Recent Progress of HPHT Pressure Sensor Suite for Real-Time Monitoring of Subsea And Downhole Environments

SESSION 5: SUBSEA

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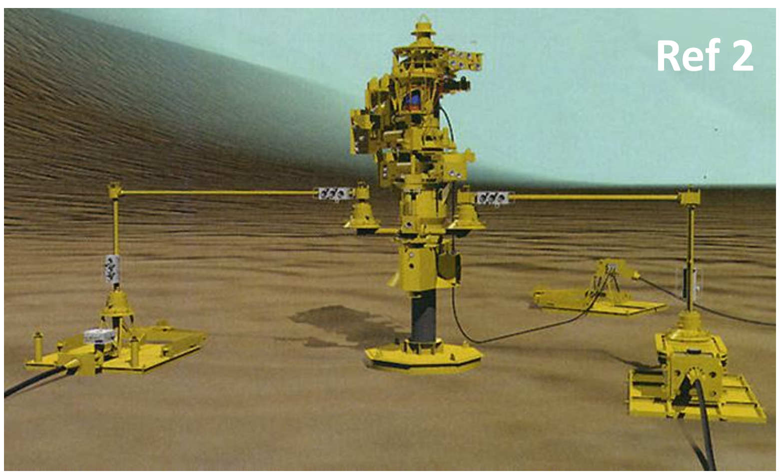
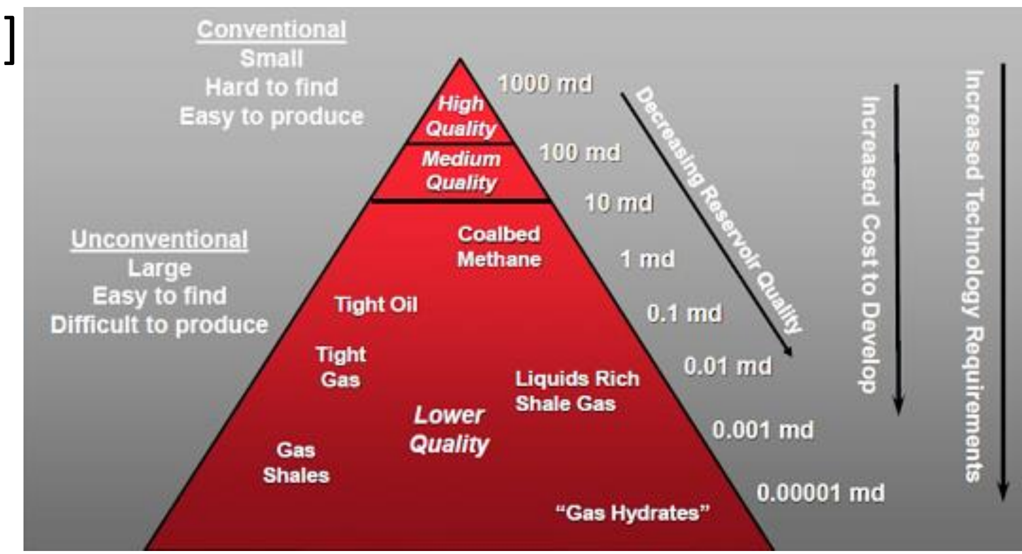
Agenda

- Introduction
- HPHT Applications
  - Multi-Phase Flowmeters
  - Subsea Wellheads, Equipment
  - Downhole: Kick Detection/Real-Time Monitoring
- Our Pressure Sensor Suite: P, DP, MDS (Mud Density Sensor)
- HPHT P, DP Sensors
  - Design/Fabrication Overview
  - Performance/Calibration Results
- HPHT MDS Sensors
  - Design/Fabrication Overview
  - Performance/Calibration Results
- Conclusions

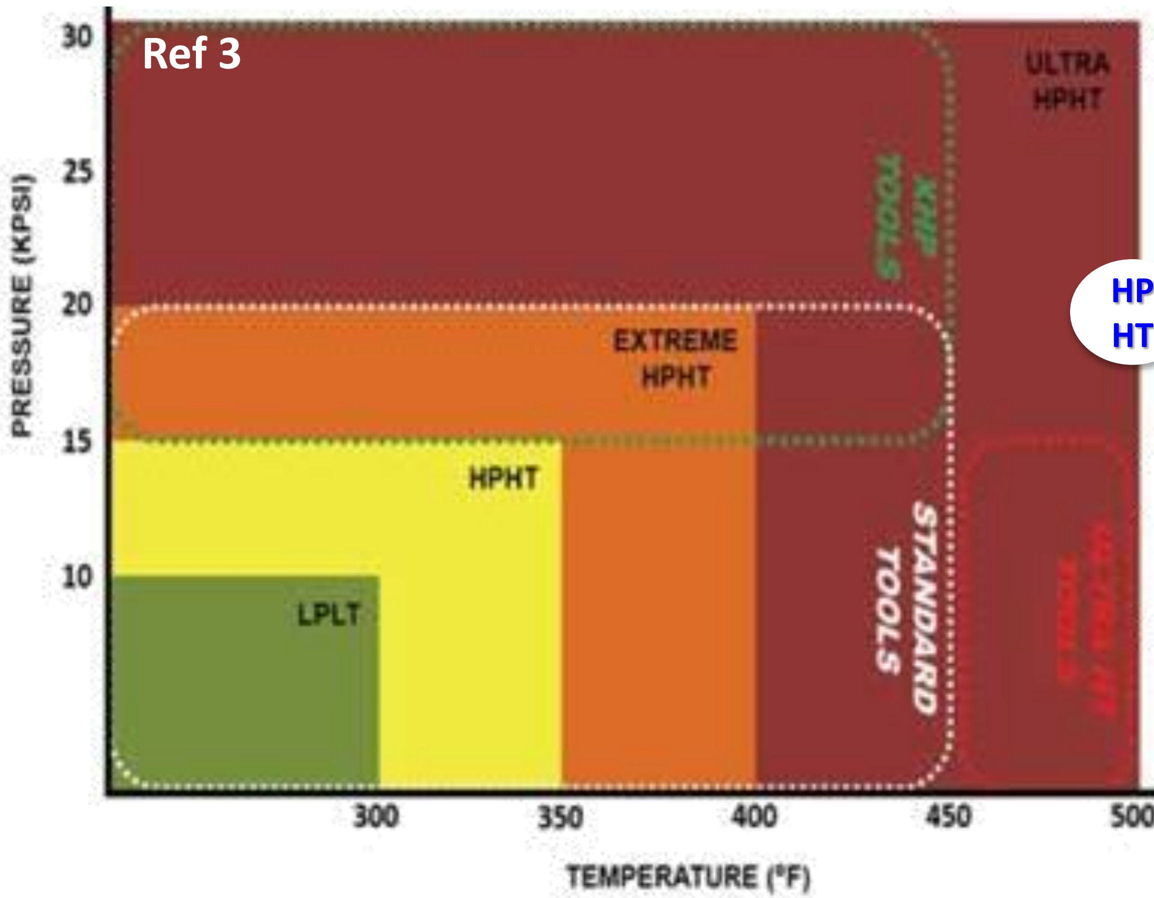
Introduction

- In past decade, Oil and Gas (O&G) exploration and operations have never been more abundant throughout the world.
- During this downturn focus is on cost effective production
  - new HPHT technologies needed
  - improvements in production efficiency, reliability and safety of existing processes.
  - need for subsea and downhole equipment and their instrumentation to withstand 20 ksi, 200°C [1]





Critical Issues in HPHT Drilling



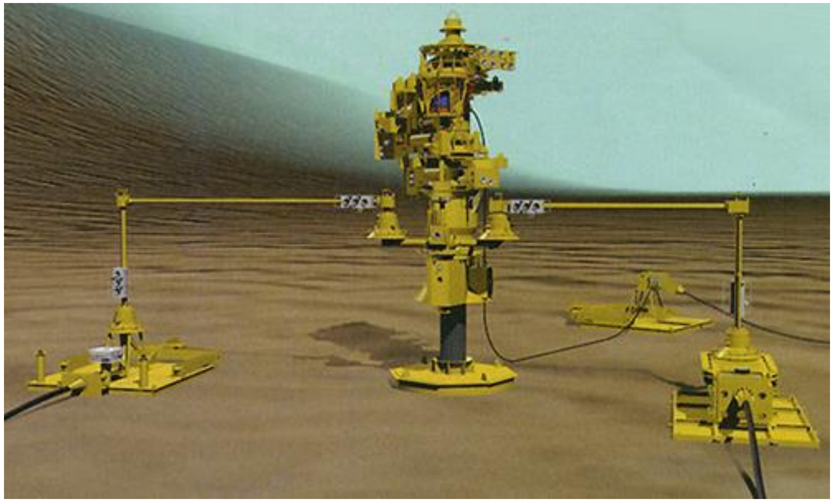
HP HT

Unconventional oil exploration

- Subsea, downhole
- High pressures (20 ksi)
- High temperatures (250 °C)
- challenges to equipment materials, packaging, performance, safety and reliability;
- Technologies to mitigate control incidents.
- need for highly accurate p, DP sensor measurements in the HPHT downhole environment.

The following applications will show the need for High Accuracy High Pressure High Temperature (HPHT) Pressure Sensors.

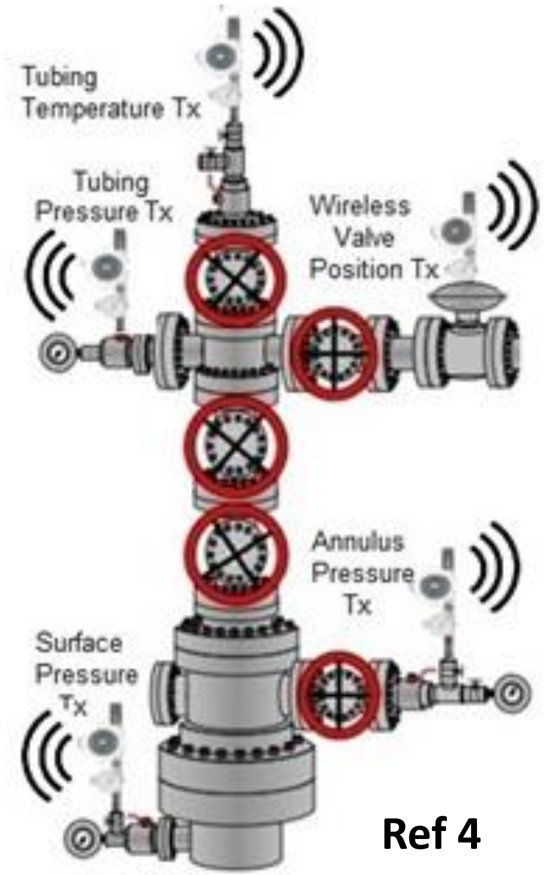
HPHT Applications: MPFM



- Equipment: subsea MPFM
- Challenging to obtain highly accurate DP measurements, with two absolute sensors, particularly at HPHT conditions.
- DP measurements with absolute P sensors could lead to significant error, especially in comingling pipelines.
- Errors in total volumetric flow rates, even, if 1-2%, can lead to substantial under or over-accounting of oil product revenue.

HPHT Applications: Smart Wellheads

- Subsea equipment: Christmas Trees, Wellheads.
- **Wellhead P,T**: to monitor the health of the well and aid in understanding the fluid composition;
- **Well Annulus Pressure**: helps monitor casing pressure, whereby a pressure increase would require well relief;
- **Oil Production Totalized Flow**: several sensors utilized to calculate total flow output, as discussed earlier, in the case of DP measurements for MPFMs;
- **Injection Wellhead Monitoring**: P, T and DP measurements provide status of the injection process;
- **Steam Injection Heat Exchanger Management**: measurements of P and DP across heat exchangers allow monitoring of their performance;



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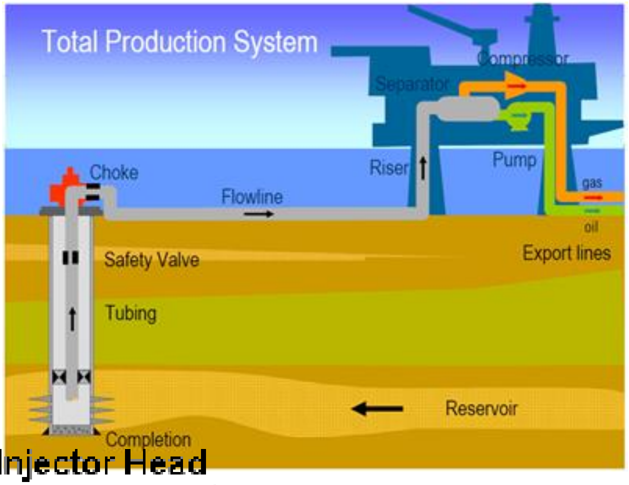
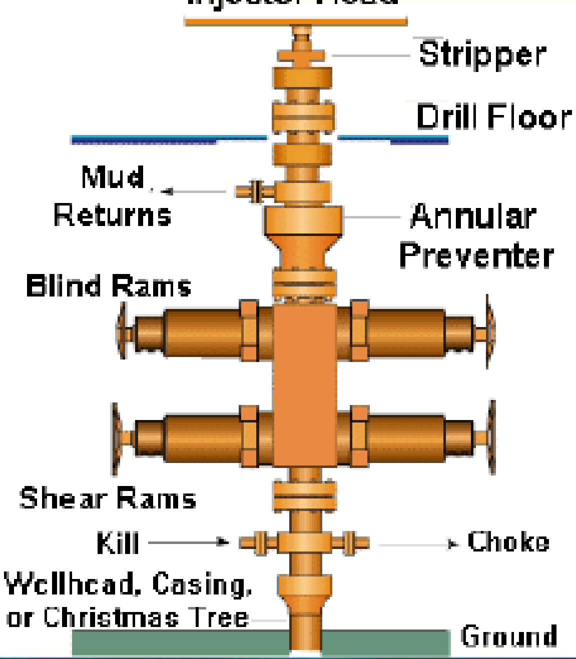
HPHT Applications: Downhole/Kick Detection Monitoring

- The blowout accident is one of the most common and dangerous safety concerns.
- An unbalanced event or encounter with a gas pocket, ultimately leads to a “kick”.
- Sudden change in mud density may be result of lost mud circulation to the reservoir or formation causing changes in the annular pressure or the BHP.
- A low density kick may occur in the downhole environment before anything is detected at the surface.



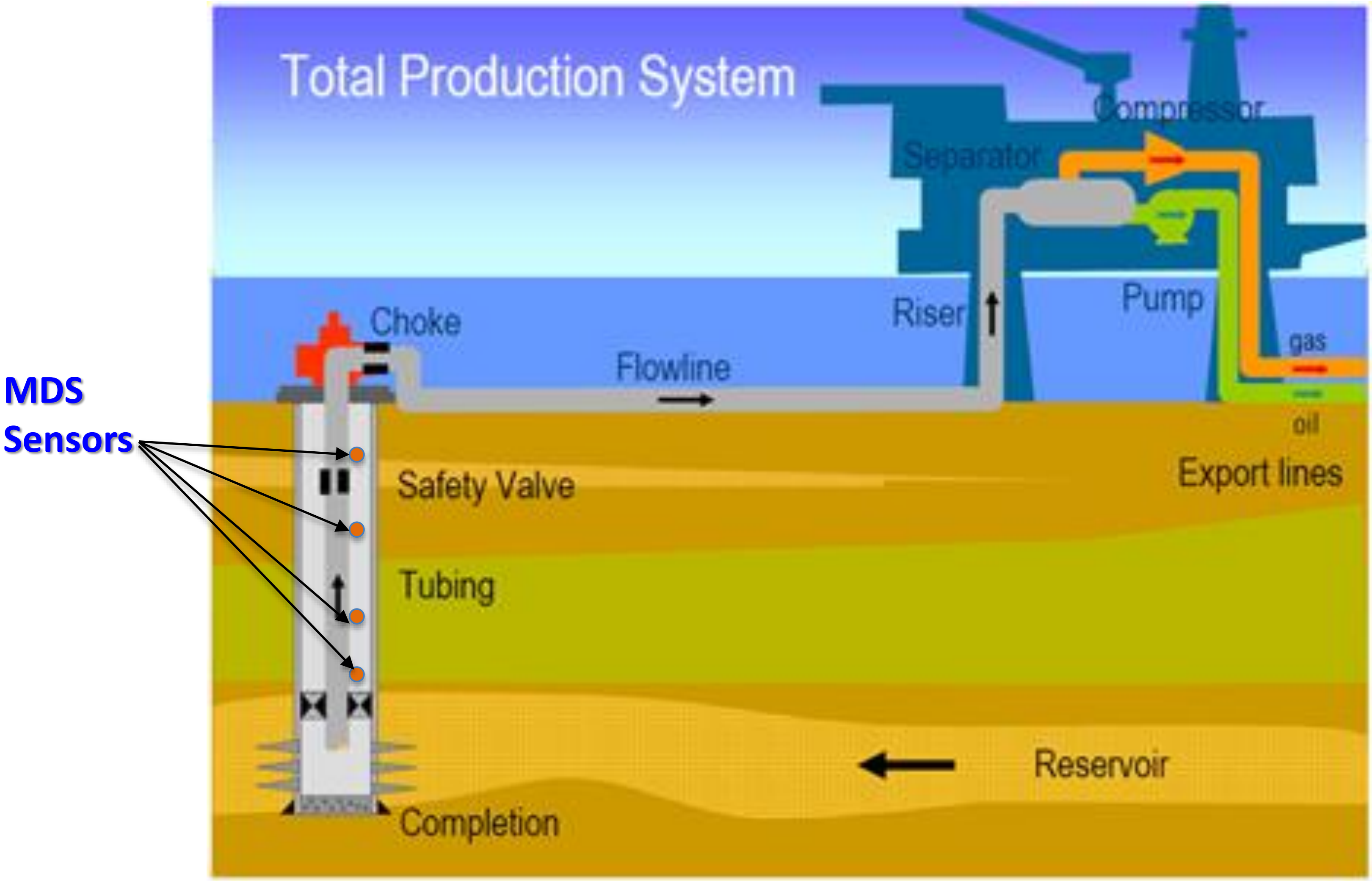


HPHT Applications: Downhole/Kick Detection Monitoring

To provide better kick detection we need to:

- Detect it faster and sooner!
- Implement an array of accurate HPHT DP sensors within mud logging tools;
- Locate HPHT MDS sensors, every 20-30 feet, along mud logging obtaining :
  - downhole conditions (P,T);
  - mud density profile, $\rho(h, t)$;
  - mud density changes $\partial(\dot{m})_{mud}/_{\partial t}$
  - information on forecasting expansion rate of gas during kick event.
- Such timely, accurate and distributed sensing would allow for better drilling management and well control (eg. changing the BOP choke settings to regulate the mud flow rate into and out of the well) and isolating the kick location.

HPHT Applications: Downhole/Kick Detection Monitoring



Our HPHT P, DP Sensor Suite

- Funded by RPSEA/DOE (1301, 4304 Programs): Fig 1, 2.
- Original (1301) sensor design combined two MEMS die (P, DP) into 2” OD packaging; Fig 1.
- This sensor suite leverages our team’s 2nd Generation MEMS Silicon-on-Insulator (SOI) chip technology (1st Gen. was used on NASA Space Shuttle Pressure Transducers):
  - Piezo-resistors embedded onto MEMS die
  - Half & Full Wheatstone bridge options.
- Follow on 4304 Sensor Designs (P, DP)
  - All leverage common (1” OD) packaging (Figs 3-4)
  - Different MEMS die

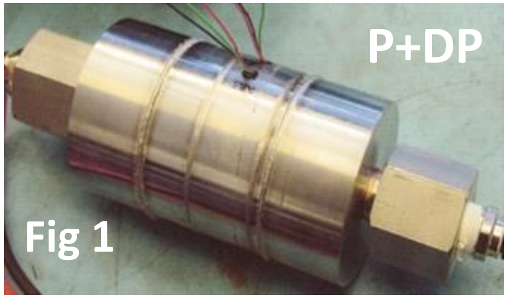


Fig 1

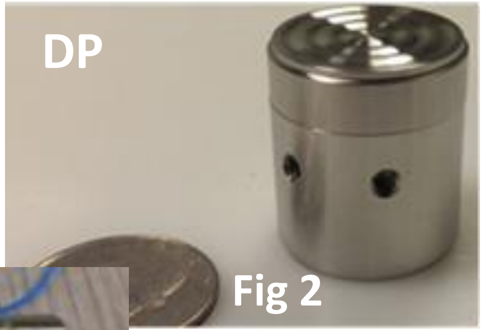


Fig 2

Fig 3

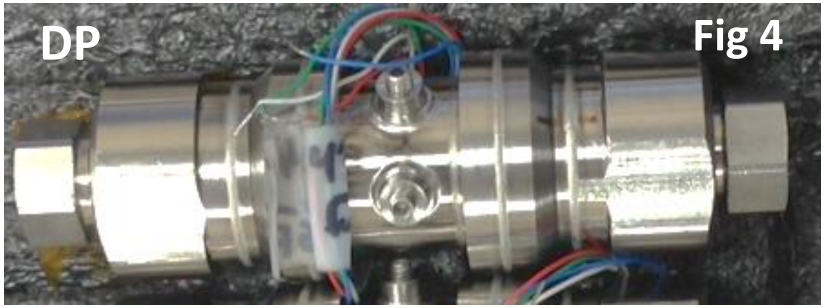
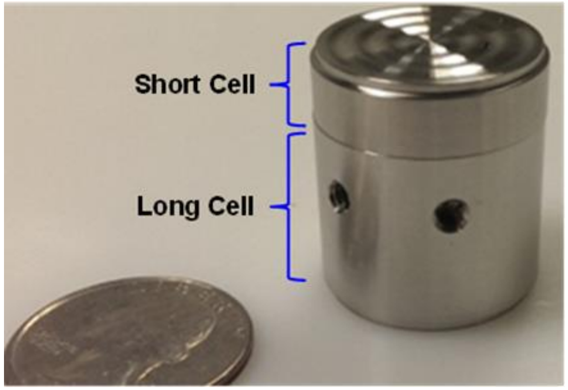


Fig 4

Our Team's Approach to HPHT MEMS Pressure Sensor Development



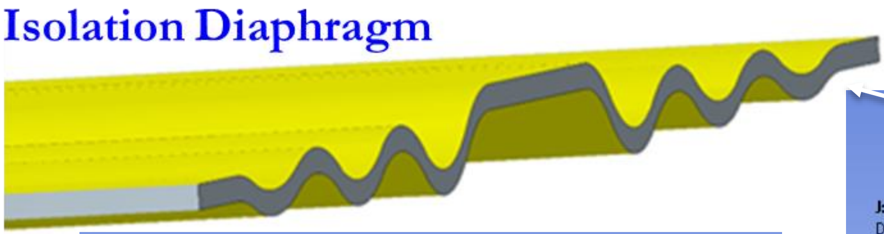
- CONOPS of our P, DP Sensor Suite:
  - Hydraulic force transmission of the externally applied pressure (@ the isolation diaphragm) is used to deflect a MEMS diaphragm.
  - The MEMS diaphragm is embedded with piezo-resistors arranged in a full Wheatstone bridge configuration, transmitting a mV level voltage signal proportional to this differential pressure force.
  - Second Gen MEMS die technology developed by Letton Hall Group.
  - 1st Gen MEMS die was used on NASA's Space Shuttle

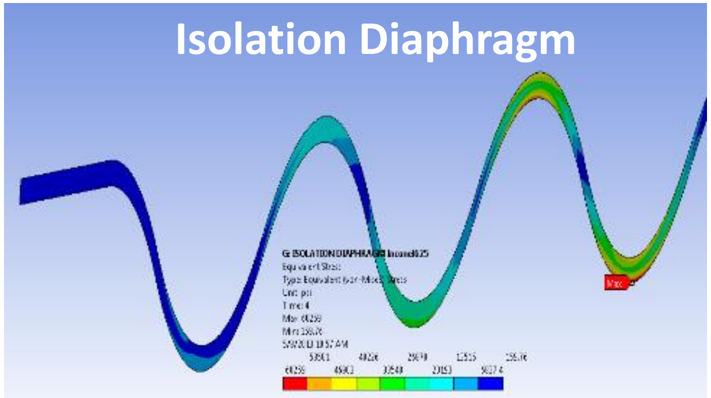
HPHT P, DP Sensors

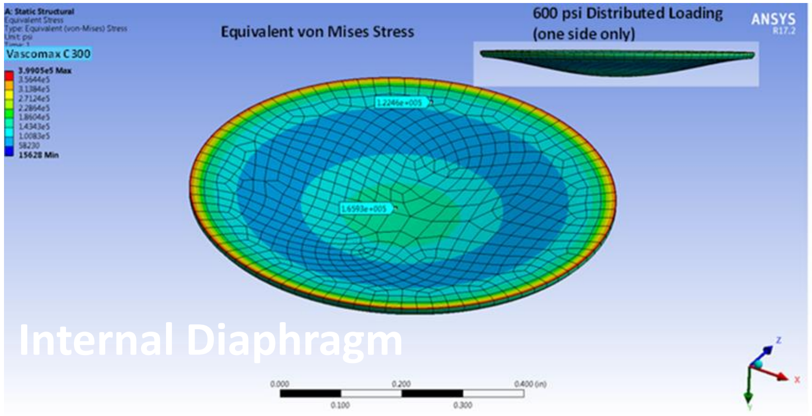
Design Requirements

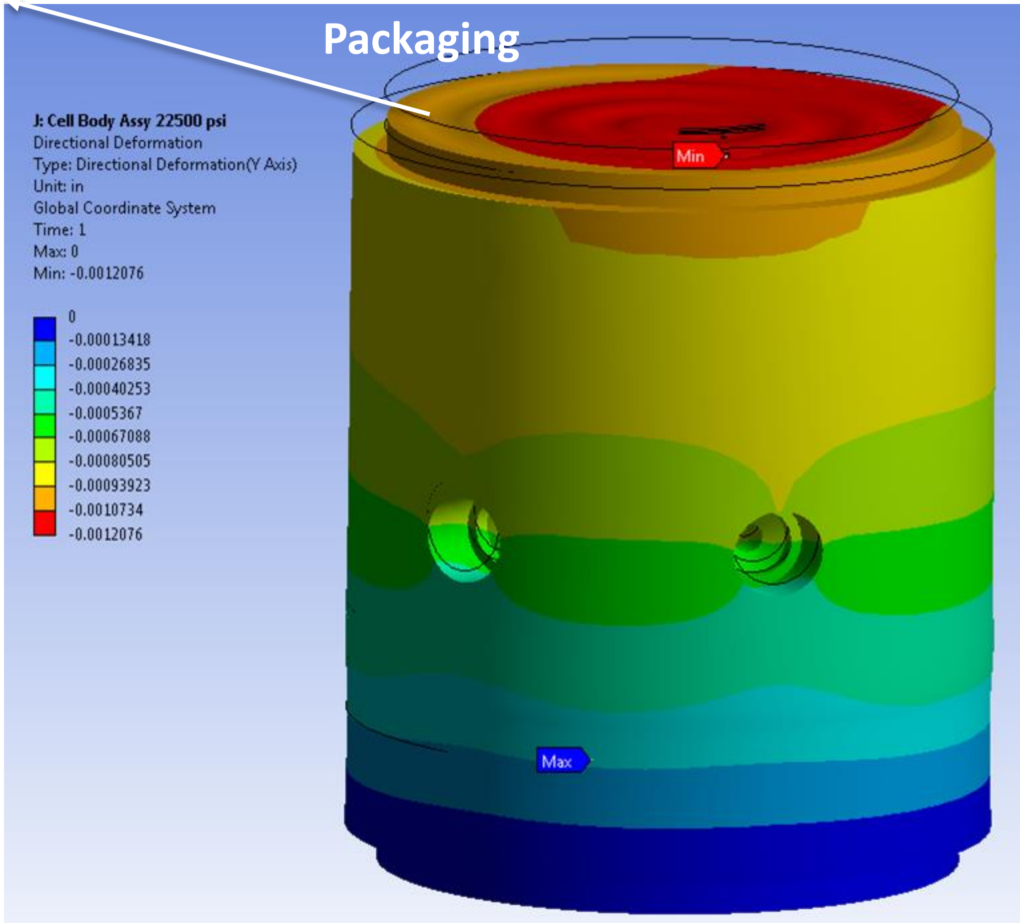
- Overall DP sensor OD ≤ 1.0 " for downhole units;
- Survive up to 15,000 psia with 1.5x pressure (22,500 psia);
- Operating temperature range of -10°C to 250 °C;
- Maintain good linearity, minimal sensitivity to temperature and CMP (Common Mode Pressure) effects;
- Maximum total uncertainty of +/- 0.1 percent FS;
- Withstand corrosive environment.

HP/HT P, DP Sensor Design/Analysis

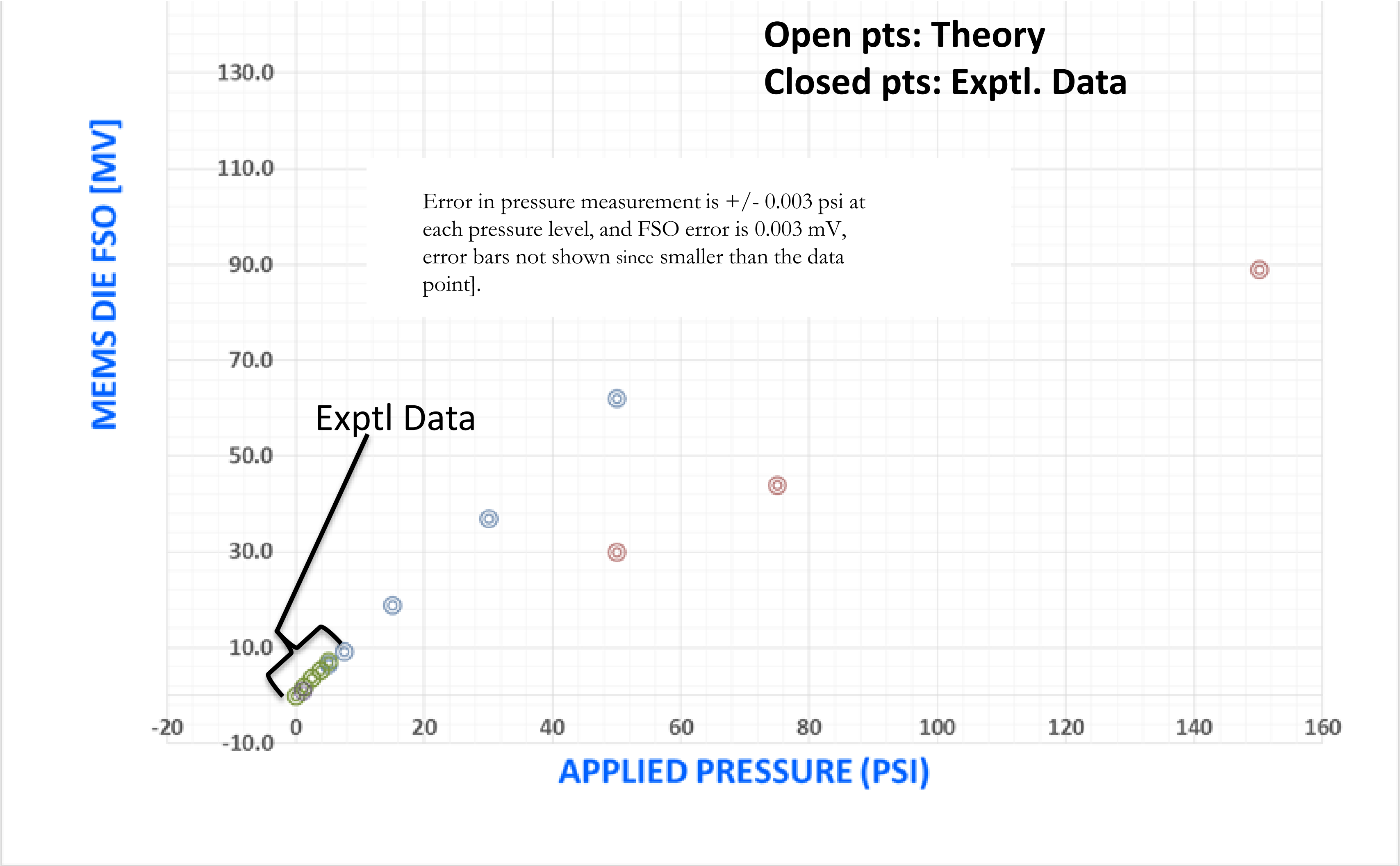






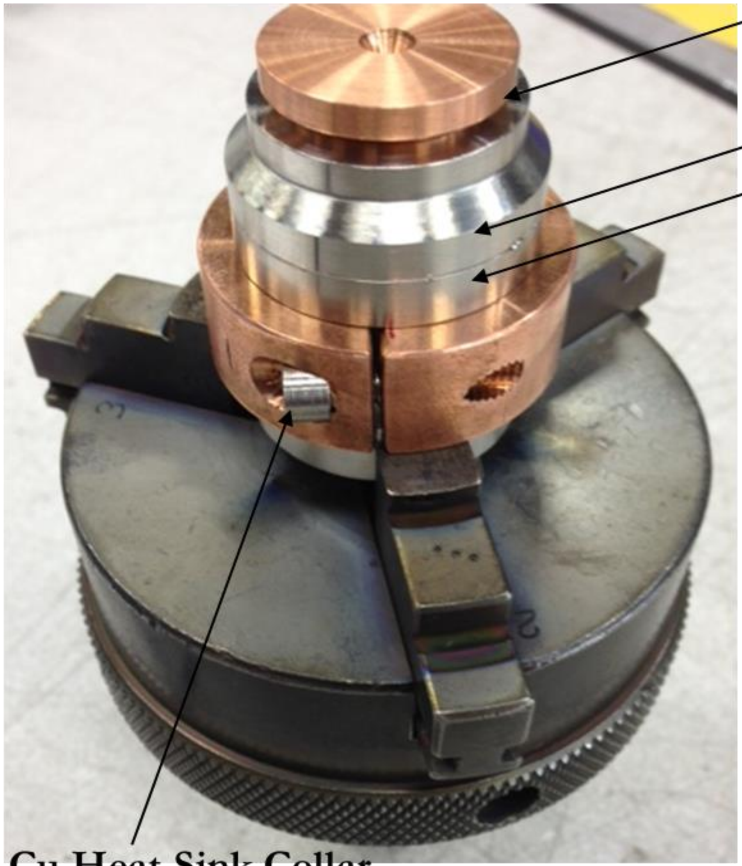


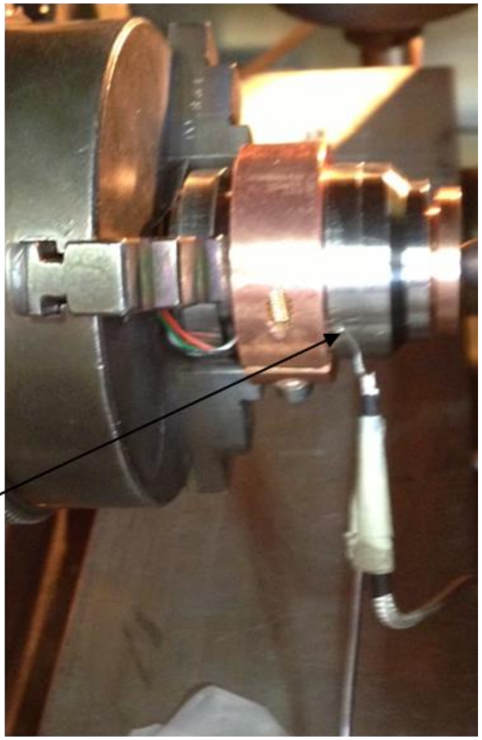
HP/HT P, DP Sensor Design/Analysis: MEMS die



HP/HT P, DP Sensor Fabrication

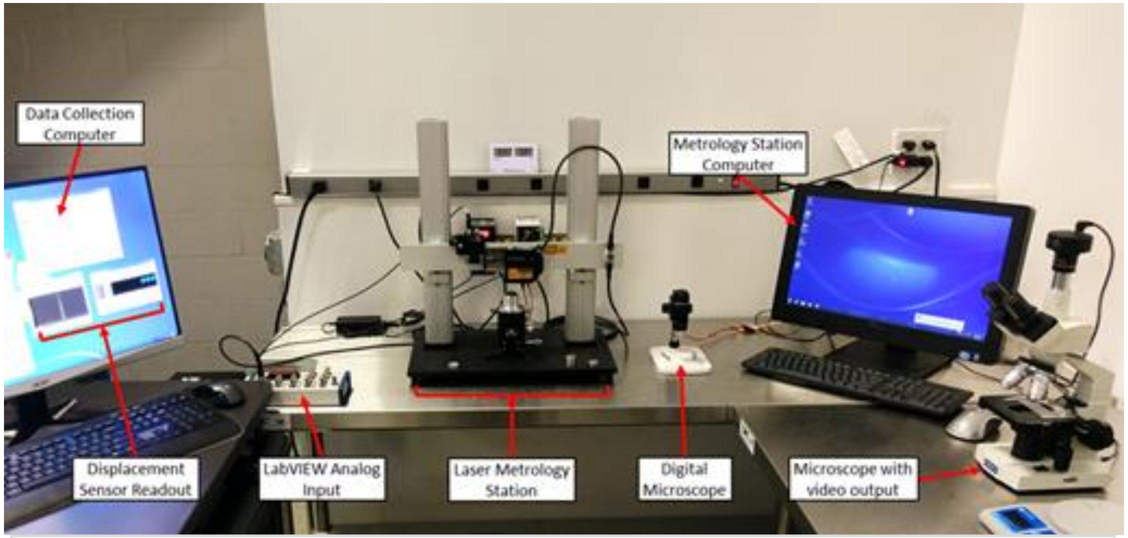
Welding of Packaging Requires Heat Sink Tooling to keep packaging internal volume < 250 °C

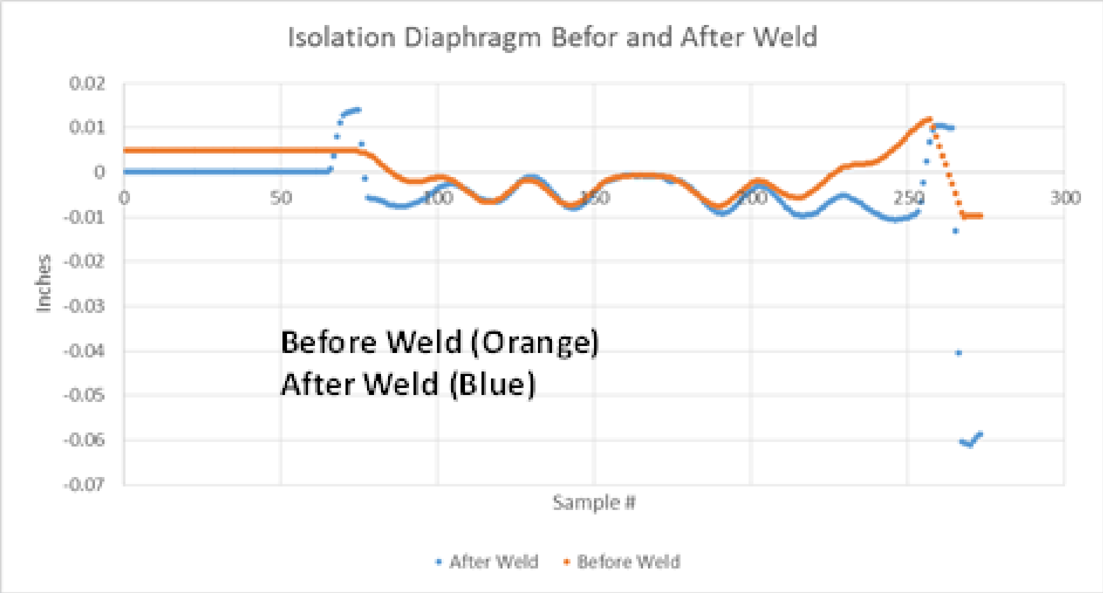




Metrology/Quality Control

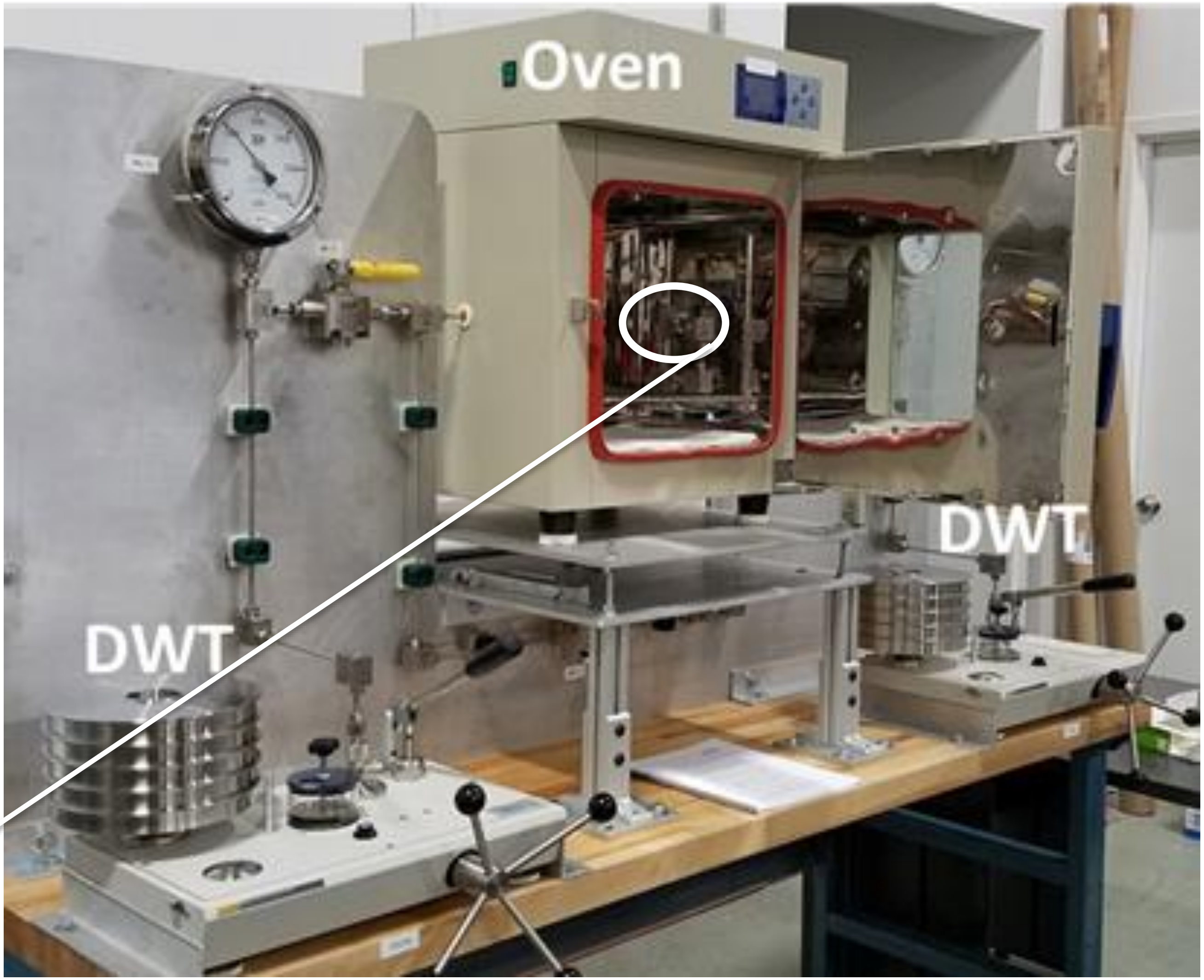
- All assembly processes were carefully implemented and tracked (Lessons Learned).
- Conducted methodical metrology
  - non-contact laser system, with 2 μm resolution.
- All welding processes were carefully monitored
  - All external welds were e-beam welded while all internal welds were laser welded.

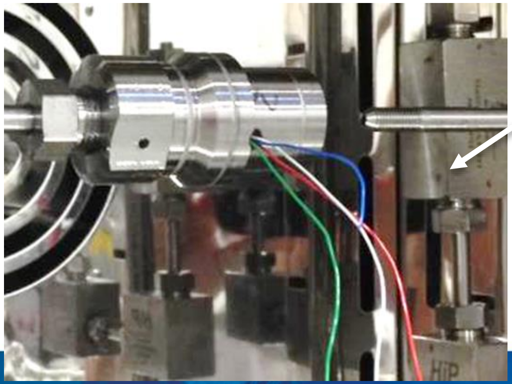




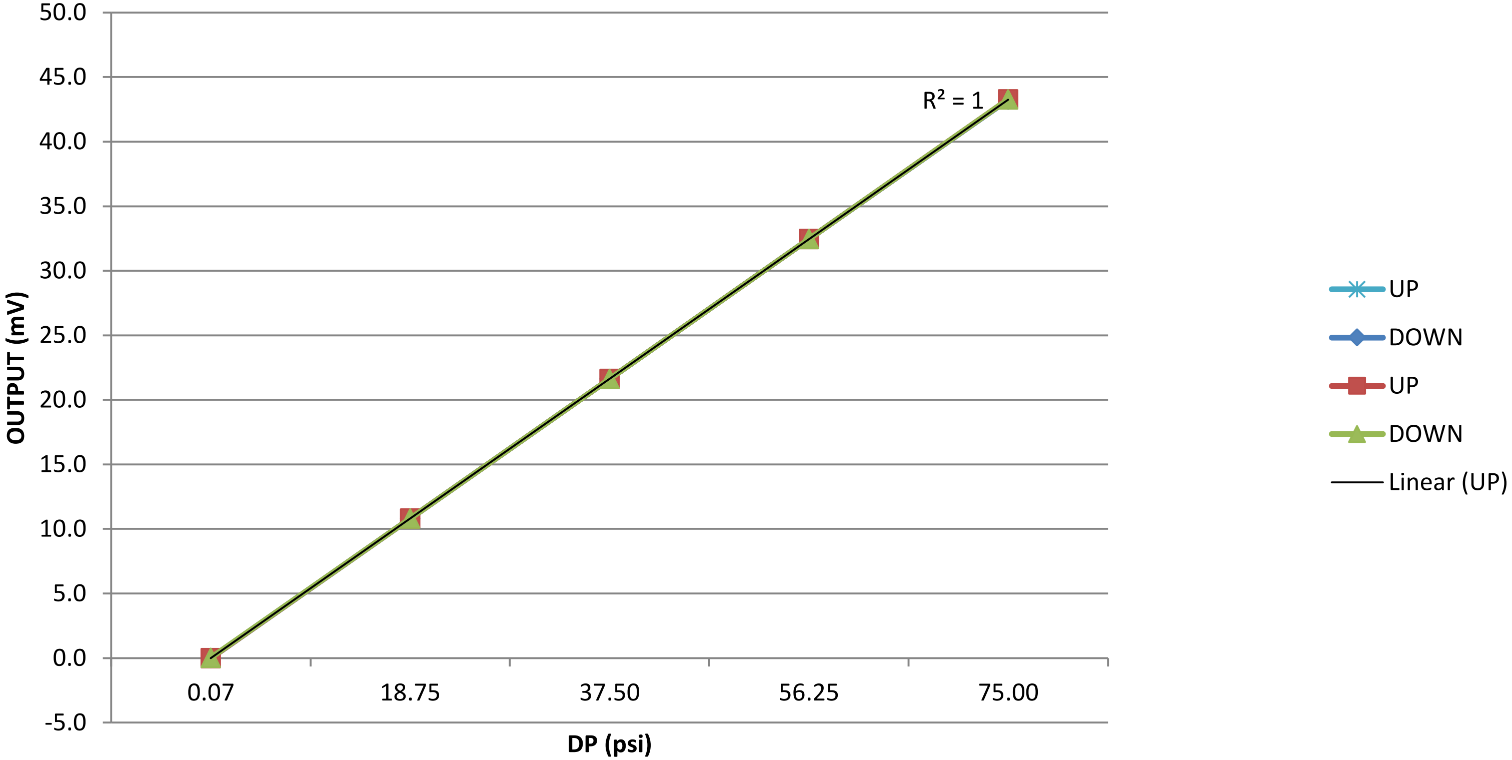
Testing: Dead Weight Testing

- Very accurate (0.01% FS)
- Max: 20 ksi
- Oven: 300 °C
- Capable of conducting simultaneous P, T calibration tests





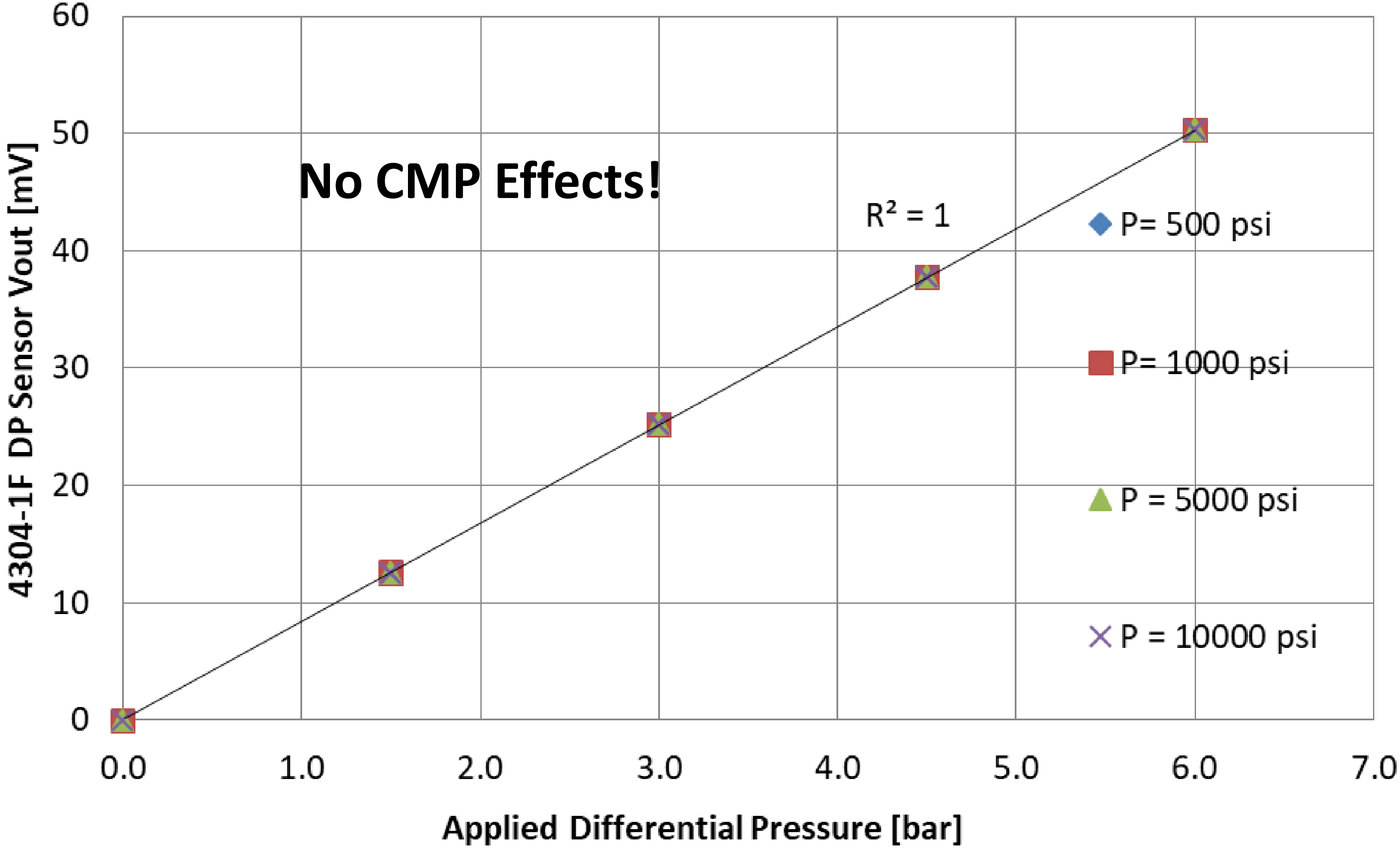
HP/HT DP Sensor Performance/Calibration



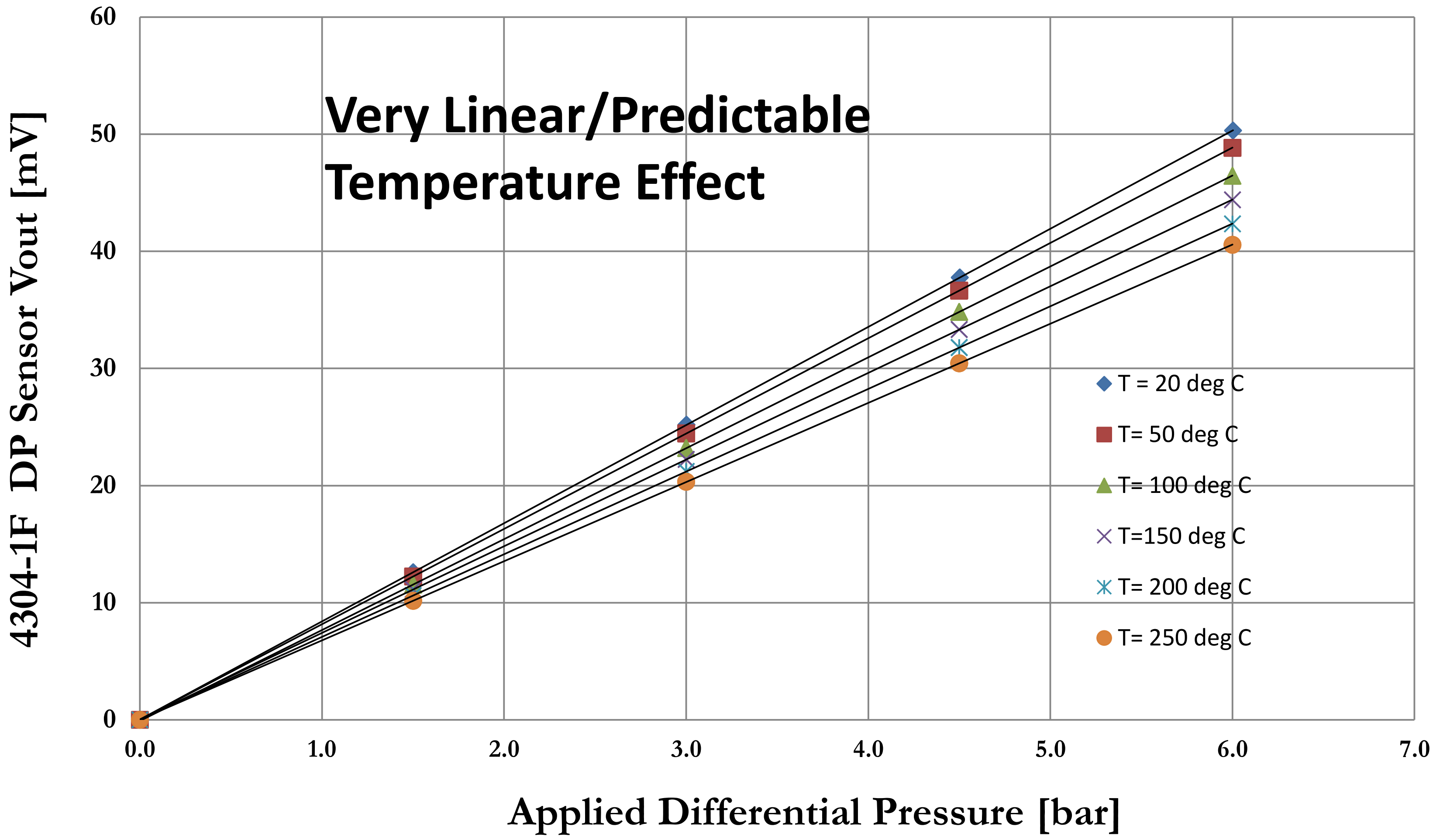
	OUTPUT (corrected for zero offset)					
DP(psi)	UP	DOWN	UP	DOWN	MAX ERROR	
0.07	0.0000	0.0016	0.0016	0.0038		
18.75	10.7955	10.7967	10.7987	10.8002	Repeatibility	0.005%
37.50	21.6243	21.6259	21.6294	21.6302	Linearity	0.000%
56.25	32.4473	32.4481	32.4517	32.4534	Hystersis	0.004%
75.00	43.2584	43.2584	43.2613	43.2613	**Total =**	**0.006%**

HP/HT DP Sensor Performance/Calibration

(Vary Common Mode Pressure-CMP; Fix Sensor Temperature @ ambient)



HP/HT P, DP Sensor Performance/Calibration
(Vary Sensor Temperature; Fix CMP @ ambient pressure)



Continuing the DP Sensor Work

- Can additional DP Sensors be fabricated with the same outstanding performance at HP/HT conditions?
- Can the cell be modified for an absolute pressure HP/HT sensor die?
- Can the performance of this DP sensor be maintained when the unit is calibrated with a large 'turn-down', i.e., can the same cell be utilized as a low-range DP?
- What would be the sensitivity to density change when the cell is utilized for 'kick detection'?
    - Build a downhole wellbore fluid density measurement system and determine the sensitivity to a change in fluid (mud) density for use in 'kick' detection/real-time monitoring.

Testing: DP Turn Down Calibration Results

Positive Side Loading: 4304-2F DP SENSOR

DP Range (psid)	Max Avg Hysteresis (% FS)	Max Avg Diff In Repeatability (% FS)	Linearity Correlation Factor	Max Avg. Total Uncertainty (% FS)	Max Sensitivity (mV/psid)
0-75	0.0019%	0.0028%	1	0.0029%	0.653
0-25	0.0056%	0.0049%	1	0.0112%	0.653
0-15	0.0082%	0.0124%	1	0.0148%	0.653
0-5	0.0235%	0.0220%	1	0.0345%	0.653

Negative Side Loading:4304-2F DP SENSOR

DP Range (psid)	Max Avg Hysteresis (% FS)	Max Avg Diff In Repeatability (% FS)	Linearity Correlation Factor	Max Avg. Total Uncertainty (% FS)	Max Sensitivity (mV/psid)
0-75	0.0033%	0.0031%	1	0.0035%	0.653
0-25	0.0032%	0.0038%	1	0.006%	0.653
0-15	0.0106%	0.0016%	1	0.0182%	0.653
0-5	0.0042%	0.0096%	1	0.0337%	0.653

Excellent turn down ratio of 4304 DP Sensor provided starting point for MDS MEMS die design (lower range DP than 4304)

HPHT Mud Density Sensors (MDS)

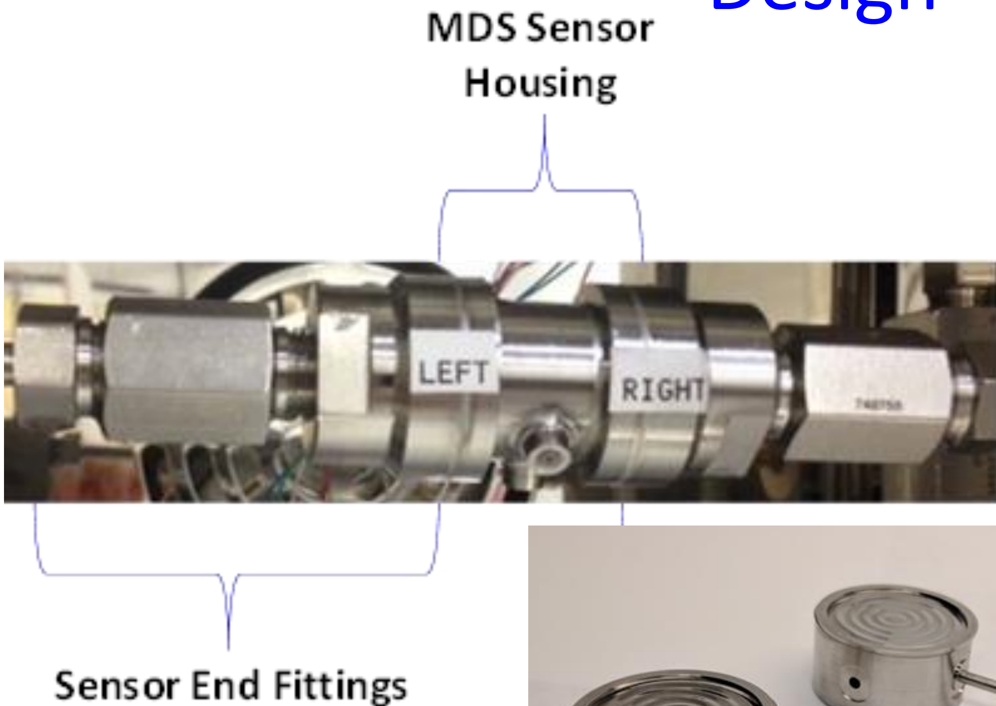
Design Requirements

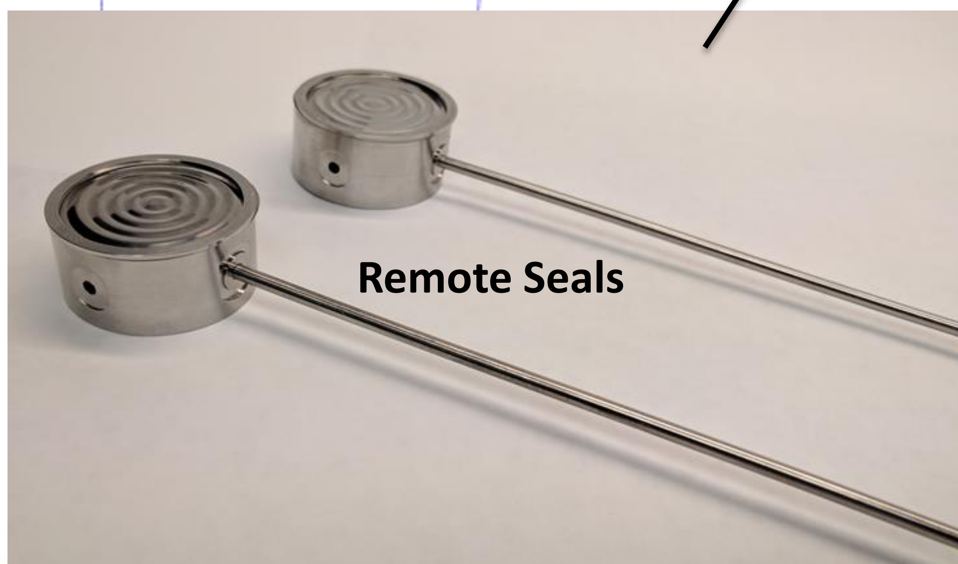
- Overall DP sensor OD ≤ 1.0 " for downhole units;
- Max CMP: Survive up to 15,000 psia with 1.5x pressure (22,500 psia);
- DP range: 0-20 psid;
- Operating temperature range of -10°C to 250 °C;
- Maintain good linearity, minimal sensitivity to temperature and CMP (Common Mode Pressure) effects;
- Maximum total uncertainty of +/- 0.1 percent FS;
- Withstand corrosive environment;

Additional for the MDS Sensor

- The DP sensor will be configured for use in a "remote-seal" configuration;
- 3 foot separation between remote seals;
- Maximum remote seal OD ≤ 1.5";
- Measure minimum change in mud density of 0.1 ppg.

HPHT Mud Density Sensors (MDS)
Design

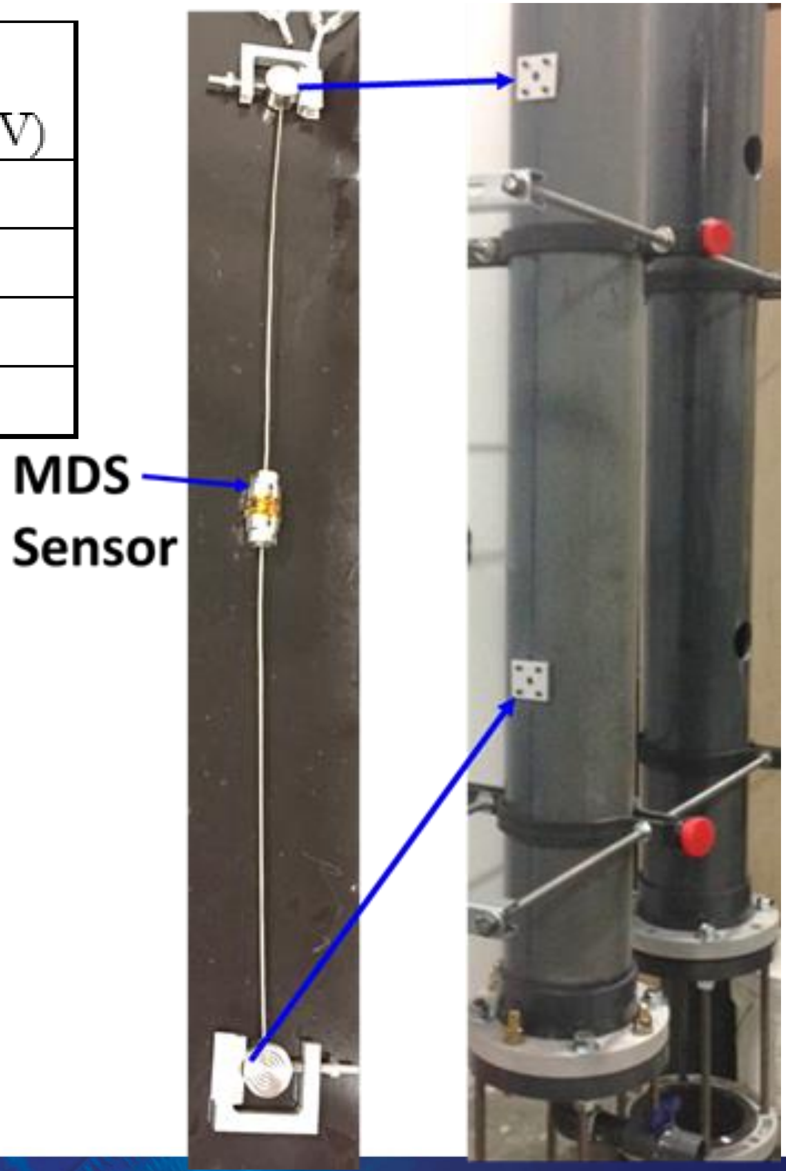




Testing: MDS Static Tests

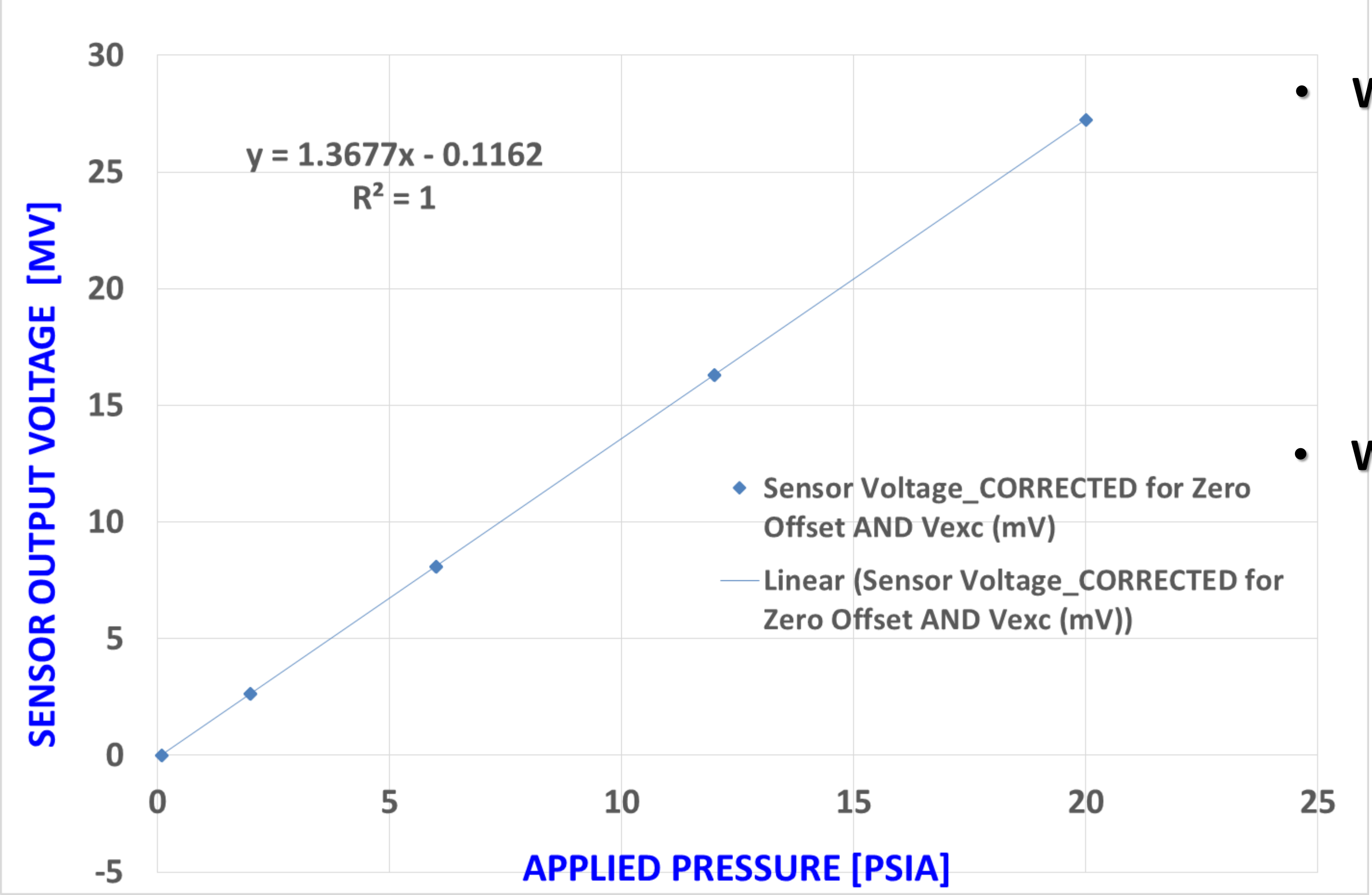
Mud Density (lbm/gal: ppg)	DP (psid) (for Δh=3 ft)	Estimated MDS Sensor Output (mV)
0	0.00	0.000
10	1.56	2.127
17	2.65	3.616
20	3.12	4.255

- Mud Static Tests conducted at Innoveering.
- Integrated MDS-1F sensor, w/its remote seals, into 7 foot PVC pipe for the following tests:
  - Air Only
  - Water Only
  - Water + Salt Mixture
  - Water Based Mud (water, soda ash, bentonite and barite mixture)



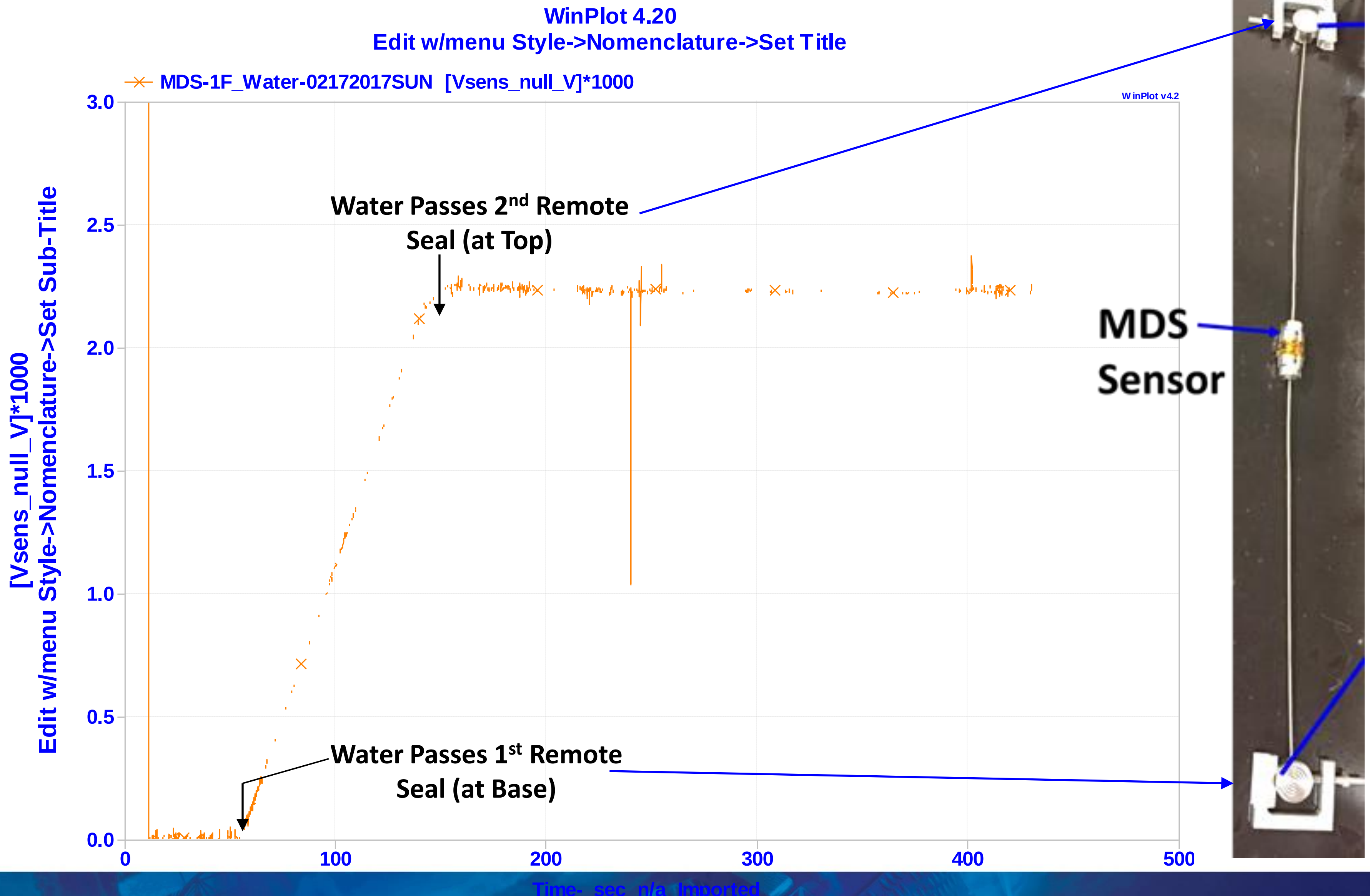
MDS Calibration Results @ Ambient Conditions

(With & Without Remote Seals)

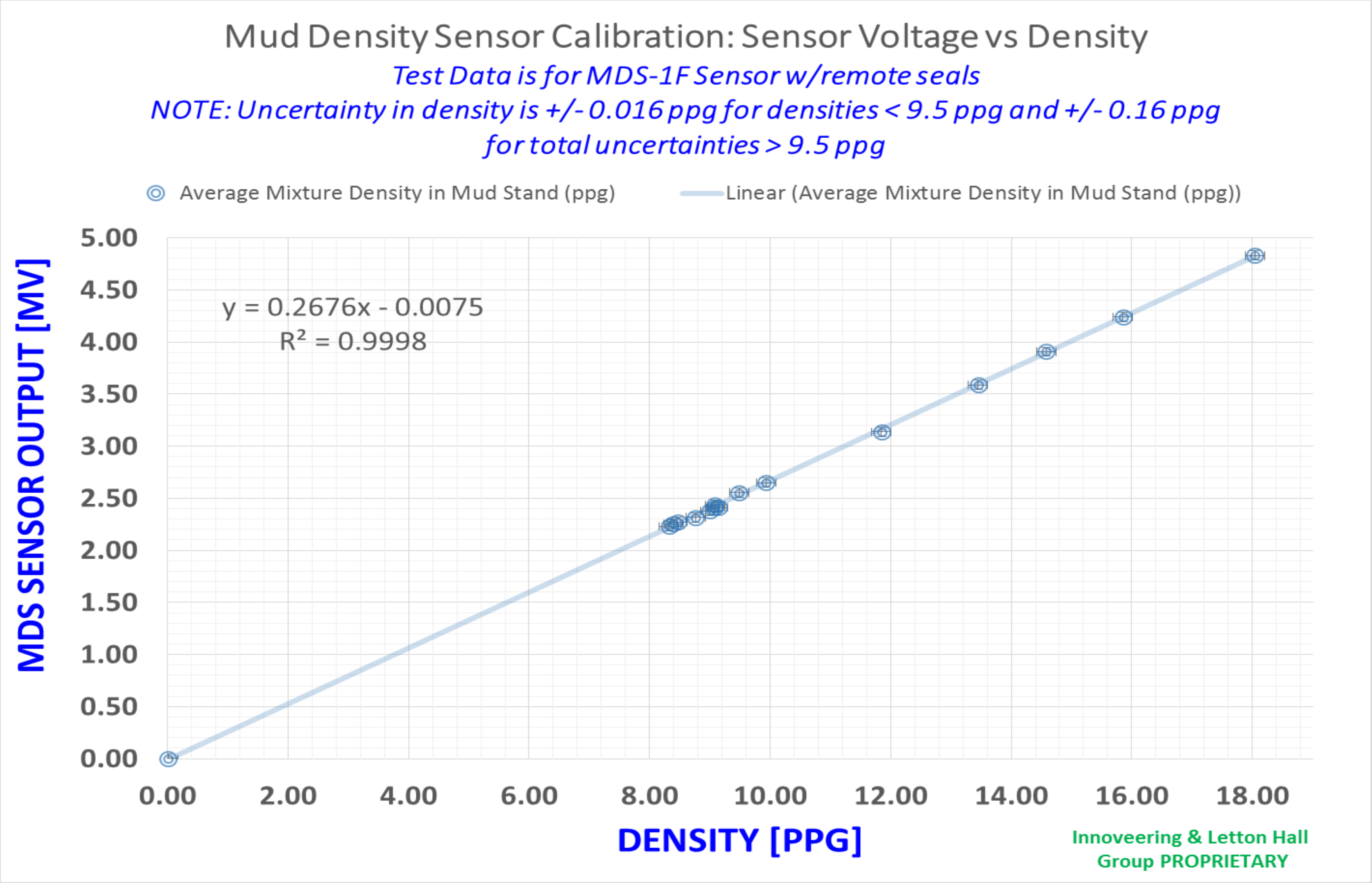


- **Without Remote Seals:**
  - ➢ excellent linearity, repeatability;
  - ➢ total uncertainty of 0.0071% FS.
- **With Remote Seals:**
  - ➢ total uncertainty ~ 0.0098%
  - ➢ sensitivity = 0.274 mV/psid/Vexc

MDS-1F Sensor (w/RS) in Water



Static MDS Calibration Results w/Drilling Mud & Brines



Conclusions

This work represents the continued technology development of our P, DP, MDS sensor suite for subsea and downhole applications with the following performance results:

- **Absolute P Sensor:**
  - Tested to 19,700 psia.

- **Differential DP Sensor**:
  - Tested to 15,000 psi.
  - excellent linearity, repeatability, minimal hysteresis over DP of 0-75 psid.
  - very good turn-down capabilities from 0-75 psid down to 0-5 psid.

Conclusions (Cont'd)

- **Mud Density (MDS) Sensor**
  - Tested to 5000 psia.
  - Preliminary data shows excellent linearity and repeatability, minimal hysteresis.
  - total uncertainty:
    - ❑ 0.0071% FS (w/o remote seals).
    - ❑ 0.0098% (w/remote seals).
  - Static calibration up to 18 ppg shows excellent linearity, sensitivity required to potentially measure 0.1 ppg in mud density.
- We believe that our suite of Highly Accurate/High Pressure/High Temperature (HAHPHT) P, DP and MDS sensors would prove helpful to several applications: upstream MPFMs, subsea wellhead instrumentation and downhole kick detection.

Conclusions (Cont'd)

- Our team's technology development effort to date has verified the performance of a downhole HP/HT DP sensor capsule at a common-mode pressure of 15,000 psia. The same sensor cell was used to fabricate a downhole HP/HT P sensor with a calibrated full scale range of 20,000 psia.

- Our downhole mud density sensor cell utilizes remote diaphragms to obtain sufficient differential pressure resolution in order to identify an inflow (kick) into the wellbore with changes in mud density as low as 0.10 lb/gal…this is only possible with high accuracy sensor performance, i.e. </= 0.01-0.02% FS accuracy.

- By including this system into a wired drill string, an early-warning of a potential blowout could be obtained in addition to allowing unprecedented control during kick displacement, especially when combined with a kick detection decision making algorithm.

Acknowledgements

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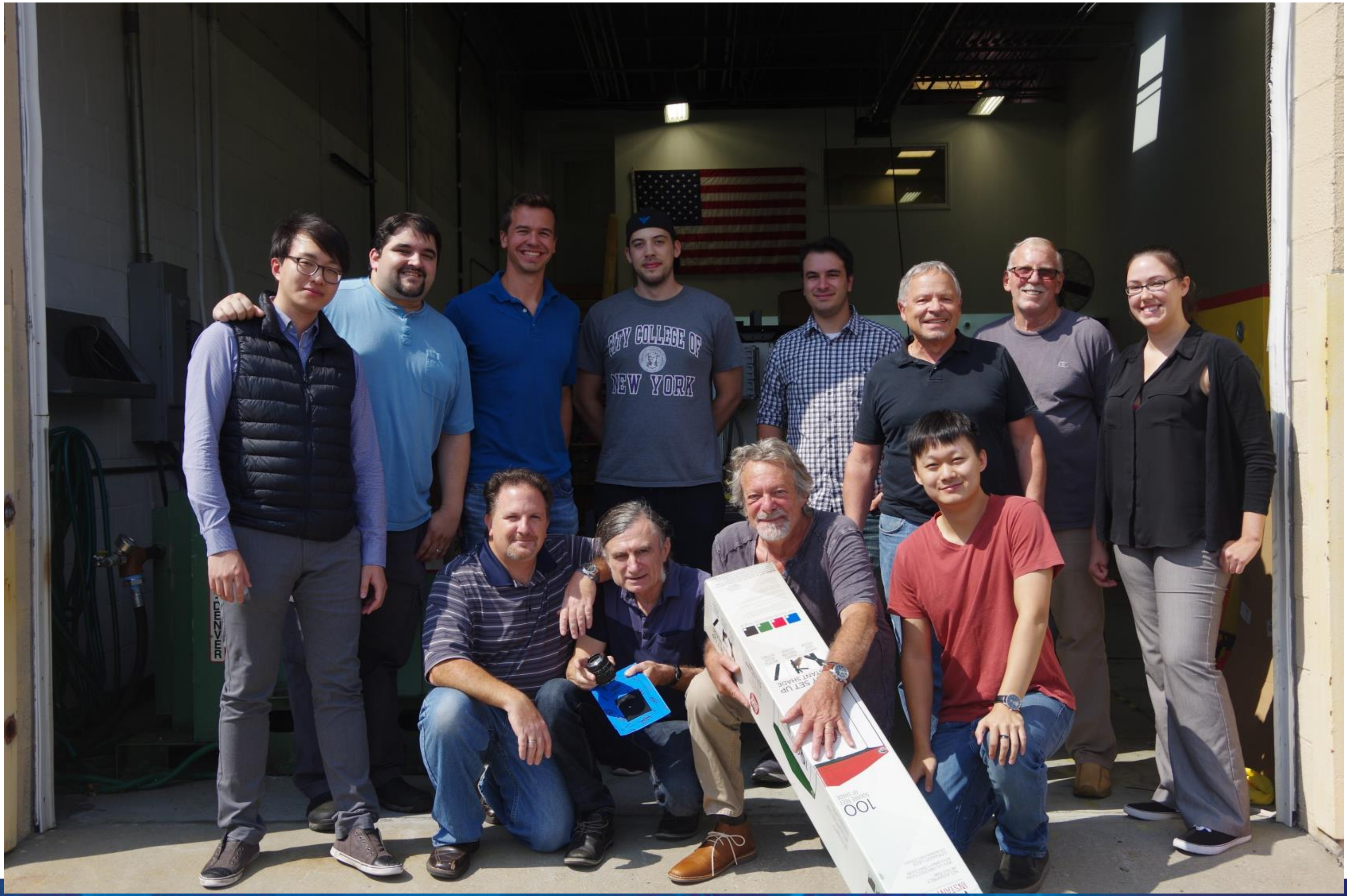
Our team wishes the good people of Texas Godspeed in their recovery from Hurricane Harvey.



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