SOFC Quality Control and the Role of Manufacturing Defects on Stack Longevity

(WO023478)

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  Michael Ulsh, Peter Rupnowski, Bhusan Sopori
• Atrex Energy Engineering Team
  Neil Fernandes, Jesus Solis, Steve Murphy, Max Knobel
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Acumentrics
Advanced Power Solutions

>480 SOFC units
Shipped

Commercial SOFC
LPG and NG

JP8 fueled SOFC
Prototype

60,000+ RUPS™
units shipped

2U Lead Acid
or Li-ion 2kW RUPS

1U Li-ion 1.5kW
RUPS

Atrex Energy
Atrex Energy fact sheet

“Powder to Power”

- **250W to 10kW**+ power generation products and prototypes, based on Solid Oxide Fuel Cell (SOFC) technology
- Natural gas, LPG and Jet fuel for deployment in remote applications
- Reliable, efficient and clean
- Field Replaceable stack

- **> 480 Commercial Units** deployed in North America
- Accumulated **>5 Million hours** run time of the commercial NG and LPG generators
- Units running in remote environments for **>35,000hrs**
- **FC1 certification** from the Canadian Standards Association (CSA)
- Completed world first demonstrations of a packaged fuel cell generator working on high sulfur JP8/F24
Project Motivation and Goals

I. Experimental investigation of cell “imperfections”; do they cause rapid degradation/failure at high temperature?

1. Mini-cell testing (similar to button cell testing)
2. Single cell testing
3. Stack testing (20 cell stacks)
4. Microscopic characterization of imperfections

II. Development of automatable imaging techniques for identification of imperfections with intelligent screening for defects

1. Screening of imaging techniques (NREL Fuel Cell Manufacturing project, Atrex)
2. Design and construct automated QC device (Atrex Energy)
# Visually Conspicuous Defects

<table>
<thead>
<tr>
<th>Description</th>
<th>Example</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contamination caused pit (&lt;1mm)</td>
<td><img src="image" alt="Image" /></td>
<td>Crack formed in processing</td>
<td><img src="image" alt="Image" /></td>
</tr>
<tr>
<td>Anode material agglomerate pop-out (~1mm)</td>
<td><img src="image" alt="Image" /></td>
<td>Crack visualized by dye</td>
<td><img src="image" alt="Image" /></td>
</tr>
<tr>
<td>Crack (1~10mm) formed in green state processing</td>
<td><img src="image" alt="Image" /></td>
<td>Pinhole (~µm) visualized by chemical etching</td>
<td><img src="image" alt="Image" /></td>
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<tr>
<td>Surface electrolyte scratch (1~10mm) (handling)</td>
<td><img src="image" alt="Image" /></td>
<td>Pinhole (~µm) visualized by dye</td>
<td><img src="image" alt="Image" /></td>
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<tr>
<td>Coating agglomerate (slurry quality) (1~5mm)</td>
<td><img src="image" alt="Image" /></td>
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</table>
Mini Cell Testing

- Possible environment of a cell defect in a stack
  - Temperatures 680-830°C (however all testing at 750°C to date)
  - Cathode atmosphere 21%-13% O₂
  - Anode atmosphere commensurate with 0-75% FU
  - Local current densities 150-700mA/cm²
- Possible transients
  - Thermal and load cycling
“Natural” Scratch 530µm wide
Electrolyte with high pinhole population

- OCV
- Low current, low FU
- Medium current, medium FU
- High current, high FU

Operation condition swing

Under-sintered electrolyte
Stack Testing CT-1: Placement Key

Instrumented bundle

- Pinhole
  - 20
  - 11
  - 10
  - 1
- Crack
  - 19
  - 12
  - 9
  - 2
- Pinhole
  - 18
  - 13
  - 8
  - 3
- Crack
  - 17
  - 14
  - 7
  - 4
- Pinhole
  - 16
  - 15
  - 6
  - 5

High leak rate

Scratch
Stack Testing CT-1

>15 thermal cycles!
## CT-2 Stack Test, Defect Placement Key

<p>| | | | | | |</p>
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<tbody>
<tr>
<td>20</td>
<td>11</td>
<td>10</td>
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- **High QC leak rate**
- **Scratch defect**
- **Pinholes**
- **Crack**
- **Control**

Atrex Energy
Load cycling of “imperfect” stack (CT-2)

200W output

400W output

Cell Voltage/V

Time/hrs

- Cell1 Nose crazing
- Pinholes
- Cracks
- Scratch
- Control
- Leak

Atrex Energy
Load cycling → Temperature cycling

2016/07/15 02:45:22:
FRONT TEMP: 791.0
MIDDLE TEMP: 784.3
REAR TEMP: 770.2
More Aggressive Cycling
More Aggressive Cycling

![Graph showing More Aggressive Cycling](image-url)

- **Atrex Energy**
- **Cell 2 IC del pinhole**
- **Cell 17 scratch 2 cracks**
- **Cell 1 noze crazing**
- **Cell 5 Popout**
- **Cell 181 R1p9**
- **Av. Temperature**

**Time/hrs**

**Cell Voltage/V**

**Avg Temperature/°C**

- 0.500W output
Ranking Defects

- Build *stress-defect-interaction* matrix
- Interaction metrics: failure mode, time to failure (TTF), degradation rate, etc.

<table>
<thead>
<tr>
<th>IMPERFECTION CATEGORY</th>
<th>STRESS TYPE</th>
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<tbody>
<tr>
<td></td>
<td>Power cycling</td>
</tr>
<tr>
<td>High leak rate</td>
<td></td>
</tr>
<tr>
<td>Crack</td>
<td></td>
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<tr>
<td>Pop out</td>
<td></td>
</tr>
<tr>
<td>Scratch</td>
<td></td>
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<tr>
<td>Pinhole</td>
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<tr>
<td>Other types</td>
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Automated Quality Control System

**NDT Techniques Evaluated**

- **IR Imaging**
  - with thermal activation - for surface/subsurface non-homogeneities (Thermal Scanning)
  - with voltage excitation – for electrical shorts
  - with CO$_2$ pressurization– for cracks
  - with ultrasound excitation for cracks, separations

- **Ultrasonic**
- **Optical Reflectance Imaging** – surface anomalies
- **2D/3D Laser Profile** – For topographical defects.
Imaging of Imperfections

**Optical Reflectance**
- Electrolyte scratch
- Crack
- Cathode Delamination

**Thermal IR Imaging – Ultrasound Excitation**

**Thermal IR Imaging – Thermal Excitation**

**Thermal IR Imaging – Electric Excitation**
Acoustical Microscopy at Sonoscan, Inc

Preliminary experiments using acoustic microscopy

Ultrasound does not travel through air gaps and is reflected at the air/solid interface

3D Tomography is possible using C-SAM software
3D-2D Laser Profile Sensor

- Fast data acquisition: surface speed 35.8mm/sec
- Z axis resolution of 1.8 – 3 microns, X axis resolution of 14 – 21 microns
- 3-D capability, thickness measurement, tube off-straightness, etc
Image processing software

• Determine the ease and feasibility of detecting the defects in these images automatically with the tools available in the machine vision.
Defect Screening System: in progress

- Vibration isolation table
- Horizontal Actuator
- Y Axis Actuator
- Laser Profile Sensor
- Cell
Future works

- Finish up cell and stack testing
- Conduct microanalysis of defects
- Build and implement automatable QC device

Video clip for Atrex ARP unit:

https://vimeo.com/191661007/807843bf0e