2021 Annual SOFC Project Review Meeting (11/17/2021)

Low Cost SOFCs for Small-Scale Distributed Power Generation (FE0031976)

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Agenda

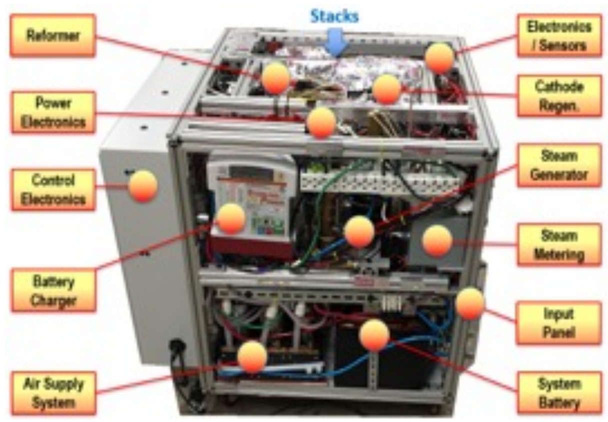
- Project Goals/Objectives
- Technical Approach
  - *Stack*: Increased power and reduced cost
  - *Key BOP*: Microchannel HX/SR
  - *System Design*: smaller/fewer key BOP and industry best practice
- Project Structure
- Project Progress

Project Goal: Reduce cost of small-scale (5-25kW) SOFC power systems to ≤ $1,000/kW at lower production volume (e.g., ≤ 250 MW/year or 10,000 25-kW systems/year).

Small-Scale Power Systems & Prototypes

- Redox's Product Strategy
  - Single scalable system platform to address currently underserved markets (e.g., < 100 kW)
  - Daisy chain smaller units for larger implementations
- Key Subsystems (5-25 kW scale)
  - Stack hotbox, fuel processor, air delivery, electronics (control/power)
  - Stack hotbox is 25-40% cost
  - $/kW ↑ substantially as system size ↓

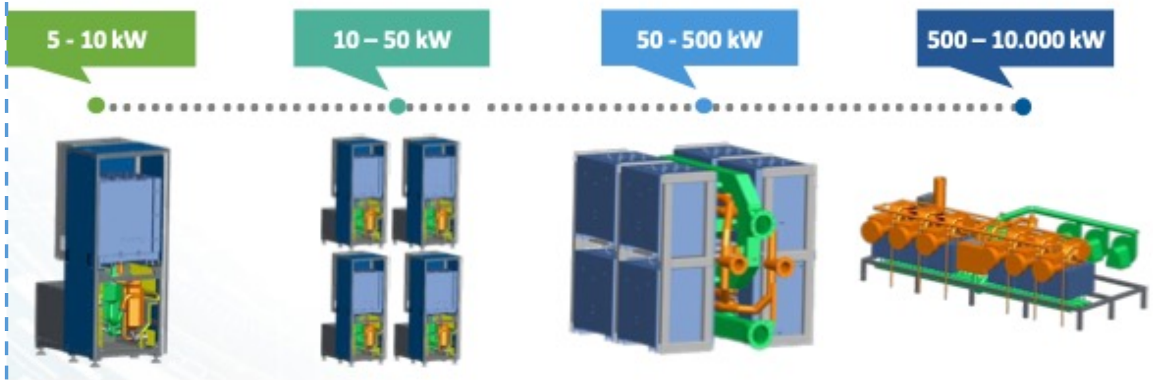
REDOX



Up to 750W

10-30kW

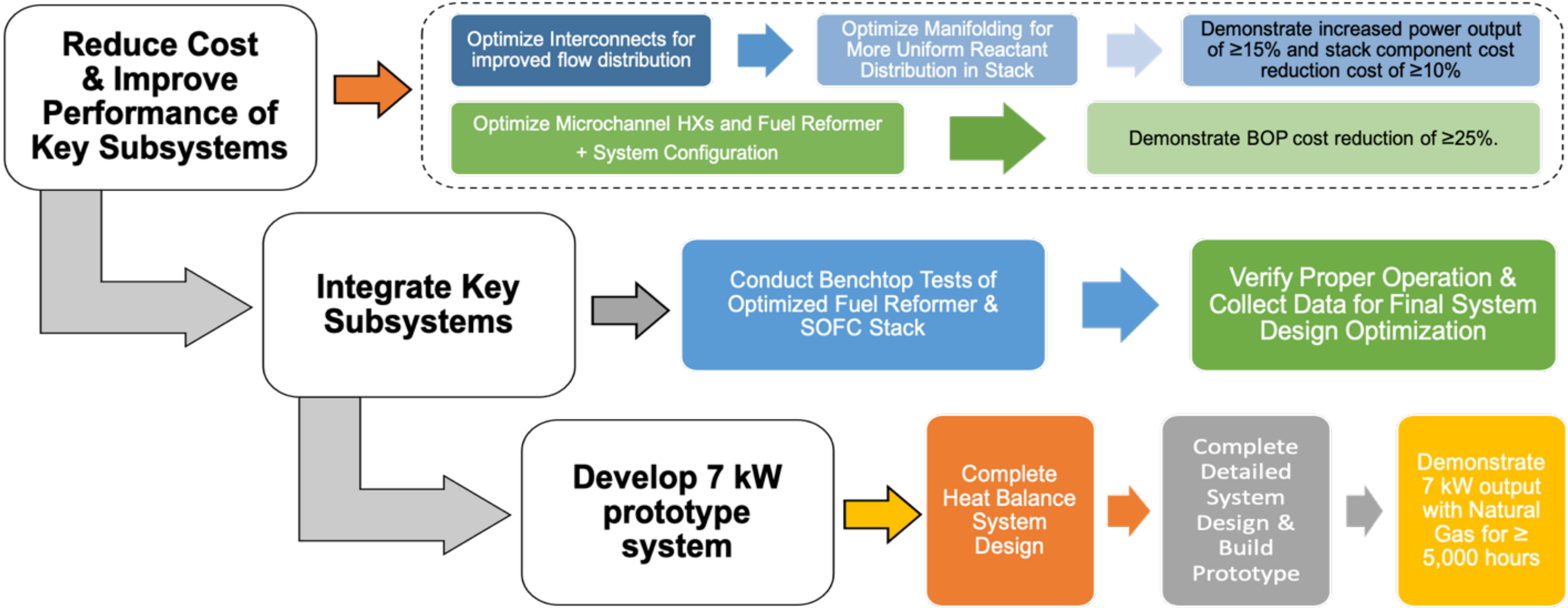
AVL



Project Objectives

- ↓ cost of stack hotbox subsystem with optimized interconnects (IC) and manifolds
- ↓ cost of fuel processor and air delivery subsystems with optimized microchannel HX/SR and system config.
- Design, build, and demonstrate integrated, 7 kW system prototype running on natural gas for ≥ 5,000 hours
- Demonstrate a path to ≤ \$1,000/kW at production volumes ≤ 10,000 systems/year with a detailed techno-economic analysis

Technical Approach Summary



- **Stack:** improved thermal management and heat recovery & (ultimately) improved cell/stack durability
- **HX/Fuel reformer:** simpler manufacturing, improved thermal management, increased system efficiency
- **TEA:** Show clear path for meeting cost targets of ≤ $1,000/kW at ≤ 10,000 systems/year

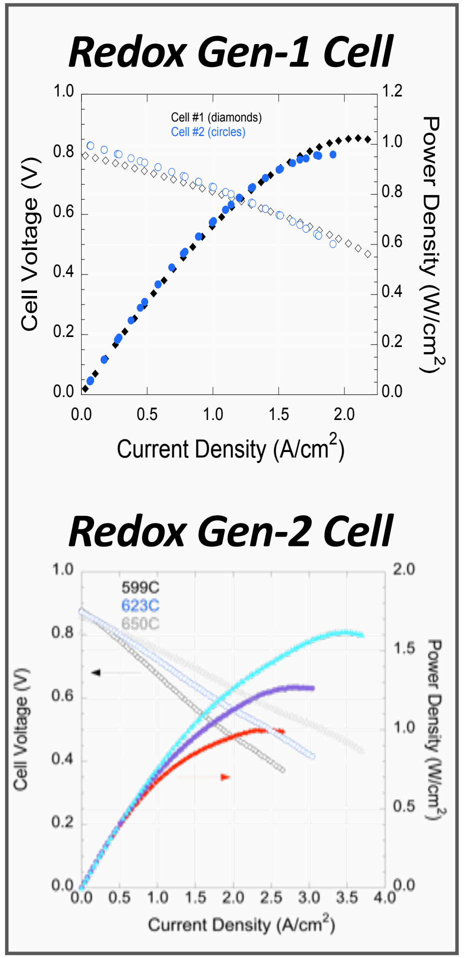
Project Structure: Tasks

Task 1: Project Management Sub1.1– Project Management Plan (PMP) Sub1.2–Technology Maturation Plan (TMP)	• Project schedule/milestones • Risk management • Path to reaching cost targets
Task 2: Optimize Performance/ Reduce Cost Stack Hotbox Sub2.1–Reduce the IC Cost and Improve Flow Distribution Sub2.2–Optimize Manifolding for More Uniform Reactant Distribution in Stack	• Flow field visualization studies/similarity analysis • Flow field, multi-physics simulations • Stack tests • Conductivity, seal integrity, mechanical tests (thinner parts) • Geometry modification internal/external manifold, simulations • Stack manifold pressure tests
Task 3: Reduce Cost of Critical BOP Sub3.1–Reduce the Cost of Microchannel Heat Exchangers and Fuel Reformer Sub3.2–Evaluate Performance of Reduced Cost Microchannel HX and SR BOP	• Cost-of-manufacturing evaluation (manufacturing processes, device geometry, and/or catalysts) • Overall SOFC system design requirements + system config. • System heat balance modeling (reduce size, number HX) • Multi-physics modeling verification • Degree of internal reforming

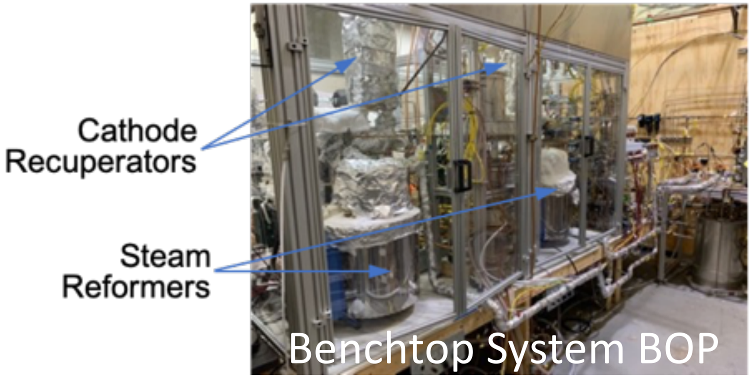
Project Structure: Tasks

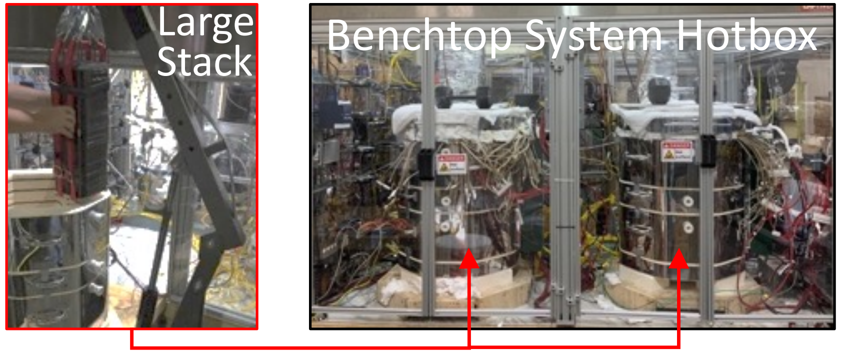
Task 4: Complete Detailed Design for a 7 kW SOFC Power System Sub4.1–Test Fuel Processor with Updated Stack Sub4.2–Complete Detailed Design for 7 kW SOFC Power System Sub4.3–Build the SOFC System Prototype	• Integrated testing of fuel processor/stack hotbox (≥1.2kW) • Measure electrical, thermal data; eval. heat transfer efficiency, fuel reforming composition, and pressure drops • Finalize test site (permitting, environmental approval, etc.) • Integrate key subsystems, detailed layout, proper mating • Design integrated controls and safety chain • Shipping/assembly/testing criteria + checkout tests
Task 5: Demonstrate 7 kW SOFC Power System at a Relevant Test Site	• Delivery and installation at host site • Startup, heat up, conditioning/burn-in, characterization • Remote operation and monitoring (5,000 hours)
Task 6: Complete Techno-Economic Analysis Sub6.1–Integrate Individual Cost Models for Small-Scale SOFC System Sub6.2–Run Sensitivity Analysis and Refine Cost Projections Based on Test Data	• Integrate, update, and validate cost models (manufacturing processes and component design characteristics) • Complete TEA based on final designs and test data (cell, stack, BOP component, capital, O&M costs) • Sensitivity analysis (e.g., impact of lower operating temp.) • Path to target cost, including specific cost reduction strategies (e.g., roll-to-roll (R2R) cell manufacturing)

Redox SOFC Technology

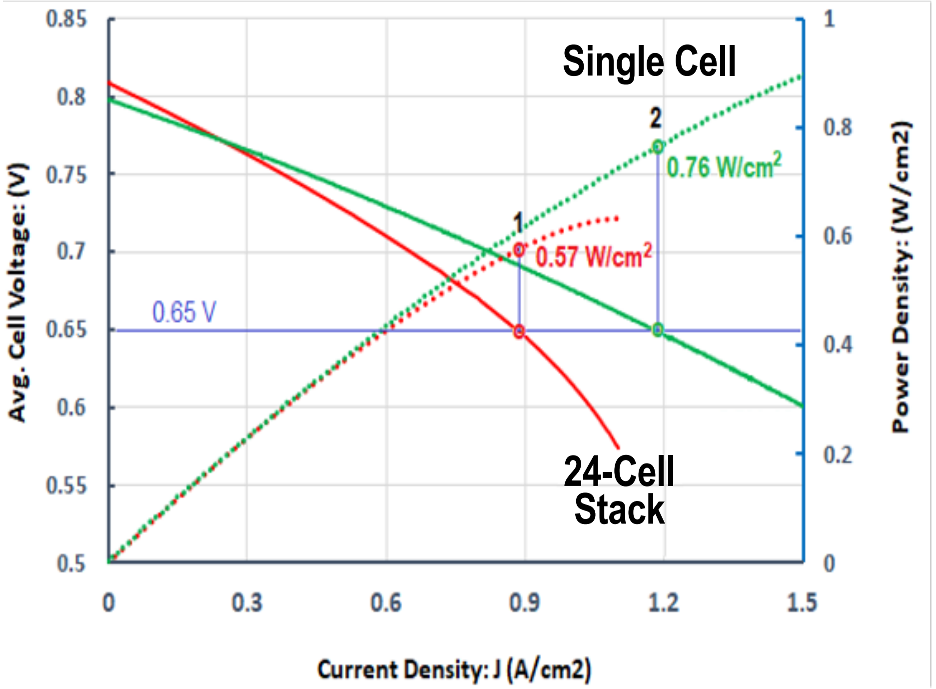


- GDC based electrolyte on robust (standard) Ni-YSZ support
  - Lower operating temperature
  - High power density
- Stacks as large as ~2.5 kW on natural gas
- But in larger stacks we are leaving power “on the table”
  - Non-uniform flow across the stack and within each repeat unit
  - Non-uniform temperature distribution

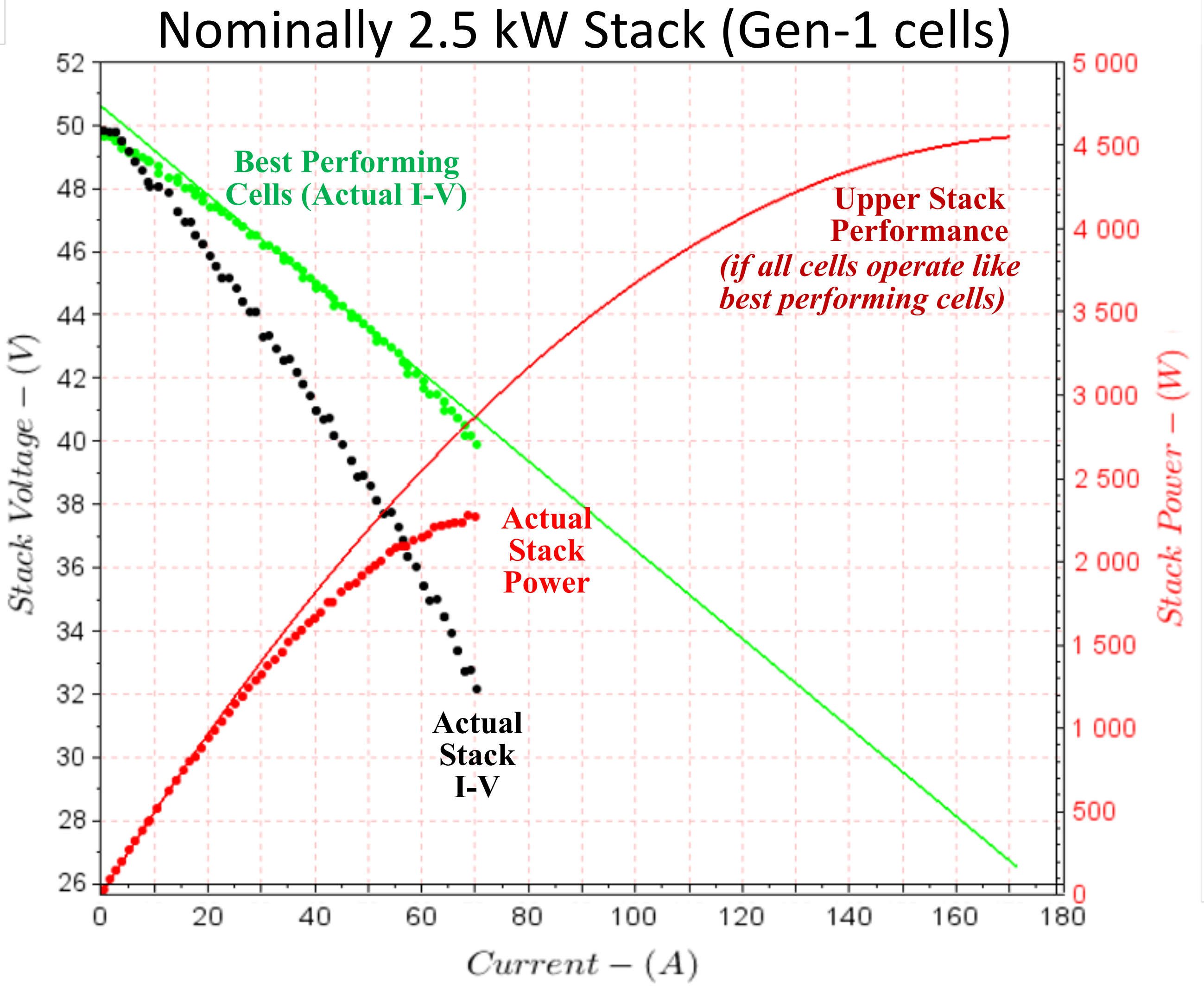




What can be gained from stack optimization

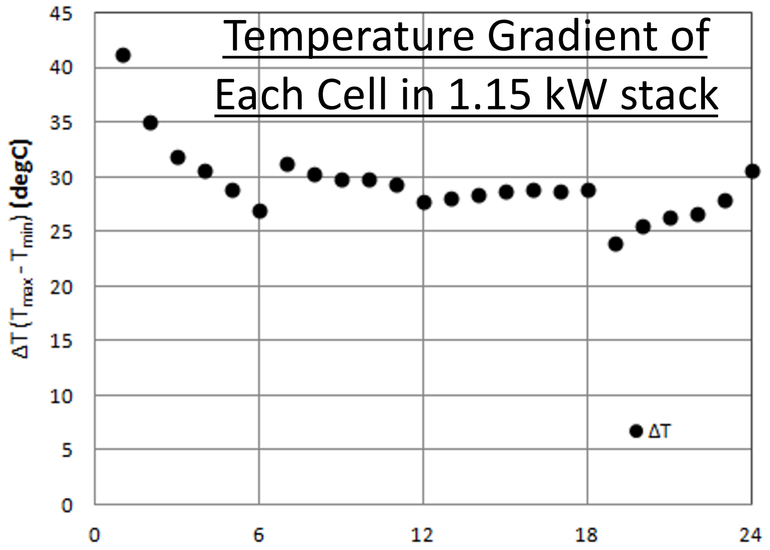


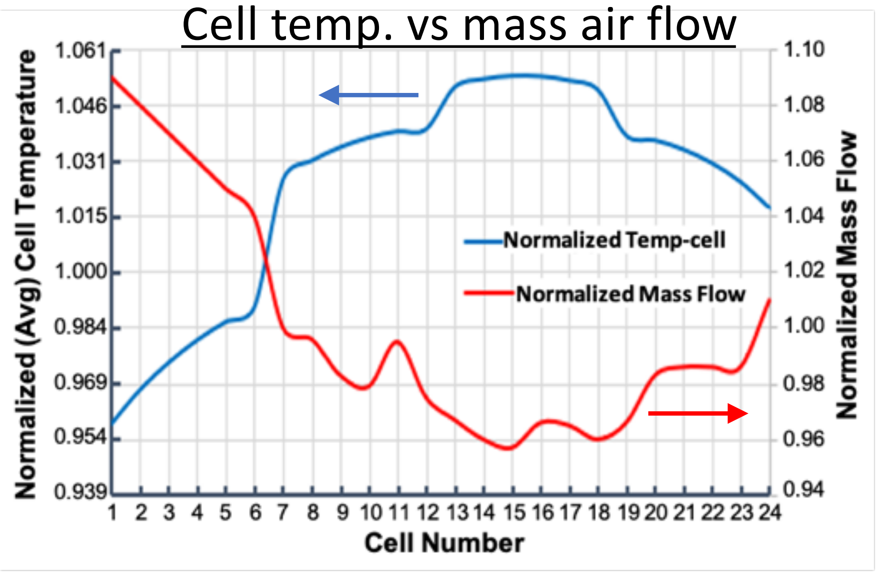
Gen-1 Cells	Cell Voltage (V)	(W/cm²)
Single Cell (green)	0.65	0.76
24-Cell Stack (red)	0.65 (avg.)	0.57



Stack Thermal Management

- Thermal issues impacting stack
  - Stack temp nonuniformity
  - Cell temperature nonuniformity
  - Inadequate stack cooling
  - Thermally driven gas flow nonuniformity
- Stack cooling options
  - Excess air
  - Internal reforming
  - Heat transfer to hotbox
- Largest gradients near manifold, and therefore optimized manifold (flow distribution/quenching) will improve thermal management
- Better internal/external manifold and optimized IC flow field can yield > 15% more power



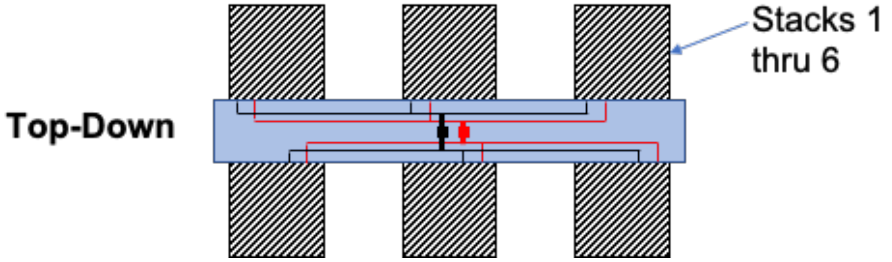


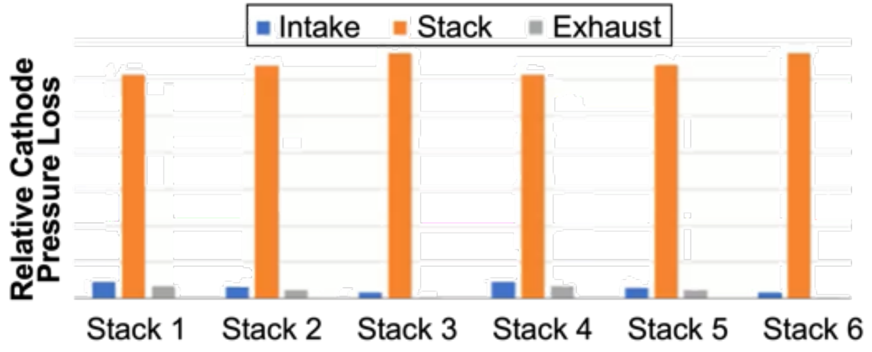
Stack Optimization: *Internal / External Manifolding*

- Optimized internal manifold
  - Improved pressure/flow distribution
  - Must obey known rules for sealing
  - Avoid increased manufacturing cost
- External Manifold
  - Reduce stack cost
    - Thinner endplates (material/design change)
    - Modify flow arrangement (inlet/outlet) locations
  - AVL's CFD modeling results for current iteration of stack manifold and optimized stack design shows acceptable balanced flow and pressure loss for stack assembly

Proposed Prototype Configuration

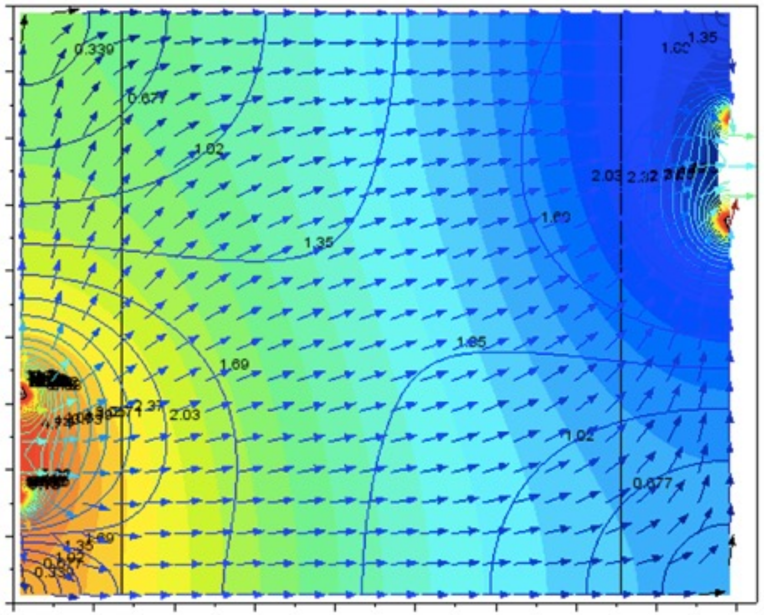
System output power	≥ 7 kW (DC)
System Efficiency	≥ 50% (LHV)
Stack (nominal) output power	1.2 kW (DC)
Anticipated number of stacks	6
Max. Number of cells/stack	32-36*
Anticipated stack manifold arrangement	3 groups of stacks connected in parallel (stack module), where each group of stacks consists of two series-connected stacks (submodule)
Stack submodule and module total (nominal) output voltage	45-50 V
Stack submodule (nominal) output current	46-52 A
Stack module (nominal) output current	138-156 A



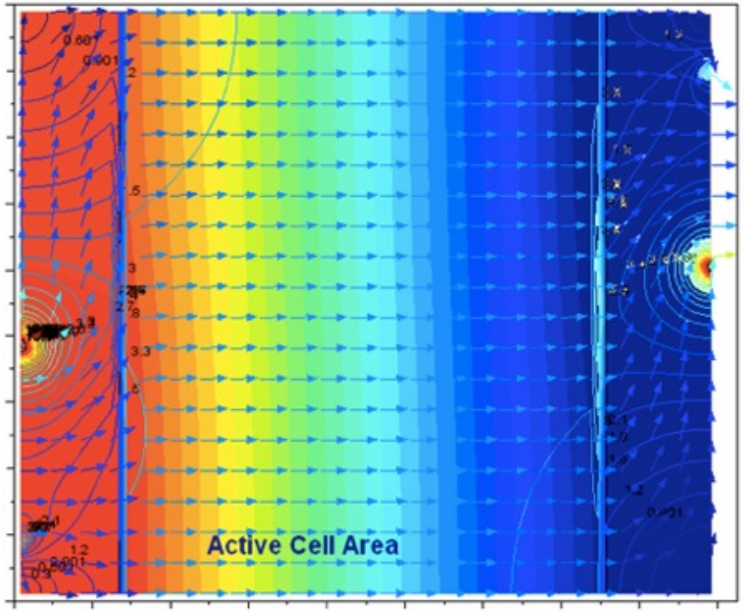


Improved IC Flow Distribution: *CFD Modeling*

"Standard" Geometry

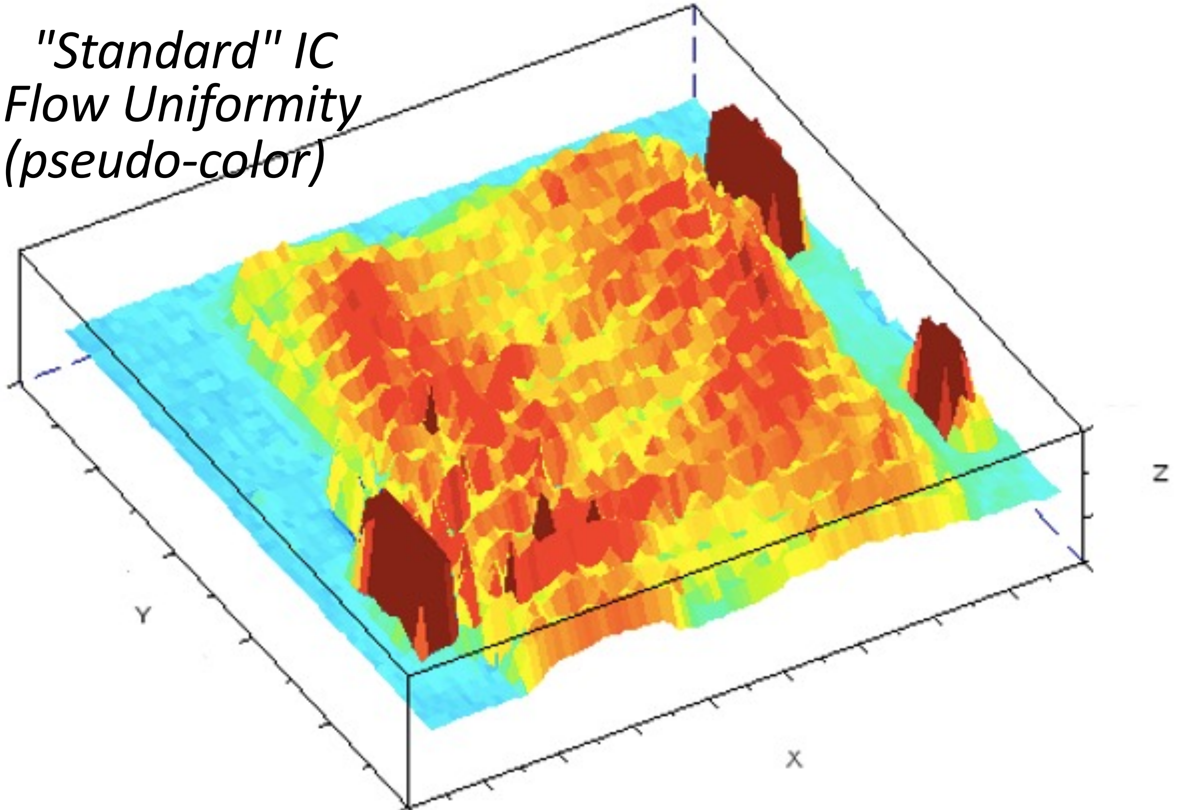


"New", Slightly Modified Geometry

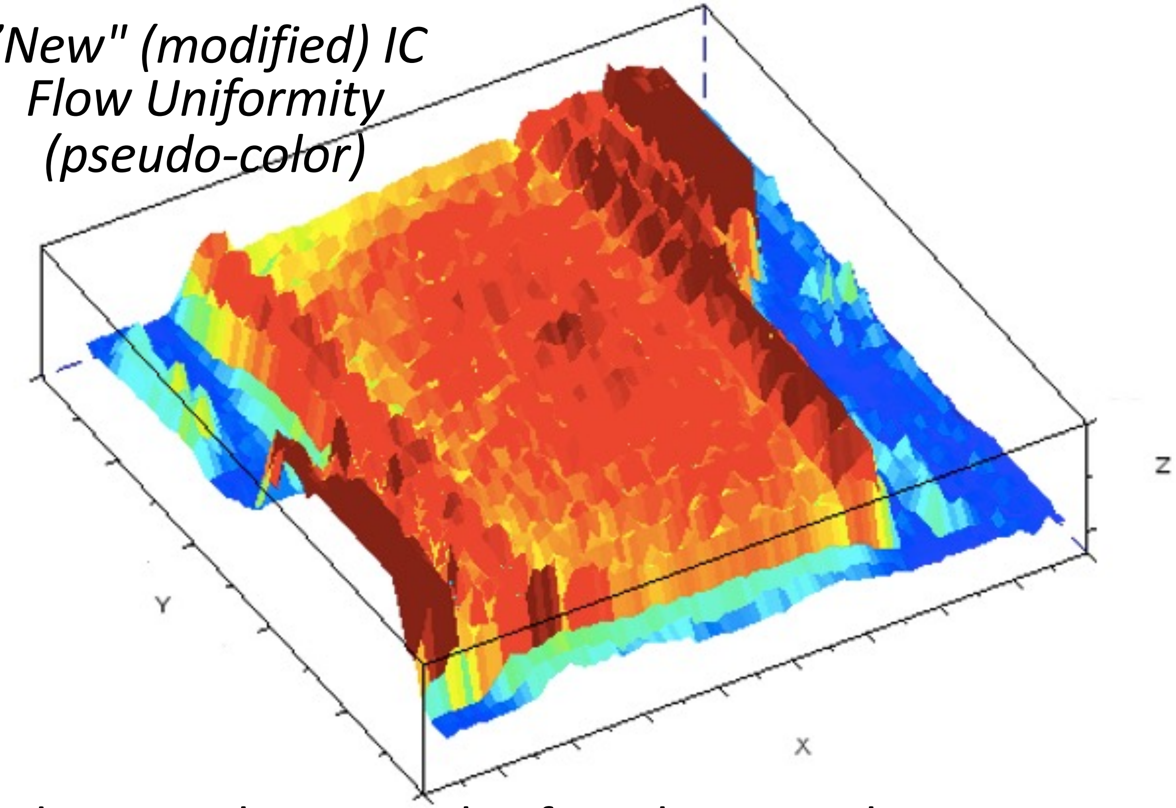


- Extra power through improved flow uniformity (fewer repeat units: ↓ cost)
- Simulated pressure & velocity
  - >70% more uniform flow (relative flow in corners vs central region)
  - 55% increase in total interconnect flow at same available driving pressure
- Slight modification to internal manifold and inlet/outlet portion of flow field results in dramatically improved flow distribution

Improved IC Flow Distribution: *Flow Visualization*



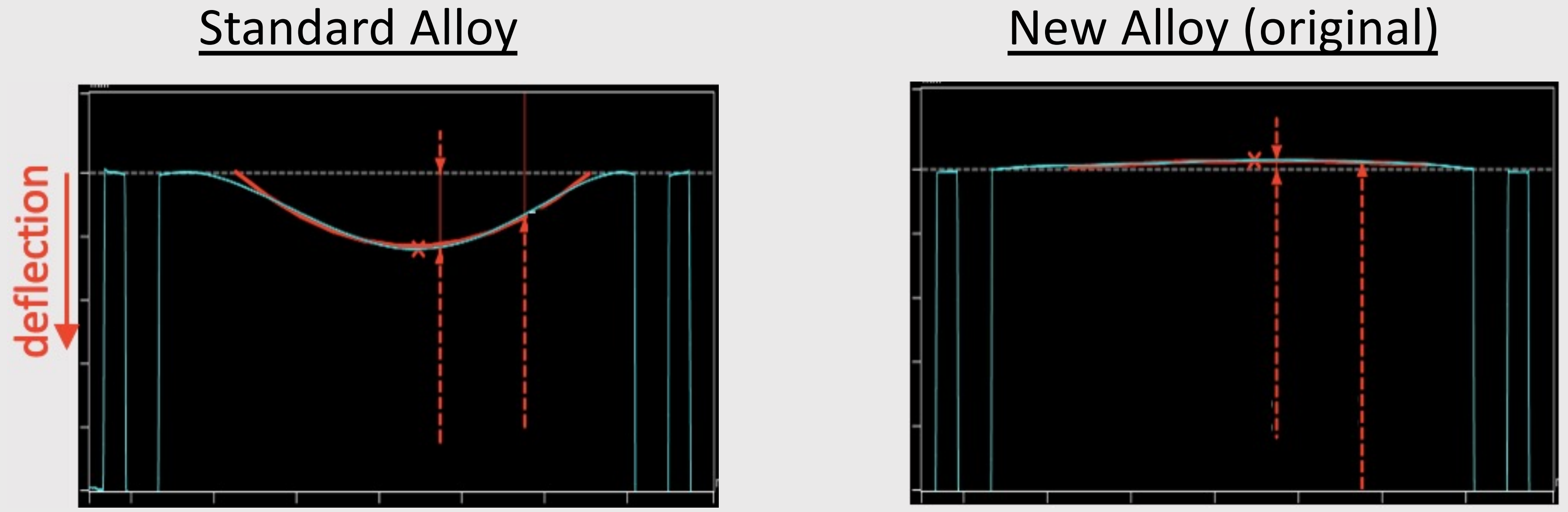
"Standard" IC Flow Uniformity (pseudo-color)



”New" (modified) IC Flow Uniformity (pseudo-color)

- Flow visualization set up and performed in accordance with principals of similarity analysis
- Video recordings were used to capture smoke entrained gas flow (at room temperature)
- Still images were then processed (e.g., remove background with now smoke) and used to create instantaneous light intensity maps due to light reflection from smoke particles
- Currently working to evaluate cell performance with modified IC

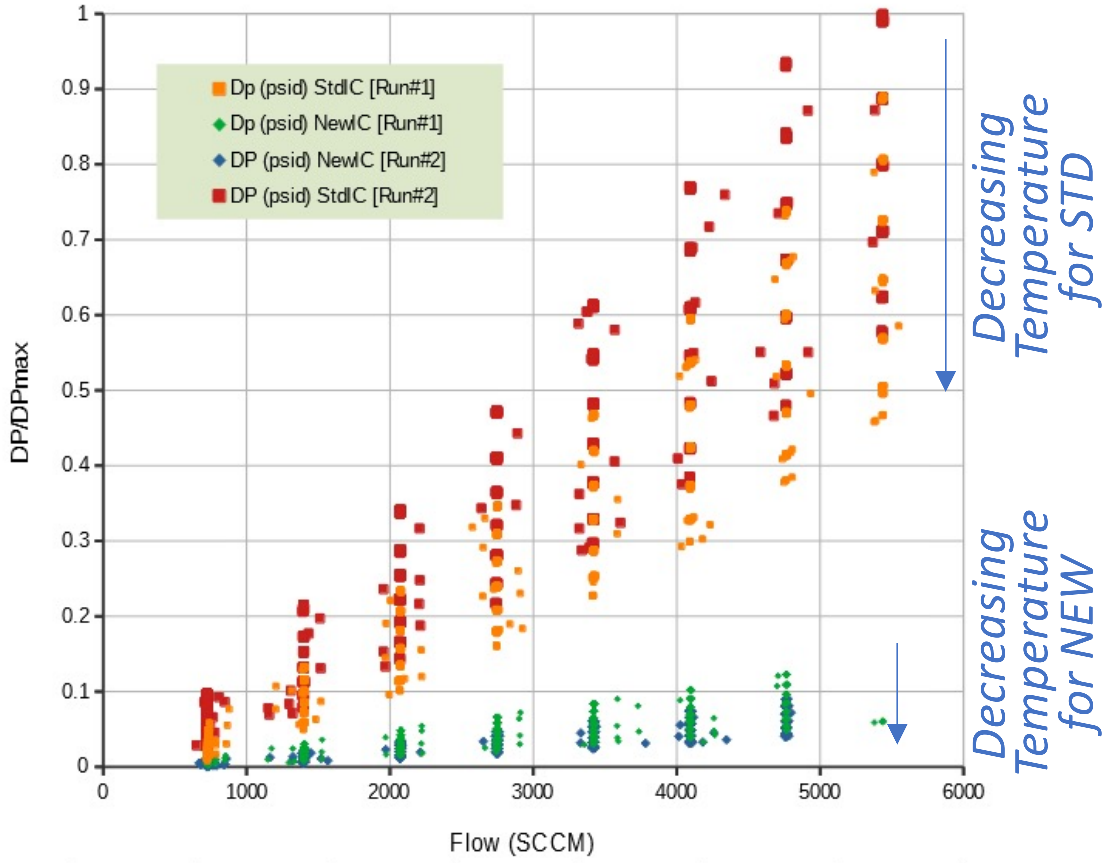
Thinner Stack IC & Endplates

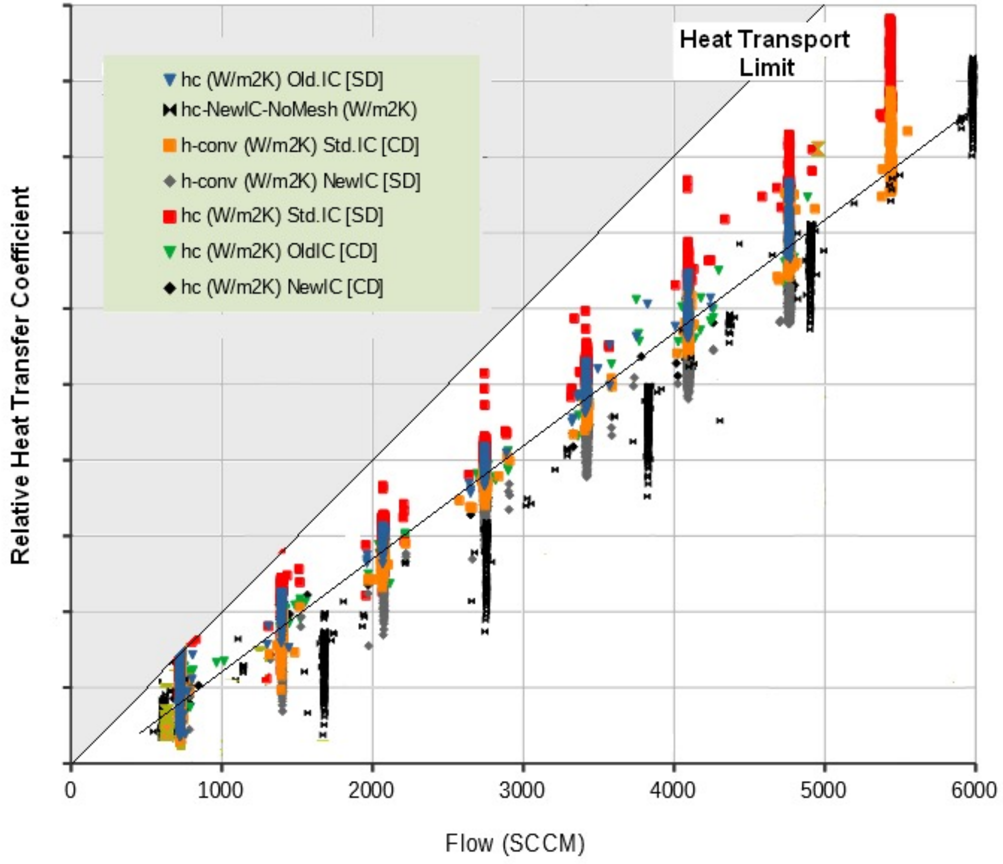


Coupon Tests with same thickness at 650°C (clamped ends/unsupported middle – *extreme case*)

- Reduced cost through decreased thickness, but must maintain mechanical integrity
  - Lower material cost and fabrication cost (e.g., stamping)
- Supply chain issues have delayed progress in this project
- Recently, a slight variant of the "new" material has been sourced domestically
  - Initial sag tests suggest very similar performance as the original "new" alloy

Interconnect Performance: *Pressure Drop & Heat Transfer*





- The stack pressure drop and convective heat transfer coefficient are important metrics for system design
- Differences in pressure drop vs flow rate for the "Std" and "New" interconnect designs
  → 8X reduction in dP observed
- H-conv: small decrease for "New" interconnect but not expected to impact performance much (dP so low)

PNNL Microchannel Heat Exchanger/Steam Reformer

- High-Efficiency Microchannel HX
  - laminar flow, small hydraulic diameter channels (0.005- 0.040”)
  - high surface area to volume ratio
  - high heat transfer coefficient (*h*)
- Compact, Fast Acting Steam Reformer
  - High-*h* HX quickly transfers heat into SR catalyst
  - A fast response reformer allows for better fuel load following
  - provides further enhancement to system efficiency by reducing the amount of excess fuel during high transient loading.
- Low volume HX and SR → more compact system, lower heat loss

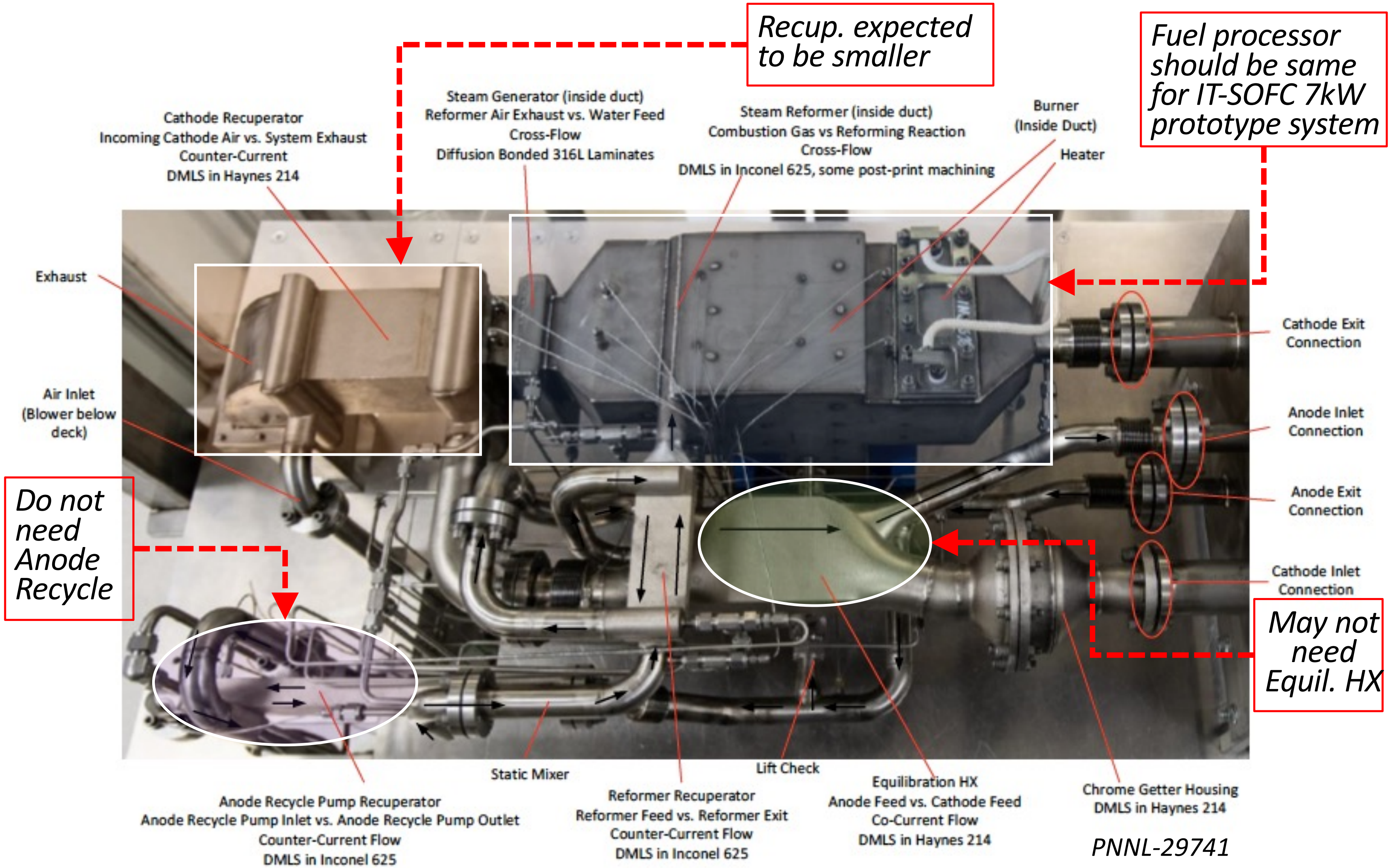
<u>Air-to-Air HX / 3.5kW</u>

(approx. relative scale)

PNNL HX: *same dP, 28 times less vol., 7% more eff.*

Key BOP in PNNL SOFC Test Stand Platform

- Provides test bed for new IT-SOFC specific design
- Optimize HX/SR designs for ↓ manufacturing cost (maintain performance)
  - Simplify component design (single pass)
  - Evaluation of simpler (more cost effective) manufacturing methods
  - Alternate materials (Redox SOFC operates at lower temperatures)
- System configuration that reduces cost
  - Reduced size or number of heat exchangers (including SR)



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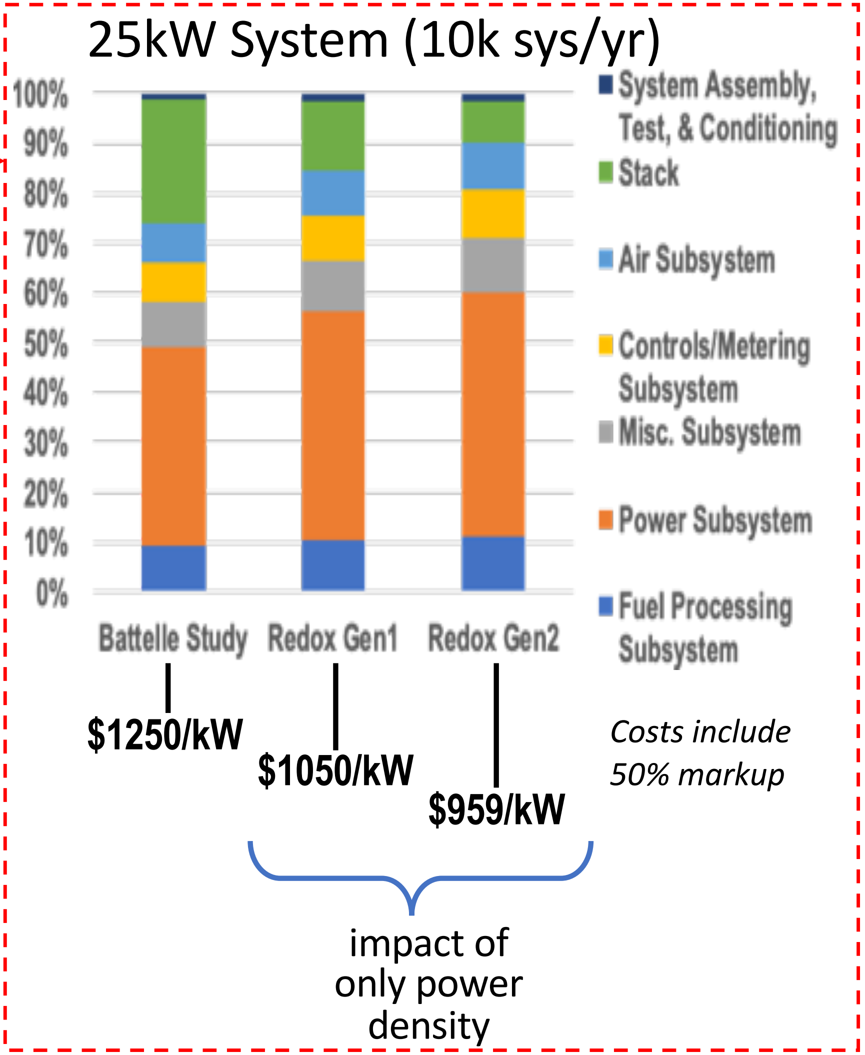
TEA & Path to Target Costs (TMP)

- Government sponsored Battelle ('17) & LBNL/SA ('15) studies as cost benchmarks
  - PNNL still working to update cost model for microchannel-based fuel processor and cathode recuperator
  - Some delays in receiving sizing/cost information for some of the manufacturing equipment
- Additional savings expected project outcomes
  - Lower operating temperature (600-650°C vs ~800°C)
  - Smaller HXs/blower – lower stack cooling requirements
  - PNNL microchannel HX/SR (≥25% cost reduction)
  - Lower stack endplate cost – single central manifold
- Other Efforts in support of technology maturation plans
  - High speed roll-to-roll (R2R) dev with ORNL (NFE-17-06781)
    - Same cell performance but reduced cost at < 5 MW/year (i.e., < 200 sys/yr)
  - TCF award offers continued R2R development (NFE-20-08382)



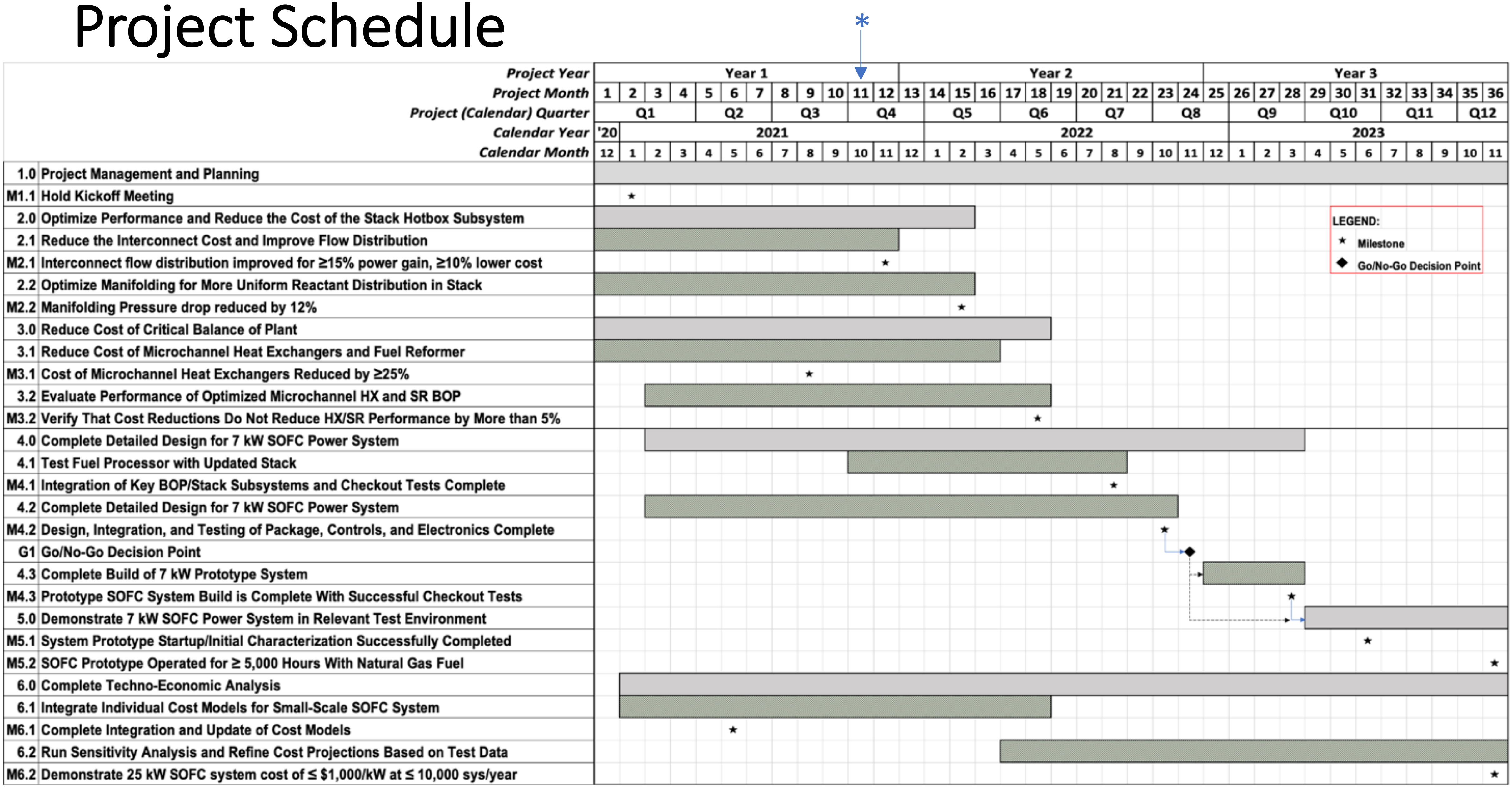
Battelle (2017): Manufacturing Cost Analysis of 1, 5, 10 and 25 kW Fuel Cell Systems for Primary Power and Combined Heat and Power Applications

LBNL/SA (2015): A Total Cost of Ownership Model for Solid Oxide Fuel Cells in Combined Heat and Power and Power-Only Applications

7 kW Demo Test Site: *Washington Gas Chillum Station*

- Washington Gas has joined the project team and will host the demo site for the 7 kW prototype
- The prototype will be situated near a natural gas backup generator and feed power into the building

Project Schedule



Acknowledgements

- Jason Montgomery — NETL Program Manager
- Dr. John Kasab — AVL Powertrain Engineering
- Dr. John Hardy and Greg Whyatt — PNNL
- Andrew Kent — Washington Gas