Solid Oxide Fuel Cell Power System Development DE-FE0001179

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Delphi

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Outline

- Summary Highlights of Past Year
- System Development and Testing
  - System B Laboratory Test
  - System C In-Ground Test

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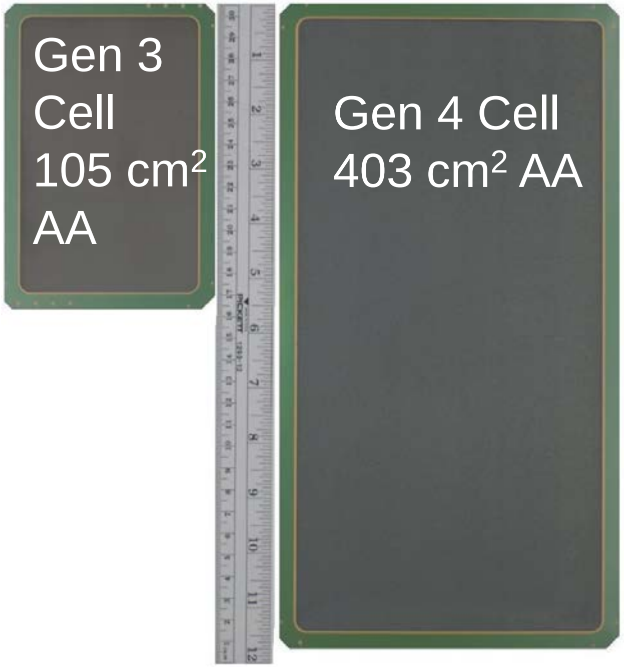
Gen 3 and Gen 4 Stacks

Gen3
9 Kg, 2.5 liters
for a 30-cell
stack, 1.5 kW



Gen4
57.5 Kg, 17.5 liters
for a 38-cell stack,
7 kW

Performance Highlights Summary

- Fabricated 390 Gen 4 cells (equiv. to 1170 Gen 3 cells) in the past year
- Fabricated and tested 38 stacks of various Gen 3 and Gen 4 configurations in the past year
- Demonstrated over 15,000 hours continuous NOC durability on Gen 3 stack (continuing) with degradation rate at 0.4%/1000 hrs
- Completed numerous cell and stack investigations relating to interconnect geometry and coatings, stack operating conditions, repeating unit seal material and processing, metal coating cost reduction, and cathode performance improvement
- System testing
  - Completed laboratory furnace testing of 3-stack, SOFC power system
  - Completed in-ground testing of fully integrated, 9-stack SOFC power system

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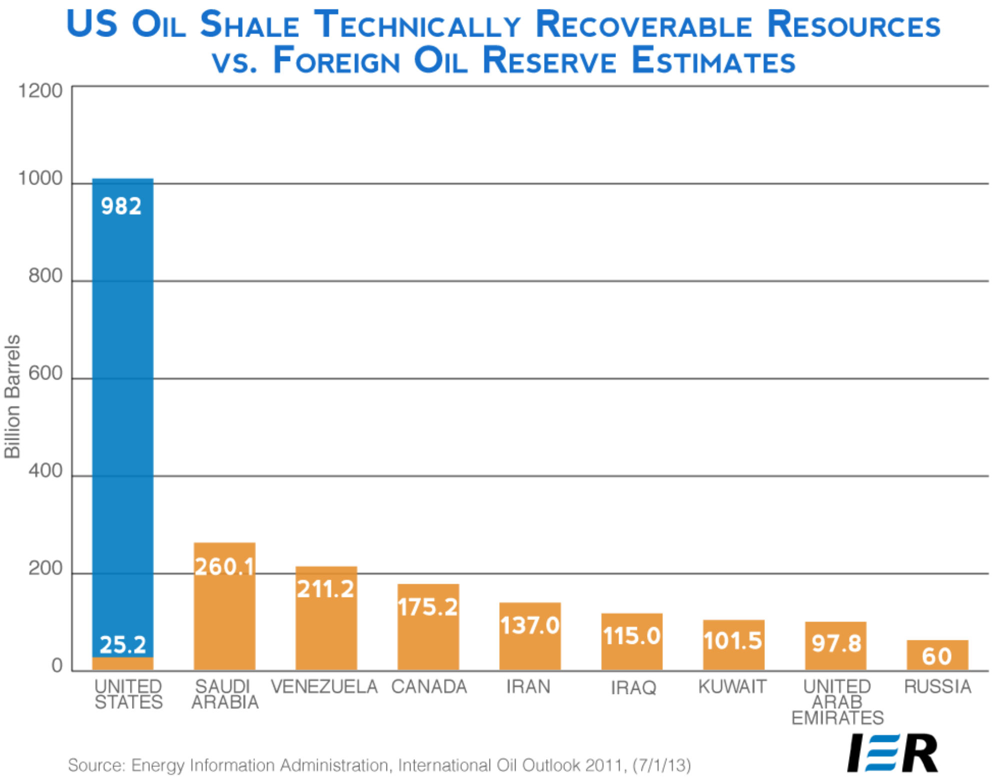
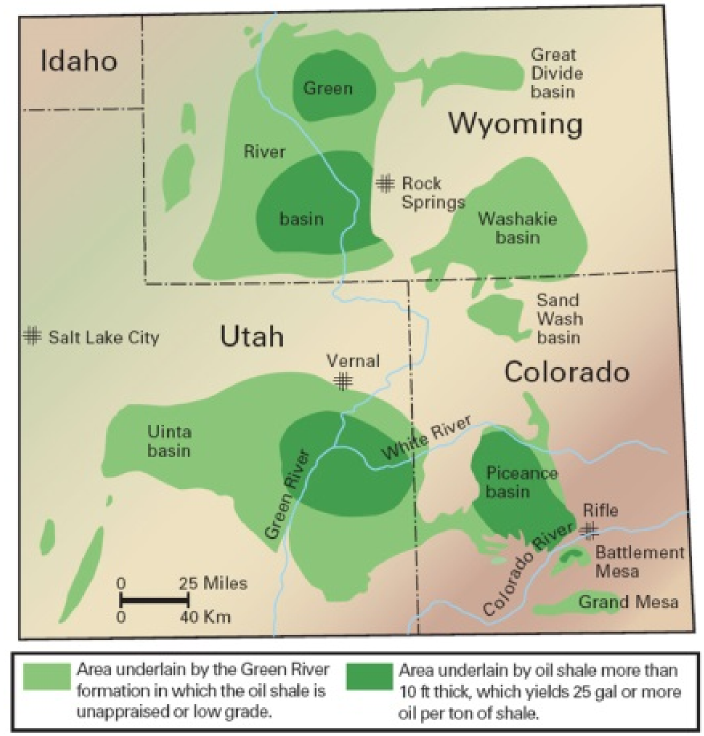
Thermally Self-Sustaining, Multiple Stack Systems

System	Timeframe	Stack Type	Number of Cells/Stack	Number of Stacks	Rated System Power	Electrical Configuration	Hot Zone Instrumentation
A	Q3 2013	Gen 3	29	3	4.5 kW	Two Stacks in Parallel, One Independent	Thermocouples - 51 Pressure Taps - 17 Voltage Leads 12
B	Q2-3 2014	Gen 3	29	3	4.5 kW	All Stacks in Series	Thermocouples - 32 Pressure Taps - 16 Voltage Leads 6
C	Q3-4 2014	Gen 3	29	9	13.5 kW	Stacks in Series-Parallel Architecture	Thermocouples - 23 Pressure Taps - 4 Voltage Leads 10

US Oil Shale Reserves

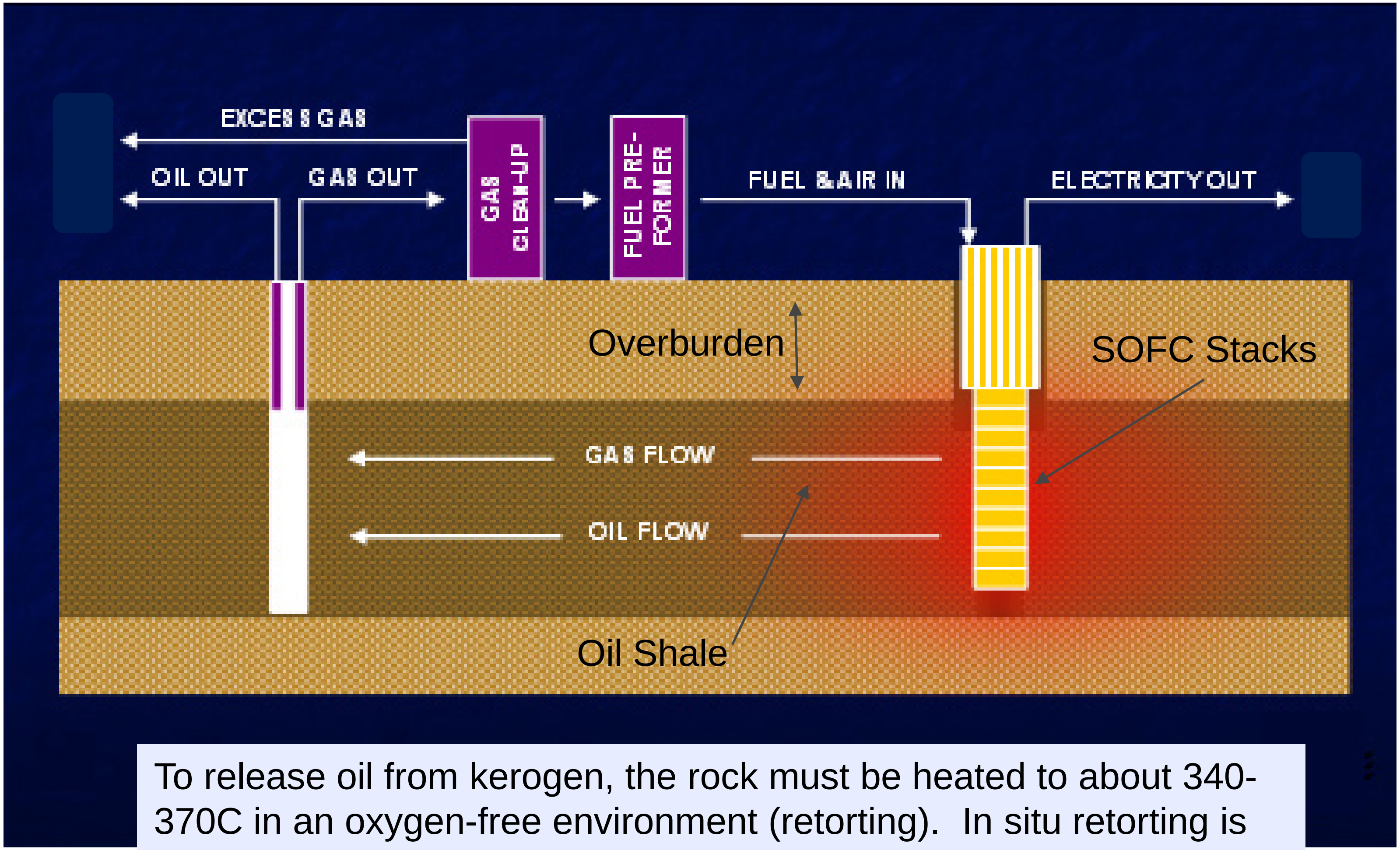




Oil shale is a fine-grained sedimentary rock that contains various amounts of organic matter. Oil in the shale is contained within a waxy, bituminous substance called kerogen.

Colorado's Piceance Basin contains about 1,300,000 barrels of oil per acre on average

Use of SOFC Technology for Unconventional HC Recovery



To release oil from kerogen, the rock must be heated to about 340-370C in an oxygen-free environment (retorting). In situ retorting is done at varied depths, leaving the oil shale in the ground.

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Stack Modules for System B

- Three SOFC Gen 3 stacks
- 4.5 kW rated power
- Series electrical architecture
- One module to module connection

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Test Stand for System B

Indoor laboratory test stand for System B, located in the Colorado Fuel Cell Center

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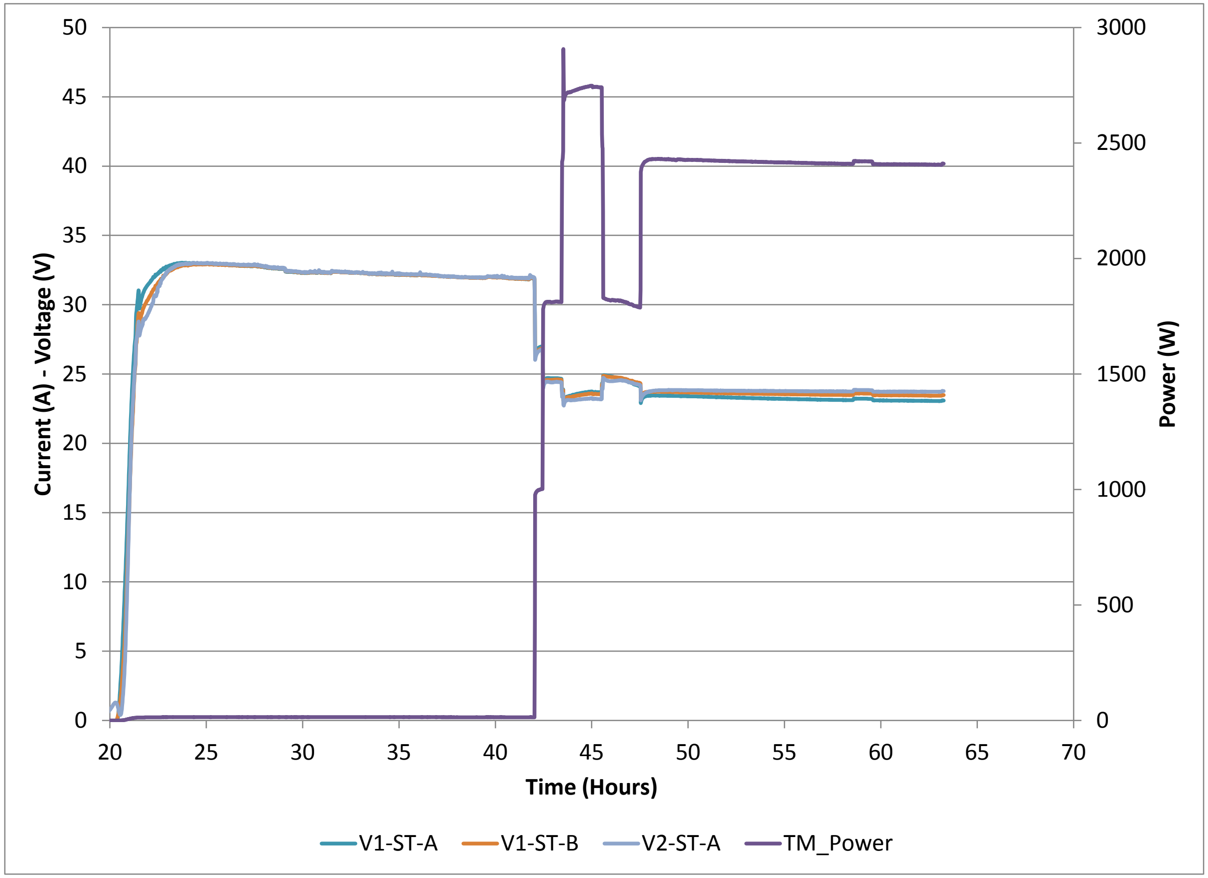
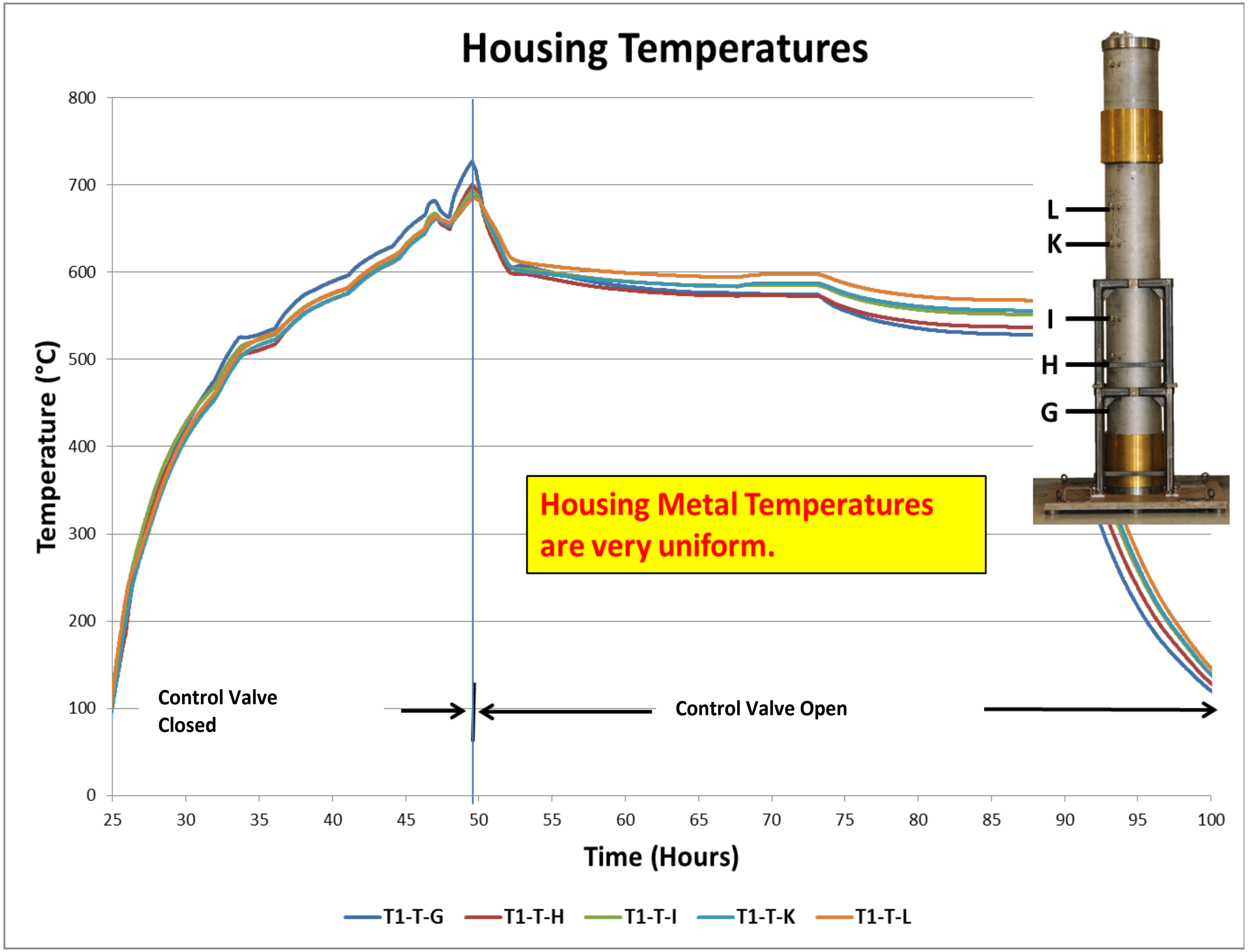
Stack Voltage and System B Power Performance



- System completed numerous discrete tests to define/explore operational parameters
- System accumulated hundreds of hours of total test time

Outer Housing Temperatures on System B Stack Module



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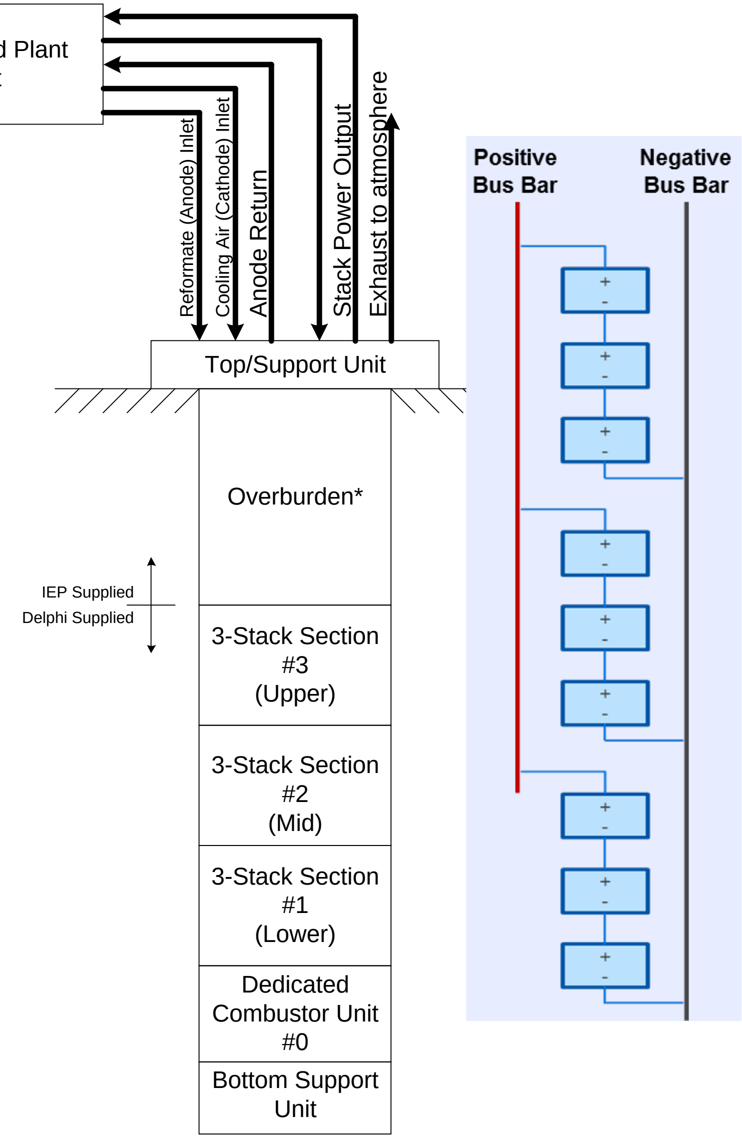
In-Ground SECA System C Test Mechanization

- System C assembly contains three stack module sections. Each contains three Gen 3 stacks connected in series. The three sections are then connected in parallel.
- Each Gen 3 stack provides approximately 30 VDC and up to 60 amps for 4.5 kW gross power per section and 13.5 kW total electrical output
- Electrical, mechanical, and instrumentation connections are made between sections
- The overburden section contains heat exchanger and routings for fuel and air in and out, power, and instrumentation



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System C Integration Test Site at Colorado School of Mines

System C Test Site Development

35 ft bore hole

32 ft liner installed

30 ft of HEX + stack modules assembled and installed down hole

Stack Module Installation for In-Ground Test

System C Integration

- All components were installed in October 2014 at the test site outdoors on the Colorado School of Mines campus
- The stack modules, integrated heat exchanger, and wellhead were assembled in the 32 ft borehole
- A trailer with test stand, controls, and supporting equipment was connected to the system
- Start up protocols and operating protocols were developed
- The ATR reactor was placed as close to the stack modules as possible to minimize heat loss
- Natural gas and electricity were provided by CSM, remainder of service was local to the test site

Well Head and HEX

Well head suspending the stack modules from the surface

Interior of the HEX, assembled into outer housing and coupled to stack modules

Reformer Development

Reactor

Control cart

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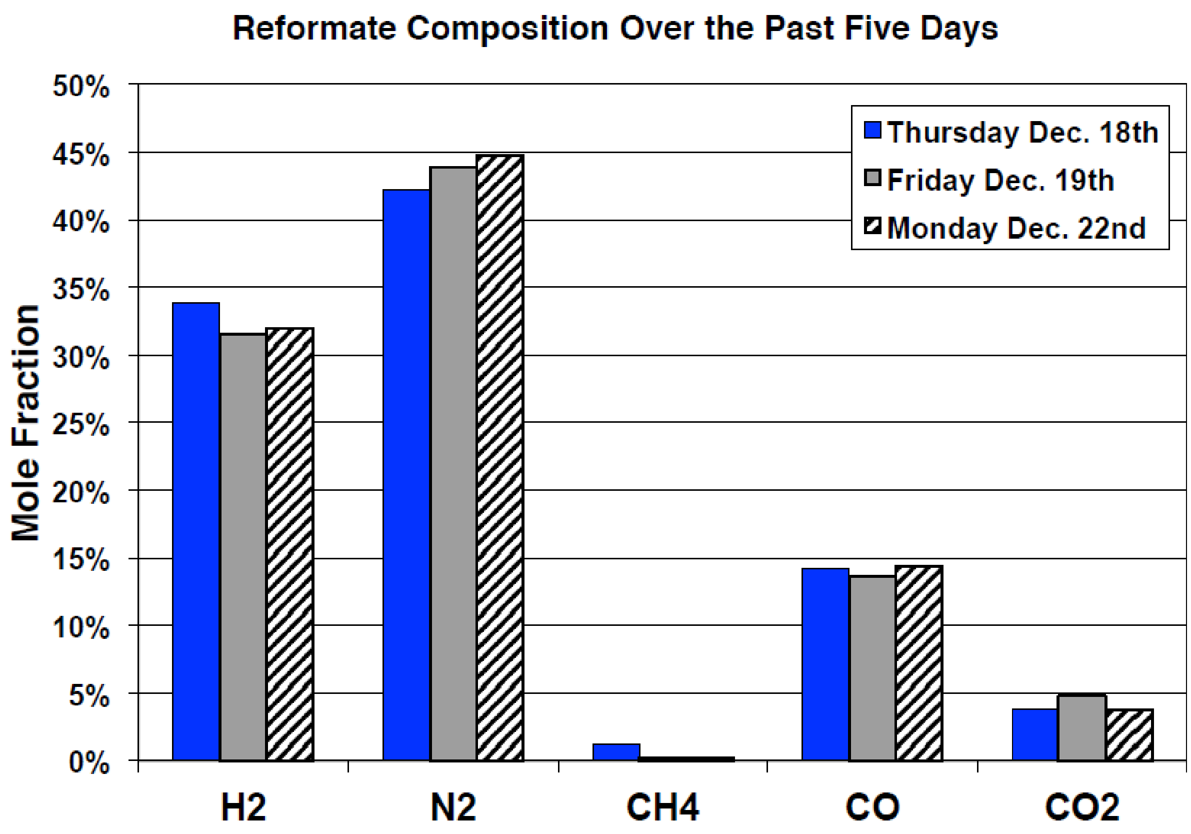
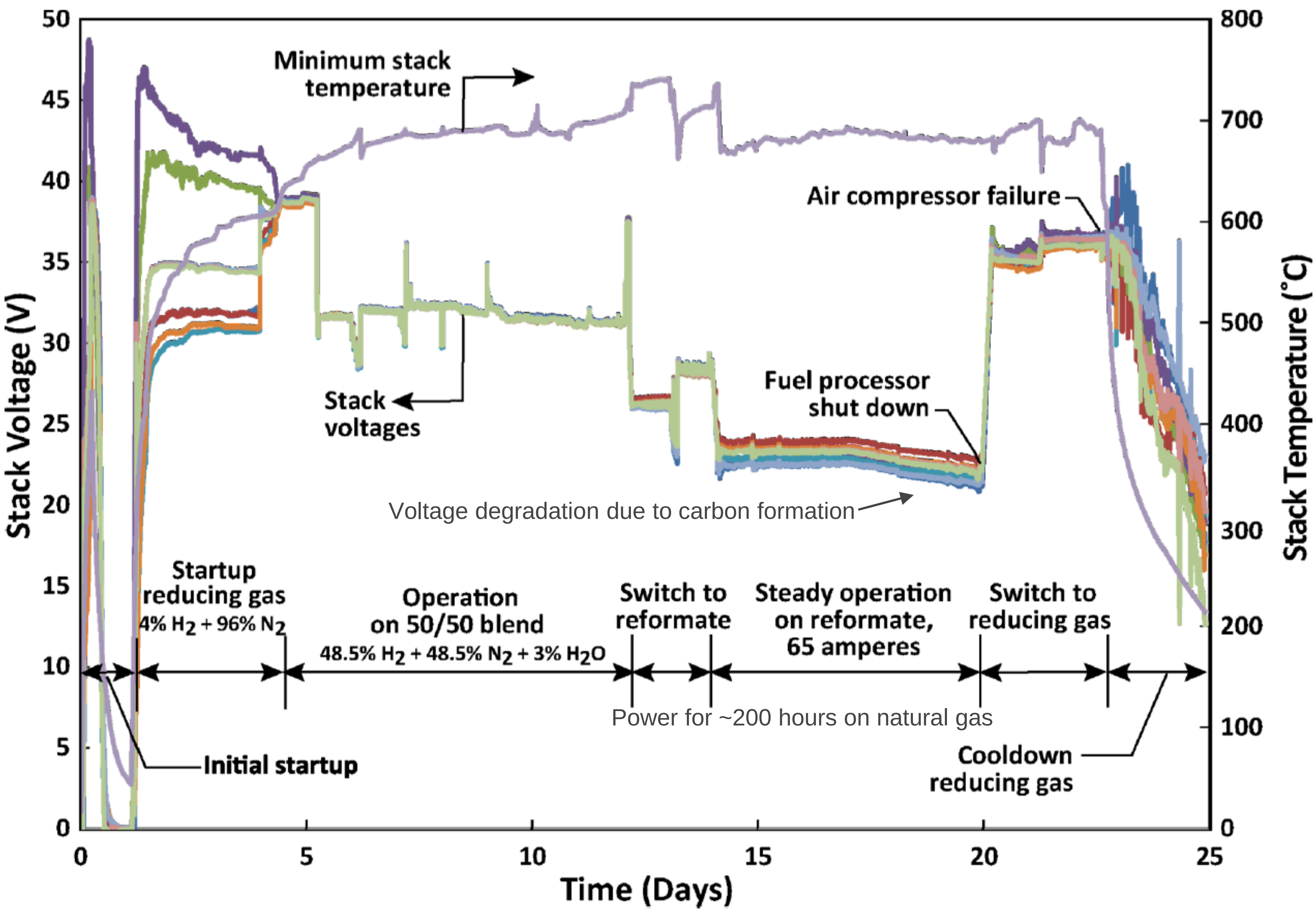
Reformate Composition Stability for In-Ground System Test



Test System C Operational Results



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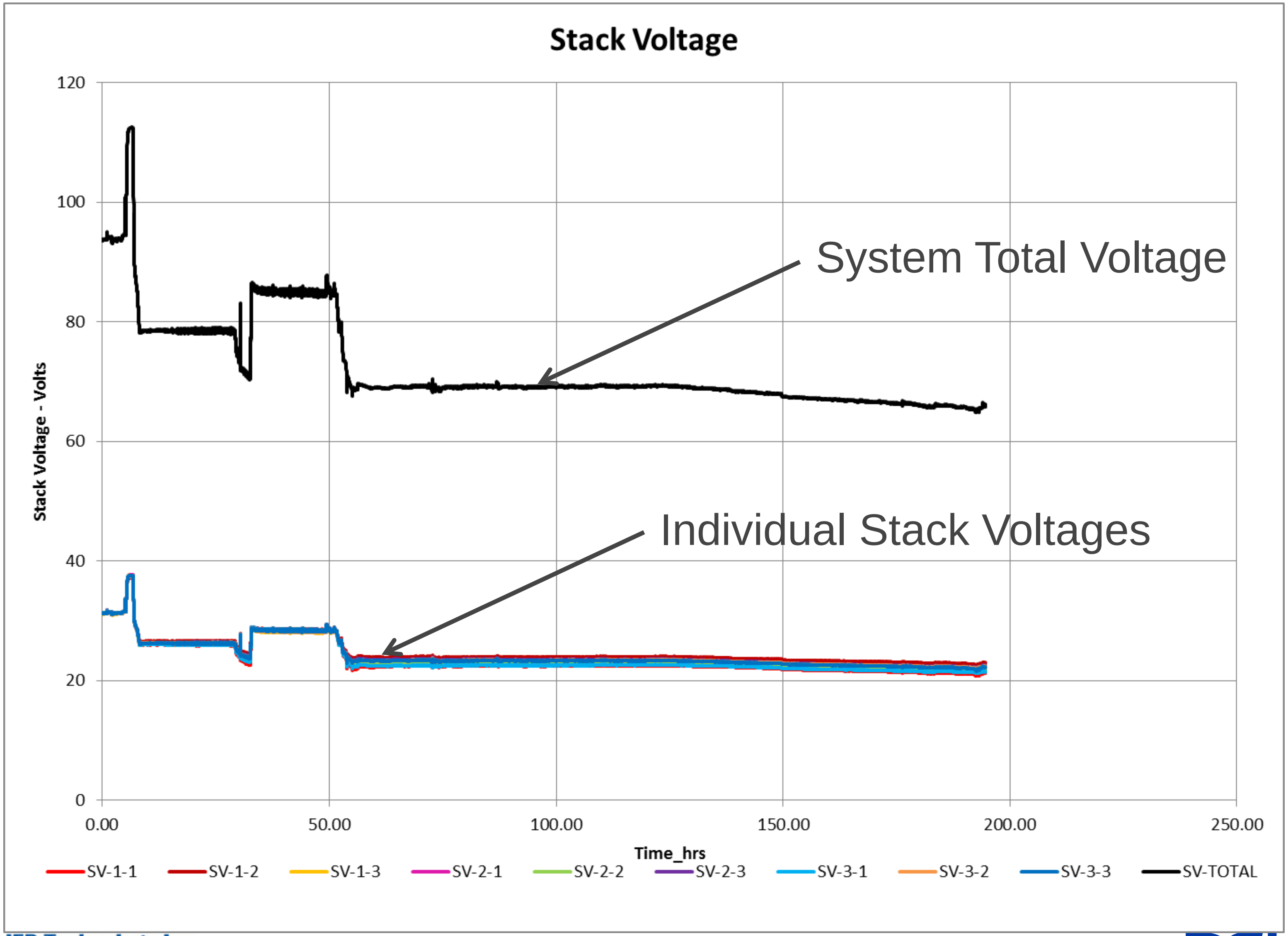
SECA Test System C In Ground Stack Performance



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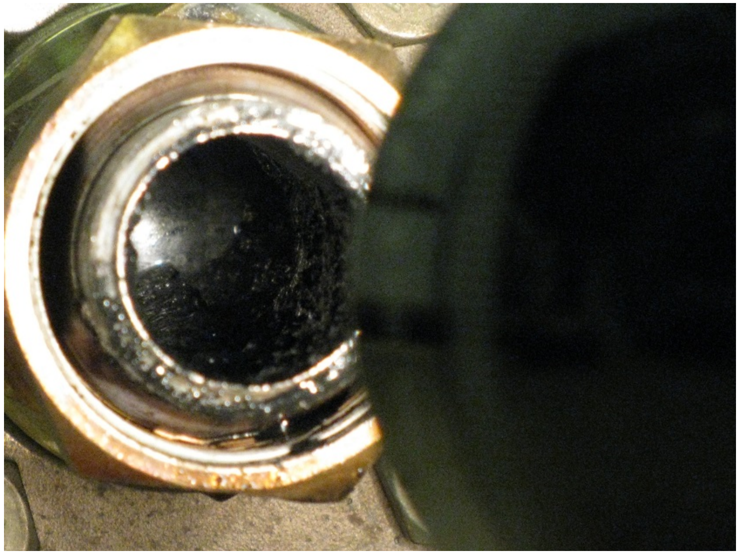
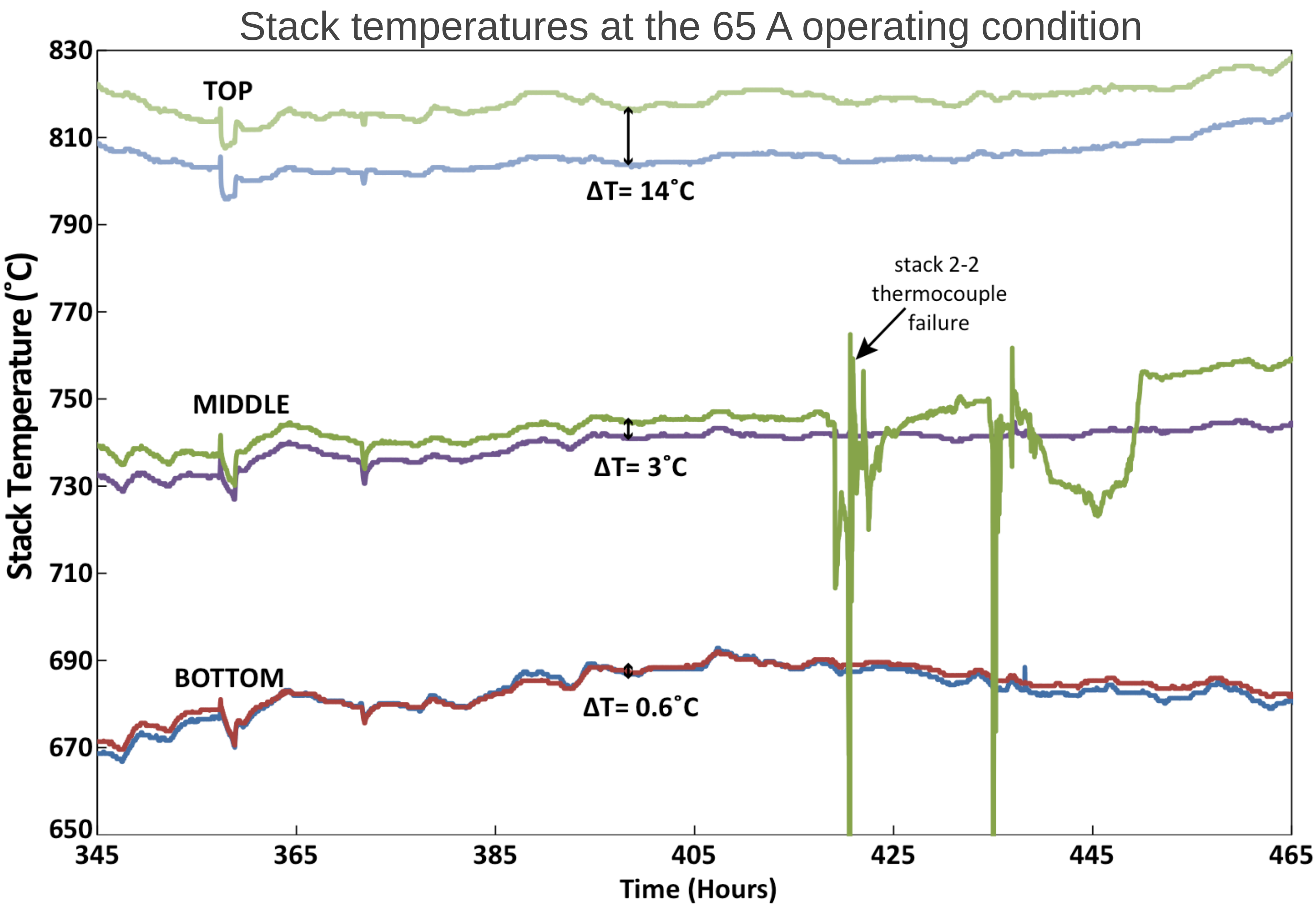
Carbon Formation Limited System Test Duration



Carbon build-up on bypass side of reformer.

Carbon build-up on first elbow after the valve

Stack Temperature Gradient From Top to Bottom Modules



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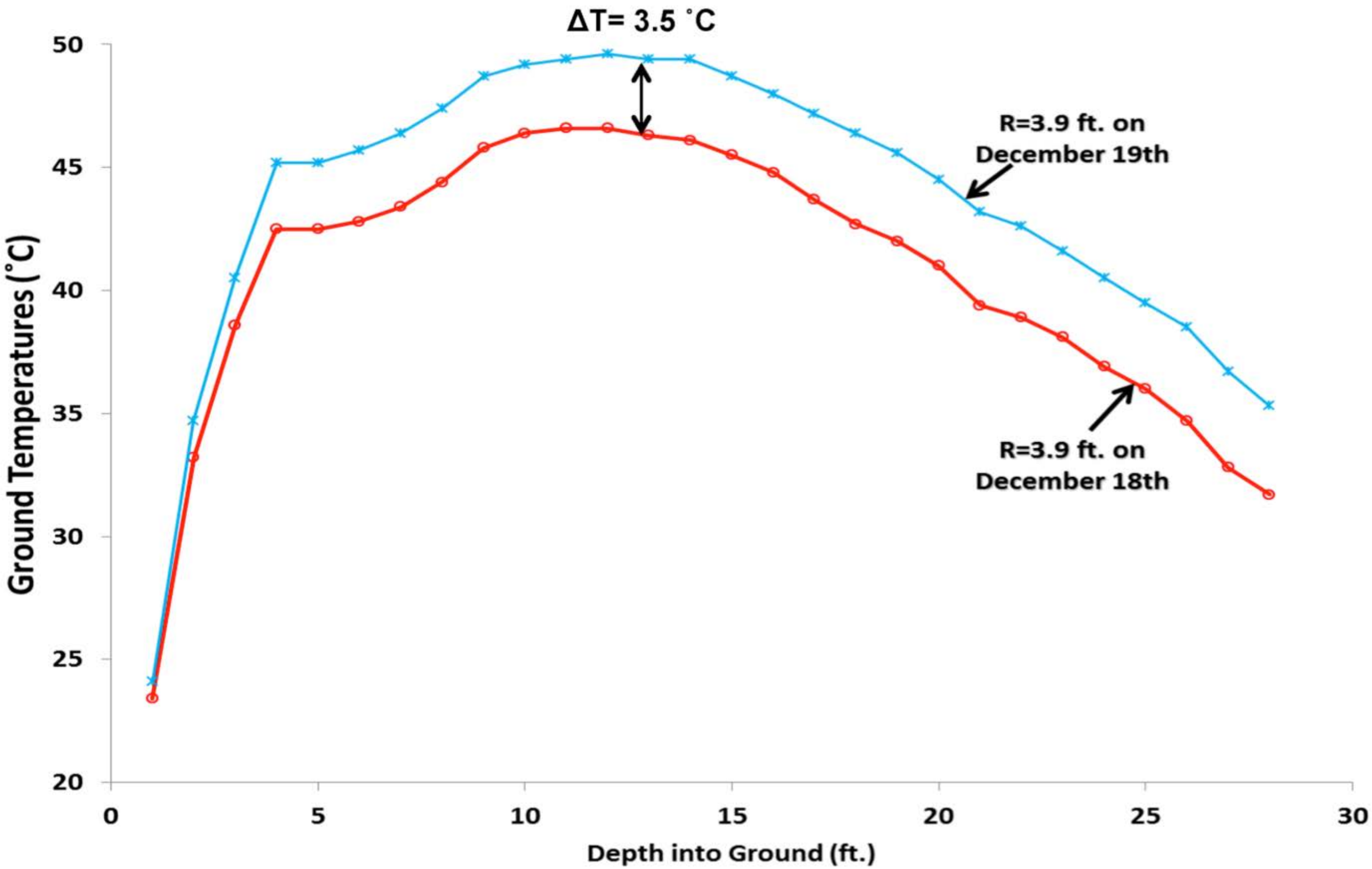
Heat Transferred to the Ground

Geology temperature as a function of vertical depth from the surface measured on consecutive days of testing



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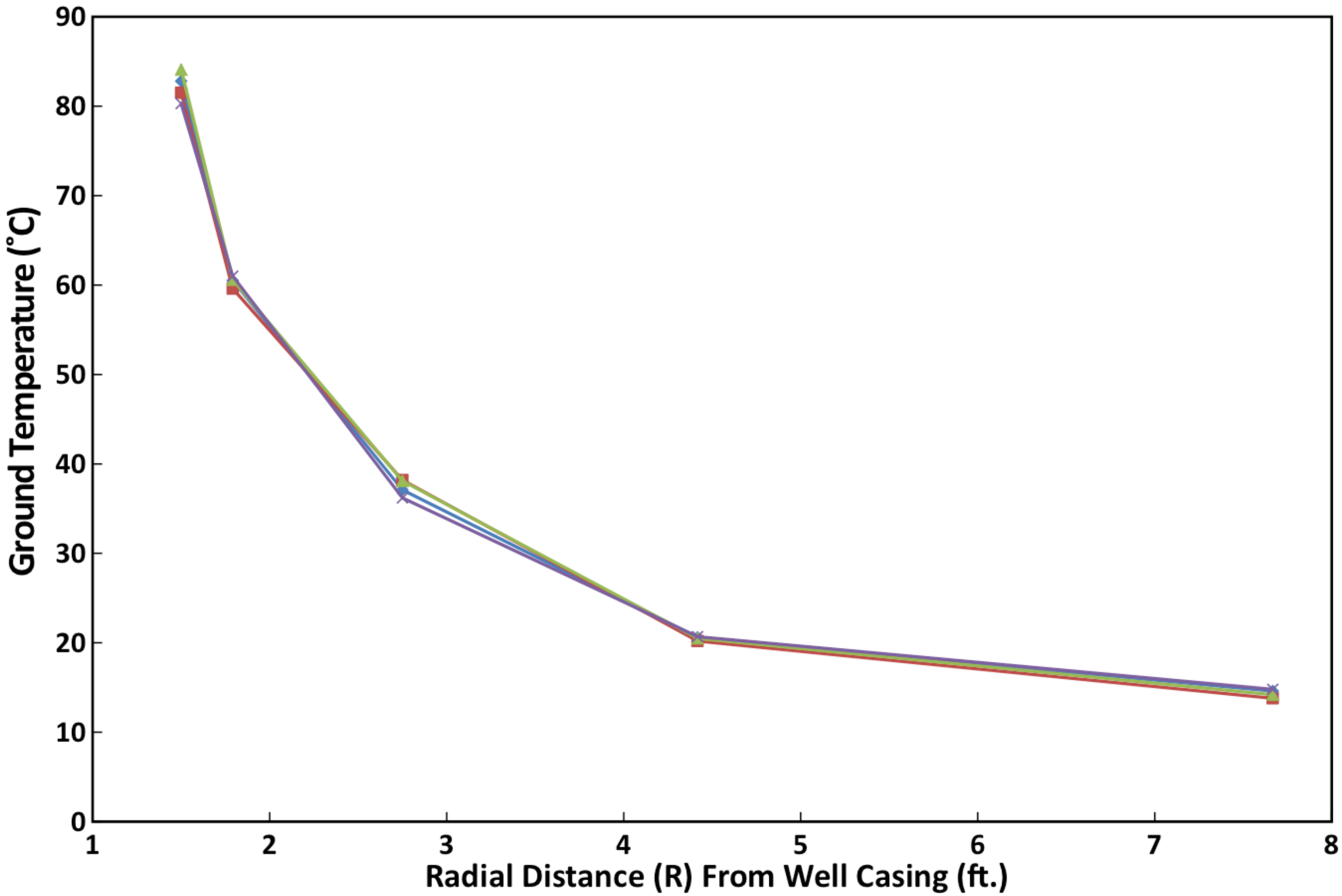
Heat Transferred to the Ground

Geology temperature (12' down) as a function of radial distance from the sidewall of the test assembly



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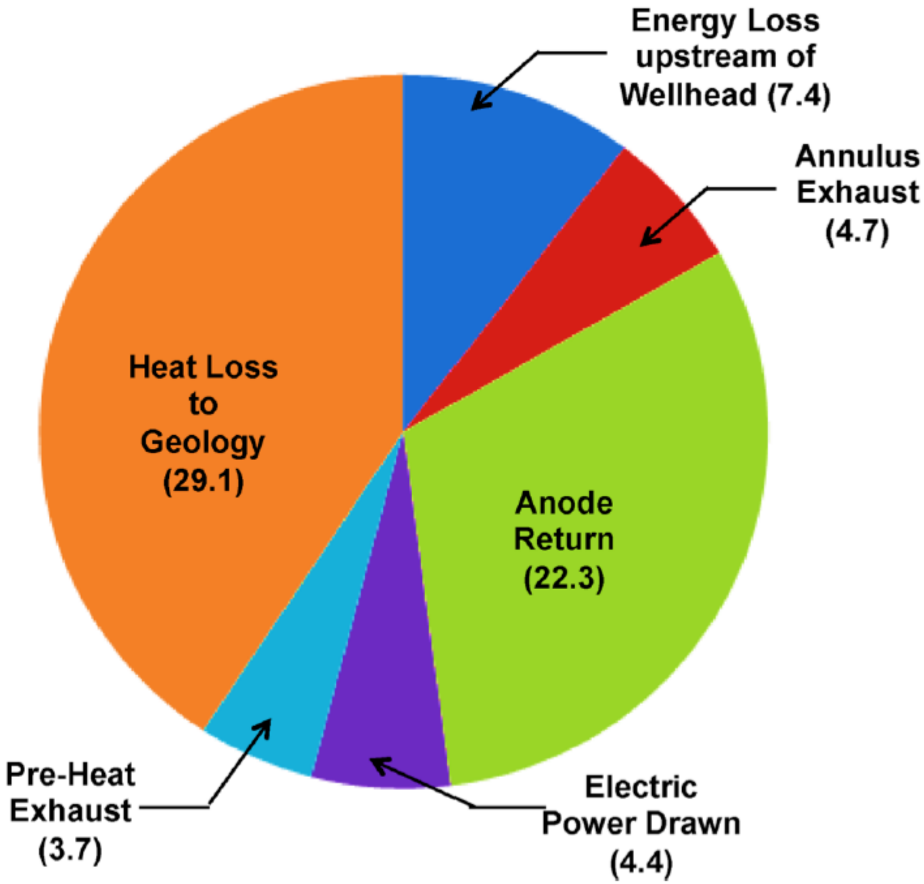
Test System Energy Distribution Summary at 65 A Operation



Test System C Challenges

- Weather was a significant challenge
  - Installing outdoors and exposing the test system and its supply lines to the elements made for a difficult installation and operating environment. Unusually cold weather also presented additional challenges
  - Freezing lines, water intrusion, flooding, water in instruments and controls led to shutdowns and costly repairs and maintenance
- Water occurring at 24 ft below the surface caused issues with temperature uniformity and distribution in the lower stack module
  - The cold ground also presented problems – the lower stack module had to warm much larger volume than the middle and upper sections, contributing to the non-uniform temperature distribution
- Manufacturing defects in some of the equipment surfaced during the testing, leading to unanticipated shutdowns and delays
- Operating an integrated system outdoors for the first time surfaced unanticipated needs and issues
  - Ignition sequences, control limits, unexpected behaviors

Test System C Successes

- Test system was operated in total for nearly 1000 hours and under load on natural gas reformate for about 200 hours
- Validated that the stack module concept can be successfully operated in difficult environments
- Significant operating experience and lessons were learned during the test that will lead to substantial refinements and improvements in the hardware
- Substantial data was collected and still must be analyzed to understand what works and what does not, leading to further improvements in the system and the components, reducing component count, risk and improving reliability

Acknowledgements

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