High Temperature Electrolysis Test Stand

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Idaho National Laboratory
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Project ID # tv040
Overview

Timeline
Project Start Date: 4/1/2017
End Date: currently planned through FY20; Project continuation and direction determined annually by DOE

Barriers
This project addresses the following technical barriers from the Technology Validation section of the FCTO MYRDD Plan:

• (G) Hydrogen from Renewable Resources
• (H) Hydrogen and Electricity Co-Production

Budget
FY17 DOE Funding: $1.49M
FY18 DOE Funding: $800k

Partners
• US DOE: Project Sponsor and Funding
• NREL: Power converter and front-end controller integration
• PNNL: HTE stack design
• SNL: front-end controller development and testing with respect to grid interactions
Relevance

Overall Objective:

I. Advance the state of the art of High Temperature Electrolysis (HTE) technology by discovering, developing, improving and testing thermal/electrical/control interfaces for highly responsive operations

II. Support the DOE-NE/EERE collaboration in Nuclear-Renewable Hybrid Energy Systems Integration

• Develop infrastructure to support systems integration HTE operations up 250 kW scale
• Support HTE research and system integration studies
• Measure cell-stacks and performance and materials health under transient and reversible operation
• Characterize dynamic system behavior to validate transient models used for process control
• Demonstrate integrated operation with co-located dynamic thermal energy systems including a high-temperature, high-pressure water flow loop and a thermal energy distribution and storage system
• Operate the HTE test station with co-located digital real-time simulators for dynamic performance evaluation and hardware-in-the-loop simulations

Impact to date vs Barriers

• Facility will be commissioned for initial HTE hydrogen production at the 5 kW scale this month
Approach

• Deploy flexible 25 kW_{DC} multi-stack and 250 kW_{DC} HTE testing units in the INL Dynamic Energy Transport and Integration Laboratory (DETAIL)
  – Provide a testing platform to HTE technology developers to test stack performance under dynamic operating conditions
  – Demonstrate and characterize simultaneous coordinated multi-directional transient distribution of electricity and heat for multiple industrial process heat applications
  – Characterize system performance under flexible operating conditions
  – Simulate broader systems through the use of real-time digital simulators with hardware-in-the-loop
  – Document HTE operational and performance characteristics in a grid-dynamic environment

• Evaluate the potential of HTE systems to achieve efficient, low-cost hydrogen production with optimized operational profiles designed to take advantage of intermittent low-cost electricity and integrated process heat
  – Help industry identify HTE technology gaps relative to optimized stack and systems designs for hybrid systems applications
  – Document performance characteristics associated with intermittent HTE operations
  – Investigate the impacts of grid instability on HTE operations
  – Demonstrate the utility of HTE thermal integration with co-located systems
NE-EERE Collaboration: Experimental Demonstration of Integrated Systems

Dynamic Energy Transport and Integration Laboratory (DETAIL)

Objective: Demonstrate simultaneous, coordinated, controlled, and efficient multi-directional transient distribution of electricity and heat for power generation, storage, and industrial end uses.

Data Links to DETAIL Components and Unit Operations:
System-Level Controller to Unit-Level Controllers

System Monitoring & Control

Digital Real-Time Simulator Stations

Wind
PV Solar
Flow-Through Chemicals
EV and Battery Charging

System Integration Lab Microgrid Components

Power Grid or Community Power

Power System: Cycle, Microgrid
ARTIST: (Heat Transfer Loop)
HTE: SOEC, SOFC

Simulated Nuclear Reactor
ARTIST
Programmable Heating Elements

Intermediate Heat Exchanger

Thermal Energy Distribution System (TEDS)

Steam or Gas Turbine
Dynamometer
Future Baseload Power Gen Capability

Other Power Generation Operations

High Temperature Steam Electrolysis
Power Converter

O2, H2
Storage

Chemicals / Fuels Synthesis

Carbon Feedstocks: CO2, Biomass, Natural Gas, Coal

Digital Real-Time Simulator Stations

Thermal Energy Storage

Evaporator

Intermediate Heat Exchanger

Dynamometer
Future Baseload Power Gen Capability

Other Power Generation Operations

High Temperature Steam Electrolysis
Power Converter

O2, H2
Storage

Chemicals / Fuels Synthesis

Carbon Feedstocks: CO2, Biomass, Natural Gas, Coal
Approach: HTE Stack Integration and Control Scheme

- Stacks for cyclic operations
- Heat integration improvements
- Modular units
- Reversible operation
- Co-electrolysis
- Oxygen recovery

<table>
<thead>
<tr>
<th>Test Article</th>
<th>Electrolysis Power at Design Condition (1.2 V, 0.5 A/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Button cell (2.5 cm²)</td>
<td>1.5 W</td>
</tr>
<tr>
<td>Single cell (16 cm²)</td>
<td>9.6 W</td>
</tr>
<tr>
<td>Small stack (100 cm², 10 cells)</td>
<td>600 W</td>
</tr>
<tr>
<td>Large Stack (100 cm², 50 cells)</td>
<td>3 kW</td>
</tr>
<tr>
<td>Multiple-stack modules (4 large stacks)</td>
<td>12 kW</td>
</tr>
</tbody>
</table>
Approach: HTE Stack Integration and Control Scheme

What’s new?

- Versatile design for larger, User-Provided stacks
- Grid-level Front-End Controller (FEC)
- Responsive power converter tied to digital real-time simulation of grid and FEC
- Controllable steam supply
- Connected to Thermal Energy Distribution System
- Stack instrumentation and monitoring
- Connection to H₂ user (e.g. chemical synthesis with CO₂ feedstock)
### Approach

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Date</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Report on 25 kW HTE test systems design and stakeholder value</td>
<td>12/31/2017</td>
<td>complete</td>
</tr>
<tr>
<td>Demonstrate operability and data management of 25 kW HTE test station</td>
<td>3/31/18</td>
<td>Expected 6/15/18</td>
</tr>
<tr>
<td>Demonstrate HTE module response rate of 0-95% capacity in 30 minutes or less, with an electricity demand response rate of 0-98% capacity in 10 minutes or less.</td>
<td>9/30/2018</td>
<td>On schedule</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Go/No-Go Decision</th>
<th>Date</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Successful initial operation of the flexible HTE 25 kW station</td>
<td>3/31/18</td>
<td>pending</td>
</tr>
</tbody>
</table>
Accomplishments and Progress

• Completed Design and Installation of Facility Support Infrastructure

✓ Power,
✓ DI water system,
✓ drain, enclosure,
✓ ventilation system,
✓ H₂ vent,
✓ gas monitoring,
✓ safety interlocks,
✓ fire protection,
✓ structural support
Accomplishments and Progress

• Completed Design and Installation of 25 kW HTE Test Facility

• Initial testing is currently under way
  ✓ High-temperature furnace
  ✓ High-temperature air supply for sweep gas
  ✓ N\textsubscript{2} purge systems
  ✓ Gas dryer and hydrogen recycle system
  ✓ Gas monitoring system with interlocks
  ✓ Methanol synthesis integration
Accomplishments and Progress

High Bay location of DETAIL within the INL Energy Systems Laboratory

DI Water System

4 kW HTE test stacks at INL, 2012

Steam Generator

Furnace

Hydrogen recycle compressor

Condenser array
Established Technical and Functional Requirements for Dynamic Energy Transport and Integration Lab (DETAIL)

- Thermal and electrical integration to represent commercial-scale units
- Monitoring and controls performed locally, in communication with Power Systems/Grid Real-Time Digital Simulation (RTDS, right)
- Thermal energy relay to match nuclear reactor thermal hydraulics test loop
- Design of Phase I for Advanced Reactor Technology Integrated System Testing completed
- Thermal Energy Delivery System design underway

Accomplishments and Progress (Coordination)

INL Power Systems/Grid Real-Time Digital Simulation (RTDS)

TEDS (ties ARTIST to the HTE Test Modules)

ARTIST Thermal Hydraulic Test Loop
Reviewer Comments

This project was not reviewed last year
Collaboration and Coordination

DOE Partnerships
- DOE-NE / DOE-EERE Collaboration
  - Nuclear-Renewable Hybrid Energy Systems

Industrial Partnerships
- OxEon Energy
  - Stack development and testing
- Haldor Topsoe
  - Stack and system supplier
- Fuel Cell Energy
  - Large-scale systems
- Exelon
  - Grid stability, non-electric markets for nuclear
- Small Modular Nuclear Reactor
  - Joint-Use Modular Plant
Collaboration and Coordination

National Laboratory Partnerships

- PNNL
  - HTE Stack development
- NREL
  - Power converter and Front-End Controller testing
- SNL
  - Front-End Controller development and testing with respect to grid interactions
Remaining Challenges and Barriers

• Long-term performance of Solid Oxide Electrolysis Cell (SOEC) stacks
  – Degradation must be 0.5%/k-hr or lower for economic viability
  – Intermittent operation and thermal cycling may accelerate degradation
  – Reversible operation may improve long-term degradation characteristics
  – Effects of grid instability on HTE system performance must be determined

• Optimization of HTE operation in dynamic environment for achievement of low-cost $\text{H}_2$ production while providing grid stabilization services

• Reduction of HTE system capital costs

• Effective thermal integration and thermal management for intermittent/reversible operation
Proposed Future Work

Remainder FY18

• Complete Initial HTE testing in new facility at the 5 kW scale
  – Steady-state, baseline testing; long-term degradation
  – Effects of intermittent operation and thermal cycling
• Complete initial HTE test campaign at 25 kW scale (FY18/19)
  – Exercise full system capacity
  – Steady-state, baseline testing; long-term degradation
  – Effects of intermittent operation and thermal cycling
  – Operation with variable front-end power profiles
• Support the advancement of HTE stack technology, working with industry partners, for robust performance even with the demanding load profiles associated with deployment in flexible hybrid energy systems

FY19

• Thermal integration of 25 kW system with the DETAIL thermal network
• Conduct 25 kW grid demand response exercises, documenting the thermal energy latency and system electrical characteristics

Note: Any proposed future work is subject to change based on funding levels
Technology Transfer Activities

- Working with HTE Systems Integration Companies
  - FuelCell Energy
  - OxEon
  - Boeing Company
  - Others...

- CRADAs with Industry
  - Exelon/Fuel Cell Energy (Poster No. h2052)
  - TerraPower
  - Terrestrial Energy, USA

- Working with large companies to identify new markets for large-scale hydrogen production with thermal integration
  - Direct-reduced iron
  - Grid stabilization
  - Enhanced profitability for existing light-water reactor fleet (non-electric application)
  - Synthetic liquid fuels
Summary

**Objective:** Advance the state of the art of High Temperature Electrolysis (HTE) technology while demonstrating grid and thermal energy integration

**Relevance:** The growing contribution of renewable sources of electric power onto the grid requires increased flexibility in dispatchable energy producers. Appropriately staged hydrogen production via HTE provides a potential high-value product for increased profitability

**Approach:** Establish a large-scale High-Temperature Electrolysis test capability within the INL Dynamic Energy Transport and Integration Laboratory for demonstration and characterization of simultaneous coordinated multi-directional transient distribution of electricity and heat for multiple industrial process heat applications

**Accomplishments:** Design and installation of a flexible 25 kW HTE test facility has been completed and initial testing is in progress

**Collaborations:** Collaborations have been established with several National Laboratory and industry partners.
Technical Backup Slides
### Nominal operating conditions for full 25 kW testing

#### Assumptions
- Acell = 12 cm x 12 cm
- Ncells = 50
- Nstacks = 4
- ASR = 0.6 Ω cm²
- i = 0.67 A/cm²
- steam utilization, U = 0.6
- inlet mole fraction steam: 0.7, 0.9
- inlet mole fraction H2: 0.1
- inlet mole fraction N2: 0.2, 0.0
- Air sweep gas, Nstoichs = 0.5

#### Flow Rates

<table>
<thead>
<tr>
<th></th>
<th>With N2</th>
<th>No N2</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2 in</td>
<td>32.0</td>
<td>24.9</td>
<td>SLPM</td>
</tr>
<tr>
<td>H2 Production rate</td>
<td>134.5</td>
<td>134.5</td>
<td>SLPM</td>
</tr>
<tr>
<td>H2 out</td>
<td>166.5</td>
<td>159</td>
<td>SLPM</td>
</tr>
<tr>
<td>H2O in (liq)</td>
<td>180</td>
<td>180</td>
<td>gm/min</td>
</tr>
<tr>
<td>H2O in (liq)</td>
<td>10.8</td>
<td>10.8</td>
<td>kg/hr</td>
</tr>
<tr>
<td>H2O in (steam)</td>
<td>224</td>
<td>224</td>
<td>SLPM</td>
</tr>
<tr>
<td>H2O out (steam)</td>
<td>89.6</td>
<td>89.6</td>
<td>SLPM</td>
</tr>
<tr>
<td>N2 in</td>
<td>64</td>
<td>0</td>
<td>SLPM</td>
</tr>
<tr>
<td>Total Cathode gas flow in</td>
<td>320.2</td>
<td>249</td>
<td>SLPM</td>
</tr>
<tr>
<td>Air in</td>
<td>160</td>
<td>160</td>
<td>SLPM</td>
</tr>
<tr>
<td>O2 Production rate</td>
<td>67.2</td>
<td>67.2</td>
<td>SLPM</td>
</tr>
<tr>
<td>Air+O2 out</td>
<td>227</td>
<td>227</td>
<td>SLPM</td>
</tr>
<tr>
<td></td>
<td>8.03</td>
<td>8.03</td>
<td>SCFM</td>
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#### Recycle Flow Rates

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<th>With N2</th>
<th>No N2</th>
<th>units</th>
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</thead>
<tbody>
<tr>
<td>Recycle compressor flow rating (@150 psig discharge pressure)</td>
<td>6.1</td>
<td>6.1</td>
<td>SCFM</td>
</tr>
<tr>
<td>Recycle compressor VFD setting</td>
<td>100</td>
<td>75</td>
<td>% of FS</td>
</tr>
<tr>
<td>H2 through beds (avg)</td>
<td>1.131</td>
<td>0.879</td>
<td>SCFM</td>
</tr>
<tr>
<td>H2O into beds (avg)</td>
<td>0.0038</td>
<td>0.0021</td>
<td>SCFM</td>
</tr>
<tr>
<td>N2 Through beds (avg)</td>
<td>0.435</td>
<td>0</td>
<td>SCFM</td>
</tr>
<tr>
<td>H2 through beds (during compressor operation)</td>
<td>4.285</td>
<td>4.212</td>
<td>SCFM</td>
</tr>
<tr>
<td>H2O through beds (during compressor operation)</td>
<td>0.014</td>
<td>0.0103</td>
<td>SCFM</td>
</tr>
<tr>
<td>N2 Through beds (during compressor operation)</td>
<td>1.648</td>
<td>0</td>
<td>SCFM</td>
</tr>
<tr>
<td>N2 added after recycle</td>
<td>1.826</td>
<td>0</td>
<td>SCFM</td>
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</table>

#### Stack Electric

<table>
<thead>
<tr>
<th></th>
<th>With N2</th>
<th>No N2</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell voltage</td>
<td>1.309</td>
<td>1.302</td>
<td>V</td>
</tr>
<tr>
<td>Stack voltage</td>
<td>65.5</td>
<td>65.1</td>
<td>V</td>
</tr>
<tr>
<td>Stack current</td>
<td>96.5</td>
<td>96.5</td>
<td>A</td>
</tr>
<tr>
<td>Module current</td>
<td>385.9</td>
<td>385.9</td>
<td>A</td>
</tr>
<tr>
<td>Module Power</td>
<td>25.3</td>
<td>25.1</td>
<td>kW</td>
</tr>
</tbody>
</table>

#### Hot Zone

<table>
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<tr>
<th></th>
<th>With N2</th>
<th>No N2</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Temp</td>
<td>800</td>
<td>800</td>
<td>°C</td>
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</table>

#### Heater Power Requirements

<table>
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<tr>
<th></th>
<th>With N2</th>
<th>No N2</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam generator (H2O from 20 to 150 C)</td>
<td>8.1</td>
<td>8.1</td>
<td>kW</td>
</tr>
<tr>
<td>Superheater (H2 +N2 from 20 to 800 C + steam from 150 C to 800 C)</td>
<td>5.87</td>
<td>4.15</td>
<td>kW</td>
</tr>
<tr>
<td>Air heater/ superheater</td>
<td>2.87</td>
<td>2.85</td>
<td>kW</td>
</tr>
</tbody>
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