Solid Oxide Electrolysis System Demonstration

DE-EE0009290

FuelCell Energy

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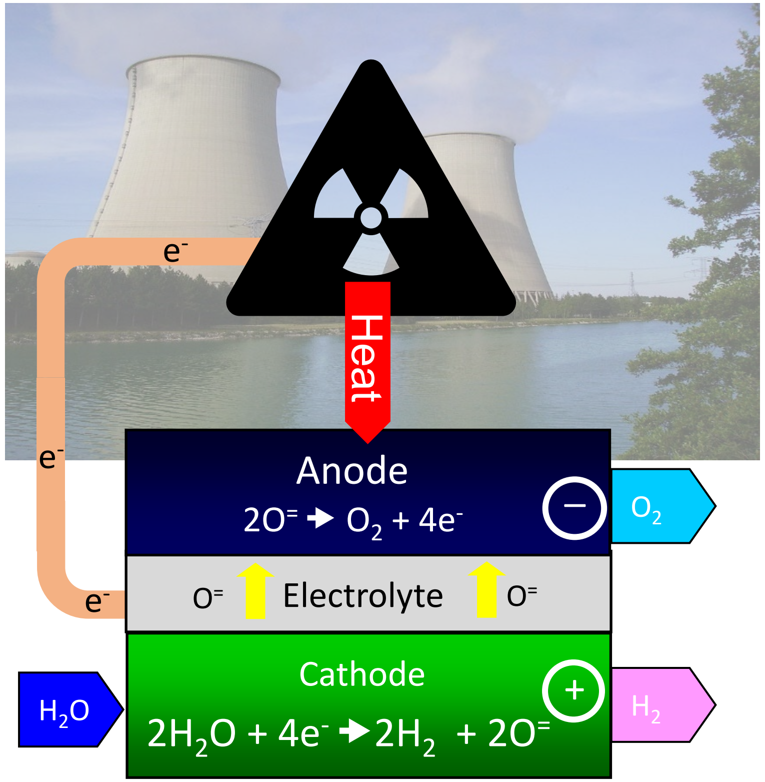
DOE Hydrogen Program
2023 Annual Merit Review and Peer Evaluation Meeting

Project ID# TA039

Project Goal

- Project goal is to validate that integration of solid oxide steam electrolysis with nuclear plants will provide a high efficiency and low-cost alternative for production of hydrogen utilizing electricity and waste heat



Solid Oxide Electrolysis Cell (SOEC)

Timeline

- Project Start Date: 10/01/2020
- Budget Period 1 End Date: 05/31/2023
- Project End Date: 05/31/2024

Barrier

- Key barriers addressed in the project are:
  - F. Capital Cost
  - G. System Efficiency and Electricity Cost
  - J. Electricity Generation Integration

Budget

- Total Project Budget: $10,500,000
  - Total Federal Share: $8,000,000
  - Total Recipient Share: $2,500,000
  - Total DOE Funds Spent*: $8,000,000
  - Total Cost Share Funds Spent*: $2,382,919

  ** As of 3/31/2023*

Partner

- FuelCell Energy (FCE) – Project Lead
- Versa Power Systems (VPS)
- Idaho National Laboratory (INL)

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Relevance and Impact Potential

Project objectives relate to the hydrogen production subprogram of HFTO by addressing the technology validation at a pilot scale and operational verification of solid oxide electrolysis integrated with a nuclear plant

Project Objectives:

- Validate SOEC technology performance and reliability for steam electrolysis and hydrogen production in a packaged system
- Develop and verify system operational and control strategies specific to nuclear industry
- Demonstrate key features of SOEC electrolysis systems including high electric efficiency and waste heat utilization in a 250kW class unit prototypical of larger scale systems suitable for integration with nuclear plants
- Obtain the data necessary to valorize the integration of SOEC systems in LWR (Light Water Reactor) facilities for increasing their operational flexibility and profitability by switching between electricity production and hydrogen generation

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Technology Development Approach

Technical approach includes design, build and test a 250kW (input) steam electrolysis system using hardware-in-the-loop simulation of nuclear plant operation

Design

- Develop process, mechanical and electrical designs of a 250kW steam electrolysis prototype unit
- Develop balance of plant equipment designs for the 250kW system including heat exchangers, steam generator, and rectifier for ac-to-dc conversion
- Complete design of SOEC stack module hardware for housing electrolysis stacks
- Prepare 3-D CAD and fabrication drawings for construction of the 250kW steam electrolysis demonstration unit

Build

- Fabricate electrolysis stack module consisting of pressure vessel, thermal insulation, electric power take-offs, instrumentation, support structure, and gas distribution conduits
- Fabricate balance-of-plant process equipment and electrical/control system hardware
- Develop control strategies and software for the 250kW electrolyzer include HMI (Humane Machine Interface), data-base of test results and sensors data, safety alarm tags and limits, and control loop algorithms

Test

- Perform system factory tests and commissioning
- Perform operational tests of the 250 kW demonstration unit at Idaho National Laboratory (INL) using controller hardware-in-the-loop (CHIL) combined with High-Level front-end Controller (HLC) simulating communications from a nuclear plant and electric grid

T2M

- Conduct Techno-Economic Assessment (TEA) of large-scale electrolysis systems of up to 500MW based on the cost/performance of the 250kW SOEC demonstration unit and operation data acquired from the tests at INL

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Budget Period 1 (BP1) Milestones

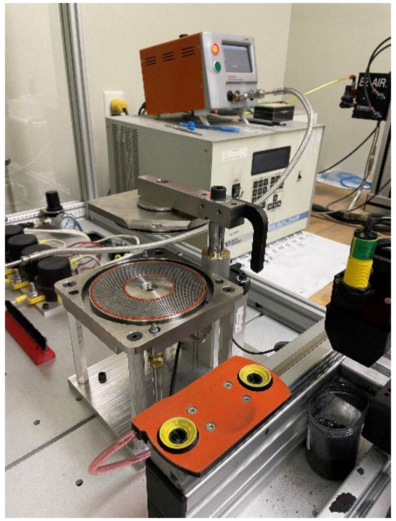
Milestone Type (Milestone, Go/No-Go Decision Point, End of Project Goal)	Milestone Number* (Go/No-Go Decision Point Number)	Milestone Description (Go/No-Go Decision Criteria)	Anticipated Date (Months from Start of the Project)	Anticipated Quarter (Quarters from Start of the Project)	Status
Milestone	M 1.1.1	Acquisition of major raw materials to initiate cell fabrication completed	M2	Q1	completed
Milestone	M 1.1.2	≥ 50% of Cell subcomponents fabrication for use in stacks completed	M4	Q2	completed
Milestone	M 1.1.3	Electrochemical cell fabrication for integration in stacks completed	M6	Q2	completed
Milestone	M1.2.1	Fabrication of the stacks to be included in the 250kW system completed	M7	Q3	20%
Milestone	M2.1.1	Final 3-D CAD stack module design completed	M2	Q1	completed
Milestone	M2.1.2	Module assembly fabrication drawing completed	M3	Q1	completed
Milestone	M2.2.1	Final Process Flow Diagram (PFD) prepared	M2	Q1	completed
Milestone	M2.2.2	250kW system process design including equipment specification completed	M2	Q1	completed
Milestone	M2.2.3	250 kW system packaged mechanical layout including detailed component assemblies, instrumentation, and skid completed	M4	Q2	completed
Milestone	M2.2.4	250 kW system electrical design including detailed wiring diagrams and equipment specifications completed	M6	Q2	completed
Milestone	M2.3.1	INL's facility design modifications to accommodate installation of the 250 kW electrolysis system completed	M8	Q3	80%

Budget Period 1 (BP1) Milestones (Continued)

Milestone Type (Milestone, Go/No-Go Decision Point, End of Project Goal)	Milestone Number* (Go/No-Go Decision Point Number)	Milestone Description (Go/No-Go Decision Criteria)	Anticipated Date (Months from Start of the Project)	Anticipated Quarter (Quarters from Start of the Project)	Status
Milestone	M3.1.1	Electrolysis stack module fabrication completed ready for installation of SOEC stacks	M6	Q2	60%
Milestone	M3.2.1	Balance of Plant components fabrication completed ready for installation of SOEC stacks	M6	Q2	10%
Milestone	M4.1.1	Control philosophy and the associated control software completed	M8	Q3	50%
Milestone	M4.2.1	Stack Module assembly including installation of SOEC stacks and instrumentation completed	M7	Q3	
Milestone	M4.2.2	250kW electrolysis system assembly including integration of BoP components and stack module completed	M8	Q3	
Milestone	M4.3.1	250kW electrolysis system commissioning and factory acceptance tests completed	M10	Q4	
Go/No-Go Decision Point	G-n-G 1	Integration of the stack module with the balance-of-equipment is completed leading to completion of the system construction and commissioning	M10	Q4	

Cell Fabrication



Tape Casting — Automated Screen Printing — Co-Sintering

" TSC 3 Process "

Cell QC

Solid Oxide Electrolysis Cell (SOEC) Constituent Layers

Component	Materials	Thickness	Porosity	Process
Anode	Conducting ceramic	~ 50 μm	~ 30%	Screen printing
Barrier	CGO	~4 μm	<10%	Screen printing
Electrolyte	YSZ	~5 μm	< 5%	Screen printing
Cath. Functional Layer	Ni/YSZ	~8 μm	~ 40%	Screen printing
Cathode Support	Ni/YSZ	~0.3 mm	~ 40%	Tape casting

Cell fabrication and QC for the 250kW SOEC prototype system was completed

Compact Solid oxide Architecture (CSA) Stack Overview

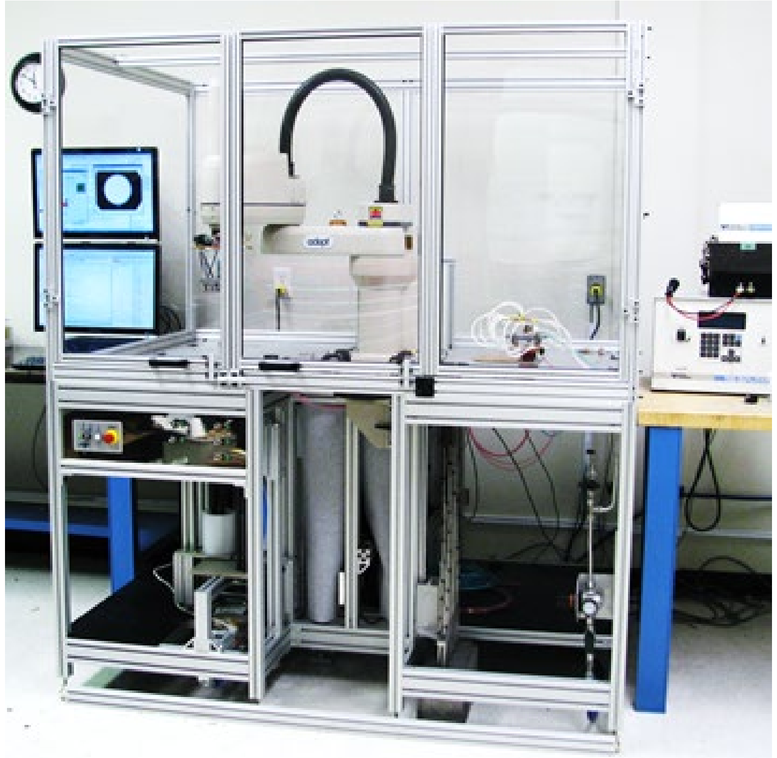
Integrated mechanical compression

Air outlet manifold

350 cells - 17" tall

250kW SOEC prototype system uses

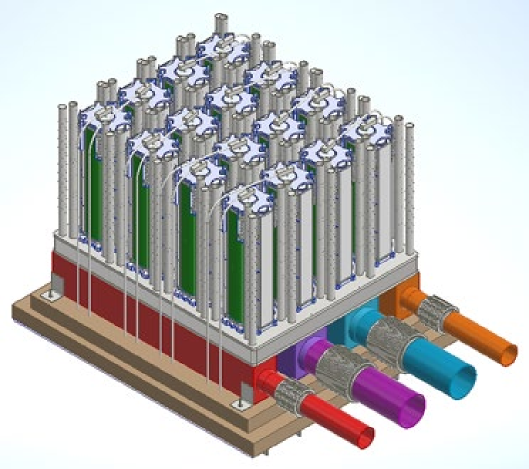
CSA stack technology for steam electrolysis



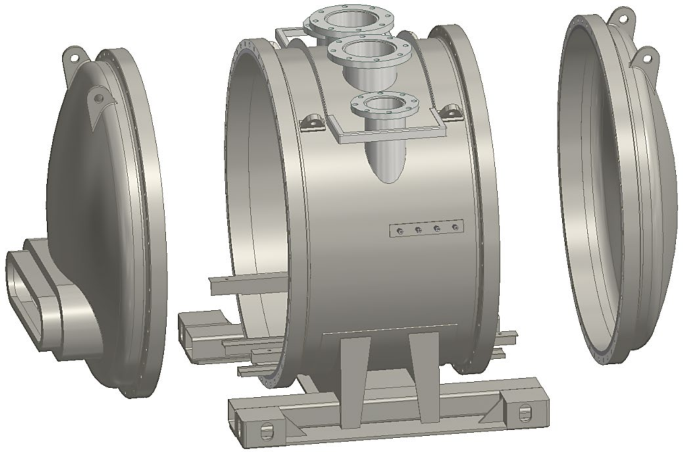
Automated QC / Stack Assembly

Stack fabrication for 250kW SOEC prototype system is utilizing a robotic assembly and QC station

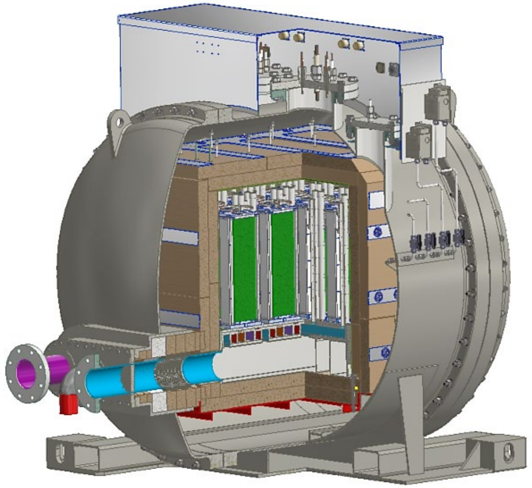
Stack Module Design



Multi-Stack Array

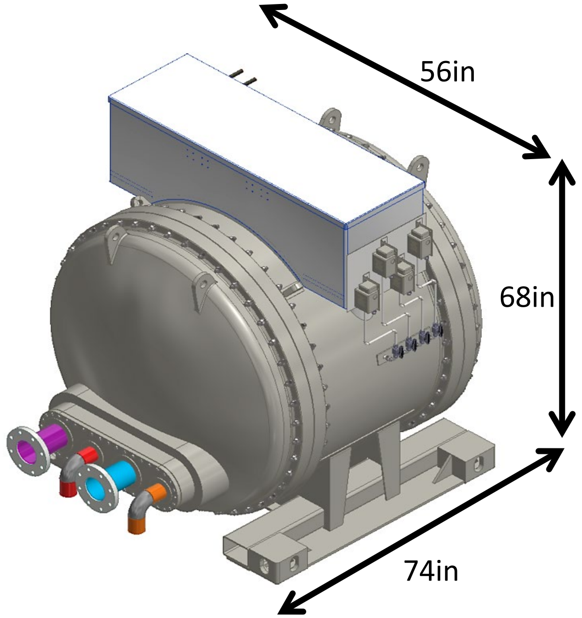


Module Vessel Enclosure Components



Stack Module (cut-away)

- Solid oxide electrolysis stack module design:
  - Lifting access via standard ISO container corner blocks while providing option for forklift access
  - Process gas header channels underneath the multi-layered base tapered to ensure adequate gas flow to the entire length of the base
  - Designed for ease of factory assembly and future commercialization
  - Stacks pre-conditioned and acceptance tested prior to integration



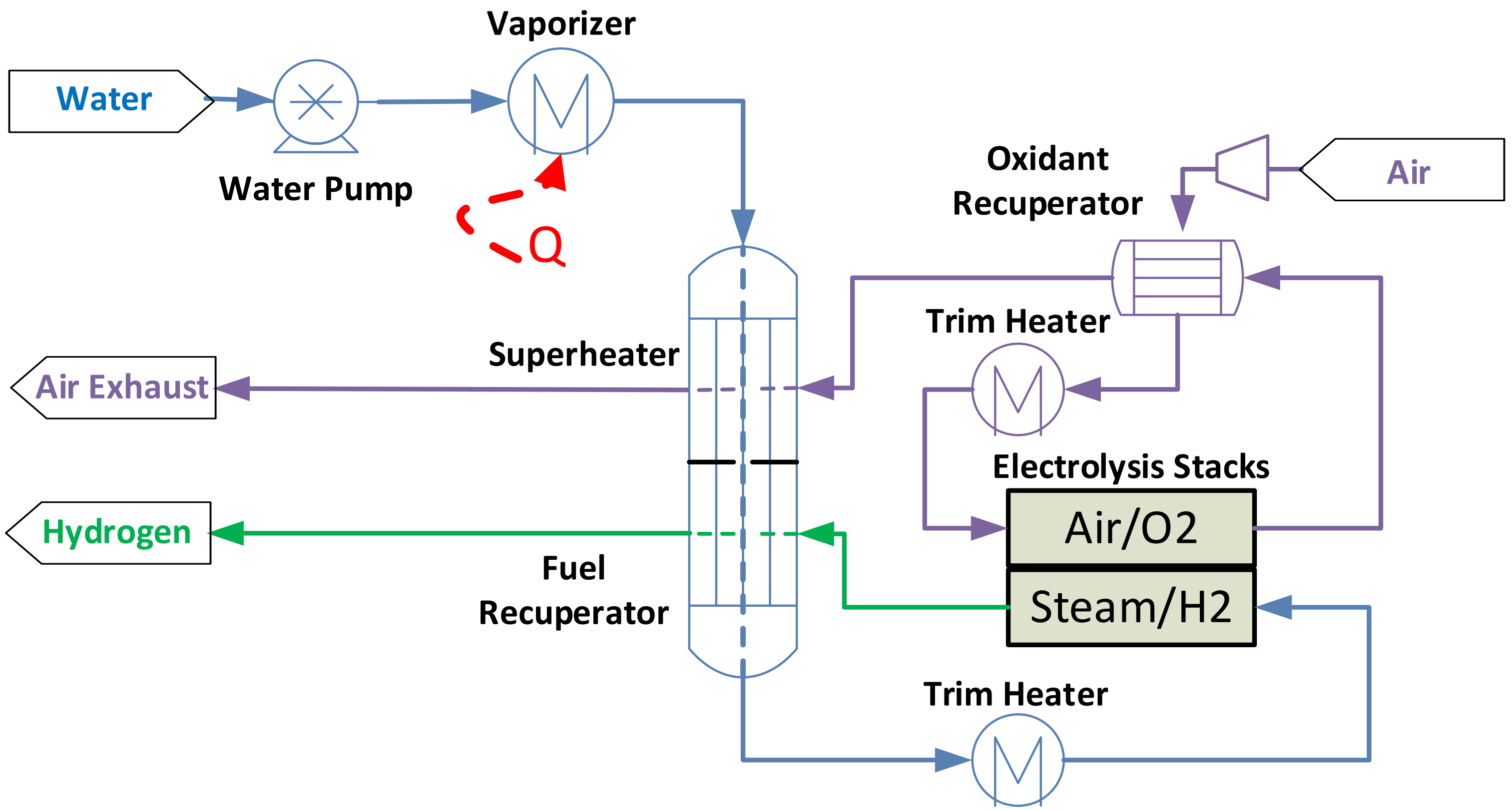
Multi-stack module design capable of producing 150 kg H_2/day was completed

250 kW Electrolysis System

System Characteristics

Parameter	Value	Units
Inputs		
Water	0.25	gpm
Energy		
Heat Recovery/Thermal Input (Q)	30	kW
Total Electrical Input	247	kW
Total Energy Input	277	kW
Output		
Hydrogen Production	150	kg/day
System Efficiencies (HHV)		
Stack Electrical Efficiency (HHV)	126%	
System Electrical Efficiency (HHV)	100%	
System Total Efficiency (HHV)	89%	
Consumption		
Total Electrical Consumption	39.6	kWh/kg H_2
Total Energy Consumption	44.3	kWh/kg H_2

System Process Flow Diagram



System process design was completed:

Results indicate high system efficiency in production of 150kg H_2/day is achievable

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Examples of System Components Fabricated

Technical Accomplishments and Progress

AC-to-DC Rectifiers

Un-interruptible
Power Supply (UPS)

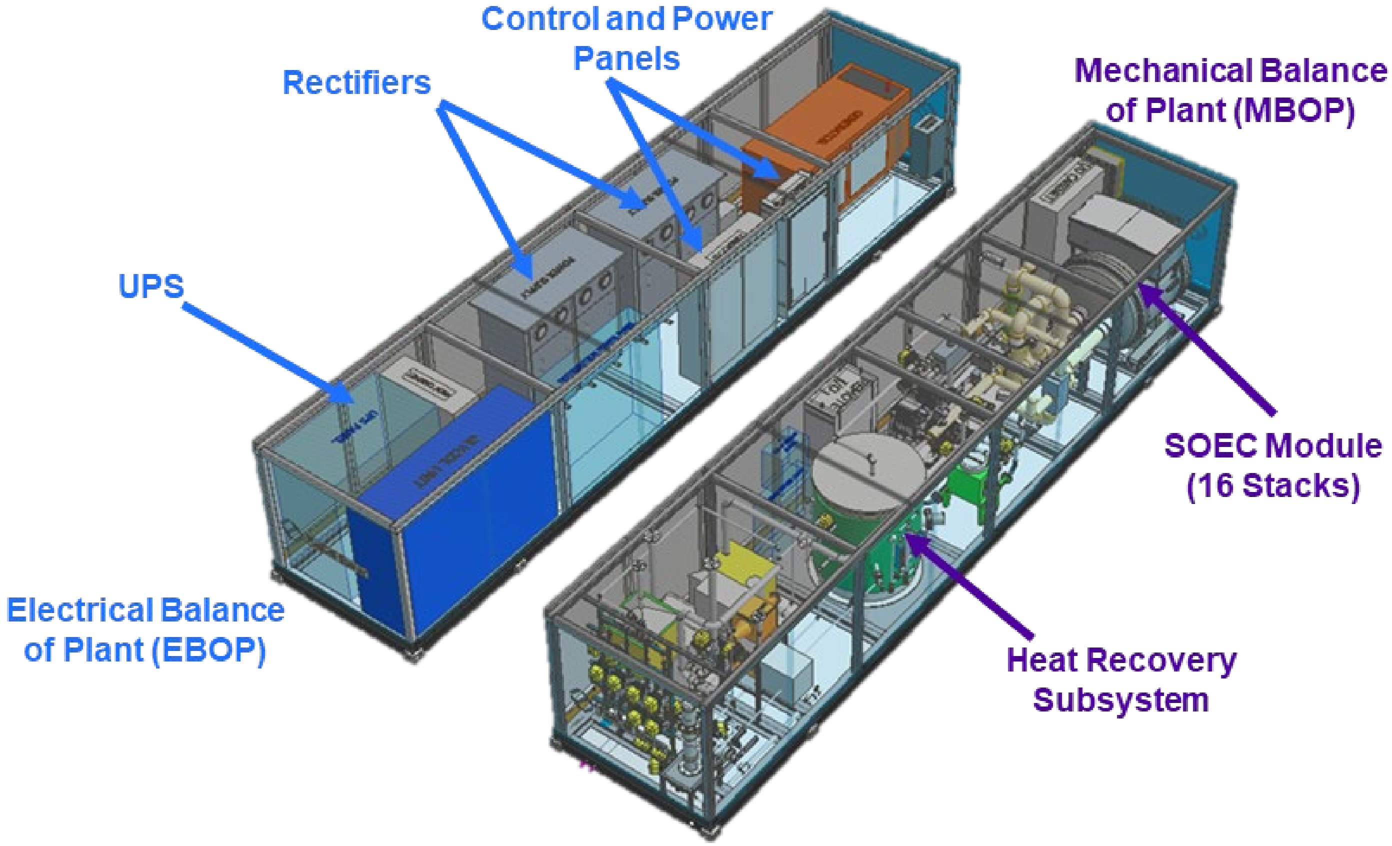
480V Power Panel

Water Vaporizer

Heat Exchangers

Stack Module Shell

250 kW SOEC System Design



38' L x 7'-10" W x 7'-7" H (x 2 skids)

250 kW SOEC Installation

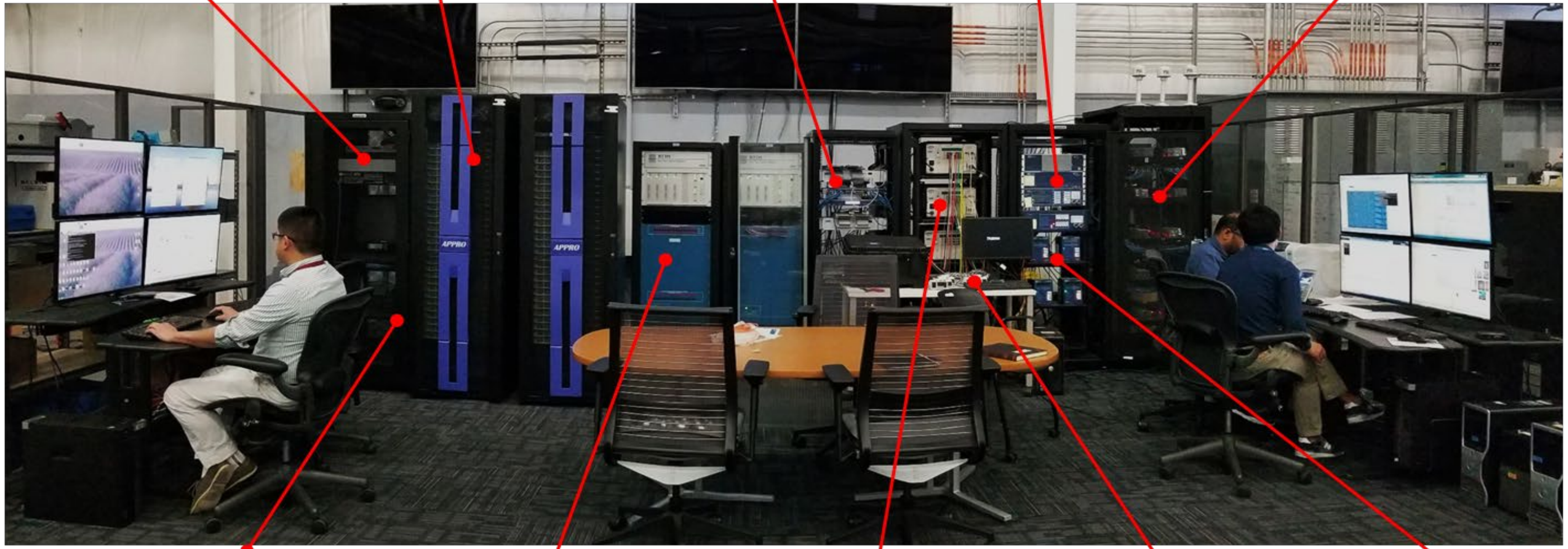
250 kW SOEC system design includes two transportable skids that are factory assembled

Planned 250kW Steam Electrolysis System Tests

- Connect real-time digital simulator to 250 kW SOEC system
- Controller Hardware-in-the-Loop (CHiL) tests to implement control strategies while simulating power grid characteristics

Idaho National Laboratory

INL Power and Energy Real Time Laboratory



Demonstration Site Development at INL

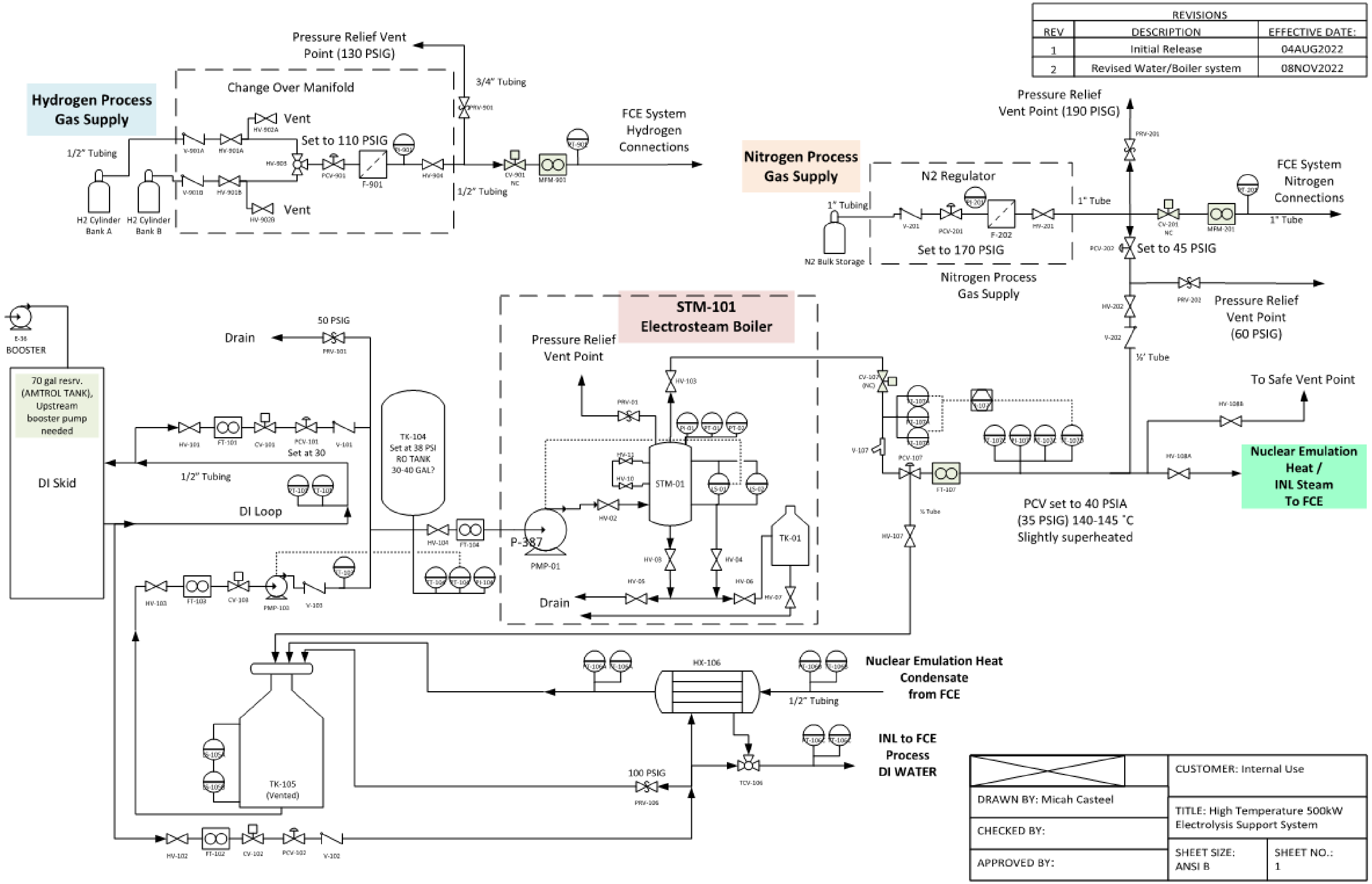
Energy Systems Laboratory (ESL)

INL Idaho National Laboratory

Preparation of the 250kW demonstration site at ESL North Yard is underway

Demonstration of the 250kW solid oxide electrolysis cell (SOEC) system at INL will validate utilization of electricity and waste heat from nuclear plants for efficient production of hydrogen

Site Process Design



- Site support design is completed:
  - Water-treatment
  - Steam boiler simulating waste heat from nuclear plant)
  - Condensate return
  - N2 and H2 purge systems

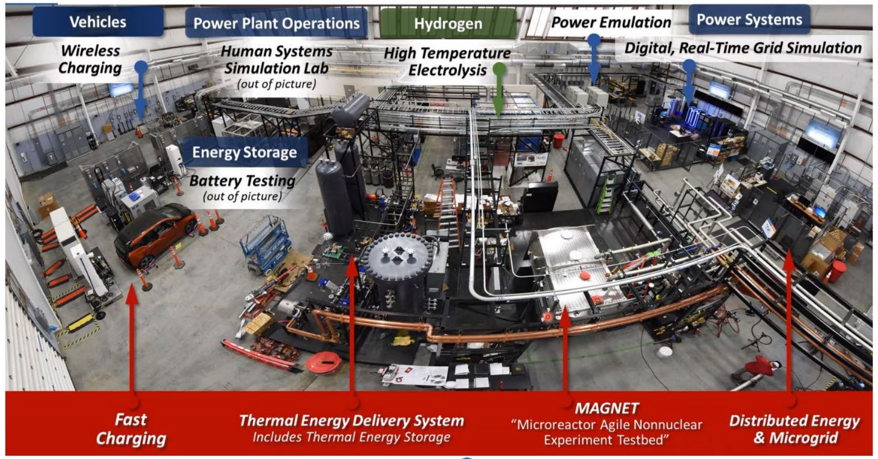
Responses to Previous Year Reviewers' Comments

- This project was not reviewed last year

Collaborations

- Idaho National Laboratory (INL)
  - INL's Energy System Integration Laboratory will be utilized for demonstration of the 250kW SOEC system
    - 16,000 square-feet
    - 600kW AC available power
  - INL expertise in Techno-Economic Analysis (TEA) of steam electrolyzers integrated with nuclear plants will be employed

INL's Energy Systems Integration



Idaho National Laboratory

- Versa Power Systems (VPS), Operating as FuelCell Energy
  - VPS, a wholly owned subsidiary of FCE, will be providing the following expertise in the project:
    - Cell materials & testing
    - Stack design & testing
    - Cell/stack pilot manufacturing and QC

Cell Pilot Manufacturing Processes at VPS: (Tape Casting, Screen Printing, and Co-sintering)

Remaining Challenges and Barriers

- Fabrication of truck-transportable SOEC system skids
  - Delays caused by supply chain of key components and materials
- Production of CSA stacks in accordance with schedule
  - Focus on automation and quality control
  - Targeted stack manufacturing yield >90%
- Development of control systems for autonomous operation of 250kW SOEC packaged system capable of producing 150 kg H_2/ day
- Operation of the system integrated with INL's Controller Hardware-in-the-Loop (CHiL) to simulate dynamic behavior of a nuclear power plant
- Verification of electrolysis stacks durability under dynamic operation

Future Work

- Complete fabrication of solid oxide stacks and stack module
- Development of control hardware and software for autonomous operation
- System assembly and commissioning
- Operation of the 250kW system at INL's Energy Systems Integration Laboratory for >2000 hours
- Techno-economic Analysis
  - SOEC product configuration
  - Stack and system cost at high volume production
  - Operating and maintenance costs

Any proposed future work is subject to change based on funding levels

20

Summary

- Fabricated more that 5600 cells to accommodate building of 16 stacks
- Initiated fabrication of stack module and BOP skids
- Completed design of a 250kW SOEC system capable of producing 150kg/day of hydrogen, including:
  - Process (Mass & Energy Balances, PFD, P&ID, HAZOP analysis, and Equipment Specification Sheets)
  - Mechanical Design (3D drawings, piping analysis, general arrangement, and equipment acquisition)
  - Electrical Design (one-line and three-line diagrams, control and electrical panel designs, instruments)
- Completed fabrication of balance-of-plant equipment such as steam vaporizer, heat exchangers, pump, steam recycle blower, rectifier, UPS, and control system
- Initiated INL site preparation including installation of concrete pad, steam generator, water treatment, and electrical panel upgrade

Technical Backup and Additional Information

22

Technology Transfer Activities

- FCE's SOEC system is a potential candidate for a Department of State project announced by John Kerry at the *COP27 Climate Conference* related to cooperation between Ukraine and the USA to demonstrate production of hydrogen and ammonia using Small Modular Reactor (SMR) nuclear technology and innovative electrolysis technologies in Ukraine.
- Other US participating partners include Argonne National Laboratory, Clark Seed, and NuScale. On the Ukraine side, participants include nuclear operator Energoatom, the National Security and Defense Council, and the State Scientific and Technical Center for Nuclear and Radiation Safety. In addition, Korea's Doosan Energy and Samsung C&T and Japan's IHI Corporation and JGC Corporation will participate in the consortium.
- The project aims to evaluate and demonstrate the technical capability, economic competitiveness, as well as the possibility of production and use of hydrogen and ammonia on an industrial scale from SMRs using solid oxide electrolysis. For this purpose, it is planned to construct a pilot plant and carry out a corresponding technical and economic analysis of its operation.
- The project seeks to support Ukraine's energy security goals, enable decarbonization of hard-to-abate energy sectors through clean hydrogen generation, and improve long-term food security through clean ammonia-produced fertilizers. Further, it aims to demonstrate Ukraine's innovative clean energy leadership through the use of advanced technologies.

US Special Presidential Envoy for Climate, John Kerry, announcing the cooperation project at COP27 in Sharm el-Sheikh, Egypt

Technology Transfer Activities

1.1 MW SOEC Product

Solid Oxide Electrolysis Platform

- 1.1MW Rated Input
- 600 kg/day hydrogen production
- Power input reduced to 1.0 MW with supplied waste heat
- Two modules – stack/mechanical BOP and electrical BOP
- Stack/Mechanical BOP is repeating unit in larger systems

Specifications subject to change without notice. All specifications quoted at initial operation.

Hydrogen

Production Rate ____ ~600 kg/day

Pressure ____ 14.7 psia (1 bar(a))*

Performance (With and Without Heat Input)

Efficiency (HHV) With Heat ____ 100%

Electricity Consumption With Heat ____ 39.4 kWh/kg

Efficiency (HHV) No Heat ____ 90%

Electricity Consumption No Heat ____ 43.8 kWh/kg

Efficiency levels are +/- 2%.

Product Composition

H_2 ____ 99% dry basis, by volume

Purification and compression options available.

N_2 ____ ~1% dry basis, by volume

Ramping (Increasing or Decreasing)

0% - 100% load ____ 10% per minute

Module Dimensions (W x L x H)

Width: 8’ Length: 40’ Height: 10’

Width: 2.43m Length: 12.19m Height: 3.04m

There are two modules in a standard configuration.

Electrical Input

Plant Power Input ____ 1.1 MW

Voltage (3-phase) ____ 480 V (400 V Option)

Frequency ____ 60 Hz (50 Hz Option)

Water

Water Conductivity ____ < 1 μS/cm

Treatment options available for lower quality water.

Nominal Consumption ____ 1 gpm (5,451 SLPD)

Drainage for Maintenance ____ 46 gallons (174 L)

Sound Levels

Standard ____ < 72 db(A) @ 10 Feet (Option < 65)

Optional Customer Steam Supply for Higher Efficiency (Saturated or Superheated)

Recommended Temperature Range ____ 259 - 295 °F (126 - 146 °C)

Recommended Pressure Range ____ 20.0 - 47.1 psig (1,379 - 3,254 mbar)

Recommended Flow Rate Range ____ 340 - 570 lb/hr (154 - 258 kg/hr)

*Optional compression is available and will add 2 to 4 kWh/kg power consumption depending on pressure level.

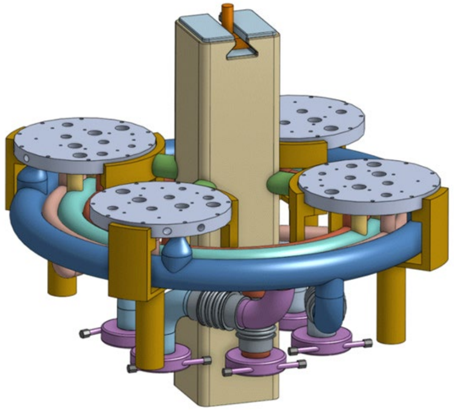
Cell Manufacturing Capacity Increase

- Cell and stack fabrication yield improvements
- Automated screen printing on half-cells
- Multi stack conditioning
- Advanced manufacturing technology, automation and quality control

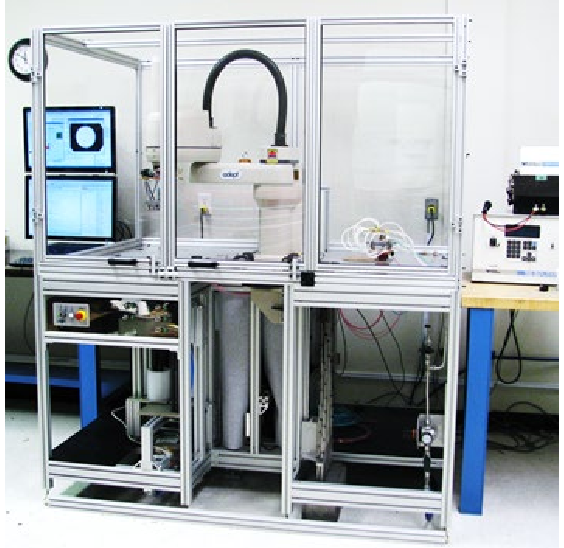
Robotic Sprayer

Auto Screen Printer and Dryer

Stack Transporter



Multi-Stack Conditioning Manifold



Automated QC / Stack Assembly

Solid Oxide cell and Stack fabrication processes have evolved from laboratory to automated production

Backup Slide

150-Cell Electrolysis Stack Test

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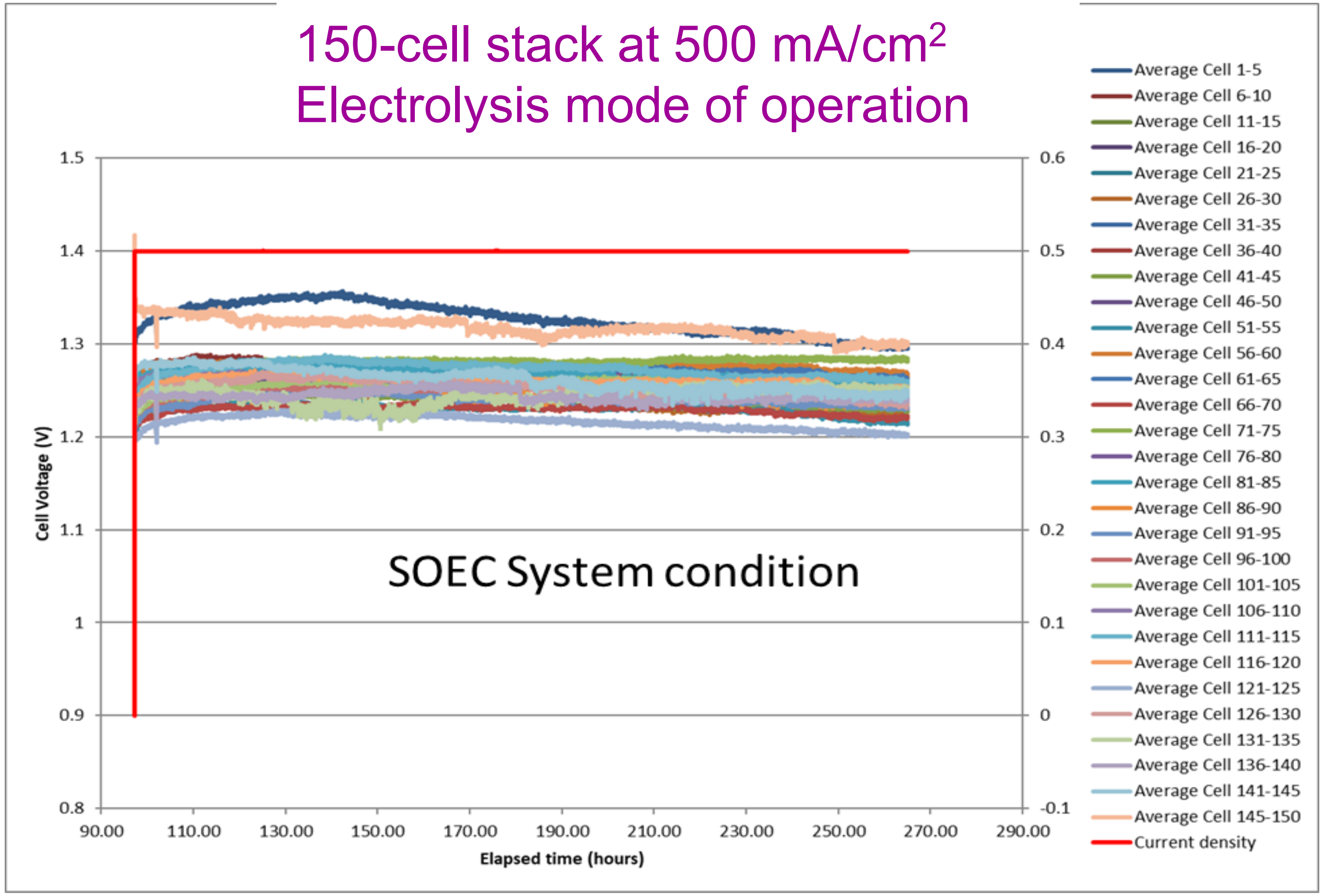
150-cell stack (GT60247-0005)

- 150-cell stack was fabricated and conditioned for further testing in the Pilot RSOFC System



- Furnace: 627 C
- Fuel: 50% H_2O , 50% H_2 @ 76.05 SLPM H_2
- Air: 150 SLPM @ 40.5 A -- 76.05 SLPM H_2O
- Usteam = 60.0%

Backup Slide

50-Cell Solid Oxide Electrolysis Test at Idaho National Laboratory

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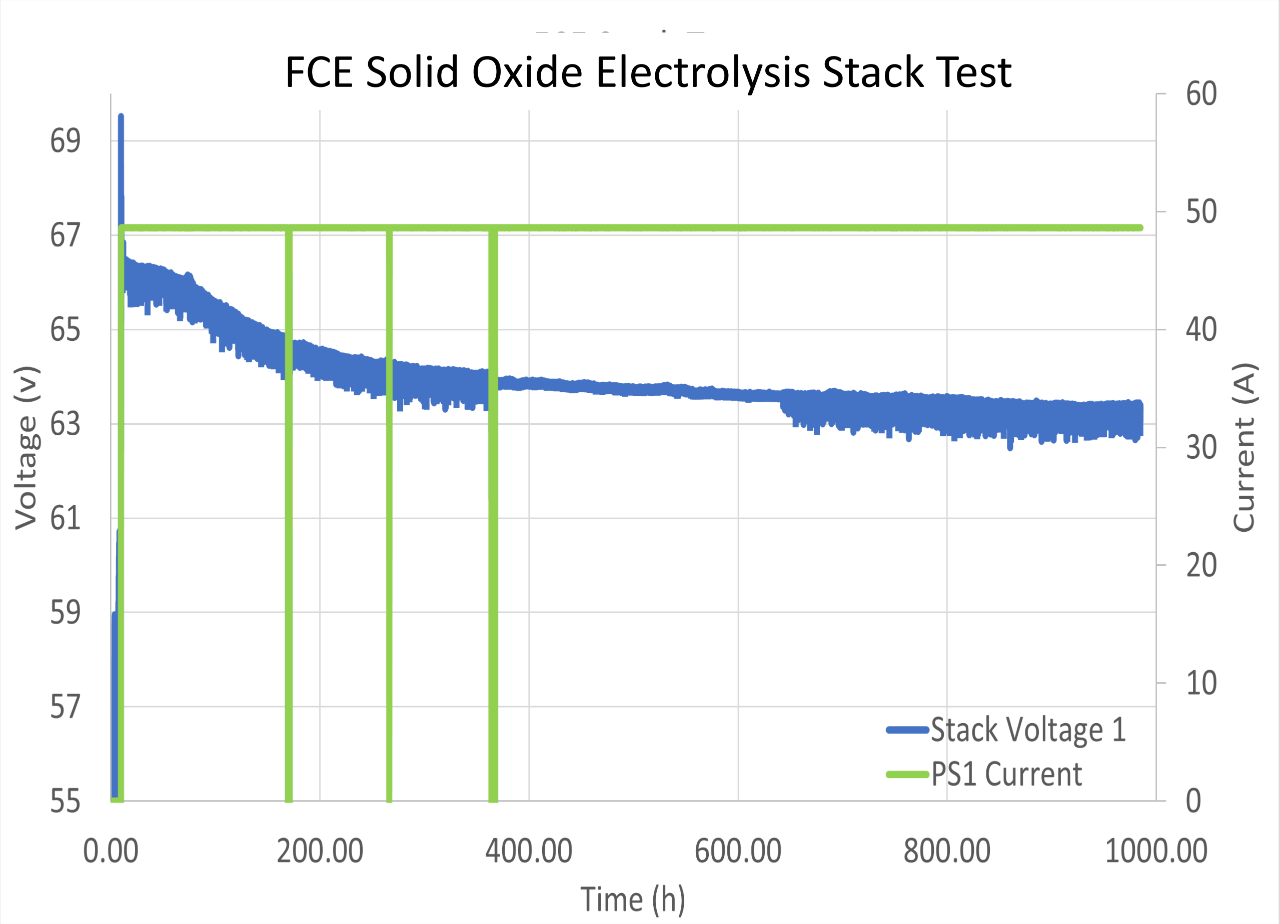
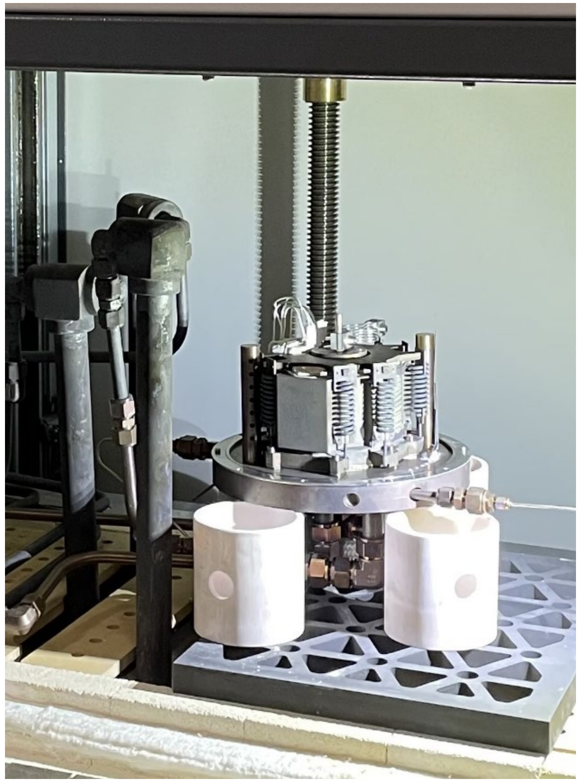


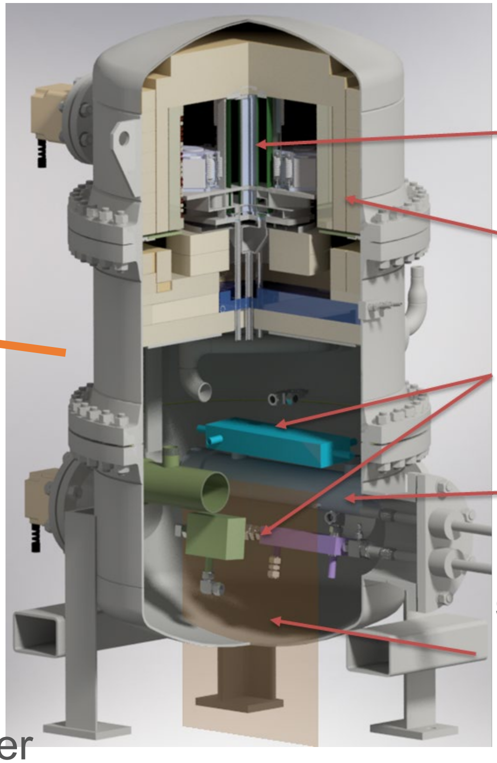


50-Cell Solid Oxide Electrolysis Stack Installed at INL test station

Independent test of FCE's stack at Idaho National Laboratory (INL) has shown steady operating voltage after initial performance improvement

Background:
Steam Electrolysis Pilot System

SOEC Electrolyzer System



SOEC Electrolyzer Module

Mid Size CSA Stack

Stack Module Assembled

Stack Module:

- 125 psig (8.6 barg) design pressure
- Accommodates 1x150-cell stack or 4x45-cell stacks with adapter
- Three thermal zones:
  – Hot zone for the electrolyzer stack
  – Mid-temp zone for BOP components such as electric heaters and heat exchangers
  – Cool zone for Instrument termination points
- Vessel is designed in accordance with ASME B&PV Code Section VIII Div. II, with internal insulation to allow a touch-safe vessel wall temperature

Backup Slide

4kg H2/day Pilot System Performance

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Hydrogen
4.0 kg/day
5.6 kW (LHV)

SOEC Stack
6.1 kW

Electrical Input
6.5 kW

Balance of Plant
0.4 kW

Thermal Input, Simulated
1.1 kW

Water
1.9 l/h

System Performance Parameter	Value
Stack Electrical Efficiency (LHV)	93.1 %
System Electrical Efficiency (LHV)	85.1 %
System Total Efficiency (LHV)	73.0 %
Electricity Consumption	39.2 kWh/kg
Thermal Consumption, Simulated	6.5 kWh/kg
Total Energy Consumption	45.7 kWh/kg

Backup Slide