Sensor Development for PEM Fuel Cell Systems

Contract DE-FC36-02AL67615

Honeywell Sensing and Control
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Executive Summary

This document reports on the work done by Honeywell Sensing and Control to investigate the feasibility of modifying low cost Commercial Sensors for use inside a PEM Fuel Cell environment. Both stationary and automotive systems were considered. The target environment is hotter (100°C) than the typical commercial sensor maximum of 70°C. It is also far more humid (100%RH condensing) than the more typical 95%RH non-condensing at 40°C (4% RH maximum at 100°C).

The work focused on four types of sensors, Temperature, Pressure, Air Flow and Relative Humidity. Initial design goals were established using a market research technique called Market Driven Product Definition (MDPD). A series of interviews were conducted with various users and system designers in their facilities. The interviewing team was trained in data taking and analysis per the MDPD process. The final result was a prioritized and weighted list of both requirements and desires for each sensor.

Work proceeded on concept development for the 4 types of sensors. At the same time, users were developing the actual fuel cell systems and gaining knowledge and experience in the use of sensors and controls systems. This resulted in changes to requirements and desires that were not anticipated during the MDPD process. The concepts developed met all the predicted requirements. At the completion of concept development for the Pressure Sensor, it was determined that the Fuel Cell developers were happy with off-the-shelf automotive pressure sensors. Thus, there was no incentive to bring a new Fuel Cell Specific Pressure Sensor into production. Work was therefore suspended.

After the experience with the Pressure Sensor, the requirements for a Temperature Sensor were reviewed and a similar situation applied. Commercially available temperature sensors were adequate and cost effective and so the program was not continued from the Concept into the Design Phase.

The Airflow Sensor Concept development included 2 flow ranges (400 LPM and 4000 LPM). We intended to use a new type of sensor chip specifically intended to survive and accurately sense airflow in the extremely challenging environment, the on board reformer. The chip was a derivation of the commercially available Mass Airflow Microbridge chip, a thermal transfer type of sensor used since 1986 in Medical and HVAC applications at room temperatures, low flow rates and non-condensing humidity. Successful and well behaved airflow sensing was demonstrated and a condensing proof configuration developed. An analog voltage signal that met requirements was also demonstrated, but the raw signal was too low to use with present past ASICs. Follow-on work to improve sensitivity was suspended when discussions with DOE and users revealed that there was no longer a requirement for airflow sensing due to elimination of the on-board reformers. There was limited user non-specific interest in hydrogen flow sensing, but the available airflow sensing technology was not easily adapted to hydrogen flow. The platinum film element becomes unstable when exposed to hydrogen and the power required to operate the thermal sensor in hydrogen is too high.

The humidity sensor development was much more difficult. The technology, a capacitive polymer dielectric, has previously been limited to 85°C maximum and less than 90%RH. Previous attempts to measure RH> 95% using earlier product designs had major problems with unstable output and infant mortality. Honeywell has developed a higher temperature chip that requires an external ASIC, but the ability to deal with the much higher condensing humidity levels at high temperatures was unknown. The concept in this effort was to mount the sensor inside a heated chamber that would locally prevent relative humidity from exceeding 90%. Actual life testing found that absolute humidity (rather than relative humidity) was critical and the sensors drifted by unpredictable magnitudes. It was decided that the technology was incapable of maintaining long term accuracy, although it was a major accomplishment that no sensors failed and the drifts were not extreme. Future attempts might have used a combination of burn-in (including humidity) and autocalibration techniques to reduce the effects of drift.

Temperature Sensor

The overall concept for the temperature sensor is shown below. The sensing technology chosen is the HEL 700 chip, manufactured in Richardson, TX. This is a miniature Platinum thin film RTD deposited on thin (0.015inch) aluminum oxide. The greatest challenge was to design the sensor to achieve the fast response time needed per the MDPD. The HEL 700 is our fastest temperature sensor. However, the probe added sufficient thermal mass that the response time was unacceptably lengthened. Computational Fluid dynamics was used to redesign the probe and later test samples were acceptably quick. This first figure shows the overall sensor appearance. The second figure shows the assembly.

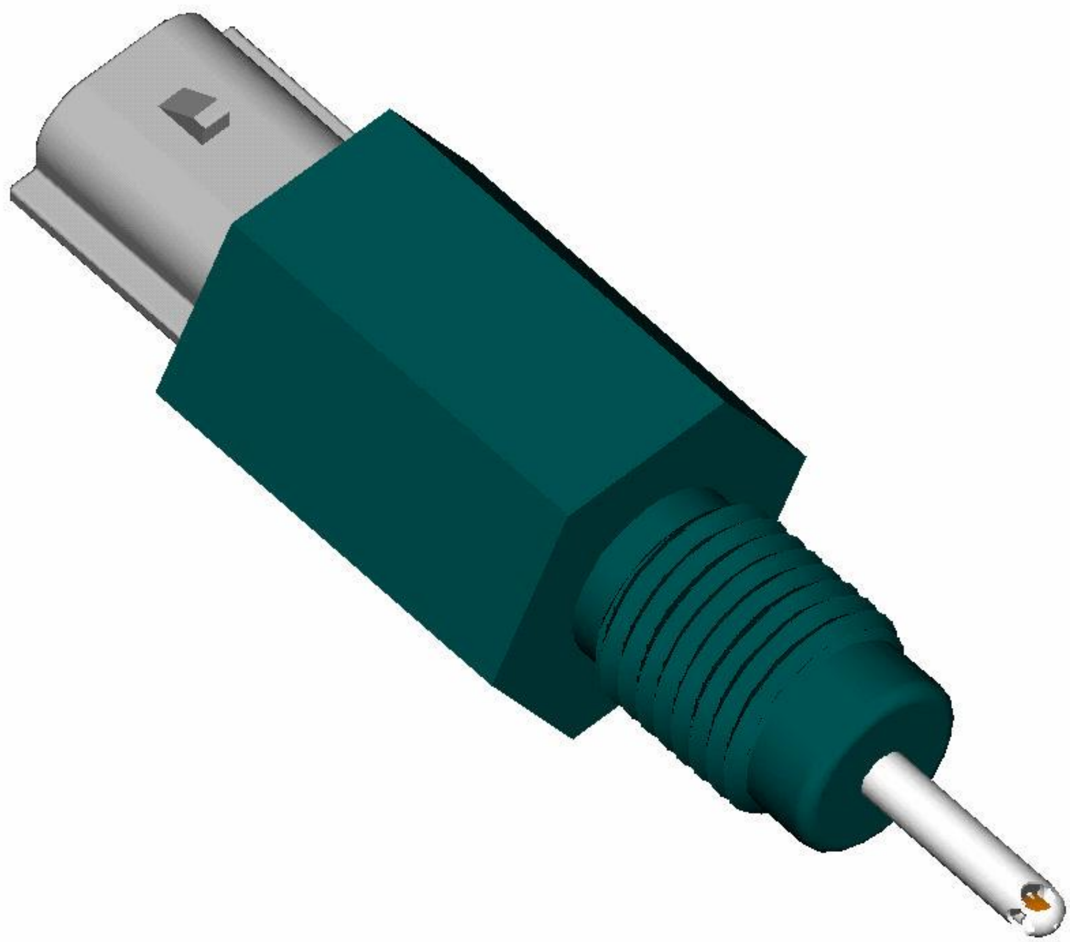


Figure 1 – Overall concept for Temperature Sensor

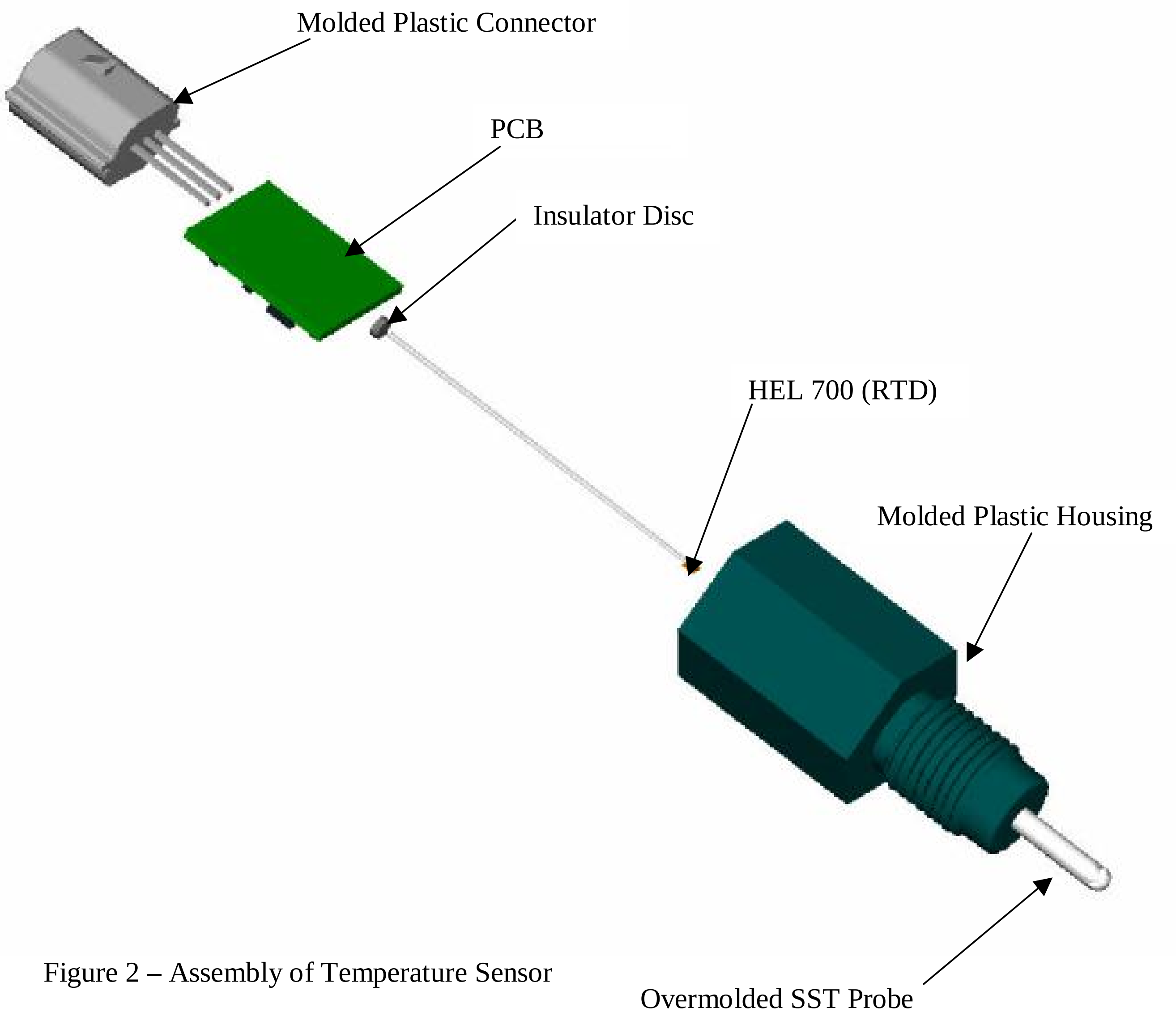


Figure 2 – Assembly of Temperature Sensor

1. Product Considerations/Specifications

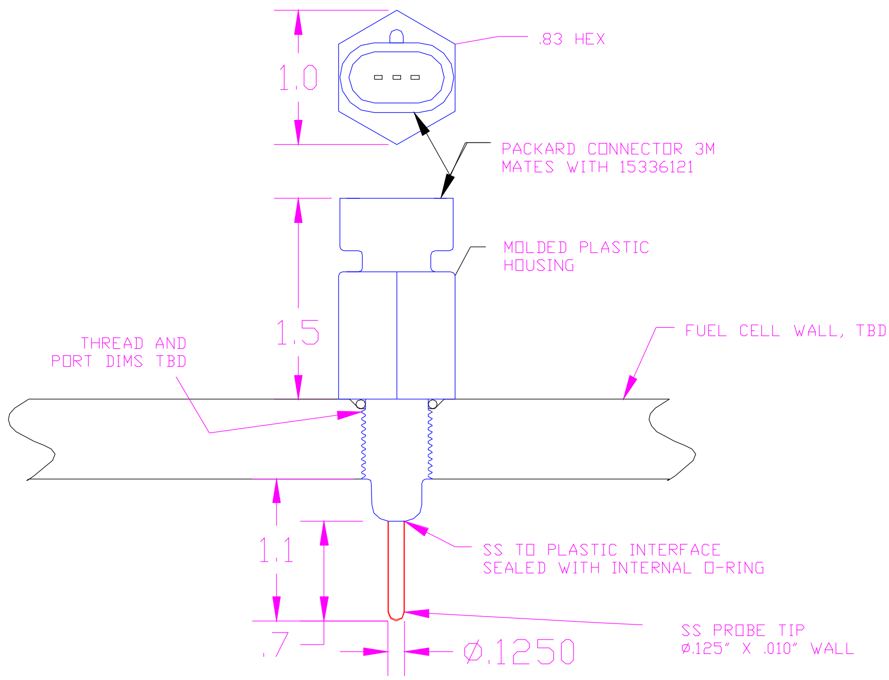
A. Application and Operational Description

This Temperature sensor is a feasibility prototype. The design is for PEM fuel cell use.

B. Features/Functions

Diagnostics & Protection:		Reverse supply protection Output shorted to supply or ground protection Open supply or ground diagnostic Internal fault = output max or min reading
Temperature Output:		
	Operating temperature	-40 to 150 deg C
	Sensitivity	0 to 5VDC linear BFSL
	Response time	2 sec in water to achieve a 63.2% change
	Accuracy	+/- 1% of operating span

C. Construction and Appearance



D. Materials chosen

Housing	-	Ryton 40% glass filled PPS
Tube	-	316 Stainless Steel
O-Ring	-	Viton fluoroelastomer
Seal	-	Stycast 2651-40 epoxy

E. Performance

Supply Voltage: 7 to 25VDC

Measurement range: -40C to 150C

Storage:	-50C to 150C
Media composition:	H_2 30-75%, CO_2, N_2, H_2O, CO
Output:	0 to 5 V, Linear output over operating span, BFSL
Response time:	Approx. 20sec @ 2SLP min flow
Repeatability:	1% of operating span
Pressure:	1 to 3atm

2. Test/Approvals Requirements

A. Customer Field/Beta Tests

This temperature sensor was intended for customer field tests scheduled to start 4/15/2005 and require field feed back by 9/30/2005. The development effort was terminated at the end of 2004.

B. Internal Development and Qualification Tests

Shock:	50g, 10 ms, 3/ axis	MIL-STD-883
Vibration:	10g 100 to 1000 Hz	MIL-STD-202F method 204D
Insulation:		MIL-STD-202F method 302
Dielectric:		MIL-STD-202F method 301
Sealing:	IP65 water jet	
Salt Spray:	96 hour 5% solution mist	MIL-STD-202F method 101D
Humidity:	95% RH non-condensing 40 hours	
EMI susceptibility:	30V/m 80MHz-1GHz, 80% mod 100V/m design goal	IEC61000-4-3
ESD susceptibility:	+/- 8KV	IEC61000-4-2, ISO 10605
Temperature cycle:	-40C to 150C, 100 cycles, 10C/min rate	

3. Option

Full CAN 2.0B	ISO11898 High Speed	50% cost adder

Testing Results

A first round of testing was performed on samples with solid probes. Testing was successful but response time was at the very limit of acceptability. The following are excerpts from the test report.

EVALUATION PERFORMED

1. RESPONSE TIME ....
2. HYDROGEN RESISTANCE ....
3. TEST OVER TEMPERATURE ....

SUMMARY:

In Summary, the Response Time for all samples was approximately 20 seconds. All samples passed the Leak and Hydrogen Soak test. For future testing, the RTD was chosen over the thermistor based on linearity and accuracy data.

TEST EQUIPMENT USED

Equipment	Test	Lab Number	Calib. Due Date	Loc.
MKS Flow Meter	Response Time	EL 07-77C	10-31-04	Comm
MKS Mass Flow Meter	“	EL 07-092A	5-31-05	“
HP 34970A Data Acquisition Unit	“	EL 38-010F	9-30-05	“
Thermotron Temperature Chamber	“	EL 01-094B	4-30-05	MC
Copper tubing, air line and appropriate fixture	“	N/A	N/A	“
Thermotron Temperature Chamber	Leak Test Over Temperature	EL 01-068A	4-30-05	Comm.
Manifold	“	N/A	N/A	“
Torque Wrench	“	IT-86-EL-7	4-30=05	“
Socket (21mm) and socket adapter (4215)	“	N/A	N/A	“
Helium Tank	“	N/A	N/A	“
Manifold and associated hoses	Hydrogen Resistance	N/A	N/A	FH
Torque Wrench	“	IT-86-EL-7	1/31/05	“
Socket (21mm) and socket adapter (4215)	“	N/A	N/A	“
Power Supply	“	EL 13-217A	1-31-05	“
HP 34970A Data Acquisition Unit	“	EL 38-010S	1-31-05	“
One 20 channel card	“	N/A	N/A	“

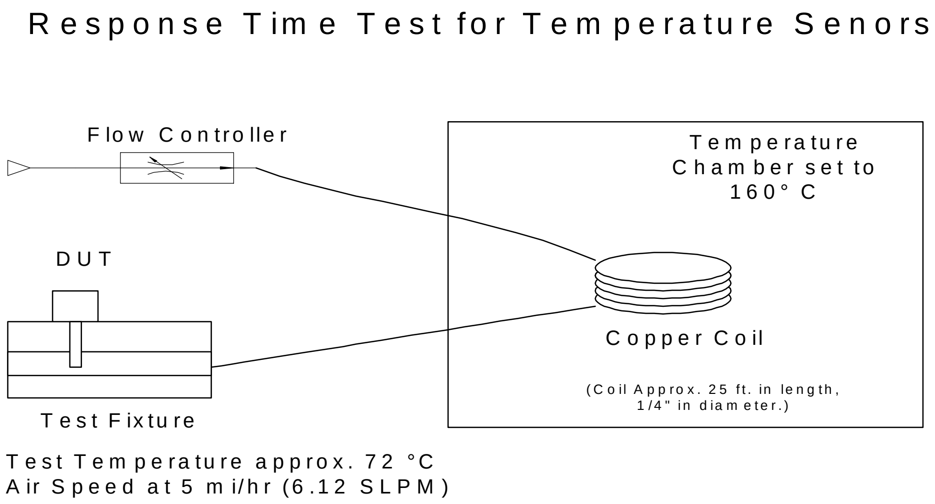
Test Procedure:

Samples 10 through 13 and 15 through 18 were subjected to the Response Time Test. Coiled copper tubing was placed in a temperature chamber set at 160°C. Both ends of the coil protruded out of the port-hole. One end was connected to the output of the MKS flow Controller and the other end quick connected to the aluminum block fixture. The input of the MKS Controller was connected to shop air-line with a regulator set to 10 psi and its flow rate set to 6.12 SLPM in order to achieve the 5mph of gas flow. A thermocouple was taped to the fixture block and set inside the flow hole to monitor the flow temperature coming through the copper tubing. The samples output was wired to a 34970A data logger with a 20-channel card. The scan interval was set to once every 0.001 seconds. The scan button was pushed and the samples probe was placed and held in the top hole of the fixture for approximately one minute. The scan button was pushed again to stop the scanning and the data was dumped onto a laptop.

Test Conditions:

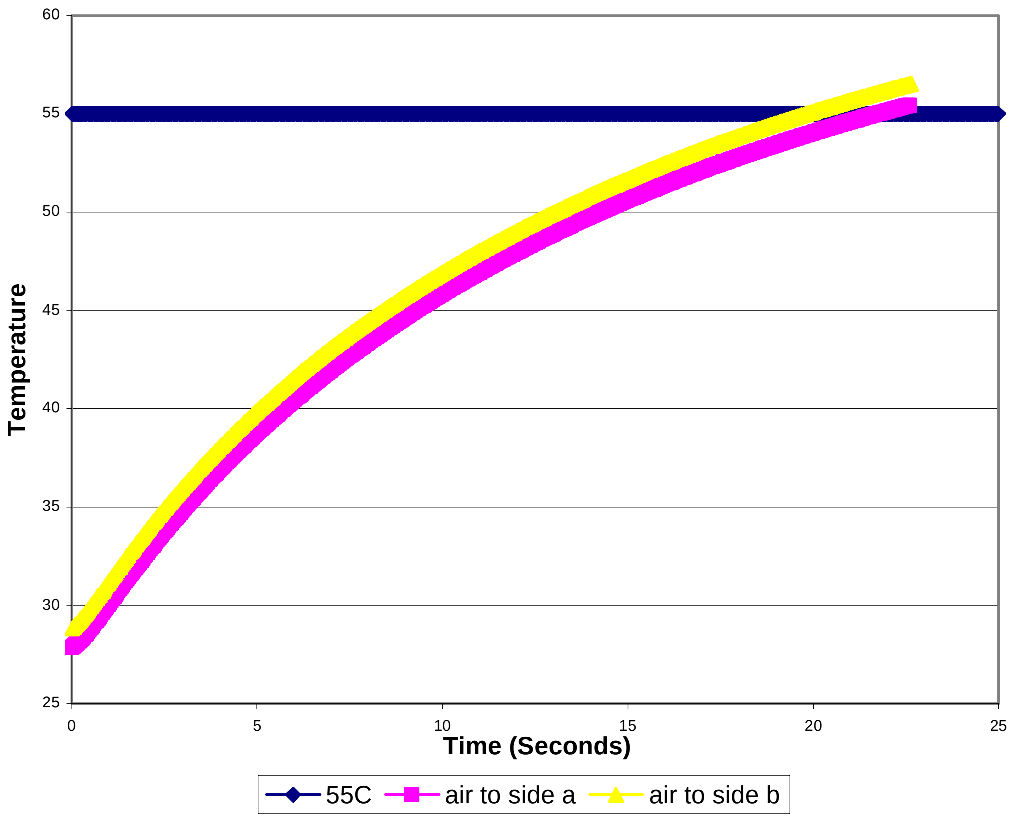
Response Time: 20 seconds max. to achieve 63.2% of span change
Gas Flow Rate: 5mph (6.12 slpm)

Response Time Setup



Test Results:

All samples exhibited approximately a 20 second response time. Below is a graph showing one samples time. The RTD was chosen over the thermistor based on linearity and accuracy.



LEAK TEST OVER TEMPERATURE

Specification:

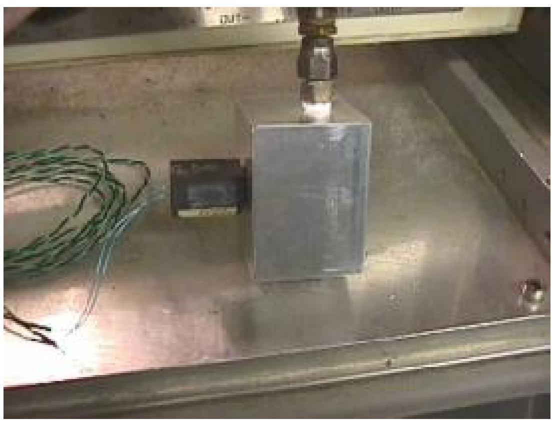
This test was performed per originator's request.

Test Procedure:

Samples 10 through 13 and 15 through 18 were subjected to the Leak Test Over Temperature Test. One sample at a time was mounted to the manifold at 345 oz in (21.5 in lbs). The manifold was connected to the pressure line hose and placed into the automated characterization chamber with a helium tank and the pressure set manually set to 15 psi. The chamber was set to 25°C for a one-hour soak. After one-hour, the pressure was then removed and the leak rate was recorded after one minute. This leak check process was completed at –40° and 150°C.

Test Conditions:

Material:	Helium (69-50405)
Pressure:	1 atmosphere (15psi)
Temperatures:	25, -40 and 150°C
Soak Length:	1 hour at each temp.
Leak Test Length:	1 minute
Maximum Leakage:	10% of 15psi (1.5psi)



Test Equipment Required:

Outlined in the TEST EQUIPMENT USED section of this report.

Test Results:

All samples passed this test as they did not exceed the Maximum Leakage of 10% of 15psi or 1.5psi. Based on these results, various redesigned assemblies were built and tested. The best design was a vented probe where the sensor element was coated with Parylene. Excerpts from the test report follow:

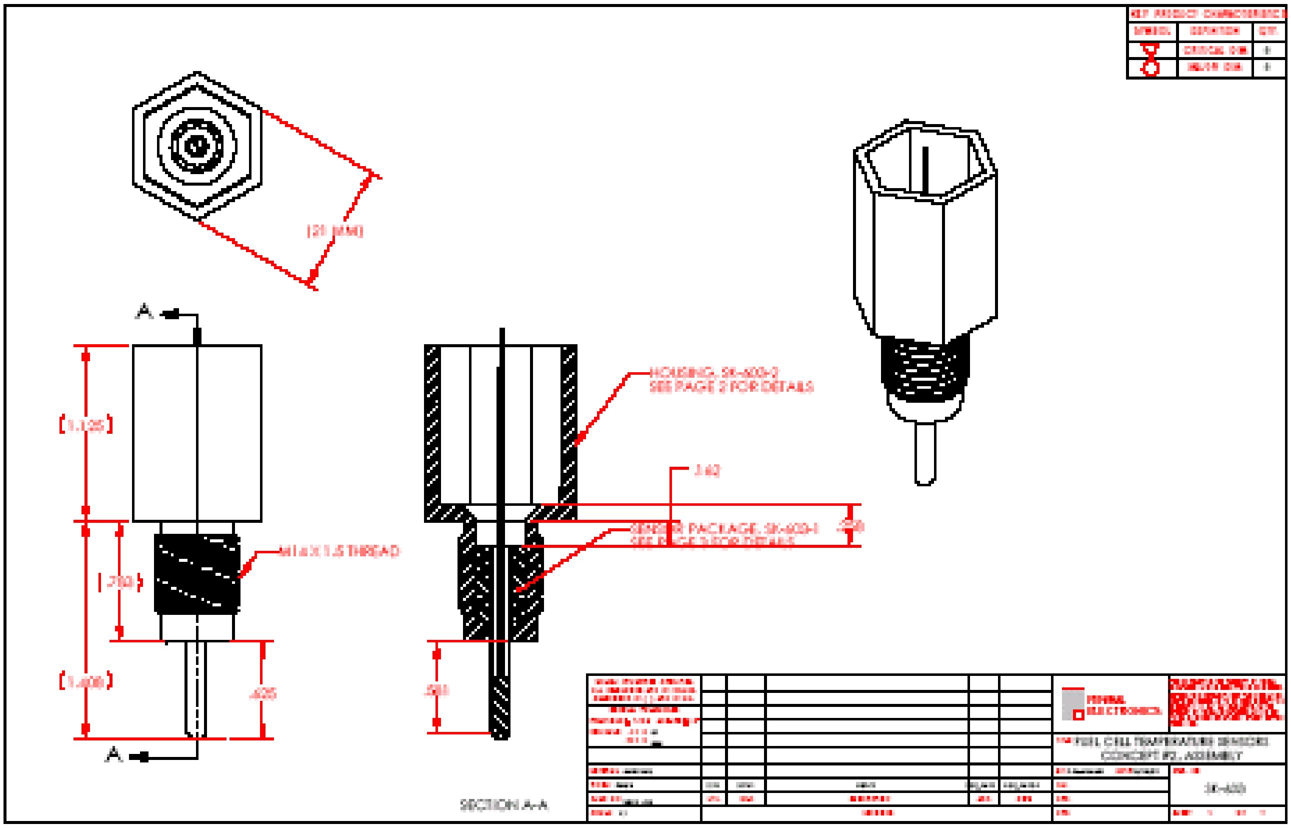
SUBJECT: EVALUATION OF THE DEPARTMENT OF ENERGY FUEL CELL TEMPERATURE SENSORS WITH RTD'S AND PROBES OF VARIOUS DESIGNS. (ALPHA II)

SUMMARY:

Samples built (group 2) with the HEL700 RTD with parylene coating in the 4-hole probe exhibited the best probe design in regards to response time.

TEST EQUIPMENT USED

Equipment	Test	Lab Number	Calib. Due Date	Loc.
MKS Flow Meter	Response Time	EL 07-77C	10-31-04	Comm
MKS Mass Flow Meter	"	EL 07-092A	5-31-05	"
HP 34970A Data Acquisition Unit	"	EL 38-010F	9-30-05	"
Thermotron Temperature Chamber	"	EL 01-094B	4-30-05	MC
Copper tubing, air line and appropriate fixture	"	N/A	N/A	"
Thermotron Temperature Chamber	Characterization over Temperature	EL 01-62G	3-30-05	Comm.
HP 34970A Data Acquisition Unit	"	EL 38-010F	9-30-05	"
Thermotron Temperature Chamber	Leak Test Over Temperature	EL 01-068A	4-30-05	Comm.
Manifold	"	N/A	N/A	"
Torque Wrench	"	IT-86-EL-7	4-30=05	"
Socket (21mm) and socket adapter (4215)	"	N/A	N/A	"
Helium Tank	"	N/A	N/A	"
Manifold and associated hoses	Hydrogen Resistance	N/A	N/A	FH
Torque Wrench	"	IT-86-EL-7	1/31/05	"
Socket (21mm) and socket adapter (4215)	"	N/A	N/A	"
Power Supply	"	EL 13-217A	1-31-05	"
HP 34970A Data Acquisition Unit	"	EL 38-010S	1-31-05	"
One 20 channel card	"	N/A	N/A	"



Note: The probes (stainless steel) with 4 - 0.075"diameter holes, plastic housings (Ryton R4 material) and small pucks (made from the walls of a sample housing, 0.110" in diameter with 2 – 0.020" diameter holes centered and approximately 0.035" apart) that were evaluated during this testing, were fabricated in the Model Shop in Freeport, IL.

<u>SAMPLE DESCRIPTION – GROUP 2</u>

The goal of the **Design of Experiment Group 2** was to evaluate the Heraeus 0.027" thick MK213 RTD against Honeywell's own HEL700 RTD. We also evaluated the HEL700 with and without glass and parylene coating in 4-hole probe assemblies. The samples evaluated are listed below. Samples 700pg1 thru 3 include the printed circuit board assemblies to be used for the Characterization over temperature testing.

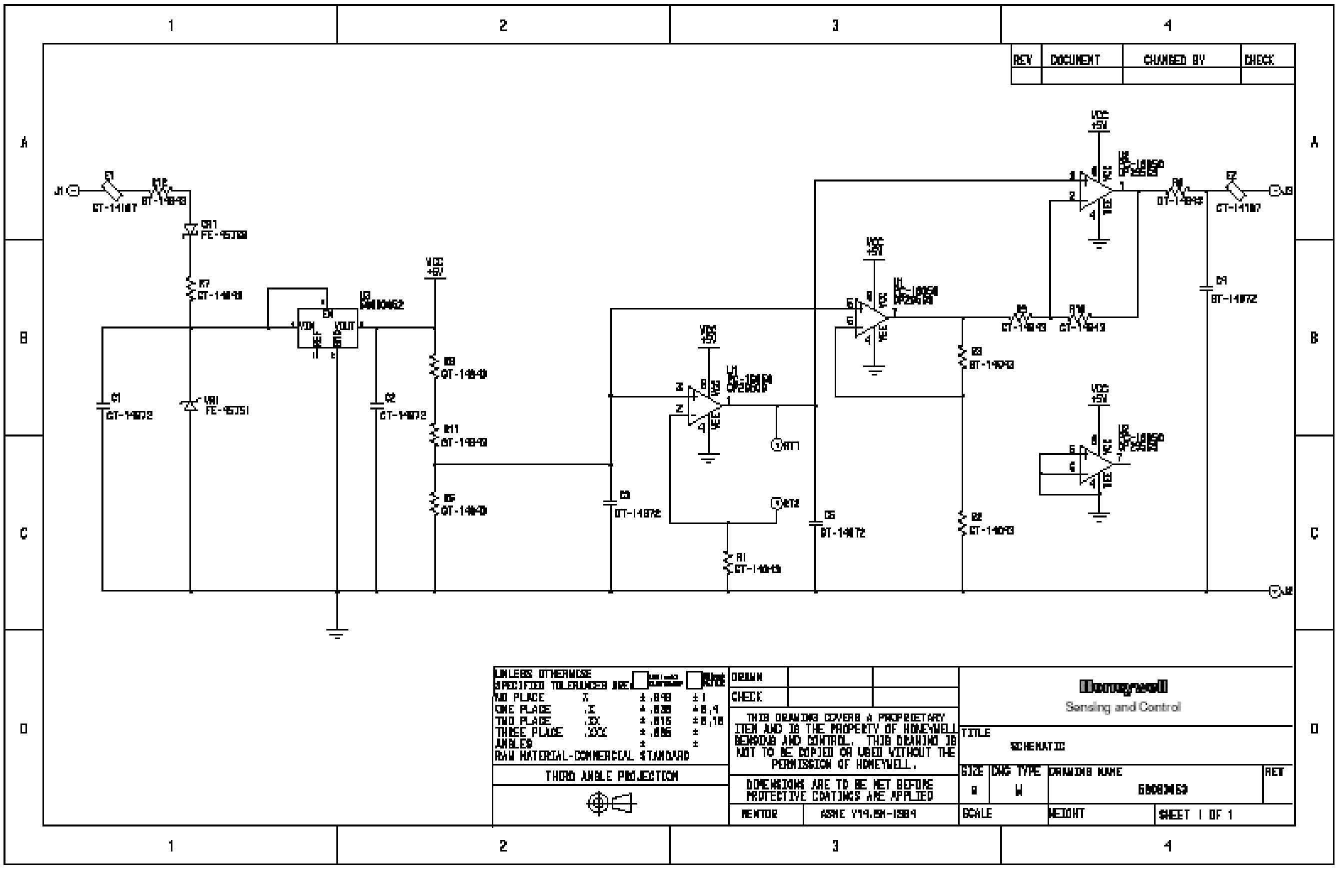
Probe assembly procedure: The RTD leads were lengthened and placed through the holes in the small puck. Shrink tubing was placed over each individual lead and one additional piece of shrink tubing was then placed over both leads. The RTD was slid up into the tip area of the probe into position. To hold the RTD and puck into position, a small amount of Loctite 498, #65-51334, was applied to the shrink tubing of the leads and edges of the puck to bond them to the inner wall of the probe. When sliding the probe into the end of the housing, this Loctite was also applied around the base of the probe sealing purposes. A Hysol epoxy was applied to the inside of the housing where the leads came though for strain relief and sealing purposes.

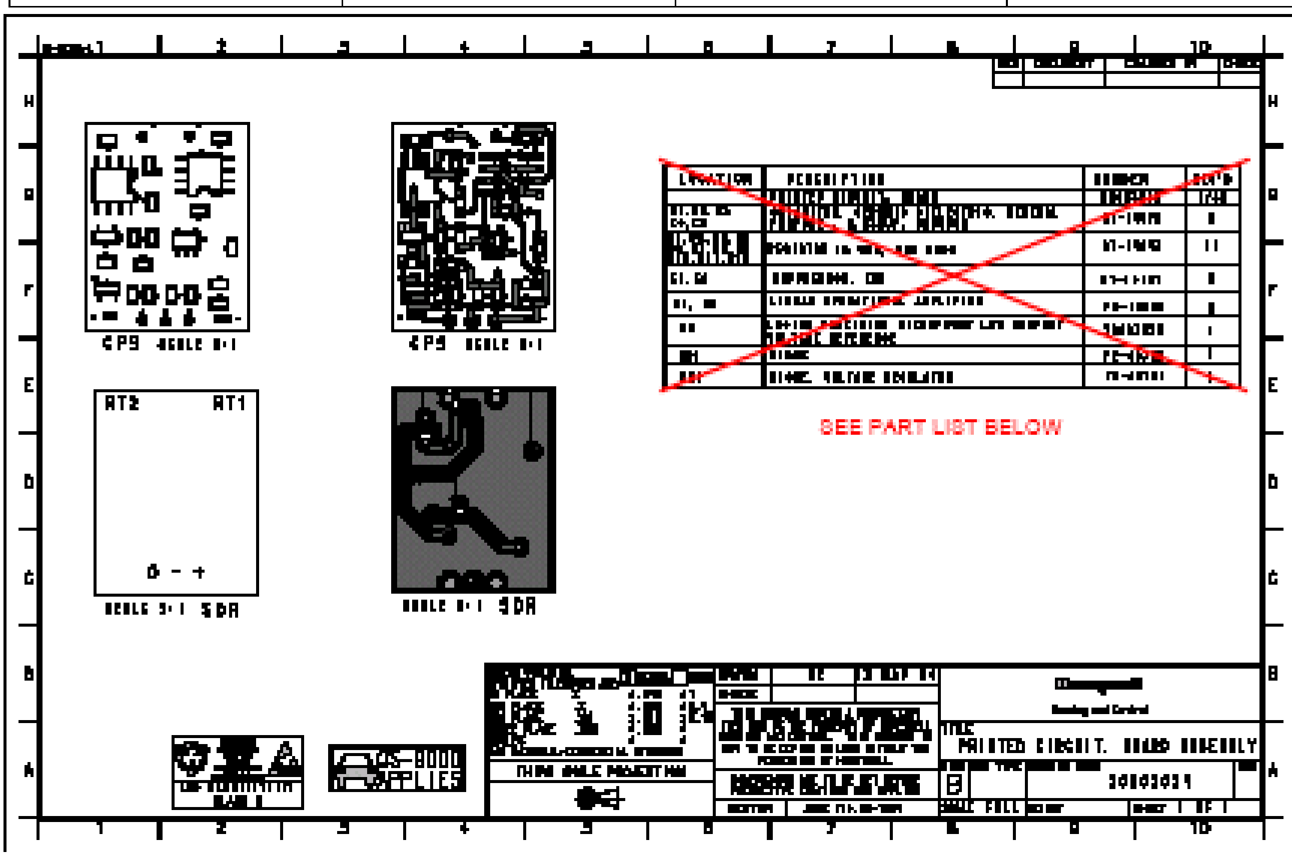
Sample #	**RTD**	**Probe Design**
1	700eg1-3	HEL700 RTD exposed with a glass coating
2	700eun1-3	HEL700 RTD exposed and uncoated
3	700pg1-3	HEL700 RTD assembled in a 4-hole probe with a glass coating with pc board assemblies
4	700pun1-3	HEL700 RTD assembled in a 4-hole and uncoated
5	700epar1-3	HEL700 RTD exposed with Paraline coating
6	700ppar1-3	HEL700 RTD assembled in a 4-hole probe with paraline coating
7	Mkeg1-3	MK213 RTD exposed with a glass coating
8	Mkpg1-3	MK213 RTD assembled in a 4-hole probe with a glass coating

The following gives the circuit diagram and parts list for the samples tested.

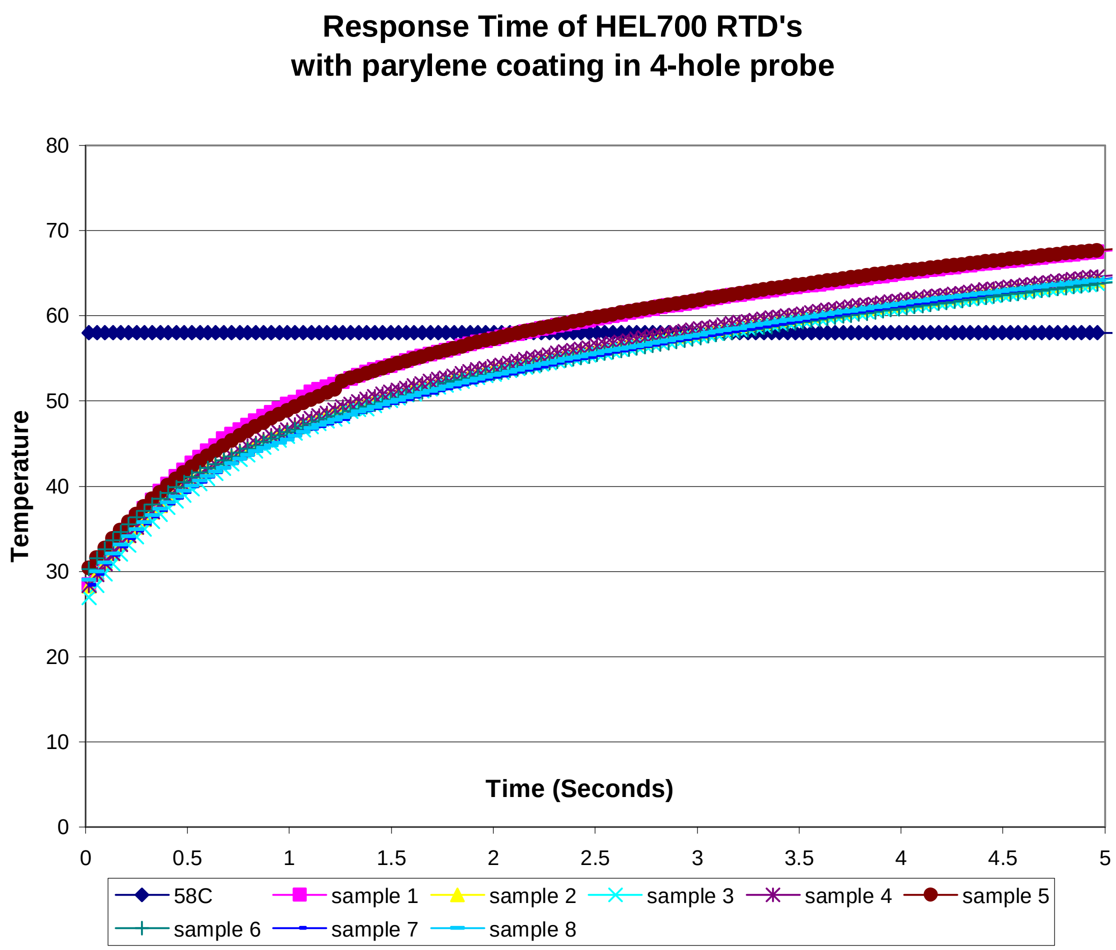
Updated parts list:

LOCATION	MFG TYP	DESCRIPTION	SIZE	PART NO	QTY
E1, E2	MURATA BLM11HA102SG	SUPPRESSOR, EMI	0603	GT-14107	2
CR1	SGS BAR43FILM	DIODE	SOT23	FE-45760	1
VR1	MMBZ5242B	12 V ZENER	SOT23		1
U3	LM4120AIM5-5.0	5V REGULATOR	SOT23-5	50003052	1
U1, U2	OP295GS	OP AMP 8lead SOIC		PC-16050	2
C1, C2, C3, C5	VITRAMON VJ0805H333JXAMR	.033MFD	0805	GT-14072	4
C4	VISHAY	1000PFD	0805		1
R1, R2, R3,	VISHAY SERIES TNPW0805	RESISTOR 1.0K	0805		3
R4	HONEYWELL 3750ppm	RTD SENSE ELEMENT			OMIT
R5	VISHAY SERIES TNPW0805	RESISTOR 10.0K	0805		1
R6	VISHAY SERIES TNPW0805	RESISTOR 62.0K	0805		1
R7, R12	VISHAY SERIES CRCW0805	RESISTOR 392ohm	0805		2
R8	VISHAY SERIES CRCW0805	RESISTOR 10ohm	0805		1
R9	VISHAY SERIES TNPW0805	RESISTOR 6.04K	0805		1
R10	VISHAY SERIES TNPW0805	RESISTOR 44.2K	0805		1
R11	VISHAY SERIES TNPW0805	RESISTOR 2.7K	0805		1
		PRINTED CIRCUIT BOARD		50003053	1


Honeywell
Sensing and Control
SCHEMATIC
THIRD ANGLE PROJECTION
SHEET 1 OF 1


SEE PART LIST BELOW
AT2
AT1
PRINTED CIRCUIT BOARD ASSEMBLY

The uncoated and exposed samples described below were used for baseline testing. When comparing the samples exposed with parylene and with glass, the HEL700 samples exposed with parylene coating responded the fastest.



Serial #	Type	Test ID	Probe	Exposed	RTD Time (seconds)	Ceramic (seconds)	Side Time (seconds)
1	HEL700	700eg1		Glass	1.847	1.942	2.004
2	"	700eg2		"	2.509	2.393	2.354
3	"	700eg3		"	1.769	1.651	1.924
1	HEL700	700eun1		Uncoated	1.262	1.301	1.069
2	"	700eun2		"	1.185	1.185	1.224
3	"	700eun3		"	2.315	2.12	1.731
1	HEL700	700pun1	Uncoated		1.651	1.535	1.886
2	"	700pun2	"		1.692	1.808	1.847
3	"	700pun3	"		2.081	2.081	2.354
1	**HEL700**	**700epar1**		**Parylene**	**1.77**	**1.972**	**1.635**
2	**"**	**700epar2**		**"**	**2.036**	**2.185**	**2.571**

CHARACTERIZATION AND ACCURACY - GROUP 2

Specification: This test was performed per the DOE Temperature Fuel Cell EDS.

Test Procedure:

Three (3) HEL700 RTD's with glass coating in a 4-hole probe assembly wired to printed circuit board assemblies labeled 700pg1 thru 700pg3 were subjected to the Characterization over Temperature Test.

Test Conditions:

Temperatures: 20, 0, -40, 20, 50, 90 and 20°C (temperatures were set manually)
Bias Voltage: 12.0 ± 3% Vdc
Monitored: the samples were allowed to soak at each given temperature for one hour and their output was recorded.

Test Equipment Required:

Outlined in the TEST EQUIPMENT USED section of this report.

Test Results:

All samples passed this test. The following data was recorded on 6/18/04.

Chamber Temp °C	20°C	0°C	-40°C	20°C	50°C	90°C	20°C
Ext T/C Temp	19.5°C	-0.2°C	-40.8°C	19.5°C	49.2°C	89.4°C	20.1°C
Sample G1	1.77082 vdc	1.34230 vdc	0.45727 vdc	1.76434 vdc	2.38753 vdc	3.22471 vdc	1.76541 vdc
Sample G2	1.76513 vdc	1.34318 vdc	0.45312 vdc	1.76439 vdc	2.38821 vdc	3.22399 vdc	1.76615 vdc
Sample G3	1.76485 vdc	1.34231 vdc	0.45081 vdc	1.76522 vdc	2.39121 vdc	2.23460 vdc	1.76459 vdc

After these series of tests, further development was terminated. Conversations with users determined that these prototypes were not sufficiently different than commercially available sensors.

Pressure Sensor

The technology chosen for the Fuel Cell pressure sensor was an automotive grade piezoresistive sensor similar to those manufactured in our factory in Shelby, NC. The sensor is a combination of the classic silicon strain guage physics married with modern ASIC calibration and its associated accuracy. The primary package approach is automotive quality but improved to enhance sealing, to prevent hydrogen leakage. In addition, the prototypes were tested for long term hydrogen exposure.

1. <u>Product Considerations/Specifications</u>

A. Application and Operational Description

This Pressure sensor is a feasibility prototype. The design is for PEM fuel cell use.

The description of this pressure sensor is based on target specifications compiled through the MDPD exercise and customer application requirements. Normal operation of the sensor is in a non-condensing environment. However, the sensor will withstand periods of condensation although functionality may be affected. Media composition: 0-100% H_2, CO_2, N_2, H_2O, CO, 100% DI water.

Piezoresistive Technology (PRT) is the core of this sensor design. A Wheatstone bridge silicon sense die outputs a voltage as a function of the input pressure. A digital ASIC measures the sense die output and performs pressure and temperature correction via a second order curve fitting equation. The calculated output is converted to an analog voltage.

The design provides complete media isolation of the electronics. A topside absolute reference allows for absolute pressure measurement.

B. Features/Functions

Continuous voltage output

Diagnostics & Protection:

Reverse supply protection

Short circuit protection (output shorted to supply or ground)

Diagnostic rail limits shown in Section 1E effective in event of sense die connection fault.

ASIC microcontroller diagnostic zero volt output effective in event of checksum fault.

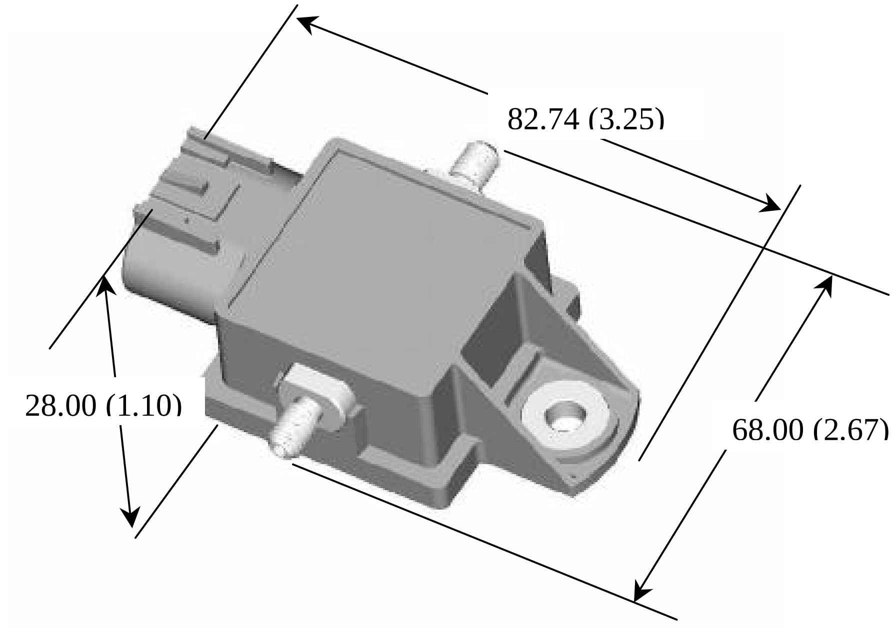
ASIC reset effective in event of RAM parity fault.

C. Construction and Appearance

Housing material: High Temperature Nylon

Port material: 316L stainless steel

Final material selection is heavily dependent on resistance to hydrogen embrittlement and DI water corrosion.

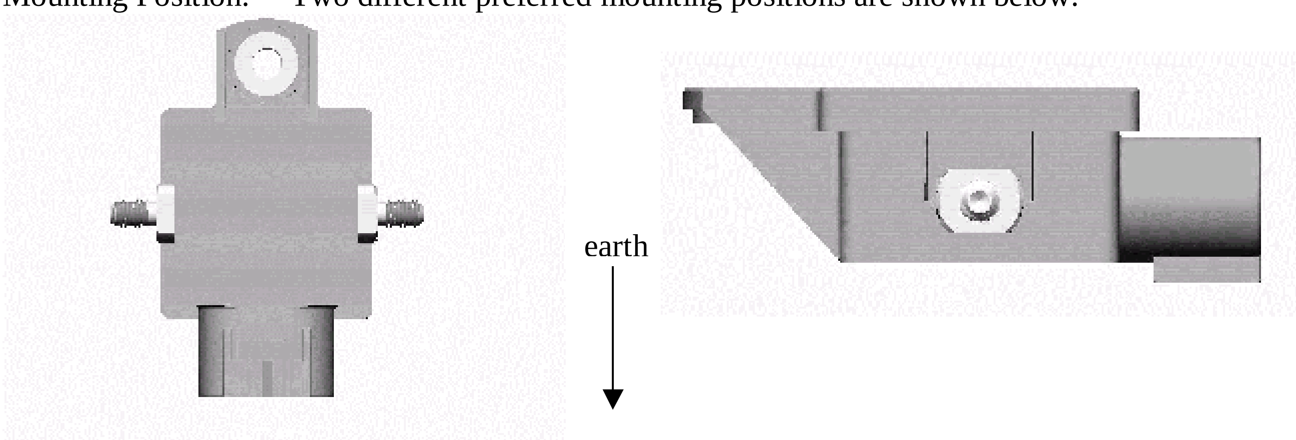


D. Installation/Mounting

Connector:	Packard-compatible GT 150 15326820 (requires 15326815 mate)
Pin out:	VCC, Ground, V_{OUT} (Pressure), V_{OUT} (Temperature)
Mass:	approx. 80 grams

Threaded ports: M6x1 threads

Mounting:	(2) Screw flange
Mounting Position:	Two different preferred mounting positions are shown below.



E. Performance

Supply Voltage:	9 to 25VDC
Operating Temperature:	-40°C to 125°C
Storage Temperature:	-50°C to 125°C
Proof pressure:	400 kPa absolute
Burst pressure:	600 kPa absolute
Output:	0.5 to 4.5 VDC linear BFSL
Low Rail:	0.12 ± 0.05 VDC

High Rail:	4.88 ± 0.05 VDC
Linearity:	±0.85% FS
Hysteresis:	±0.5% FS

ABSOLUTE

Measurement range:	5 to 205 kPa absolute
Accuracy:	±3%
Transfer Function:	$V_{MAP} = 0.02 * P + 0.4$
Time Response:	< 10 ms

DIFFERENTIAL

Measurement range:	0 to 40 kPa differential
Operating span:	5 to 205 kPa absolute
Accuracy:	±5%
Transfer Function:	$V_{DP} = (P2 – P1) * 0.1 + 0.5$
Time Response:	80 ms ±30 ms

TEMPERATURE

Measurement range:	-40°C to 125°C
Accuracy:	±5%
Transfer Function:	$V_T = 0.02424 * T + 1.469$
Time Response:	3 min (based on response to Thermal Shock testing)

F. Reliability Considerations

Product life: 5000 operating hours for automotive PEM fuel cell
10 years for stationery PEM fuel cell

MTBF: Prototypes = no design effort
Production = theoretical and empirical tests

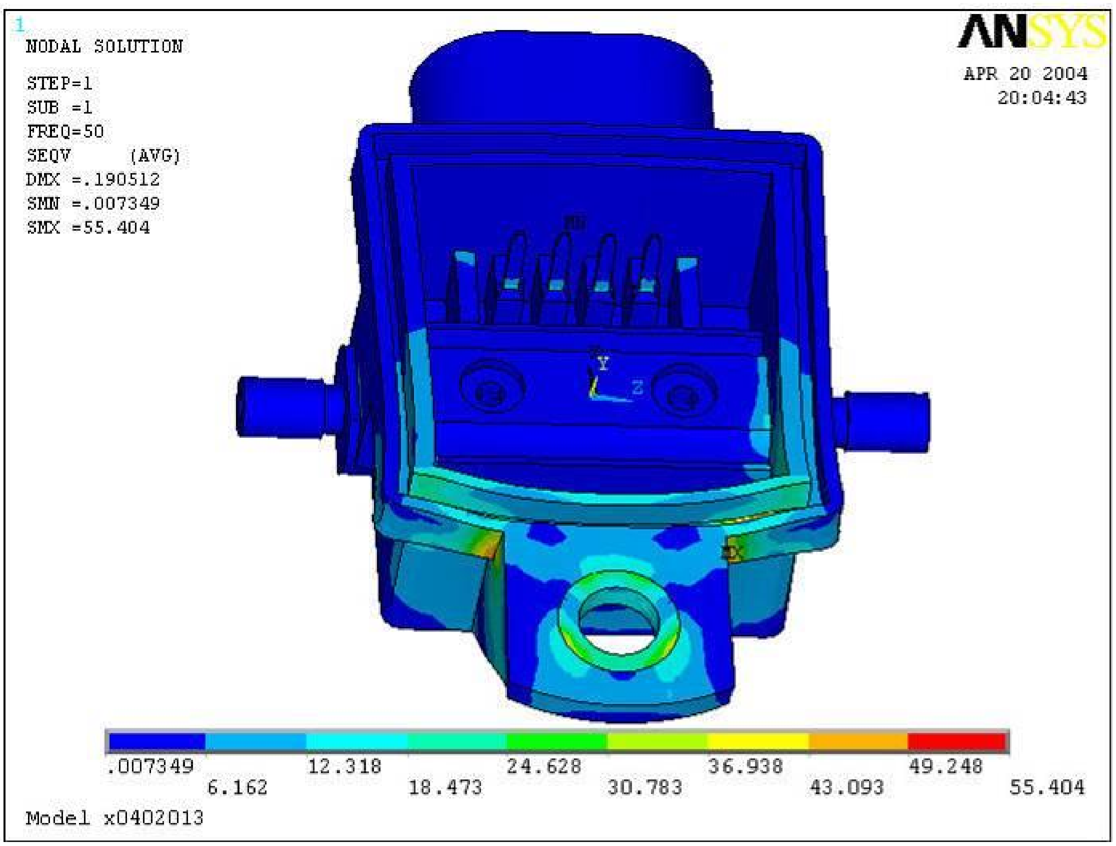
G. Internal Development and Qualification Tests

Test	Specification	Description	Quantity
1.0 Durability	Honeywell	-40-125C, 0-30 kPa abs, 500 cycles, Air, Powered	3
2.0 Thermal Shock	MIL-STD-202G Method 107G	-40-125C, 30 minute dwell, <5 second transfer, 500 cycles Air, 100 cycles Liquid, Powered	16
3.0 Vibration	MIL-STD-202G Method 204D	10g, 100-1000 Hz, Air, Powered	16
4.0 Salt Atmosphere (Corrosion)	MIL-STD-202G Method 101E	Condition A: 96 hours, 5% mist solution, Powered	16
4.1 Input Current	Honeywell	-40:25:125C, Air, Powered	16
4.2 Intermittent Circuit	Honeywell	25C, Air, Powered	16

4.3 Short Circuit	Honeywell	25C, Air, Powered	16
4.4 Voltage Transients	Honeywell	25C, Air, Powered	16
5.0 Humidity	MIL-STD-202G Method 103B	95% Rh, 40C, 96 hours, Powered	8
5.1 Dielectric Withstanding Voltage (High-Pot)	MIL-STD-202G Method 301	1 kV, >5.5 MΩ:<180μA	8
6.0 Pressure Leak	Honeywell	-40:25:125C, Air	8
6.1 Mechanical Shock	MIL-STD-883E Method 2002.3	50g, 10 ms, 3-axis	8
7.0 EMC/ESD	Honeywell IEC 61000-4-2 ISO 10605	30 V/m, 80 MHz – 1 GHz, 80% modulation ± 8 kV	2
8.0 Impact Drop	Honeywell		8
9.0 Temp Storage	Honeywell	-40C, 150C, 300 hours	6

FEA Modeling: Stress Analysis

Configuration: Frequency - 50 Hz, Acceleration – 10g in X dir



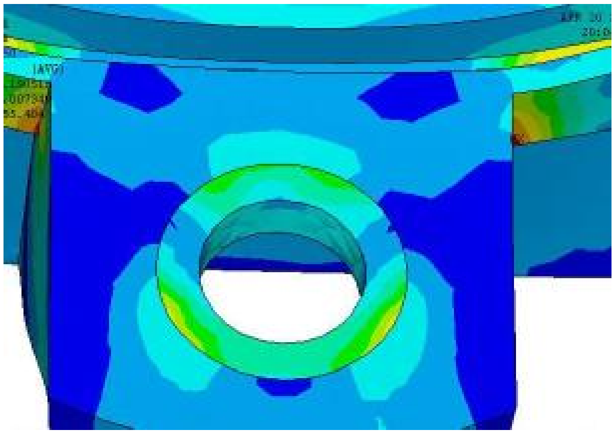
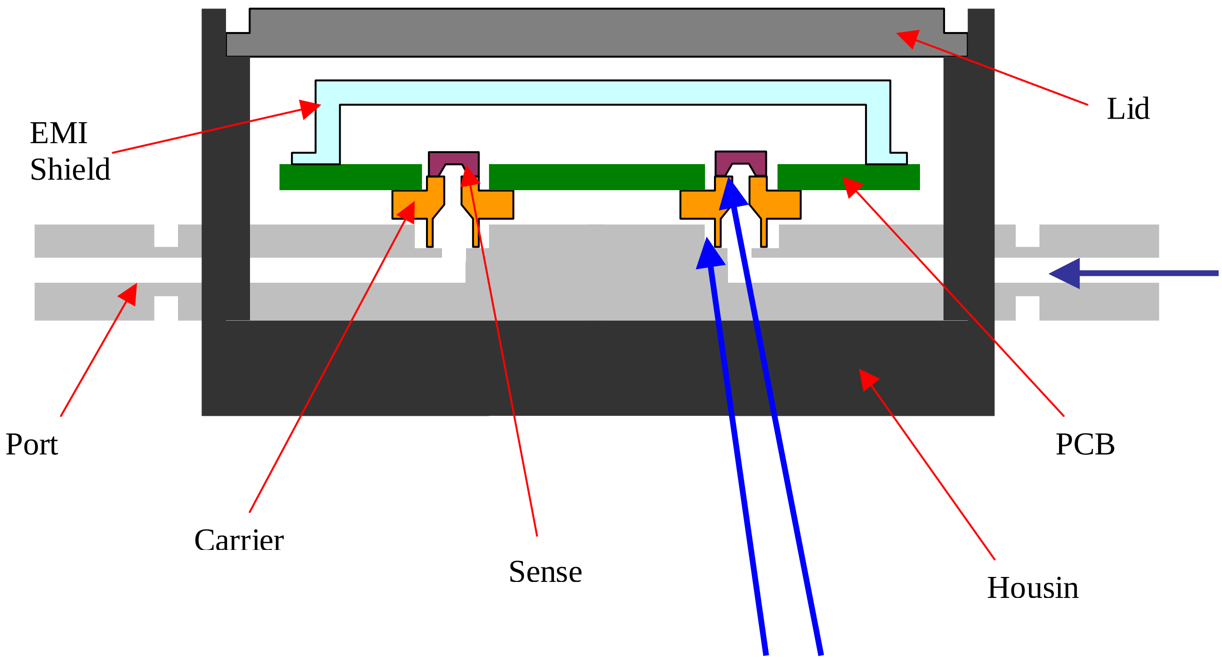
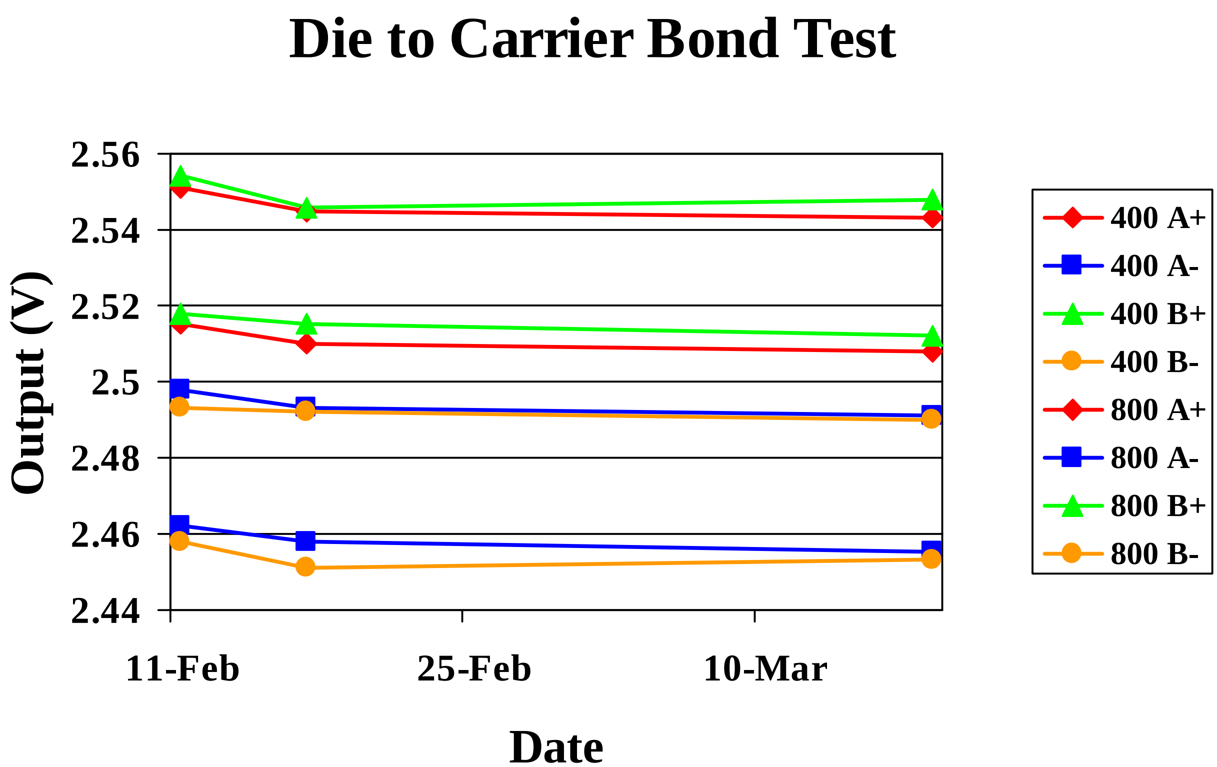
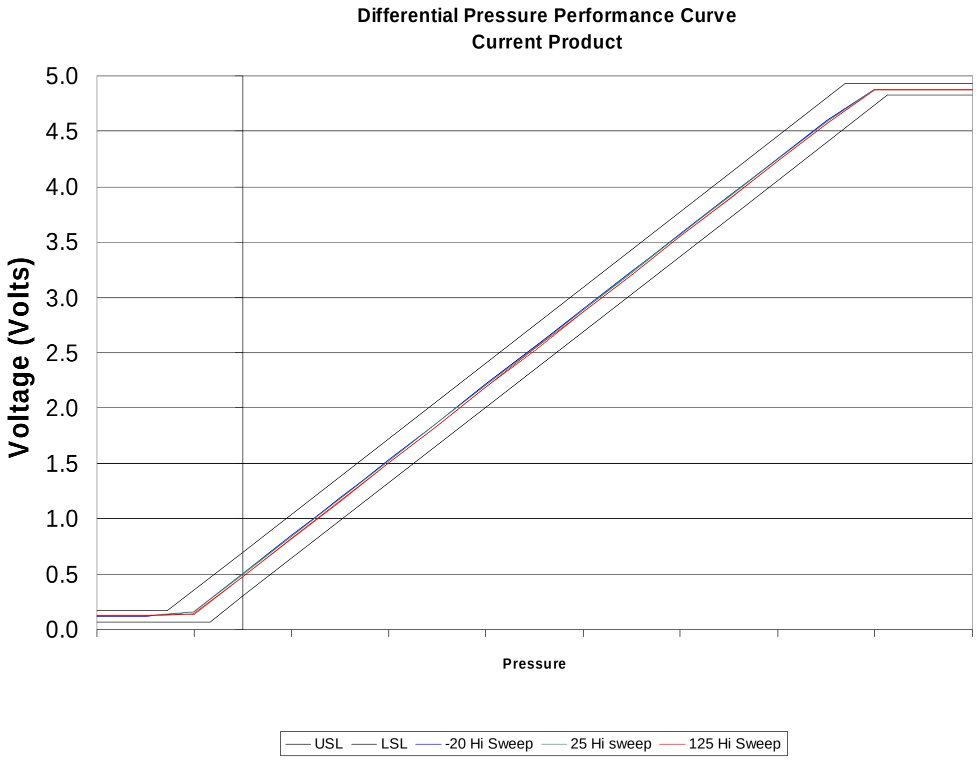


Figure 2 Assembly

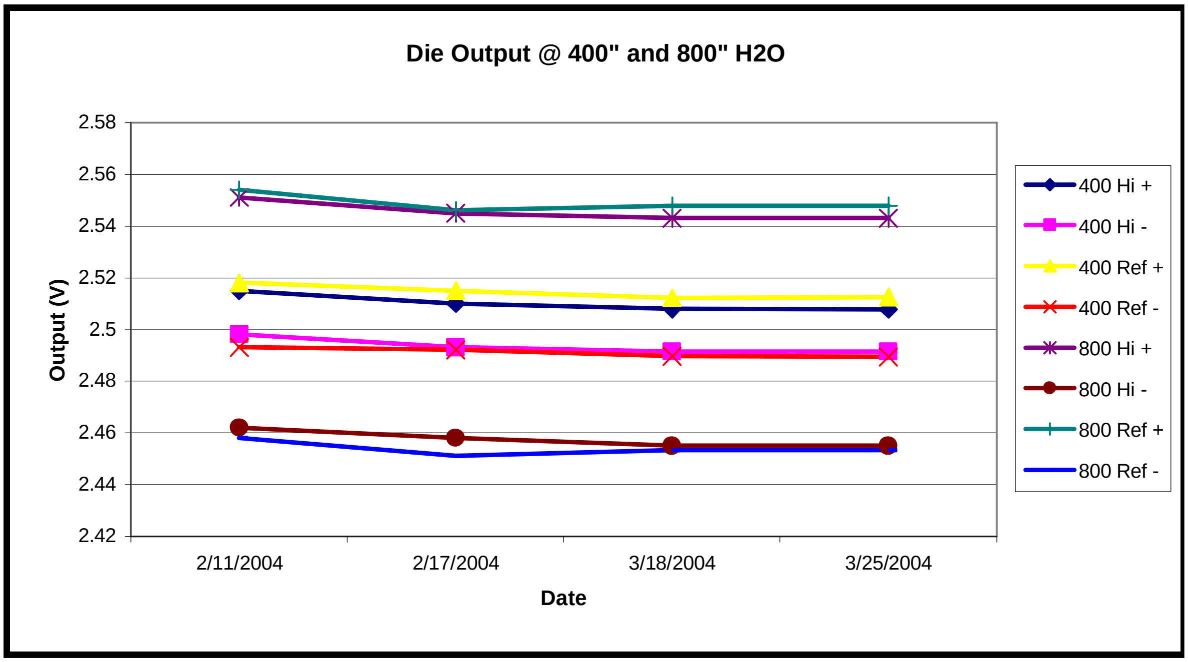


Testing of Pressure Sensors

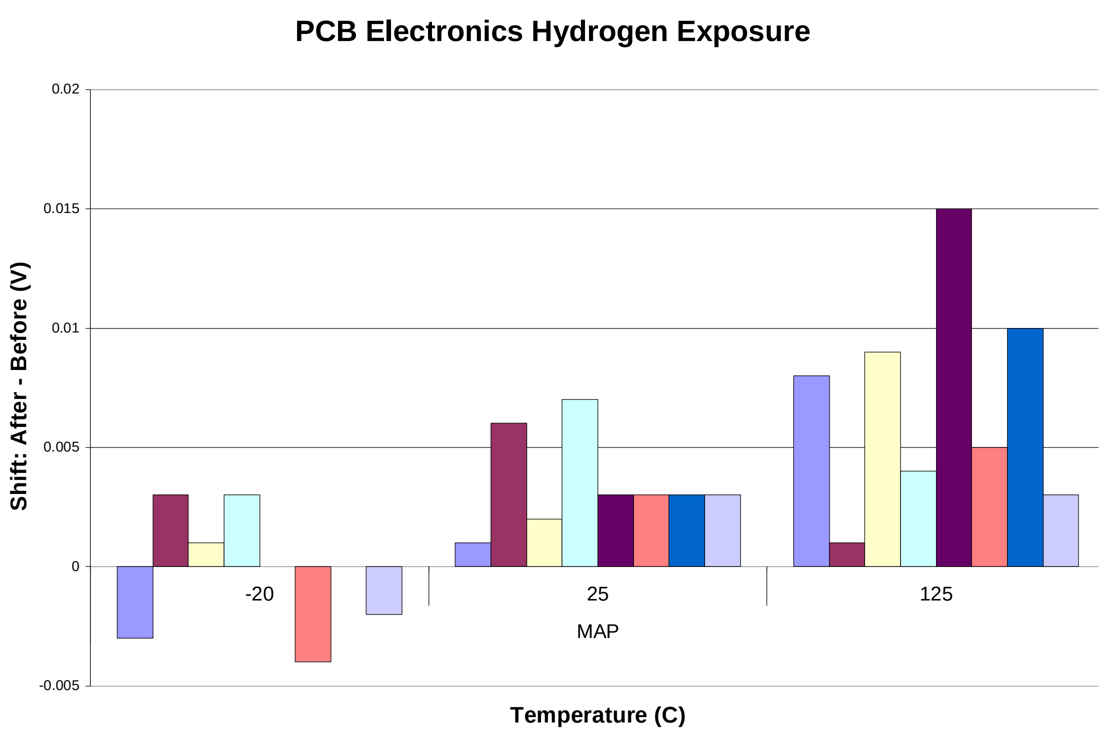


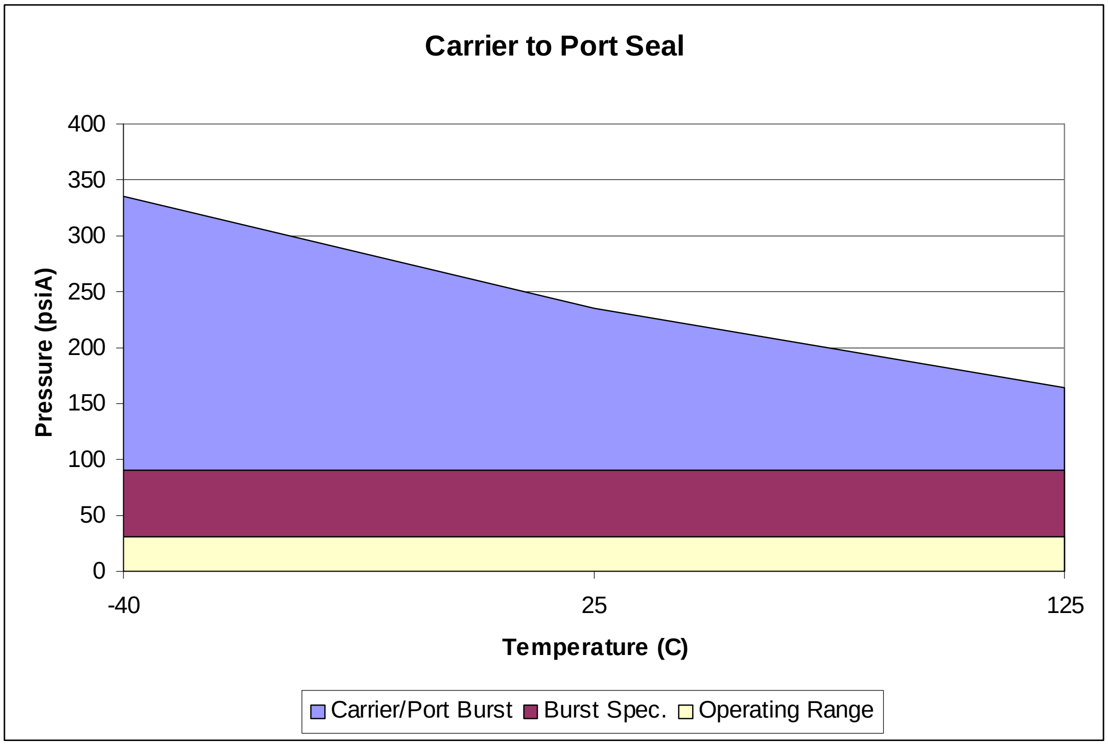


Graph below shows stability of sense die during Hydrogen gas exposure



– **Maximum 0.3% FS shift shows stability of PCB and electronics during Hydrogen exposure**

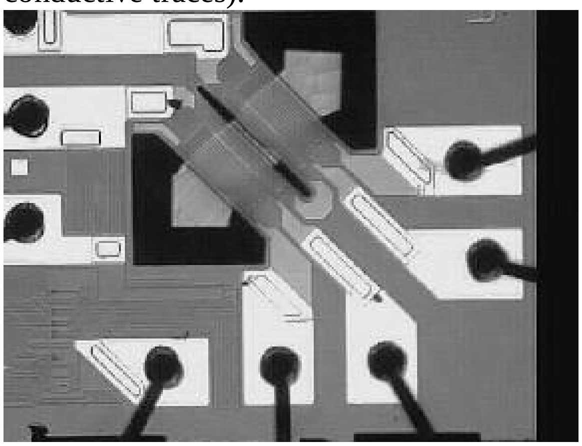




At the conclusion of this test series, the sensor design was essentially complete. The next step in the development process would be to commit substantial resources to tooling and capital to produce significant quantities of production quality sensors. At this point, a revisit was made to the potential users to determine their level of interest in this new pressure sensor. By this time, the users had gained sufficient experience with off-the–shelf automotive pressure sensors that they saw no need for a newer custom designed sensor. Accordingly, further development of this pressure sensor was halted and resources redirected to the more unique airflow and humidity sensors.

Airflow Sensors

The original requirements for Flow Sensors in the PEM Fuel Cell application were directed towards large volume Airflow Sensing. The original targets were full scale of 400 SLPM for automotive and 4000 SLPM in stationary fuel cell power plants. Honeywell Sensing and Control had extensive commercial experience (since 1986) in low cost, high accuracy thermal flow sensing up to 1 SLPM. Using flow sampling in bypasses, the flow range was extended to 200 SLPM. The technology was not suitable for use in condensing or aerosol environments, although continuous operation at 125°C was not a problem. The wet environment would cause early failures both at the chip level and between interconnections at the package level (wire bonds and conductive traces).



The current technology was a micromachined thermal sensor shown above. The sensing and heating circuits were separated and the sensor output was designed as a difference of 2 temperature sensors one on each side of the heater (upstream and downstream). The heater and sensors consist of a thin film of high tcr (thermal coefficient of Resistance) platinum deposited between two layers of silicon nitride passivation. Holes are cut through the passivation and silicon is anisotropically etched from under the Si_3N_4 to form 2 bridges each of which includes one temperature sensor and ½ of the heater. Each bridge is arbitrarily designated as either upstream or downstream and is approximately 150 µm square. The heater is set to draw power until it is 160°C above ambient. Under zero flow, the 2 temperature sensors have the same output, giving zero voltage difference. When flow is applied, the upstream sensor cools down and the downstream sensor heats up thus giving a voltage difference proportional to mass flow. The sign of the voltage difference tells the direction of the flow.

Because of the small size, extremely low thermal mass and large temperature gradients, this type of sensor is inherently very fast (about 1 msec) and has high repeatability and low hysteresis. Its proportional method of sensing gives maximum accuracy near zero flow and most errors are proportional to reading rather than full scale. It is easily packaged to have low pressure drops over wide flow ranges. Its fast response time dictates that laminar flow must take place over the chip since turbulence will not be averaged out in the output and will appear as a noisy signal. Using computational fluid dynamics (CFD) it is possible to design a bypass assembly that preserves the advantages of the low flow sensor while allowing the measurement of much higher flow rates, although it was a major stretch to go beyond 200 SLPM. Proper inlet and outlet designs also provide limited protection from high velocity particles and aerosols but the wet environment still causes premature failures at the interconnections due to galvanic corrosion or dendritic growth. What was needed was a desensitized chip with no electrical connections exposed to the environment. We tried both coated wirebond devices as well as developing a new chip with a completely passivated sensing surface and all electrical connections **T**hrough **T**he **W**afer to the backside, where standard flip chip assembly techniques can be used to build a rugged sensor. The micromachined elements were eliminated and the Pt deposited on fused quartz to achieve the desired desensitization. Examples are shown below.

Figure 3a TTW chip with back side interconnects

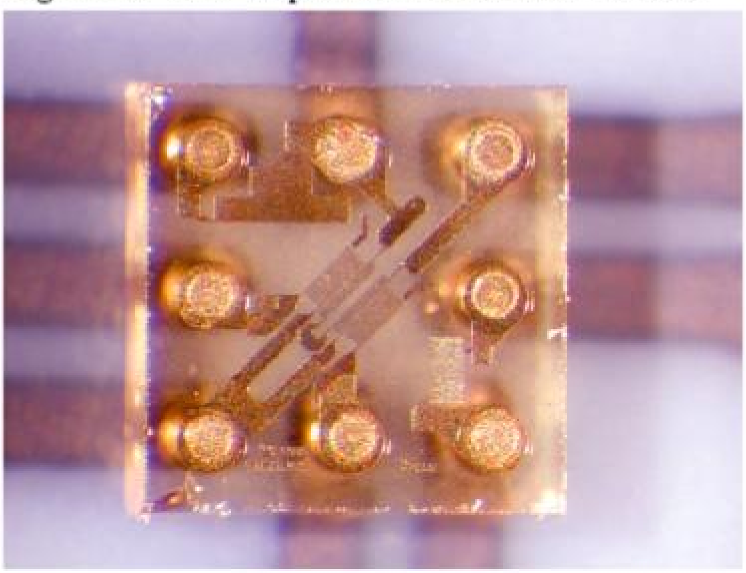
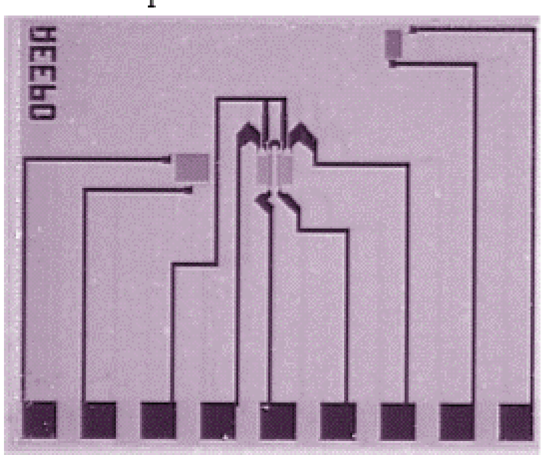


Figure 2a Photo of the wire bond version of a rugged sensor chip



Virtually all actual sensor development used the wire bond chips. Numerous attempts to build working sensors with TTW chips resulted in premature failures. In other words, the chips worked quite well as sensors for a short time and then died when open circuits appeared inside the through wafer connections. This was traced to a fundamental incompatibility between the chemistry and structure of the via fill versus the processing required to deposit, etch and anneal the platinum thin films. The via fill consisted of tungsten powder coated by copper metal, the details of which were not shared by the vendor with Honeywell. At the conclusion of Honeywell processing, most vias were depleted of copper. Improvements were made over several wafer runs, but completely reliable via connections were never achieved. All test data reported are with wire bond devices.

1. Product Considerations/Specifications

A. Application and Operational Description

This Flow sensor is a feasibility prototype. The design is for PEM fuel cell use.

The description of this flow sensor is based on target specifications compiled through the MDPD exercise and customer application requirements. The current revision is due to initial testing and modeling. Normal operation of the sensor is in a non-condensing environment. However, the sensor will withstand periods of condensation although functionality may be affected.

B. Features/Functions

Linear voltage output

Diagnostics & Protection:

Reverse supply protection
Short circuit protection (output shorted to ground)
Bridge sensor diagnostics
ASIC self-check diagnostics

Temperature Sensor output:

Operating temperature:	-40°C to 85°C
Sensitivity:	0.5 to 4.5VDC linear
Response time:	10 sec
Accuracy:	±3%

C. Construction and Appearance

Housing and port material: Ryton, opaque black.

Final material selection is heavily dependent on resistance to hydrogen embrittlement and DI water corrosion. The figures are for reference only, the first is 0-400SLPM, the second is 4000SLPM

D. Installation/Mounting

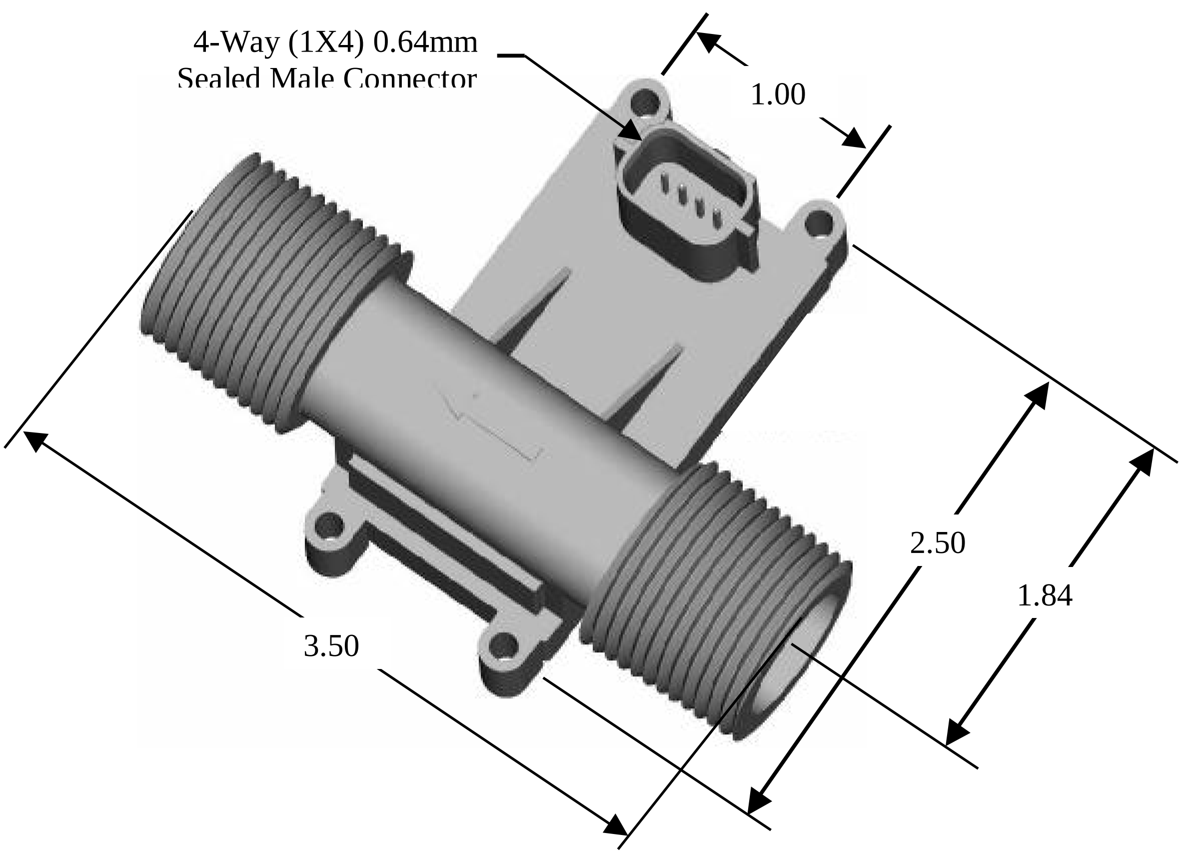
Threaded ports:	(400 SLPM) ¾-14 NPT or SI Metric Equivalent
	(4000 SLPM) 2 ½" or SI Metric Equivalent
Torque:	(400 SLPM) TBD
Mounting:	(4) Screw flange
Torque	TBD
Connector:	Packard-compatible, sealed, overmolded
Pin out:	VCC, Ground, V_{OUT} (Flow), V_{OUT} (Temperature)

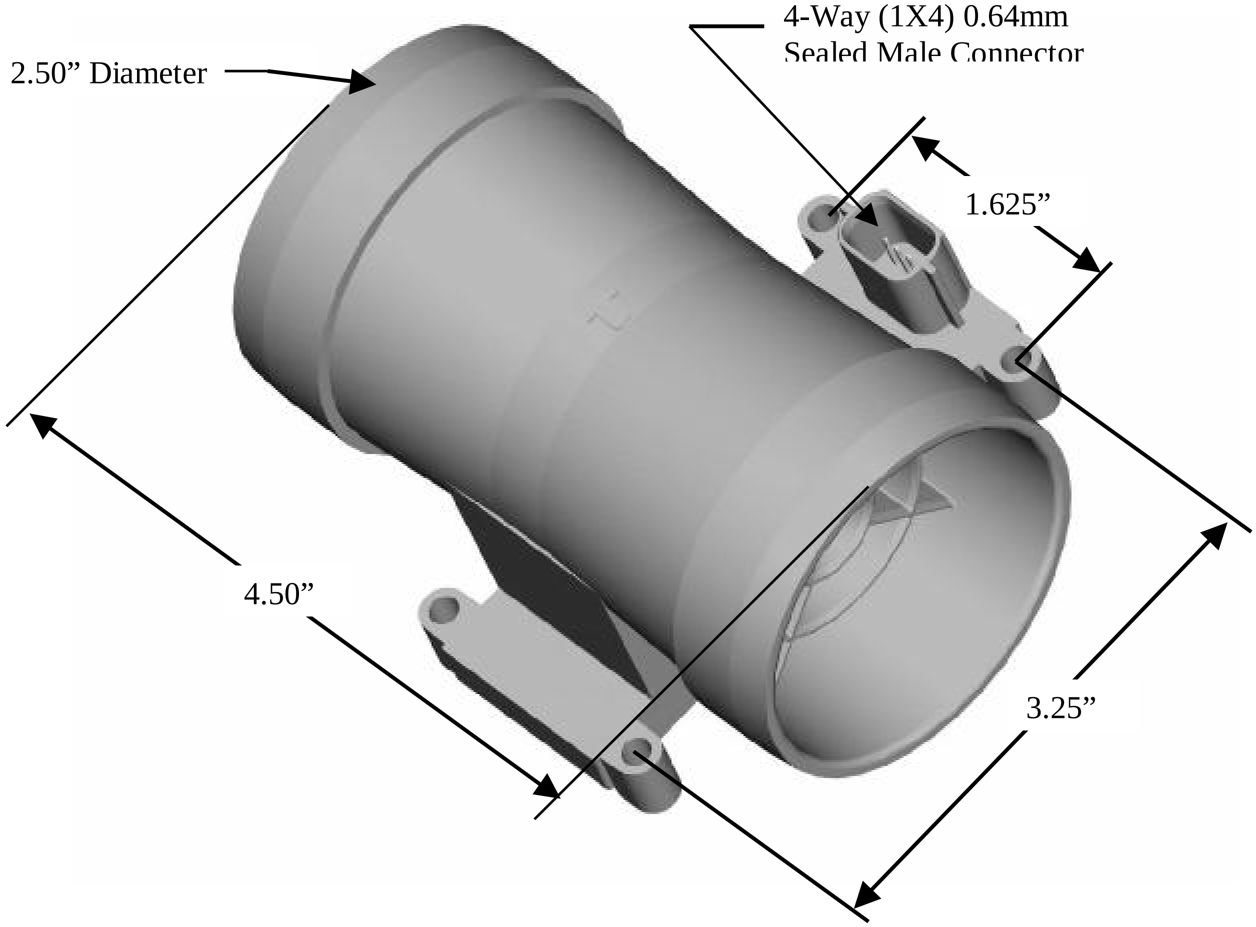
E. Performance

Supply Voltage:	10 to 25 VDC
Supply Current:	30 mA max
Measurement range:	0 to 400SLPM prototype #1
	0 to 4000SLPM prototype #2
Output:	0.5 to 4.5 VDC linear
Null output	0.5 VDC
Operating temperature:	-40°C to 85°C
Storage:	-50°C to 125°C
Media composition:	H_2 0-100%, CO_2, N_2, H_2O, CO, 100% DI water
Response time:	20ms
Condensation recovery time:	30 sec. @ 5mph air flow to 62.3% of actual reading
	NOTE: test condition (95% Rh to 115%RH back to 95%
Accuracy:	±2%
Repeatability:	±0.5%
Pressure drop	3mbar max low flow
	10mbar max high flow
Pressure:	1 to 3atm

Diagnostic:

Bridge sensor connection lost	Vout = >4.75 VDC
Bridge sensor common mode error	Vout = >4.75 VDC
ASIC self-check error	Vout = <0.15 VDC





Agency Approvals

Prototypes: none, design to operate in an explosive media stream
Production: TUV, CSA (FC1), IEC, VP119

F. Product Safety Requirements
TBD CSA and ANSI customer requirements

G. Reliability Considerations
Product life: 5000 operating hours for automotive PEM fuel cell
10 years for stationery PEM fuel cell
MTBF: Prototypes = no design effort
Production = theoretical and empirical tests
Product Release: per Honeywell standard product release testing suite

H. Cataloging Requirements
Prototypes: Experimental X-number
Production: Released part number

2. **Test/Approvals Requirements**

A. Customer Field/Beta Tests

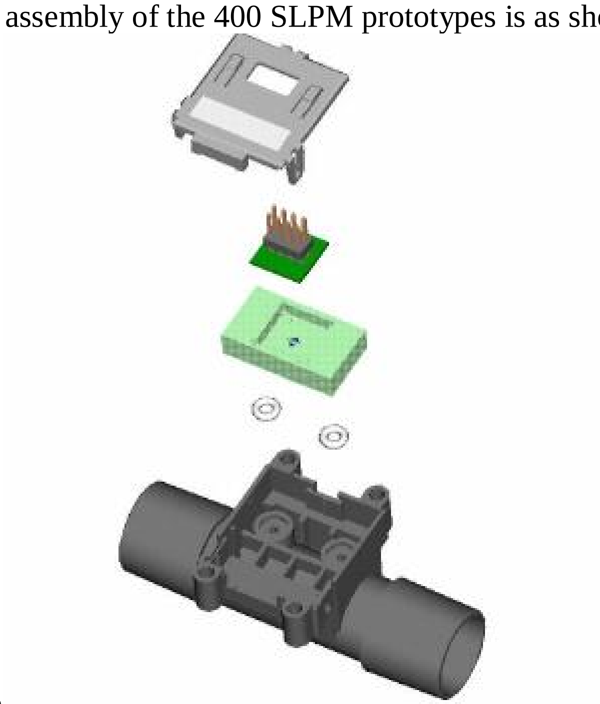
This flow sensor is intended for customer field tests. These tests are scheduled to start 4/15/2005 and require field feed back by 9/30/2005.

B. Internal Development and Qualification Tests

Shock:	50g, 10 ms, 3/ axis	MIL-STD-883
Vibration:	10g, 10 to 1000 Hz	MIL-STD-202F method 204D
Insulation:		MIL-STD-202F method 302
Dielectric:		MIL-STD-202F method 301
Sealing:	IP67 immersion	
Salt Spray:	96 hour, 5% solution mist	MIL-STD-202F method 101D
Humidity:	95%Rh non-condensing, 96 hours	
Temperature cycle:	-40°C to 85°C, 100 cycles, 10C/min rate	
EMI susceptibility:	30V/m 80MHz-1GHz, 80% mod	IEC61000-4-3
	100V/m design goal	TBD = customer requirements
ESD susceptibility:	±8KV direct contact	IEC61000-4-2, ISO 10605

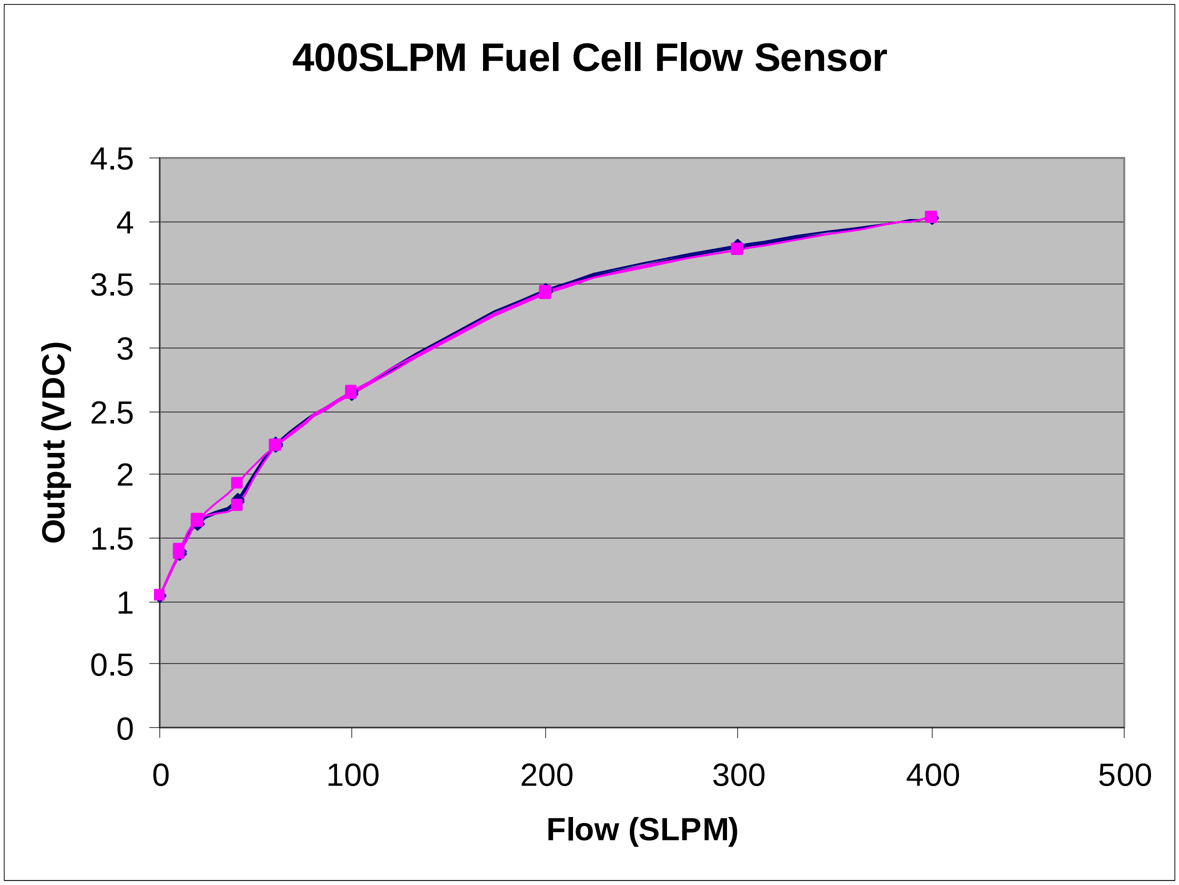
Assembly

The assembly of the 400 SLPM prototypes is as shown



here

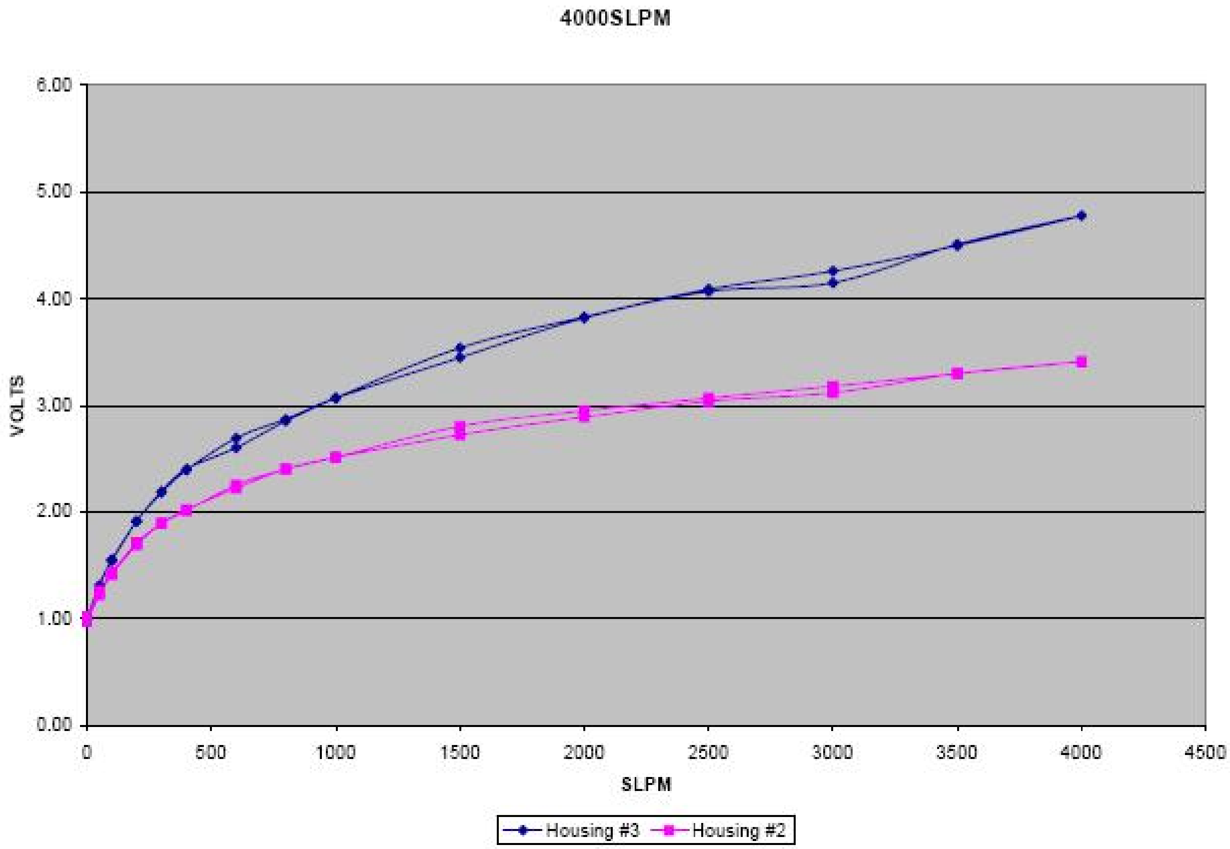
Typical test data was a curvature, best described (mathematically) as a 7th order polynomial. Test data here

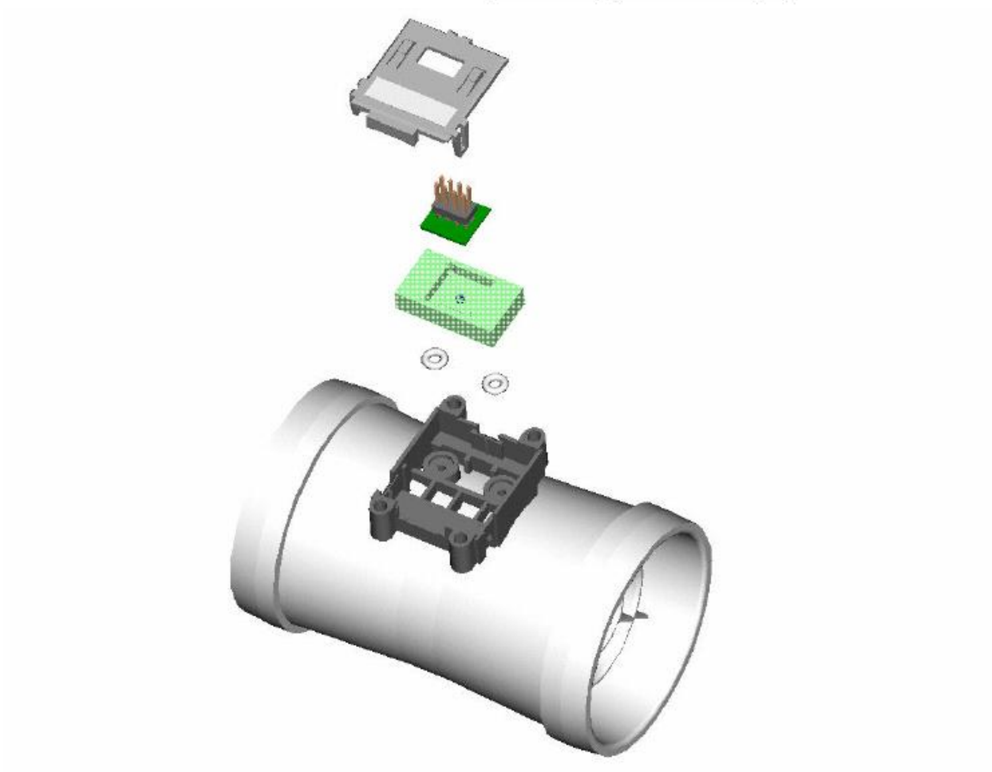


All samples of both this first 400 SLPM package as well as the 4000 SLPM package were built using Stereo-lithographic (SLA) prototype parts. The concepts were designed and computationally tested using CFD techniques.

The 400 SLPM output (above) was achieved as amplified sensor output without using an ASIC to linearize the output. Attempts to use the past appliance based ASIC were unsuccessful because the raw chip output was inadequate to achieve the accuracy desired. This was particularly true at the extremes of low and high flow rates. In addition, in order to achieve consistent and well behaved output, it was necessary to power the heater at 18VDC which was higher that the supply voltage preferred by most users.

Similar SLA prototype results were obtained at 4000 SLPM





The last major obstacle in demonstrating a concept involved dealing with condensation. While several coatings, like Teflon or Parylene, have been used to enhance reliability and guarantee smooth operation, the PEM fuel cell environment has so much water that condensation can actually block the bypass tube, driving the sensor output to zero. With the flowtube filled by water, there isn't any flow in the bypass and therefore, no signal. This phenomenon was consistently observed in the Fuel Cell Simulator (a copy of the same test system used at Plug Power). The technical solution was to heat the bypass by mounting flexible heaters on the bypass to raise the bypass temperature above the dewpoint. With this improvement the concept worked well and reliably.

At this point, we felt ready to proceed with prototype plastic tooling and molds. We also prepared circuit revisions involving the use of a more advanced ASIC able to perform higher order math, more quickly. Minor modifications to both housings and the bypass would also provide more flow to the sensor and therefore increase the output. However, continuing reviews with DOE and potential users revealed that Control Systems development no longer needed airflow as an input because eon-board reformers were no longer required. It was thought that Hydrogen flow would be more useful although it wasn't certain that even hydrogen flow was strictly required.

Trying to adapt Honeywell's airflow sensing technology to the sensing of hydrogen would require truly major R&D effort as well as capital expenditure. First, it would be necessary to use a metal film other than Platinum, where resistance drifts unpredictably when hydrogen is absorbed by the platinum. This can be mitigated by using autozeroing circuits, at least in the short term. Long term effects of exposure are unknown and weren't tested. In addition, since hydrogen has a much higher thermal conductivity and much lower specific heat than air, a thermal hydrogen flow sensor would require substantially higher voltage to operate and the output signal would be significantly reduced for a given flow rate. A final major barrier to extending the airflow sensing technology into hydrogen flow sensing is that completely new test and calibration facilities would need to be implemented in order meet safety requirements and deal with hydrogen leakage and sealing. Given all of these objections and considering that there is no established requirement for hydrogen flow sensing, work was halted and resources redirected to the Humidity Sensor.

Humidity Sensor

The measurement of water content in the PEM Fuel Cell environment in a cost effective manner was a major gap in sensing technology. Sensors fully capable of withstanding the environment are very expensive and low cost humidity sensors cannot survive the environment. Honeywell has some low cost capacitive membrane humidity sensors that are more durable than other sensors of similar technology. The sensors work by having a polyimide film in between two capacitor plates. The polyimide absorbs water molecules from the atmosphere which changes the dielectric constant of the film and thus the capacitance of the sensor. The amount of water molecules absorbed is dependent on the relative humidity between 2% and 90-95% RH.

This portion of the development program was to ruggedize the best of our sensors so that they could accurately and reliably withstand the PEM Fuel Cell environment. The failure modes to be overcome included thermal degradation (and hard failure) due solely to the higher temperatures, short circuiting (and hard failure) of dielectric membranes under condensing conditions and the time dependent (and unpredictable) sensitivity shifts when operating at RH greater than 90%. At very high humidities, the polyimide swells with time and opens up more potential sites for water molecules to occupy. This causes a time dependent sensitivity shift in the sensor that can be reversed, over time, by baking at low humidity or simply waiting a very long time at low humidity.

The strategy to mitigate the high temperature and high humidity failures was to use a previously developed high temperature Humidity chip, the "Ultra H" and design a heated package for it that would precisely lower the Relative Humidity to 90% maximum, even if the exterior of the package was at 100% RH condensing. That would eliminate any shorting problems and was expected to eliminate the sensitivity shifts.

1. **Product Considerations/Specifications**

   A. Application and Operational Description
   This humidity sensor is a feasibility prototype for use in PEM fuel cells for automotive markets.

The objective of this project is to apply humidity sensing technology to the harsh environments of PEM fuel cells. Historically, most humidity sensor applications are HVAC markets. The environment in this market is usually room temperature and less than 70% humidity. Fuel cell environments are ambient high temperature and high humidity. This requires new design approaches in order to produce a more robust humidity sensor.

The description of this humidity sensor is based on target specifications compiled through the MDPD exercise and customer application requirements. The sensor will be designed to recover from a condensing environment but still respond in appropriate time for automotive systems. Additionally, temperature sensing will be incorporated into the package. It is intended to use an ASIC to provide critical signal processing. The ASIC will have the general capabilities of the ZMD 31050.

B. Features/Functions

Linear voltage output continuous within the specified range of operation

Hydrophobic PTFE filter to partially block condensation on the sensor

Diagnostics & Protection:

- Reverse supply protection
  - No function during reversed supply
  - Sensor functions normally when correct orientation restored
- Short circuit protection
  - Output = upper or lower supply rail during short
  - Sensor functions normally when short is removed
- Open supply or ground diagnostic
  - Output = lower supply rail when open
  - Sensor functions normally when proper connection is restored
- Internal fault diagnostic
  - Output = upper supply rail during fault
  - Sensor function recovery

Temperature Sensor output:

Operating temperature:	-40°C to 90°C
Sensitivity:	0.5 to 4.5VDC linear
Response time:	10 sec
Accuracy:	±3% of reading

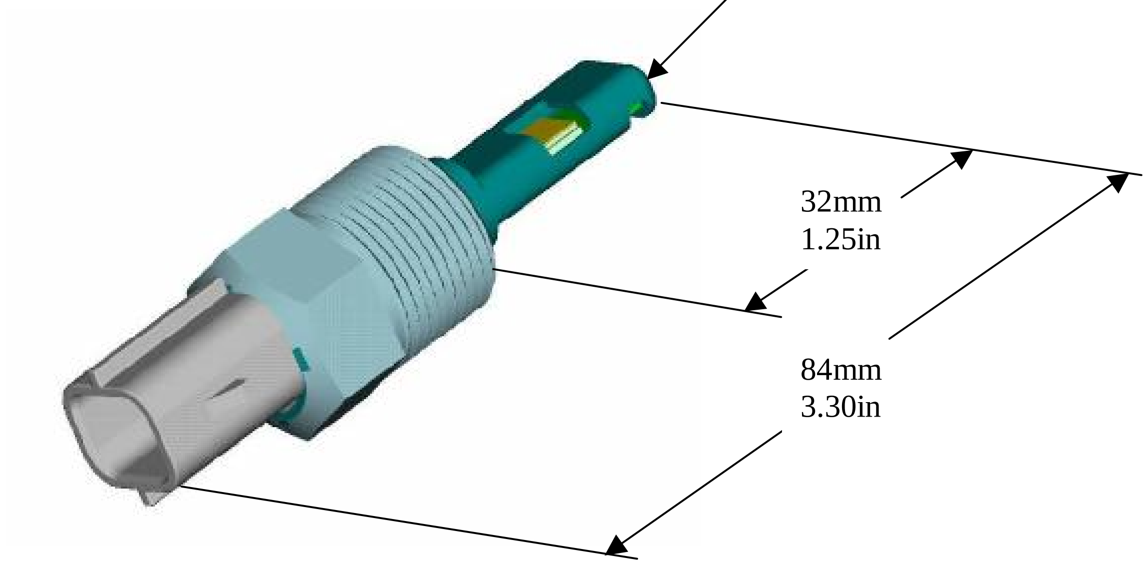
C. Construction and Appearance

Housing material: Radel R5100, opaque black

Final material selection is heavily dependent on resistance to hydrogen embrittlement and DI water corrosion.

D. Installation/Mounting

Threaded bushing:	M22 x 1.5
Mounting:	Hexagonal head with Viton o-ring seal
Connector:	4-pin (2x2) Packard-compatible, sealed, overmolded
Pin out:	VCC, Ground, V_{OUT} (Humidity), V_{OUT} (Temperature)



E. Performance

Supply Voltage:	7 to 25VDC
Power:	
Sensor	100mW
Heater	1000mW
Measurement range:	0 to 100%RH, non-condensing
Output	0.5 to 4.5VDC linear BFSL
Null output	0.5VDC
Operating temperature:	-40°C to 90°C
Storage:	-50°C to 125°C
Media composition:	0 to 100% H_2, CO_2, N_2, H_2O, CO, 100% DI water
Warm up time:	30sec
Response time:	5sec (62.3% of actual reading)
Condensation recovery time:	30sec @ 5mph air flow (62.3% of actual reading) NOTE: test condition = 95% RH to 115%RH back to 95%
Accuracy:	
80 to 100%Rh	±2%
0 to 80%Rh	±4%
Repeatability:	±0.5%
Pressure:	1 to 3atm

F. Agency Approvals

Production: TUV, CSA (FC1), IEC,VP119

G. Reliability Considerations

Product life: 5000 operating hours for automotive PEM fuel cell
10 years for stationary PEM fuel cell

MTBF: Prototypes = no design effort
Production = theoretical and empirical tests

Product Release: per Honeywell standard product release testing suite

2. Test/Approvals Requirements

A. Customer Field/Beta Tests

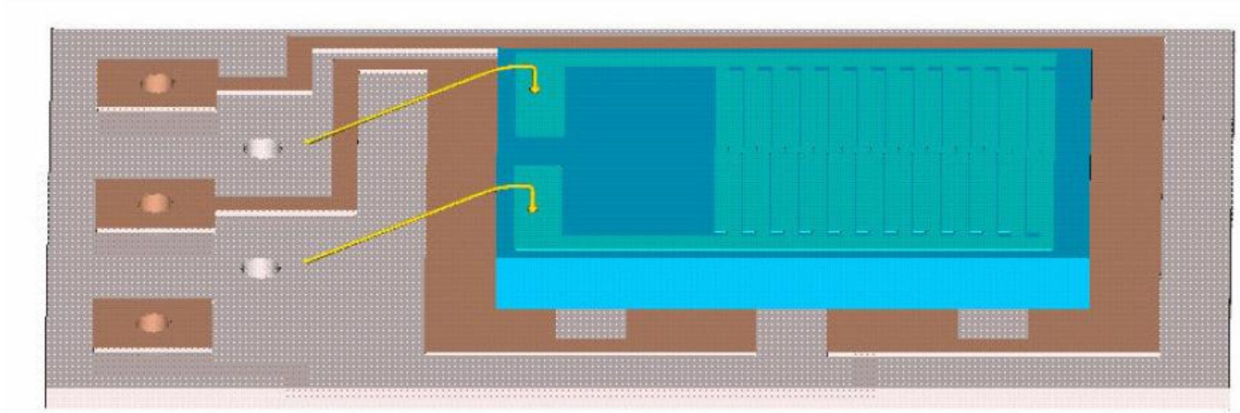
This humidity sensor is intended for customer field tests. These tests are scheduled to start 4/15/2005 and require field feedback by 9/30/2005.

B. Internal Development and Qualification Tests

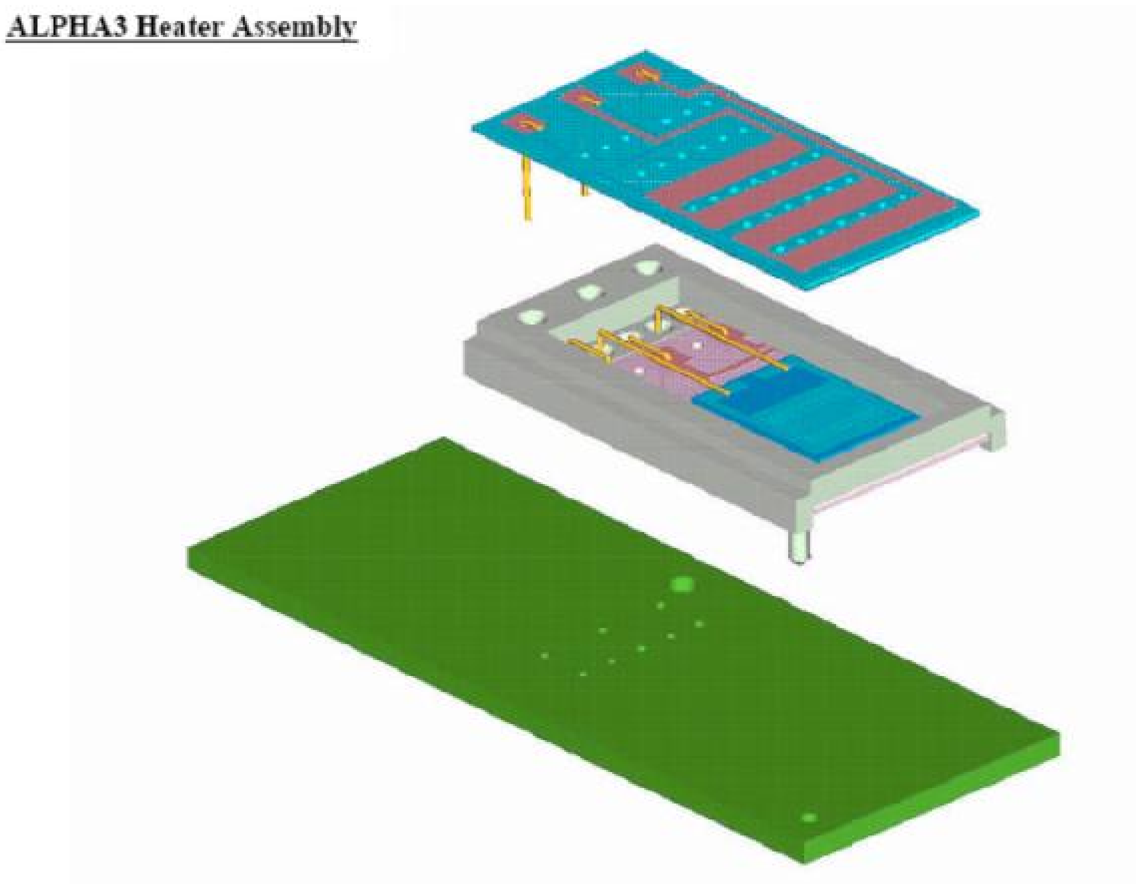
Shock:	50g, 10 ms, 3/axis	MIL-STD-883
Vibration:	10g, 10 to 1000 Hz	MIL-STD-202F method 204D
Insulation:		MIL-STD-202F method 302
Dielectric:		MIL-STD-202F method 301
Sealing:	IP67 immersion	
Salt Spray:	96 hour, 5% solution mist	MIL-STD-202F method 101D
Humidity:	95%Rh non-condensing, 96 hours	
Temperature cycle:	-40°C to 90°C, 100 cycles, 10°C/min rate	
EMI susceptibility:	30V/m 80MHz-1GHz, 80% mod	IEC61000-4-3
	100V/m design goal	TBD = customer requirements
ESD susceptibility:	±8KV direct contact	IEC61000-4-2, ISO 10605

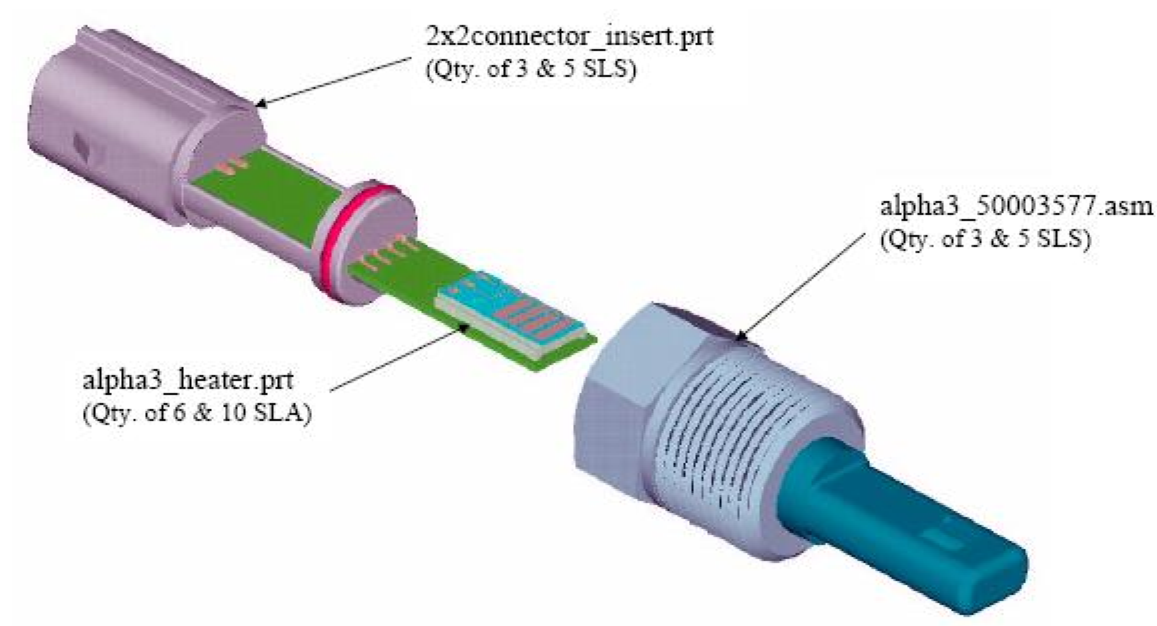
This picture shows the high temperature Ultra H chip mounted on a thick film ceramic heater

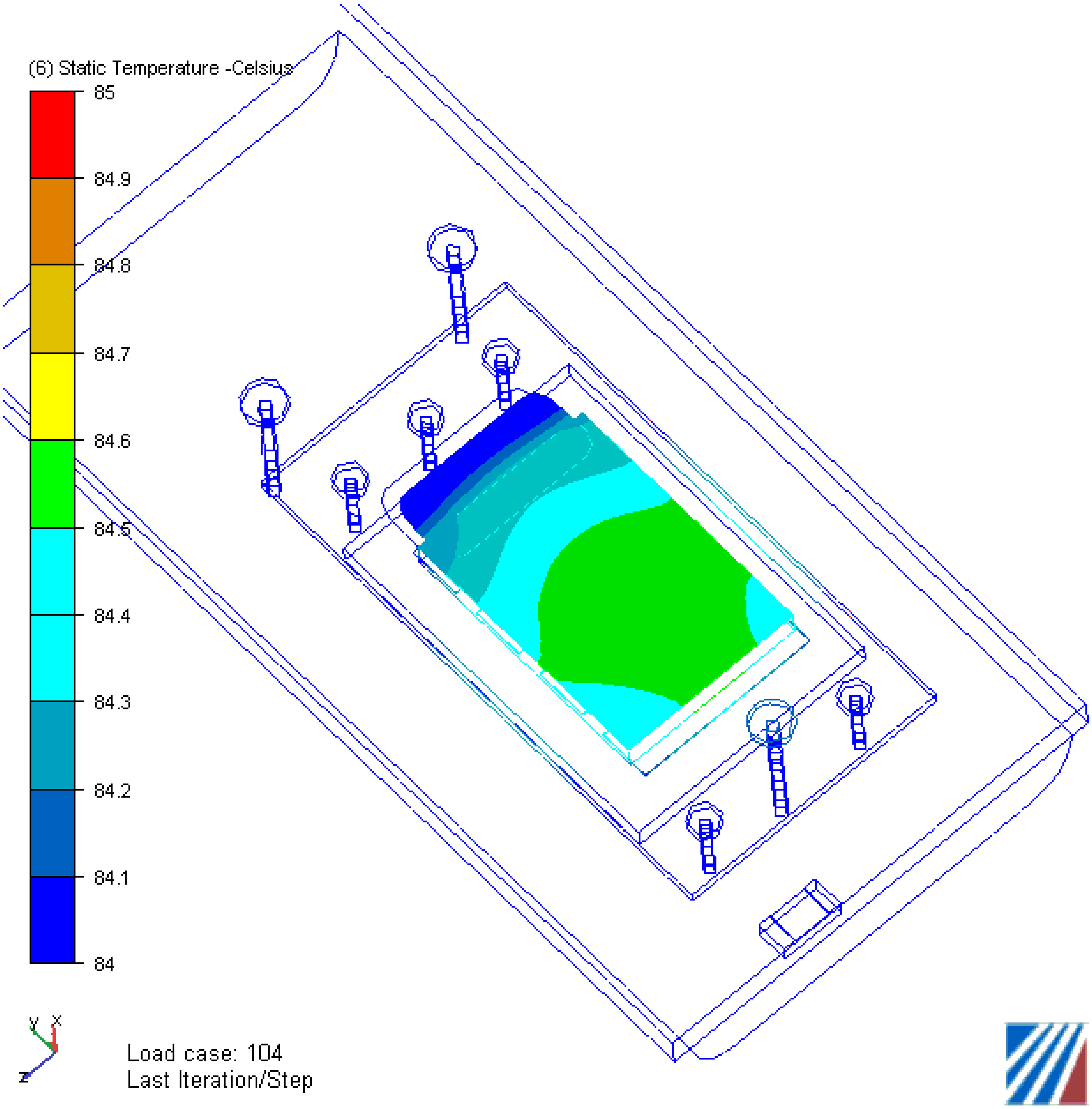
[redacted]



The heated chip is then mounted inside a heated chamber that is specifically designed to achieve uniform heating to 0.2°C uniformity in order to precisely reduce the relative humidity of the chip surface into the linear and time independent range of the sensor. The prototypes were built using conductive pins, silver filled epoxy adhesives and solder joints. A production sensor would use a three dimensional package with integral heaters and embedded interconnections. Candidate technologies would be Low Temperature Co-fired Ceramic or molded leadframe thermal plastics with attached flex heaters. An extensive computer modeling effort was undertaken prior to fabrication of the package and the test results matched the predicted values. Here is the heated package assembly with the previously shown chip/ceramic, the second is the complete assembly.

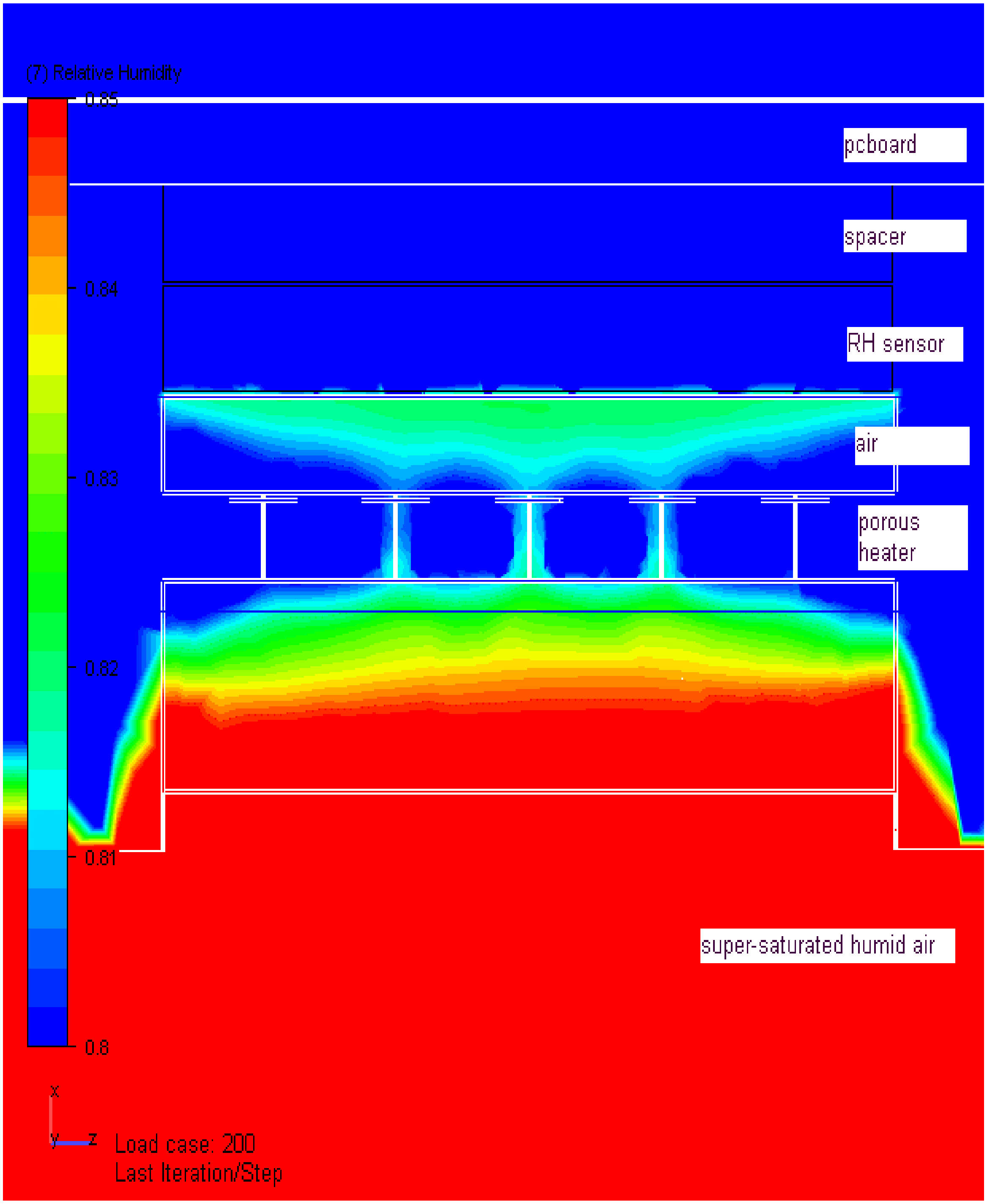


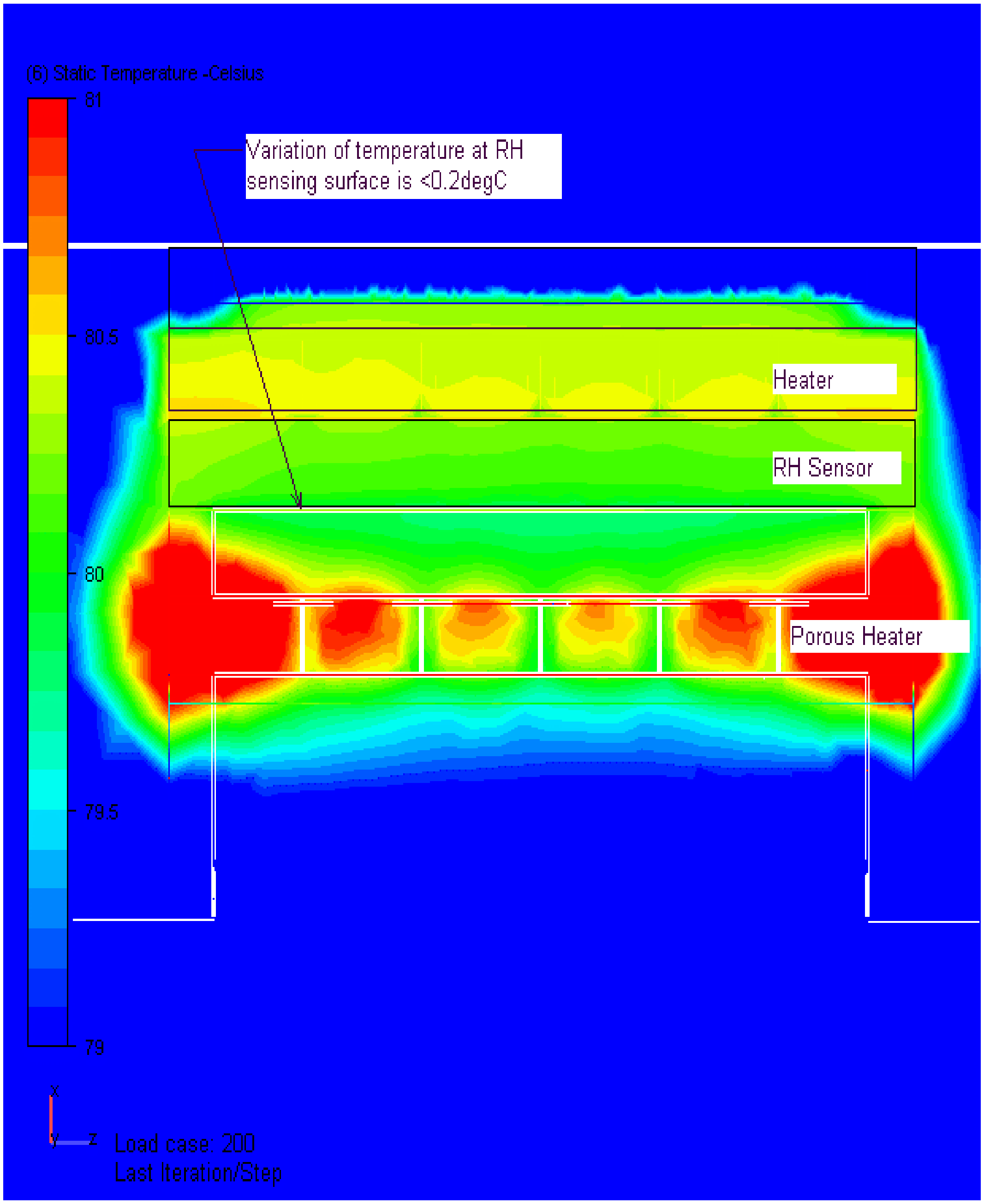




The figure above is the validated thermal model for the alpha 3 configuration

On the next pages are photos showing a graphical version of the analysis used to design the "oven". Sensors in these configurations were built on prototype tooling and submitted for environmental and life testing. Hydrogen leak testing was performed by an outside contractor and the balance of the testing was done internally.


(7) Relative Humidity
0.85
0.84
0.83
0.82
0.81
0.8
pcboard
spacer
RH sensor
air
porous
heater
super-saturated humid air
Load case: 200
Last Iteration/Step



Test Results

While the heated sensor worked well in terms of withstanding condensing, the response time was slowed to 6 seconds versus a specification of 5 seconds. More holes or larger holes would be needed to get acceptable response time. This is not a major effort.

Here is the outside testing report detailing Helium leak tests preformed on three configurations of the humidity sensor. Two groups passed all tests and one was marginal. A final configuration was not selected because work had stopped on the project.

Helium Leak Testing, Inc. QHe+

19348 Londelius Street, Northridge, Calif. 91324
(818) 349-5690 (800) 423-1701 FAX (818) 717-8584
www.heliumleaktesting.com
E-mail: info@heliumleaktesting.com

TO: Honeywell Sensing and Control
Plant 2, B3-546
11 West Spring Street
Freeport, IL 61032

DATE: **4-26-2005**

HLT JOB NO: **51276**

DESCRIPTION 1 – EPOXY E815 HYDROGEN SENSOR PROTOTYPE
1 – EPOXY FP4401 HYDROGEN SENSOR PROTOTYPE
1 – EPOXY 1059R HYDROGEN SENSOR PROTOTYPE

Date of Test: 4-25-05

Test Operator: C. Cater, NDT Level II Inspector

Instrumentation: The test was performed with a Pfeiffer Helium Mass Spectrometer Leak Detector (MSLD), Model HLT-260, S/N 4011004057, in accordance with Honeywell Sensing and Control PO# 2715553 and MIL STD 883E, Method 1014.9 Condition A4.

The MSLD was calibrated with an LDS Calibrated Leak, S/N 3952, ID# 100092, calibration due 12-10-04.

The sensitivity of the MSLD was such to detect a leak greater than or equal to 5 X 10-12 sccs He with an external pressure of one atmosphere.

A Wallace & Tiernan 0-30 PSIA Gauge, ID#100325, calibration due 5-27-05 and

an Ashcroft 0-60 PSIG Gauge, ID#1000323, calibration due 10-21-05 were used to monitor the test pressure.

The Sensors were pressurized and held for 1 minute intervals. Test Results are

listed below.

P/N	**BKGD**	**7.3 PSIA / HE**	**14.6 PSIA / HE**	**30 PSIA / HE**	**45 PSIA / HE**
E815	1.8 E-8 cc/sec	9.3E-6 cc/sec	2.1E-5 cc/sec	5.5E-5 cc/sec	1.0E-4 cc/sec
FP4401	9.8 E-9 cc/sec	1.0E-7 cc/sec	1.4E-7 cc/sec	4.2E-7 cc/sec	4.8E-7 cc/sec
1059R	1.5 E-8 cc/sec	1.0E-7 cc/sec	2.2E-7 cc/sec	4.0E-7 cc/sec	4.3E-7 cc/sec

P/N E815 leakage was pinpointed to the outer feed thru pin on the opposite side of ID sticker.

Internal Testing was then performed to verify survival and stability of the entire probe while heated. The report follows:

ACCELERATED LIFE TEST OF 0858 CAPACITIVE HUMIDITY SENSOR

Description

The purpose of this report is to describe the results from accelerated life testing of the 0858 humidity sensor die.

Conclusion

The 0858 device shifts more than desired for the Fuel Cell program requirements. A burn-in process or some form of normalization may help minimize the shift in applications. The %RH seems to be related to shift over time. The standard deviation of the population was quite high. External conditioning is needed to minimize variation.

Scope

The scope of this activity was to analyze the performance and drift of the 0858 die in a simulated life span. Twenty-eight samples were submitted to each of 3 variations of accelerated life tests.

Table 1 describes the test schedule.

Table 1: Summary of Test Population

# of Samples	Temperature (°C)	Humidity (%RH)	Length (hours)	Comment
28	85	85	1000	
28	85	65	1000	#10 large shift
28	100	65	1000	#12, #26 large shifts
Notes: Test samples characterized at 25°C only				

TEST METHOD

The method used to complete characterization of these capacitive sensors is described below.

The equipment used to test capacitive-output sensors includes a multi-layer interface board, HP LCR meter, PLC, and Thunder Scientific humidity chamber.

The devices are allowed to soak at each humidity level (except 0%RH) for 3 hours. 0%RH is generated by flooding the test chamber with nitrogen. The PLC controls both the Thunder chamber settings and the timing for taking data. Ten readings are taken and averaged at each humidity level. The multi-layer interface board enables each channel to be read by the HP LCR meter. The meter is set to measure capacitance at 1V and 1kHz excitation.

Analysis & Data

The sensor data was acquired using the standard 9-point characterization implemented in the Honeywell evaluation lab. The 0858 sensor die interchangeability and accuracy are relatively poor compared to a laser-trimmed product (such as the 1466). Tables 1 through 3 illustrate the initial accuracy of the test devices. The range of measurements gives rise to a large variation in the sample population. This means that the sensor signal needs to be conditioned in order to meet the accuracy specifications of the program.

Table 1: Average Accuracy (%) of Initial Characterization							
Test	**25%**	**53.2%**	**75.3%**	**93.8%**	**75.3%**	**53.2%**	**25%**
85°/85%	0.448	-2.588	-2.141	2.675	-0.062	-0.009	1.676
85°/65%	0.010	-3.311	-2.694	3.030	0.223	0.328	2.415
100°/65%	-0.272	-3.127	-2.752	3.107	0.066	0.339	2.640

Table 2: Maximum Accuracy (%) of Initial Characterization							
Test	**25%**	**53.2%**	**75.3%**	**93.8%**	**75.3%**	**53.2%**	**25%**
85°/85%	1.299	-1.304	-0.582	4.358	4.849	1.356	3.814
85°/65%	0.602	-2.695	-1.266	5.098	0.827	3.142	5.004
100°/65%	0.323	-0.279	-1.854	4.685	2.796	3.098	7.009

Table 3: Minimum Accuracy (%) of Initial Characterization							
Test	**25%**	**53.2%**	**75.3%**	**93.8%**	**75.3%**	**53.2%**	**25%**
85°/85%	-1.788	-3.997	-3.548	0.676	-3.720	-0.889	0.558
85°/65%	-1.911	-5.184	-3.852	2.028	-0.927	-0.052	1.933
100°/65%	-4.459	-5.184	-4.841	0.792	-3.138	-1.629	2.103

The following paragraphs present the results from each of the 3 accelerated life tests. Tables 4 through 8 summarize the 85°/85% test. Since the sensor output can vary so widely, as described above, the results will be presented as raw sensor output in picofarads.

Table 4: Initial Characterization (pF) for 85°/85%									
Sample	**0%RH**	**25%**	**53.2%**	**75.3%**	**93.8%**	**75.3%**	**53.2%**	**25%**	**0%**
Average	80.554	87.062	94.410	100.991	107.797	101.596	95.162	87.424	80.783
Sigma	1.118	1.132	1.154	1.081	1.174	1.189	1.084	1.121	1.002
Maximum	82.098	88.709	96.074	102.618	109.890	103.639	96.769	88.989	82.172
Minimum	78.800	85.200	92.300	98.900	105.500	99.300	93.000	85.400	78.800

The average slope from initial characterization was approximately 0.296 pF/%RH. Therefore, it can be seen the standard deviation is relatively poor. Tables 5 through 8 show the statistical results of the shift from the 85°/85% environment. While the average shift is similar to other polyimide devices, it is still evident that some devices shift much more than desired. One can see that average shift continues to increase as the test goes on. However, the variation in shift seems to level off after the first 168 hours.

Table 5: Shift (pF) after 168hrs of 85°/85%									
Sample	**0%RH**	**25%**	**53.2%**	**75.3%**	**93.8%**	**75.3%**	**53.2%**	**25%**	**0%**
Average	-0.828	-0.222	0.022	-0.188	-0.198	-0.144	-0.187	-0.079	-0.020
Sigma	1.371	1.253	1.083	1.176	1.393	1.429	1.328	1.047	1.298
Maximum	1.200	2.430	3.020	1.960	1.900	2.000	3.360	2.340	1.180
Minimum	-5.000	-2.950	-1.900	-2.556	-5.399	-3.800	-2.976	-2.400	-2.983

Table 6: Shift (pF) after 300hrs of 85°/85%									
Sample	**0%RH**	**25%**	**53.2%**	**75.3%**	**93.8%**	**75.3%**	**53.2%**	**25%**	**0%**
Average	-0.257	-0.261	0.182	0.466	0.655	0.536	0.431	0.099	-0.590
Sigma	0.937	0.899	0.866	0.857	0.981	0.829	0.816	0.804	0.960
Maximum	1.979	2.295	3.102	2.661	3.227	3.171	2.808	2.532	1.628
Minimum	-2.400	-2.300	-1.700	-1.800	-2.290	-1.330	-1.100	-1.200	-2.400

Table 7: Shift (pF) after 500hrs of 85°/85%									
Sample	0%RH	25%	53.2%	75.3%	93.8%	75.3%	53.2%	25%	0%
Average	-0.180	-0.047	0.572	0.601	0.978	0.717	0.454	0.452	0.293
Sigma	1.087	1.266	1.208	1.184	1.321	1.182	1.285	1.139	0.730
Maximum	1.811	3.510	3.401	3.334	3.281	3.220	3.385	2.853	2.086
Minimum	-2.400	-2.100	-1.700	-1.100	-2.060	-1.000	-2.326	-1.579	-1.600

Table 8: Shift (pF) after 1000hrs of 85°/85%									
Sample	0%RH	25%	53.2%	75.3%	93.8%	75.3%	53.2%	25%	0%
Average	0.399	1.185	1.390	1.250	1.736	1.556	1.573	1.528	0.412
Sigma	1.012	1.019	1.175	1.405	1.278	1.238	1.129	0.989	1.205
Maximum	3.316	3.845	4.081	4.150	4.812	4.447	4.114	4.087	3.597
Minimum	-1.300	-0.500	-1.600	-1.800	-1.600	-0.500	-0.800	-0.600	-1.700

Tables 9 through 13 summarize the 85°/65% test.

Table 9: Initial Characterization (pF) for 85°/65%									
Sample	0%RH	25%	53.2%	75.3%	93.8%	75.3%	53.2%	25%	0%
Average	81.118	87.467	94.883	101.656	108.880	102.526	95.968	88.184	81.371
Sigma	0.917	1.128	1.167	1.111	1.216	1.136	1.052	1.008	0.937
Maximum	82.326	88.875	96.378	103.082	110.920	103.957	97.322	89.487	82.651
Minimum	78.400	84.000	91.700	98.500	105.100	99.100	92.900	85.700	78.700

The standard deviation is still relatively poor. Tables 10 through 13 show the statistical results of the shift from the 85°/65% environment. While the average shift is similar to other polyimide devices, it is still evident that some devices shift much more than desired. Device 10 shifted much more than the other devices in this test. One can see that average shift continues to increase as the test goes on. Unlike 85°/85%, the devices followed a steady trend in shift over time. This may be an indication that high humidity induces a larger shift, yet maximum shift is somewhat fixed.

Table 10: Shift (pF) after 168hrs of 85°/65%									
Sample	0%RH	25%	53.2%	75.3%	93.8%	75.3%	53.2%	25%	0%
Average	-0.031	0.473	0.592	0.595	0.274	0.422	0.422	0.303	0.113
Sigma	1.660	0.680	0.690	0.655	1.037	0.909	0.784	0.746	0.964
Maximum	2.254	3.029	2.946	2.904	2.960	2.754	2.488	2.010	2.179
Minimum	-7.994	-0.460	-0.737	-1.118	-3.580	-1.860	-1.780	-2.551	-3.722

Table 11: Shift (pF) after 300hrs of 85°/65%									
Sample	0%RH	25%	53.2%	75.3%	93.8%	75.3%	53.2%	25%	0%
Average	0.375	1.004	0.807	0.735	0.319	0.521	0.395	0.357	0.489
Sigma	0.486	0.939	0.749	0.406	1.211	0.991	0.469	0.603	1.261
Maximum	1.800	4.600	2.700	2.000	2.000	4.200	1.450	1.990	6.600
Minimum	-0.740	0.060	-1.900	-0.330	-4.700	-2.000	-1.000	-1.510	-0.480

Table 12: Shift (pF) after 500hrs of 85°/65%									
Sample	**0%RH**	**25%**	**53.2%**	**75.3%**	**93.8%**	**75.3%**	**53.2%**	**25%**	**0%**
Average	no data	0.511	1.093	0.783	0.768	0.599	0.723	0.651	no data
Sigma	no data	1.124	1.025	0.384	0.648	0.915	0.433	0.451	no data
Maximum	no data	2.155	6.000	1.860	2.300	4.200	2.600	2.300	no data
Minimum	no data	-4.570	0.600	-0.100	-0.909	-1.100	0.298	-0.156	no data

Table 13: Shift (pF) after 1000hrs of 85°/65%									
Sample	**0%RH**	**25%**	**53.2%**	**75.3%**	**93.8%**	**75.3%**	**53.2%**	**25%**	**0%**
Average	0.232	1.386	1.299	1.171	-0.344	-0.350	-0.338	-0.236	0.097
Sigma	0.811	0.767	0.886	0.789	1.008	1.024	0.934	0.843	0.586
Maximum	2.001	3.883	3.497	3.194	2.144	1.965	1.685	1.262	1.824
Minimum	-3.360	-0.510	-1.760	-1.510	-4.220	-4.570	-4.230	-3.710	-1.641

Tables 14 through 18 summarize the 100°/65% test. The standard deviation is still relatively poor. Tables 10 through 13 show the statistical results of the shift from the 100°/65% environment. Devices 12 and 26 shifted much more than the other devices, up to 10%. Once again, the devices steadily shift over time, indicating that high humidity has more of an effect than high temperature.

Table 14: Initial Characterization (pF) for 100°/65%									
Sample	**0%RH**	**25%**	**53.2%**	**75.3%**	**93.8%**	**75.3%**	**53.2%**	**25%**	**0%**
Average	80.855	86.908	94.489	101.213	108.497	102.054	95.527	87.781	80.988
Sigma	0.935	1.628	1.367	1.305	1.239	1.393	1.265	1.165	1.090
Maximum	81.896	88.475	96.040	102.857	110.189	103.716	96.990	89.084	82.138
Minimum	78.100	82.900	91.100	98.000	105.500	98.900	92.400	85.100	78.600

Table 15: Shift (pF) after 168hrs of 100°/65%									
Sample	**0%RH**	**25%**	**53.2%**	**75.3%**	**93.8%**	**75.3%**	**53.2%**	**25%**	**0%**
Average	0.144	0.836	0.716	0.605	0.305	0.335	0.413	0.430	0.228
Sigma	0.436	0.732	0.445	0.299	0.239	0.389	0.327	0.582	0.382
Maximum	1.500	2.800	2.200	1.600	0.800	1.500	1.500	2.600	1.400
Minimum	-0.900	0.345	0.000	0.200	-0.400	-0.600	-0.400	-1.200	-0.200

Table 16: Shift (pF) after 300hrs of 100°/65%									
Sample	**0%RH**	**25%**	**53.2%**	**75.3%**	**93.8%**	**75.3%**	**53.2%**	**25%**	**0%**
Average	0.260	0.970	1.036	0.789	0.574	0.770	0.638	0.678	0.559
Sigma	0.322	0.742	0.701	0.387	0.725	0.764	0.620	0.598	0.777
Maximum	1.600	3.300	3.500	2.000	2.100	3.200	2.700	2.500	3.500
Minimum	-0.300	0.468	0.100	0.100	-1.400	0.226	-0.900	-0.800	0.142

Table 17: Shift (pF) after 500hrs of 100°/65%									
Sample	**0%RH**	**25%**	**53.2%**	**75.3%**	**93.8%**	**75.3%**	**53.2%**	**25%**	**0%**
Average	no data	1.177	1.184	0.836	0.647	0.663	0.983	0.970	no data
Sigma	no data	0.843	0.555	0.545	0.442	0.677	0.750	0.560	no data
Maximum	no data	4.242	3.200	2.964	1.800	2.470	3.700	3.100	no data
Minimum	no data	0.710	0.784	-0.200	0.100	-0.900	0.510	0.490	no data

Table 18: Shift (pF) after 1000hrs of 100°/65%

Sample	0%RH	25%	53.2%	75.3%	93.8%	75.3%	53.2%	25%	0%
Average	0.569	1.322	1.213	0.863	0.359	0.621	1.060	1.299	0.685
Sigma	0.453	0.906	0.673	0.903	0.651	0.684	0.690	0.496	0.602
Maximum	2.224	4.962	2.800	4.857	2.328	2.602	3.849	2.500	3.122
Minimum	-0.400	0.820	0.748	0.304	-0.178	0.086	0.540	0.760	0.343

Final Conclusion, Humidity Sensors

While we succeeded in producing Humidity sensors that survived long term exposure to high temperatures and high humidities, the sensitivities of individual sensors increased over time and unpredictably, in terms of magnitude. Heating the sensors and lowering the Relative Humidity in the vicinity of the sense element did not insure stability under PEM Fuel Cell conditions. Evidently, it is ABSOLUTE humidity effects that control stability under these conditions. Our overall conclusion is that polyimide membrane technology is incapable of providing adequate sensor accuracy in PEM Fuel Cell environments. The fact that no sensors died in the 1000 hour test is encouraging and some sort of pre-conditioning and autozero technology would likely give marginal accuracy for 1000 hour tests. But 1000 hours is not long enough. Stationary PEM Fuel Cells are expected to last 10 years and it is extremely unlikely that 1000 hours can be extrapolated that far.

Alternate Technology

If the other chemical composition of the gases does not change, a Thermal Conductivity Sensor could be used to measure Absolute Humidity (mole fraction) of H2O in air, or in hydrogen. IR sensors should work quite well but may be too expensive.

Project Conclusion

As in any major systems development effort, there is a constant learning process. The original Market Driven Product Definition (MDPD) identified four gaps in sensor requirements for use in PEM Fuel Cell control systems. The worst part of these systems involved exposure of the sensors to temperatures of approximately 100°C in extremely high humidities where condensing conditions are frequent. Available sensors for these environments were very expensive where available. It was desired to adapt low cost automotive and commercial sensors to meet these needs. At the beginning of the effort, it was thought that new sensor designs would be needed to sense temperature, pressure, airflow and humidity. Successful sensor concepts were developed for temperature and pressure, but when the time came to commit to tooling, a review with potential customers revealed that they had found off-the-shelf sensors that met all their requirements. Thus, there was no need to further develop those concepts.

Airflow sensor concepts were partially developed for 400 SLPM (automotive) and 4000 SLPM (power plant) flow ranges. Acceptable analog (raw sensor) outputs were achieved but couldn't be acceptably linearized by an appliance grade ASIC. The power required was too high by automotive standards. Before committing to the redesign activity needed to remedy these problems, a review was done with potential users. We found that the need for airflow sensing no longer existed but there was a potential need for hydrogen flow sensing. A complete review of Honeywell airflow sensing technology revealed major and probably fatal technology gaps when measuring hydrogen flow. The most important is that the null drifts unpredictably if the platinum resistors absorb hydrogen. In addition, the power required to achieve stable sensing rises in proportion to the thermal conductivity of the gas being measured. Hydrogen has much higher thermal conductivity than air, where we already had a power problem. This problem could probably be fixed using a new sensor chip but that wouldn't help the null stability. A lesser problem is that, again due to thermal conductivity, hydrogen would have substantially lower signal at a given flow. A fix for that would be reasonably straightforward. A final major complication is that all new test and calibration equipment and facilities would be required in order to handle hydrogen. As the need for hydrogen flow measurement was not certain, we deemed it uneconomical to pursue a major redesign and equipment/facility purchase and there was a mutual agreement to terminate the effort.

Humidity Sensor development achieved the greatest success, achieving all objectives except a very minor miss on response time and a major miss on long term stability under PEM Fuel Cell operating environment. The fix for the response time is quite minor and inexpensive. The stability problem is a fundamental limitation in the sensor physics. In the benign environments in which the commercial products are used, instability seemed to be a function of Relative Humidity greater than 90% and the solution is to heat the sensor a few degrees. When this was attempted in the PEM Fuel cell environment, 1000 hour stability was NOT achieved. Although none of the 81 sensors tested failed hard, their stability was unpredictable. There is some consolation that must humidity sensor products would have been killed in a PEM environment. Evidently, the instability occurs as a result of ABSOLUTE humidity under these conditions. While several techniques could be used to improve the stability somewhat, these would improve life by the 1-2 orders of magnitude required. These techniques include, burn-in under high humidity, auto-calibration or population polling (use multiple sensors and "vote"). It is believed that the sensor is limited by the chemistry and physics of the polyimide membrane use in the capacitor dielectric. A search by our laboratories and by an outside consultant could not find a superior polymer membrane. A switch to a different sensing technology is required.

Of the sensors developed in this effort, the only one with a continuing need is the Humidity Sensor. We have demonstrated acceptable short term performance but the stability problem seems insurmountable. Other (non-Honeywell) technologies that are more durable include IR Spectrophotometry and Thermal Conductivity Sensors. Expected problems are cost of the IR sensors, and non-selectivity of the Thermal Conductivity (e.g. misinterpreting CO_2 as H_2O).