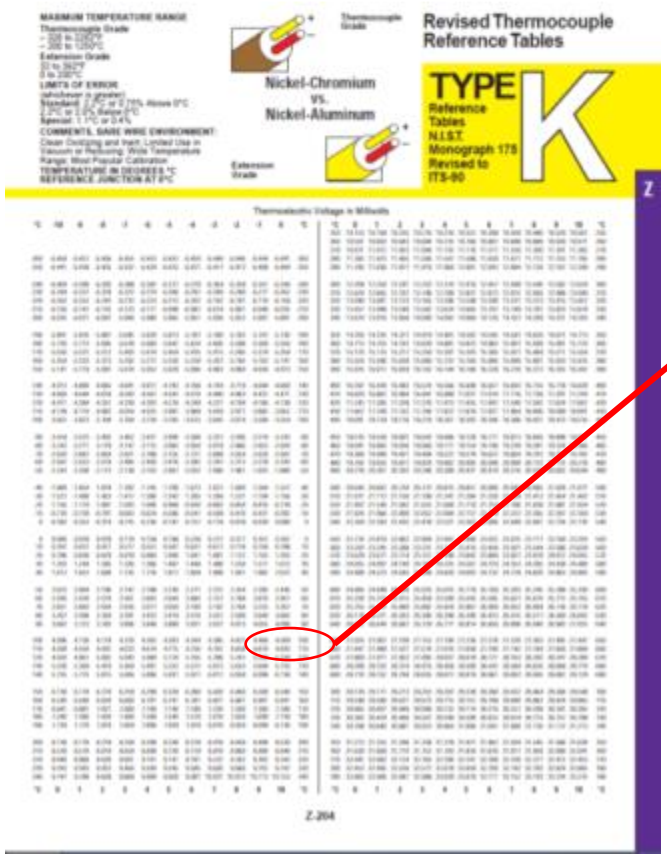
- Jet-Blast Deflector (JBD) testing collecting the sound pressure level (SPL) of the engine exhaust. The microphones are on the tripods on the right.

Thermocouples

- One of the most common ways to measure temperature is with a thermocouple.
- When two wires composed of dissimilar metals are joined at one end and heated as shown below, an open circuit voltage can be measured. This voltage is known as the Seebeck Voltage.
- The Seeback Voltage is 0 V at 32^{o}F or 0^{o}C

Thermocouple Junction

Thermocouples – Thermocouple Reference Table



4.509 mV = 100°C

- Thermocouple Reference Tables give the mV Seebeck Voltages at various temperatures for a particular thermocouple type.

- The actual equation for this data is a fifth order equation.

TEMPERATURE CONVERSION EQUATION: $T = a_0 + a_1 x + a_2 x^2 + \ldots + a_n x^n$

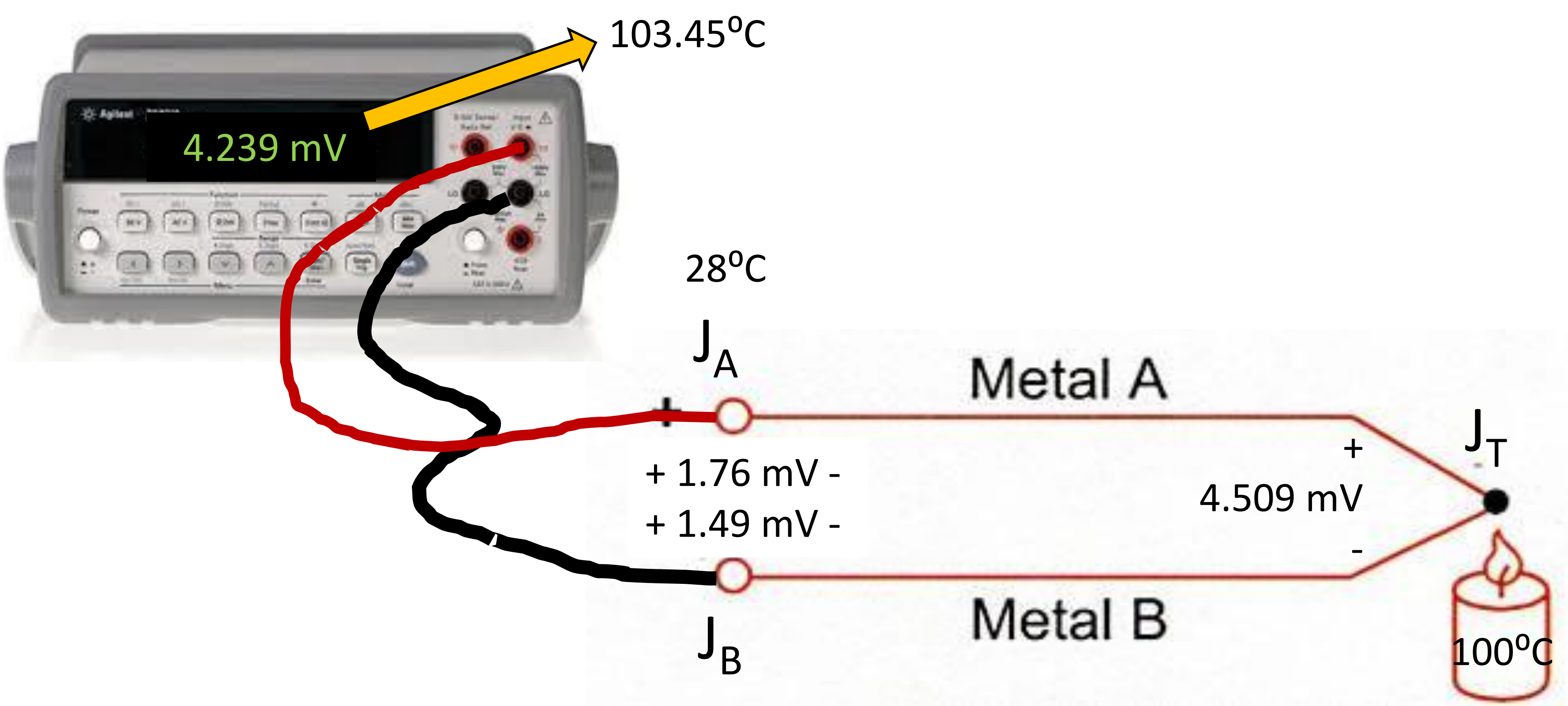
NESTED POLYNOMIAL FORM: $T = a_0 + x(a_1 + x(a_2 + x(a_3 + x(a_4 + a_5 x))))$ (5th order)

where x is in Volts, T is in °C

NBS POLYNOMIAL COEFFICIENTS

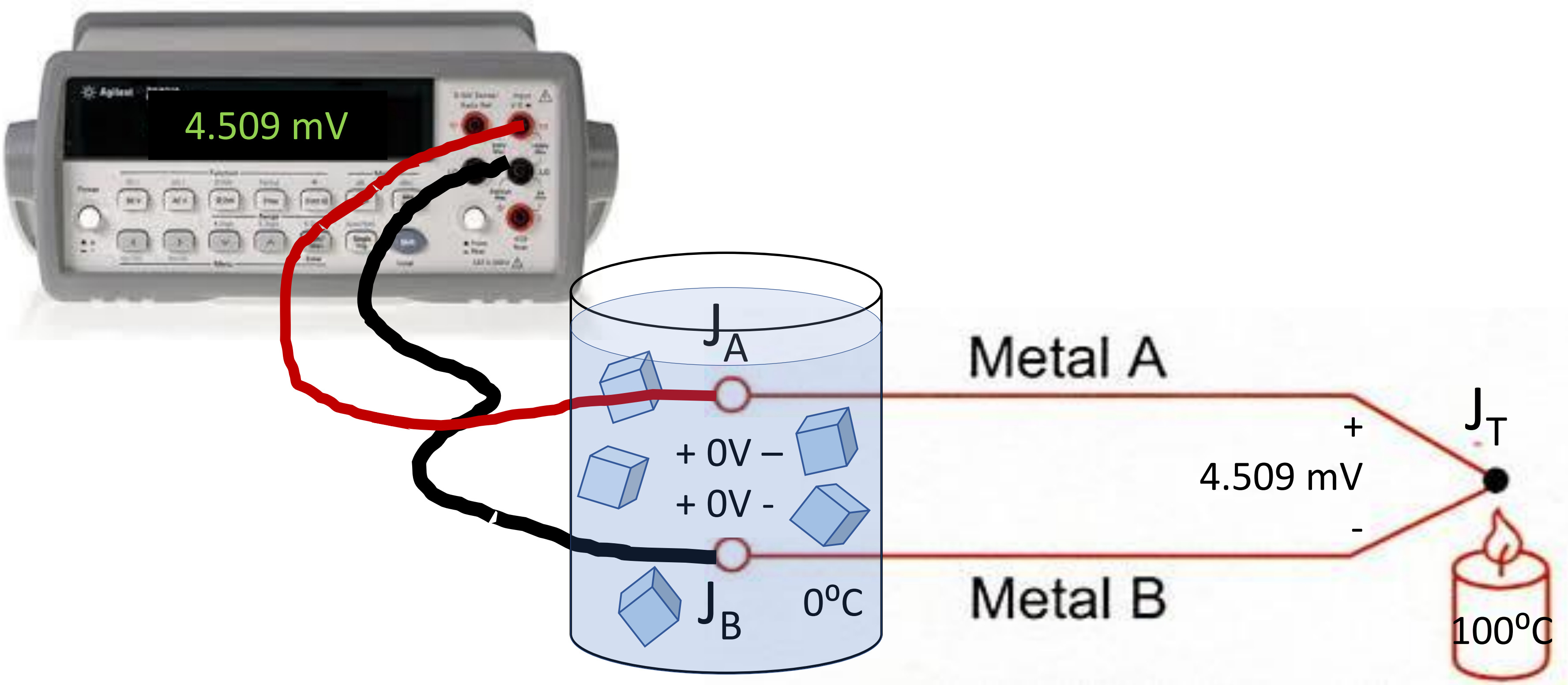
Thermocouples – Measuring the Voltage

- You cannot just measure this voltage with a multi-meter because two other thermocouple junctions are created (J_A and J_B) between the copper test leads and the Metal A and Metal B thermocouple wire.



Thermocouples – Measuring the Voltage

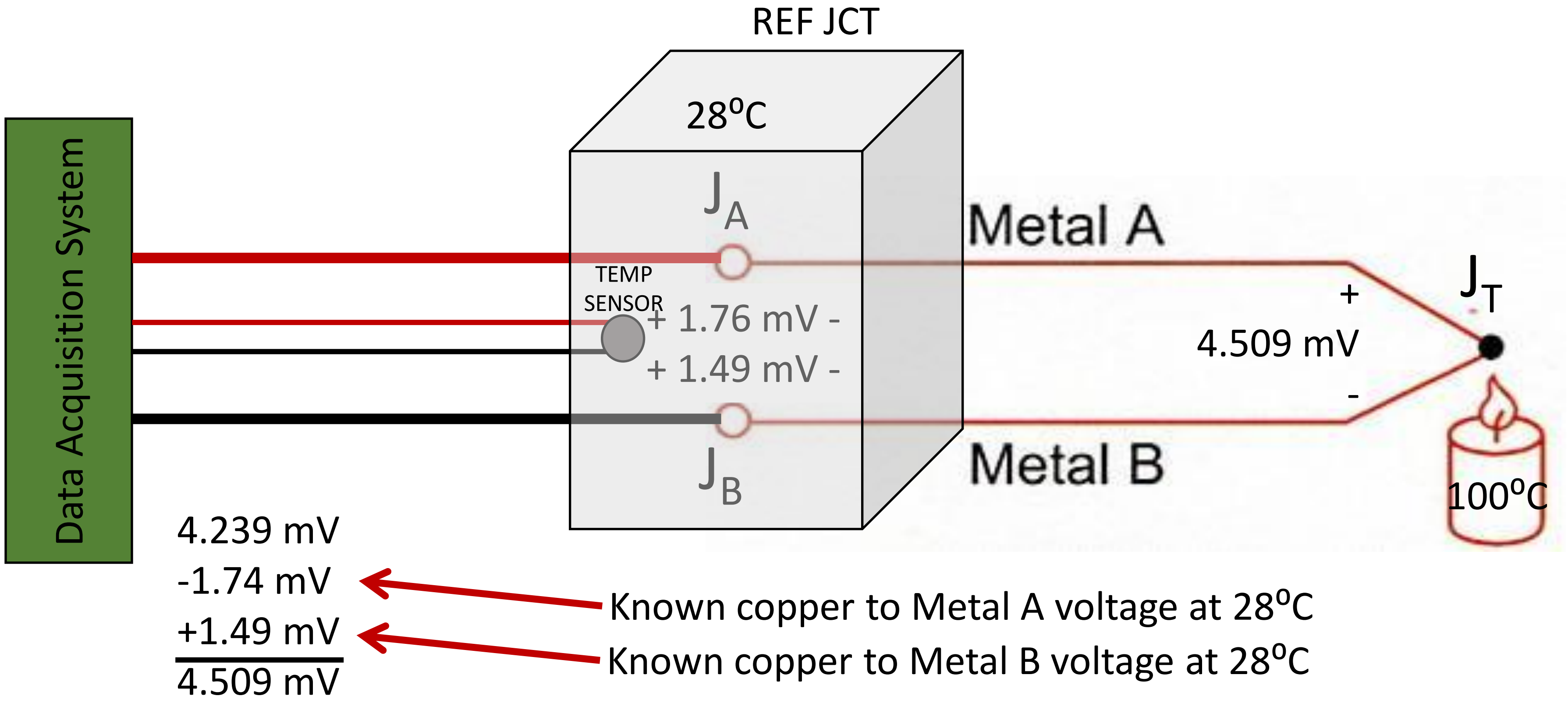
- One way to remove the voltages generated at J_A and J_B is to place it in an ice bath (at 32^{o}F or 0^{o}C). Now only the voltage generated at J_T are being measured.



Not very practical to have an ice bath on an aircraft

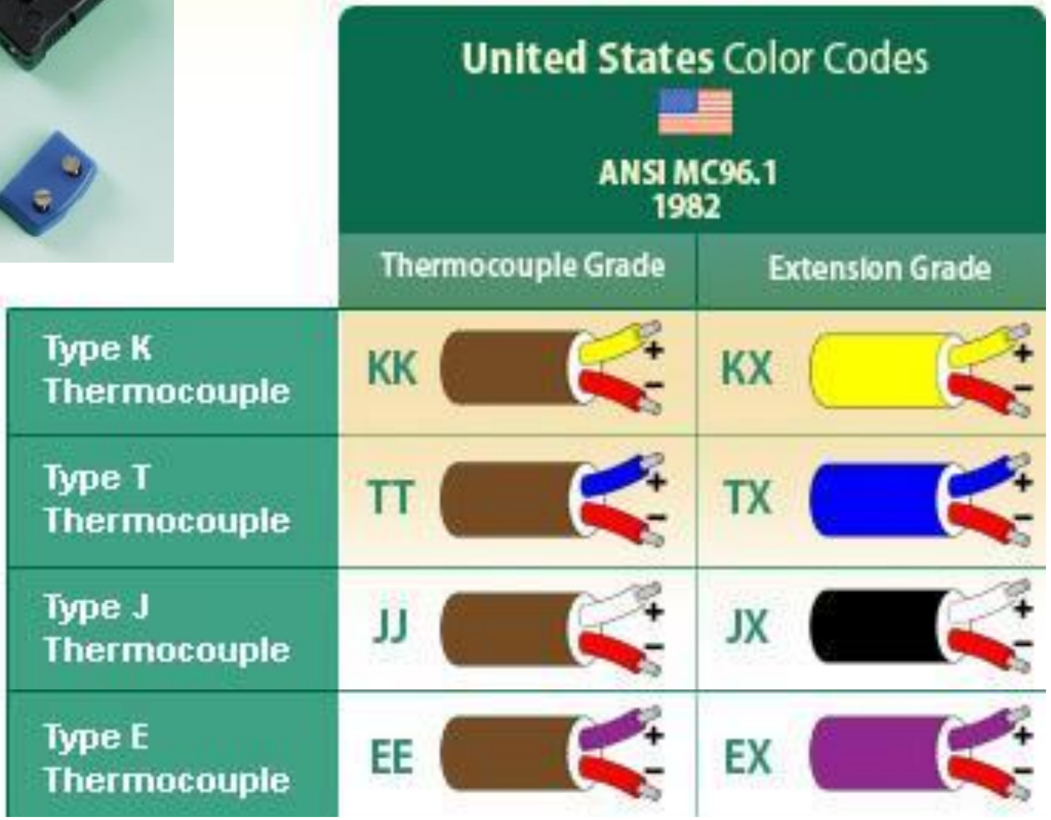
Thermocouples – Reference Junction

- A reference junction contains a temperature sensor to measure the temperature in a block of metal where the copper to Metal A/B junctions occur. The electronics within the data acquisition system subtracts out the voltages generated at J_A and J_B such that the correct voltage at J_T is being measured.



Thermocouples – Color Codes

Thermocouple connectors have pins of the same material as the wire. The casing has the same color as the thermocouple wire.



ALLOY

Chromel
Alumel

Copper
Constantan

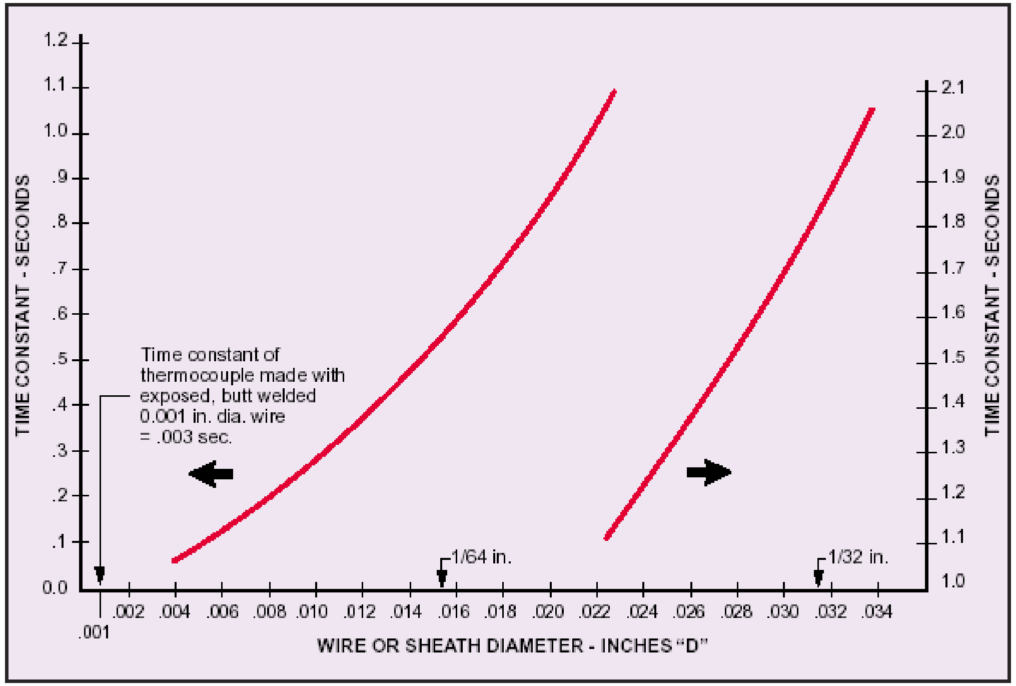
Iron
Constantan

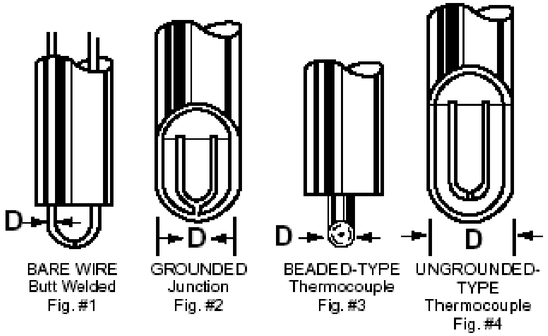
Chromel
Constantan

Note: Red is the negative lead.
There are other standards out there, so be aware.

Thermocouples – Response Time

- The response of a thermocouple (or other similar type transducers) is determined by its time constant. The time constant is the time it takes for the thermocouple to reach 63% of the temperature environment.
- The size and shielding type of the thermocouple wire at the junction determine the time constant.
- Manufacturers such as Omega Engineering have time constant curves which give the value for various thermocouple types and wire sizes.





Thermocouples – Response Time

- The increasing sensed temperature of a thermocouple follows the equation:

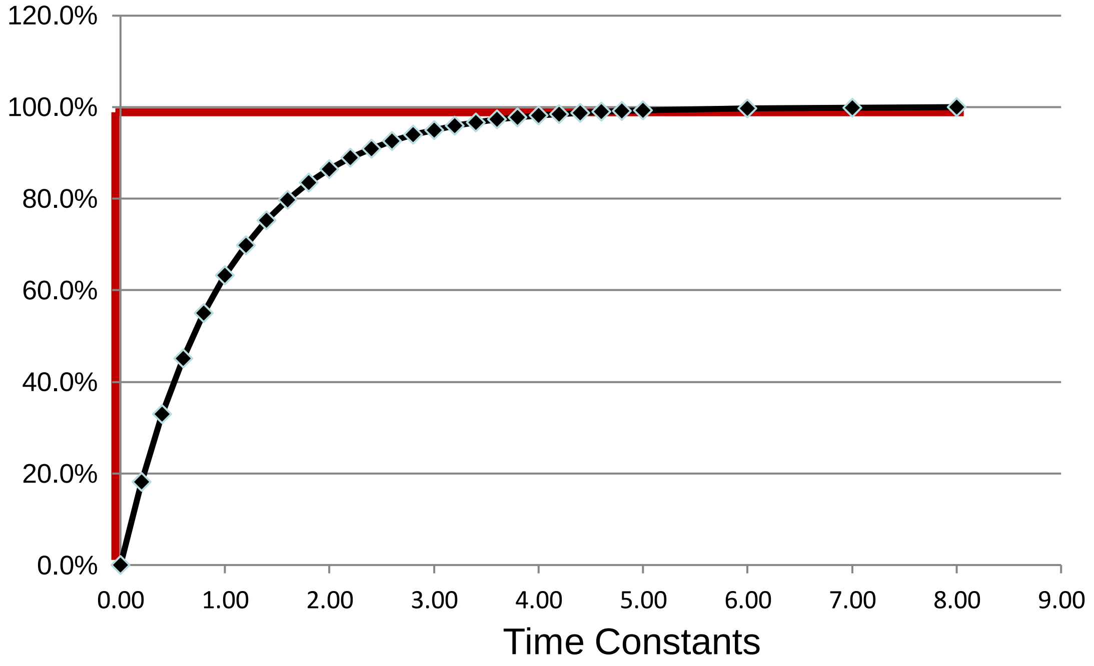
$$T = T_0\left(1 - e^{-t/\tau}\right)$$

T_0 is the environment temperature

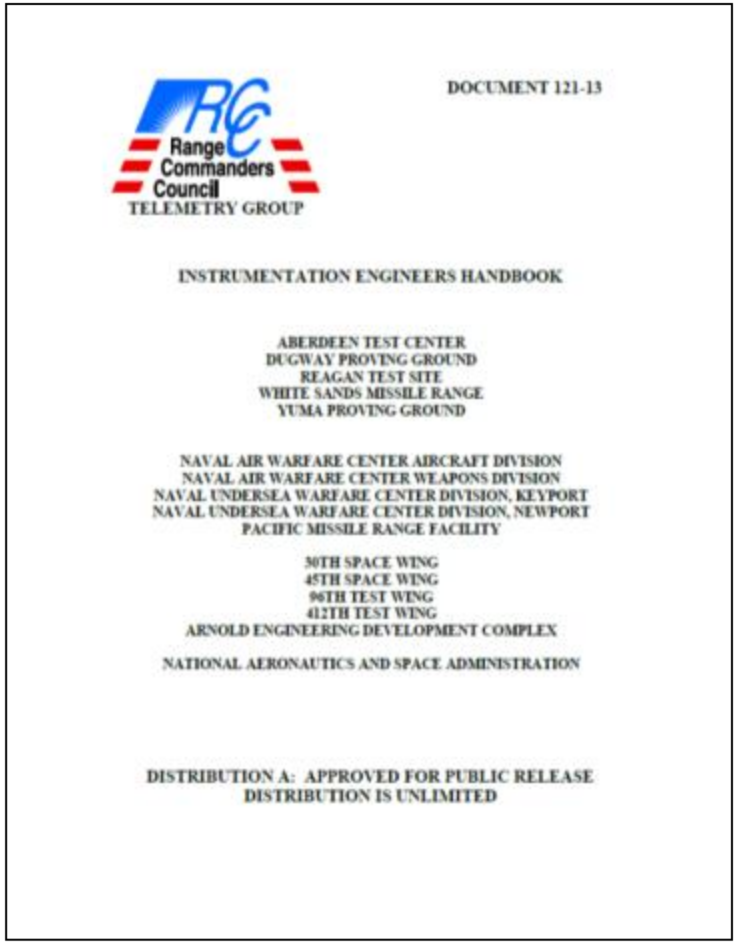
t is the time

τ is the time constant of the thermocouple

Time	% Full Temp
0	0%
1τ	63.2%
2τ	86.5%
3τ	95.0%
4τ	98.2%
4.6τ	99%
5τ	99.3%



Other Transducers


Range Commanders Council
TELEMETRY GROUP

DOCUMENT 121-13

INSTRUMENTATION ENGINEERS HANDBOOK

ABERDEEN TEST CENTER
DUGWAY PROVING GROUND
REAGAN TEST SITE
WHITE SANDS MISSILE RANGE
YUMA PROVING GROUND

NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
NAVAL AIR WARFARE CENTER WEAPONS DIVISION
NAVAL UNDERSEA WARFARE CENTER DIVISION, KEYPORT
NAVAL UNDERSEA WARFARE CENTER DIVISION, NEWPORT
PACIFIC MISSILE RANGE FACILITY

30TH SPACE WING
45TH SPACE WING
96TH TEST WING
412TH TEST WING
ARNOLD ENGINEERING DEVELOPMENT COMPLEX

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

DISTRIBUTION A: APPROVED FOR PUBLIC RELEASE
DISTRIBUTION IS UNLIMITED

We do not have time to go through every transducer type. If there are other measurement types you need to make, please refer to IRIG-121 Instrumentation Engineers Handbook for additional information.

Transducer Specifications

When looking at transducer specifications, you have to know the requirements of the data, and the environment the transducer will be located in. There are many specifications listed, but these are the most common ones.

Electrical:
Power (voltage and current) Requirements
Transducer Sensitivity (output voltage)

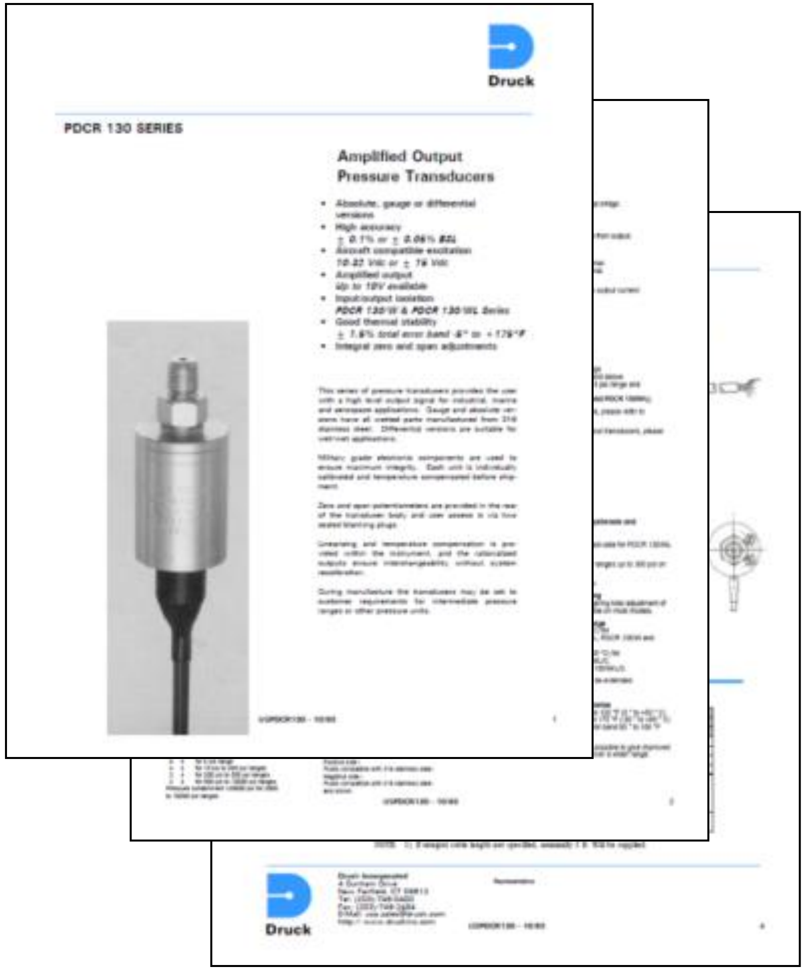
Data:
Frequency response
Engineering Unit Range

Environment:
Temperature, humidity, altitude
Fluid being measured (if a pressure transducer or flow meter)

Physical:
Size
Electrical and Mechanical Interfaces

Transducer Specifications

- For this example, we will look at a pressure transducer specification.



Let's say we are making a pressure measurement on an engine.

- The EU range is 0 to 60 PSIA
- The frequency response is 0 – 100 Hz
- The medium being measured is air
- The temperature environment is up to 200^{o}F
- The burst pressure of the system can be up to 200 PSIA.

- Note that errors specified within a spec sheet are usually assumed to be 95% (2σ) uncertainty numbers.
- Always contact the manufacturer if you are unsure.

Transducer Specifications – Electrical

Power: 10VDC preferred or 28VDC

Supply Voltage

PDCR 130 Series
10-32V d.c. @20mA isolated from output.

A power source of 10 VDC at 40mA is available.

Why is "isolated from output" important to pay attention to?

Output Voltage: ±5 volt input range to analog to digital converter

Output Voltage
2.5V standard for 2.5 psi range
5V standard for 5 psi range and above
(10V maximum available for 5 psi range and above)
(Isolated on PDCR 130/W and PDCR 130/WL)

Bi-directional output available, please refer to manufacturer.

For alternative amplified output transducers, please refer to manufacturer.

0-5V is acceptable. With some gain and offset used, the full 4000-count range of a 12-bit data channel is used.

Gain = 2, Offset = -5V

Transducer Specifications – EU Range/Frequency Range

EU Range: 0 – 60 PSIA

Operating Pressure Ranges
PDCR 130/W and PDCR 135/W
2.5 psi gauge only
5, 10, 15, 20, 30, 50, 100, 150, 200, 300, 500, 900, 1000 psi gauge or absolute
2000, 3000, 5000, 7500, 10000 psi absolute or sealed gauge

Other pressure units may be specified, e.g. ins. H_2O, kPa, etc.

Must select the 100 PSIA range to meet the requirements. Note that errors are based on 100 not 60 PSIA.

Frequency Range of Interest: 0 – 100 Hz

Natural Frequency (Mechanical)
PDCR 130/W and PDCR 135/W,
PDCR 130/WL and PDCR 135/WL
10.5 kHz for 5 psi range increasing to 210 kHz for 500 psi range.

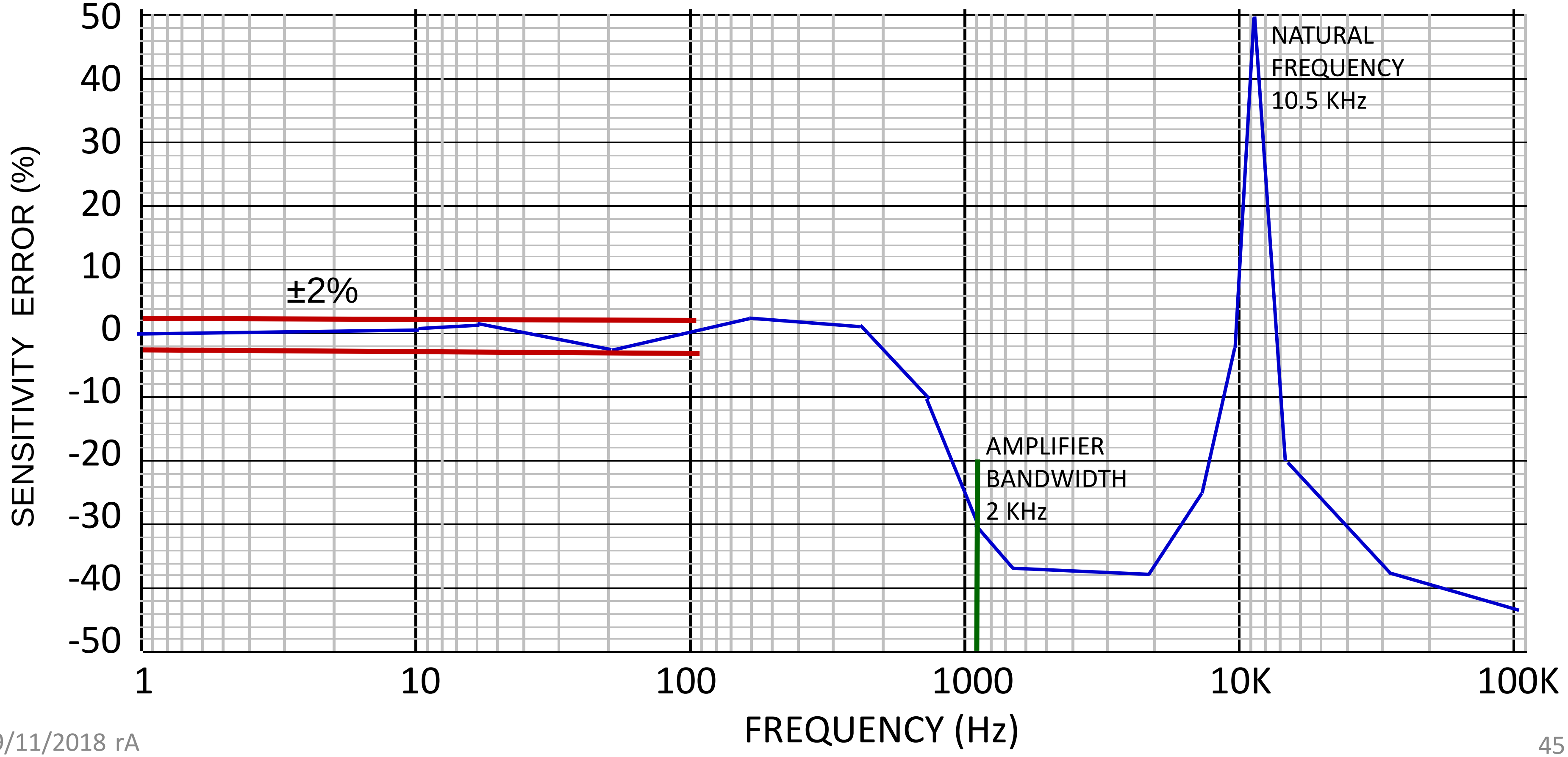
For more detailed information please refer to manufacturer.

Amplifier Bandwidth
-3dB at 2kHz nominal.

Need to contact the manufacturer for the specifics, but most likely this will satisfy the 100 Hz frequency response request.

Transducer Specifications – Frequency Range

- The frequency response as specified was ambiguous.
- If given a sensitivity frequency response graph, note the maximum error in the frequency of interest (0 – 100 Hz)
- For this example, the error of the sensitivity is within ±2%.



Transducer Specifications – Burst Pressure

Burst Pressure: 200 PSIA

PDCR 130/W and PDCR 135/W

10	x	for 2.5 psi range
6	x	for 5 psi range
4	x	for 10 psi to 200 psi ranges
3	x	for 200 psi to 500 psi ranges
2	x	for 900 psi to 10000 psi ranges

Pressure containment >20000 psi for 2000 to 10000 psi ranges.

For our 0-100 PSIA transducer range, that would result in a max pressure of 400 PSIA.

Exceeding Burst Pressure will damage the sensing element in the pressure transducer (such as the diaphragm).

It can also lead to a catastrophic failure (hydraulic fluid loss, leakage in pitot-static system).

Transducer Specifications – Temperature

Temperature Range: up to 200°F

Operating Temperature Range
-40° to +175°F (-40° to +80°C) for
PDCR 130/W, PDCR 130/WL, PDCR 135/W and
PDCR 135/WL
-40 ° to +250 °F (-40 ° to +125 °C) for
PDCR 130/WC, PDCR 130/WL/C,
PDCR 135/W/C, and PDCR 135/W/L/C.

This temperature range can be extended.

Temperature Effects

PDCR 130 and PDCR 135 Series
± 0.5% total error band 32 ° to 122 °F (0 ° to +50 ° C)
± 1.5% total error band -5 ° to 175 °F (-20 ° to +80 ° C)
2.5 psi range, ±0.5% total error band 50 ° to 105 °F
(10° to 40 °C)

For special applications it is possible to give improved temperature compensation over a wider range.

The transducer will operate fine up to 250°F without being damaged.

The error is going to be greater than ±1.5% at 200°F.

We may want to take them up on their offer of a wider range.

Or it may have to be mounted remotely in a cooler area of the engine bay.

Transducer Specifications – Medium and Size

Medium: Air

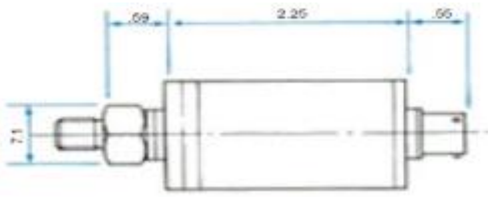
Pressure Media

PDCR 130/W and PDCR 135/ W
Fluids compatible with 316 stainless steel.

PDCR 130/WL and PDCR 135/WL
Positive side:-
Fluids compatible with 316 stainless steel.
Negative side:-
Fluids compatible with 316 stainless steel and silicon.

Air is compatible with stainless steel, so no issue exists.

Size Constraints:



PDCR 130/W/C & PDCR 135/W/C

Depending upon available mounting locations, this transducer may not fit in the area desired.

Transducer Specifications – Electrical and Pressure Interfaces

Electrical Connection

PDCR 130/W and PDCR 135/W
3 feet integral shielded/vented cable supplied.

PDCR 130/WL and PDCR 135/WL
3 feet teflon shielded cable supplied.
Longer lengths available on request.

Connector Versions

PDCR 130/W/C, PDCR 135/W/C,
PDCR 130/WL/C and PDCR 135/WL/C
6 pin Bayonet receptacle, PT1H-10-6P or equivalent
(Hermetic stainless) to MIL-C-26482.
Mating electrical socket type PT06A-10-6S or equivalent available on request (P/N 163-009).

Verify that you have or can obtain the correct mating electrical connectors.

Pressure Connection

PDCR 130/WL, PDCR 135/WL,
PDCR 130/WL/C, and PDCR 135/WL/C
Positive Port: 1/4" NPT male or 7/16 UNF male (MS33656-4)
Negative Port: 1/4" NPT male or 7/16 UNF male (MS33656-4)

PDCR 130/W, PDCR 135/W,
PDCR 130/W/C and PDCR 135/W/C
Gauge, Absolute and Sealed Gauge: 1/4" NPT male or 7/16" UNF male (MS33656-4).
Other pressure connections available on request.

Verify that the pressure fittings are compatible to the tubing being used