Fuel Cell Balance of Plant Reliability Testbed

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&

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Project ID #: **FC075**

Overview

Timeline

- Start – Aug 2008
- Finish – July 2012
- 95% Complete

Barriers

- Education: Lack of Educated Trainers and Training Opportunities
- Fuel Cell : Durability

Budget

- Total project funding
  - DOE $787,200
  - Contractor 196,800
- Fully funded

Partners

- Lockheed Martin: Location of 1 of 3 testbeds and design

Relevance

Technical Barrier Category	DOE Barriers	Team Project Goal
Education	(D) Lack of Educated Trainers and Training Opportunities	Coordination of testbed construction and operation with Fuel Cell Education.
Fuel Cells	(A) Durability	Identification of durable BOP components and/or failure modes.

Approach

- Develop testbeds to address the challenge to the fuel cell industry for the durability and reliability of components that comprise the complete system - Balance of Plant (BOP).
- Develop test plan to address the candidate BOP components and basic testbed design for long-term operation.
- Collaborate with component manufacturers to develop and enhance final product performance.
- Develop statistical models for extremely small sample sizes while incorporating manufacturer validation data for future evaluation of candidate components.
- Conduct real-time, in-situ analysis of critical components' key parameters to monitor system reliability.
- Utilize testbeds to enhance the education of the technical workforce trained in PEM fuel cell system technology.

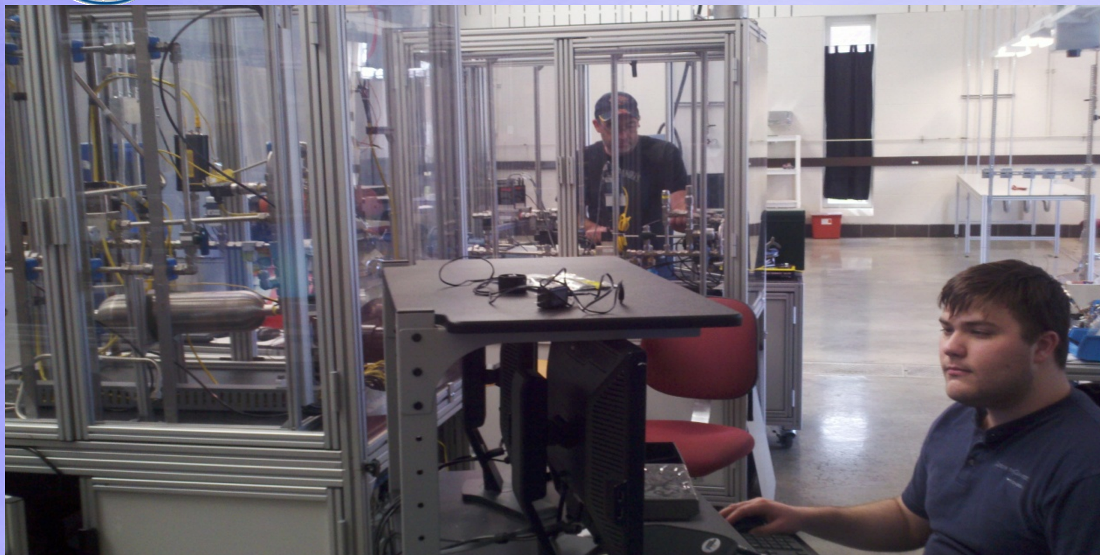
Approach / Progress

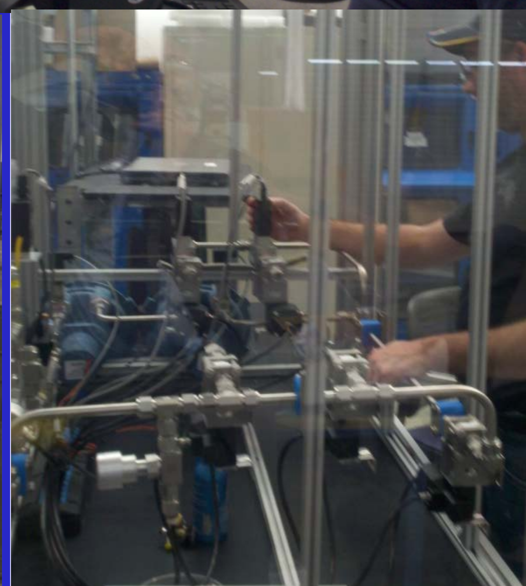
Task #	Project Milestones	Task Completion Date				Progress Notes
		Original Planned	Revised Planned	Actual	Percent Complete	
1	**Test Bed Design**	3/31/09		3/31/09	100%	
2	**Renovation of College Facility**	3/31/09	9/30/09	9/31/09	100%	
3	**College Testbed Fabrication & Test**	6/30/09	3/30/11	9/31/11	100%	All Stands are built.
4	**Parallel Testbed Fabrication & Test**	6/30/09	3/30/11	3/30/11	100%	Components are identified and undergoing testing. System testing is underway.
5	**Reliability Analysis**	6/30/11	7/12		80%	Tested components are under analysis
6	**Failure Analysis**	6/30/11	7/12		80%	Tested components are under analysis
7	**Consulting**	6/30/11	7/12		100%	
8	**Project Management & Reporting**	4/30/11	7/12		99%	Final Testing in Process.

Technical Accomplishments & Progress

- ✓ Reliability data generated for pressure sensors, temperature sensors, tubing, hydrogen circulating pump and valves.
- ✓ Students have been trained in construction, programming, operation, data acquisition and automated control of testbeds.
- ✓ The Hydrogen Safety plan has been implemented to ensure safe operation of the testbeds utilizing hydrogen.
- Continue to test components and document reliability
- Continue to evaluate failure modes of tested components

Fuel Cell Testbeds





Fuel Cell BoP Reliability Testbeds

Technical Accomplishments and Progress

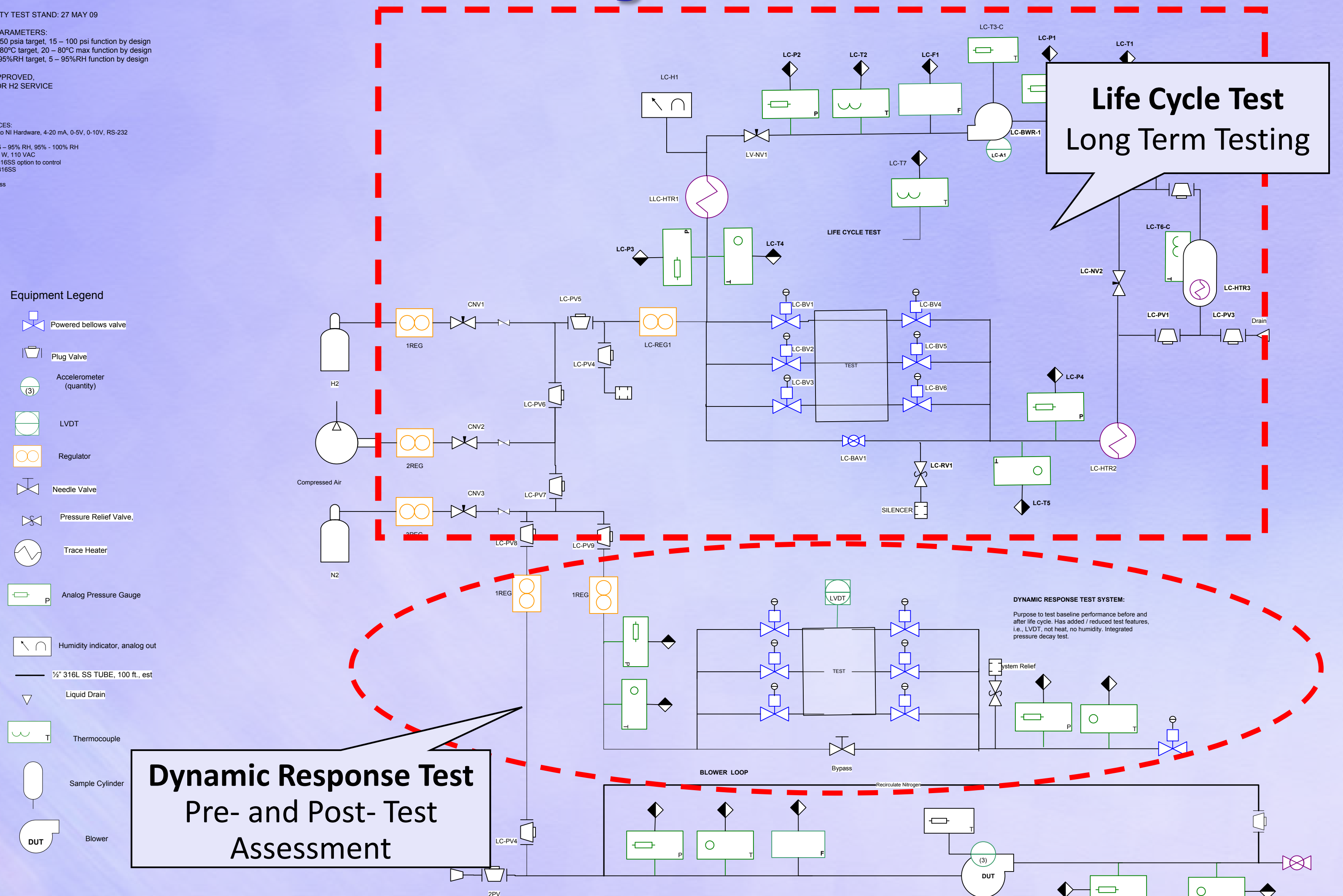
Testbed Design - Hydrogen Recycle

PEM BOP RELIABILITY TEST STAND: 27 MAY 09

LIFE CYCLE TEST PARAMETERS:
Pressure……………..50 psia target, 15 – 100 psi function by design
Temperature………...80ºC target, 20 – 80ºC max function by design
Relative Humidity…..95%RH target, 5 – 95%RH function by design

ALL DEVICES FM APPROVED,
OR EQUIVALENT FOR H2 SERVICE

LIFE CYCLE TEST DEVICES:
Analog and digital output to NI Hardware, 4-20 mA, 0-5V, 0-10V, RS-232
Thermocouple, K-Type
%RH detectors, Vaisala, 5 – 95% RH, 95% - 100% RH
Heaters, Heat trace, 1000 W, 110 VAC
Stainless control valves, 316SS option to control
Stainless tubing, ½" OD, 316SS
High Purity Regulators
Sample Cylinders, Stainless
H2, N2, Air input streams
Silenced exhausts



Test Bed Designed for Multiple Test Modes

Weibayes Analysis

Reliability is the ability of an item to perform the required function, under stated conditions, for a period of time.

Candidate BOP Components

COTS - Commercial off-the-shelf components

- High-production products such as piping, fittings, etc. where past history is available.
  - Use Weibull and Weibayes Analysis for those components with previous history. This procedure incorporates test and field data (vendor reliability and quality analysis) to demonstrate the component product meets the reliability target at the desired confidence level.
- Low production units with no manufacturer reliability data.
  - End-of-life component data and Forensic Failure Analysis will be the most important test data.

PEM Fuel Cell BOP Dynamics

Component	Mechanical	Chemical	Purity	Transducer Effects
Pumps	Heat Generation Fatigue		Particle generation by erosion	Controller tuning, accuracy
Valves	Leak Integrity Flow Capacity Cycle Life Thermal cycles		Particle generation by actuation, wear out, elastomer leach contaminants	Controller tuning, accuracy
Fittings	Make-up Thermal cycle	Chemical compatibility	Low-level trace elements leach	
Heater	Cycle Life	Hydrogen – Embrittlement	Whittling of elements, particle shedding Particle shedding, Elastomer leach contaminants	Controller tuning, accuracy
Heat Exchanger	Fouling	Oxidation	Particle shedding, Elastomer leach contaminants, Low-level trace elements leach	
Meters / Analyzers	Fatigue			Linearity, hysteresis, accuracy, repeatability, reproducibility, drift, bias

Analysis Method for Test Components

Weibull Test Parameters

Parameter of Test Time Calculation

$$t_n = B_i \cdot \left[\frac{\ln(1-CL)}{n \cdot \ln(1-p)}\right]^{\frac{1}{\beta}} \quad , \quad t_t = B_i \cdot \left[-\frac{1}{\ln(1-p)} \cdot \frac{\chi^2(\alpha, 2r+2)}{2n}\right]^{\frac{1}{\beta}}$$

$$t_t = f(B_i, n, p, CL, \beta, R_t)$$

- t_n : No Failure Test Time
- t_t : Test Time
- B_i : Reliability Measure
- n : Number of Sample
- p : Percentile
- CL : Confidence Level
- β : Shape Parameter of Weibull Distribution
- R_t : Failure Acceptance Rule
- χ^2 : Chi-Square Distribution

Threshold = 2000 hrs

Objective = 5000 hrs

Confidence Level = 85%

n\β	1	2	3
1	36012	8487	5242
2	18006	6001	4161
3	12004	4900	3635
5	7202	3795	3066
7	5145	3208	2740

n\β	1	2	3
1	90030	21217	13105
2	45015	15002	10402
3	30010	12249	9087
5	18006	9488	7664
7	12861	8019	6851

Confidence Level = 90%

n\β	1	2	3
1	43709	9350	5592
2	21854	6611	4438
3	14570	5398	3877
5	8742	4181	3270
7	6244	3534	2923

n\β	1	2	3
1	109272	23374	13979
2	54636	16528	11095
3	36424	13495	9693
5	21854	10453	8175
7	15610	8835	7308

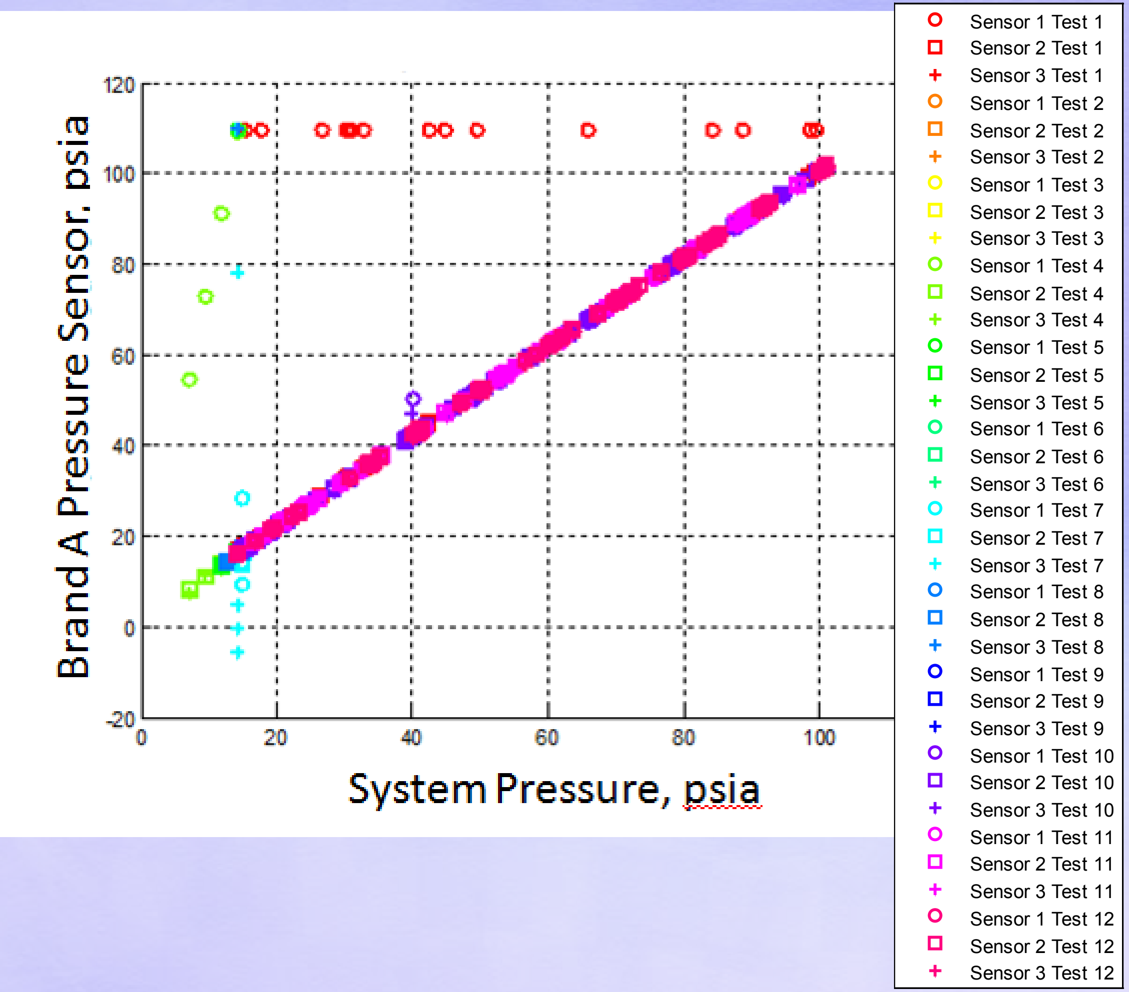
- ***Utilize COTS Components.***
- ***Sample Size and Weibull Shape Factor Determine Test Time.***
- ***Longer testing increases Confidence Level in Hours of Operation.***

Test Criteria Developed For Devices Under Test

Technical Accomplishments and Progress

Pressure Sensors

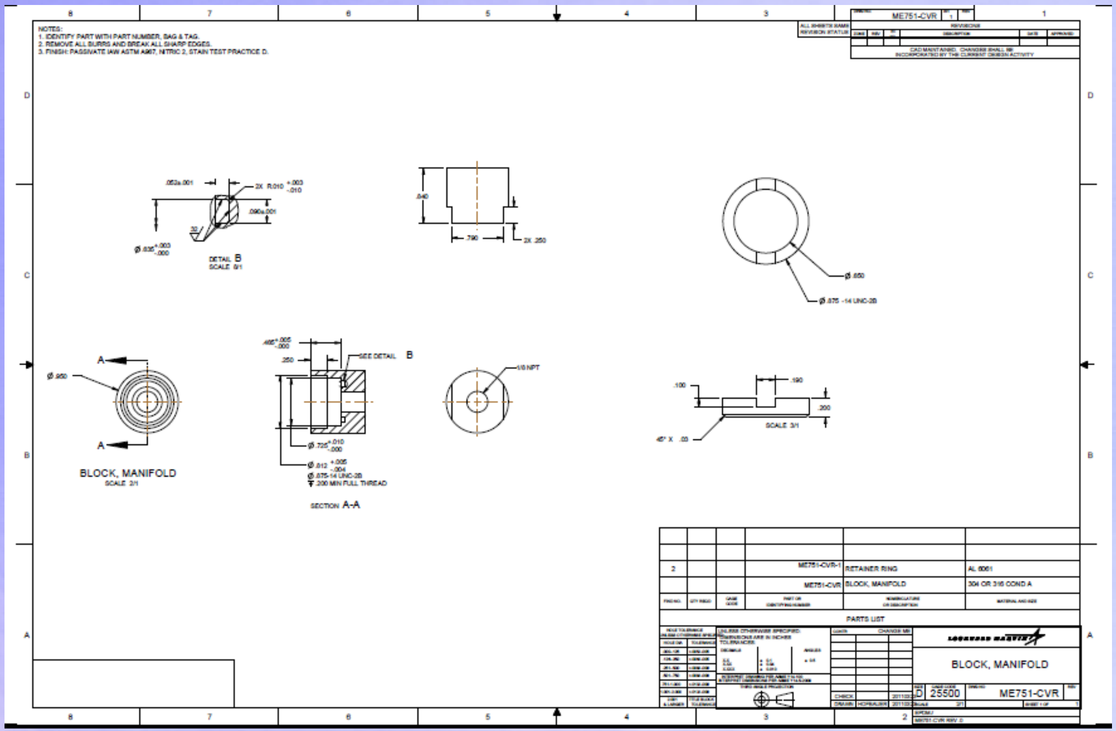
- **Test Matrix was Developed to Determine Sensor Sensitivity to Temperature, Pressure and Relative Humidity.**
- **Sensors were evaluated with respect to both a change in stressor and ramping stressor.**
- **No significant impacts when stressors are changed.**



Sensor Response Invariant with Temperature, Pressure and Humidity

Technical Accomplishments and Progress

Pressure Sensors



COTS Sensors used with mechanical envelope.

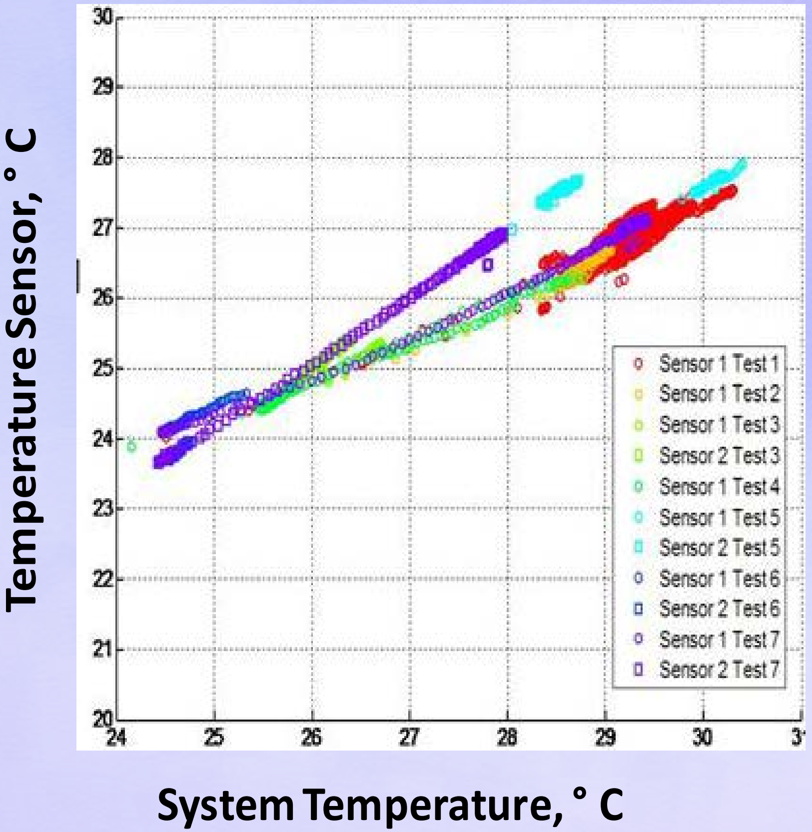
Students gained experience in the modification of sensor envelope design.

Sensor Envelope Design

Temperature Sensor

	Test Description		Mean Difference [°C]		Standard Deviation of the Difference	
	Temp [C]	RH [%]	Sensor1	Sensor2	Sensor1	Sensor2
Test 1	26-27.5	40	-2.441	NA	0.125	NA
Test 2	26	62-50	-2.468	NA	0.138	NA
Test 3	26	47-43	-2.309	-0.910	0.074	0.015
Test 4	24-30	60-30	-1.203	NA	0.107	NA
Test 5	30	46	-1.181	-0.911	1.150	0.013
Test 6	28	37	-2.448	-0.999	0.042	0.033
Test 7	28	17	-1.945	-0.990	0.638	0.083

- Small Light weight temperature sensors.
- Sensors were encapsulated in high temperature epoxy.
- Packaging of the sensors became an issue in subsequent testing.

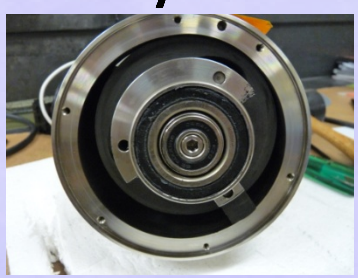


Light Weight Sensor Temperature Sensor

Hydrogen Recirculation Pump

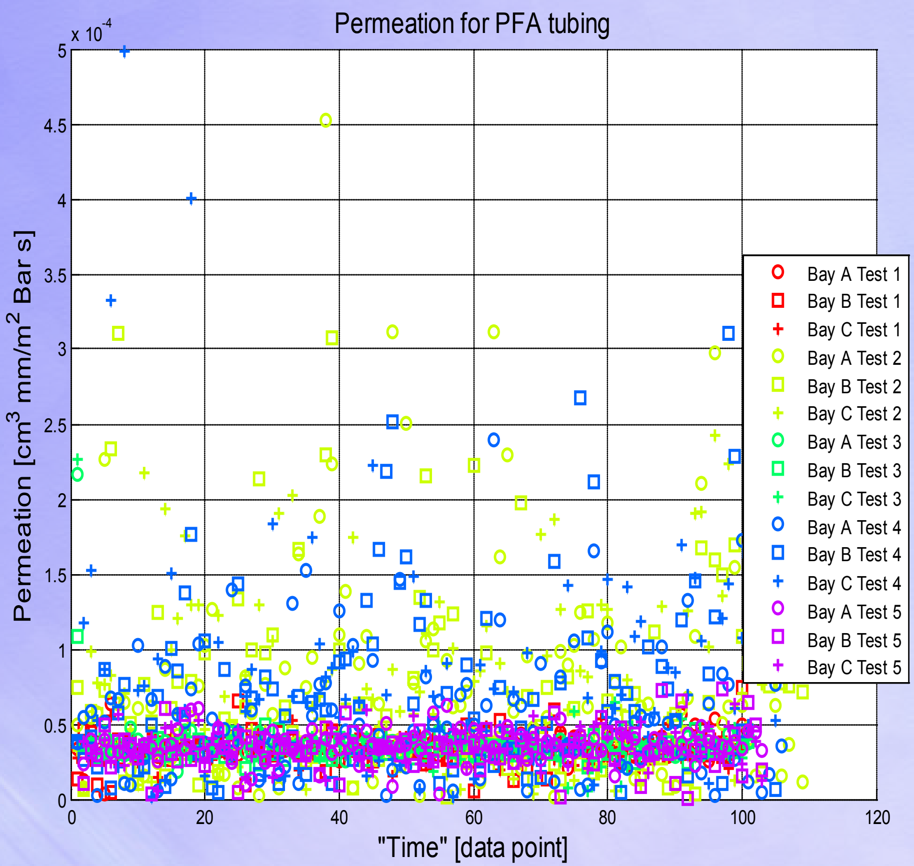
- Hydrogen recycle pump was retired from testing with >5000 hours of test.
- Failure: Slow starts and eventual seizing of the rotor.
- Failure Analysis shows:
  - Rotor contact with housing may be source of noise during operation and reason for slow starts.
  - Wear and staining observed on bearings.
  - The graphite was heavily worn.



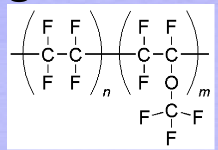



Pump Failure Analysis

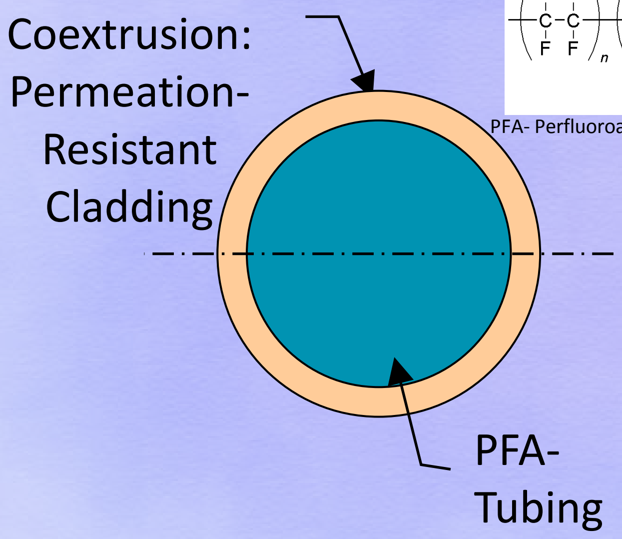
Fuel Cell Tubing



Zeus® PFA Tubing



PFA- Perfluoroalkoxy polymer



Component	Comments
316 Stainless Steel Tubing	**DI water compatible**
Coextrusion PFA Tubing	**DI water and chemical resistant, corrosion resistant, lightweight**

- Comparisons between 7 stainless steel tests and 5 PFA tests.
- PFA had a greater "leakage rate" by an order of magnitude.
- Seal between tubing and fitting appears to be the source of leakage
- Alternate fitting tested with similar results.

Lightweight, Chemical Resistant Tubing

Technical Accomplishments and Progress

Valve Testing

Historically appropriate commercial off-the-shelf components were difficult to find, many were custom modified after deterioration due to operation in the PEM environment. To the right is a commercial off-the-shelf valve with all 316 SS internal parts.

In addition to experience in design modification for improved performance, students were exposed to valve qualification test methods to verify seat sealing and to quantify deterioration of performance.

Environmental Testing

Final sequencing programming test enclosure for device life cycle testing with the insulation and heat tape on piping.

Accelerated life testing at higher temperatures

Collaborations

Lockheed Martin

- Subcontract,
- Initial Testbed Design
- Parallel Testbed Construction
- Failure & Reliability Analysis

Educational Institution Dialogue

NSF Great Lakes Fuel Cell Education Partnership State Coordinators

- Indiana
  Vincennes University
  Rose Hulman Institute of Technology
- Michigan
  Kettering University
  Lansing Community College
  Michigan Technical College
- New York
  Rensselaer Polytechnic Institute
  Hudson Valley Community College
- Ohio
  University of Akron
  Stark State College
  Kent State University
  Hocking Technical College
- Pennsylvania
  Penn State University
- *Tennessee*
  University of Tennessee

Educational Outreach Activities

- Early College course
  Alternative Energy and Fuel Cells
- Engineering & Science Career Field Technical Fuel Cell Energy
- Project Lead the Way, Ohio Fuel Cell Option
- Upward Bound Fuel Cell Course
- Support for First Fuel Cell Contest teams
- High School Student Science Projects
- Ohio Energy Project

Proposed Future Work

- Continue round robin testing of components.
- Accelerated testing of components.
- Complete failure analysis and reliability analysis of components.
- Continued testing of Balance of Plant components for Fuel Cell System Analysis and Fuel Cell Technical Project courses.
- Explore future testing collaborations at end of program.

Acknowledgements

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  Stark State College; vsproat@starkstate.edu
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- Rob Shutler, Swagelok
- Marc Griffin, Lockheed Martin MS2
- DOE Managers:
  Greg Kleen, Project Officer
  Kathi Epping, Technology Development Manager

Project Summary

- **Relevance**: Balance of Plant (BOP): To use hydrogen in fuel cells, a balance must be engineered for reliability and technician training for fuel cell system.
- **Approach**: Develop BOP testbeds, collaborate with component manufacturers to enhance product performance, and train technical workforce in PEM fuel cell systems.
- **Technical Accomplishments & Progress**: Final Testing Sequence

  Students have been trained on the construction, operation and maintenance of the test bed, and the Hydrogen Safety Plan has been implemented to ensure safe operation of the testbeds with hydrogen.
- **Technology Transfer/Collaboration**: Active partnership with Lockheed Martin and industry dialogue with Parker, Swagelok, National Instruments, Omega Dyne, and others.
- **Proposed Future Work**: Accelerated Testing of Components and Failure Analysis.