Sensor Development for PEM Fuel Cell Systems
DOE Cooperative Agreement DE-FC36-02AL67615
Annual Program Review

Honeywell International
Sensing and Controls
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This presentation does not contain any proprietary or confidential information.
Program Objectives

A 38-month research and development program leading to the creation of physical sensors suitable for monitoring and controlling a polymer electrolyte membrane (PEM) fuel cell-based power plant, including the fuel reformer, fuel cell stack, and thermal management system.

Task 1 – Sensor Requirements – October 2003 to September 2003 (Completed)
This task will define the requirements of each of the physical sensors. The preliminary sensor requirements will be evaluated against the requirements created from the customer interviews. A broad market survey will validate the requirements and provide the inputs to the design task.

Task 2 – Sensor Development – October 2003 to October 2004
This task will be an initial development of the Physical Sensors to demonstrate their ability to meet the necessary requirements in a laboratory environment. Several subtasks are identified to meet this objective.

Task 3 – Prototype Sensor Build and Test – November 2004 to June 2005
The proposed Physical Sensors developed in Task 2 shall be manufactured into operating prototypes suitable for third-party fuel cell system testing and evaluation. This includes all necessary design, fabrication, and rework necessary to meet the requirements set forth in Task 1.

Task 4 – Field Testing – July 2005 to October 2005
It is Honeywell's position that the proposed sensors will gain technical and/or cost advantage by combining their functionality into an overall system architecture and testing them in their intended fuel cell system environment. The purpose of this task is to test and demonstrate the sensors on operating fuel cells and reformers at third-party facilities.
DE-FC36-02AL67615 Project Costs

Total Project Funding ($1.9M)
DOE 80% = $1,521,524
Honeywell 20% = $380,381

Pre-Award Nov-02 Feb-03 May-03 Aug-03 Nov-03 Feb-04 May-04 Aug-04

Forecasted Through Sept '04
Actual To Date

$1,000,000
$800,000
$600,000
$400,000
$200,000
$- $200,000 $400,000 $600,000 $800,000 $1,000,000 $968,858 $613,484 $566,788

DOE = $453,431
Honeywell = $113,358
### Specification Comparison

<table>
<thead>
<tr>
<th></th>
<th>DOE Technical Plan 6/3/03</th>
<th>Honeywell (VOC)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Humidity</strong></td>
<td>Rh Range 20 – 100%</td>
<td>0 to 100%</td>
</tr>
<tr>
<td></td>
<td>Temperature Range 30 – 110C</td>
<td>-40 to 90C</td>
</tr>
<tr>
<td></td>
<td>Accuracy 1%</td>
<td>0 to 80% Rh – 4% / 80 to 100% Rh – 2%</td>
</tr>
<tr>
<td><strong>Flow</strong></td>
<td>Flow Range 30 to 300 SLPM</td>
<td>0 to 400 SLPM / 0 to 4,000 SLPM</td>
</tr>
<tr>
<td></td>
<td>Temperature Range 80C</td>
<td>-40 to 90C</td>
</tr>
<tr>
<td><strong>Pressure</strong></td>
<td>Pressure Range 0 to 1 psi Diff / 0 to 10 psi Diff</td>
<td>0 to 6 psi Diff / 1 to 30 psi Abs</td>
</tr>
<tr>
<td></td>
<td>Temperature Range 30 to 100C</td>
<td>-40 to 125C</td>
</tr>
<tr>
<td></td>
<td>Response Time &lt;1 second</td>
<td>&lt;0.1 second</td>
</tr>
<tr>
<td></td>
<td>Accuracy 1% FS</td>
<td>3% FS</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td>Temperature Range -40 to 150C</td>
<td>-40 to 150C</td>
</tr>
<tr>
<td></td>
<td>Response Time &gt;1 seconds</td>
<td>&lt;2 seconds</td>
</tr>
<tr>
<td></td>
<td>Accuracy 1.5%</td>
<td>1%</td>
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</table>
Humidity Barriers and Targets

General Barriers
- Robust to high humidity and high temperature
- Exposure to DI and Hydrogen media
- Automotive grade
- Cost
- Overall package size
- Overall package weight

Technical Barriers
- *Recovery from a condensing environment
- *Accuracy at high temp and high humidity w/ minimal drift

Targets
- 75C, 100% Rh (environment)
- 0 to 80% Rh – 4% / 80 to 100% Rh – 2%
- 30 second recovery time to 62.3% of Actual
Flow Barriers and Targets

General Barriers
• Robust to high humidity and high temperature
• Exposure to DI and Hydrogen media
• Automotive grade
• Cost (4,000 SLPM)
• Overall package size

Technical Barriers
• Existing flow sensors cannot operate in condensing environments
• Flow sensors today are not robust to media with particulate matter

Targets
• 75C, 100% Rh (environment)
• 30 second recovery time to 62.3% of Actual
• Input Voltage 10V to 25V (Field Test)
General Barriers

- Cost
- Overall package size
- Overall package weight

Technical Barriers

- Protection of the electronics (sense die and PCB) from the media
- Packaging strategy resistant to stress

Targets

- 75°C, 100% Rh (environment)
- -40 to 125°C
- 3% accuracy FS

Width – 2.67”
Length – 3.25”
Temperature Barriers and Targets

General Barriers
• Exposure to DI and Hydrogen media
• Automotive grade
• Cost

Technical Barriers
• Time Responsiveness

Targets
• <2 second response time

Probe Diameter - .25”
Probe Length – 2.5”
Technical Approach

Look at the fuel cell system and establish the requirements for each physical sensor. Deploy existing technologies and develop packaging strategies to minimize sensor cost. Prototype sensors will be designed, fabricated, and tested in third party fuel cell systems.

Fuel Cell manufacturers now use Instrument-grade sensors to accommodate sensing requirements. Do to cost, size, and weight, instrument-grade sensors do not provide a long term sensing solution for Fuel Cell applications.

<table>
<thead>
<tr>
<th>Humidity Sensor</th>
<th>Flow Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitive humidity sense die on ceramic with an Application Specific Integrated Circuit (ASIC). The technology is packaged in a heated die chamber with a micro-filter and controlled to shift the Dew Point.</td>
<td>Thermal mass flow micro anemometer (Wheatstone Bridge) on a smooth sensing surface utilizing backside interconnects with linear transfer function output. Diagnostics for failed known state.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pressure Sensor</th>
<th>Temperature Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemically etched Silicon sense dies (2) utilizing backside die sensing. Packaged to isolate the circuitry from the media. Diagnostics for failed known state.</td>
<td>Amplified Resistive Temperature Device (RTD) in a Stainless Steel probe with a signal conditioned output. Diagnostics for RTD open / short.</td>
</tr>
</tbody>
</table>
Technical Accomplishments

Humidity:

- Micro-filter research and performance testing in a condensing environment has been completed
- Initial condensation recovery tests, with the selected sensing technology, completed
- Selection of ASIC completed
- Bench top testing completed using chosen ASIC and “best of” humidity sense die
- Research of Rh alternative and emerging technologies complete
- Modeling has shown that temperature control at the sense die will allow a uniform dew point shift
- Material analysis and selection complete
Technical Accomplishments

- Load case: 200
- Last iteration/step

Variation of temperature at RH sensing surface is <0.2°C.
Technical Accomplishments

Flow

- Rugged glass sense die development with backside interconnects
- Package modeling completed for 400 SLPM and 4,000 SLPM
- Performance tested mechanical bypass sampling technology
- Material analysis and selection complete
- Test methodology for humidified flow defined
Technical Accomplishments

Velocity Magnitude
- Evenly distributed across the restrictor

Static Pressure
- Even pressure drop across the restrictor
- Stability at point of bypass
- Minimal pressure drop across device
**Technical Accomplishments**

**Pressure**

- Concept validation testing has proven the design to be inert to Hydrogen gas
- Design robustness verified through exposure of electronics to Hydrogen gas (due care testing)
- Bond between Carrier and Stainless Steel port verified to maintain a seal across operating temperature range.
- Material analysis complete and selections made
- Package analysis and design complete
Sensing media is confined to inert surfaces by two key bond joints. Electronics are isolated from the sensing media by these joints and the silicon sense die.
Technical Accomplishments

Temperature

- Material analysis and selection complete
- Time response modeling and initial empirical testing complete
- Initial circuit design and housing tested
Fuel Cell Temperature Sensor Comparison

Time (Seconds):

Temperature (°C):

- Bare RTD
- Normal Sensor

62.3% target
## Project Timeline

<table>
<thead>
<tr>
<th>WBS</th>
<th>Task Name</th>
<th>Start</th>
<th>Finish</th>
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<tbody>
<tr>
<td>1</td>
<td>DOE Fuel Cell Project #216905</td>
<td>Mon 8/5/02</td>
<td>Tue 11/1/05</td>
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<tr>
<td>1.1</td>
<td>Sensor Requirements</td>
<td>Mon 9/2/02</td>
<td>Wed 10/8/03</td>
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<tr>
<td>1.1.1</td>
<td>Preliminary Requirements Definition</td>
<td>Mon 9/2/02</td>
<td>Fri 10/11/03</td>
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<tr>
<td>MS-1.1</td>
<td>Preliminary Requirements Review</td>
<td>Fri 11/1/02</td>
<td>Fri 11/1/02</td>
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<td>1.2</td>
<td>Update Requirements</td>
<td>Tue 11/12/02</td>
<td>Thu 6/12/03</td>
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<td>1.2.1</td>
<td>Third Party Interviews</td>
<td>Tue 11/12/02</td>
<td>Tue 5/15/03</td>
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<td>1.2.2</td>
<td>Evaluation of Third Party Requirements</td>
<td>Mon 4/14/03</td>
<td>Thu 6/12/03</td>
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<td>1.3</td>
<td>Finalize Requirements</td>
<td>Fri 6/13/03</td>
<td>Tue 9/30/03</td>
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<tr>
<td>1.3.1</td>
<td>Determine sensor requirements from transcripts</td>
<td>Fri 6/13/03</td>
<td>Thu 7/22/03</td>
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<td>1.3.2</td>
<td>Finalize Field Survey</td>
<td>Wed 7/23/03</td>
<td>Wed 8/13/03</td>
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<td>1.3.3</td>
<td>Distribute Field Survey</td>
<td>Thu 8/14/03</td>
<td>Tue 9/30/03</td>
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<td>1.3.4</td>
<td>Analyze Field Survey</td>
<td>Tue 8/19/03</td>
<td>Thu 9/20/03</td>
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<td>1.4</td>
<td>Select Third Party Test Facilities</td>
<td>Fri 7/11/03</td>
<td>Thu 7/31/03</td>
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<td>MS-1.2</td>
<td>Final Sensor Requirements Review</td>
<td>Mon 10/3/03</td>
<td>Fri 10/3/03</td>
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<td>1.1.7</td>
<td>Finalized Requirements - DOE Approval to Close T</td>
<td>Wed 10/8/03</td>
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<td>Sensor Development</td>
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<td>Mon 11/8/04</td>
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<td>Physical Sensors</td>
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<td>Mon 11/8/04</td>
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<td>Technology Concepts</td>
<td>Wed 10/8/03</td>
<td>Mon 3/22/04</td>
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<td>Packaging Concepts</td>
<td>Tue 1/20/04</td>
<td>Mon 7/5/04</td>
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<td>Physical Sensors Test Plan Review</td>
<td>Mon 12/8/03</td>
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<td>2.1.3</td>
<td>Preliminary Testing</td>
<td>Tue 5/25/04</td>
<td>Mon 11/8/04</td>
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<td>MS-2.2</td>
<td>Physical Sensor Designed</td>
<td>Mon 11/8/04</td>
<td>Mon 11/8/04</td>
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<td>1.3</td>
<td>Prototype Build &amp; Test</td>
<td>Tue 11/9/04</td>
<td>Mon 7/4/05</td>
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<td>Fabrication</td>
<td>Tue 11/9/04</td>
<td>Mon 1/31/05</td>
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<td>MS-3.1</td>
<td>Physical Sensors Demonstration</td>
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<td>Testing</td>
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<td>Rework</td>
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<td>Proto Demo-Sensors for Test</td>
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<td>Mon 7/4/05</td>
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<td>1.4</td>
<td>Field Testing</td>
<td>Mon 7/4/05</td>
<td>Mon 10/3/05</td>
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<td>1.4.1</td>
<td>Third Party Testing</td>
<td>Tue 7/5/05</td>
<td>Mon 10/3/05</td>
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<td>1.4.2</td>
<td>Field Testing Complete</td>
<td>Tue 7/5/05</td>
<td>Mon 10/3/05</td>
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<tr>
<td>1.5</td>
<td>Program Management</td>
<td>Mon 8/5/02</td>
<td>Tue 11/1/05</td>
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</tbody>
</table>
Interactions and Collaborations

Honeywell Advance Technology Laboratory; Minneapolis, MN
• Rugged flow die development for glass and silicon
• Media evaporation modeling

Micro Substrate Corporation; Tempe, AZ
• Backside interconnect R & D

United Technology Corporation; Hartford, CT
• Utilize UTC as a “test bed”

Douglas Nelson Ph.D., PE; Professor Virginia Tech, Blacksburg, VA
• In house team training on Fuel Cell systems

Exponent; Boston, MA
• Fragility testing of glass substrate

Field Testing:
• Collaborative effort to define sensing specifications
• Ongoing effort to communicate development status
• Field test planning and execution
Voice of the customer exercise did not identify the need for a 4,000 SLPM flow sensor for automotive customers.

- Specifications for the 4,000 SLPM flow sensor are defined and sensor development is active.

Honeywell project timing is not coordinated with UTC

- UTC has communicated that their contract end date now coincides with Honeywell’s.
**Humidity Sensor:**
- Alpha II sensor design
- Package modeling
- Circuit design and debug
- Humidity research
  - Accuracy
  - Drift (Condensation)

**Flow Sensors:**
- Complete Alpha II testing
- Circuit design and debug
- Alpha II second level package build and initiate test
- Complete TTW research on Silicon substrate

**Pressure Sensors:**
- Complete Beta testing
- Circuit design and debug

**Temperature Sensor:**
- Alpha II sensor design
- Circuit design and debug
- Packaging modifications to improve response time
• Standard Operating Procedures are followed in consideration of design and testing
• Ongoing risk assessment tools are utilized throughout the development process
• Material analysis has been performed for all media wetted surface materials
• Hydrogen exposure testing remains an ongoing element of all test plans
• All sensors are low voltage U.L. Class 2 designs

*Sensors being developed are prototype field test designs. Additional work may be conducted at the end of the contract to complete full environmental, EMC, and agency approval testing.