*2022 Annual SOFC Project Review Meeting (10/25/2022)*

# 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
- Stack Cost Reductions
- Microchannel HX/SR and Simpler System Design
- System Prototype Progress

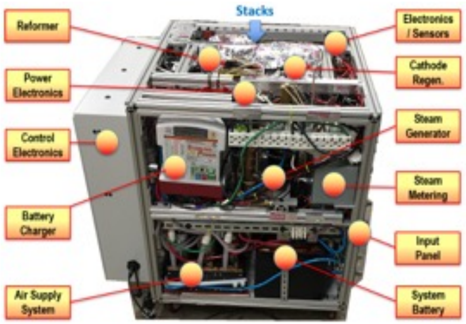
**Project Goal:** Reduce cost of small-scale (5-25kW) SOFC power systems to ≤ $1,000/kW at lower production volume (e.g., ≤ 250 MW/year or 10,000 25-kW systems/year).

# 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 ↓

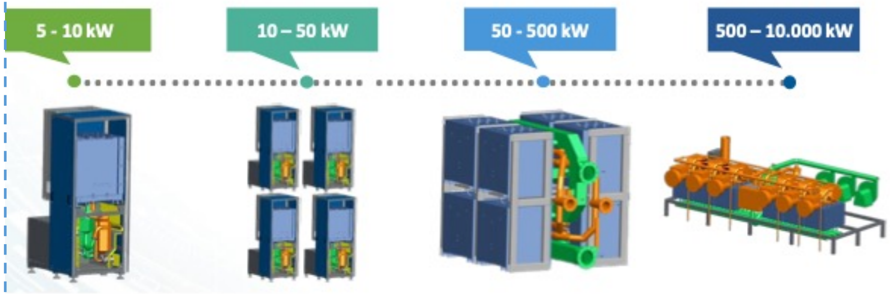
REDOX




Up to 750W

10-30kW

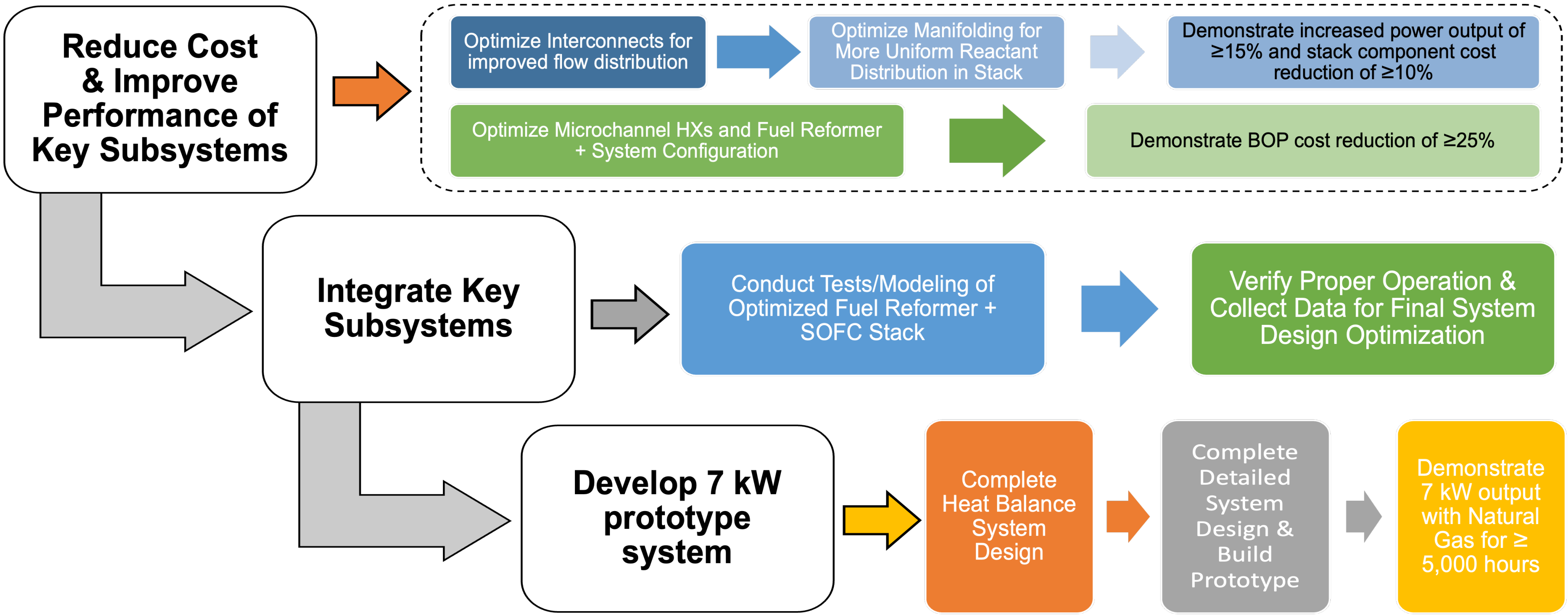
AVL



# 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

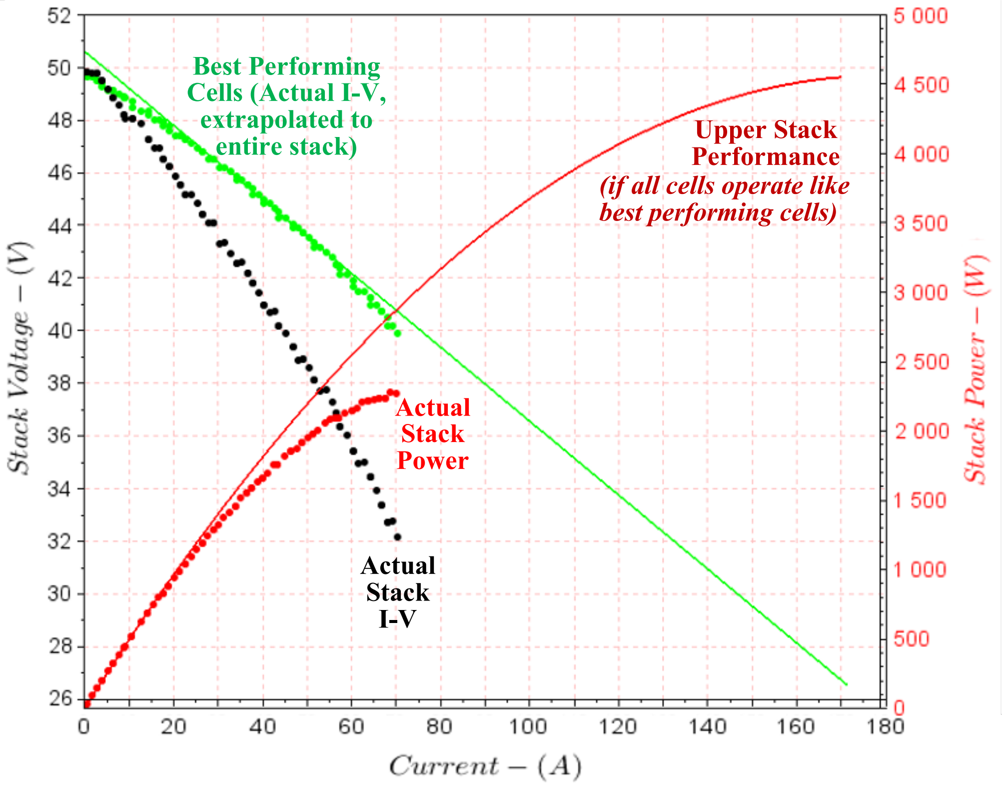



- **Stack:** improved thermal management and heat recovery & (ultimately) improved cell/stack durability
- **HX/Fuel reformer:** simpler manufacturing, improved thermal management, increased system efficiency
- **TEA:** Show clear path for meeting cost targets of ≤ $1,000/kW at ≤ 10,000 systems/year

# Stack Cost Reductions from Improved Flow Distribution

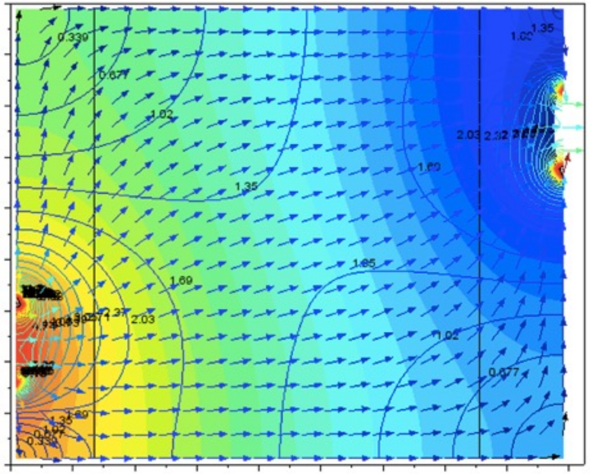
- Detailed analysis of past data showed
  - Non-uniform flow across stack and within repeat units
  - Non-uniform temperature distribution
  - Results in leaving power on the table
    - green curve ("Best Performing") represents > ½ of cells in stack
  - Results in higher cost (more repeat units)

Nominally 2.5 kW Stack (Gen-1 cells)

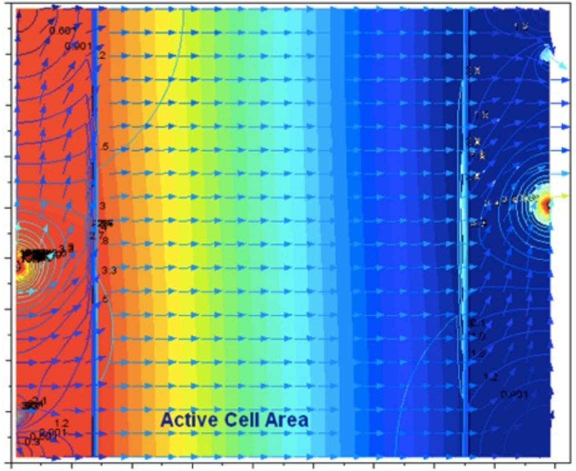


# Improved IC Flow Distribution: *CFD Modeling*

"Standard" Geometry

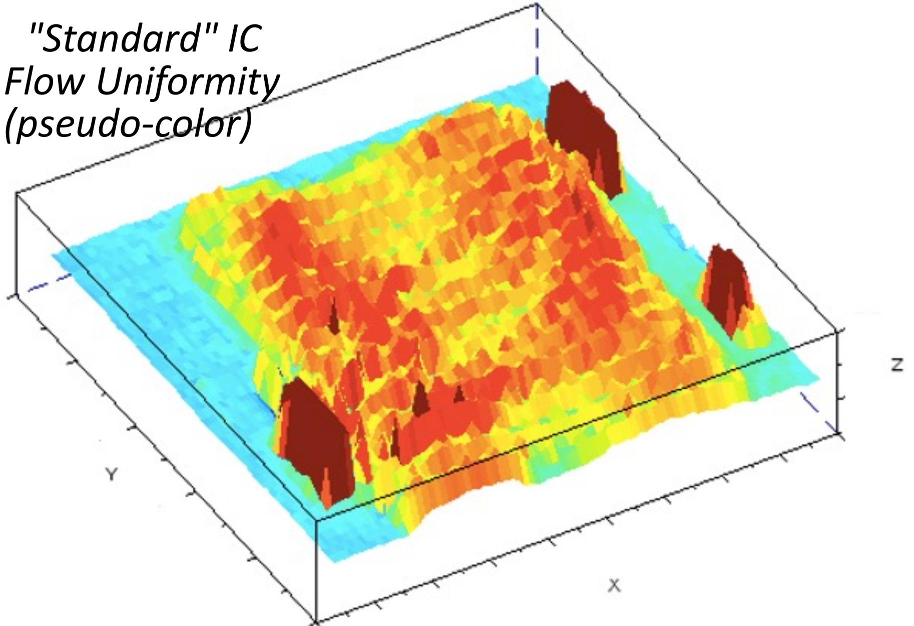


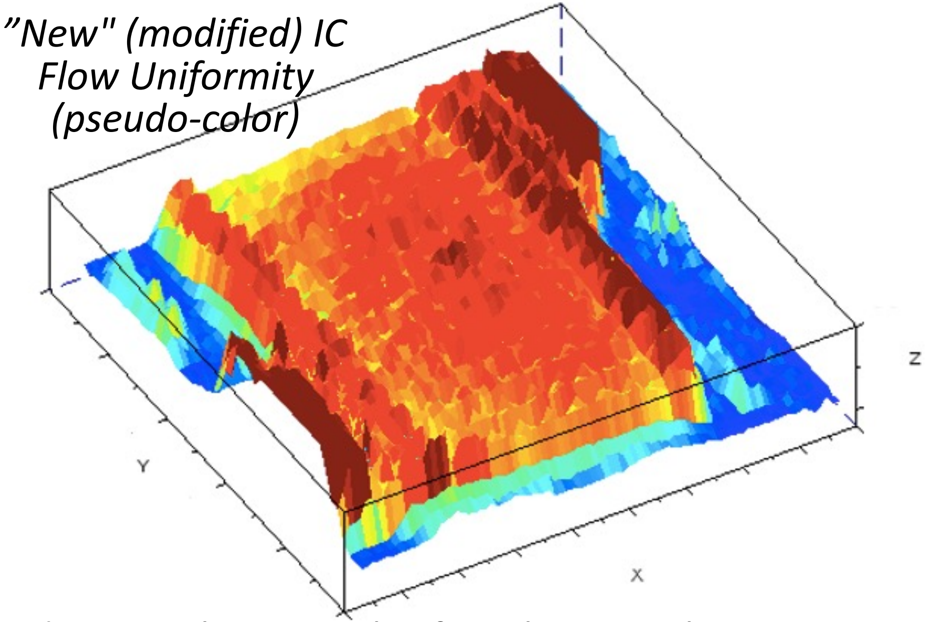
"New", Slightly Modified Geometry




- 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*

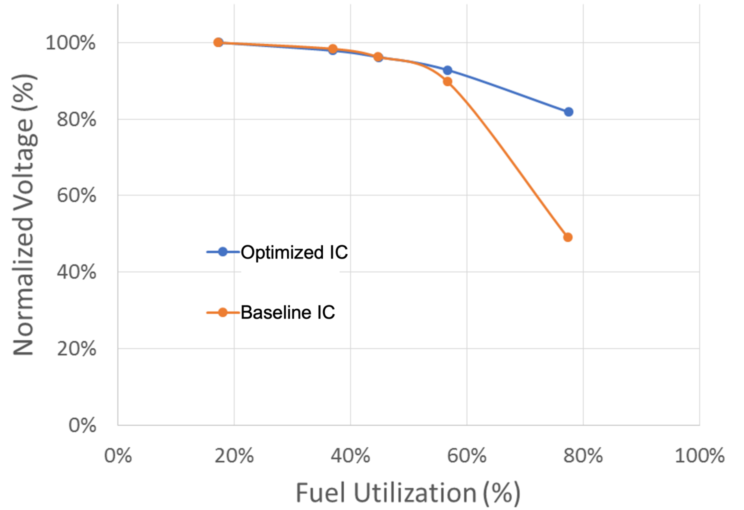



- Flow visualization set up and performed in accordance with principals of similarity analysis
- Video recordings were used to capture smoke entrained gas flow (at room temperature)
- Still images were then processed (e.g., remove background with now smoke) and used to create instantaneous light intensity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

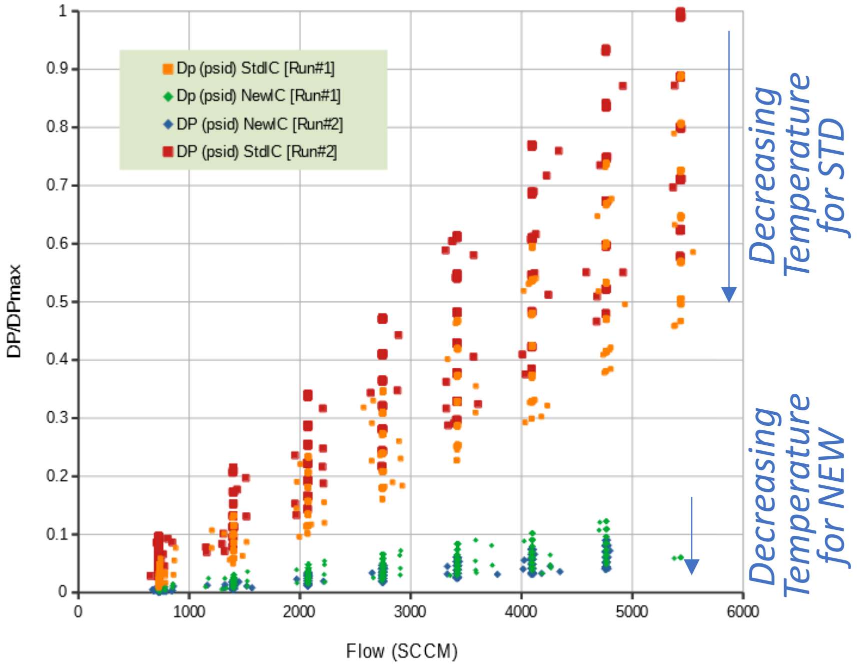
# Improved IC Flow Distribution: *Cell Tests*

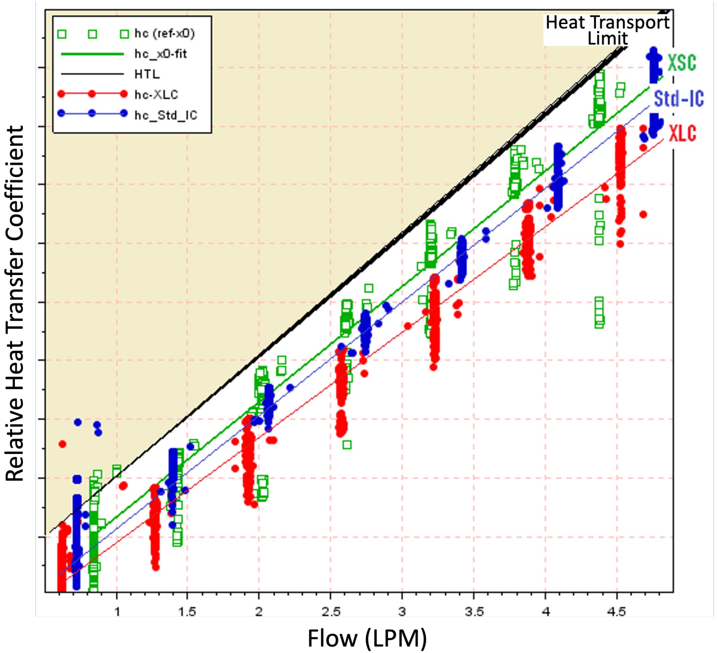
- Goal: demonstrate flow uniformity improvement with SOFC at 650 °C
- Using identical 10 cm by 10 cm cells
  - One cell tested with baseline interconnect
  - One cell tested with optimized interconnect
- To "observe" improvement in flow uniformity, current output was fixed while fuel utilization was varied
- The optimized IC showed a > 30% higher operating voltage (high $U_f$) than the baseline IC
  - Side regions of cell in baseline IC were starved of fuel, effectively reducing active area and increasing over-potential that leads to a lower $V_{op}$
- Significant cost reduction simply from increased power (flow uniformity improvement)
  - Additional cost reduction from thinner IC


**>30% higher power *vs* target: ≥15%**

# Interconnect Performance: *Pressure Drop & Heat Transfer*

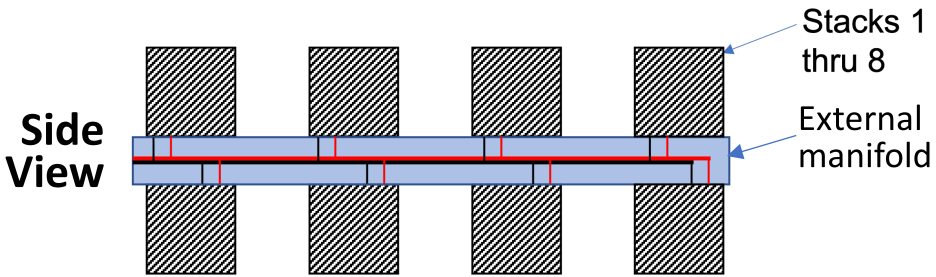


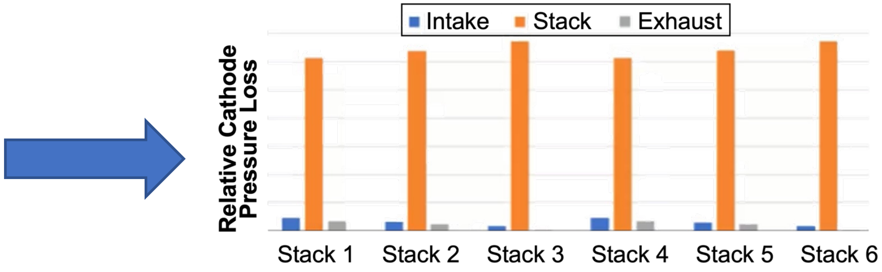




- The stack pressure drop and convective heat transfer coefficient are important metrics for system design
- Differences in pressure drop vs flow rate for the "Std" and "New" interconnect designs
  → demonstrated up to 80% lower dP
- *H-conv:* additional optimization of the “new” IC led to improved heat transfer of 85% of HTL (labeled XSC), exceeding the target of 75%

# Stack Optimization: *Internal / External Manifolding*

- Optimized internal manifold
  - Improved pressure/flow distribution
  - Must obey known rules for sealing
  - Avoid increased manufacturing cost
- External Manifold
  - 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




*Modeled at 6 stacks, similar for current 8 stacks (no change in # of cells)*

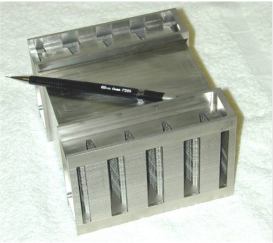
# PNNL Microchannel Heat Exchanger/Steam Reformer

- 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>

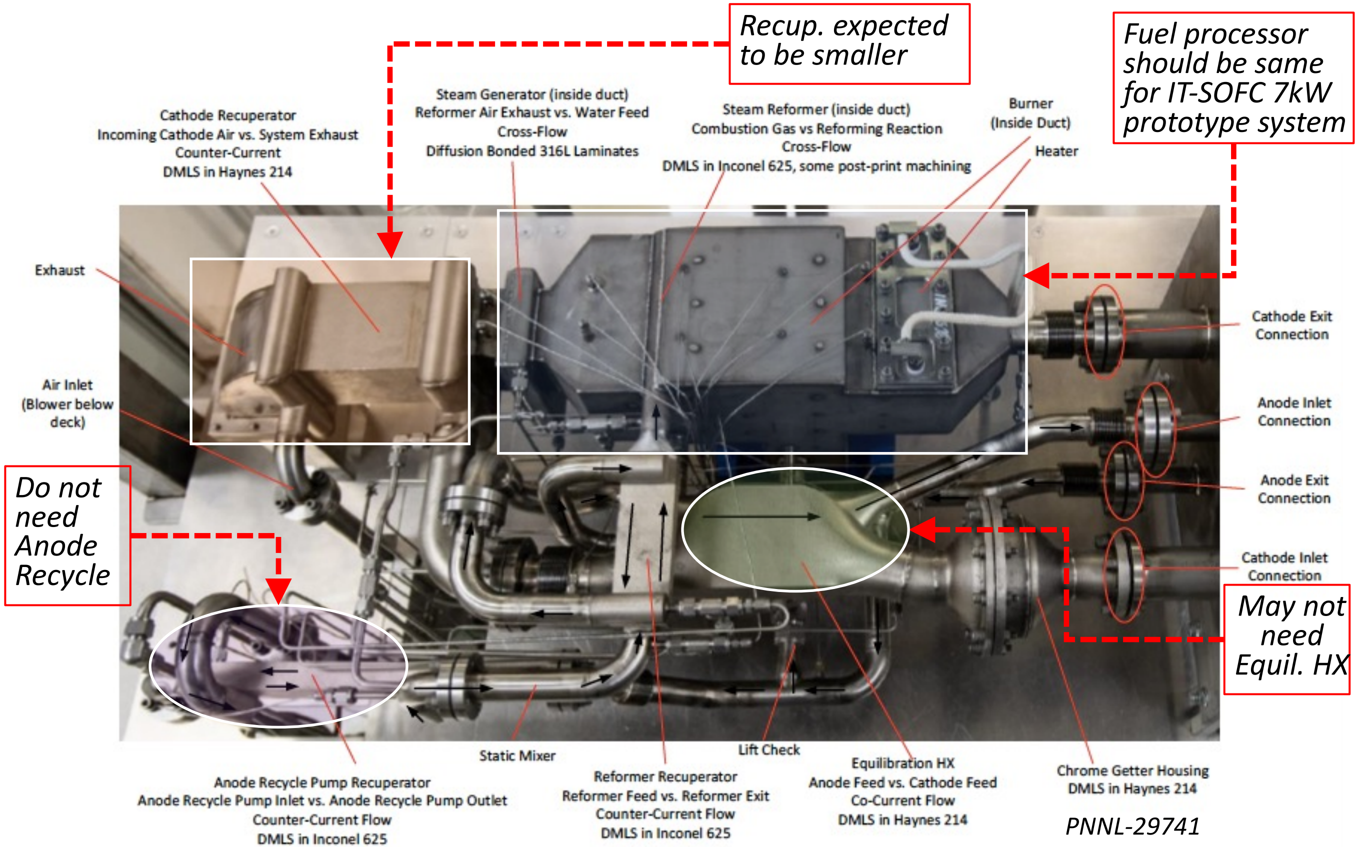
(approx. relative scale)


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



# Key BOP in PNNL SOFC Test Stand Platform

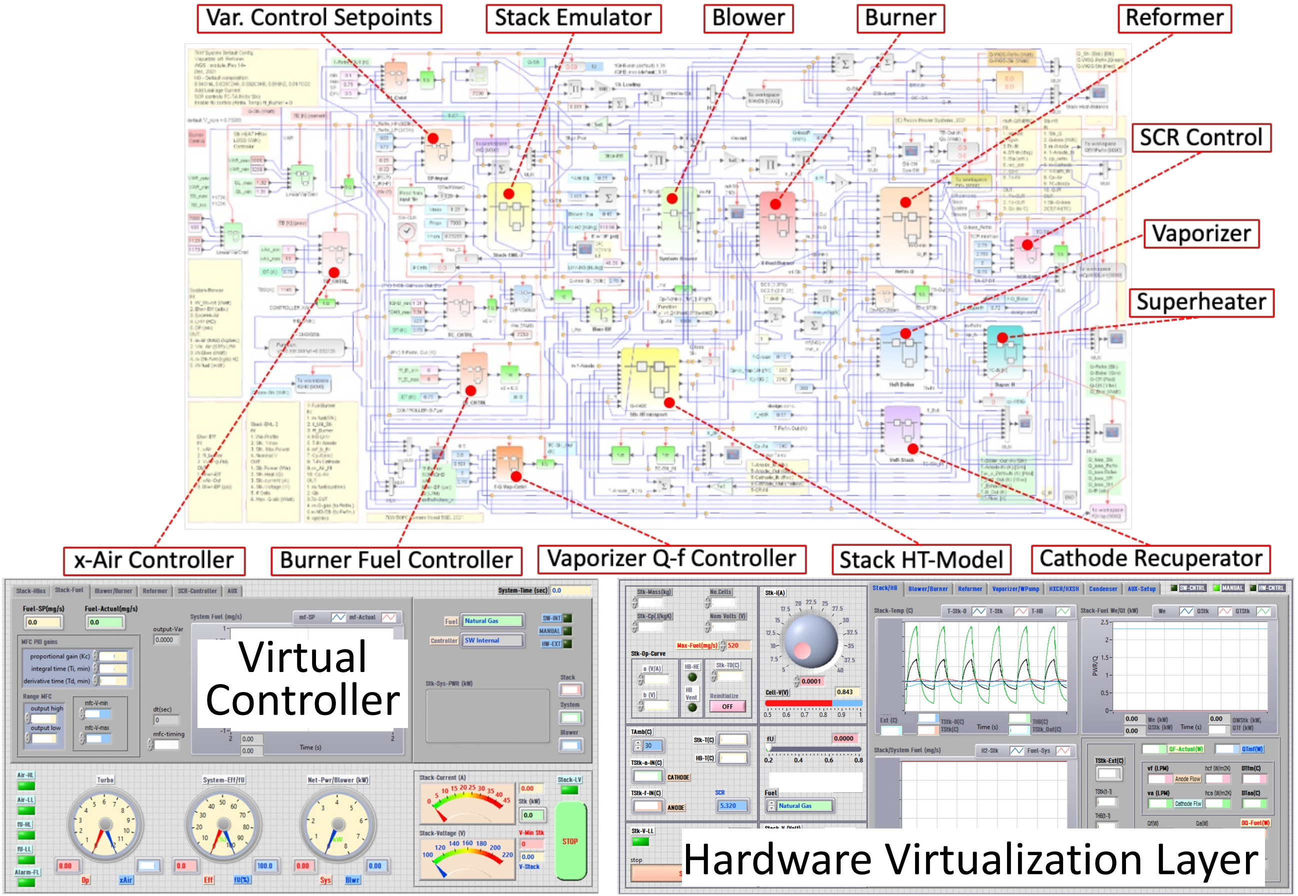
- Optimize HX/SR designs for ↓ manufacturing cost (maintain performance)
  - Simplify component design (single pass)
  - Evaluation of simpler (more cost effective) manufacturing methods
  - Alternate materials (Redox SOFC operates at lower temperatures)
- System configuration that reduces cost
  - Reduced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




PNNL-29741

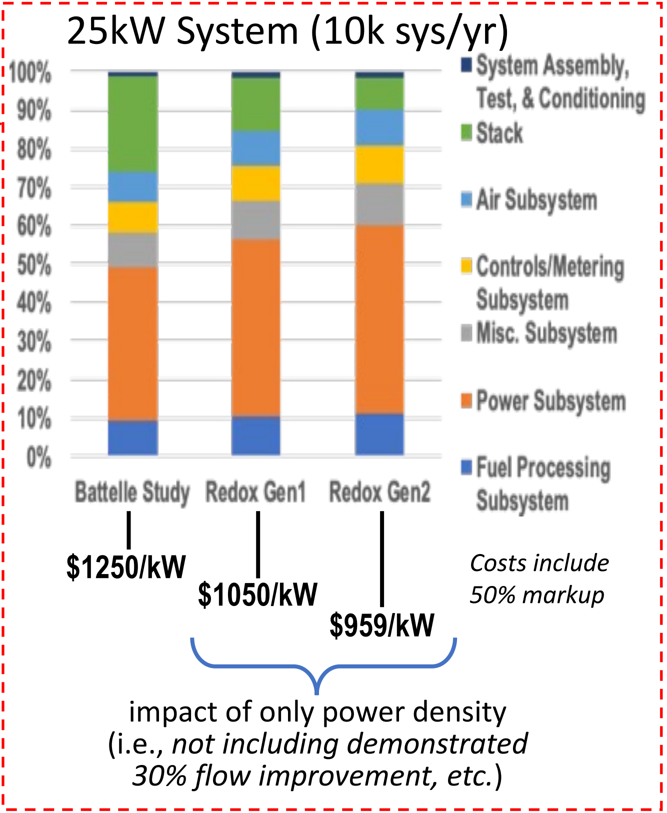
# System modeling, optimization, and controls

- Single pass design realized
- Redox: Scilab/Xcos system heat balance/dynamics simulation
  - Used for overall system component design & controls optimization
- PNNL: flow-sheet based in ChemCAD (steady state)
  - Used for sizing fuel processor and cathode recuperator components
- Controls designed in Xcos
  - Initial implementation complete
  - Actual controller received and system simulator designed/built for hardware-in-the-loop testing
    - Initial testing with virtual controller complete



# TEA & Path to Target Costs (TMP)

- Government sponsored Battelle ('17) & LBNL/SA ('15) studies as cost benchmarks
  - IC cost decrease is ~50% (less material and ↑ power density)
  - PNNL finishing up apples-to-apples comparison of microchannel-based fuel processor and cathode recuperator
- Additional savings from expected project outcomes
  - Lower operating temperature (600-650°C vs ~800°C)
  - Smaller/fewer heat exchangers
  - PNNL microchannel HX/SR (≥25% cost reduction)
  - Lower stack endplate cost – central manifold
  - Off-the-shelf (solar type) inverter / power electronics
- 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)



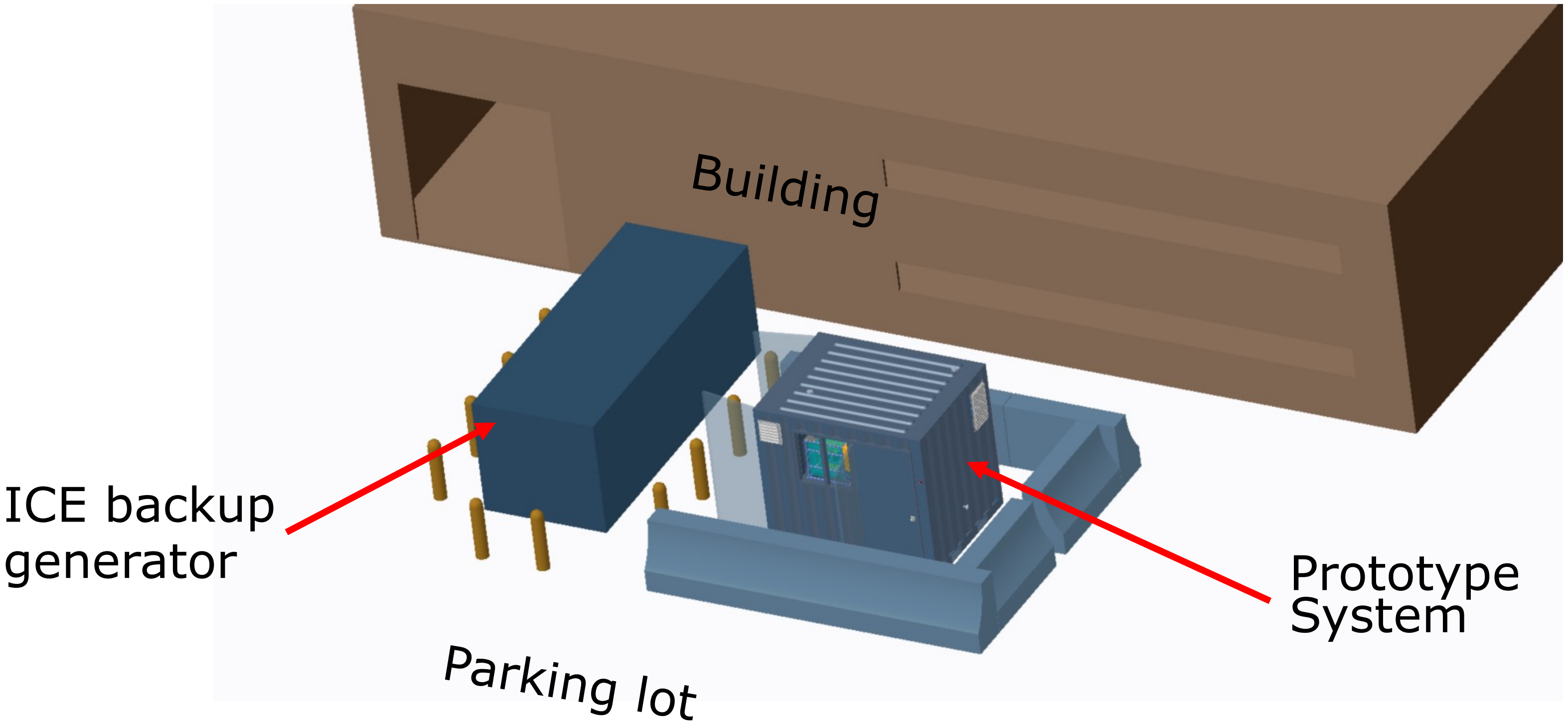

*Battelle (2017):* Manufacturing Cost Analysis of 1, 5, 10 and 25 kW Fuel Cell Systems for Primary Power and Combined Heat and Power Applications

*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

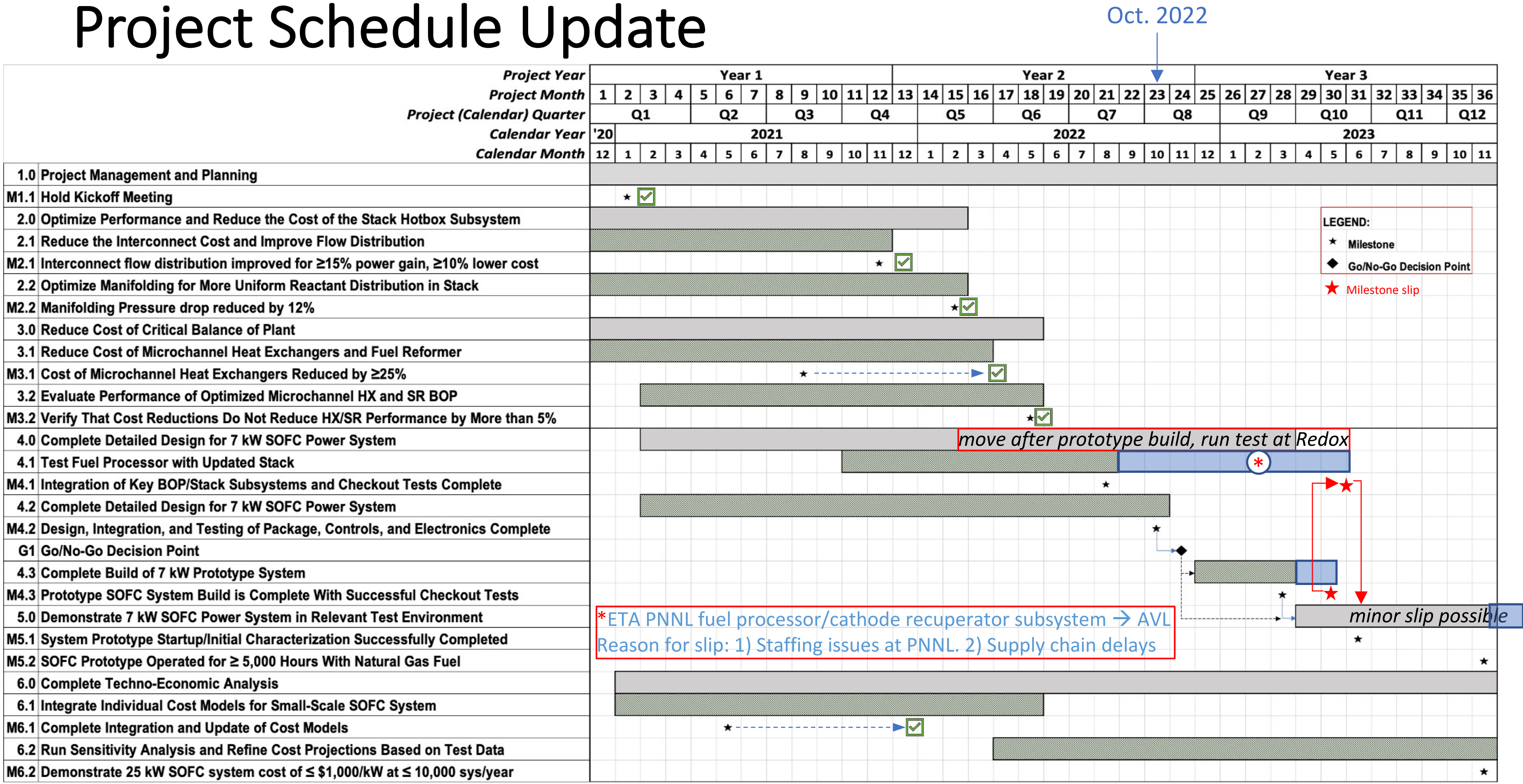
# 7 kW Demo Test Site: *Prototype Layout*



# Prototype Power System Status

- System design complete
- Most of the critical/key/hard-to-get components received or ordered
  - Enclosure
  - Blower
  - Water pump
  - Instrumentation/controls
  - Stack raw materials
  - Desulfurizer
  - Power electronics identified (in stock)
- PNNL Microchannel Fuel Processor/cathode recuperator
  - Long-lead time components ordered
- Prototype Documentation
  - Build – in progress
  - Controls – nearly complete
  - Test plan – mostly complete

# Project Schedule Update



# Acknowledgements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