IES

Integrated Energy Systems

High Temperature Electrolysis Test Stand

INL HFTO Technology Acceleration 2021 AOP – TA018

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Project Goal

- Goal: Provide support to industry to enable solid oxide electrolysis (SOC) hydrogen production at <$2.00/kg at MW scale by 2025.

- Outcome: Technology Readiness Level (TRL) of HTE will be on track to achieve TRL 7 by 2025. Key requirements include
  - **Validated demonstration of stack performance (>3,000 hours)**
  - **Demonstrated integrated system designs that maximize thermodynamic efficiency**
  - **Demonstrated open-access controls interfaces for dispatching heat and electricity from simulated nuclear power plant environments**
  - Reduced costs of HTE through advanced material manufacturing
  - Provide credible, open-access benchmark information on manufacturing, supply chain options, and costs of HTE stacks and systems

Overview

Timeline

- Project Start Date: 9/30/2020
- Project End Date: 9/30/2021

Barriers

- F. Capital Cost
- G. System Efficiency and Electricity Cost
- M. Controls and Safety

Budget

- FY21 Planned DOE Funding:
  - $3,329K
- Total DOE Funds received to Date:
  - $3,329K

Partners

- Funded Partners:
  - Idaho National Laboratory, Project Lead
  - Strategic Analysis Inc, Cost Modeling
- Industry Collaborators:
  - Bloom Energy, FuelCell Energy, OxEon, Nexceris, Energy, Xcel Energy, Anonymous

Collaboration and Coordination

Partner	Project Role
Strategic Analysis Inc	SOEC Manufacturing and System Cost Model Development
Bloom Energy	SOEC Manufacturer Collaborator
FuelCell Energy	SOEC Manufacturer Collaborator
Nexceris	SOEC Manufacturer Collaborator
OxEon Energy	SOEC Manufacturer Collaborator
Haldor Topsoe	SOEC Manufacturer Collaborator
Xcel Energy	Industry User Collaborator

Relevance – Supporting Electrolysis Scale Up

- Validated Demonstration of stack performance (>3,000 hours)
- Demonstrate integrated system designed that maximize thermodynamic efficiency
- Demonstrate open-access controls interfaces for dispatching heat and electricity from simulated nuclear power plant environments

DOE Electrolysis Milestones:

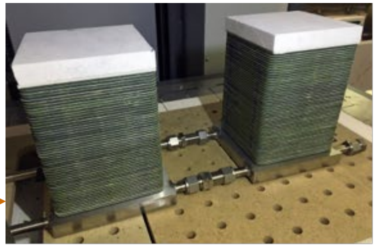
- 2.10 – Create modularized designs for central electrolysis
- 2.11 – Verify stack and system efficiencies
- 2.12 – Demonstrate integrated renewable energy electrolysis pilot plant

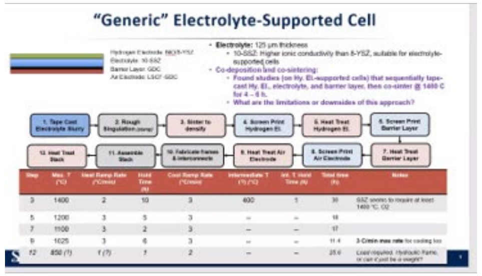
Table 3.1.5 Technical Targets: Central Water Electrolysis [a, b]

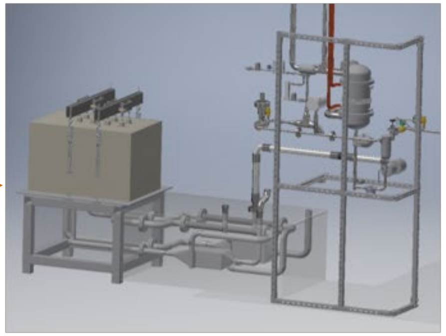
Characteristics	Units	2011 Status [c]	2015 Target [d]	2020 Target [e]
Hydrogen Levelized Cost (Plant Gate) [f]	$/kg H_2	4.10	3.00	2.00
Total Capital Investment [b]	$M	68	51	40
System Energy Efficiency [g]	%	67	73	75
	kWh/kg H_2	50	46	44.7
Stack Energy Efficiency [h]	%	74	76	78
	kWh/kg H_2	45	44	43
Electricity Price [i]	$/kWh	From AEO '09	$0.049	$0.031

Approach – Tech Acceleration Tasks

- **Task 1: Project Oversight**
- **Task 2: Commercial Stack Testing**
  - Vendor 2020-2 (anonymous), Nexceris, FuelCell Energy, OxEon
- **Task 3: SOEC Stack & System Manufacturing Cost Modeling**
  - Subcontract to Strategic Analysis
- **<u>Task 4: Integrated HTE System Development & Demonstration (D&D)</u>**
  - Open-architecture 50 kW system; reversible operation (funded by Fossil Energy)
  - Testing large stacks / systems, such as OxEon (10 kW), Nexceris (50 kW), Vendor 2021-3 (anonymous)
  - Supports HTE system integration with emulated nuclear thermal energy delivery
- **Task 5: p-Stack Manufacturing Advancement**
  - Interchangeable manifold plates/blocks to test stacks from different vendors;
  - Separate stack and recuperator boxes to facilitate testing different stack/hot box combinations







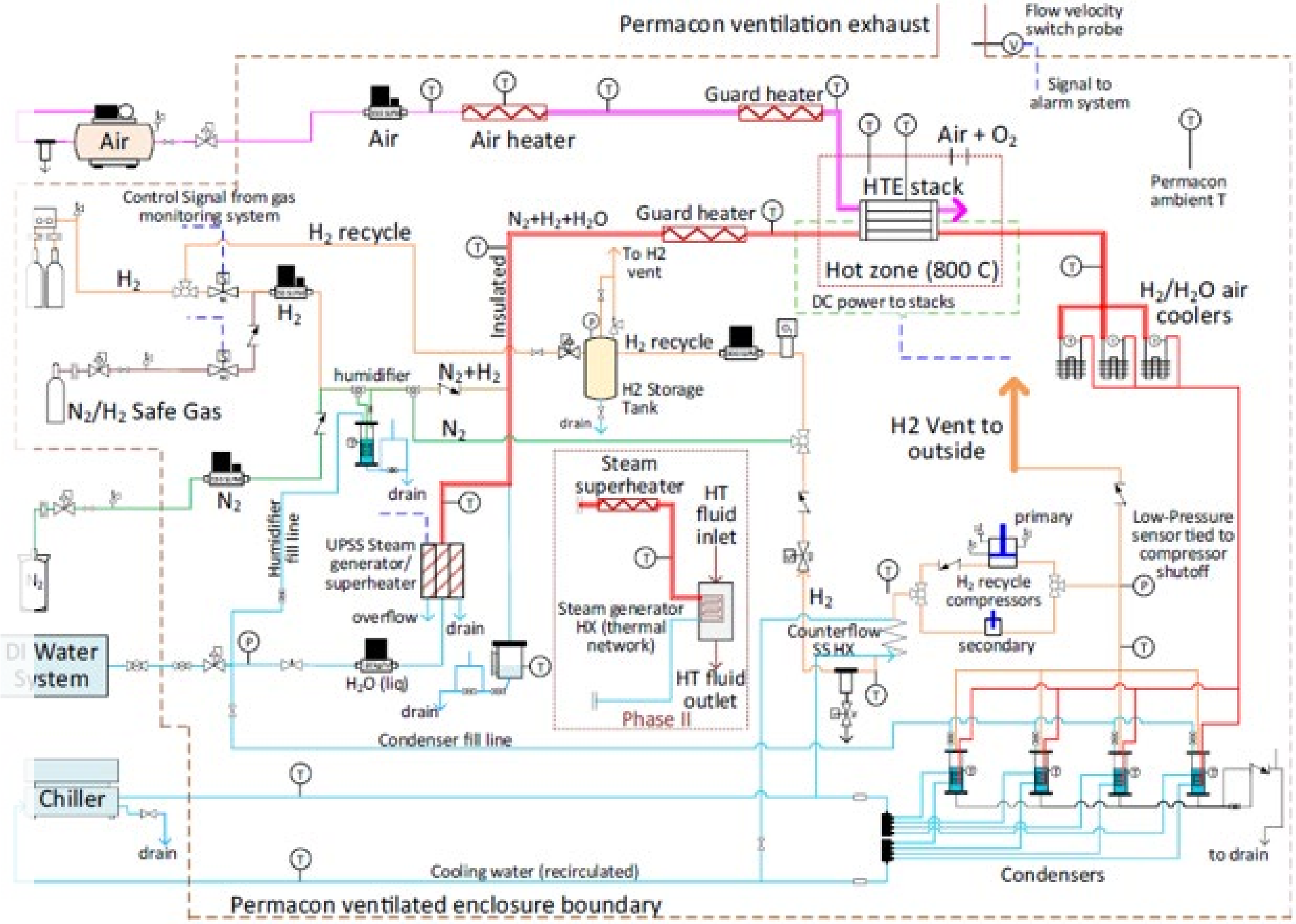
Highlighted tasks are the focus of this presentation

Approach – Commercial Stack Testing

Provide third party validation of commercial stack performance (>3,000 Hours)

Flexible electrolysis stack test platform

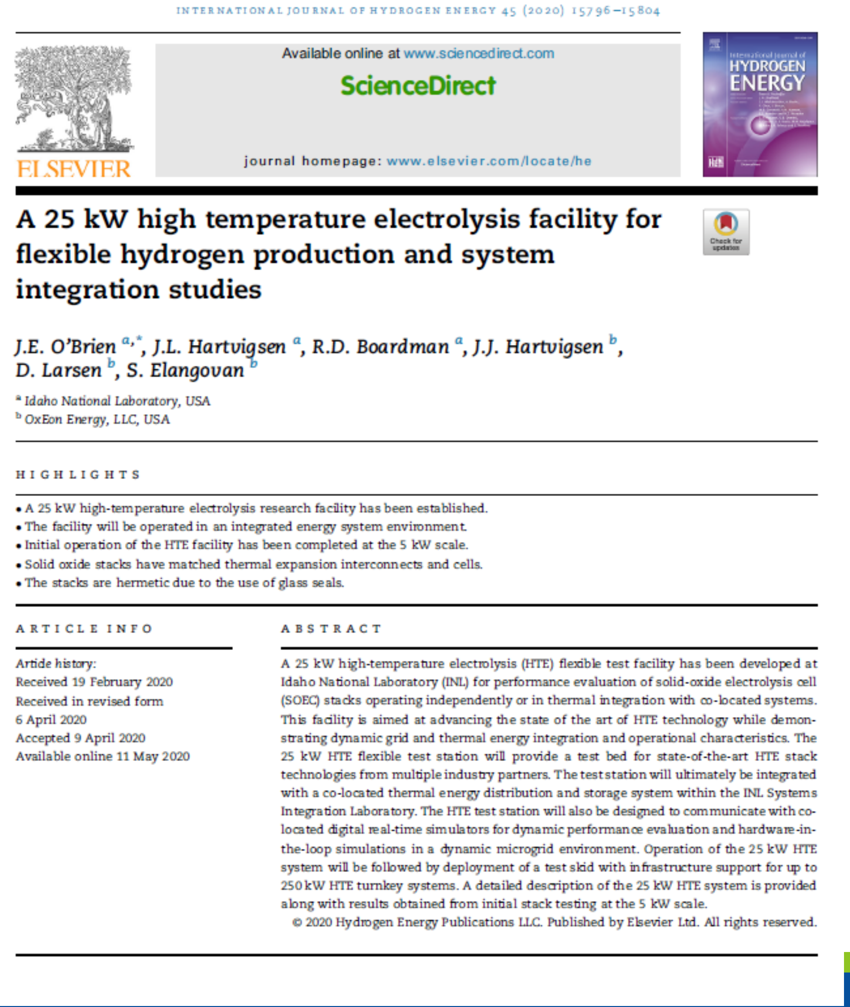
- Fully instrumented 25kW stack test platform – Vendor independent
- Atmospheric testing with hydrogen recycle capability
- Available for vendor stack validation testing



- Updated system with backup power supply for 4 hours of operation to handle frequent power failures in Idaho Falls
- Replaced aged power supply to accommodate new, larger stacks

Accomplishments – Commercial Stack Testing

Provide third party validation of commercial stack performance (>3,000 Hours)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A 25 kW high temperature electrolysis facility for flexible hydrogen production and system integration studies

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HIGHLIGHTS

- A 25 kW high-temperature electrolysis research facility has been established.
- The facility will be operated in an integrated energy system environment.
- Initial operation of the HTE facility has been completed at the 5 kW scale.
- Solid oxide stacks have matched thermal expansion interconnects and cells.
- The stacks are hermetic due to the use of glass seals.

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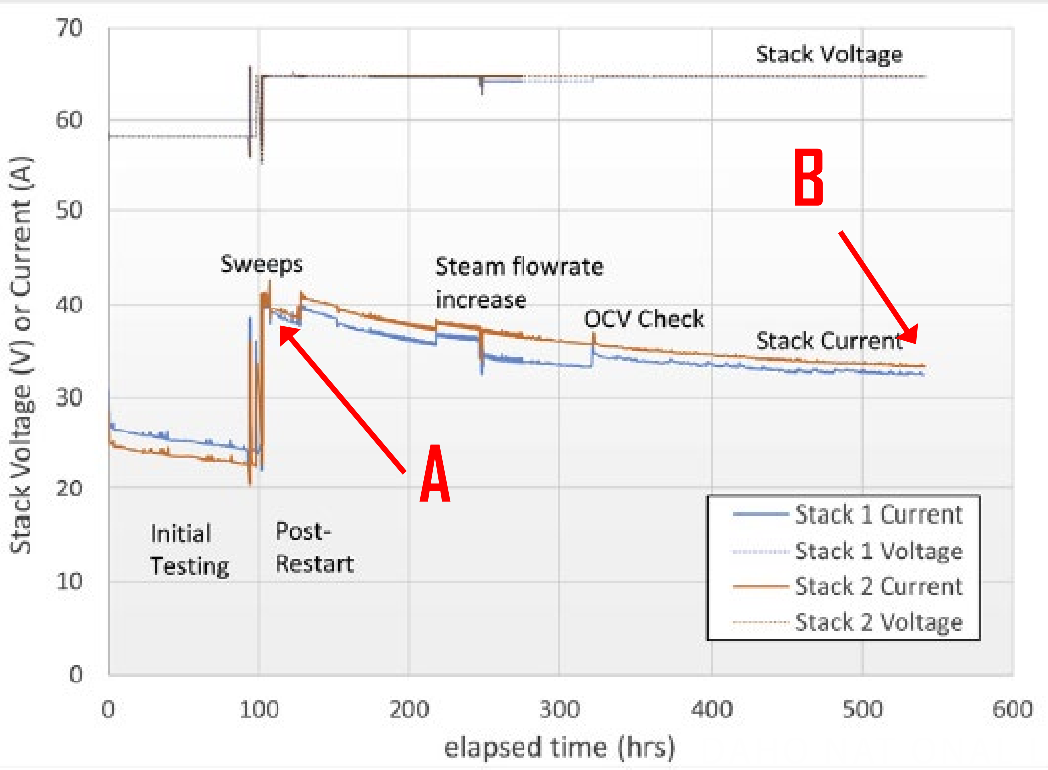
ABSTRACT

A 25 kW high-temperature electrolysis (HTE) flexible test facility has been developed at Idaho National Laboratory (INL) for performance evaluation of solid-oxide electrolysis cell (SOEC) stacks operating independently or in thermal integration with co-located systems. This facility is aimed at advancing the state of the art of HTE technology while demonstrating dynamic grid and thermal energy integration and operational characteristics. The 25 kW HTE flexible test station will provide a test bed for state-of-the-art HTE stack technologies from multiple industry partners. The test station will ultimately be integrated with a co-located thermal energy distribution and storage system within the INL Systems Integration Laboratory. The HTE test station will also be designed to communicate with co-located digital real-time simulators for dynamic performance evaluation and hardware-in-the-loop simulations in a dynamic microgrid environment. Operation of the 25 kW HTE system will be followed by deployment of a test skid with infrastructure support for up to 250 kW HTE turnkey systems. A detailed description of the 25 kW HTE system is provided along with results obtained from initial stack testing at the 5 kW scale.

- 600+ hr test of two 2.5 kW OxEon SOEC stacks
  - Point A & Point B: 34.6 kWh/kg-H2 (thermoneutral)
  - Point A: 40 A; Point B: 32.9 A



Accomplishments
- Commercial Stack Testing

- >4,000 Hours of testing completed
  (only 2,600 hours shown due to schedule)

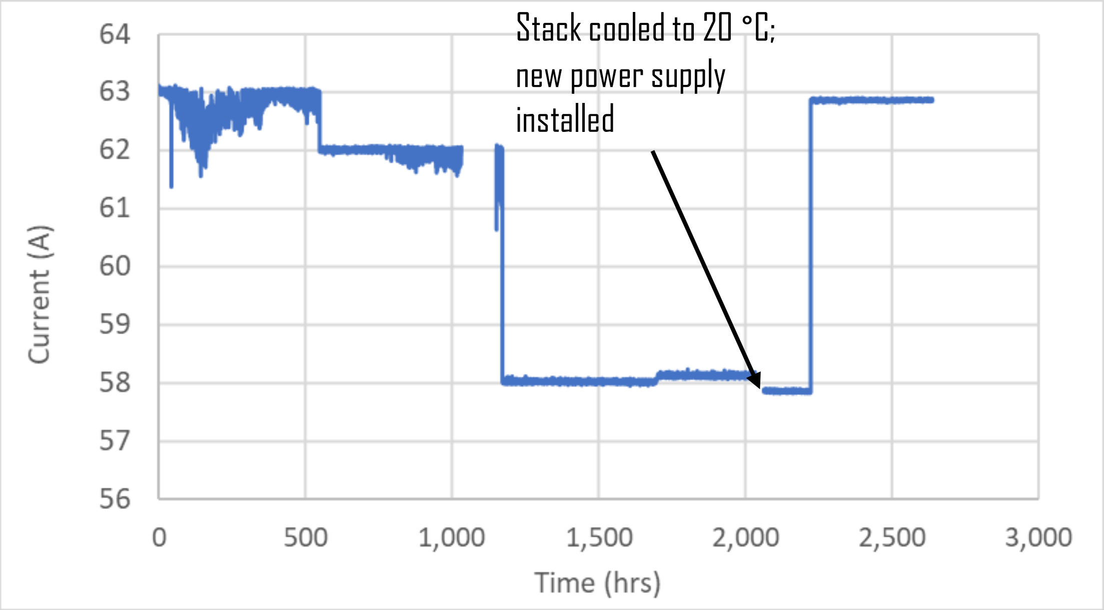
Table 1. Degradation rates per 1,000 hours for voltage, power and resistance regression fits.

	Hours	V/cell	Voltage	Power	Resistance
Fit 1	444	1.267	0.33%	0.12%	0.55%
Fit 2	460	1.264	0.49%	0.45%	0.52%
Fit 3	260	1.262	0.55%	0.50%	0.60%
Fit 4	100	1.264	0.86%	0.85%	0.88%
Fit 5	380	1.278	0.35%	0.36%	0.35%

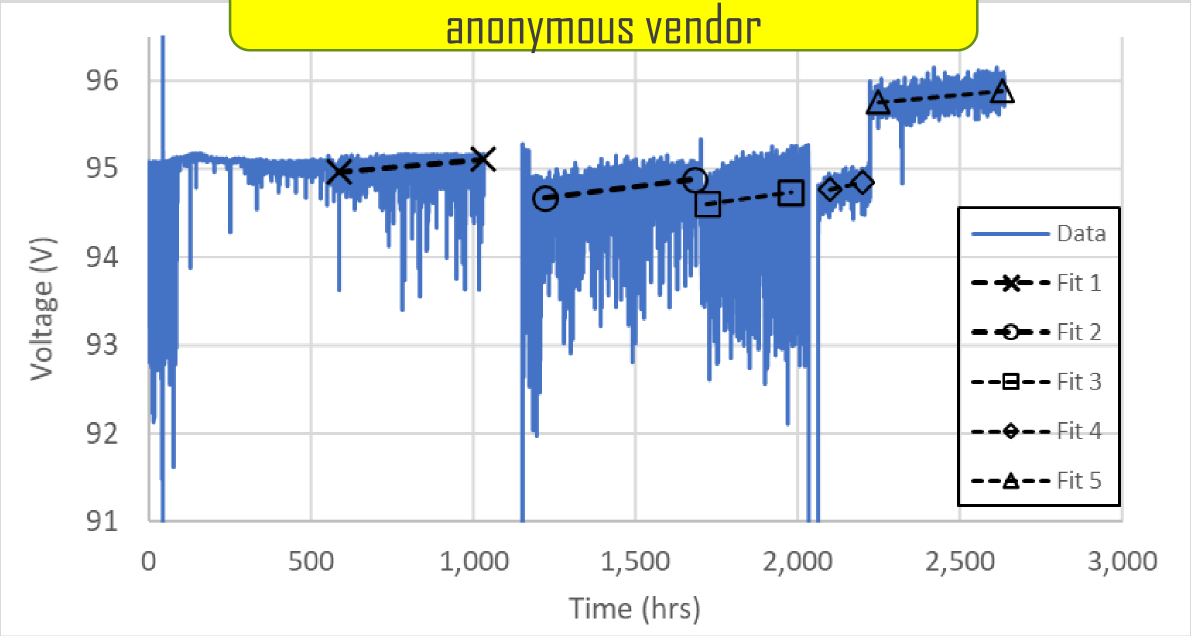
Fits 1-3: Mixed-mode operations with limited voltage/current supply
Fit 4: After installation of new power supply during 10 day shutdown
- Shutdown did not result in stack degradation

Fit 5: After increase in current set point

- All degradation rates similar: ~ 0.5%/1,000-hrs



Test results from ~5-kWe stack from anonymous vendor

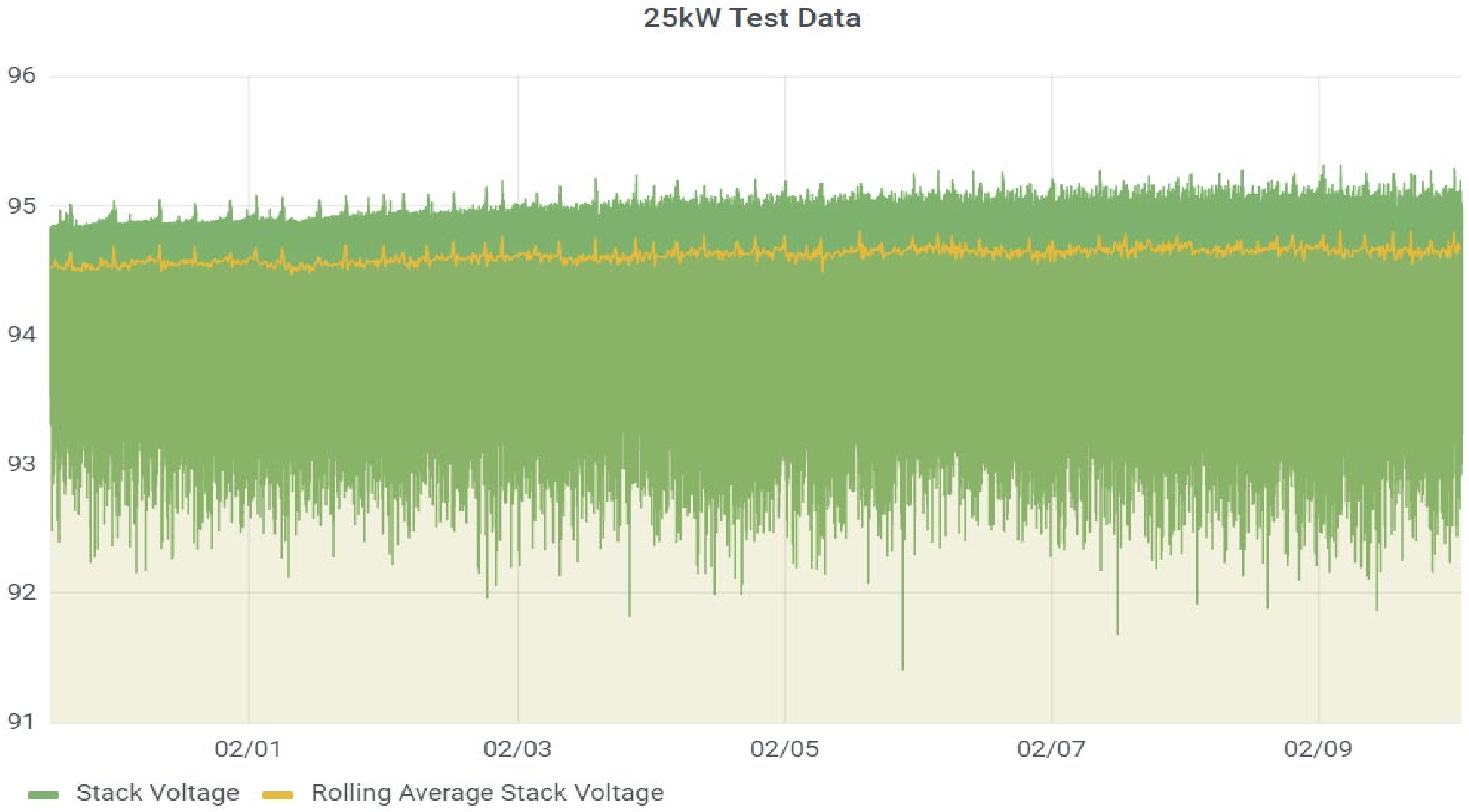


Accomplishments – Commercial Stack Testing

Provide third party validation of commercial stack performance (>3,000 Hours)

- >3,000 Hour Stack Test Complete
  - Stack voltage stable @ <0.5%/khr
  - Variations in voltage due to steam flow fluctuations

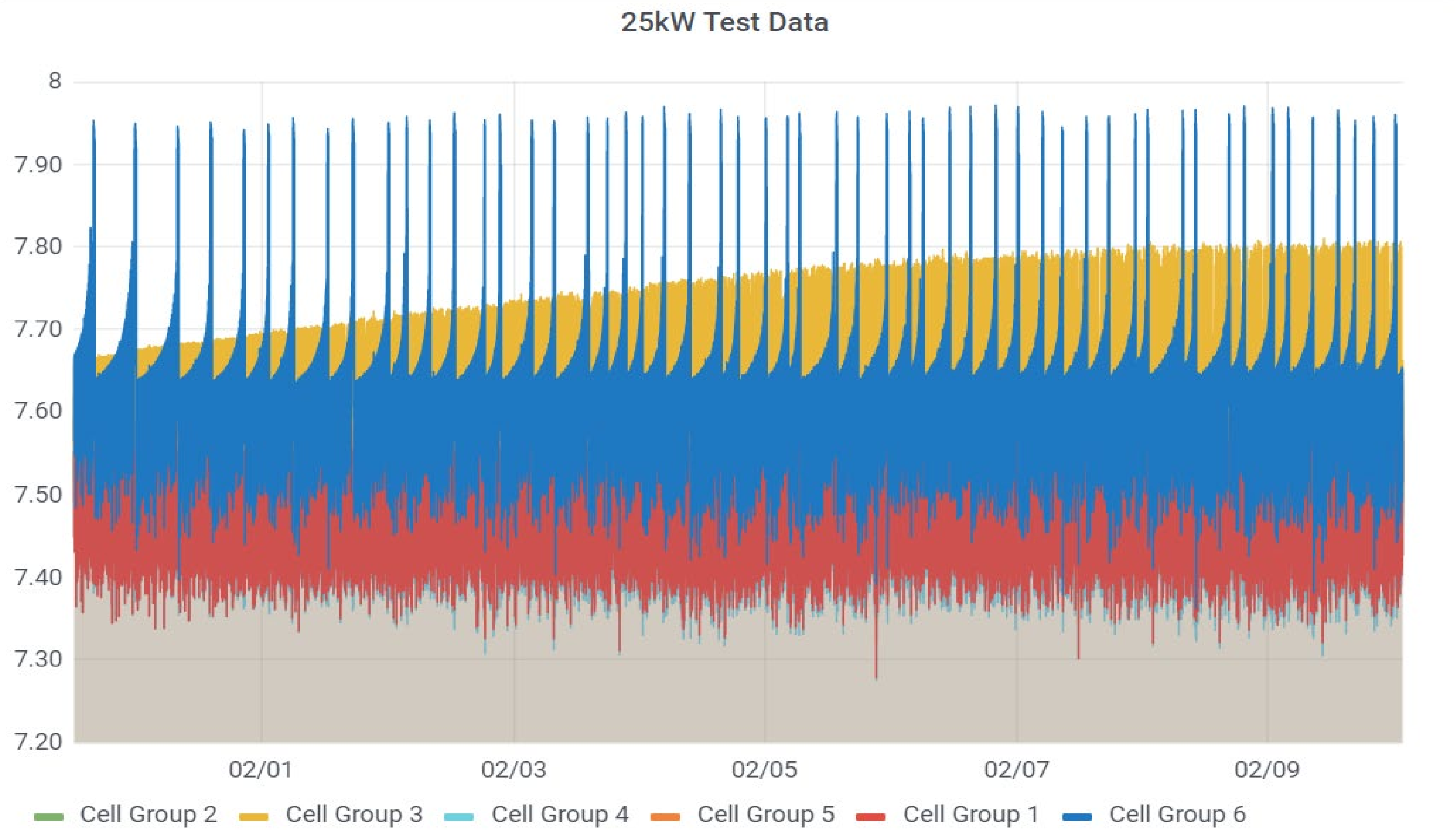
<u>Achieved Go/No-Go Decision:</u>
Measure stack degradation during 2,500+ hour test and show "steady" degradation is < 2%/1,000-hrs
(Due 09/30/2021)



Accomplishments – Stack Performance Testing

Provide third party validation of commercial stack performance (>3,000 Hours)

- Cell Groups Variations
  - Cell groups show much higher variability
  - Total degradation generally linked to individual cell groups
  - Average cell group degradation lower than overall degradation
  - Indicates improved cell consistency will improve degradation behavior



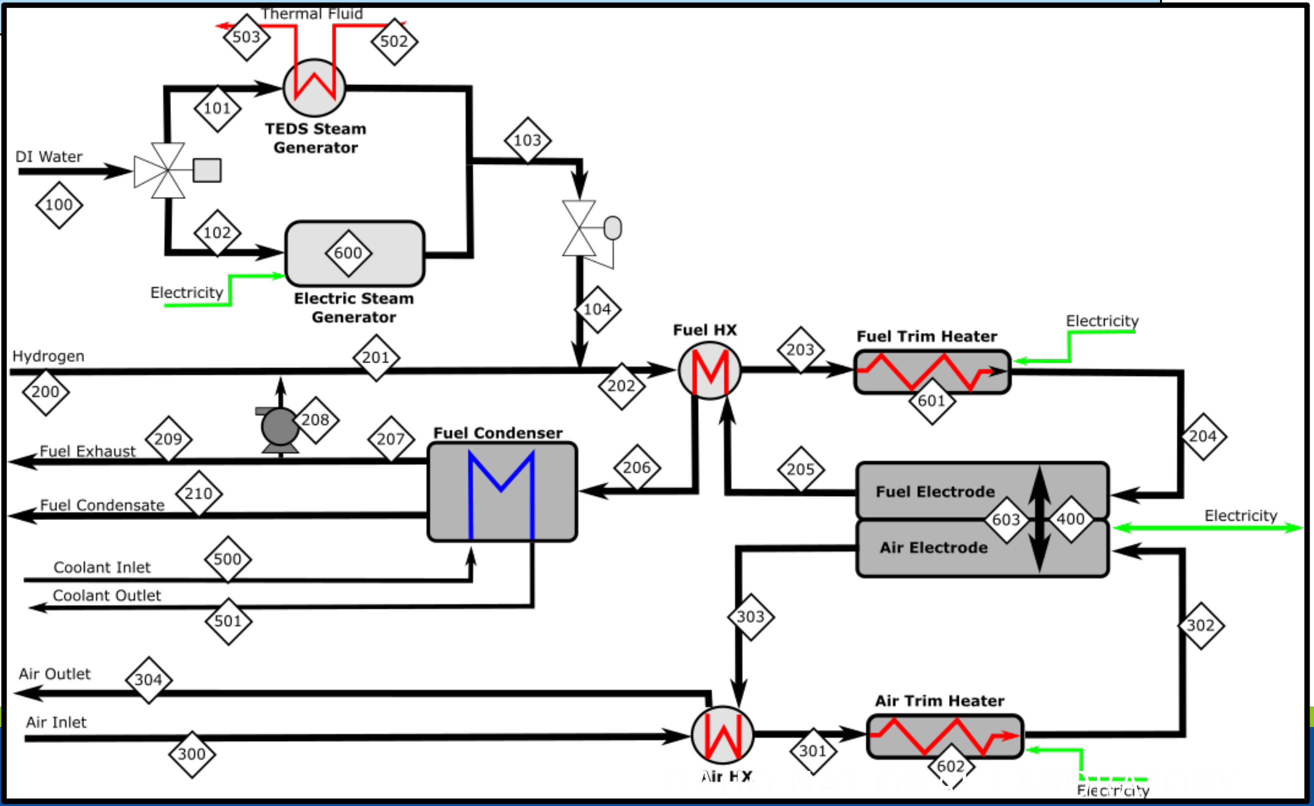
Approach – 50 kW System Integration Testing

Objectives

- Demonstrate integrated system to prove projected thermodynamic efficiency
  - Serves as DOE open-access design with published performance and cost data
- Provide an open architecture system for testing large stacks (>20 kWe), hot boxes, and hot modules

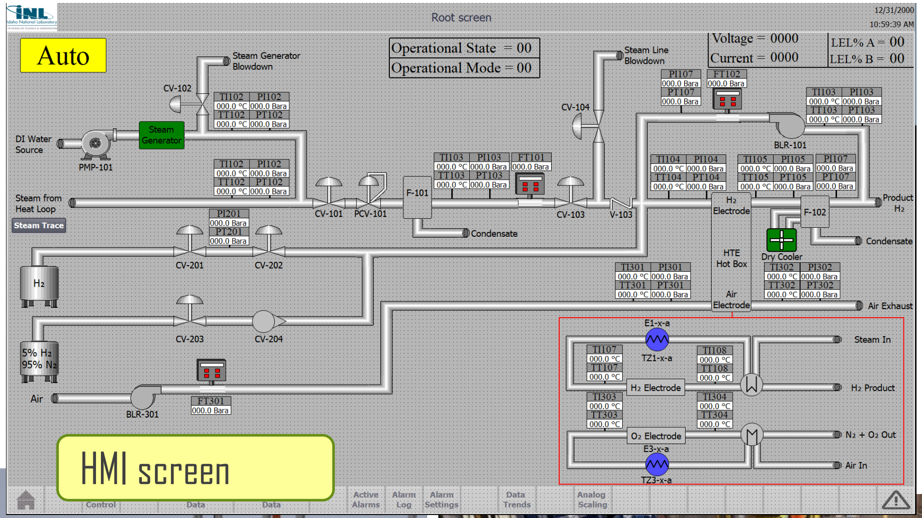
Flexible electrolysis system test platform

- Fully instrumented 50 kW stack test platform – vendor independent
- Atmospheric testing with hydrogen recycle capability
- Can provide steam and power for testing HTE systems (up to 250 kW)

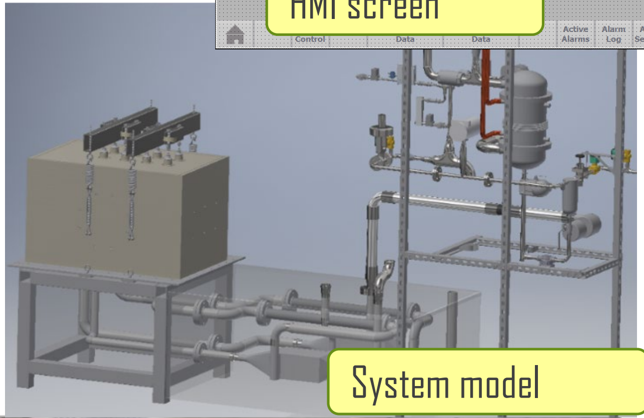


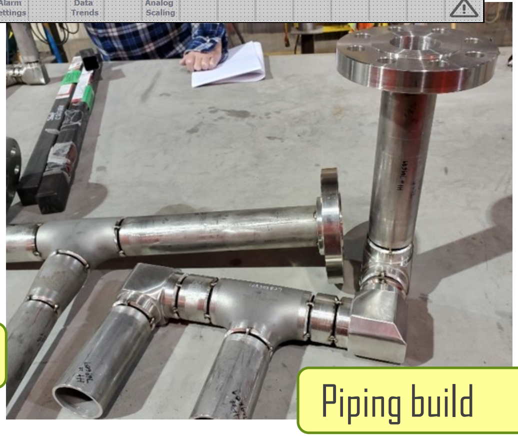
Accomplishments
– 50 kW System Integration Testing

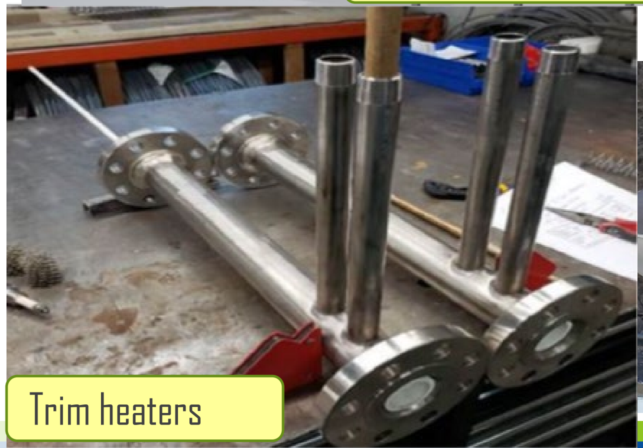
- System Features
  - Separate stack and recuperator boxes to facilitate testing a wide range of industry offerings
  - Provides coupling to INL nuclear power plant emulator for studies of integrated nuclear/HTE hydrogen production
- Schedule
  - ✓ Order long lead time items: May. 2020
  - ✓ System fabrication started: Jan. 2021
  - System fabrication complete: June 2021
  - System validation complete: Aug. 2021
  - Integration testing: Sept. 2021
  - Start fabricating Unit #2 (May 2021)



HMI screen


System model


Piping build


Trim heaters


Recuperator

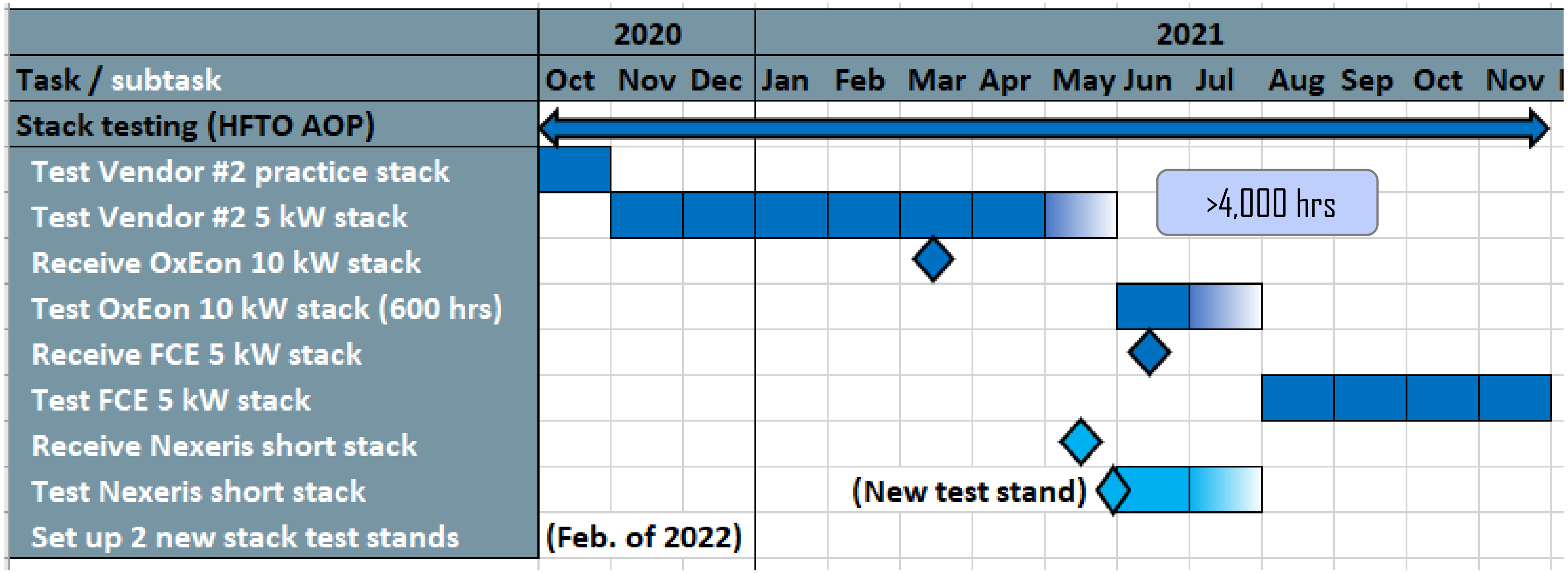
Accomplishments
– Previous Reviewer Comments (2019)

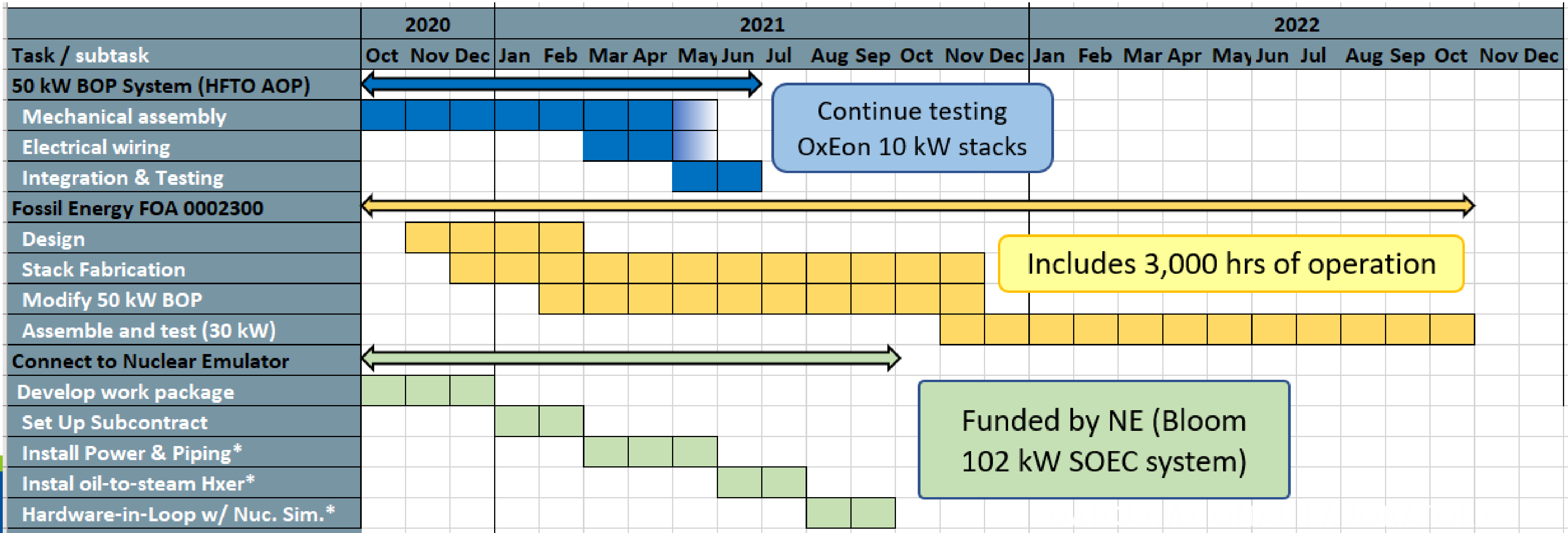
- Approach
  - Excellent approach to provide initial understanding of HTE on a large scale.
  - Should rely on generic stack degradation data, not just data from a single stack design or supplier.
  - The team needs to clarify the value proposition.
- Collaboration & Coordination
  - Employs an excellent mix of partners, including industry
  - HTE is important and should be part of the overall portfolio
  - If the project results finds and communicates significant benefits, it could be very useful resource to better inform future decisions around nuclear energy resources

- Responses
  - We have now tested stacks from two suppliers and have plans to test stacks from three more
  - Project data and designs are being used by several additional projects:
    - Xcel Energy HTE 150 kW demo at a nuclear plant (proposal based on 50 kW open architecture HTE design)
    - FuelCell Energy 250 kW demo (will use infrastructure designed by this project)
    - 30 kW reversible solid oxide system (FOA-0002300; will use 50 kW HTE design)
    - Bloom CRADA (102 kW HTE demo with nuclear integration)
    - Planning tests of >25 kW HTE stacks from two additional vendors

Testing Summary

- Tests that will use the 25 kW test stand
  - Vendor #2 (anonymous)
  - OxEon (10 kW)
  - FuelCell Energy (5 kW)
  - Nexceris (5 kW)
- Demo projects
  - Reversible SOC (FOA 0002300)
  - Bloom CRADA
  - Xcel 150 kW
  - FCE 250 kW
  - >25 kW stacks from two more vendors





Project Impact – Enabling Broad Progress

INL HFTO Technology Acceleration 2021 AOP

25 kW HTE Test Facility

50 kW Open Architecture HTE System

- Energy Efficiency and Renewable Energy
  - H2New Stack Scale Up Testing
- Industry Funded
  - Nexceris short stack
  - 10 kW OxEon Stack
  - 17.5 kW Fuel Cell Energy Stack
- Proposed (Funding Pending)
  - Other stacks from vendors, inc. long-term (>3,000 hour tests)

- Nuclear Energy
  - 150 kW Demo at Xcel Energy Nuclear Plant
  - 102 kW Bloom Demonstration
  - 250 kW FCE Demonstration
- Fossil Energy DE-FOA-0002300 Award
  - 30/5 kW Reversible SOC System with OxEon Energy
- Hydrogen Fuel Cells Technologies Office
  - Long-term test of 10 kW OxEon Stack
  - 50 kW Nexceris Stacks
  - 35 kW Stack from Anonymous Vendor
  - Other stacks/hot boxes/hot modules from vendors

Remaining Challenges and Barriers

- Challenge: Completion of system validation on schedule
  - Manufacturing delays due to COVID-19 have pushed procurement out further than anticipated (several items nearly 12 months late)
- Challenge: Coordination of current system build, facilities validation, and stack testing with future work
  - Interest in access to stack testing and system testing has been far higher than anticipated
  - Potential for up to five systems and three large commercial stacks concurrently on test

Proposed Future Work

- FY 2021
  - Test Nexceris short stack; FuelCell Energy Stack, and OxEon stack
  - Complete Open Architecture Integrated HTE System and commence test with stack from commercial vendor (>10 kW)
  - Start fabrication of second HTE system to support reversible demonstration funded by FE and additional stack testing
- FY 2022
  - Commission two additional 10 kW SOEC test stands for long-term tests
    - Complete 6,000 hours of testing on two commercial stacks
  - Commission second HTE system for additional testing
    - Complete 3,000 hours of testing on a commercial stack > 25 kW
    - Complete “bottom-up” technoeconomic analysis of stack manufacturing and system cost as scales of 5-500 MW/yr

Summary

- Task 2 – Commercial Stack Testing
  - Test stand was updated with new power supply & power backup
  - Tested stack from two vendors (one test for >3,000 hrs)
    - Degradation ≈ 0.5%/1,000-hrs
  - Three more 10 kW test stands are being commissioned to test additional stacks from industry (OxEon, Nexceris, and FuelCell Energy, anonymous)
    - Specific goal is to test promising stacks for > 6,000 hours
- Task 4 – Open Architecture Integrated HTE Test System
  - Commitment to build first system enabled two projects
    - 30 kW rSOC system (FE funding)
    - 150 kW SOEC system for demo at Xcel nuclear plant)
  - Commission first 50 kW system
  - Commission second 50 kW system
    - Prepare to test >15 kW stacks from OxEon, Nexceris and other vendors

Technical Backup Slides and Additional Information

Technology Transfer Activities

- Current work focused on “enabling” SOEC Technology
  - Third party stack validation (OxEon, Nexceris, FuelCell Energy, anonymous vendors)
  - Third party system validation (Bloom, FuelCell Energy, anonymous vendors)
- Funding from alternative sources (see next three slides)
  - Project data and capabilities are being used for multiple demos
    - Nuclear Industry FOA-0001817: Demos with Xcel & FuelCell Energy
    - Office of Fossil Energy FOA-0002300: Reversible SOC system (30 kW electrolysis)
    - CRADA with Bloom Energy to demo 102 kW HTE system with nuclear integration
    - Office of Nuclear Energy: Integration of 50 kW HTE systems with nuclear emulator

Progress towards DOE Milestones

- 2.1: Verify capital cost of electrolysis stacks (Originally for PEM)
  - Completed Preliminary DFMA cost model demonstrating SOEC costs from 25 MW/year to 2,000 MW/year production cost
  - $395/kw to $115/kW for electrolyte supported cells
  - $365/kw to $85/kW for electrode supported cells
- 2.10: Create modularized designs for central electrolysis
  - System design complete
- 2.11 – Verify stack and system efficiencies
  - >3,000 hrs stack on test exhibiting electrical efficiency of >90%
  - System test planned for FY 2022
- 2.12 – Demonstrate integrated renewable energy electrolysis pilot plant
  - System integrated with thermal delivery subsystem planned for FY2022

p-SOEC Manufacturing

Goal: To develop cutting edge manufacturing technologies for p-SOEC including a package capabilities from raw powder synthesis, cell components to stack manufacturing and testing, and demonstrate the processing cost reduction compared with the state-of-the-art.

FY20 Accomplishments:

- Ameliorated bending strength of one-inch p-SOECs to ~200 MPa (150% improvement than initial cells)
- Demonstrated feasibility of using direct inkjet printing technique on green substrates for p-SOECs with an ~8 μm-thick (variation < 10%) electrolyte resulting in 63% reduction in thickness and 169% improvement in electrolysis performance compared with the baseline cells
- Incorporated a scanning laser scanning microscope in p-SOEC manufacturing as a QC/QA method to identify surface defects and assure repeatability of cell performance
- Finalized the design for a large format cell testing fixture and ancillary manifolds used for performance testing on as large as 10 ×10 cm^2 cells
- Initiated the large cell and stack testing station.
- Procured a laser cutter which will be used for large format cell manufacturing and is ready for installation
- 2 publications, and 1 IDR