LAVA Pressure Transducer Trade Study

Samuel B. Oltman
John F. Kennedy Space Center
Major: Space Systems/Mechanical Engineering
LAVA Integration and Testing Fall Session
Date: 21-11-2016

LAVA Pressure Transducer Trade Study

Samuel B. Oltman[1]
NASA John F. Kennedy Space Center, Merritt Island, FL, 32899

The Regolith and Environment Science & Oxygen and Lunar Volatile Extraction (RESOLVE) payload will transport the (LAVA) subsystem to hydrogen-rich locations on the moon supporting NASA's in-situ resource utilization (ISRU) program. There, the LAVA subsystem will analyze volatiles that evolve from heated regolith samples in order to quantify how much water is present. To do this, the system needs resilient pressure transducers (PTs) to calculate the moles in the gas samples. The PT trade study includes a comparison of newly-procured models to a baseline unit with prior flight history in order to determine the PT model with the best survivability in flight-forward conditions.

Nomenclature

GC-MS	=	gas chromatograph – mass spectrometer
ISRU	=	in-situ resource utilization
LAVA	=	Lunar Advanced Volatile Analysis
NIRVSS	=	Near Infrared Volatile Spectrometer Subsystem
NSS	=	Neutron Spectrometer System
OVEN	=	Oxygen Volatile Extraction Node
PTs	=	pressure transducers
RESOLVE	=	Regolith and Environment Science & Oxygen and Lunar Volatile Extraction
RP	=	Resource Prospector
RTDs	=	resistive temperature detectors
SS	=	stainless steel

[1]LAVA Integration and Testing Intern, NE-M1, Florida Institute of Technology/Southern Illinois University

I. Introduction

NASA's Resource Prospector (RP) mission will play a major role in the larger in-situ resource utilization (ISRU) initiative that strives to lay the groundwork for sustaining future colonies on the moon, Mars, and beyond. The Regolith and Environment Sciences & Oxygen and Lunar Volatile Extraction (RESOLVE) payload will land with a rover (the RP-15 demo rover can be seen below in Fig. 1) on the moon to drill and extract regolith samples that will then be quantified, primarily searching for water and other volatiles that can be used as resources in missions to come. The RESOLVE payload is broken up into five major subsystems. The Neutron Spectrometer System (NSS) will lead the rover and search for a high abundance of hydrogen, which suggests the presence of water. The Drill subsystem will then auger into the moon's regolith and collect a sample while being monitored by the Near Infrared Volatile Spectrometer Subsystem (NIRVSS). This sample will then be transferred to the Oxygen Volatile Extraction Node (OVEN) where it is heated to 150°C. At this point, water and other volatiles will exist in the vapor phase. Lastly, the gas sample will be transferred to the Lunar Advanced Volatile Analysis (LAVA) subsystem, which will analyze the sample using a gas chromatograph - mass spectrometer (GC-MS) system. This report will focus on an aspect of the LAVA subsystem.

Figure 1. RP-15 demo rover

The LAVA subsystem utilizes several pressure sensors in order to calculate the number of moles that are in a gas transfer from the OVEN and to assist in the dilution of gases before they are delivered to the GC-MS instruments. Pressure transducers (PTs) output voltage signals that are converted to pressure measurements for data analysis. Prior experimentation conducted using Kulite sensors proved that, regardless of their flight history, multiple units failed to survive the operational pressure range and temperature environment of 0-100psia and 152°C. Replacement units from this company were incorporated into our new trade study testing to serve as a baseline unit for comparative analysis against new models. The following trade study, comprised of running the sensors through multiple temperature and pressure cycles, was completed to better understand when/if the units fail and their performance in flight-forward conditions.

II. Experimental

The trade study was performed on eight PTs from four different companies with five models of sensors: Kulite (quantity 1), GP50 B (quantity 1), GP50 A (quantity 2) with amplification modules, Tecsis (quantity 2), and Measurement Specialties (quantity 2). These eight sensors were divided and installed into two separate but identical manifolds of stainless steel and aluminum. This was done to assist us in understanding if the PTs and their contact with material might impact the data. The manifolds were wrapped with heat tape to create a uniform thermal environment. The model list and an illustration of a loaded manifold are shown below in Table 1 and Fig. 2.

Name	Port Designation	Manifold Material	Max Torque Ratings (in-lbs)	Excitation Voltage (V)	Pressure Range (psia)
Measurement Specialties #1	PT-001	SS	88	10	0-100
Tecsis #1	PT-002	SS	300	5	0-150
GP50 A #1 (amplified)	PT-005	SS	228	24	0-100
GP50 B	PT-007	SS	34	10	0-500
Measurement Specialties #2	PT-009	Al	88	10	0-100
Tecsis #2	PT-010	Al	300	5	0-150
GP50 A #2 (amplified)	PT-013	Al	228	24	0-100
Kulite	PT-014	Al (SS insert)	12	10	0-100

Table 1. Pressure Transducer Model List

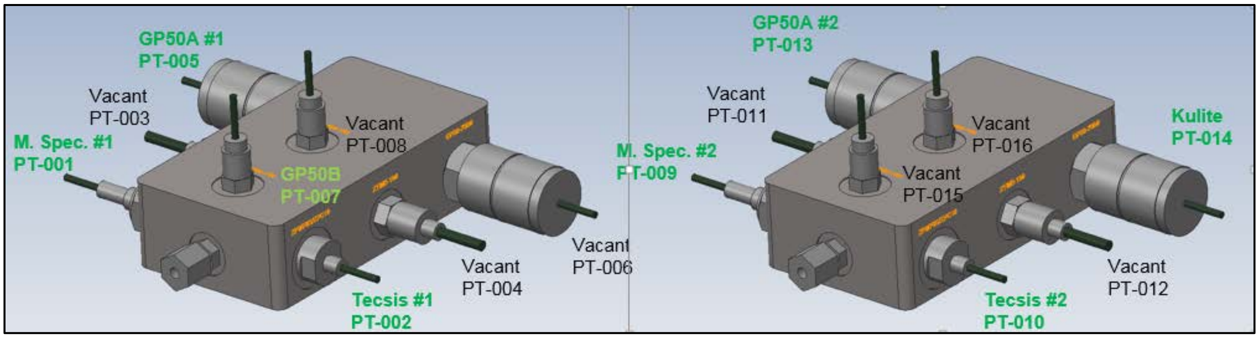

Figure 2. SS (left) and Al (right) manifold map (actual installation may look different than shown).

The PTs are assigned torque ratings from their manufacturers that are not to be exceeded upon risk of damaging the sensors. In the case of this trade study, the PTs were minimally torqued, often only to "hand tight", due to the quality of their seal and to reduce mounting stresses. The manifolds were pressurized with helium and a helium leak detector was used to guarantee the quality of the seal to an acceptable leak rate. These loaded manifolds were then placed inside of a bell jar and connected to their 24V, 10V, and 5V power supplies, as well as the DAQ junction that fed data to our LabVIEW analysis program. Resistive temperature detectors (RTDs) were placed on every PT (with the exception of the Measurement Specialties models, due to their small size) and the manifolds themselves in order to accurately monitor their temperature while under a vacuum. An image of the entire test setup can be seen in Fig. 3.

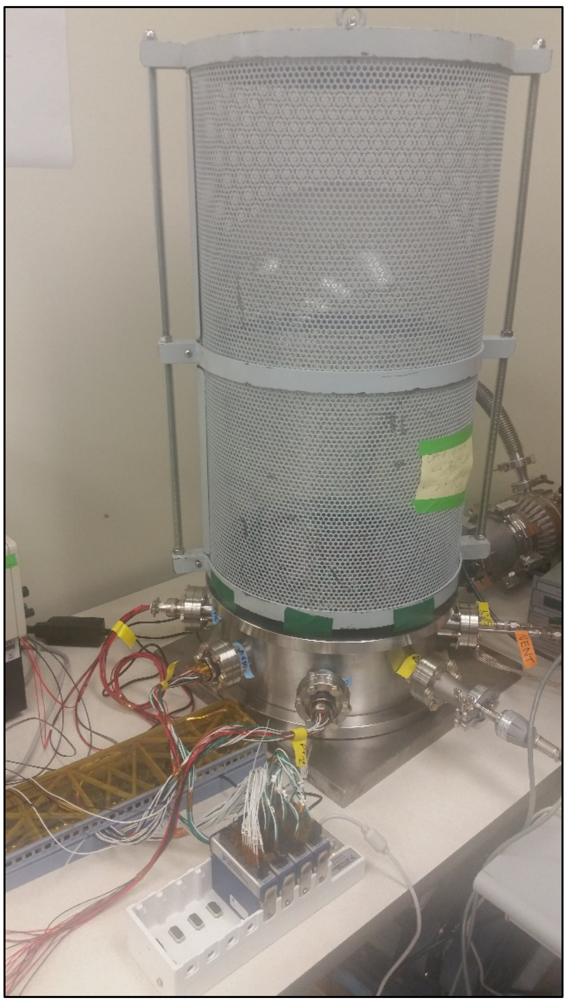

Figure 3. Bell jar, DAQ junction, and the system connections to a computer and power supplies.

The daily test procedure included a pressure ramp to evaluate the PT responses at vacuum (0.1 psia), 2psia, 5psia, 10psia, 15psia, 30psia, 50psia, 65psia, and 80psia before ramping back down to vacuum. This was then followed by a quick ramp, or burst, to 80psia before venting back down to vacuum after. Each pressure level was left to stabilize for longer than one minute so that the PT responses could settle. This process was repeated at room temperature with dry air, operating temperature (152°C) with dry air, and operating temperature with helium. Switching between gases would allow us to determine whether or not they affected the PT data differently. The pressure ramping process, as shown in Fig. 4, was handled manually at the inlet and outlet valves while automation is being looked into for future testing.

Data from the experiment was converted to an Excel file, which was then used to create visual representations of the results and form calibration curves. This general data was sent through a macro that searched for thirty pressure inputs that varied by less than 0.1psia at each pressure level – signifying a plateau in pressure response and stability for optimal calibration. These thirty values were then averaged to form the calibration points. It was through these calibrations that data was compared on a test-by-test basis to look for trends or failures in the PTs. Here we used linear curve fits, but quadratic curve fits may be used for flight to provide greater accuracy to the overall system measurements.

III. Results and Discussion

While the eight days of testing analyzed below are only a fraction of the larger, long-duration survivability testing to follow, it is already indicative of which PTs may continue to perform well. Although data has been acquired for all pressure ramps at room temperature/dry air and operating temperature/helium, it will take some time to compile all of the information in various useful forms for comparison. Operating temperature/dry air was chosen to be our independent variable due to the fact that it is the most likely and frequent scenario that the PTs will face during the mission.

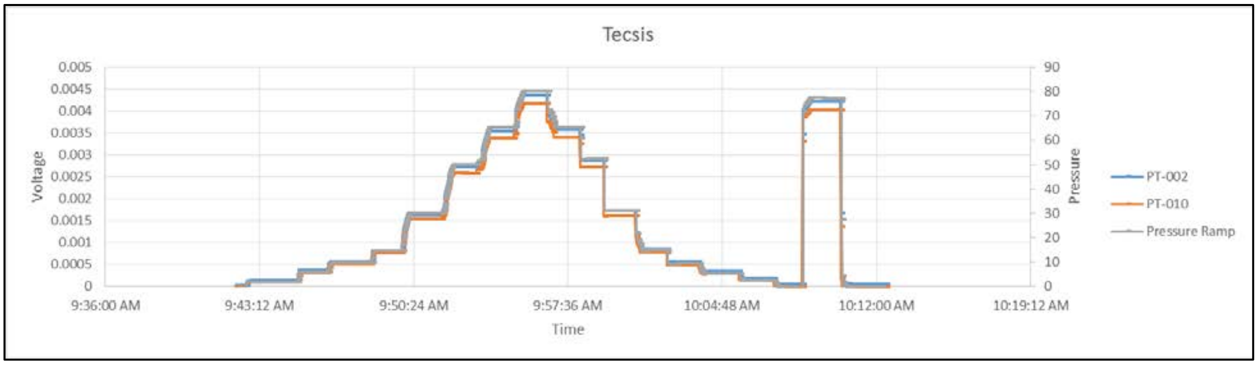

Figure 4. Pressure ramping with voltage response, Test 5 152°C Dry Air

Figures 5 through 12 below display the calibration curves for each sensor across all eight test days at 152°C with dry air in order to visually evaluate the magnitude of drift within a given sensor and between families of sensors. The calibration curve trendlines for Factory and Tests 1 to Test 8 are shown in the upper left corner of each plot. "Factory" denotes the calibration curve provided by the vendor. If the temp at which this calibration was performed is known, it is included in the legend. If not, a "?C" indicates an unknown temperature. Note that all pressure data is recorded in units of psia. All voltage data is recorded in units of V.

A. Measurement Specialties

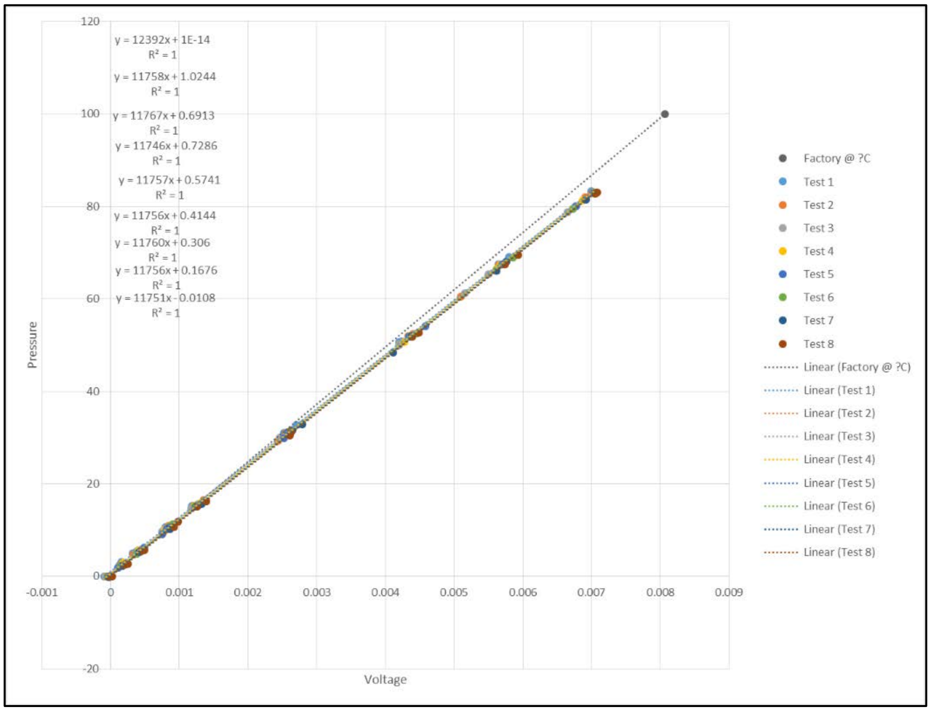

Figure 5. PT-001 calibration responses

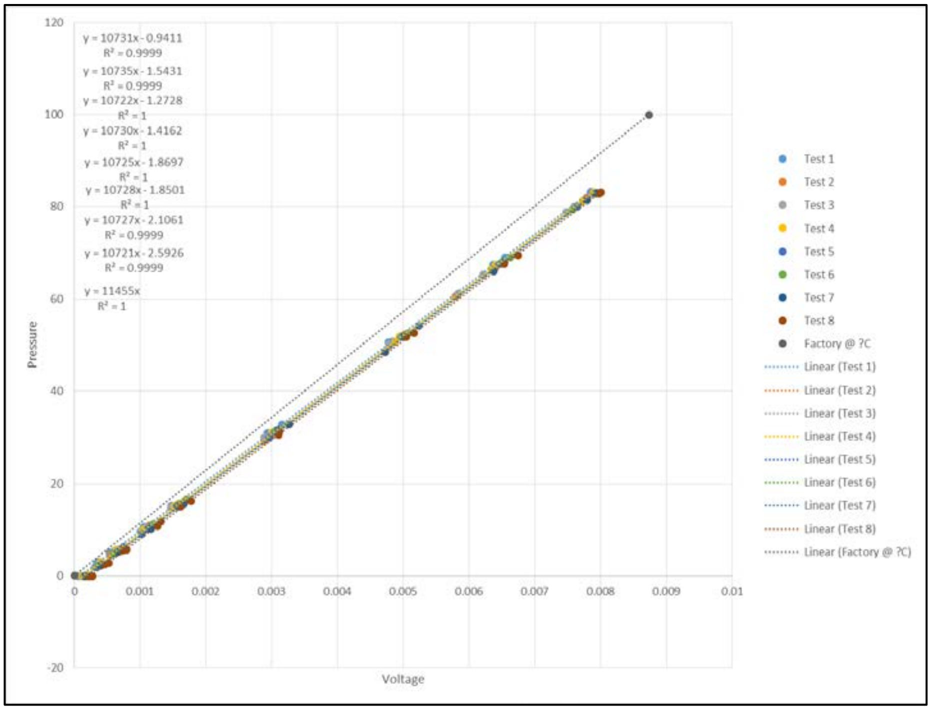

Figure 6. PT-009 calibration responses

B. Tecsis

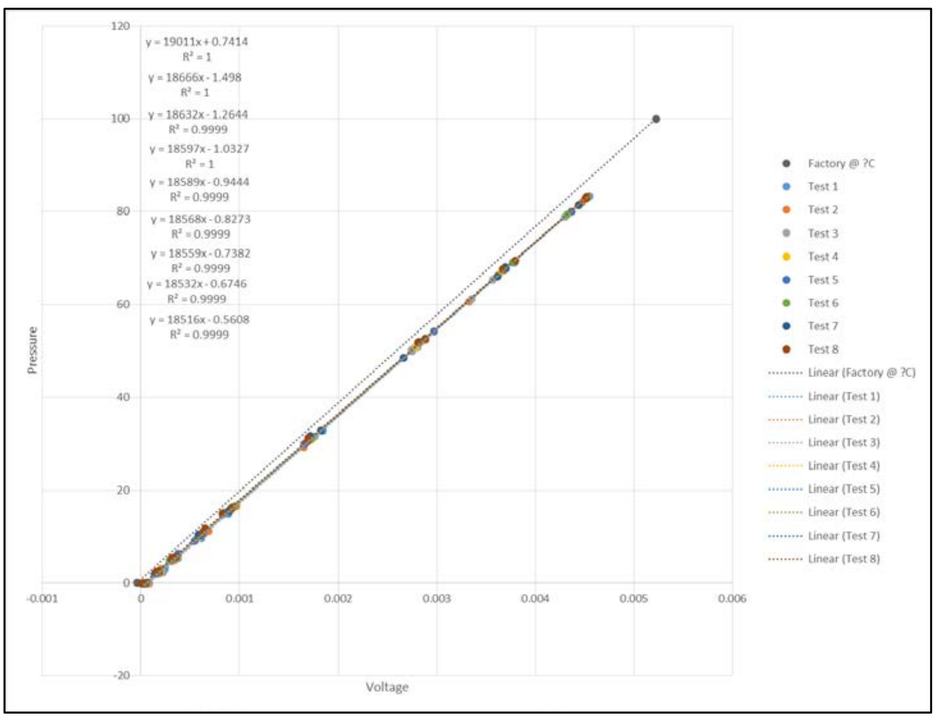

Figure 7. PT-002 calibration responses

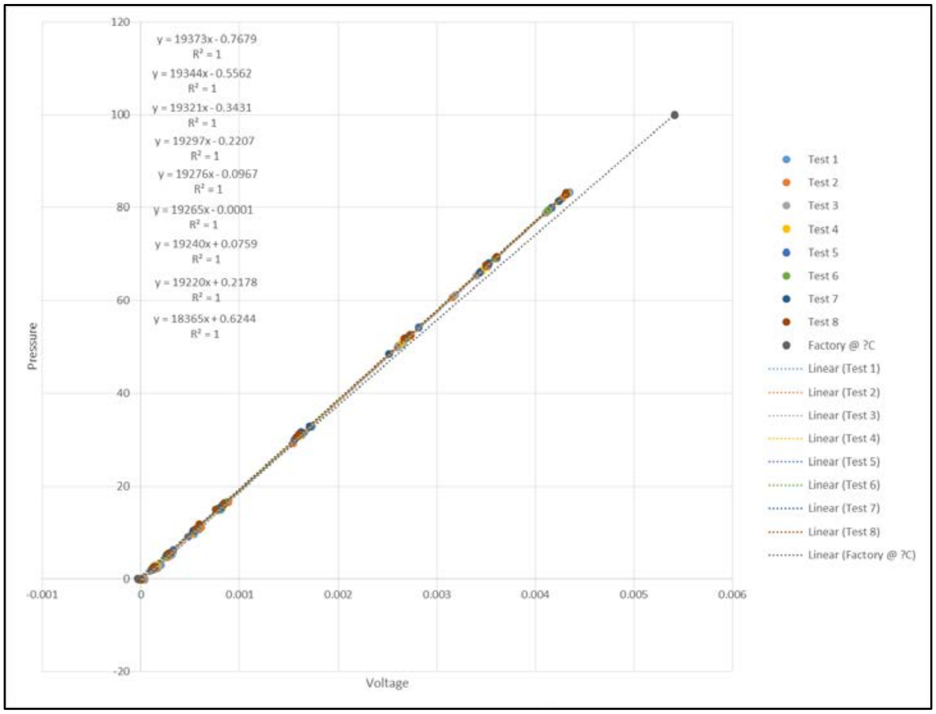

Figure 8. PT-010 calibration responses

C. GP50 A

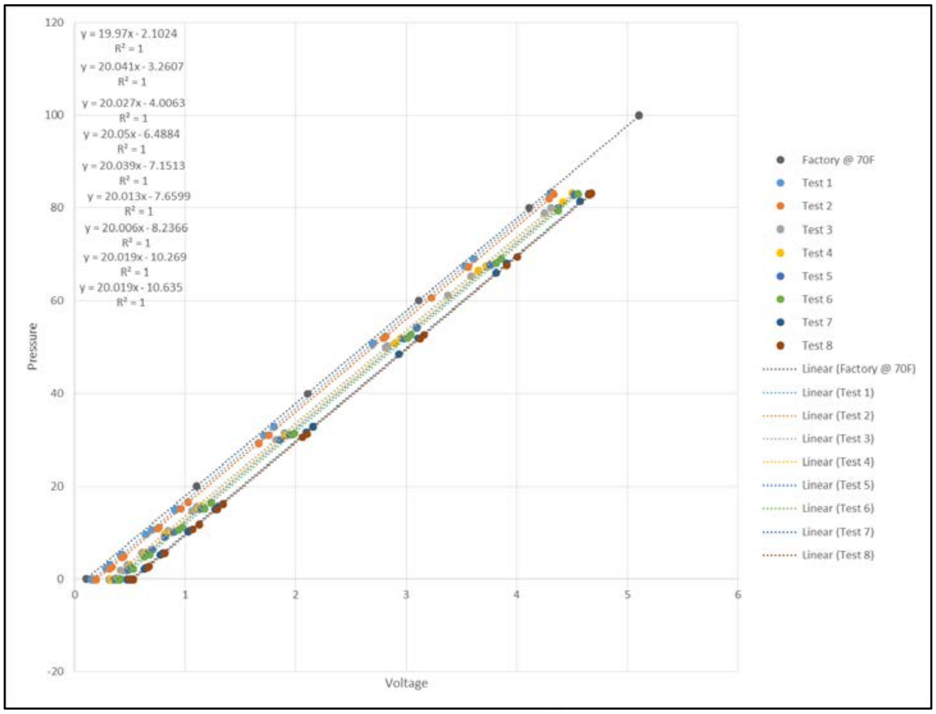

Figure 9. PT-005 calibration responses

Data gathered below 15psia were excluded from the PT-013 calibration plots for reasons discussed below.

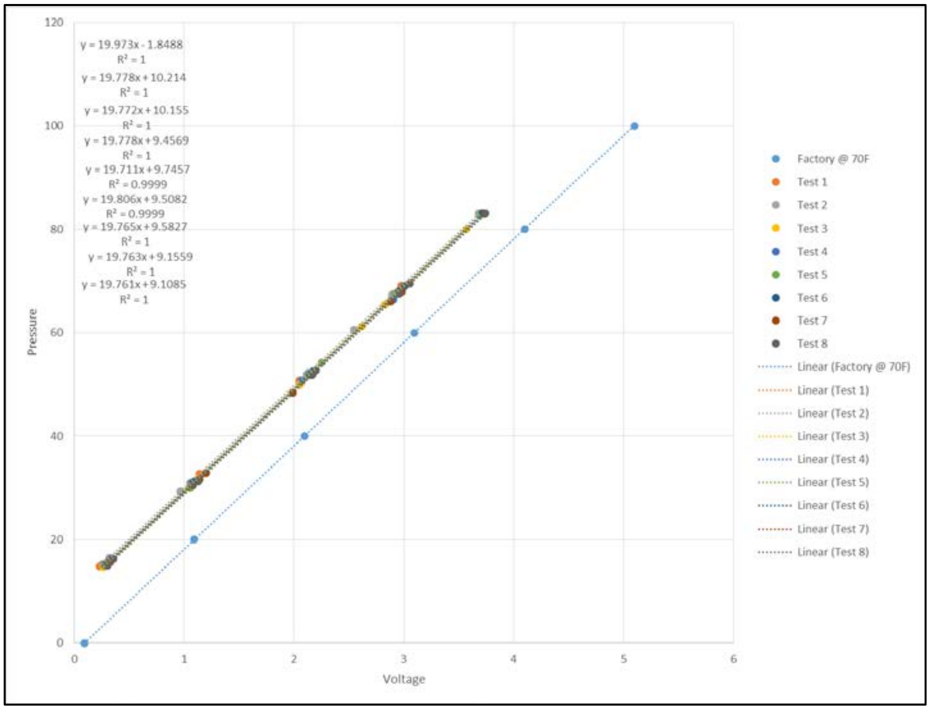

Figure 10. PT-013 calibration responses

D. GP50 B

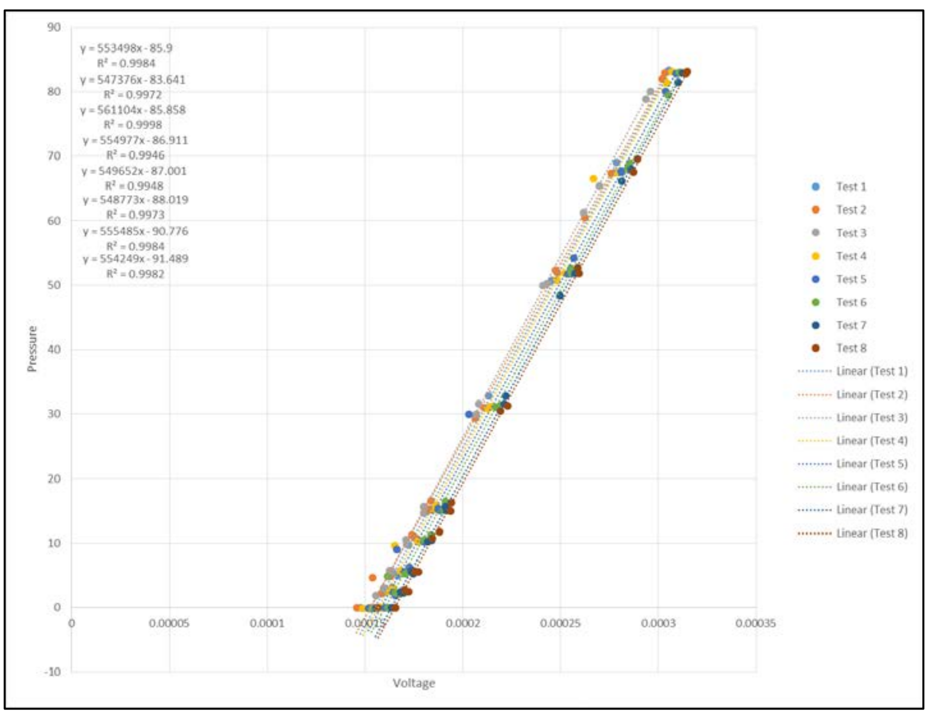

Figure 11. PT-007 calibration responses

E. Kulite

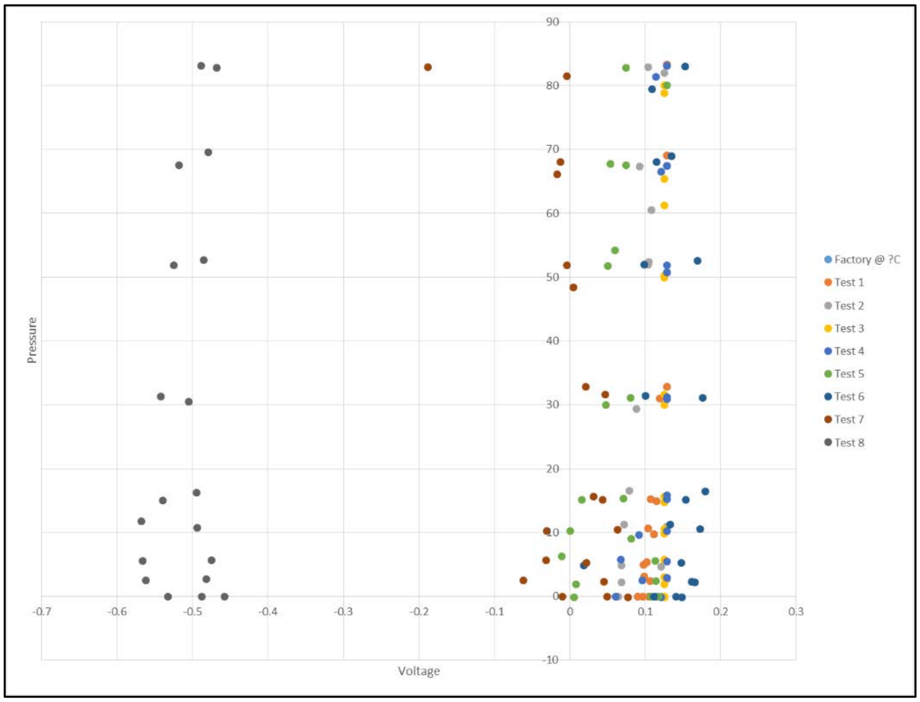

Figure 12. PT-014 calibration responses

Note that trendlines for PT-014 are not shown below due to their off-nominal behavior discussed later in the report.

F. Comparing Trendlines

Tables 2 through 8 organize the calibration curve slopes, offsets, and R^2 values for each sensor across all days of testing. The range of each is provided to easily compare performance within families. Note that the ranges below do not include the Factory and are only supplied for reference since this calibration was not performed at 152°C.

Measurement Specialties #1			
Test #	Slope (psia/V)	Intercept (psia)	R^2
1	11758	1.0244	1
2	11767	0.6913	1
3	11746	0.7286	1
4	11757	0.5741	1
5	11756	0.4144	1
6	11760	0.306	1
7	11756	0.1676	1
8	11751	-0.0108	1
Factory	12392	1E-14	1
Range	21	1.0352	0

Table 2. PT-001 trendline values

Measurement Specialties #2			
Test #	Slope (psia/V)	Intercept (psia)	R^2
1	10731	-0.9411	0.9999
2	10735	-1.5431	0.9999
3	10722	-1.2728	1
4	10730	-1.4162	1
5	10725	-1.8697	1
6	10728	-1.8501	1
7	10727	-2.1061	0.9999
8	10721	-2.5926	0.9999
Factory	11455	0	1
Range	14	1.6515	0.0001

Table 3. PT-009 trendline values

Tecsis #1			
Test #	Slope (psia/V)	Intercept (psia)	R^2
1	18666	-1.498	1
2	18632	-1.2644	0.9999
3	18597	-1.0327	1
4	18589	-0.9444	0.9999
5	18568	-0.8273	0.9999
6	18559	-0.7382	0.9999
7	18532	-0.6746	0.9999
8	18516	-0.5608	0.9999
Factory	19011	0.7414	1
Range	150	0.9372	0.0001

Table 4. PT-002 trendline values

Tecsis #2			
Test #	Slope (psia/V)	Intercept (psia)	R^2
1	19373	-0.7679	1
2	19344	-0.5562	1
3	19321	-0.3431	1
4	19297	-0.2207	1
5	19276	-0.0967	1
6	19265	-0.0001	1
7	19240	0.0759	1
8	19220	0.2178	1
Factory	18365	0.6244	1
Range	153	0.9857	0

Table 5. PT-010 trendline values

GP50 A #1 (amplified)			
Test #	Slope (psia/V)	Intercept (psia)	R^2
1	20.041	-3.2607	1
2	20.027	-4.0063	1
3	20.05	-6.4884	1
4	20.039	-7.1513	1
5	20.013	-7.6599	1
6	20.006	-8.2366	1
7	20.019	-10.269	1
8	20.019	-10.635	1
Factory	19.97	-2.1024	1
Range	0.044	7.3743	0

Table 6. PT-005 trendline values

GP50 A #2 (amplified)			
Test #	Slope (psia/V)	Intercept (psia)	R^2
1	19.778	10.214	1
2	19.772	10.155	1
3	19.778	9.4569	1
4	19.711	9.7457	0.9999
5	19.806	9.5082	0.9999
6	19.765	9.5827	1
7	19.763	9.1559	1
8	19.761	9.1085	1
Factory	19.973	-1.8488	1
Range	0.095	1.1055	0.0001

Table 7. PT-013 trendline values (excluding pressures <15psia)

GP50 B			
Test #	Slope (psia/V)	Intercept (psia)	R^2
1	553498	-85.9	0.9984
2	547376	-83.641	0.9972
3	561104	-85.858	0.9998
4	554977	-86.911	0.9946
5	549652	-87.001	0.9948
6	548773	-88.019	0.9973
7	555485	-90.776	0.9984
8	554249	-91.489	0.9982
Factory	-	-	-
Range	13728	5.589	0.0052

Table 8. PT-007 trendline values

Note that PT-014, the Kulite unit, does not have a trendline table. This is because no trendlines were formed due to the broken responses received from all eight tests as seen in Fig. 12.

With all of this data, we can compare the slope and offset ranges within each family; the smaller the range, the less variation and better the stability. Starting with the Measurement Specialties models, PT-001 and PT-009, it can be inferred from the graphs in Fig. 5 and Fig. 6 that PT-001's calibrations align more closely with its factory calibration curve. Table 2 and Table 3 confirm this by comparing PT-001's slope range of 21psia/V with PT-009's slope range of 14psia/V, as well as an intercept range of 1.0352psia to 1.6515psia. The Tecsis models, PT-002 and PT-010, performed similarly, albeit on different scales than the Measurement Specialties models. PT-002 had a slope range of 150psia/V and an intercept range of 0.9372psia, whereas PT-010 had a slope range of 153psia/V and an intercept range of 0.9857psia. PT-002 has an R^2 value range of 0.0001 while PT-010's range is 0, having an $R^2 = 1$ consistently. These factors suggest that both PTs are performing very similarly and more data is required to determine variation with time. Next comes the GP50 A amplified models, whose responses may have been impacted by a testing anomaly that will be discussed in detail below. Due to this, only data gathered above 15psia were used to develop the calibration curves for PT-013. According to the graphs and tables above, PT-005 proved to have a slope range of 0.044psia/V and an intercept range of 7.3743psia. PT-013 has a slope range of 0.095psia/V and an intercept range of 1.1055, and appeared to be the most affected by the prior testing anomaly. The GP50 B is a 0 to 500psi model and exhibits a different response than the other PTs. PT-007's slope range was 13,728psia/V, intercept range was 5.589psia, and R^2 range was 0.0052. The Kulite, PT-014, appears to have failed at the beginning of the testing. Details about and leading to the failure of this PT will be mentioned in greater detail below.

While the calibration data appears solid numerically, the graphs show all PTs exhibiting a small drift in their intercept values from Test 1 to Test 8. There does not appear to be any correlation between PTs for whether this drift is towards or away from their factory value, but it occurs consistently across all PTs and will continue to have our attention in future testing.

G. Anomalies

The anomalies witnessed over the entire pre-test and test experiments were noted and catalogued for future reference in case of similar occurrences.

1. GP50 A, PT-005 and PT-013, Amplification Module Overheating

Before we began vacuum testing the PTs, they were first thermocycled in an oven several times at the operational temperature of 152°C. This was done to gather baseline data without installation torque and manifold material as potential factors in the PT performance. After the oven that was used for testing reached 152°C during one of these tests, the data was analyzed in real time and PT-013's voltage response was seen to be falling at a significant rate. It was at this time that our team thought to question whether the inline electronics modules attached to the GP50 A units, PT-005 and PT-013, could handle the same temperature that the transducers were rated for. Without waiting for confirmation, the oven was opened and the heat vented to be cautious. The voltages returned to their original values, but the possible damage had most likely already occurred. The inline electronics modules were only rated for a temperature of 121°C, which means that they were heated 30°C over their recommended value for 20-30 minutes. Over the course of the thermocycling tests (once the inline electronics modules had been moved outside of the oven's influence), PT-013 continued to change in voltage after heating, while PT-005 showed little change at all. We reached out to the vendor for their thoughts on the matter and they confirmed that the electronics module had most likely incurred damage but the issues may appear later on into the sensor life cycle. It was later, during the vacuum testing, that a significant discovery was found regarding the PT's responses. As seen below in Fig.13, PT-013 (in orange) does not react to pressure changes less than around 15psia, essentially scaling down the voltage response. PT-005 reacts to the pressure ramping well, but sees a drift in calibration as mentioned before. A brand new GP50 A model may need to be used in future testing to provide the most accurate response or the electronics modules may need to be replaced.

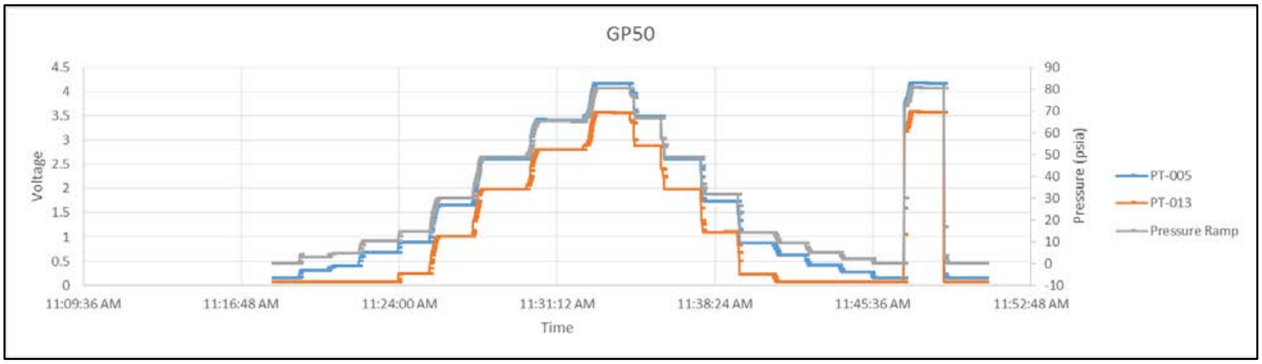

Figure 13. Test 1 GP50 A response

2. Manifold Machining

While leak checking the system, PT-002 and PT-010 were particularly troublesome. Regardless of how much torque was applied, these two ports leaked to an unacceptable amount. Through my close analysis, the PT was resting on top of the counterbore rather than inside of it, causing the o-ring to fail to seal properly. This machining error was traced back to a difference in the Tecsis model's drawing at the time of designing and the most up-to-date drawing received after manifold fabrication. The team was then brought to a crossroad of sorts, with two main options: we could craft our own, larger o-rings to try and combat the spatial difference, or peel back the heater tape and re-machine the manifolds to a sufficient counterbore diameter. This latter option could possibly damage the heaters or require a complete re-wrap of the manifolds, in addition to introducing machined debris back into the system that would necessitate cleaning. Due to these worries, custom o-rings were created and applied to the sensors. This method fixed our issue for no more than two tests before blowing out, which meant that Plan B would be our next course of action. After a few days were quickly spent machining the manifolds to acceptable dimensions, PT-002 and PT-010 were returned to their respective ports and sealed, leak free.

3. Kulite, PT-014 Failure

During testing in the spring of 2016, thermocycling tests, and trial runs prior to Test 1, the Kulite unit performed well. PT-014 experienced room temperature/dry air without any issues, starting and ending at a value of 0.032V while following the pressure ramping smoothly. The system was then heated to operational temperature and ramped again, yet this time the PT began with a response of 0.093V as shown in Fig. 14. It begins to follow the pressure ramp with periodic dips in voltage that last eight seconds until the voltage values reach 0.125V, the maximum output for the unit in LabVIEW. The response is observed to flat-line until the pressure drops below 42psia. After this point, the responses degrade consistently and continue to do so for the rest of the tests as shown in Fig. 15. The sensor does respond more effectively at room temperature than operational temperature. The sensor was not removed from the manifold in order to continue sending data back to the vendor and to determine whether the sensor may recover.

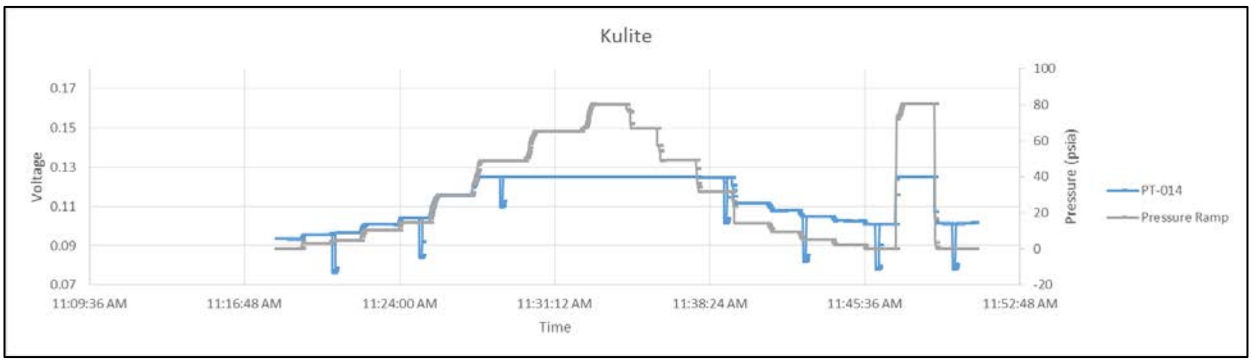

Figure 14. PT-014 first anomaly, Test 1 - 152°C Dry Air

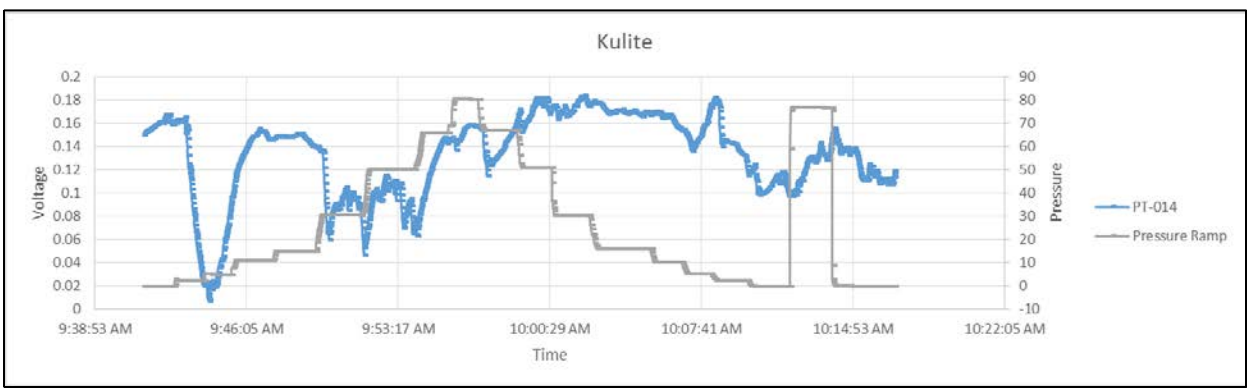

Figure 15. PT-014 continued anomaly, Test 6 - 152°C Dry Air

4. GP50 B, PT-007 Calibration

In the case of the GP50 B model's calibrations, they are different but consistently so. The factory calibration begins with -0.00061V at a temperature of 70°F, yet the response was -0.00018V at room temperature (22°C or 71.6°F)/dry air in the lab and 0.000162V at operating temperature. While numerically the values seem small, the difference can be significant as seen below in Fig. 16. This may be a result of the pressure range being so large or possibly the torque on such a small transducer affecting the response at different temperatures. We are still looking into this and are speaking with the vendor to see why it might occur, but these different calibration curves do not rule out PT-007 as a possibility.

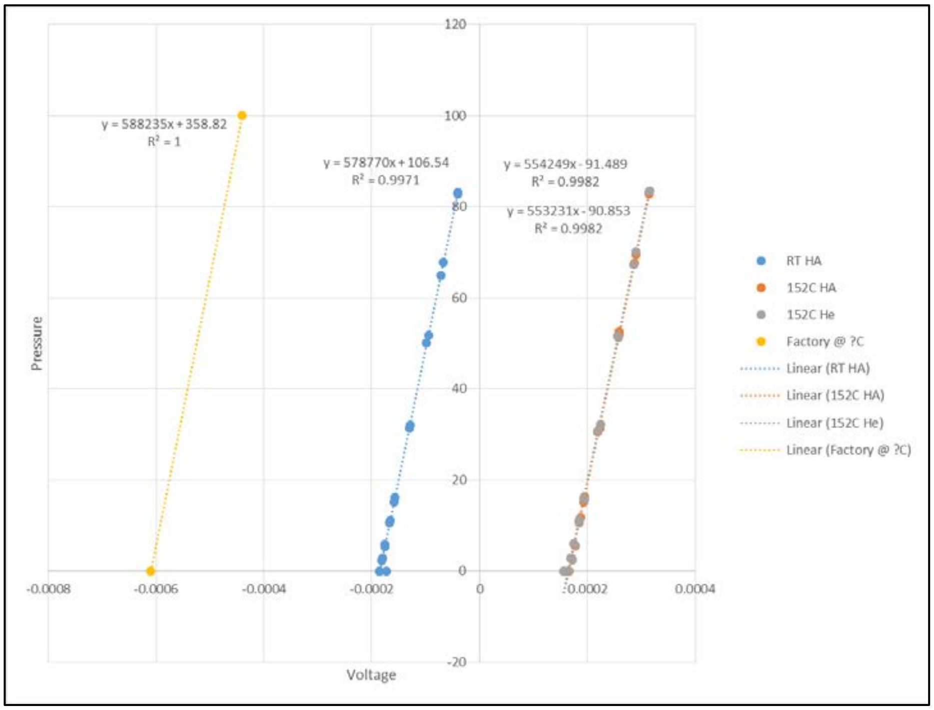

Figure 16. GP50 B, PT-007, calibration response Test 8 (RT = room temperature, HA = house/dry air, He = helium)

IV. Conclusions and Forward Work

While there is not enough data or testing completed to declare a sure winner of the PT trade study, some conclusions can be drawn. Due to the accidental overheating of the GP50 A inline electronics modules, PT-013 cannot be a viable contender until its electronics module can be replaced. Although PT-005 displays variation from day-to-day, it still displays acceptable responses at all pressure steps, so will remain under evaluation. GP50 B is still a possible choice, yet the odd calibrations would require further assessment. PT-014, the Kulite, is no longer a viable option. While we will continue to test the transducer in the case that it comes back to life, the team recognizes that the Kulite models do not exhibit the resilience to our testing required for flight-forward design. Regarding the remaining four PTs, the Measurement Specialties (PT-001 and PT-009) and Tecsis (PT-002 and PT-010) models demonstrate the most stability thus far. At this point in testing, either brand or model type satisfies our testing requirements, but the trade study will continue in order to gauge their survivability with many more temperature and pressure cycles so that the absolute best model can be chosen for flight.

After down-selection of the most viable PT based on the results of this trade study, forward work will include similar pressure and temperature ramps with the sensors swapped in the manifolds to fully eliminate material impact as a factor on performance. We will also run through a testing phase with the manifolds chilled. The chosen PT will then be torqued to different values, assuming a seal can still be made, and thermally cycled to determine how different torque ratings impact our results and how thermal cycling impacts the installation torque over time. At this time, this report only contains data regarding the test setting of operating temperature/dry air, but other information regarding room temperature/dry air and operating temperature/helium will be compiled for comparison as well. Finally, the team will decide on a slower-paced testing schedule with continued thermal cycling but limited pressure cycling for the foreseeable future.

Acknowledgments

I would like to thank everyone on the LAVA team for their help and support in the completion of this segment of the trade study: Janine Captain, Phil Maloney, and Jim Smith for their assistance in the lab at various stages of testing, Beau Peacock and Kevin Smith for their knowledge of LabVIEW and wiring of the system, Rene Formoso and Jim Kania for their support of the LAVA lab and respected advice, Jaqueline Quinn for her leadership of the LAVA and RESOLVE team, Devin Lanz for creating an Excel macro and saving me and future interns the countless hours of data crunching and fears of arthritis, Rusty Mcamis and James Niehoff for responding to our never-ending manifold requests with enthusiasm and exemplary craftsmanship, and Larry Jones for his support of the trade study and invaluable career advice. Finally, last but certainly not least, I would like to thank my mentor, Katherine Cryderman, who single-handedly made everything possible. She will never understand how truly thankful I am for the opportunity to work here at NASA and be a part of something greater.

References

[1]Captain, J. E., Weis, K., Cryderman, K., Coan, M., Lance, L., Levine, L., Loftin, K. B., Santiago-Maldonado, E., Bauer, B., Quinn, J., "Design and development of volatile analysis system for analog field test of lunar exploration mission," *Advances in Space Research*, Vol. 55, 10 Nov. 2014, pp. 2457-2471.

[2]Hinricher, J. "Test and Recommendation of Flight-Forward Resistive Temperature Detector for Resource Prospector Mission," NASA John F. Kennedy Space Center, South Dakota School of Mines and Technology, Rapid City, SD, April 2014.