Planar Solid Oxide Fuel Cells Modules with Radiant Air Preheating

> Presented at the 6th Annual SECA Workshop and Core Technology Review Meeting

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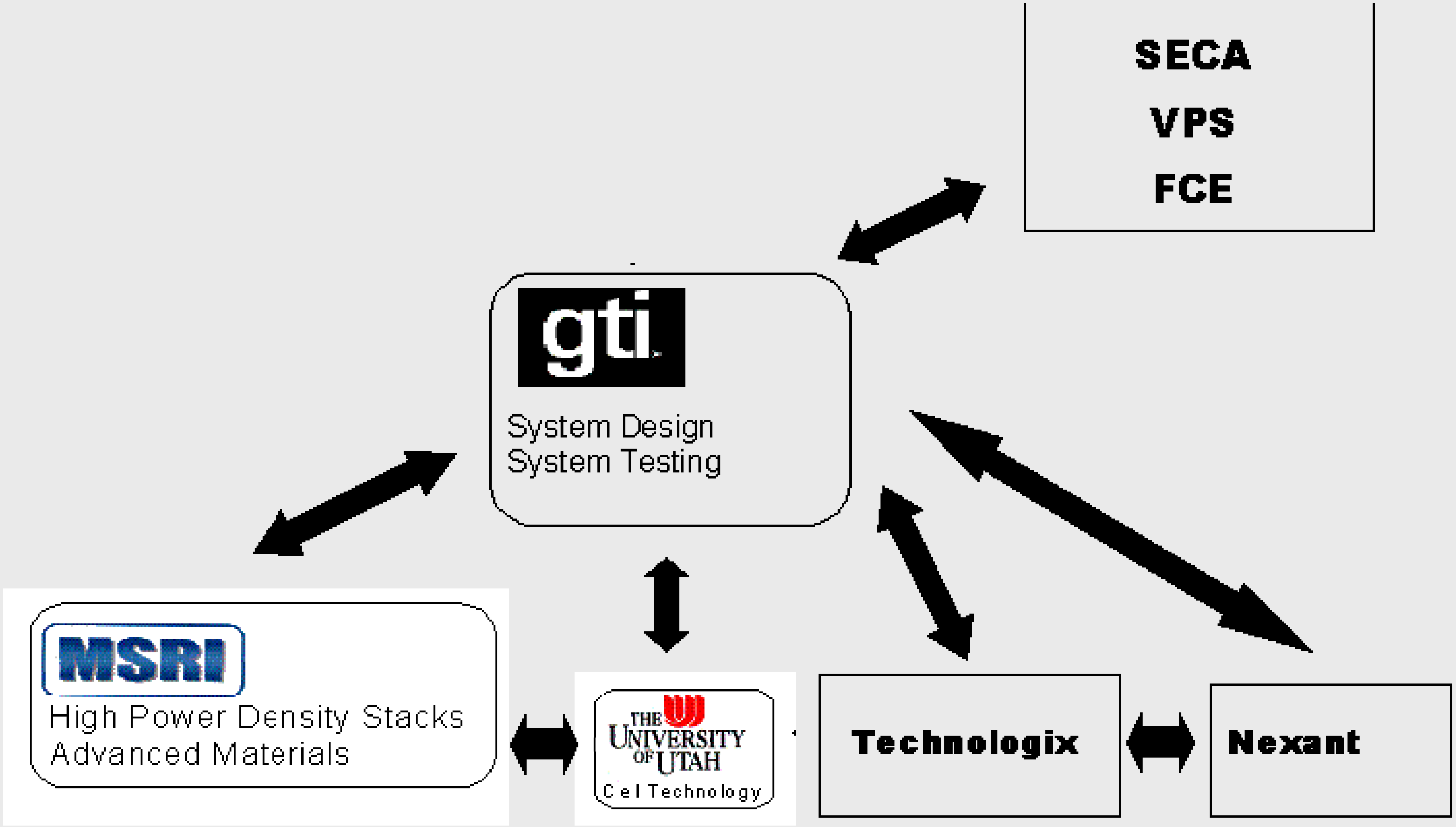
California Energy Commission (CEC), Public Interest Energy Research (PIER) Program



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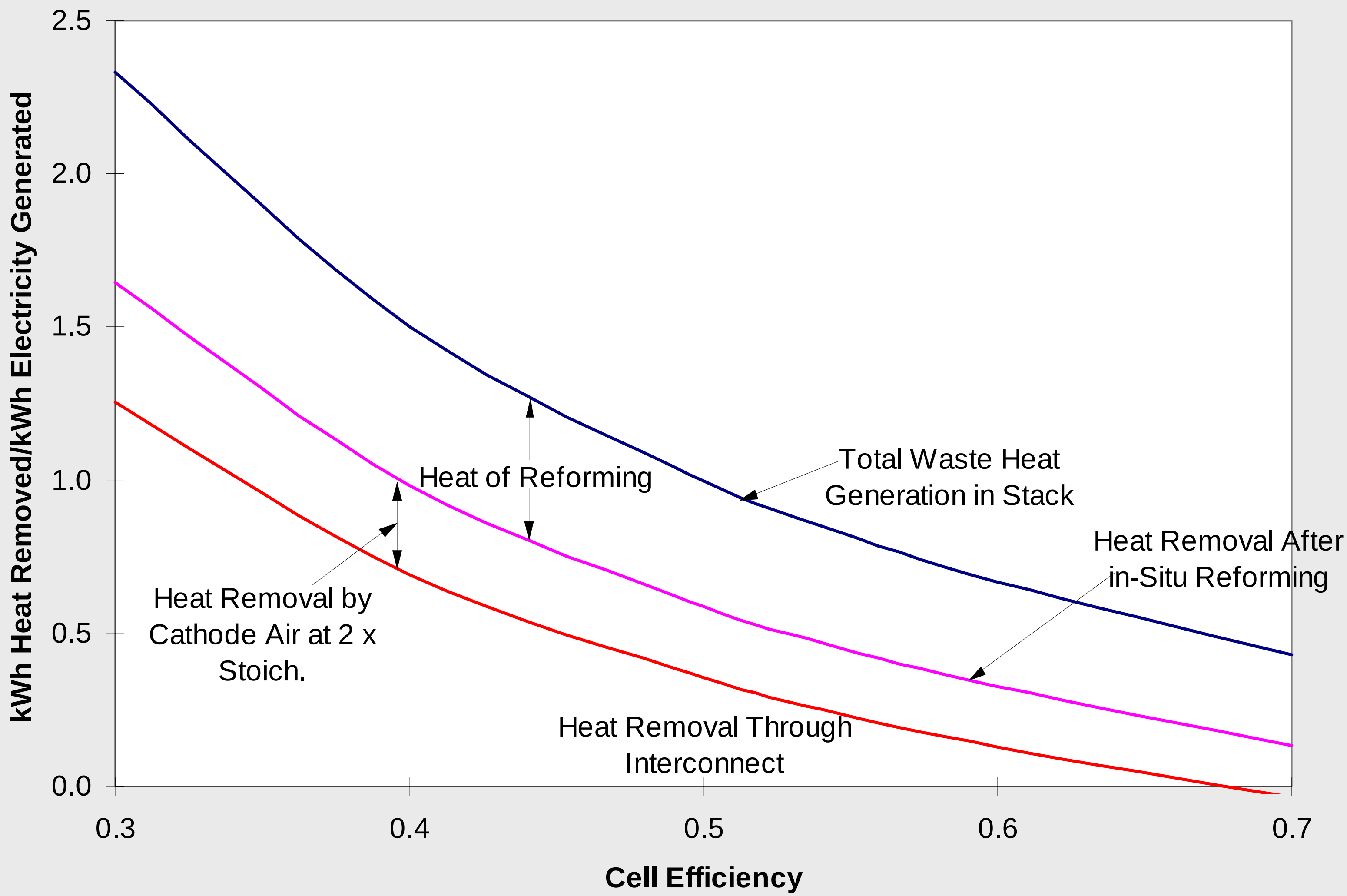
Project Goals

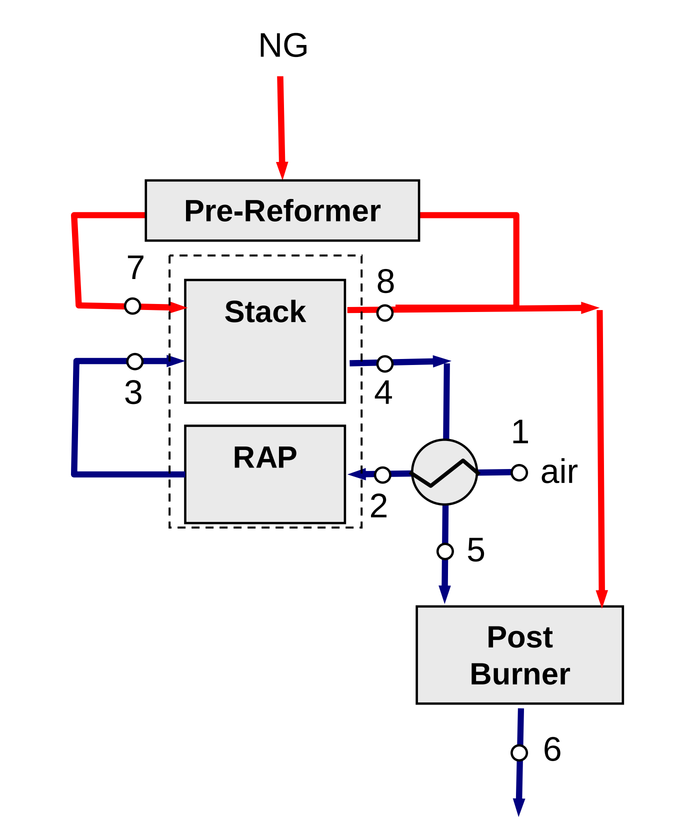
- Construction and testing of 3 sub-scale, core modules that demonstrate:
  - Improved (radiant) heat transfer
  - High-efficiency/high-power-density performance as close to 650^{o}C as possible
  - Up to 2000 hrs of operation with minimal voltage degradation
- A conceptual design of a 10-kW plant based on testing of the sub-scale module

Variation in Available Stack Heat with Electrical Efficiency



Radiant Heat Transfer to Air Pre-heater Panels

- Heat transfer *outside* the cathode compartment
  - Conduct heat to cell edge
  - Radiate to panel (RAP)
  - Convect to air in RAPs
- Post burner is remote to power module
- Reduces:
  - Airflow
  - Pressure drop
  - HX size and cost
  - Blower size and cost
  - Blower parasitic power

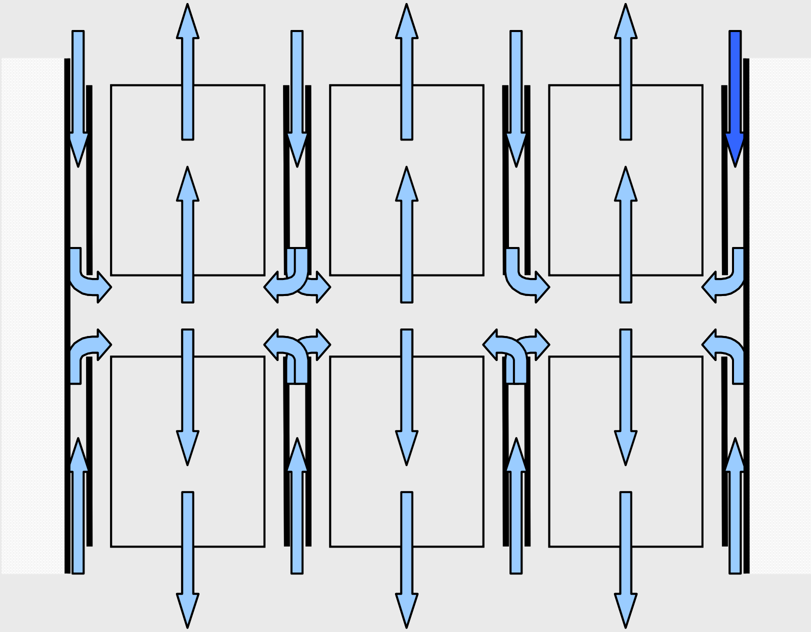


Stack/RAP Approach Offers Multiple Benefits for Cell/Stack Operation

- Higher power density operation
  - Due to faster heat removal and/or thinner airflow channels
- More flexible operation
  - By maintaining stable, low airflow and hot-zone temperature during load changes
  - By compensating for internal reforming heat-transfer effects at low and high power density
- More uniform in-plane and/or axial temperature distribution
- Reduced pressure drop in the cells
  - Improved seal durability

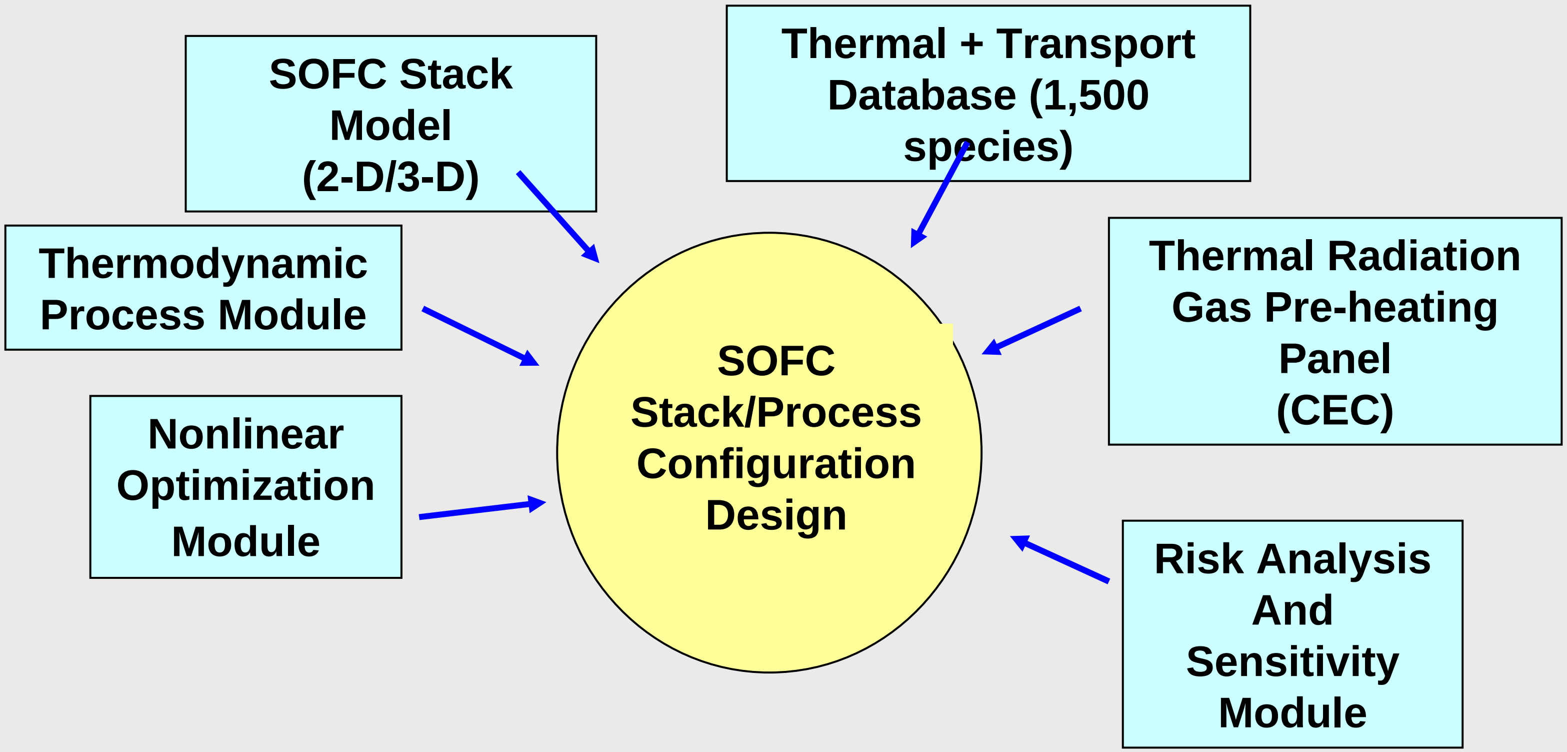
Stack/RAP Approach May Facilitate Compactness, Modularization, and Scale-Up

- Stack and air pre-heater are modularized
- Module arrays have particular advantages:
  - Fewer pre-heater panels
  - Better thermal management (stacks "share" heat)
  - Fewer pre-heater manifolds
- "Active" insulation
  - Assists thermal self-sustainability in small systems
  - Improves compactness

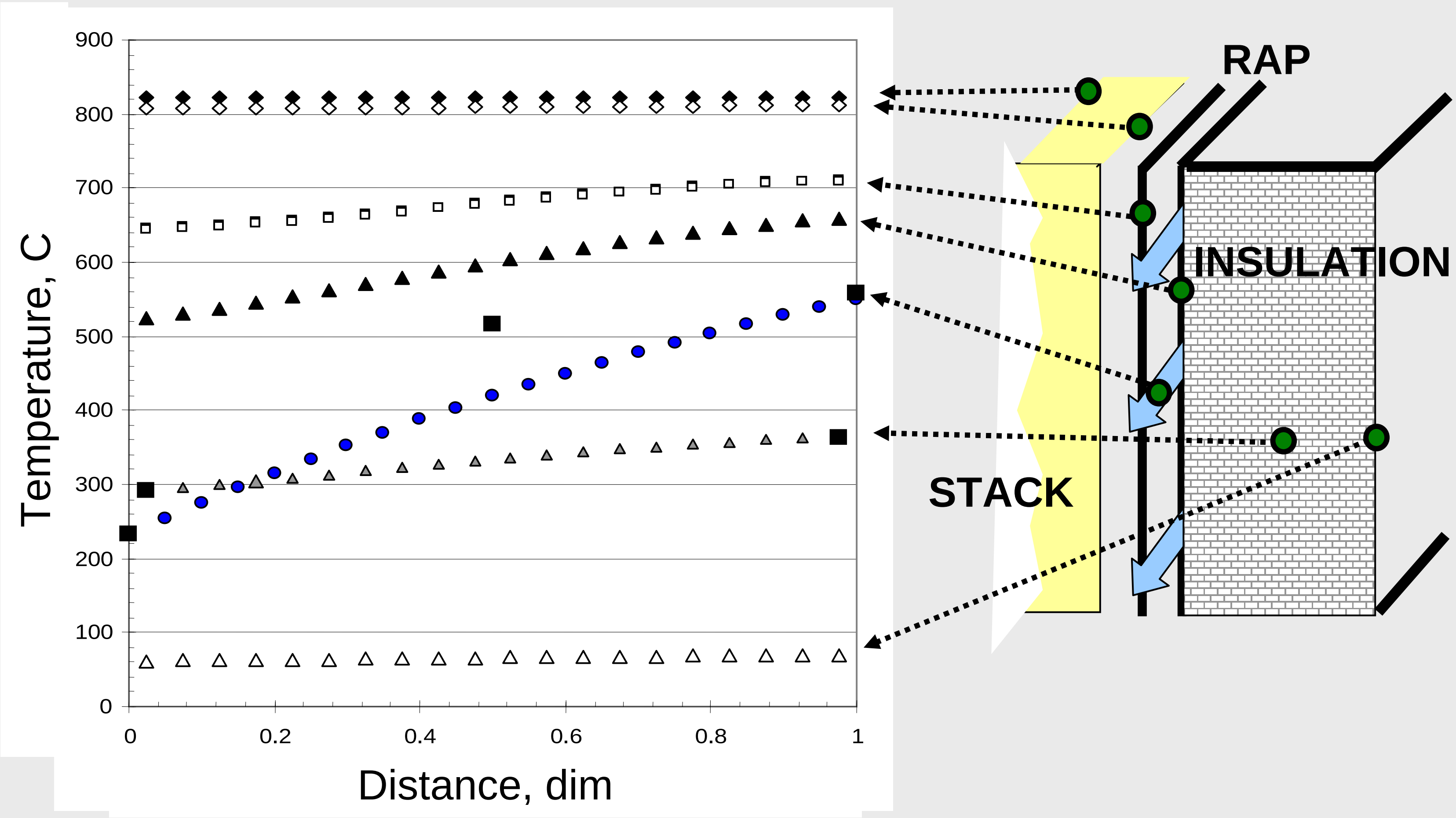


Technologix Model

- Oriented towards configuration design
- ~10^2 - 10^3 times faster than CFD
- Performs reliably

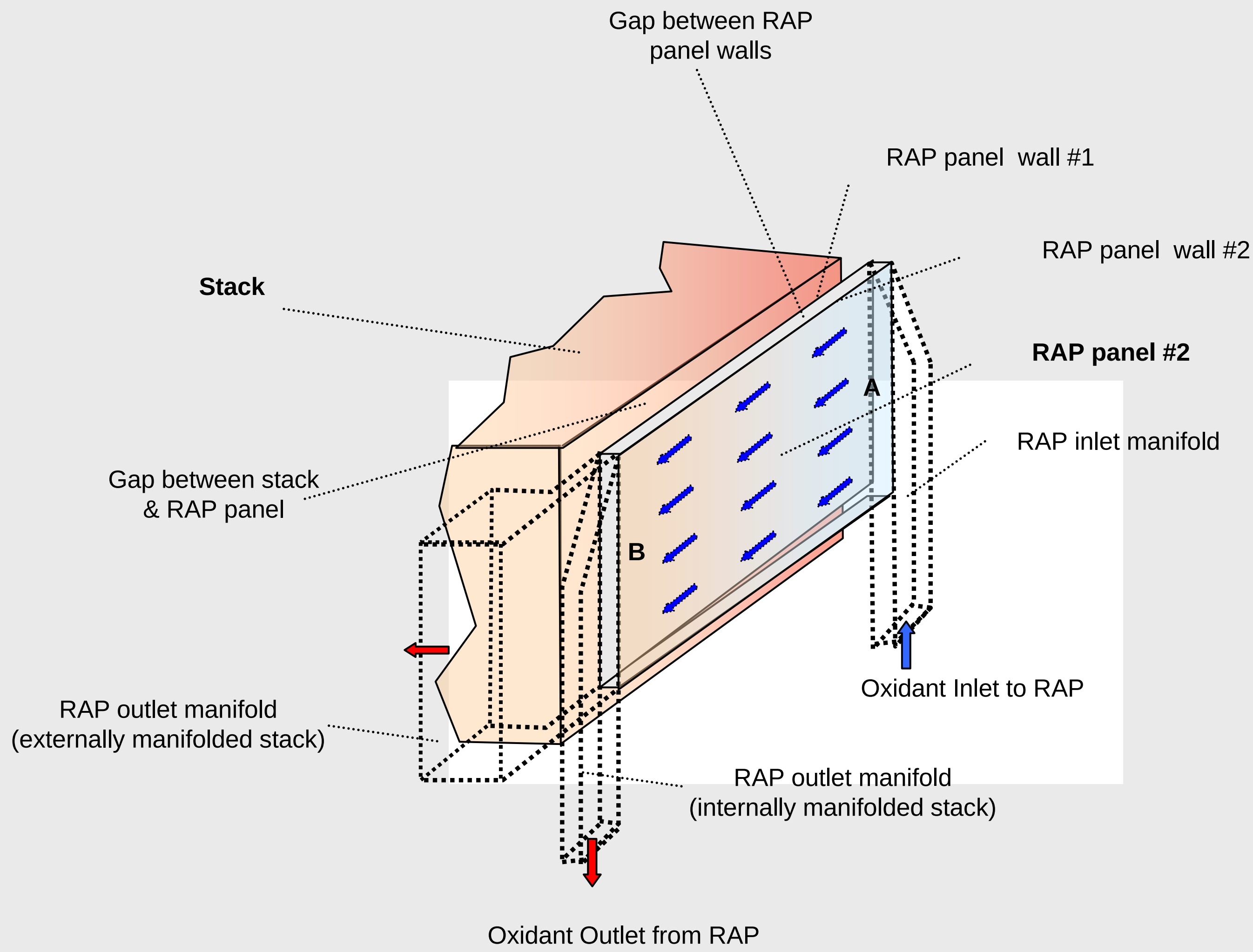


RAP Model Validation



- Measurements

RAP Panel Design



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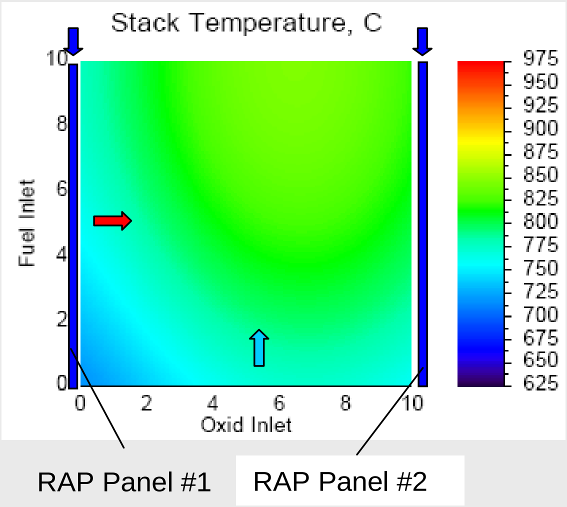
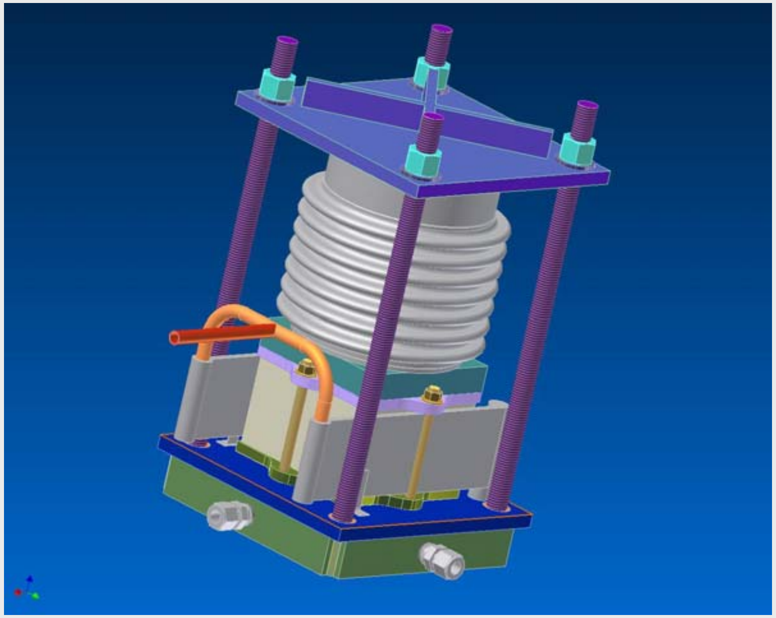
First CEC Stack/RAP Module Design

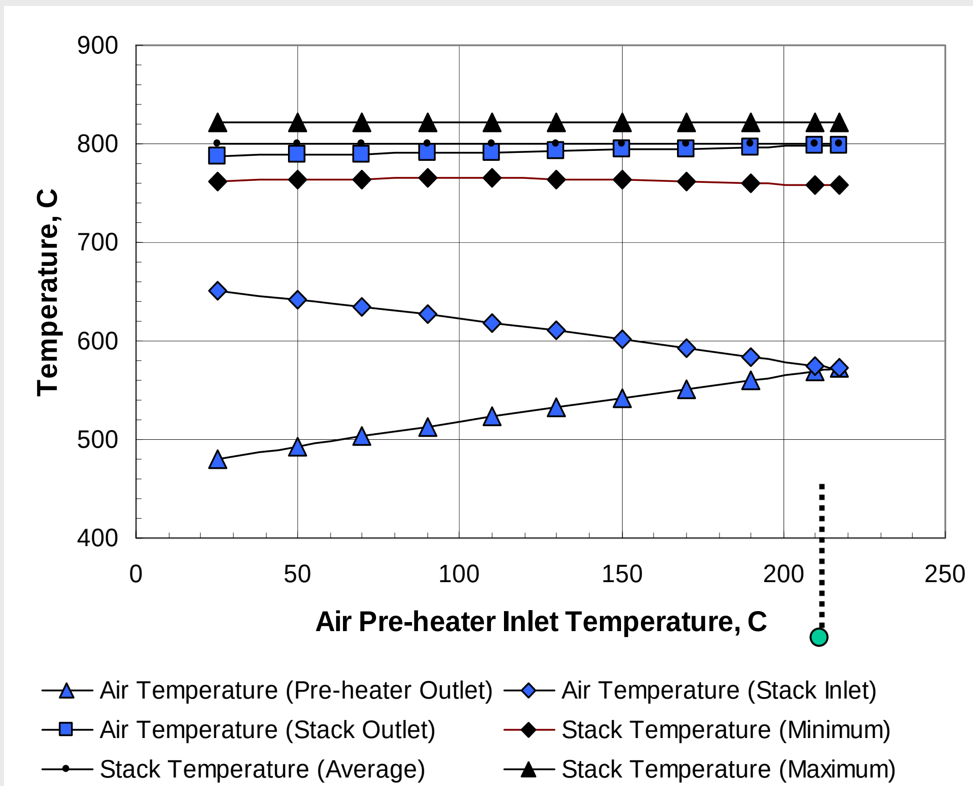
- Internally manifolded, cross-flow stack
- Stack-generated heat radiates to two air pre-heater panels
  - Panels are opposite the fuel inlet and outlet sides of the stack
- Panel airflow:
  - Perpendicular to the stacking direction
  - Counter to airflow in the cells

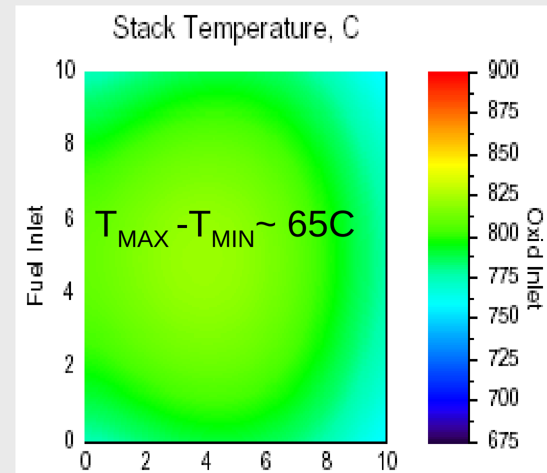


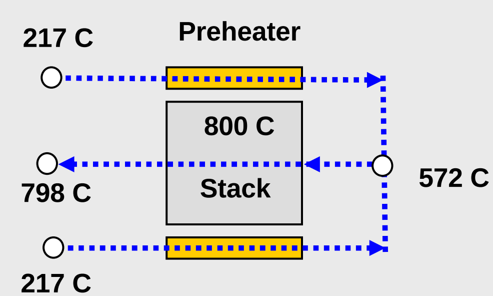


Stack/Air Pre-heater Operation

Configuration: Two integrated air pre-heaters with airflow horizontal and counter to flow in stack. Stack thermal management: 40% IR + 37% RAD + 23% AIR







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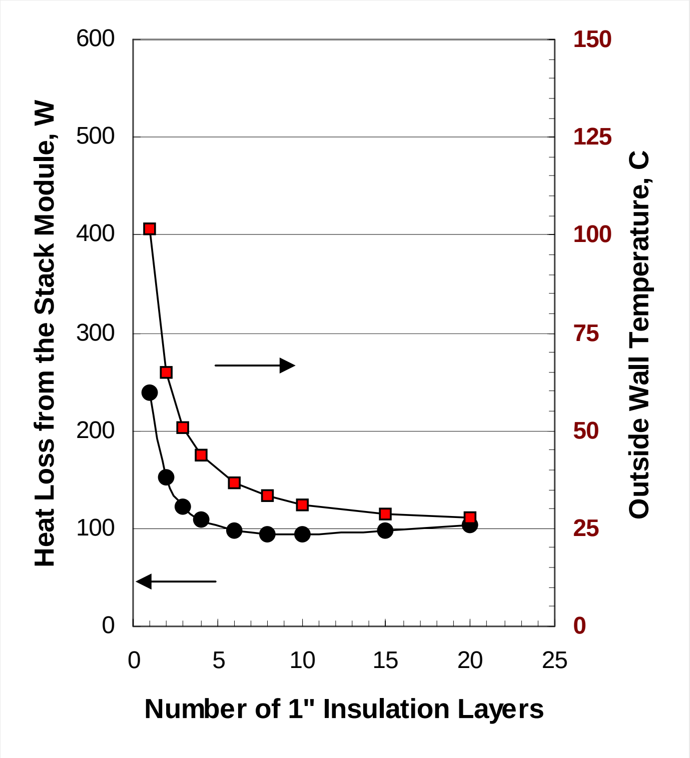
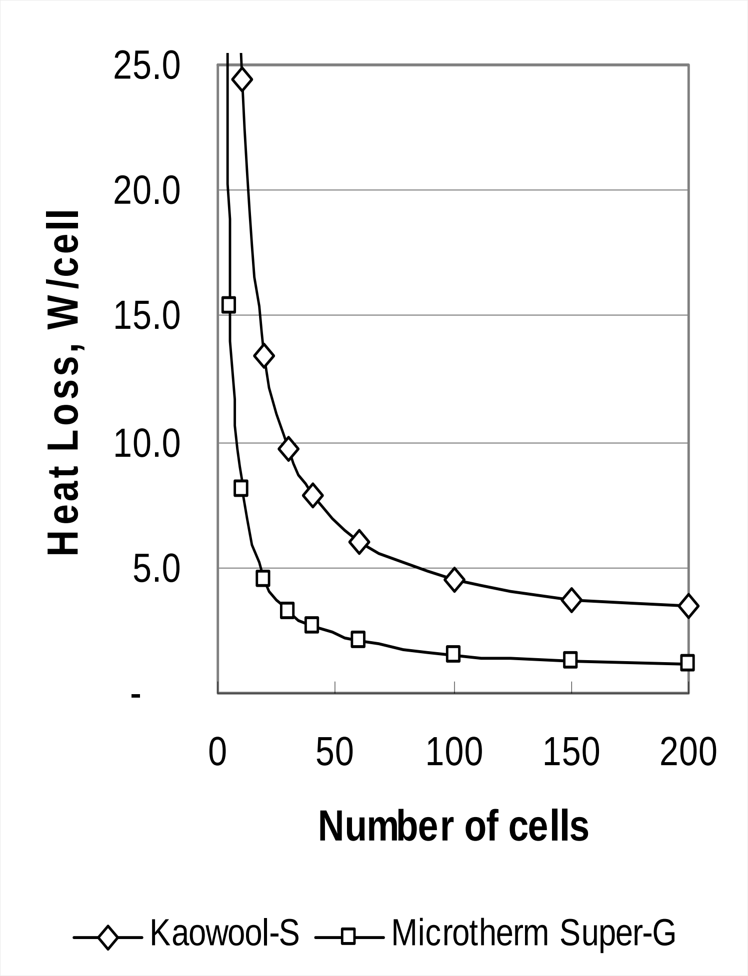
Heat Loss per Cell Vs Increasing Cell # (Stack Size)

Microtherm Super-G

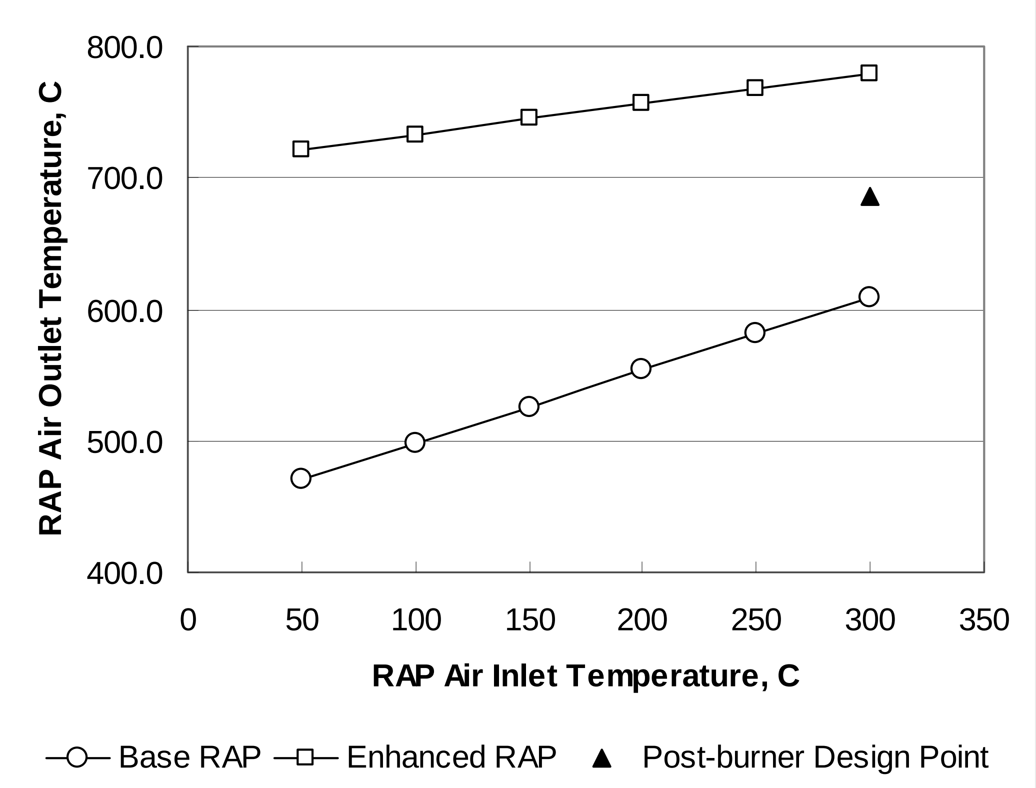


4” thick insulation, 7 cpi



RAP Performance with Heat Loss to the Surroundings

2-panel design, 7 cpi



Enhanced design: steel wool inserted between RAP walls

First Module Development

- U-Utah cell development
- MSRI tested multiple 5, 10, 20, 25, and 40-cell stacks on H_2, simulated reformate, and CH_4/steam at 650-800ºC
- GTI designed the RAPs and plenum

GTI Stack Testing Facility

- Designed for individual, un-insulated stacks at a constant, uniform temperature
  - Location of the furnace heating elements affected the results
- Diagnostic capabilities
  - Blended gases simulate different fuels
  - GC for seal efficiency and blending accuracy
  - Individual cell voltages
  - Stack internal resistance measurement capability

First Sub-Scale Module Test

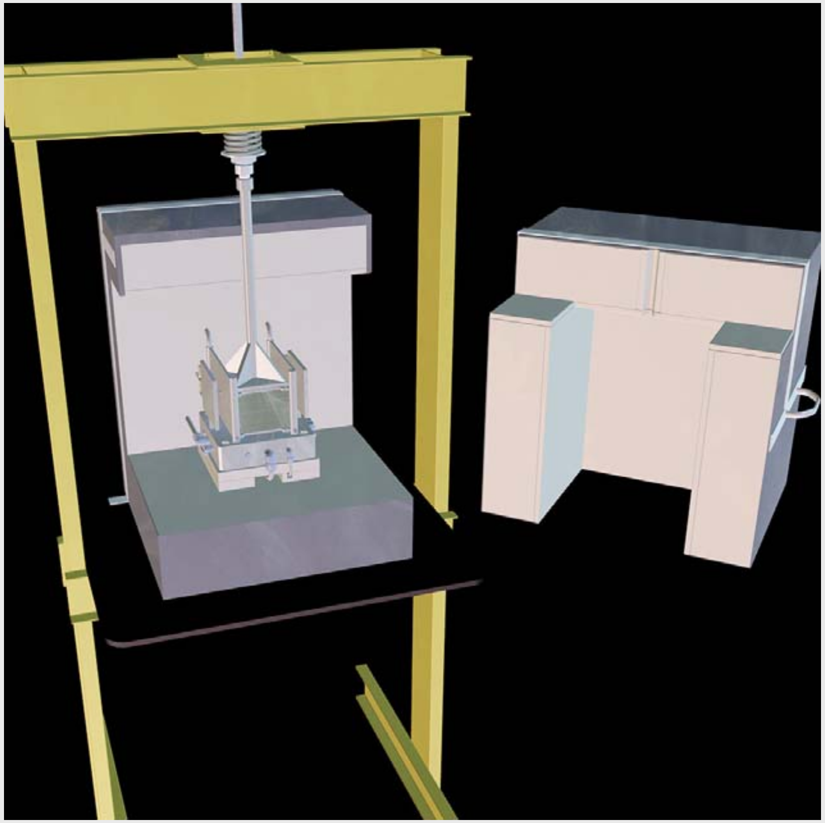
- 40-cell, 100-cm^2 stack
  - Measurements were made with modified seals on 50/50 H_2/N_2 at ~750^{o}C and constant flow and without insulation
- Power output: 550W
  - 1.2 kW peak power measured in Salt Lake City
- Obtained I-V curves
  - Power density ~100 mW/cm^2
- Demonstrated RAP concept
  - ~105^{o}C air temperature rise with only ~120 delta T between stack and RAP
- Operated unit ~3-4 weeks through ~5 thermal cycles

Second Module Design

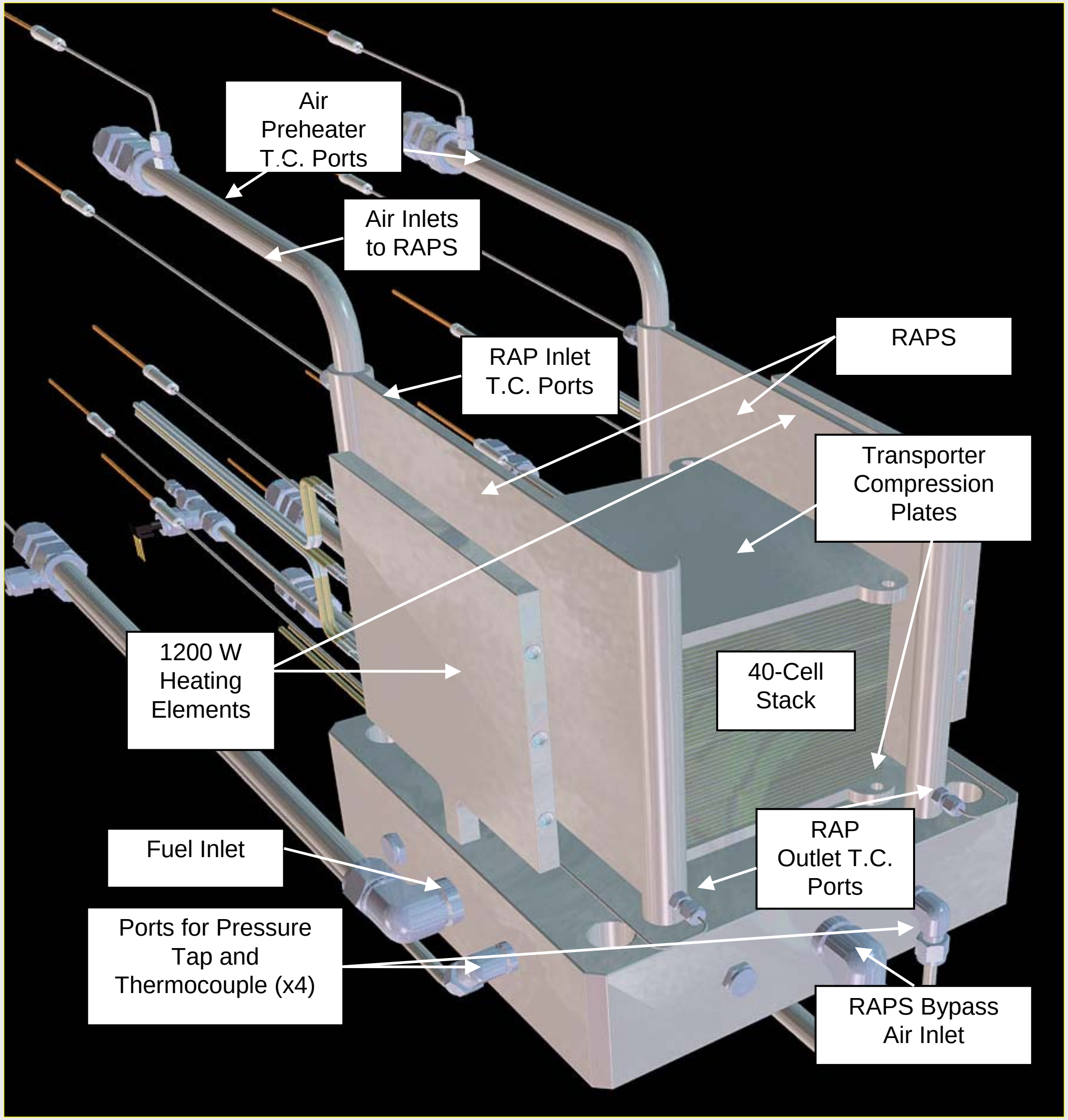
> Stack/RAP module is
  – Thermally isolated from surroundings
    > Avoids interference from a secondary heat source
  – Thermally self-sustained

> Inlet temperature to the RAPs is adequately controlled

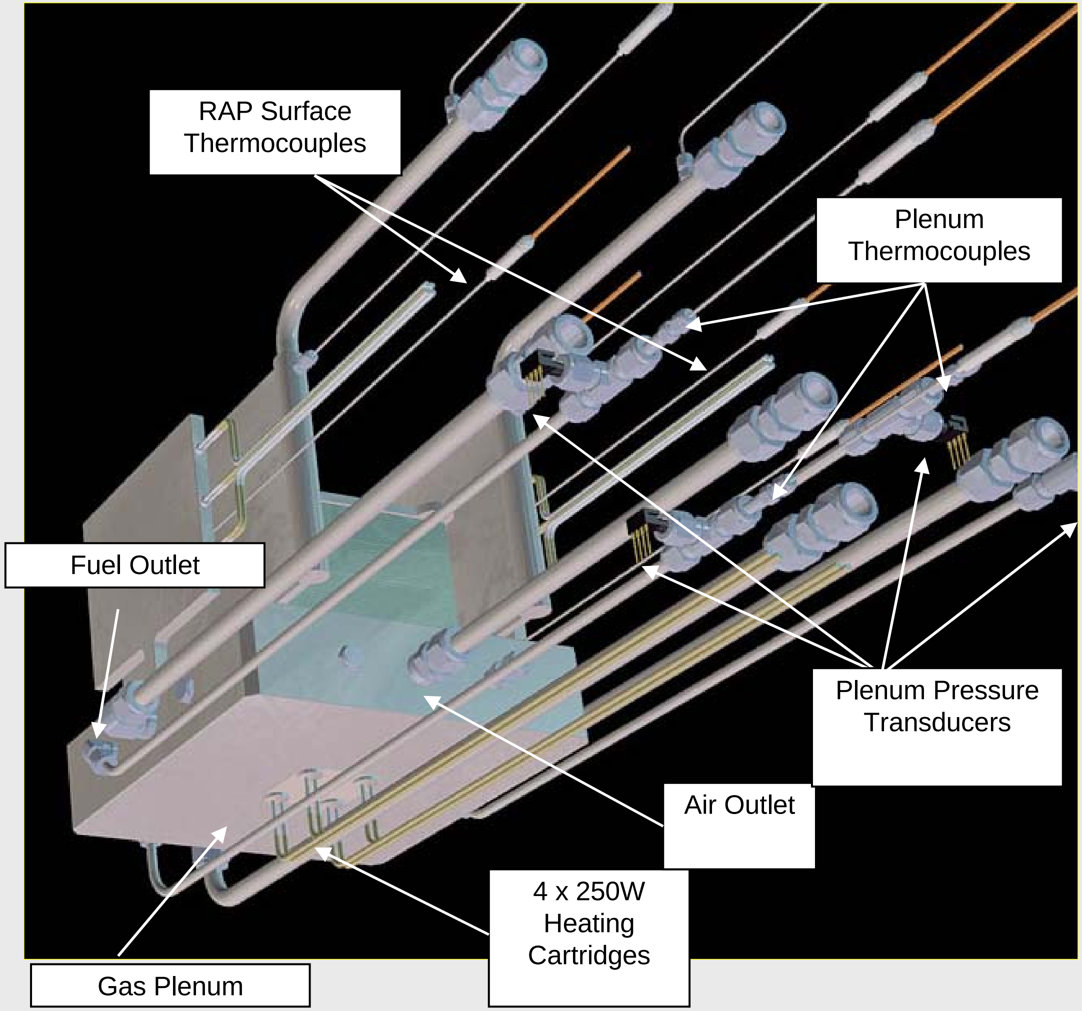
> External hydraulic compression removes minimal heat



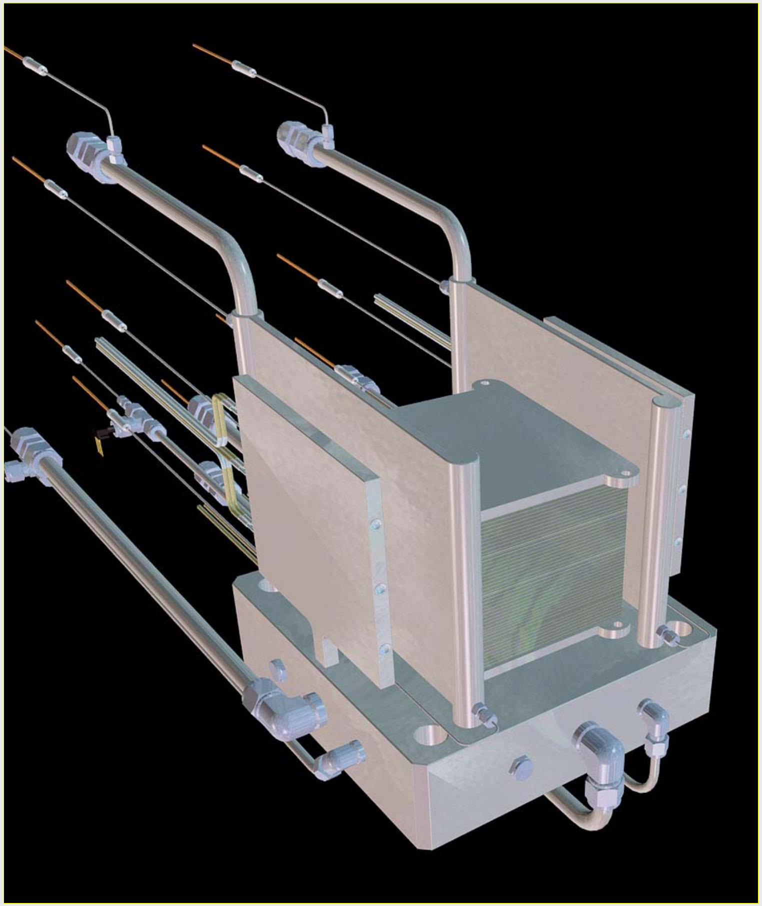
Stack/RAP Test Module Design (from Above)



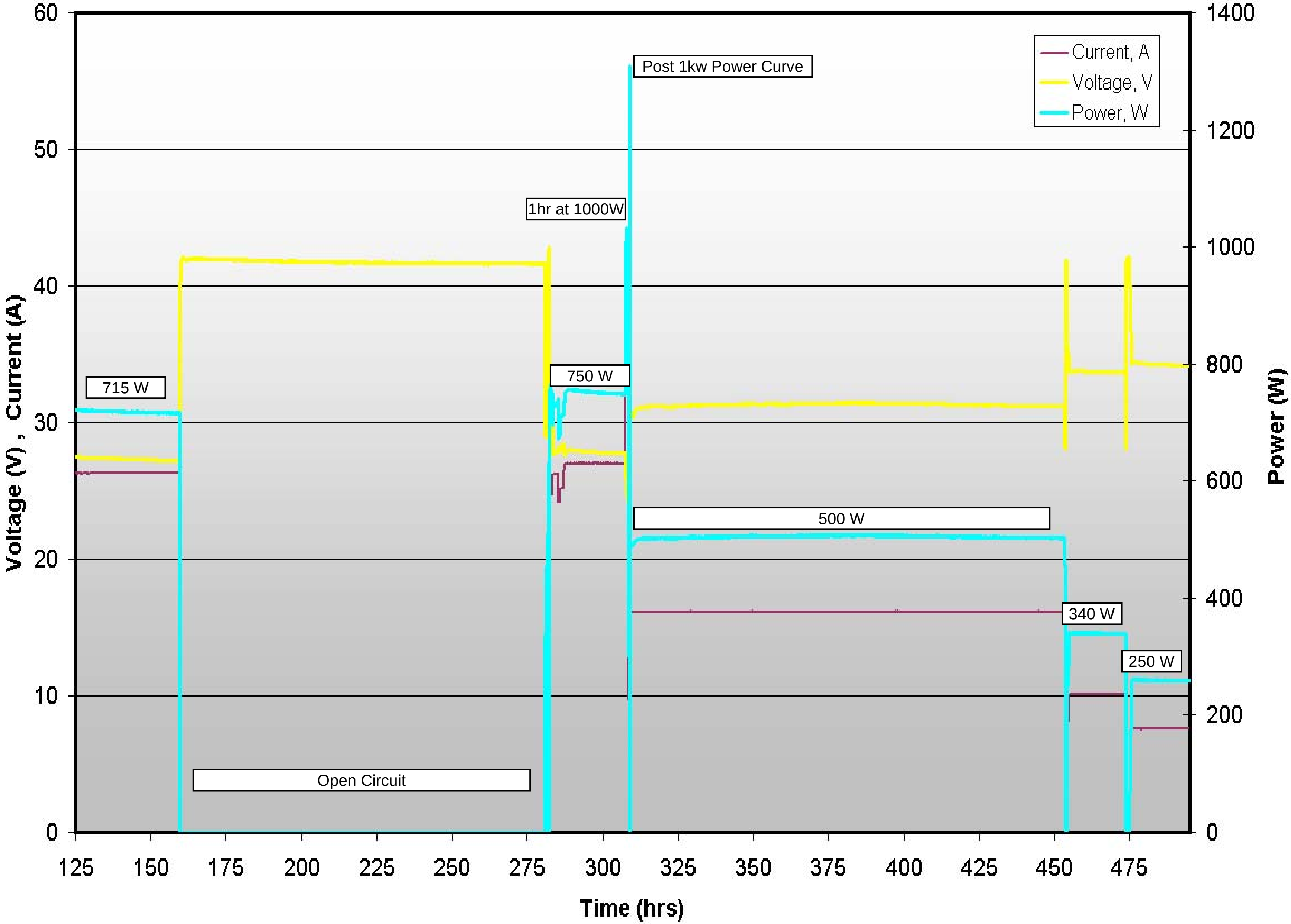
Stack/RAP Test Module Design (from Below)

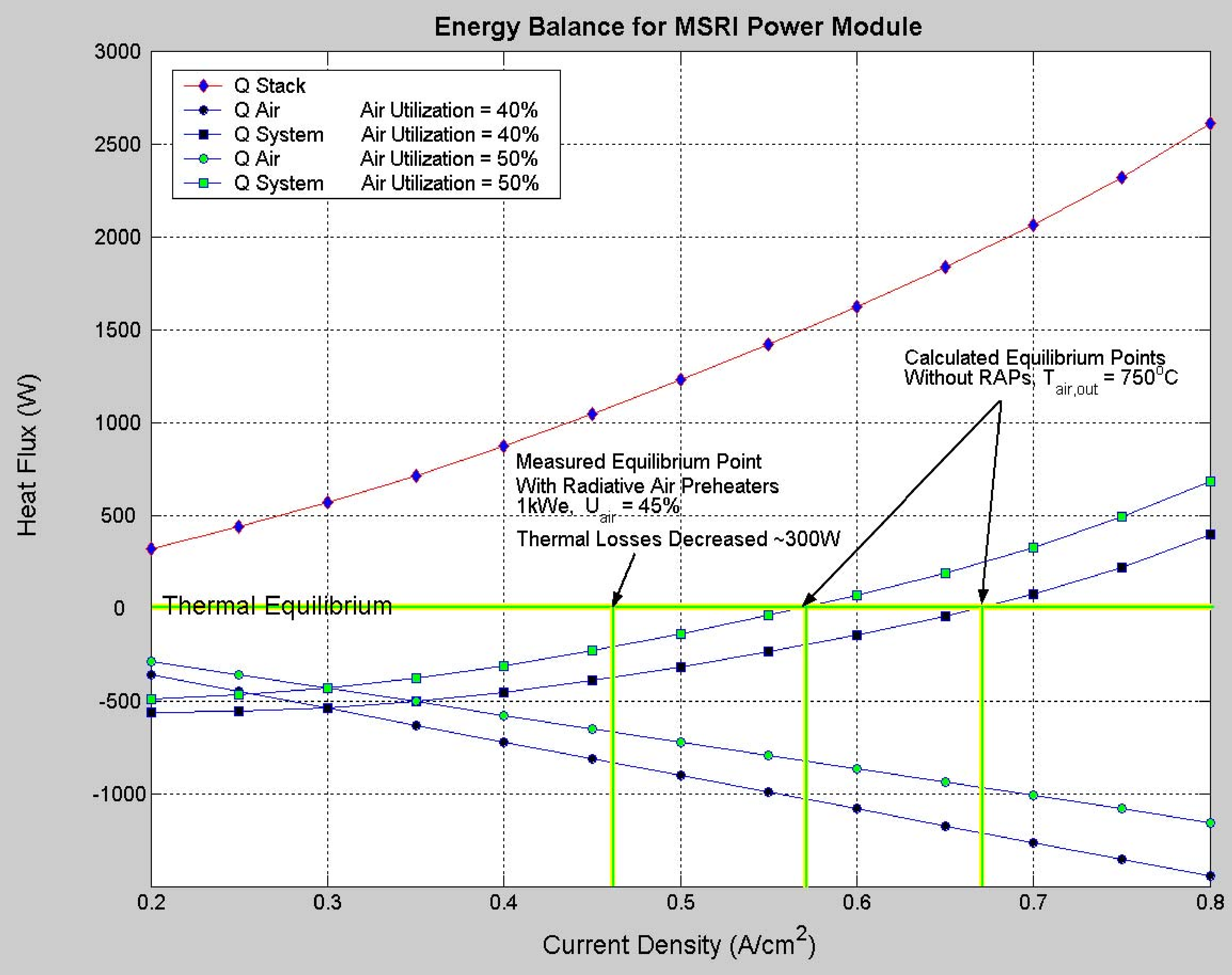


MSRI/GTI Stack/RAP Test Module

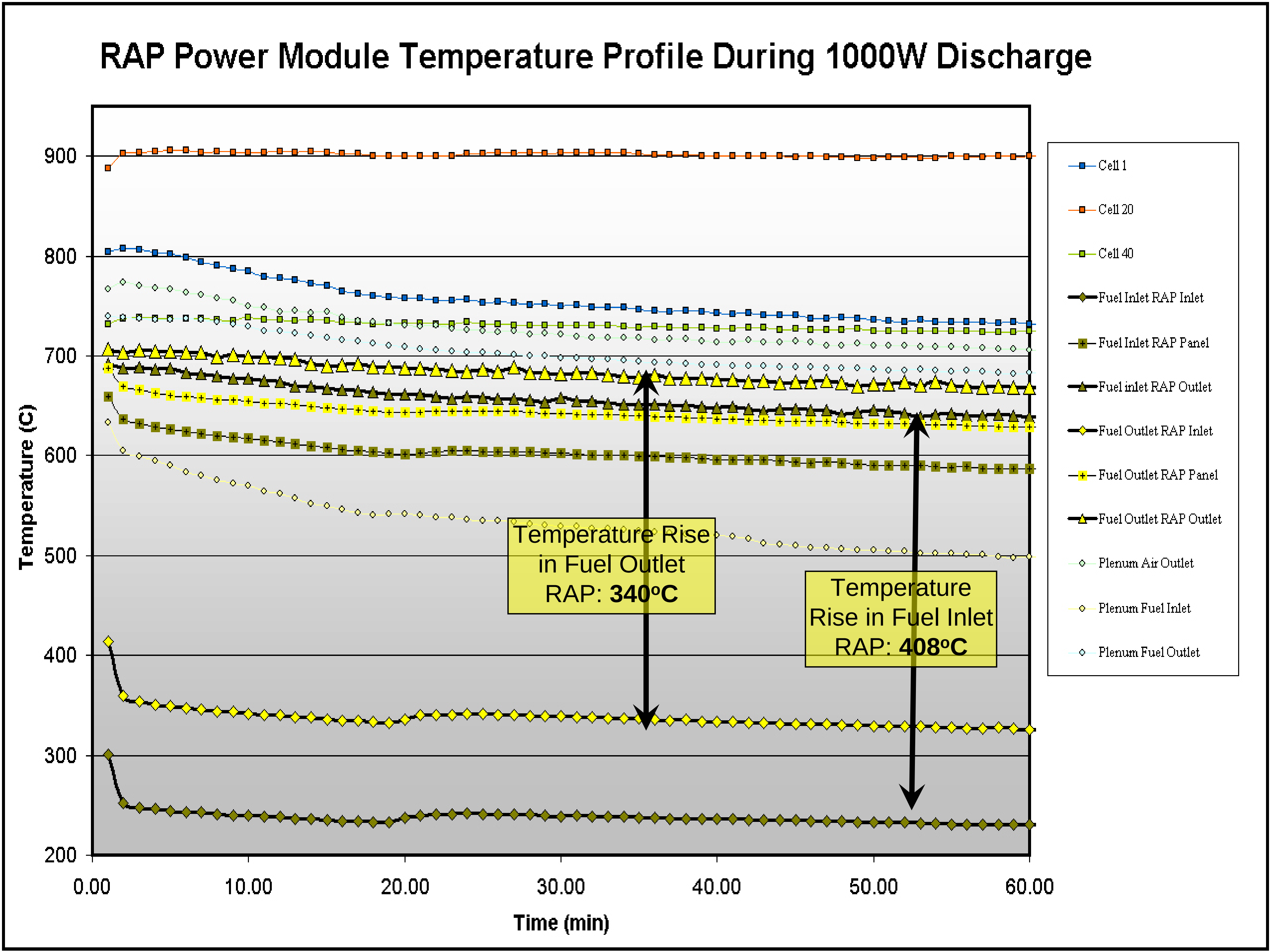


Variable Power Output of RAPs Power Module





Energy Balance for MSRI Power Module
Q Stack
Q Air Air Utilization = 40%
Q System Air Utilization = 40%
Q Air Air Utilization = 50%
Q System Air Utilization = 50%
Calculated Equilibrium Points
Without RAPs, $T_{air,out}$ = 750^{0}C
Measured Equilibrium Point
With Radiative Air Preheaters
1kWe, U_{air} = 45%
Thermal Losses Decreased ~300W
Thermal Equilibrium
Heat Flux (W)
Current Density (A/cm^2)
3000
2500
2000
1500
1000
500
0
-500
-1000
0.2
0.3
0.4
0.5
0.6
0.7
0.8



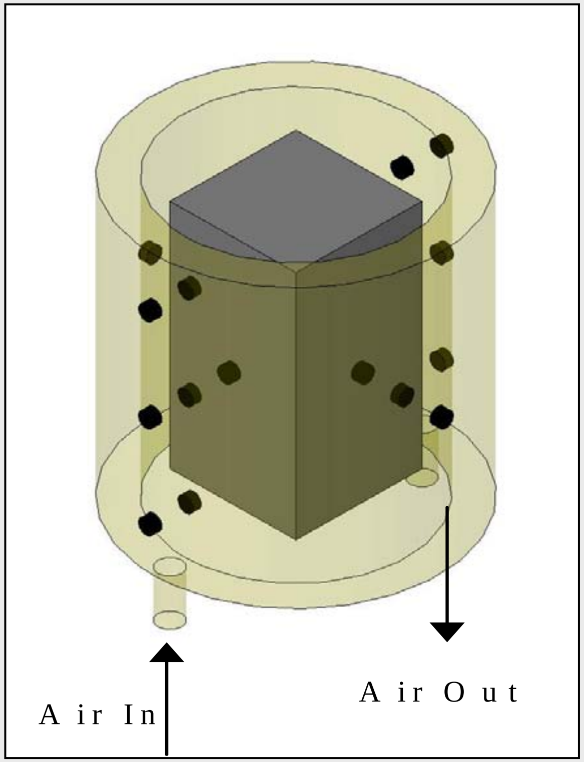
RAP Power Module Temperature Profile During 1000W Discharge
Temperature (C)
900
800
700
600
500
400
300
200
0.00
10.00
20.00
30.00
40.00
50.00
60.00
Time (min)
Temperature Rise in Fuel Outlet RAP: 340ºC
Temperature Rise in Fuel Inlet RAP: 408ºC
Cell 1
Cell 20
Cell 40
Fuel Inlet RAP Inlet
Fuel Inlet RAP Panel
Fuel inlet RAP Outlet
Fuel Outlet RAP Inlet
Fuel Outlet RAP Panel
Fuel Outlet RAP Outlet
Plenum Air Outlet
Plenum Fuel Inlet
Plenum Fuel Outlet

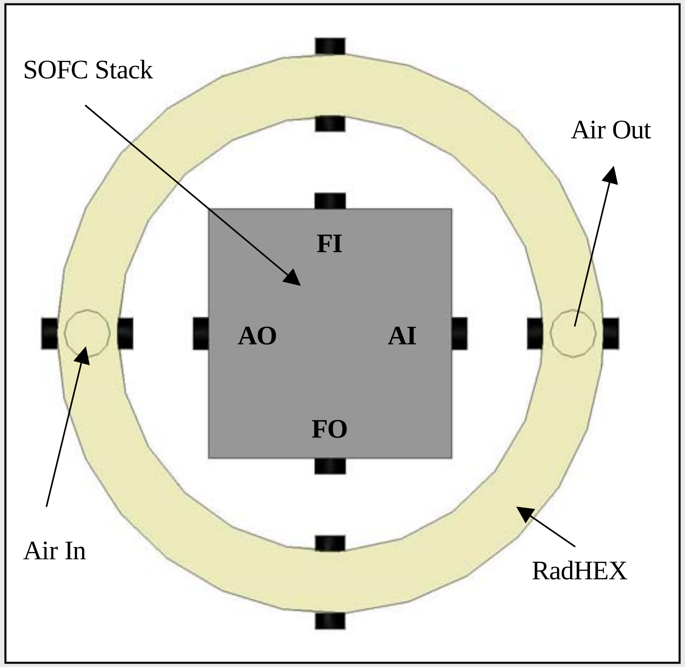
Third Power Module

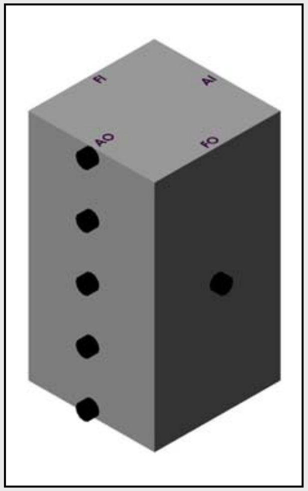
Aurora hot power module without RadHEX

Aurora hot power module with RadHEX

Aurora Thermocouple Layout







Black 'dots' denote thermocouple locations

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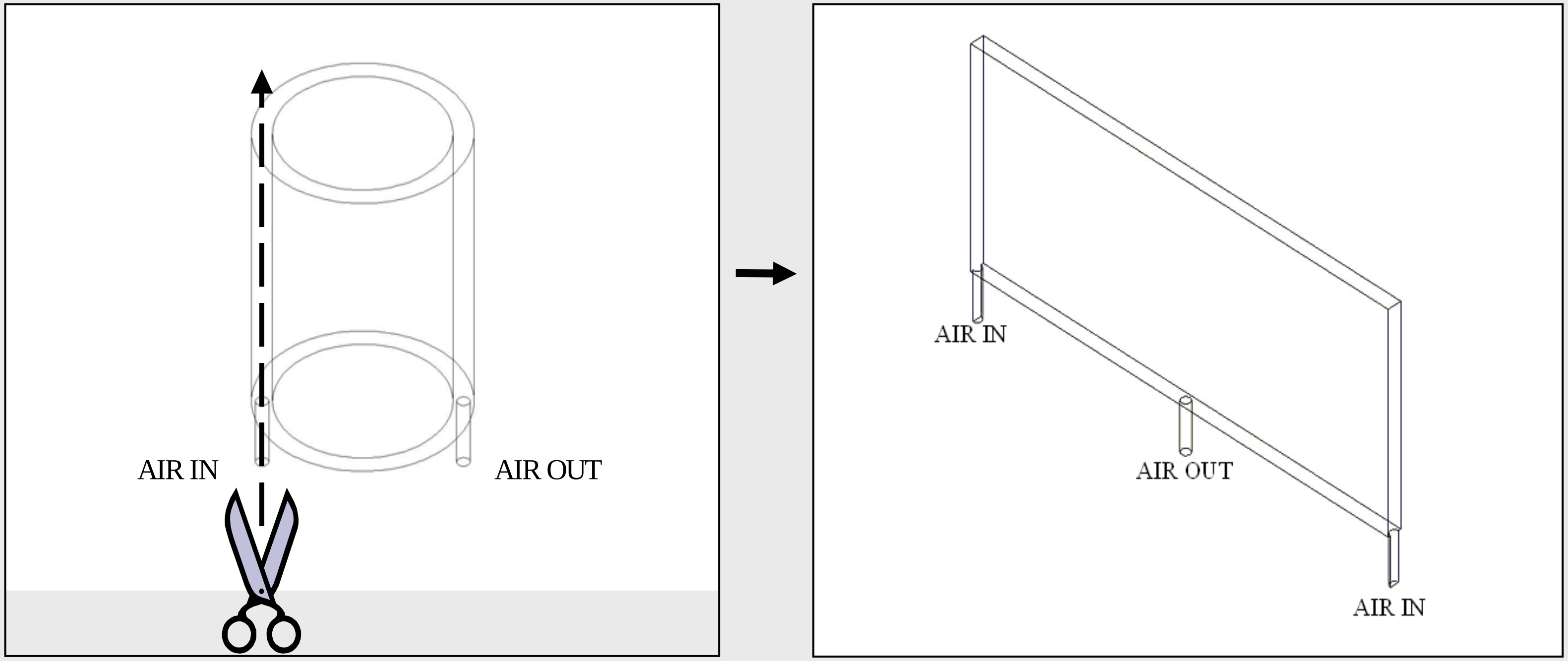
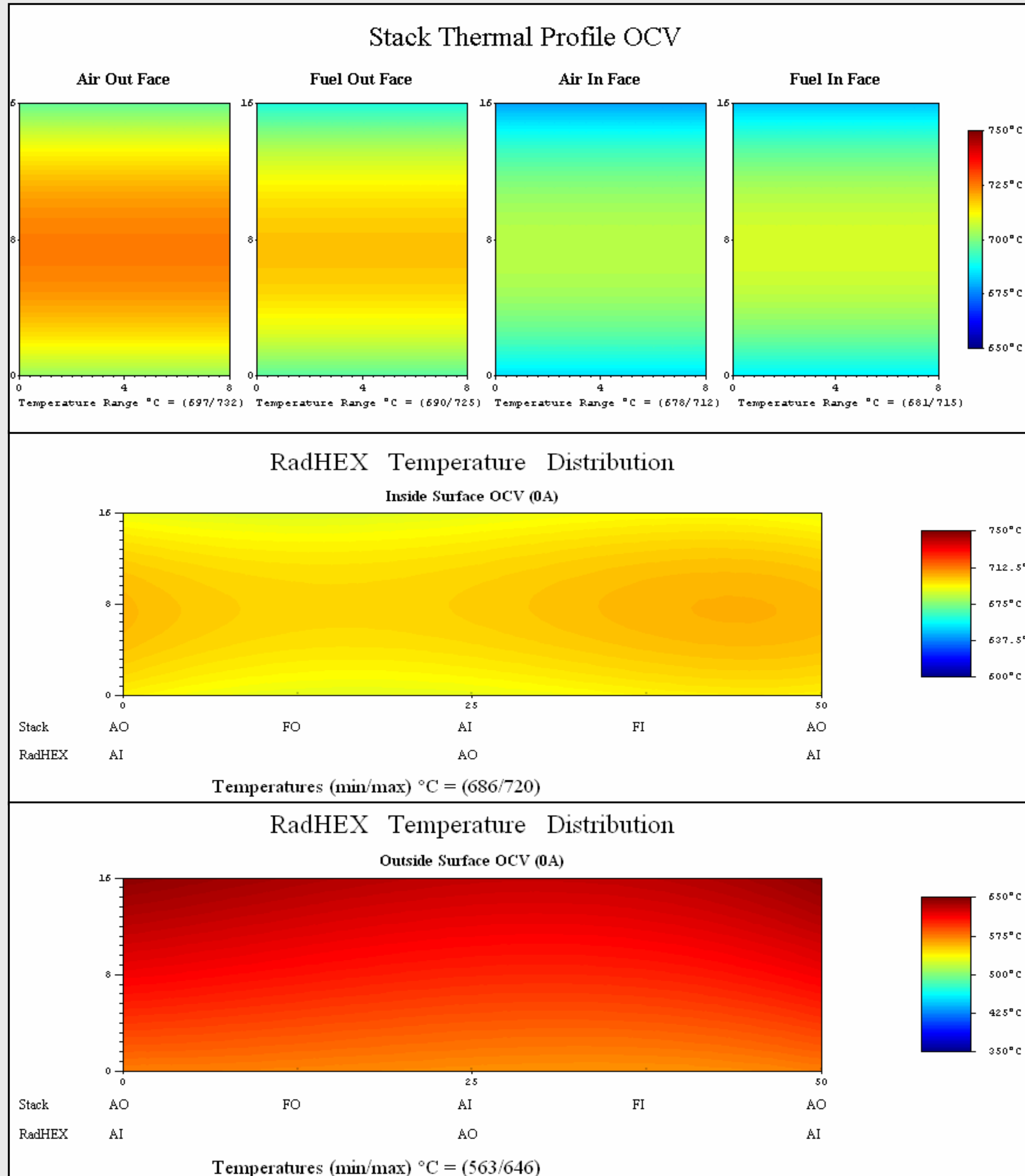
Hot Zone Thermal Analysis

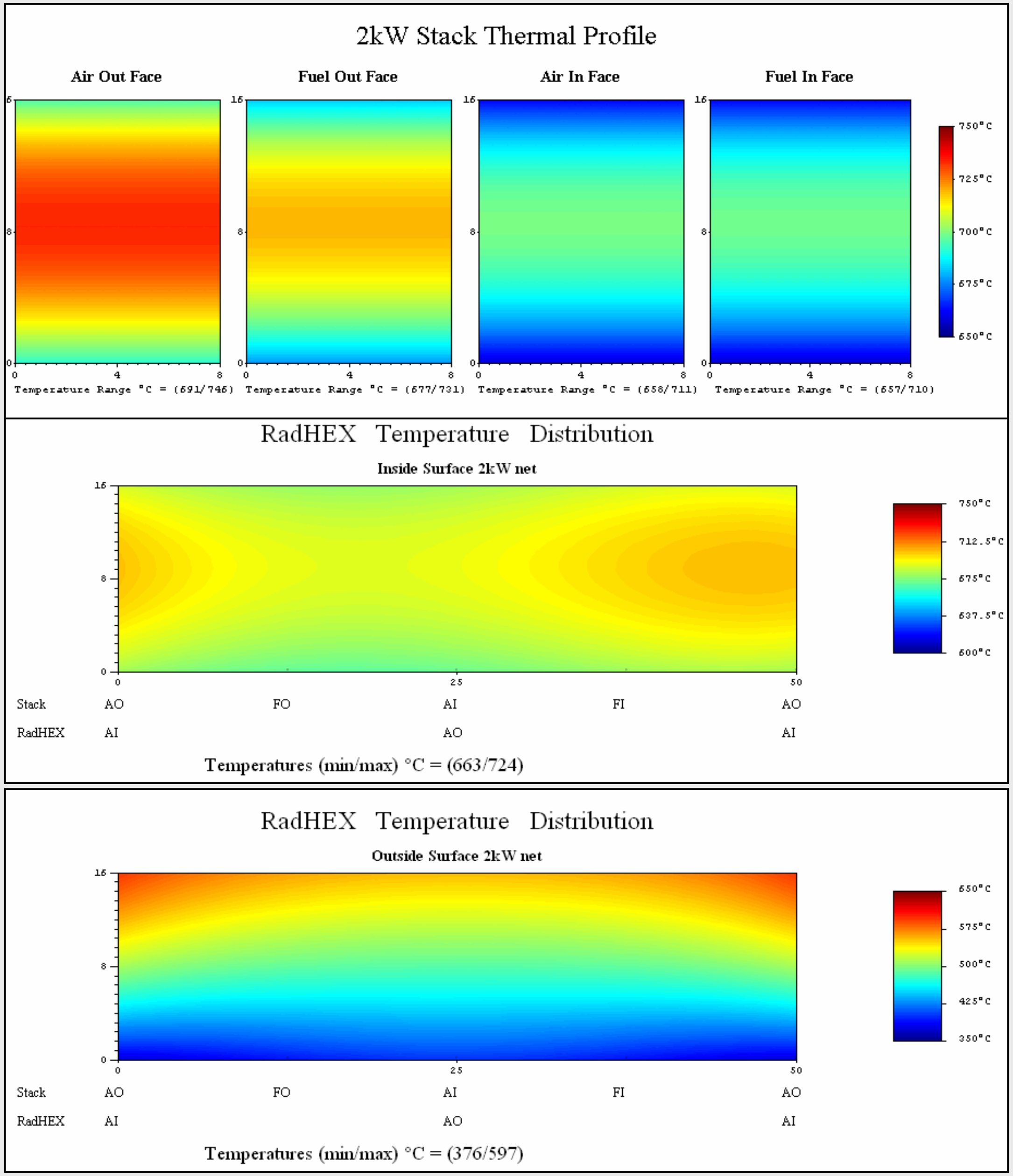
- Temperature mapped as if RadHEX was cut vertically along the air inlet side and rolled out into a flat panel
- Gives 11 measurements for each RadHEX surface (the 3 measurements at the edges are redundant)



Hot Zone Thermal Profile - OCV



Hot Zone Thermal Profile – 2kW



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Module Electrochemical Performance Comparison

Parameter	Project Goal	GTI/MSRI Test	MSRI/GTI Test	VPS Test
Stack design	NA	40 cells 92-cm^2 area Internal manifolded cell borders	40 cells 92-cm^2 area Internal manifolded cell borders	84 cells 121-cm^2 Internal manifolded picture frame
Fuel	H_2, simulated reformed natural gas, and CH_4/steam (DIR)	50% H_2/ 50% N_2	OCV: 55%H_2 /45% N_2 1 kW: 80%H_2 /20%N_2	Residential natural gas***
Module output	1-3 kW	550 W	1.0 kW	~2.8 kW DC 2 kW net AC
Stack T at full load	As close to 650ºC as possible	~759ºC	~786ºC	~719ºC Cath Out T = 730ºC
OCV	Theoretical V for VPS fuel: 78.12V	43.28 V (1.082 V/cell)	41.62 V (1.0405 V/cell)	79.67 V (0.9485 V/cell)
Gas utilizations	Not specified*	26.7% Uf 26.7% Uo	27% Uf 45% Uo	50% Uf 40% Uo
Power density under full load	0.4 W/cm^2 at 0.8V/cell**	0.11 W/cm^2 at 0.42 V/cell 0.26 A/cm^2 16.7 V at 24A	0.27 W/cm^2 at 0.59 V/cll 0.46 A/cm^2 23.7 V at 42.2 A	0.27 W/cm^2**** at 0.79 V/cell 0.35 A/cm^2 66 V at 42 A

* 40-60% Uf and 40-50% Uo targeted to approach commercial operation
** Depends on stack size, gas utilization, cell dimensions and fuel, which were not specified
*** 75% reformed externally and 25% on-cell reforming
****0.34W/cm^2 upper limit

Module Endurance and Efficiency Comparison

Parameter	Project Goal	GTI/MSRI Test	MSRI/GTI Test	VPS Test
Endurance	**Two 500-hr tests and one 2000-hr test**	**Operated intermittently for ~3 weeks**	**~500 hrs at part load**	**8,000-hr test underway. Will pass 2000 hours on 4/25/05***
Voltage degradation	**<0.6%/1000 hrs during 2000 hours**	**Unplanned power outages interfered with V degradation measurements.**	**500 test completed V degradation tbd**	**~1-2%/1000 hr at 30A ~5%/1000 hr at 40A ****
Power cycling	**Not specified.**	**~5 unplanned power outages**	**Apparent good power cycling**	**Apparent good power cycling for system**
Electric efficiency	**Projected 50% for a 10-kW system**	**Modeled by Nexant**	**Modeled by Nexant**	**~35% measured. 45-50% path identified**

*In non-CEC work, single-cell stack has operated >25,000 hrs and 20-cell stack has operated >8,000 hrs
**V degradation for a complete system can be higher than for a hot module only test

Module Thermal Performance Comparison

Parameter	Project Goal	GTI/MSRI Test	MSRI/GTI Test	VPS Test
Radiant air preheater design	Model and design	2 RAP panels adjacent to the fuel inlet and outlet, respectively RAP airflow perpendicular to the stacking direction	2 RAP panels adjacent to the fuel inlet and outlet, respectively RAP airflow perpendicular to the stacking direction	Annular RadHex RadHex airflow is proprietary
Thermally self-sustained	Yes	No	Essentially at 1.0 kW	Yes, >0.98 kW
RAP air temperature rise*	>300-400ºC at 40-50% Uo and full load**	~101ºC (due to high RAP inlet T) 300 – 400ºC in out-of-stack tests	~374ºC	~440ºC
In-plane stack delta T*	Not specified Should be <100ºC	Modeled to be <100ºC	Modeled to be <100ºC	~36ºC T/Cs on stack face
Axial stack delta T*	Not specified Should be <100ºC	~163ºC T/Cs at center of cell	~175ºC T/Cs at center of cell	~55ºC T/Cs on stack face

* Values at full load

** Needed for high electric efficiency

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Conclusions

- Radiant transfer of stack-generated heat can
  - Heat air effectively, cool the stack with low airflow, control stack temperature gradients, improve cell/stack performance, reduce thermal losses to the environment, and improve system flexibility
  - Improve system performance, cost, compactness, and scale-up
- The results
  - Suggest that designing combined stack/RAP modules may benefit SOFC technology
  - Developed module test fixtures and methods that can be used in subsequent projects
  - Identified options for minimizing axial and in-plane temperature gradients from OCV to full load
  - Produced a validated, engineering model for design of stack/RAP power modules
  - Included advances in stack design and electrochemical performance
  - Defined options for multi-module array systems

Conclusions (continued)

- The results also
  - Were at or near the CEC project goals
  - Are providing input to the design of SOFC power generators in the FCE/VPS SECA program

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  - Financial support provided by the Public Interest Energy Research (PIER) Program of the California Energy Commission, Contract 500-02-029, Arthur J. Soinski, Contract Manager
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  - Other participants