Silicon Based Solid Oxide Fuel Cell for Portable Consumer Electronics

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Overview

Timeline

- Project Start: August 2008
- Project End: March 2009
- Percent Complete: 100%

Barriers

DOE 2010 Targets for sub 50W Systems

A. Durability: 5000 hrs

B. Cost: $3/W

C. Performance: 1000 Wh/l

Budget

- Total project funding
  - DOE share: $0.492M
  - Contractor share: $0.750M
- FY08 Funding: $0.492M

Partners

- Alfred University
- Missouri S&T

Relevance

- DOE Hydrogen Program stated objectives include development and demonstration of cost-effective, reliable, durable fuel cells for portable power applications
- Fuel cells for consumer electronics is a large, early-market opportunity
  - Will familiarize a broad audience with the benefits of fuel cell technology
  - Provides a vehicle for job creation in a growing, forward-looking industry
- Lilliputian Systems' MEMS-based SOFC technology is a scalable, cost-effective, environmentally-robust approach to addressing the consumer electronics application
- The work performed under this project is directly aimed at improving the cost, durability, and performance of the MEMS SOFC technology

Relevance

Objectives:

- Task 1:

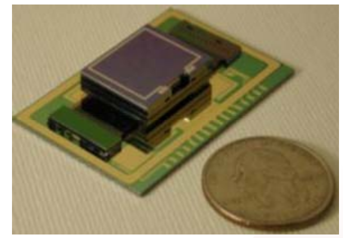
  Increase MEMS SOFC array power density toward a level sufficient to support a commercial product launch

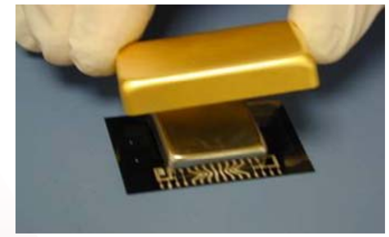
  - Milestone: Improve the average power density of the SOFC array by 50%.

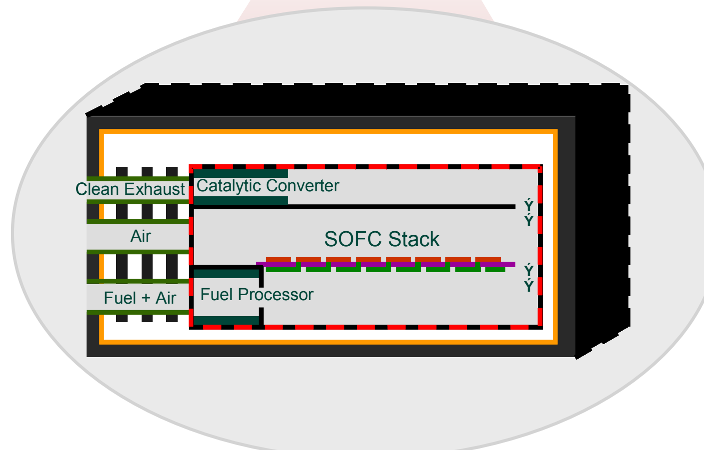
- Task 2:

  Improve vacuum sealing materials and processes to extend lifetime at higher operating temperatures

  - Milestone: Improve chip-level vacuum sealing to support operation at 800°C
  - Milestone: Fabricate and test SOFC devices that demonstrate realized improvements over current design



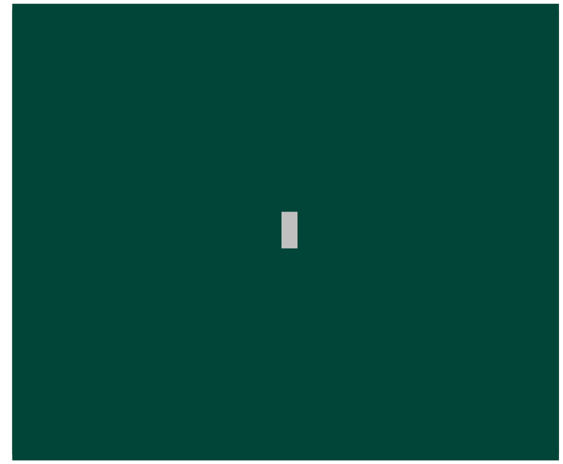




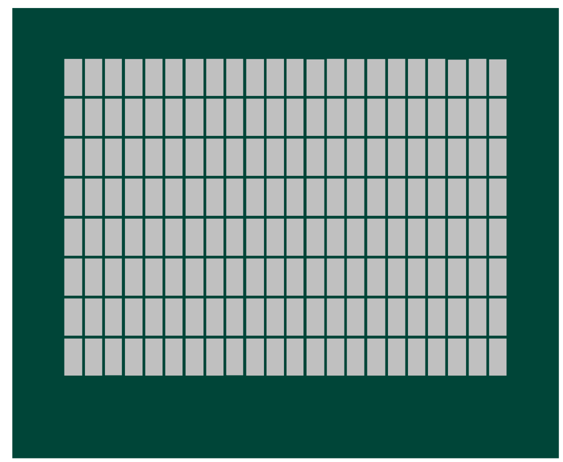
Approach

Increasing MEMS SOFC Array Power Density

- Power density on button cell test structures has historically been significantly higher than that achieved on full stacked arrays
- Even after stacking losses were carefully accounted for, a clear performance gap was evident
- The different physical structure of arrays requires different precursor solutions and process optimization to achieve maximum power density
- Performing the required number of experiments, each with a statistically significant number of samples, required development of a high throughput manufacturing process



Button Cell Test Structure



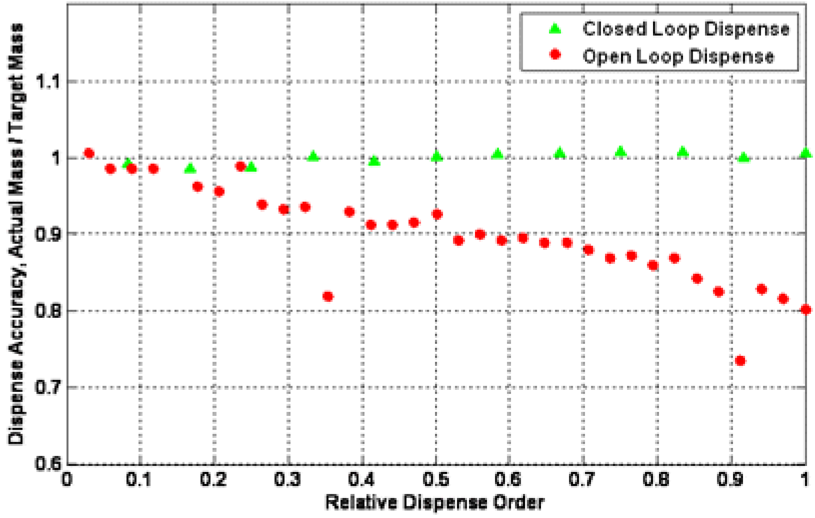
MEMS Fuel Cell Array

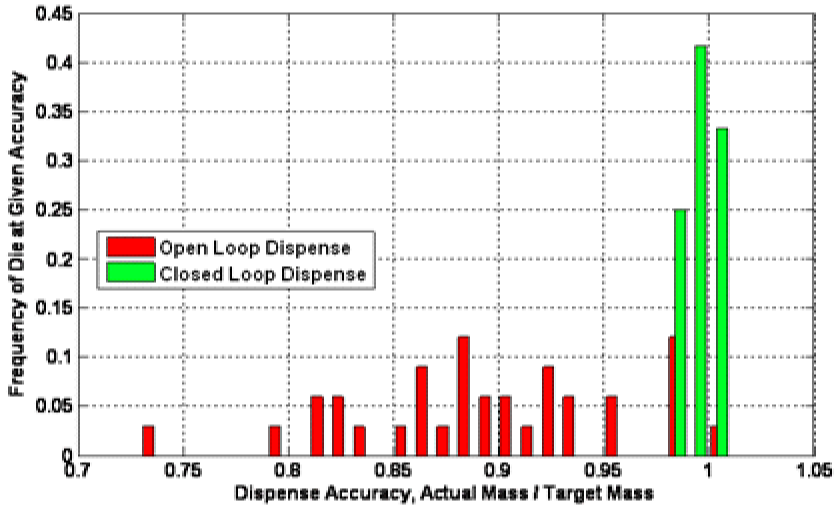
~ 200X Button Cell Active Area

Approach: Increasing SOFC Array Power Density

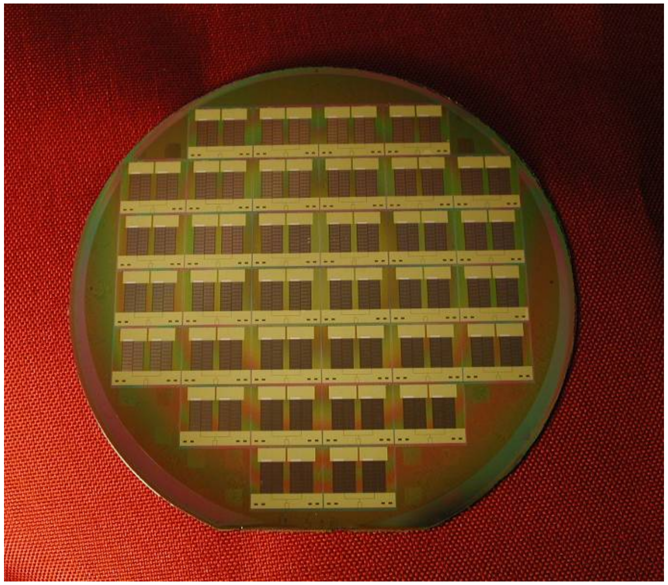
Automatic Deposition of Electrodes

- Hand processing of fuel cell electrodes is not scalable to commercial volumes and creates inconsistencies in device-to-device performance, which hampers developmental activities
- Accuracy and repeatability of commercially available automated dispense equipment is not sufficient for electrode production
- Standard equipment was modified with closed loop control of dispense volumes and improvements in positioning accuracy
- Dispense volumetric repeatability and accuracy has been significantly improved
- Result is improved electrode uniformity, faster processing, and higher yield
- Provides a solid foundation for the process refinements necessary to increase power density





Approach: Increasing SOFC Array Power Density



Better Adhesion over Large Arrays

- Scanning Electron Microscope (SEM) images of array electrodes indicated significant delamination, believed to be related to stresses during drying
- Experiments were performed varying the thickness and number of coats used to form the electrodes, however this had little effect on power density
- Additional experiments were run to optimize the drying temperature profile, which provided an observerable improvement in electrode adhesion

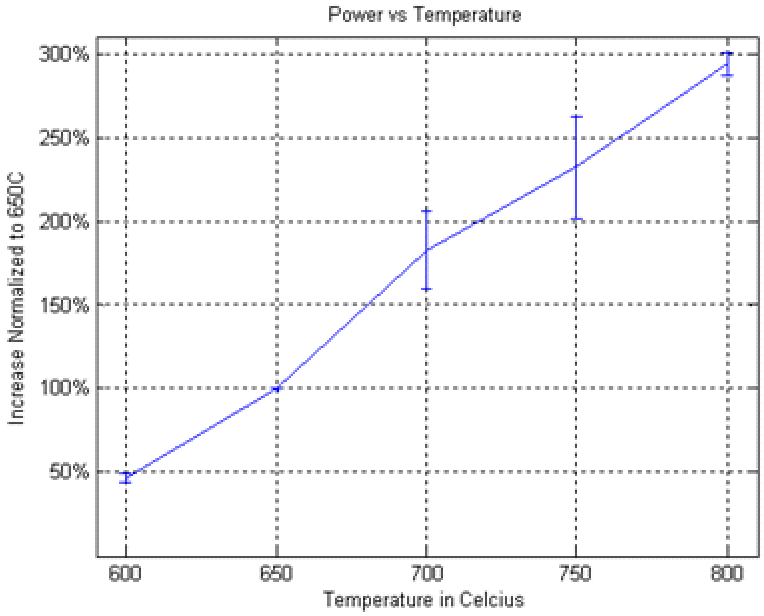
Increased Throughput to Statistically Relevant Volumes

- Implemented wafer-level processes on the improved dispense equipment to accelerate learning cycles
- Demonstrated equivalent performance from wafer-level processed devices

Approach

Improve Vacuum Seal Life

- Increasing fuel cell chip operating temperature has significant benefits for energy production, but at the expense of seal lifetime
    - ~30% power increase 700 to 750°C
    - ~25% power increase 750 to 800°C
- Interactions between the silicon fuel cell die and the sealing glass increase rapidly at temperatures above 650°C
- A multi-pronged approach to improving seal life was pursued, including:
    - Compositional changes to the sealing glass
    - Incorporation of barrier layers to slow the die/glass interactions
    - Die structure modifications



Approach: Improve Vacuum Seal Life

Compositional Changes to the Sealing Glass

- Cross sectional analysis of the glass seals by SEM and Energy Dispersive Spectroscopy (EDS) indicates that glass composition changes are occurring at high operating temperatures
- A new, higher temperature furnace was installed to allow modifications to the initial glass composition in order to improve stability
- Analytical analysis shows that the modified glasses crystallize more fully, which is indicative of improved stability
- Due to delays in bringing the new furnace on line and the increased hardness of the modified glasses necessitating new grinding equipment, chip-level testing could not be completed under the time frame of this program
- Work in this area is ongoing

Approach: Improve Vacuum Seal Life

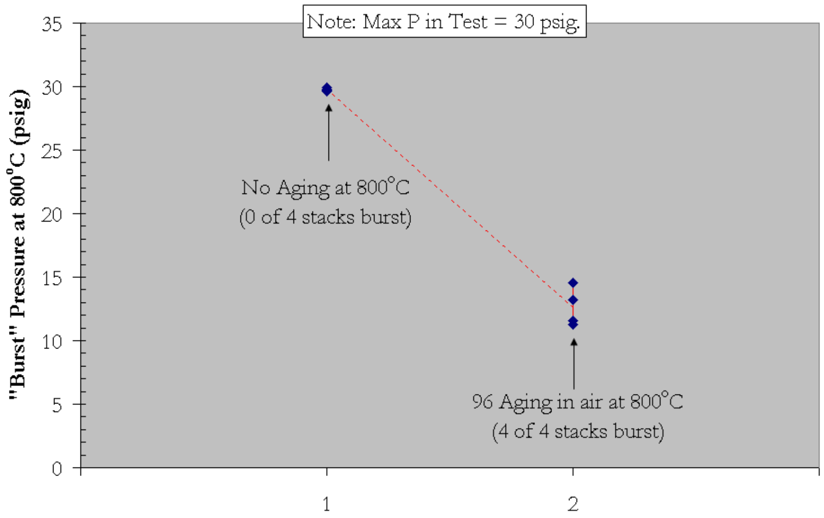
Incorporation of barrier layers to slow the die/glass interactions

- A variety of barrier layers were incorporated into the SOFC die assembly in order to isolate the reactive materials
- Several of these barrier layers showed good promise for reducing reactions, but proved difficult to incorporate into the manufacturing process
- Observations during this testing led to an improved understanding of the nature of the glass/die interactions, which guided the positive work in die structure modifications

Die structure modifications

- Changes to the structure of existing thin film coatings on fuel cell die were also shown to reduce glass/die interactions
- Although seal lifetime performance has improved, these modification required significant process development to regain previous yield levels

Strength Degradation with Aging



Approach: Milestones

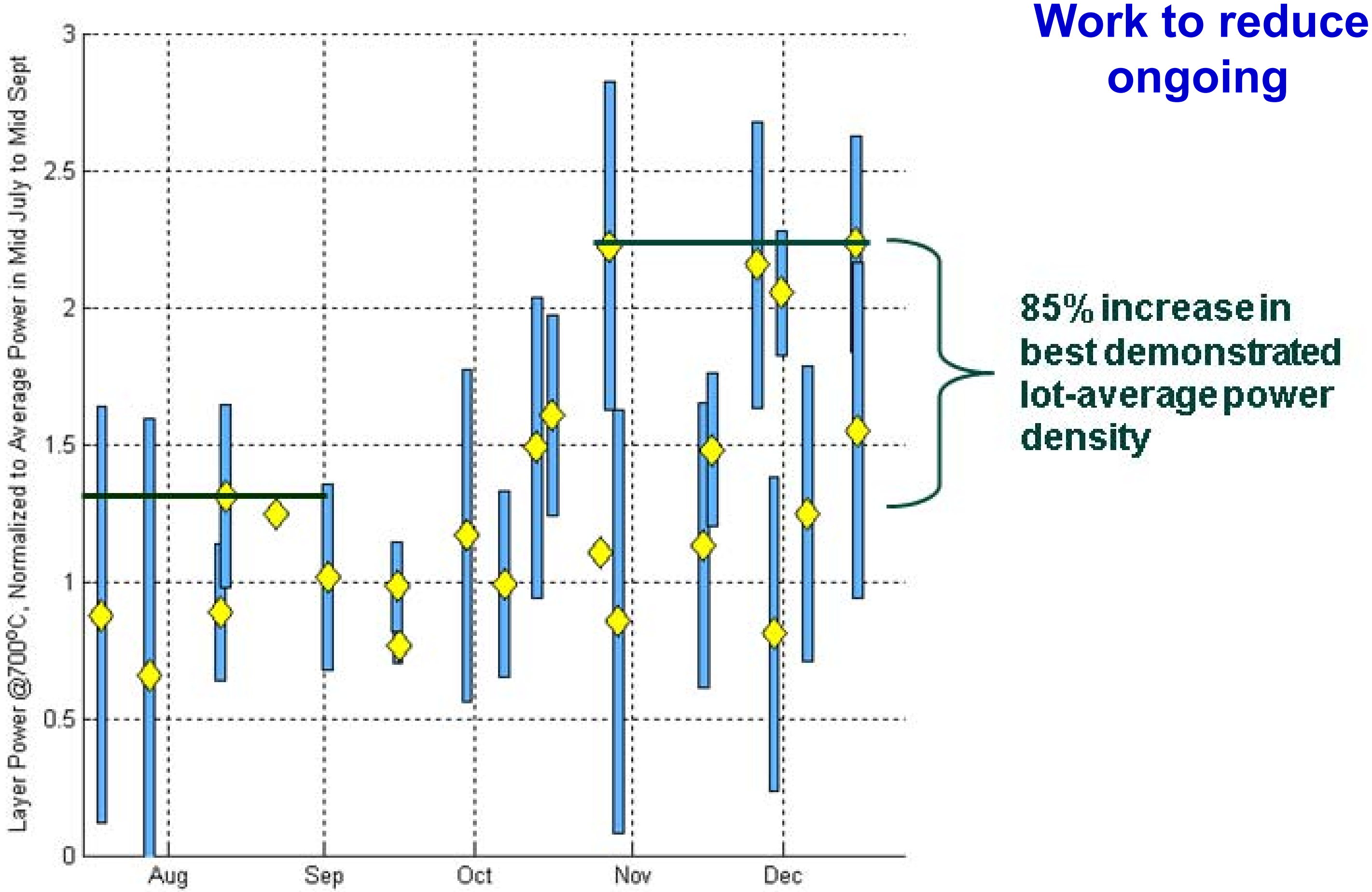
Task	Milestone	Target Date	Result
1	Improve average SOFC array power density by 50%	Dec-08	Milestone was exceeded, with best average power density increasing by over 85%.
2	Improve chip-level vacuum sealing to support operation at 800°C.	Dec-08	The full target operating temperature of 800°C was not attained, but a significant increase to 750°C was realized.
2	Fabricate and test SOFC fuel cell chips using the revisions developed under this program	Jan-09	The resulting device provided a maximum power output that is a 2.5X increase over the power record at the start of this program.

Technical Accomplishment

Objective: Improve the average power density of the SOFC array by 50%.

Exceeded goal with an 85% increase in lot average fuel cell power

Work to reduce process variability is ongoing

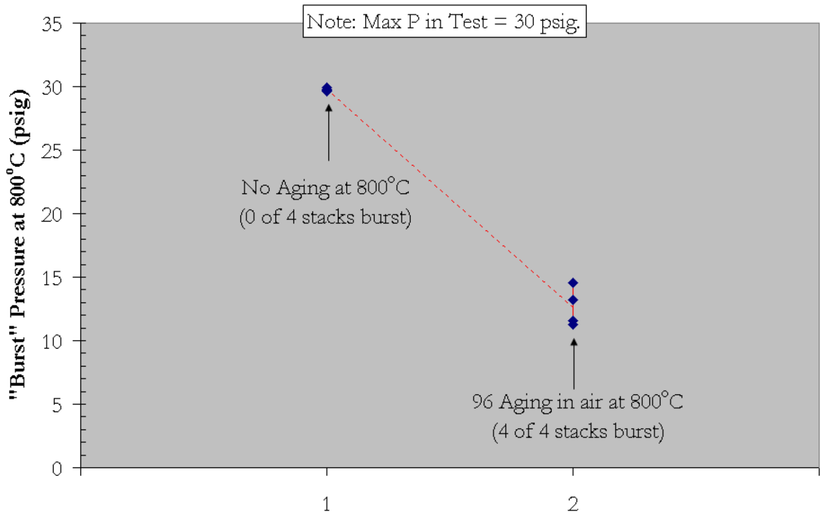


Technical Accomplishment

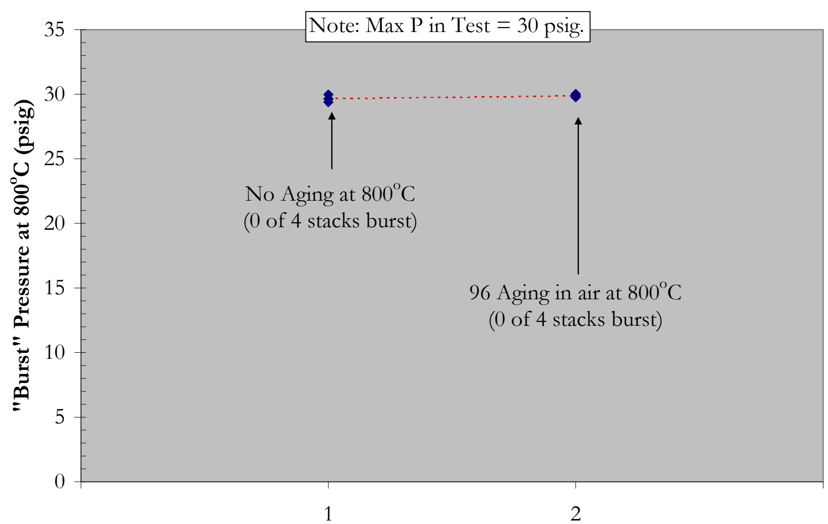
Objective: Improve chip-level vacuum seal lifetime through incorporation of barrier layers to slow die/glass interactions

- **Two candidate materials showed significant improvement in coupon testing**
- **Neither could be readily integrated into current MEMS manufacturing flow and were not tested at the SOFC chip level**
- **Results of this testing did significantly improved our understanding of the underlying material interactions**

Without Barrier Layer



With Barrier Layer

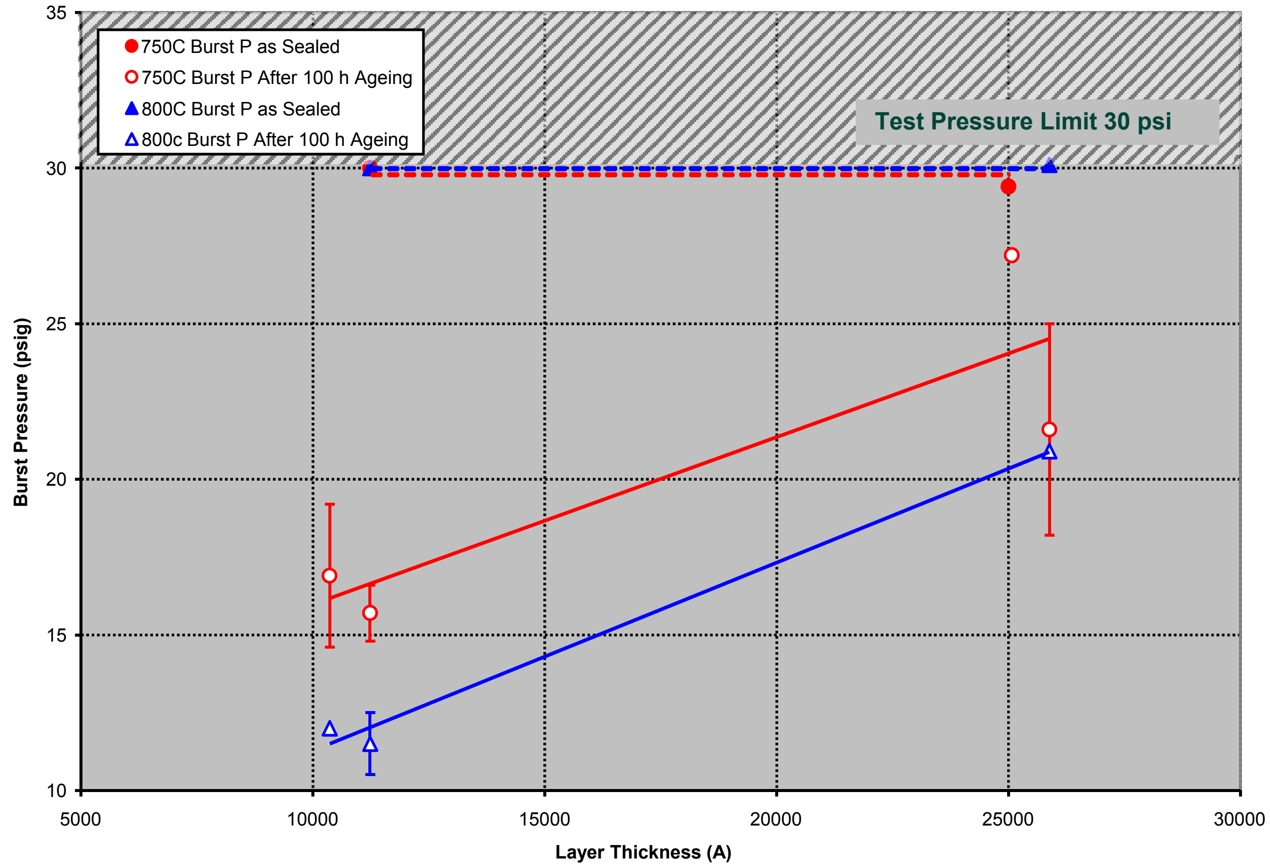


Technical Accomplishment

Objective: Improve chip-level vacuum sealing through die structure changes

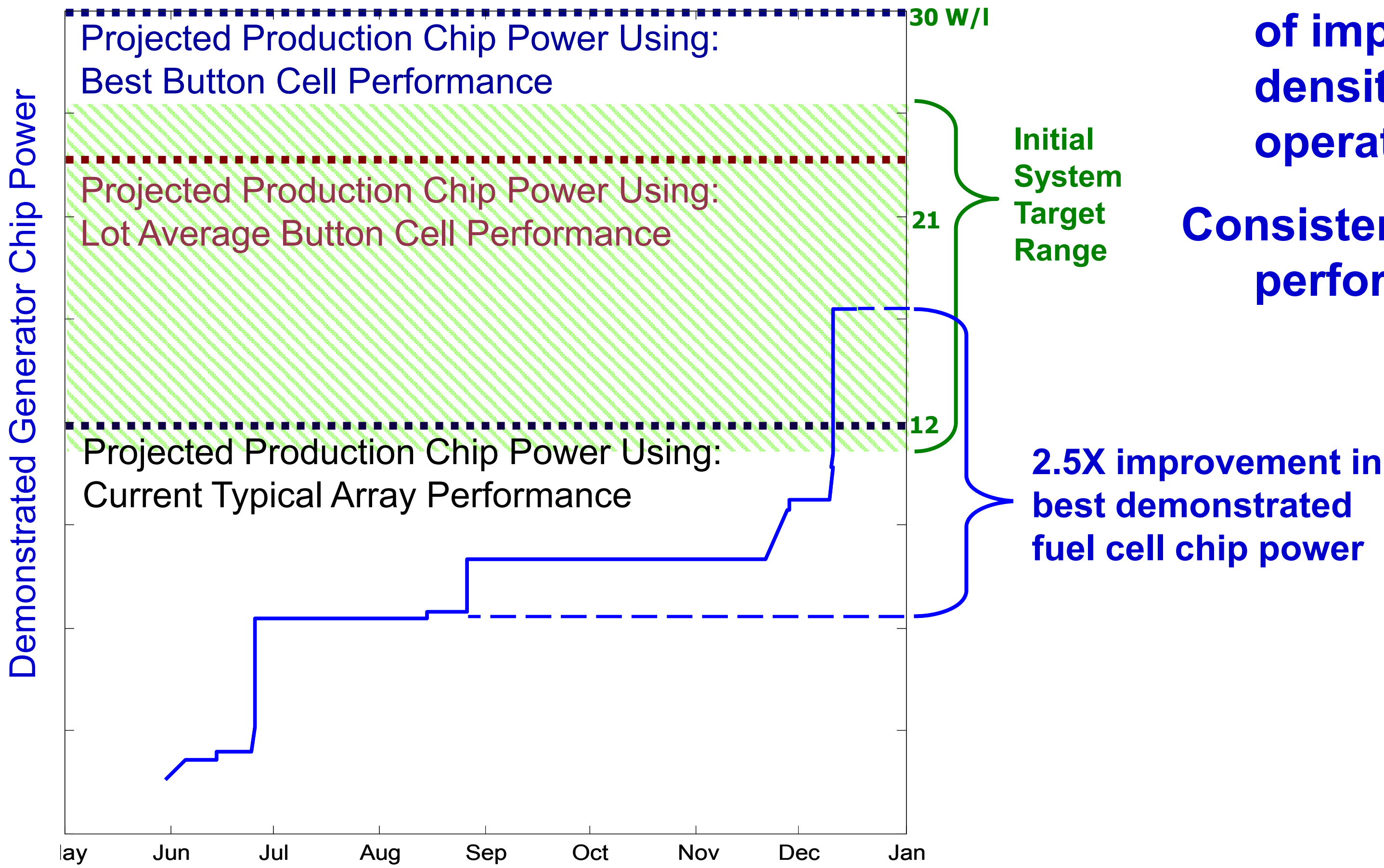
- **Increasing the thickness of an existing layer in the SOFC die thin film coatings reduced aging effects**
- **Additional improvement was realized through changes in the die sealing temperature profile**
- **Resulting improvement was not sufficient to operate at target temperature of 800°C, but did allow an increase in operating temperature to 750°C**

FC Chip Lot# - Die#	Die Structure / Sealing Process	Lifetime	Temperature
37- 1	Original	350 h	700°C
37- 8	Original	5 h	800°C
40- 7	Revised	255 h	750°C



Technical Accomplishment

Objective: Fabricate and test SOFC fuel cell chips using the revisions developed under this program



Demonstrated a 2.5X improvement in fuel cell chip power

Achieved through a combination of improved electrode power density and increased operating temperature

Consistent with target performance for product launch

Collaboration

Partners

Alfred University

Professor William C. LaCourse provides ongoing collaborative support and specialized testing for sealing glass development

Missouri University of Science and Technology

Missouri S&T provides testing support for electrode development

Technology Transfer

Lilliputian Systems' MEMS SOFC incorporates technology licensed from Lawrence Livermore National Labs and the Massachusetts Institute of Technology

Lilliputian Systems' business model is to invest in the development and initial production launch of the Silicon MEMS SOFC chip

Technology developed will also be made available for license to OEMs to provide for rapid expansion of production capacity and the associated cost reductions

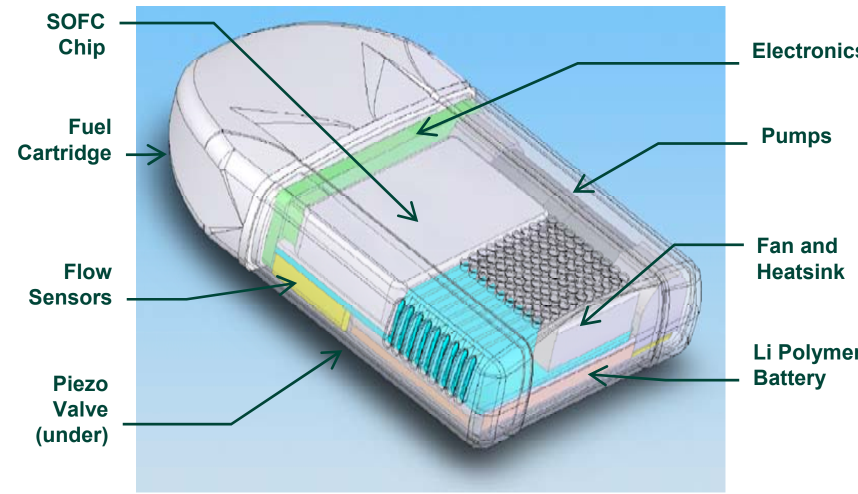
Proposed Future Work

Goal is development of commercial fuel cell chips for the consumer electronics market

- **Target first product is a USB charger capable of delivering 2.5W with the following *single cartridge* performance:**

Power Density	> 25 W/l
Energy Density	> 500 Wh/l
Run Time per Cartridge	> 30h

- **Initial product targets are below DOE 2010 targets for sub 50W systems**
  - **Metrics become more aggressive as output power decreases**
  - **Consumer requirements drive toward minimum possible size, at the expense of performance**



Proposed Future Work

Technical development projects:

- Fuel cell power
  - Investigate effects of electrode microstructure changes on power density
  - Continued optimization of array process to achieve button cell benchmark performance
  - Optimize MEMS structure to provide increased active area
- Durability
  - Continued refinement of glass composition and die structure to achieve targeted lifetime and operating temperature
  - Extended life testing of vacuum seal and fuel cell electrodes
- Setup for Volume Manufacturing
  - Develop tooling for high throughput assembly

Summary

Silicon Based Solid Oxide Fuel Cell for Portable Consumer Electronics

- Significant progress was made in increasing array power density toward that of button cell benchmarks
- Target of 50% power improvement was exceeded with improvement of 85% attained
- Implementation of automated dispense equipment with custom control enhancements increased throughput and improved repeatability
- Vacuum seal temperature/lifetime performance was significantly improved, but somewhat short of target
- Improved understanding of die/sealing glass interactions will assist in directing future work
- Fuel cell chips were built with the improved processes and a 2.5X improvement in power was demonstrated
- Performance is on track for first commercial product release
- Continued support of MEMS SOFC projects enhances US competitiveness in the foreign-dominated micro fuel cell market