Modeling Thickness Shear Mode Quartz Sensors for Increased Downhole Pressure & Temperature Applications

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- 85-year old company, spun off from Amerada Petroleum Corp.
- Privately held Tulsa firm
- Worldwide leader in downhole data acquisition
- Design and manufacture HTHP gauges and surface readout tools
- Measure, record and deliver downhole oil well data
- Extremely reliable and accurate, with high resolutions

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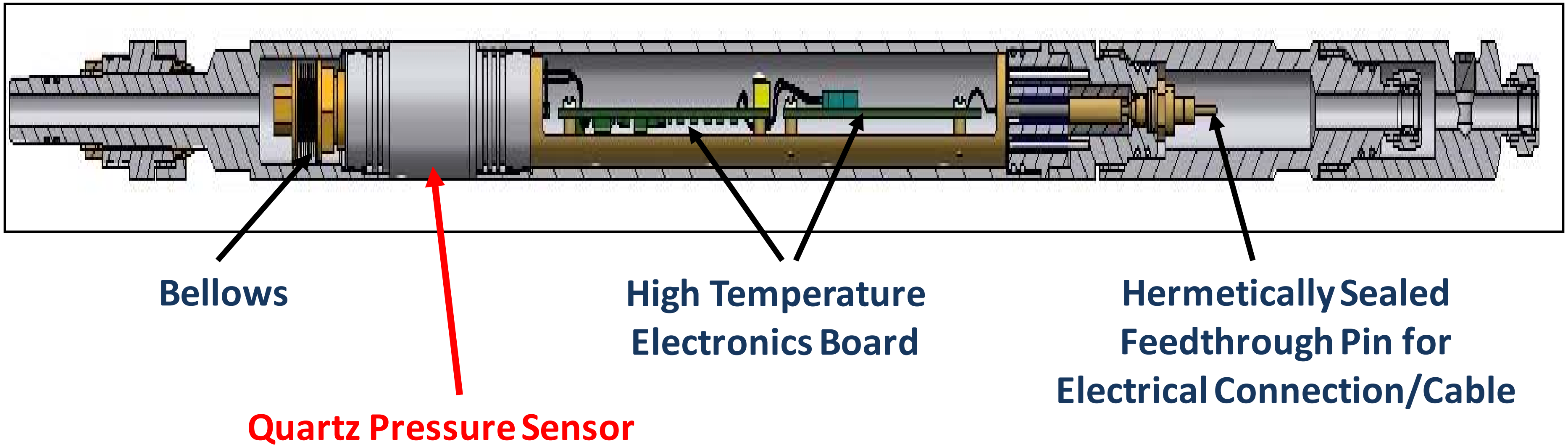
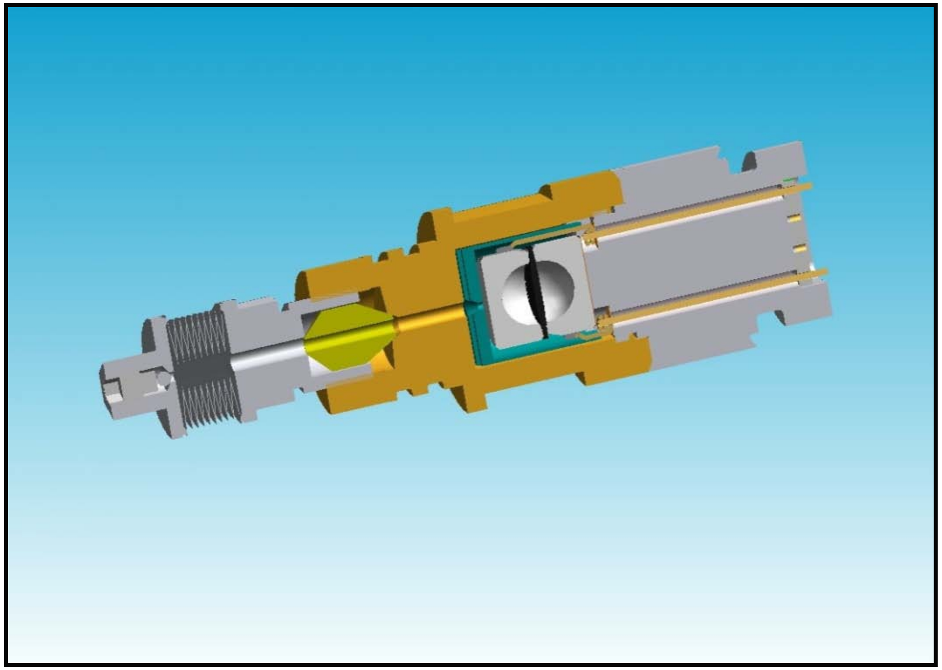
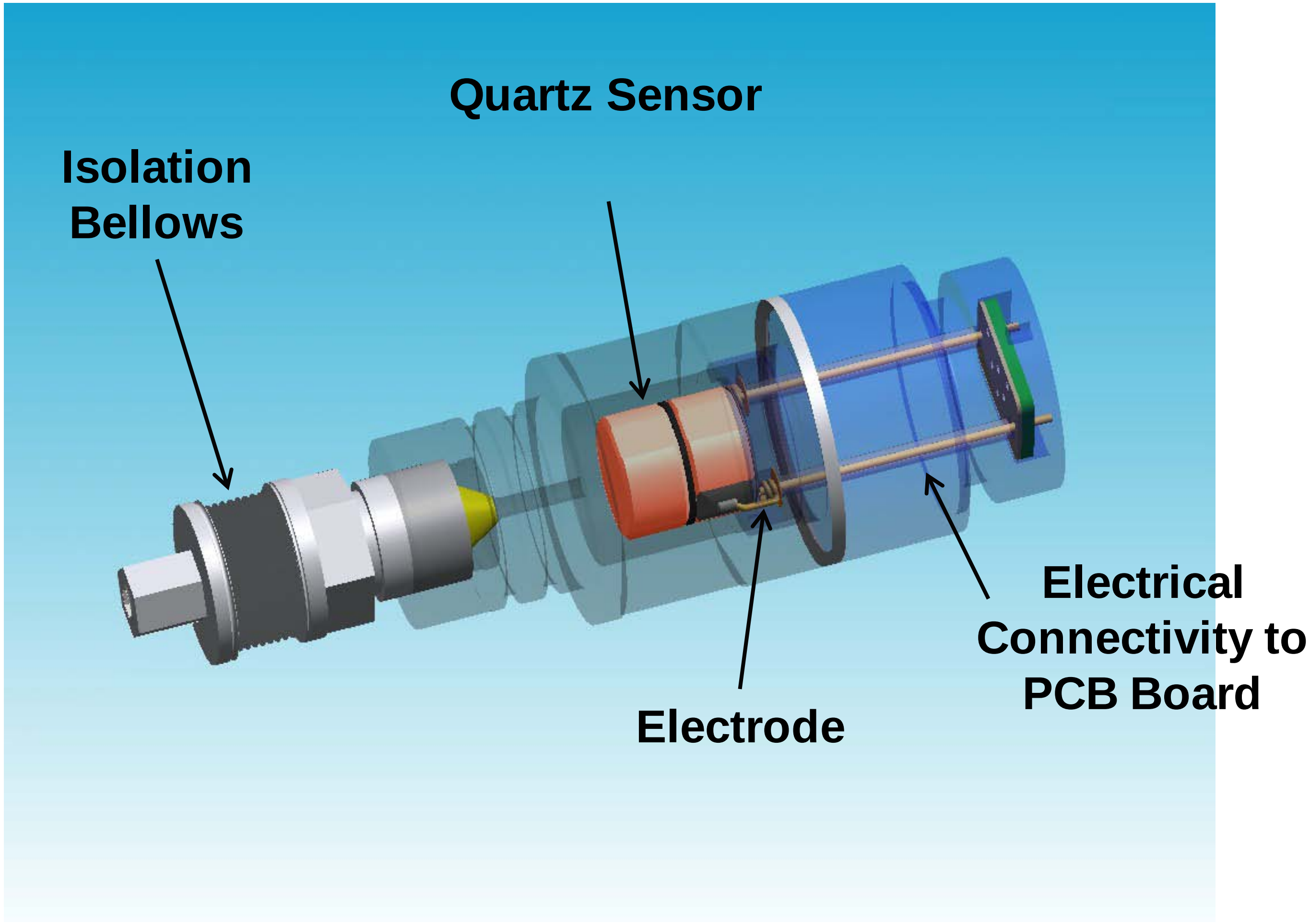


Pressure Transducer



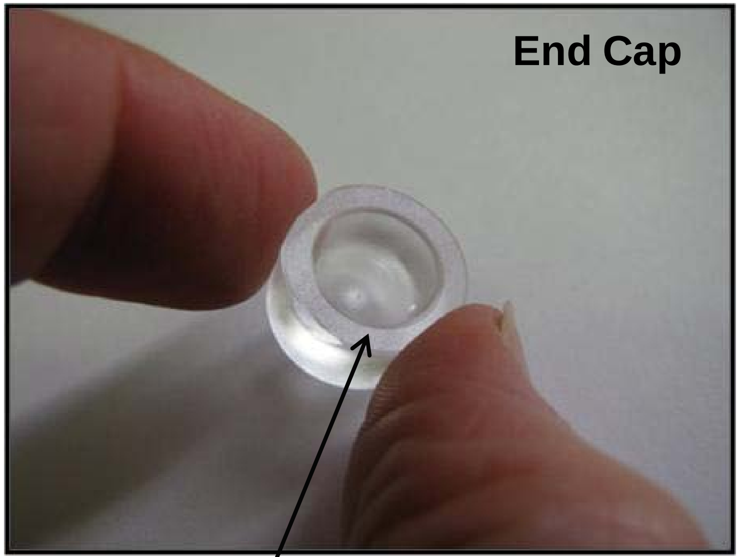
Pressure Transducer

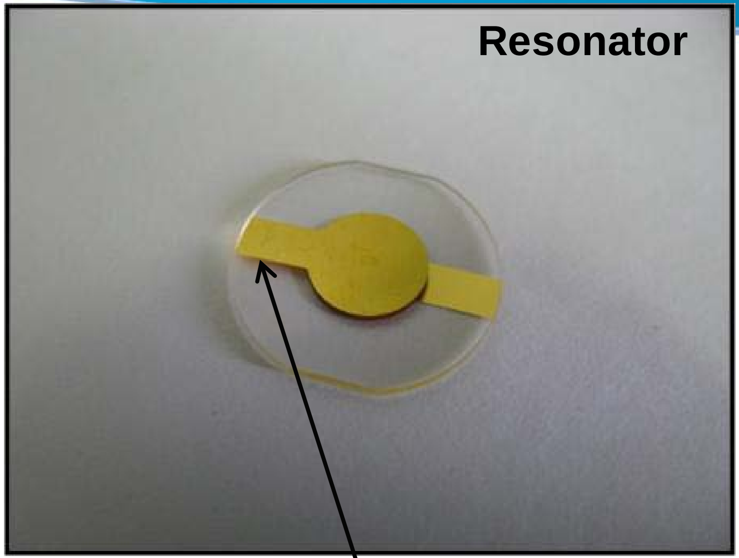


Quartz

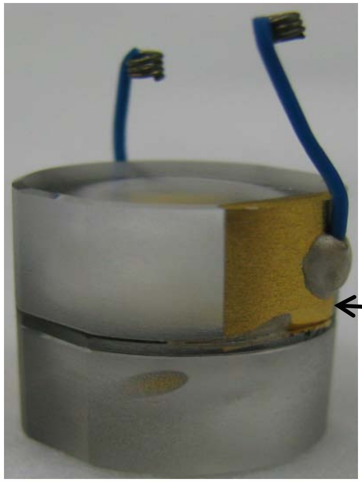

Final Sensor Assembly
Endcap
Hollow Endcap
Resonator with no electrodes
Resonator with electrodes

Quartz Pressure Sensor





Quartz Sensor

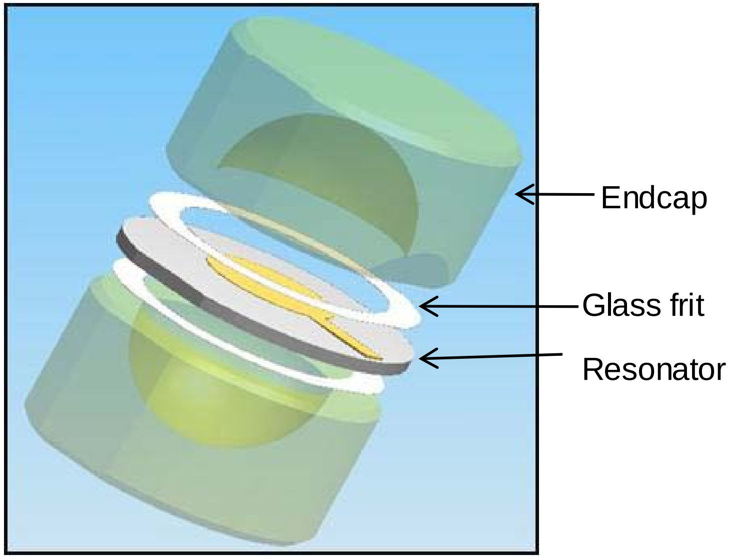


Electrode Access Chamfer

Gold Tab Electrode To Chamfer Area

Gold electrode

Quartz Pressure Sensor



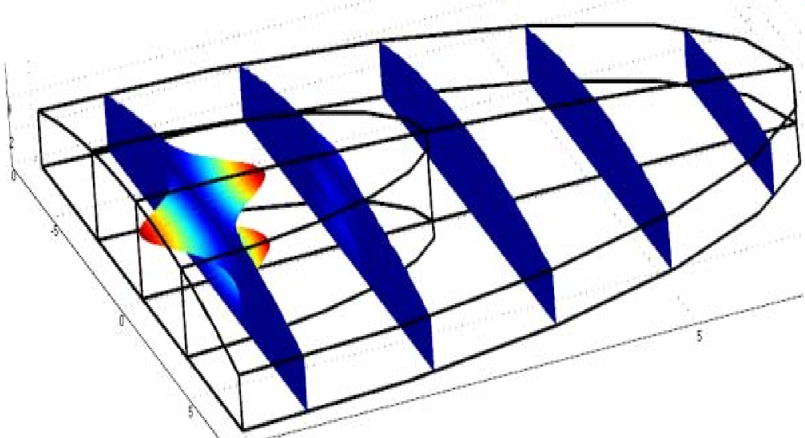


Figure. 5th overtone of a quartz piezoelectric thickness shear resonator

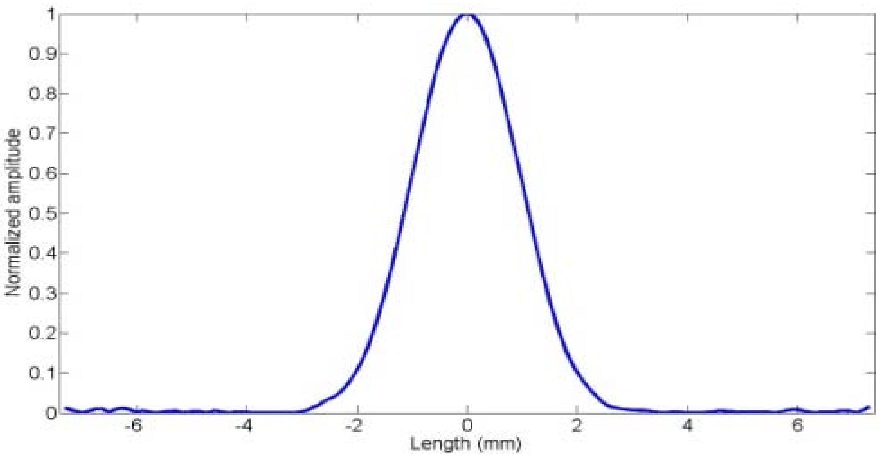


Figure. Normalized displacement indicating that the energy is contained within the resonator

<u>Requirements</u>:

- **Pressure range: 20,000psi**
- **Temperature range: 200°C / 392F**
- **Overall accuracy < 0.02% Full Scale**
- **Drift: <0.02% Full Scale**
- **Resolution: 0.01psi**

Modes of Failure

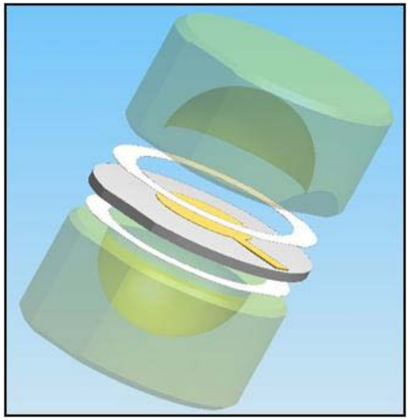
- Fracturing
  - Quartz has a tensile strength of 20,000 psi[a] as opposed to a compressive strength of 319,000psi[a]. Hence the sensors are designed to apply only compressive stress as opposed to tensile stress.

- Buckling
  - For the dimensions used in this study, buckling is not of primary concern.

- Twinning
  - Twinning is the primary mode of failure. Excessive thermal or mechanical stress causes twinning. Twinning causes a reversal (rotation of 180^{o} around the optical axis, Z-axis) of the electrical axis (x-axis) and changes the physical properties of the quartz thus rendering the sensor useless for this application. Twin limits for sensors for a few angle of cuts have been shown by EerNisse et al[a] and Anderson et al[b].

[a] E.P.EerNisse, R.W.Ward, Quartz Resonator Sensors in Extreme Environments, Forty-Fifth Annual Symposium on Frequency Control, pg 254 – 260.
[b] T.L.Anderson, R.E.Newnham and L.E.Cross, Coercive Stress for Ferrobielastic Twinning in Quartz, 31st Annual Symposium on Frequency Control, 1977, pg 171-177.

Increased Pressure Response



$$AF = \frac{\tau_r}{P_{ext}}, \tau_r < \tau_{twin}$$

$$\tau_r = AF * P_{ext}$$

$\leftrightarrow$ $\downarrow$ $\uparrow$

$$\frac{\Delta f}{f} = K * \tau_r$$

$$\frac{\Delta f}{f} = K * AF * P_{ext}$$

$$S = \frac{\Delta f}{P_{ext}} = K * AF * f$$

$AF = Amplification\ Factor / Transfer\ Function$

$\tau_r = Resonator\ Stress\ (psi)$

$\tau_{twin} = Coercive\ Stress\ for\ twinning\ (psi)$

$P_{ext} = External\ Hydrostatic\ Pressure\ (psi)$

$K = Stress\ Frequency\ Coefficient\ (1/psi) = 1.9 * 10^{-7}$

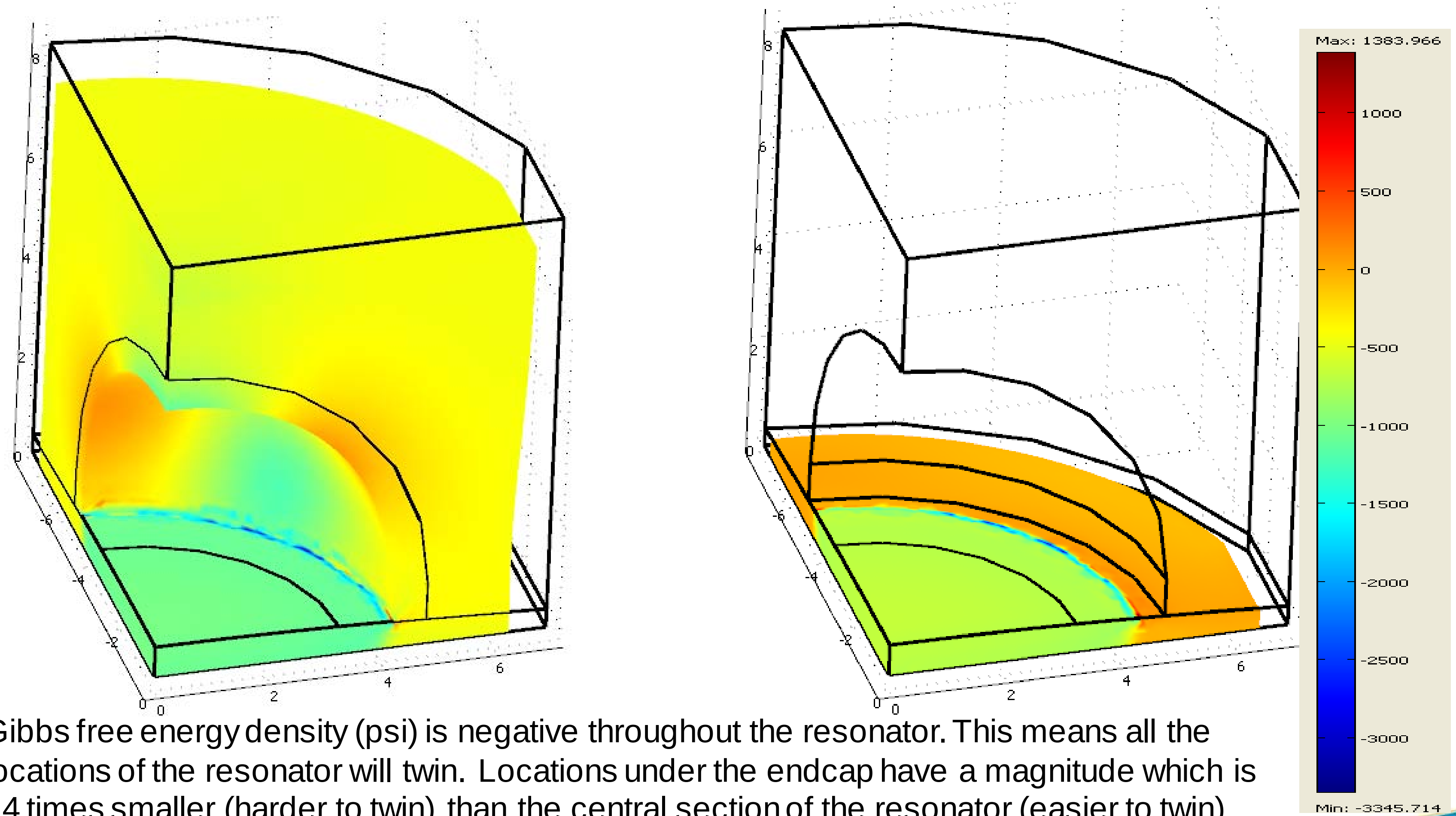
$\Delta f = Change\ in\ frequency\ (Hz)$

$f = Base\ frequency\ (7.21MHz)$

$S = Sensitivity (Hz / psi)$

Twinning

$$\Delta G = 4 * S_{1123}(\sigma_{11}\sigma_{23} - \sigma_{22}\sigma_{23} + 2\sigma_{12}\sigma_{13})$$



Gibbs free energy density (psi) is negative throughout the resonator. This means all the locations of the resonator will twin. Locations under the endcap have a magnitude which is 14 times smaller (harder to twin) than the central section of the resonator (easier to twin).

Multiple Degrees of Freedom

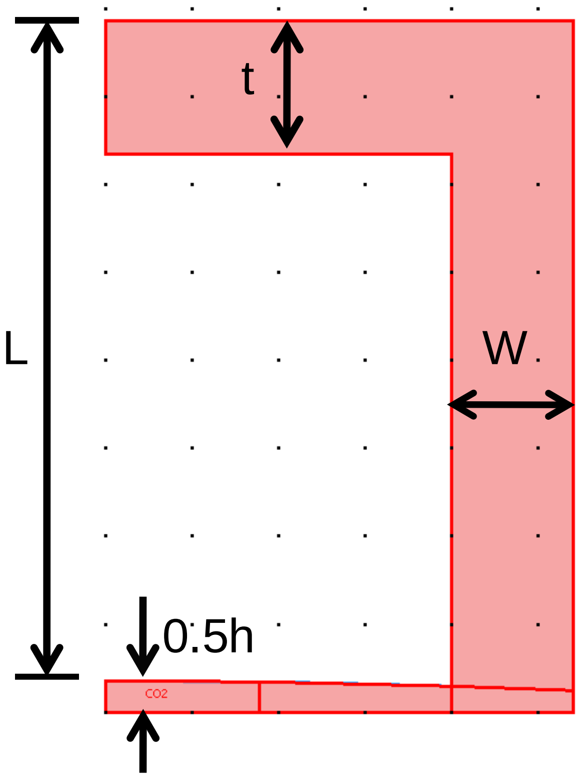


Figure. 2D quarter section model of the sensor. Note that the actual sensor does not have sharp corners as shown in this figure.

$$\tau_r = AF * P_{ext}$$

The goal is to reduce *AF* and provide leeway for an increase in P_{ext} in order to keep t_r the same and less than t_{twin}.

Reduction in AF can be achieved by varying the following

(a) Thickness of the resonator (h)
(b) Thickness of the top wall of the endcap (t)
(c) Thickness of the side walls of the endcap (w)
(d) Length of the endcap (L)

(a) Resonator thickness (h)

GRC's resonators are bi-convex energy trapped resonators and operate at 7.21MHz and at 5th overtone. The oscillation circuits that drive the crystal are designed for this frequency and overtone. Hence the choice was made not to vary the thickness of the resonator at this time. Nevertheless, a thick resonator would offer the maximum resistance for the endcaps to displace and flex under the influence of external hydrostatic pressure. Therefore a thick resonator should aid in increasing the pressure range of the quartz pressure sensor.

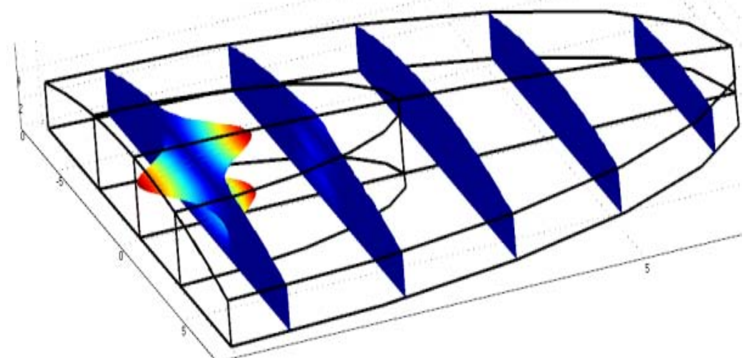


Figure. 5th overtone of a quartz piezoelectric thickness shear resonator

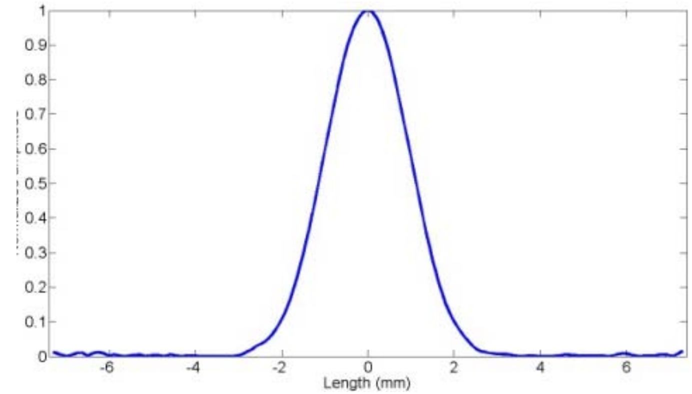


Figure. Normalized displacement indicating that the energy is contained within the resonator

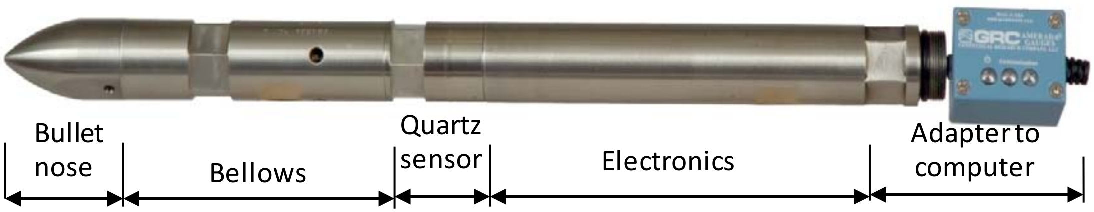
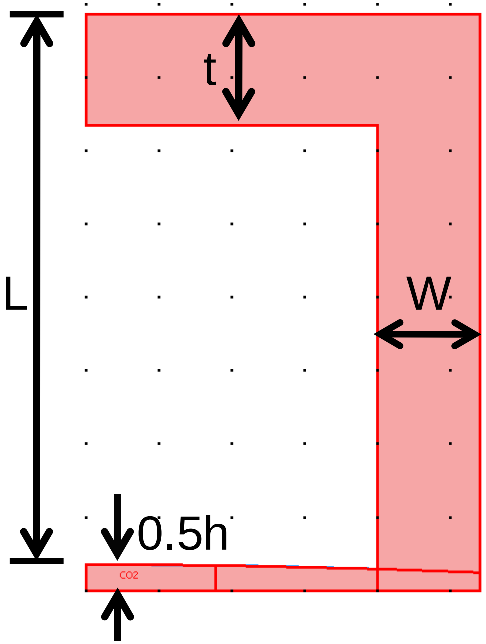


Figure. Commercially available GRC's quartz gauge with a diameter of 1inch and a length of 22 inches.

(b) Top wall thickness (t)



h= 1.178mm / 0.0464in
W=2.527mm / 0.1in
L=7.62mm / 0.3in
t = vary

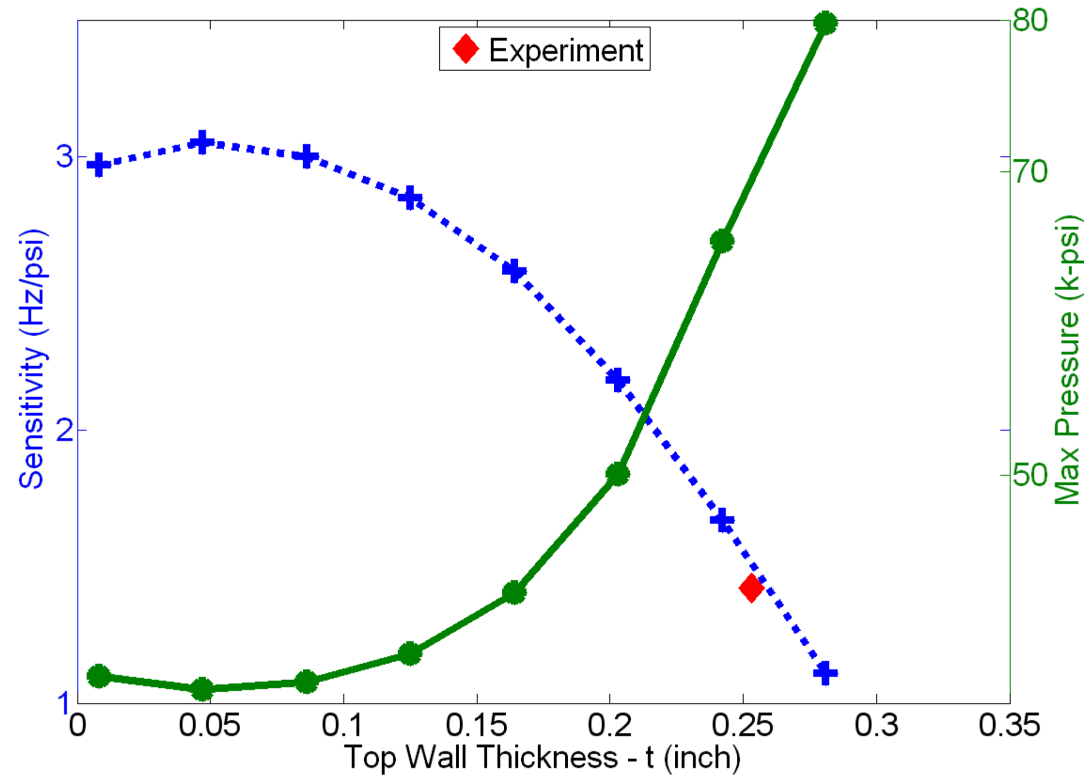
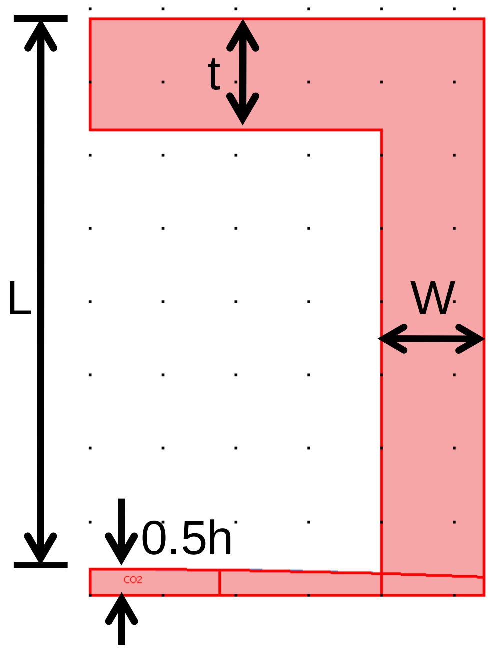


Figure. Variation of sensitivity and maximum pressure range as a function of top wall thickness (t)

(c) Thickness of Sidewall (W)



h= 1.178mm / 0.0464in
W=vary
L=7.62mm / 0.3in
t = 6.209mm/0.24in

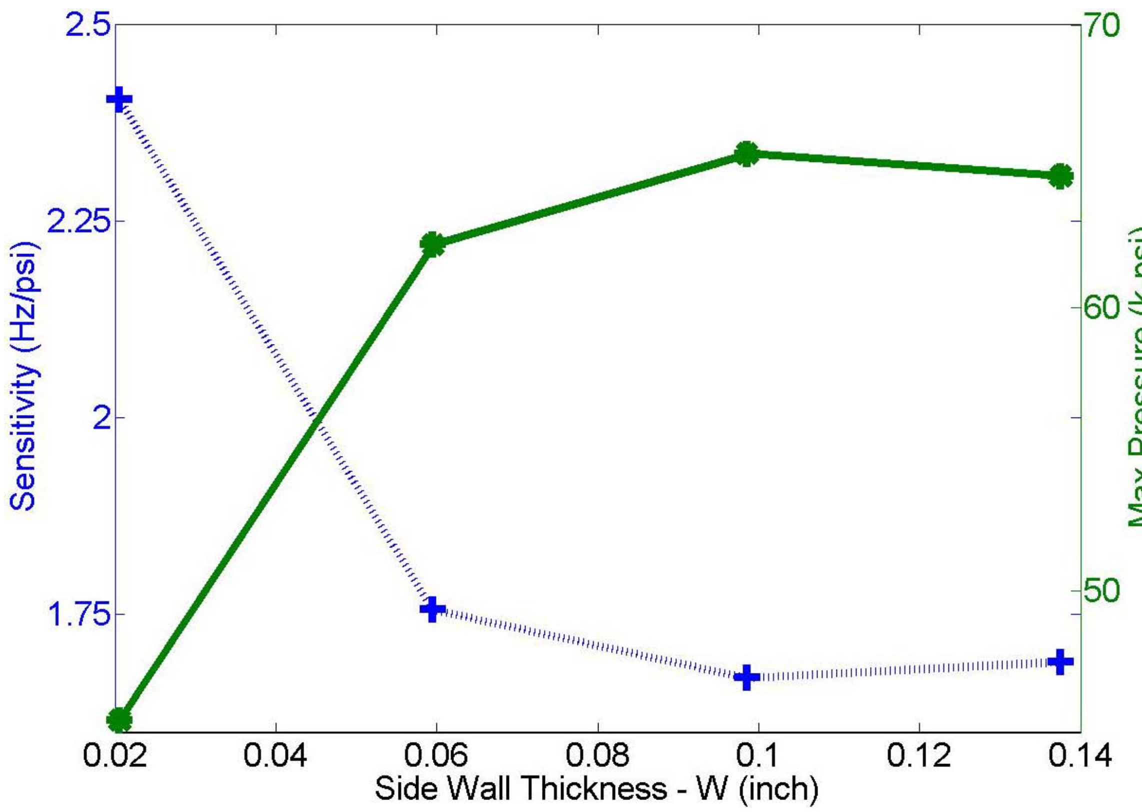
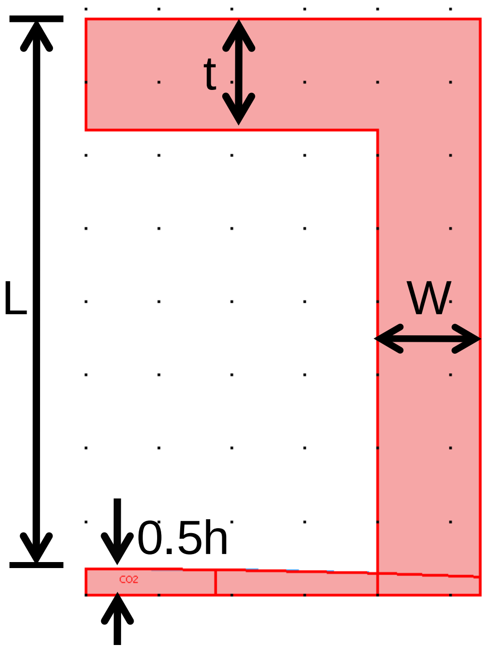


Figure. Variation of sensitivity and maximum pressure range as a function of side wall thickness (W)

(d) Length of endcap (L)



h= 1.178mm / 0.0464in
W=2.527mm/0.1in
L=vary
t = vary

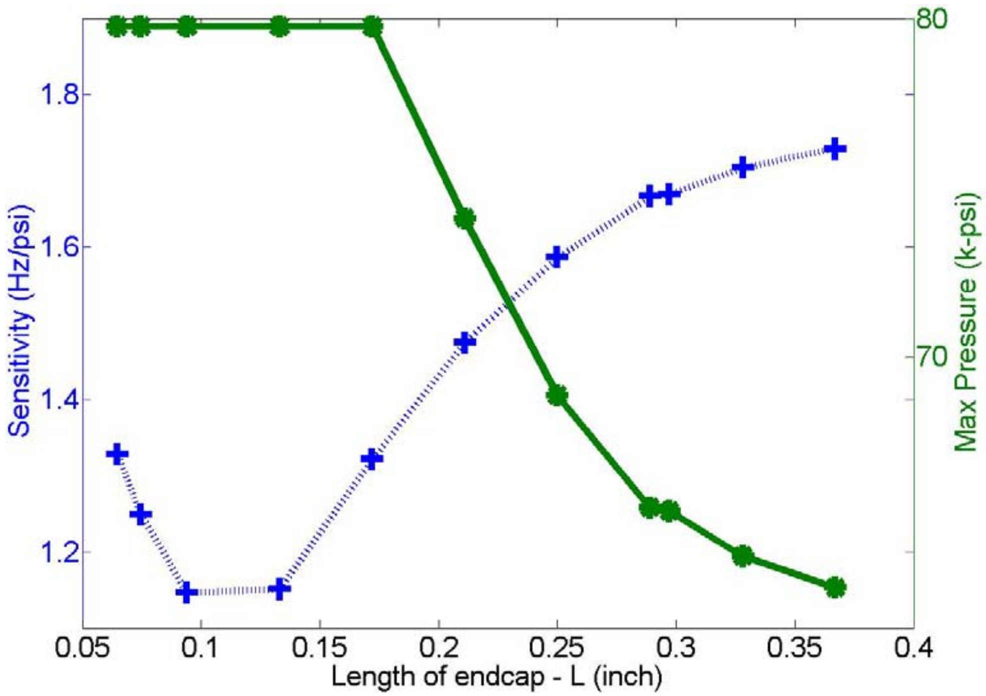
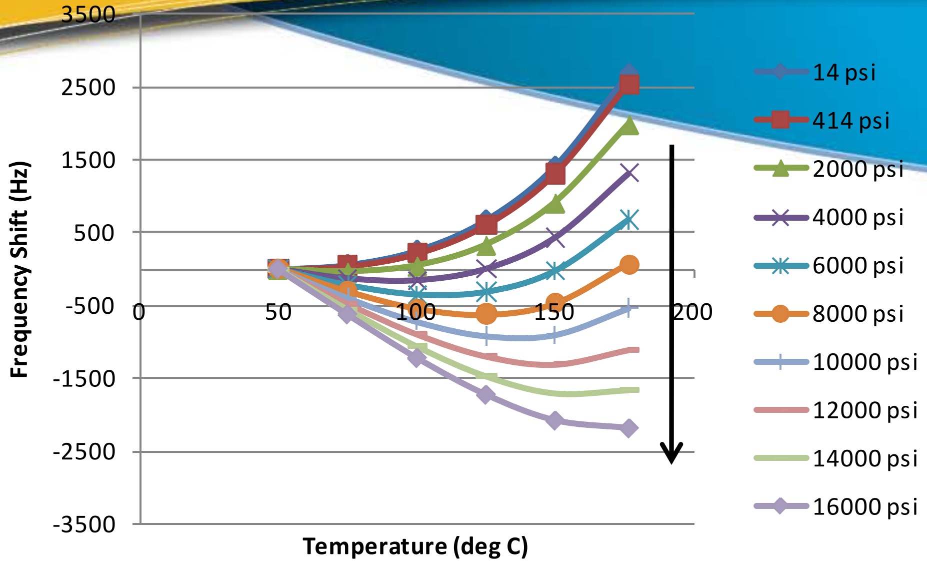
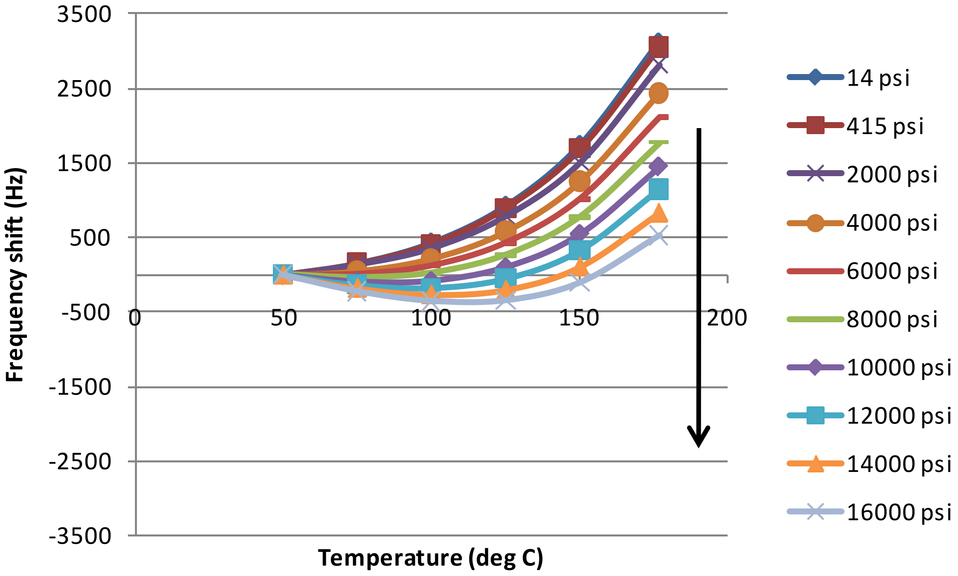


Figure. Variation of sensitivity and maximum pressure range as a function of length of endcap (L)

Quartz Sensor





Two designs are compared based on the results simulated in COMSOL. Design 1 has a sensitivity of 2.5Hz/psi and Design 2 a sensitivity of 1.45Hz/psi. Notice that the AF has significantly reduced as expected allowing for a increased pressure and temperature response.

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Conclusions

- a large top wall thickness 't', large side wall width 'w' and a short endcap length 'L' aids in increasing the pressure range.

- The maximum pressure range achievable in an AT cut pressure sensor is limited by twinning. By appropriately choosing the dimensions, a quartz pressure sensor capable of withstanding 200^{o}C and 20,000psi has been designed and commercially available to GRC's customers.

Acknowledgements

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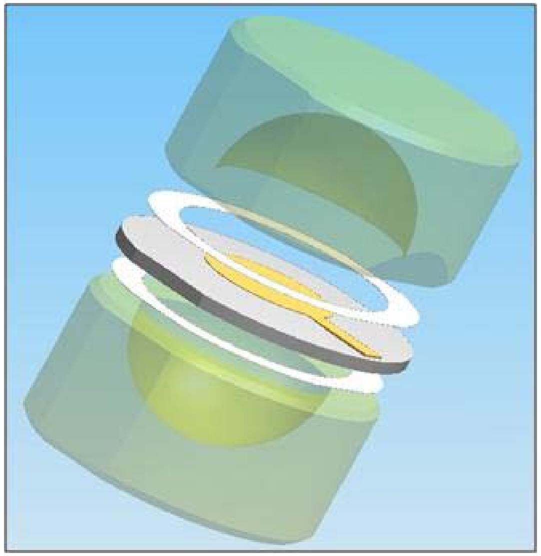

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