Design of a Compact Pressure Sensor for Multi-Layer Insulation in a Vacuum

Team 15
Sebastian Bellini
Jason Carvalho
Michael Kiefer
Stephen Johnson

Faculty Advisor: Dr. Wei Guo
Sponsor: NASA Marshall Space Flight Center
Liaison Contact: James Jim Martin
Date: 4/13/2017

Presentation Overview

- Project Scope
- Project Objectives
- Project Constraints
- Designs
    1. Capacitor
    2. Multi-Stage Capacitor
    3. Fiber Optics
- Prototype Scaling
- Design Calculations
- Prototype Production
- Experimental Setup / Testing
- Gantt Chart
- Future Work
- References

Presenter: Jason Carvalho

Project Scope

- The goal of this project is to design and implement a compact pressure sensor that is easily embedded between layers of Multi-Layer Insulation (MLI).
  - Rapid Response Time
  - The ability to measure a large pressure range
  - Noninvasive to the MLI

- This interstitial pressure is measured to quantify the heat transfer through the system

- Heat transfer is critical to cryogenic storage and applications in space

Presenter: Jason Carvalho

Project Objectives

- Develop a pressure sensor with minimal parts
- Minimize the wiring and power consumption of the device
- Minimize the heat produced by the sensor

Presenter: Jason Carvalho

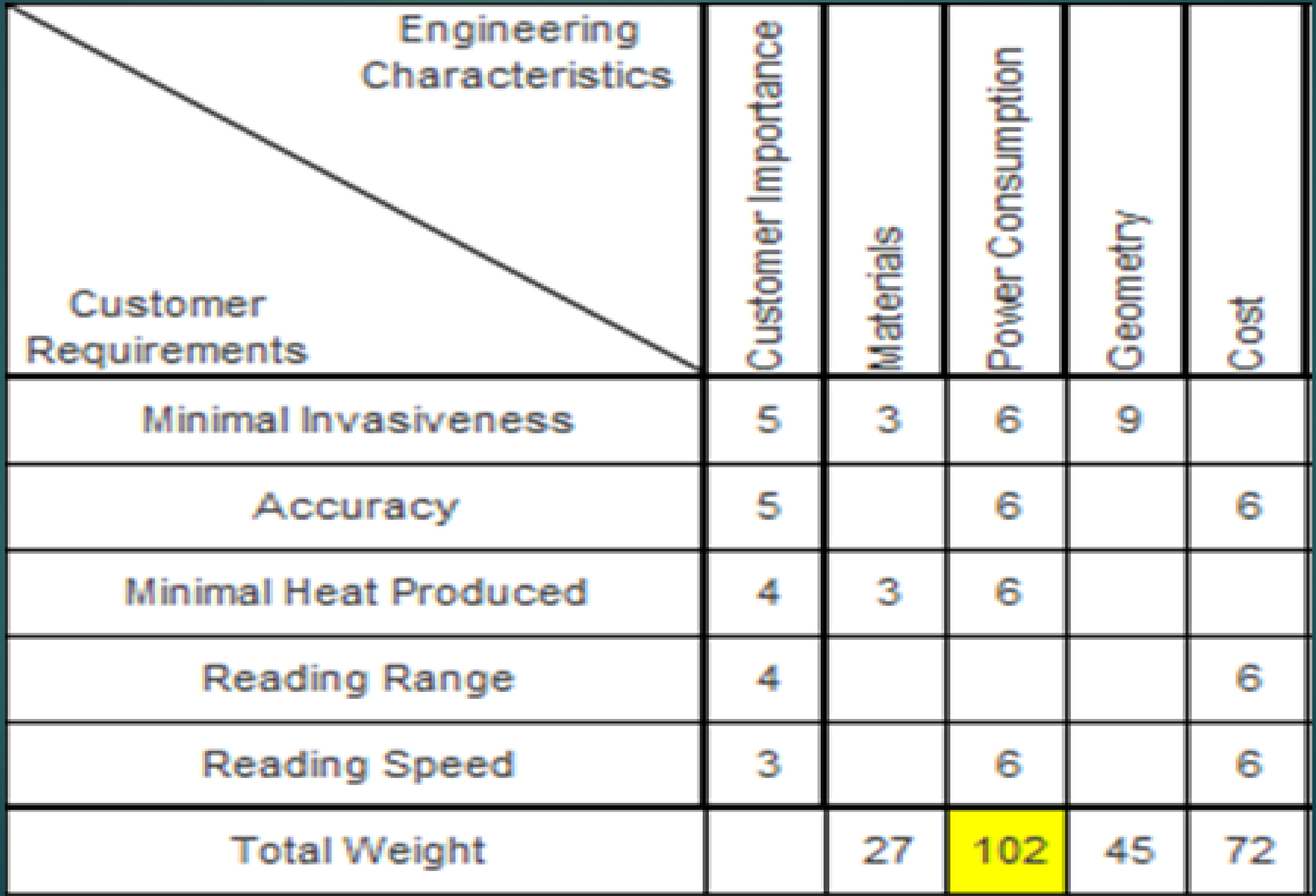
Project Constraints

- Pressure Sensor
  - Be able to measure a pressure as low as 10^{-2} Pa
  - Have a minimum response rate of 1 sample per second
- Multi-Layer Insulation
  - Sensor dimensions shouldn’t exceed interlayer spacing
    - 12 layers is roughly 5 mm
- Working environment
  - Temperature conditions range from 293 K to 77 K
  - Out gassing
  - Vacuum

Presenter: Jason Carvalho

House of Quality

Table 1 - House of Quality for Pressure Sensor Design



Engineering Characteristics Customer Requirements	Customer Importance	Materials	Power Consumption	Geometry	Cost
Minimal Invasiveness	5	3	6	9	
Accuracy	5		6		6
Minimal Heat Produced	4	3	6		
Reading Range	4				6
Reading Speed	3		6		6
Total Weight		27	102	45	72

Presenter: Jason Carvalho

Capacitor Design

1. Palladium-gold sputtered capacitance tracts

2. Silicone diaphragm
    - 125 μm diameter
    - 0.25 μm thickness
3. Capacitor base shell
    - Germanium doped Silica base with cavity hollowed by acidic etching

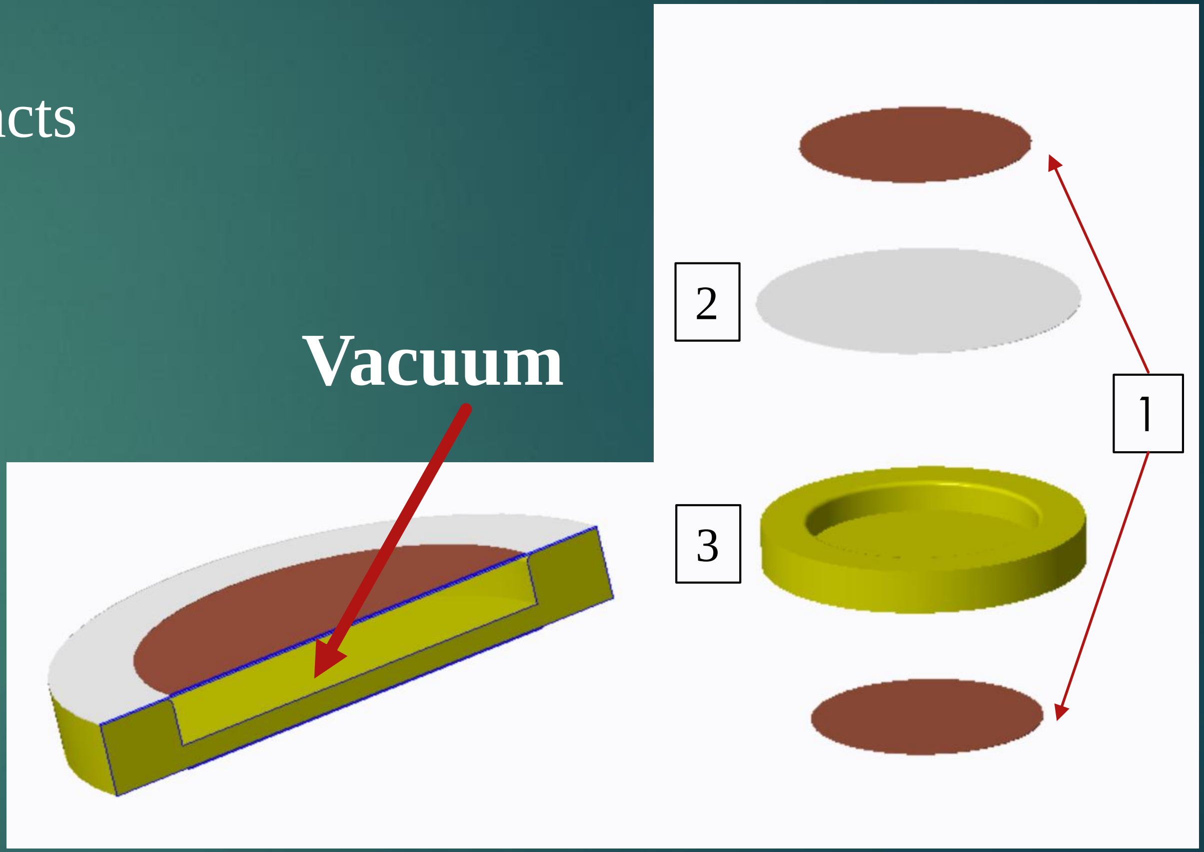


Figure 1: Cross section view of capacitor (left), and exploded view (right)

Presenter: Michael Kiefer

Multi-Stage Capacitor Design

1: Capacitor top diaphragm:
  -High sensitivity – reads low pressures
  -165 μm OD, 125 μm ID diaphragm
  - 20 nm thickness, 27 μm deflection at 10 Pa
  -Nano-metallic coating to create capacitor plate (sputtering)
2: Silica spacer
3: Intermediate diaphragm:
  -Medium to low sensitivity – reads medium to high pressure ranges.
  - 50 nm thickness, 28 μm deflection at 150 kPa
4: Silica Base plate
5: Capacitor bottom plate:
  -Rigid metallic plate

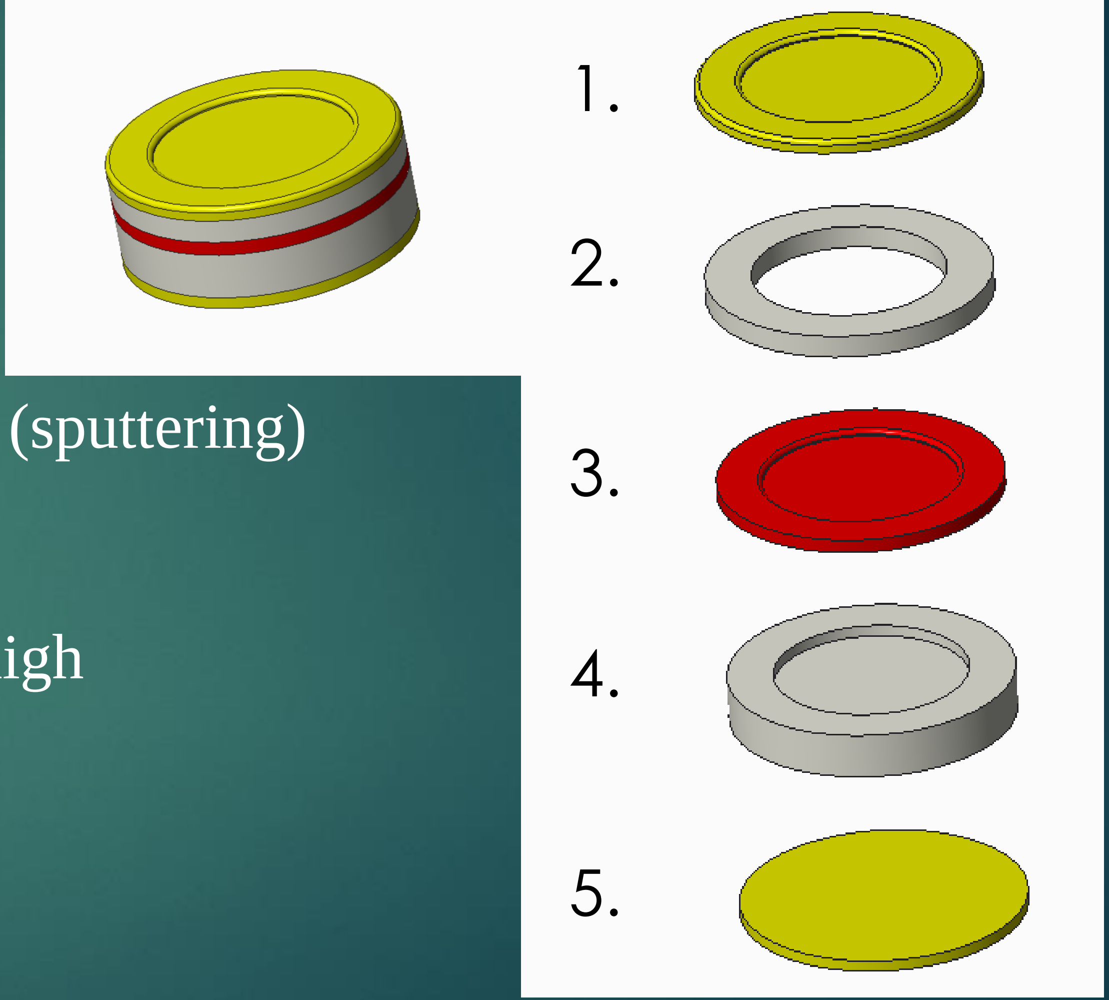


Figure 2: Displays the exploded view of the multi stage capacitor

Presenter: Michael Kiefer

Multi-Stage Capacitor Design

- Cavities formed in the silica base by parabolic germanium doped etching
- Capacitor assembled in a vacuum
- Parts either fused together, or set with a UV-reactive polymer

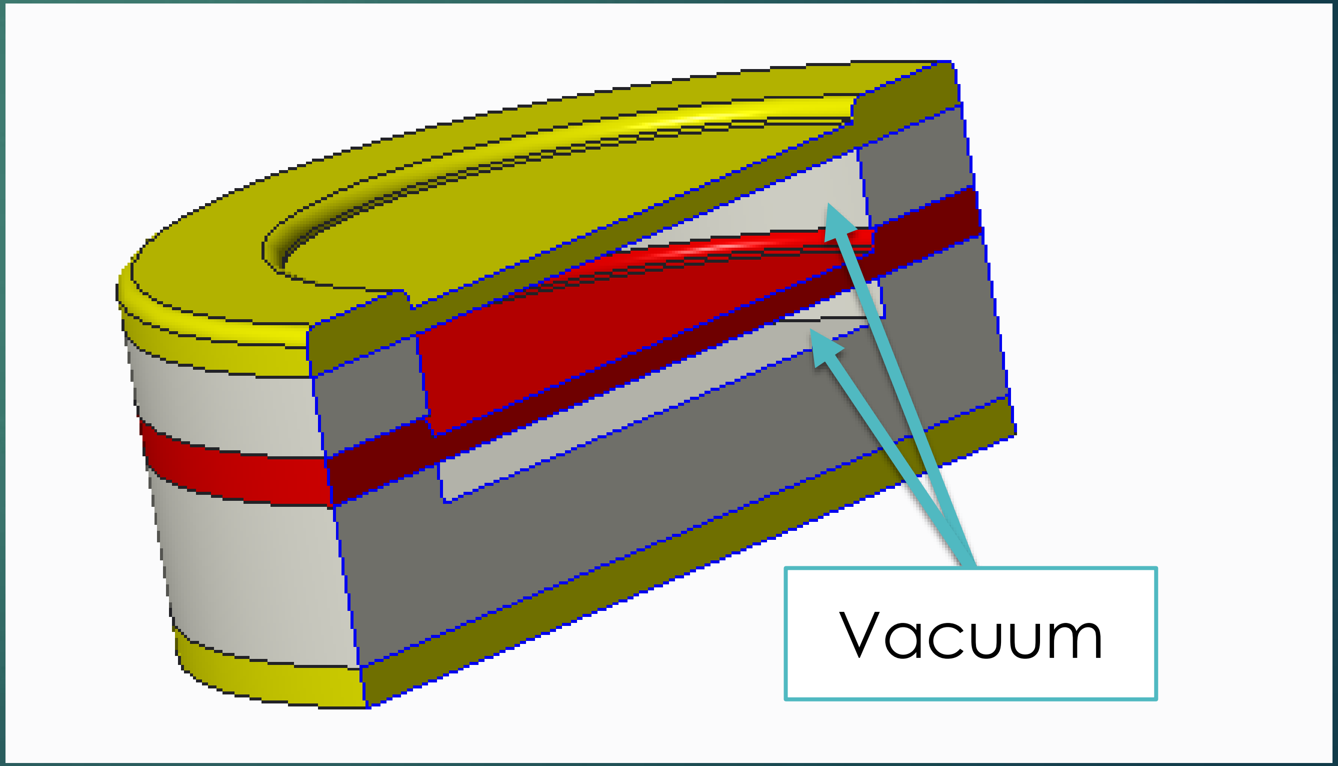


Figure 3: Multi stage capacitor cross sectional view

Presenter: Michael Kiefer

Fiber Optic Design

- 1: Silica diaphragm
  - 125 μm OD
  - 85 μm ID diaphragm
- 2: Silica core
- 3: Lead-in optical fiber
  - Multimodal or single modal

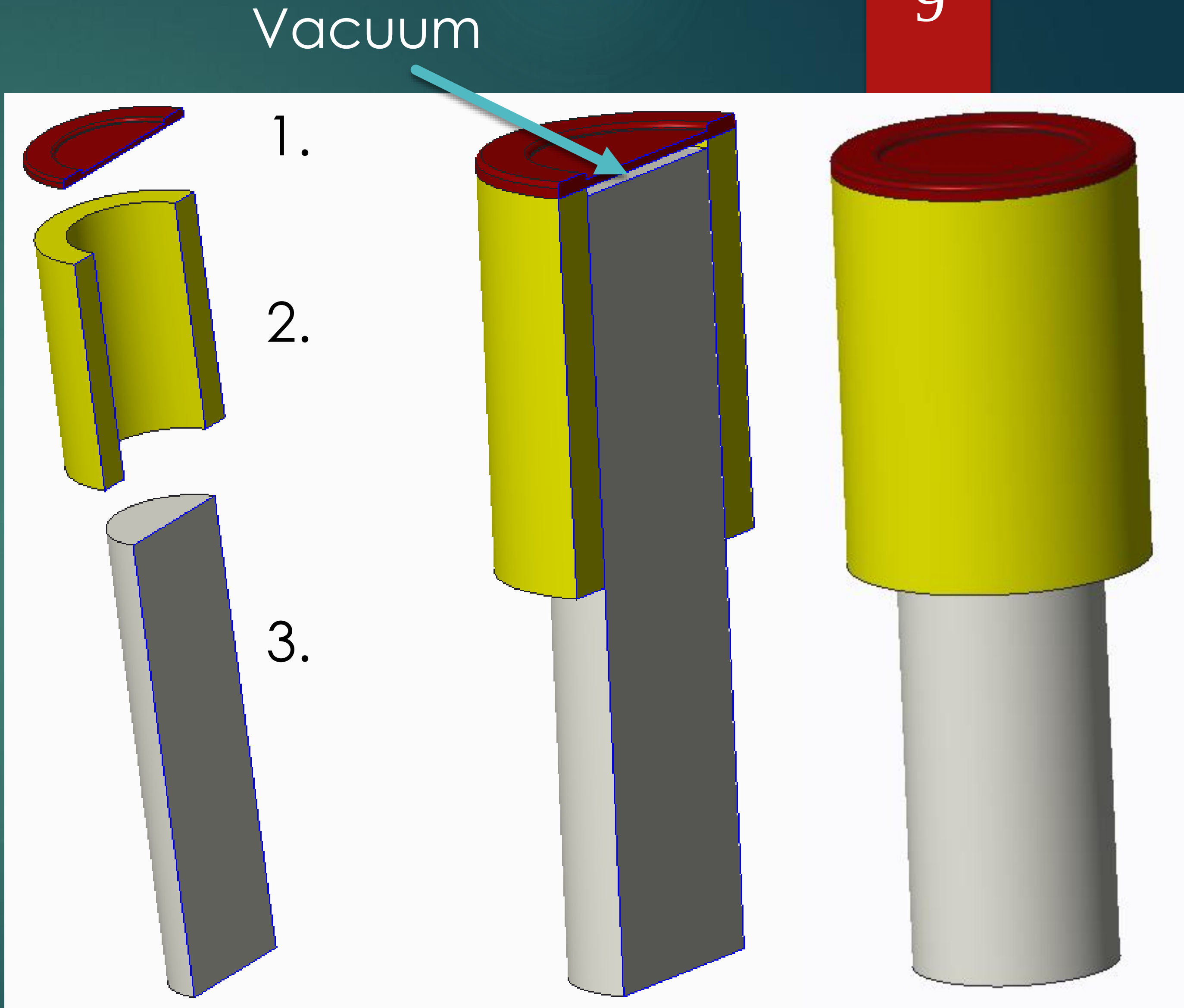


Figure 5 Cross section view and fully assembled view of Fiber optics sensor

Fiber Optics

- Observes change in phase, polarization, transmit time, or wavelength to measure pressure
- Pros
  - Good in high vibrational, wet, noisy, corrosive, and extreme heat environments
  - Immune to electromagnetic interference
  - Ability to measure a large range of pressures
  - High Sensitivity and Bandwidth
  - Size (125 micrometers)
- Cons
  - Relatively difficult design
  - Cost
  - Assembly requires special equipment

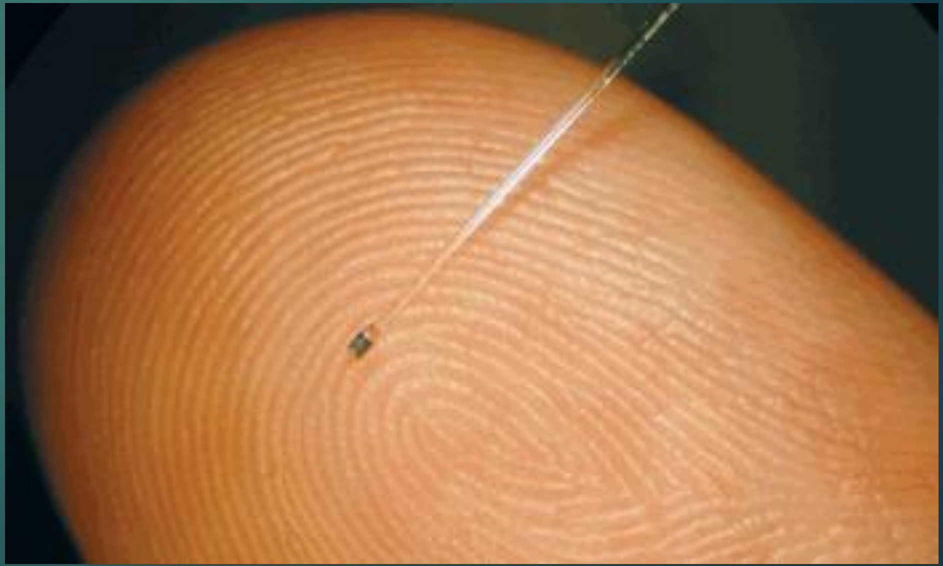


Figure 4 Displays the size of a fiber optics pressure sensor

Presenter: Michael Kiefer

Decision Matrix

Table 2 - Pugh Decision Matrix for pressure sensor concepts

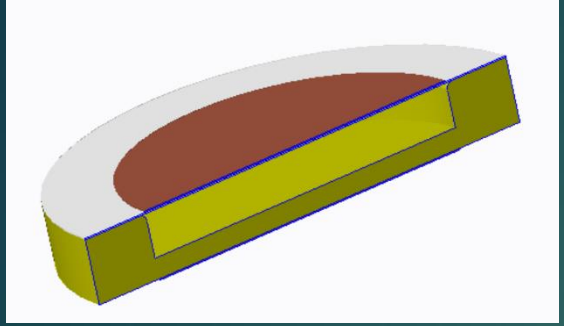
	Capacitor	Fiber Optics	Multi-Stage Capacitor
Accuracy	0	1	0
Minimal Invasiveness	0	0	0
Heat Production	0	-1	0
Reading Range	0	2	1
Reading Speed	0	0	0
Total	0	2	1

Presenter:
Stephen
Johnson

naNO

- Creating the nano-capacitance prototype falls outside of the time restraint and budget
- To progress with a prototype and testing, scaling must occur
- Wish to scale from 125 μm diameter diaphragm to a more pragmatic 25 mm (200x)
  - Enables the experimentation of capacitance pressure sensors in the previously shown design
  - Easier implementation with ongoing sensor research directed at temperature detection

Presenter: Stephen Johnson



Design Calculations

Critical minimum thickness of diaphragm at given pressure (P):

$$h = \sqrt{\frac{3\pi r^2 * P}{4\pi\sigma_y}}$$

$\sigma_y = yield\ stress$

Maximum deflection at given Pressure (P) and thickness(h):

$$w_{max} = -\frac{3\pi r^2 P\left(\left({}^{1}/_{\mu}\right)^2 - 1\right) r^2}{16\pi E h\left({}^{1}/_{\mu}\right)^2}$$

Critical maximum body pressure at given shell thickness:

$$p = \frac{0.855}{(1-\mu^2)^{\frac{3}{4}}} * \frac{E\sqrt{\gamma}}{\left(\frac{r}{t}\right)^{\frac{5}{2}} * \frac{l}{r}}$$

$$\gamma = 1 - 0.901(1 - e^{-\phi})$$

$$\phi = \frac{1}{16}\sqrt{\frac{r}{t}}$$

$\mu = Poisson's\ Ratio$

$E = Young's\ Modulus$

$r = diaphragm\ radius$

$l = sensor\ length$

$t = shell\ thickness$

Max Pressure during liftoff ≈ 150 kPa

	Diaphragm Diameter	Min. Thickness (@150 kPa)	Design Thickness	Safety Factor	Critical Diaphragm Pressure	Maximum Deflection (@150kPa)	Shell Thickness	Critical Body Pressure
Prototype	25 mm	0.05 mm	0.10 mm	2.00	600 kPa	5.60 mm	5 mm	20 MPa
Actual Sensor	125 µm	0.25 µm	0.50 µm	2.00	600 kPa	28.0 µm	20 µm	400 MPa

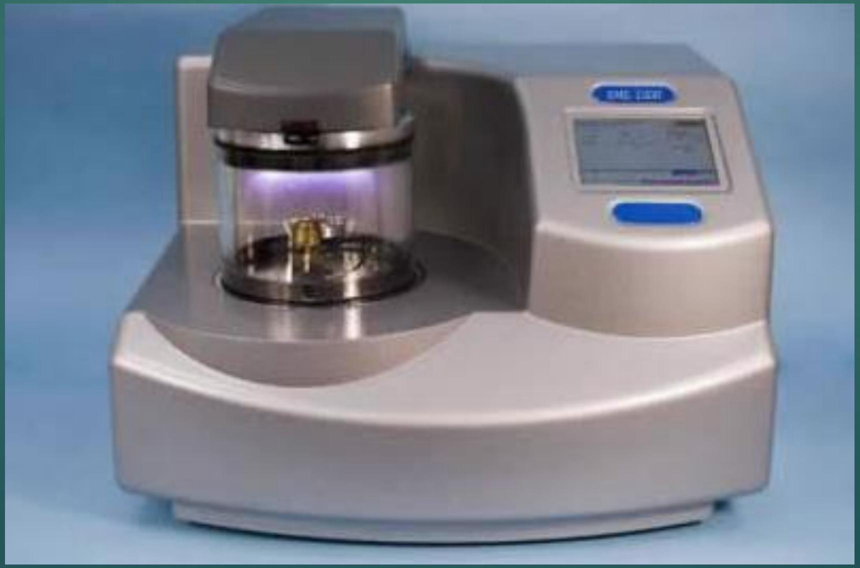
Prototype Production

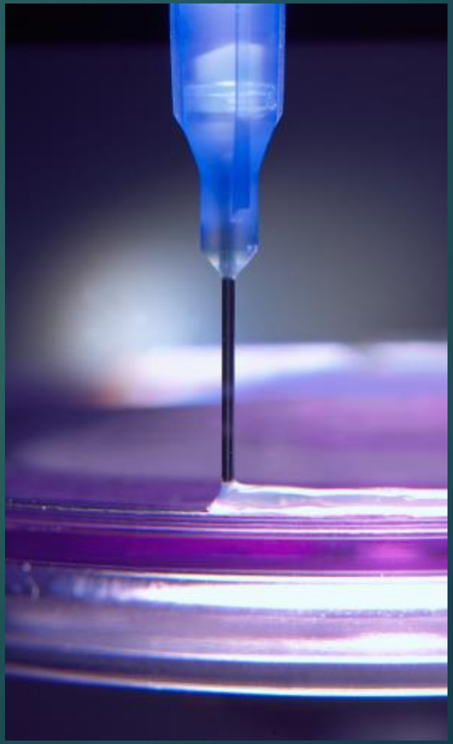
- Silicone diaphragm acquired (0.1mm and 0.2 mm)
- Epoxy capacitor base finished using HIPS dissolvable filament

Presenter: Stephen Johnson

Prototype Production

- Use SEM lab to sputtering tracts onto silicone
- UV polymer to adhere the diaphragm





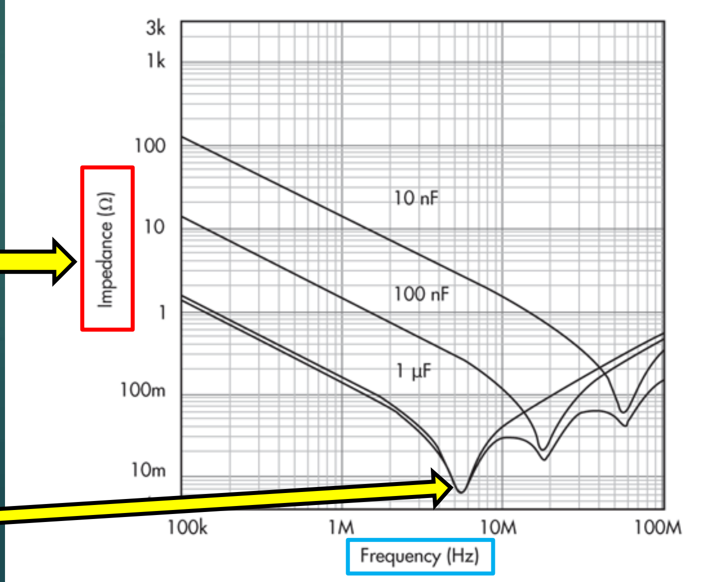
Presenter: Stephen Johnson

Experimental Testing

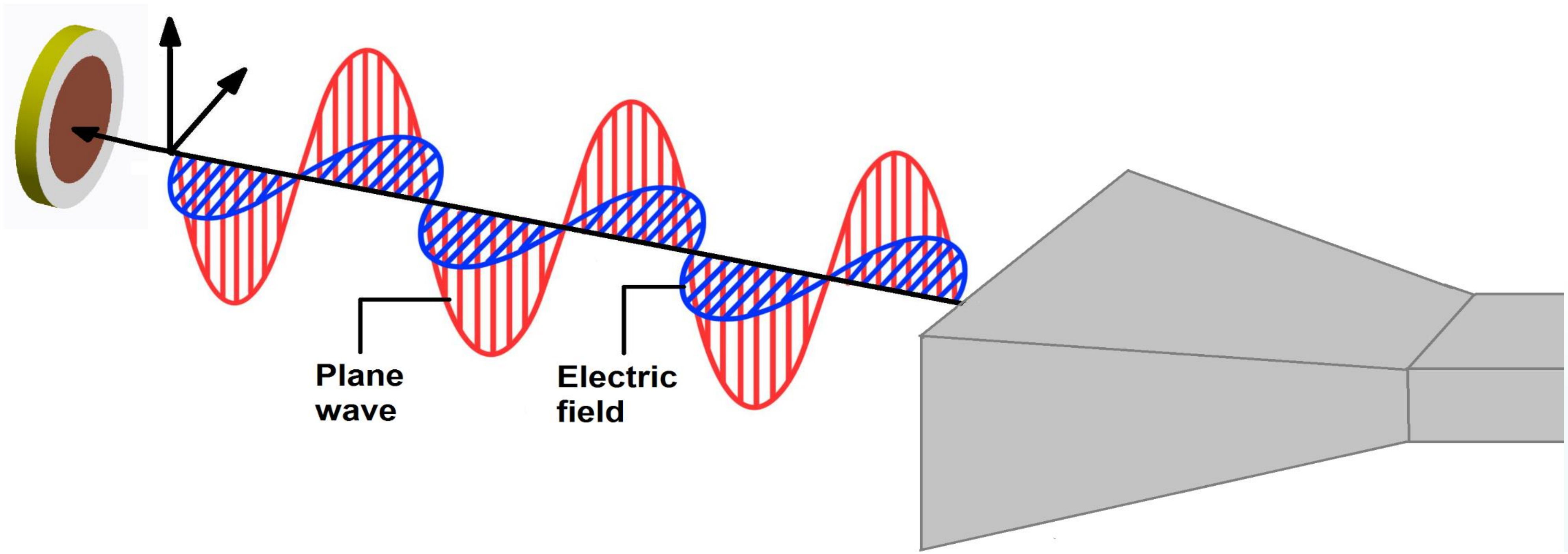
- Capacitance is a function of geometry (area and distance apart)
- Each capacitor has a resonant frequency that can be determined using a network analyzer and oscilloscope
- Network analyzer creates electromagnetic fields, which will cause voltage to oscillate in the capacitor
- Voltage read at the capacitor positive will decrease when resonance has been achieved at the dictated frequency
- Resonance becomes a function of deflection, thus a function of pressure

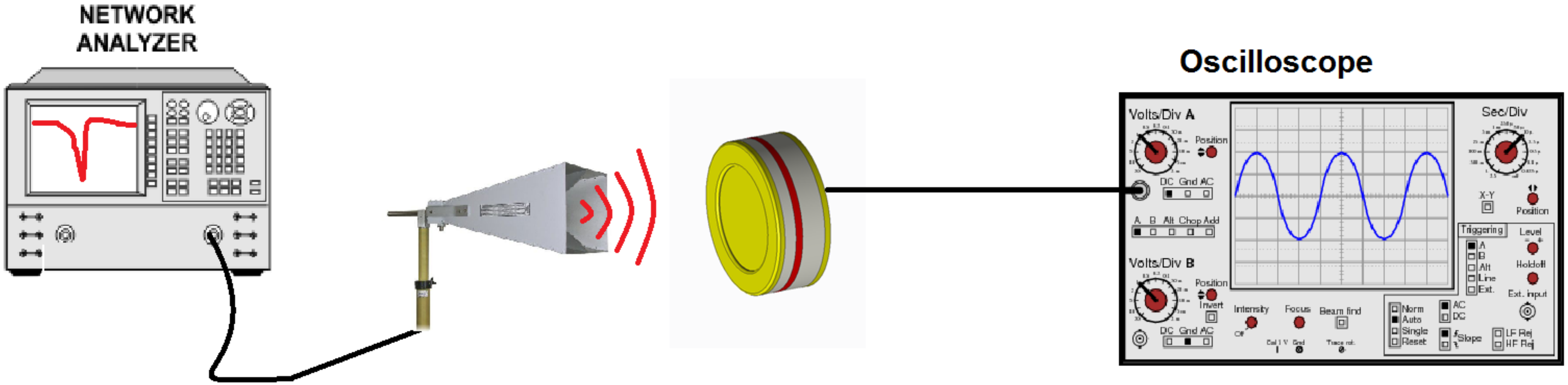
$$V = I * R$$

$$Voltage = f(frequency)$$
$$Frequency_R = f(deflection)$$
$$Pressure = f(deflection)$$
$$Pressure = f(frequency_R)$$



Presenter: Sebastian Bellini

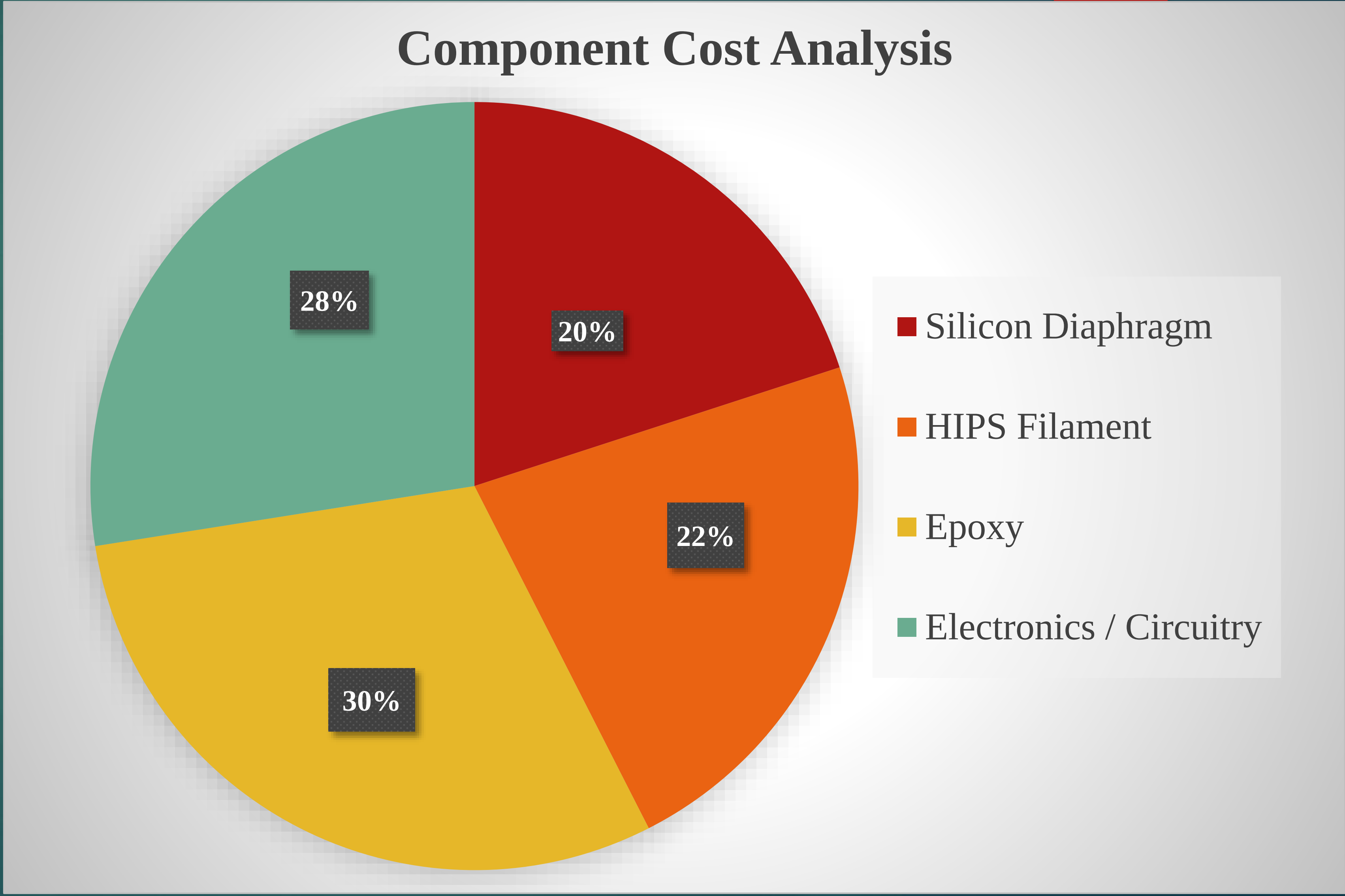

Plane wave
Electric field


NETWORK ANALYZER
Oscilloscope
Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Invert
Intensity
Focus
Beam find
Sec/Div
X-Y
Triggering
Level
Holdoff
Ext. input
A
B
Alt
Line
Ext.
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej

Budget

Total Budget: $500

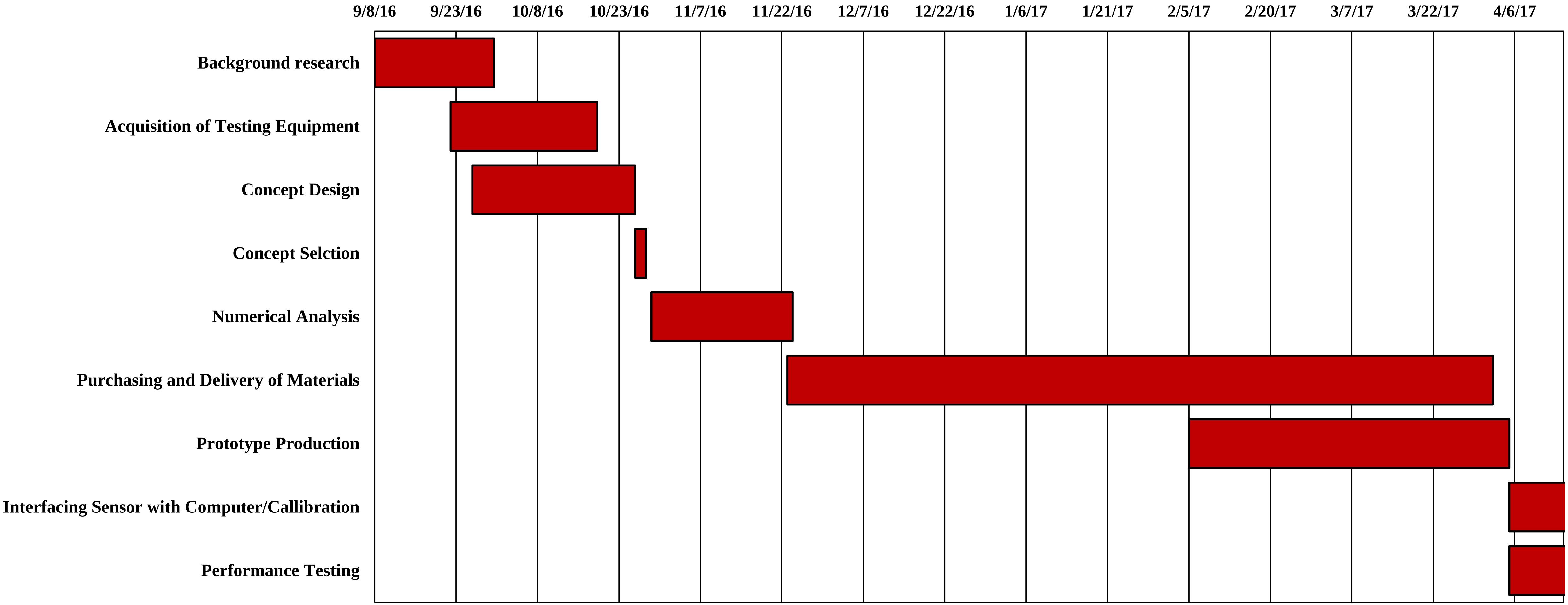
- Electronics: $55
- Silicone: $40
- Epoxy: $60
- HIPS Filament: $45



Presenter: Sebastian Bellini

Updated Gantt Chart

Presenter: Sebastian Bellini



Future Work

- Purchase Masterbond UV10 epoxy
- Interface sensor with network analyzer
- Calibrate sensor
- Determine viability

References

- *Buckling of Thin-walled Circular Cylinders* (1965): n. pag. NASA. Web. 30 Mar. 2017
- "Elastic Constants Of Unidirectional Composites." *Composite Materials* (2002): n. pag. Web
- H. Bae and M. Yu, "Miniature Fabry-Perot pressure sensor created by using UV-molding process with an optical fiber based mold," Opt. Express 20, 14573-14583 (2012).
- Herakovich, Carl T. "Thin-Walled Pressure Vessels." *A Concise Introduction to Elastic Solids* (2016): 77-81. Web. 30 Mar. 2017.
- Massi, Miranda. "'Cha-Ching': Cost-Effective Health Hacks." *UBC Human Resources*. N.p., n.d. Web. 30 Mar. 2017
- McEntee, Jarlath. "Properties of Silicon." *Properties of Silicon*. N.p., n.d. Web. 30 Mar. 2017.
- "Mesa Diaphragm-based Fabry-Perot Optical MEMS Pressure Sensor - IEEE Xplore Document."*Mesa Diaphragm-based Fabry-Perot Optical MEMS Pressure Sensor - IEEE Xplore Document*. N.p., n.d. Web. 30 Mar. 2017.
- "Miniature Fiber Optic Pressure Sensor for Medical Applications - IEEE Xplore Document." *Miniature Fiber Optic Pressure Sensor for Medical Applications - IEEE Xplore Document*. N.p., n.d. Web. 30 Mar. 2017.
- Pinet, Éric, Edvard Cibula, and Denis Đonlagić. "Ultra-miniature All-glass Fabry-Pérot Pressure Sensor Manufactured at the Tip of a Multimode Optical Fiber." *Fiber Optic Sensors and Applications V* (2007): n. pag. Web.
- http://cdn.fibreglast.com/downloads/00343-A.pdf
- http://llerrah.com/images6/footprintstop.jpg
- https://www.engr.sjsu.edu/trhsu/ME189_Chapter%204.pdf
- http://www.ferroceramic.com/silicon_table.htm

Questions?