10kWe SOFC Power System Commercialization Program Progress

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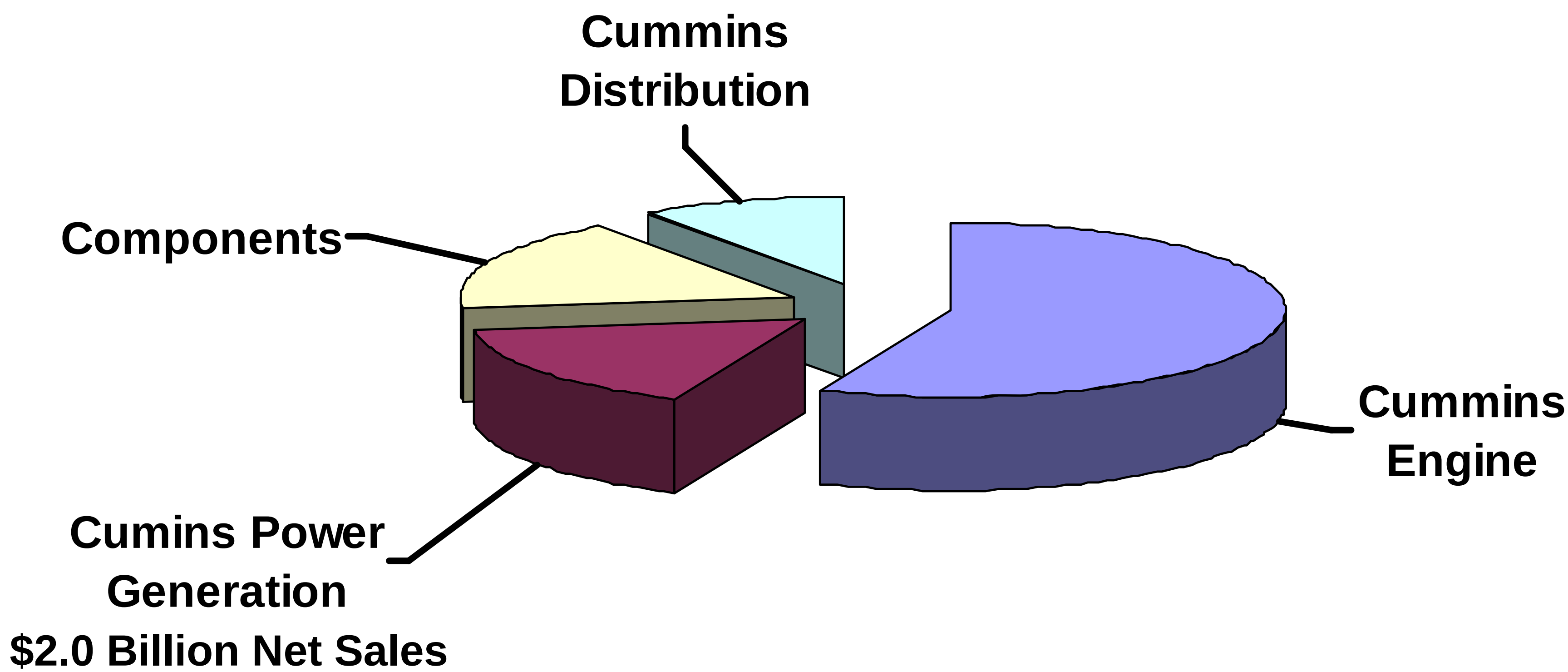
September 12, 2006
Philadelphia, PA

Cummins Power Generation

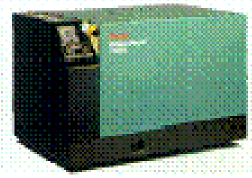
Cummins Inc

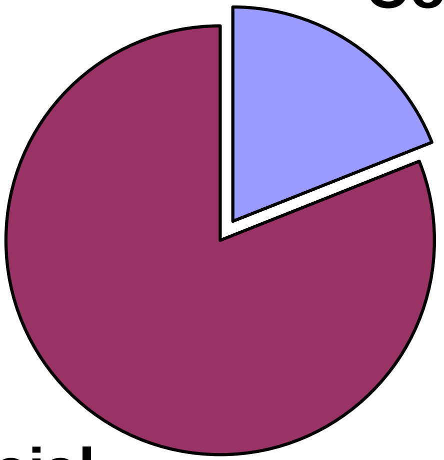
Cummins
2005 Performance
$9.9 Billion Net Sales



2005 Production
5,800 MW

Consumer

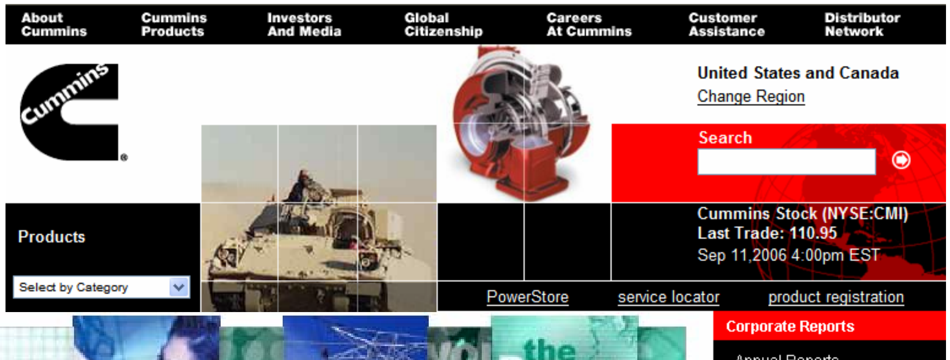




Commercial

Power Generation

http://www.cummins.com/



http://www.funroads.com/

http://www.cumminspower.com

CPG/Versa Power Systems (VPS)

- Phase 1
  - – CPG & VPS teaming for 2006 Phase 1 completion
  - – VPS 3-1 System-based prototype evolves towards mobile application requirements
  - – CPG develops and delivers new air flow and power conditioning sub-systems
- Phase 2
  - – CPG/VPS develop new system tailored to RV requirements
  - – VPS: stack, manifolds, hot section components
  - – CPG: system engineering; fuel processing; BOP and Power conditioning; packaging and market channel

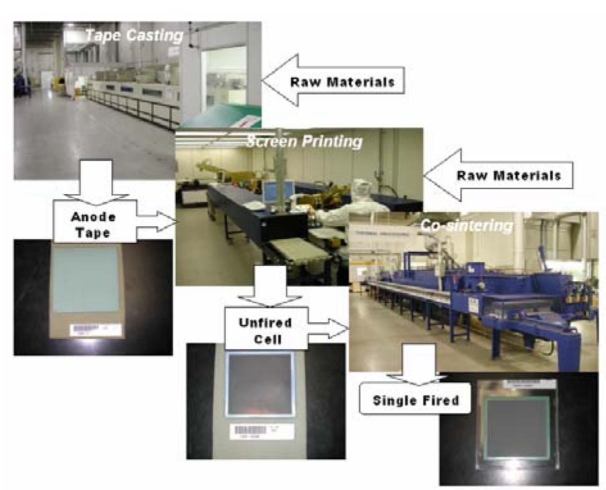
Cummins Power Generation Versa Power Systems Teaming

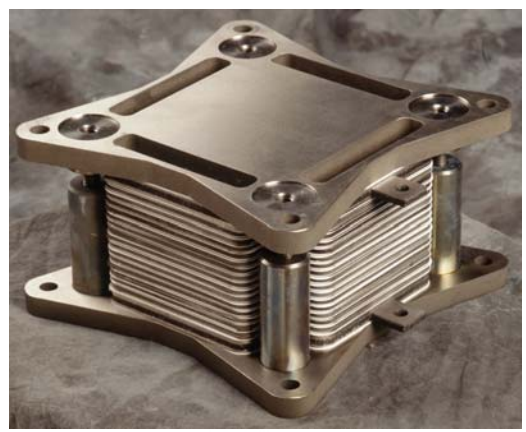
- Reformer development
- Electronic controls
- Power electronics
- Fuel systems
- Air handling systems
- Noise and vibration
- Power system integration
- Manufacturing
- Marketing, sales, distribution

- High performance planar cell & metallic interconnect technology
- Planar SOFC stacks
- High temperature thermal integration
- Experienced SOFC system integrators

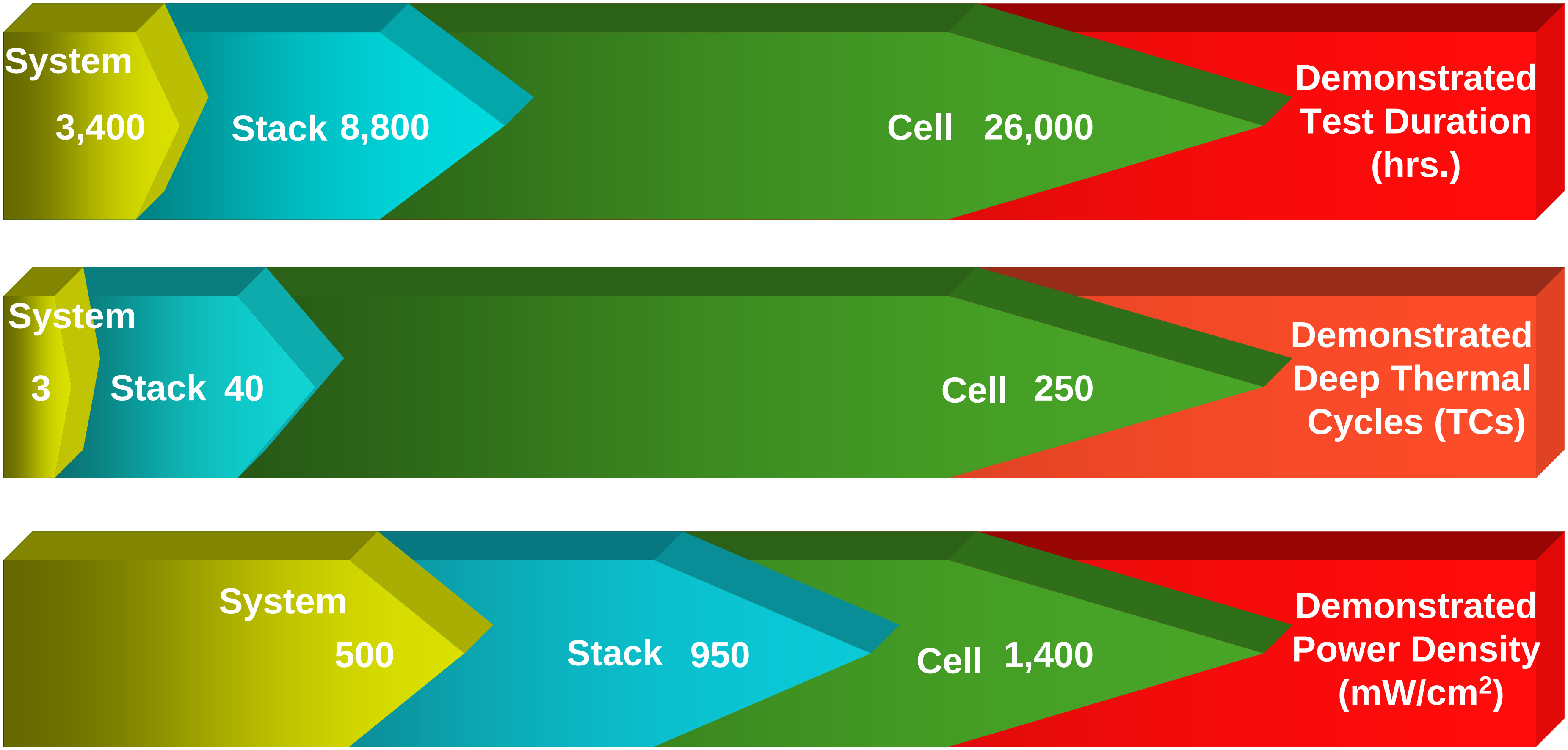
Versa Power Systems

- Focused on SOFC commercialization
- Demonstrated cost-effective SOFC ceramic cell manufacturing technology
- Highly competitive state-of-the-art SOFC stack technology
- Multiple generations of complete integrated system experience





VPS SOFC Development Status



Approach to Commercialization

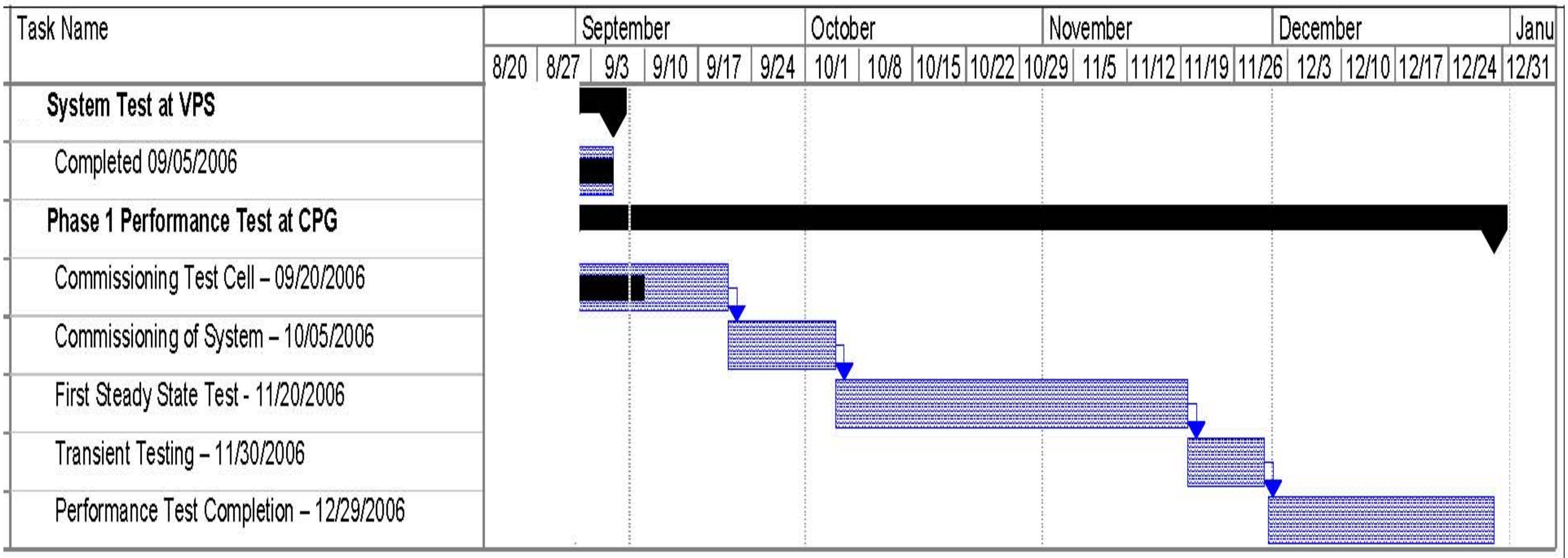
- Develop stack technology
  - Performance ($/kW)
  - Sulfur tolerance
  - Degradation
  - Redox tolerance
- Address system challenges to commercialization in mobile markets
  - Reformer operation on ULSD
  - Start-up and shut-down transient conditions
  - Shock and vibration tolerance (robustness)
  - Compact system integration (packaging)
- Demonstrate capability to incorporate technology in context of product development program

Approach to Development

- Phase 1 Prototype
  - Evolved from Versa Power Systems 3-1 system
  - Natural gas fueled, steam reformed
  - Reduced Direct Internal Reforming (DIR)
  - Internal stack clamping design
  - Cost reduced air supply
  - Simplified DC output (boost)
- Phase 2 Prototype
  - ULSD fueled
  - Start-up and shut-down w/o supplementary gases
  - Sulfur and redox tolerance
  - Packaging and system integration
  - Shock and vibration tolerance (robustness)

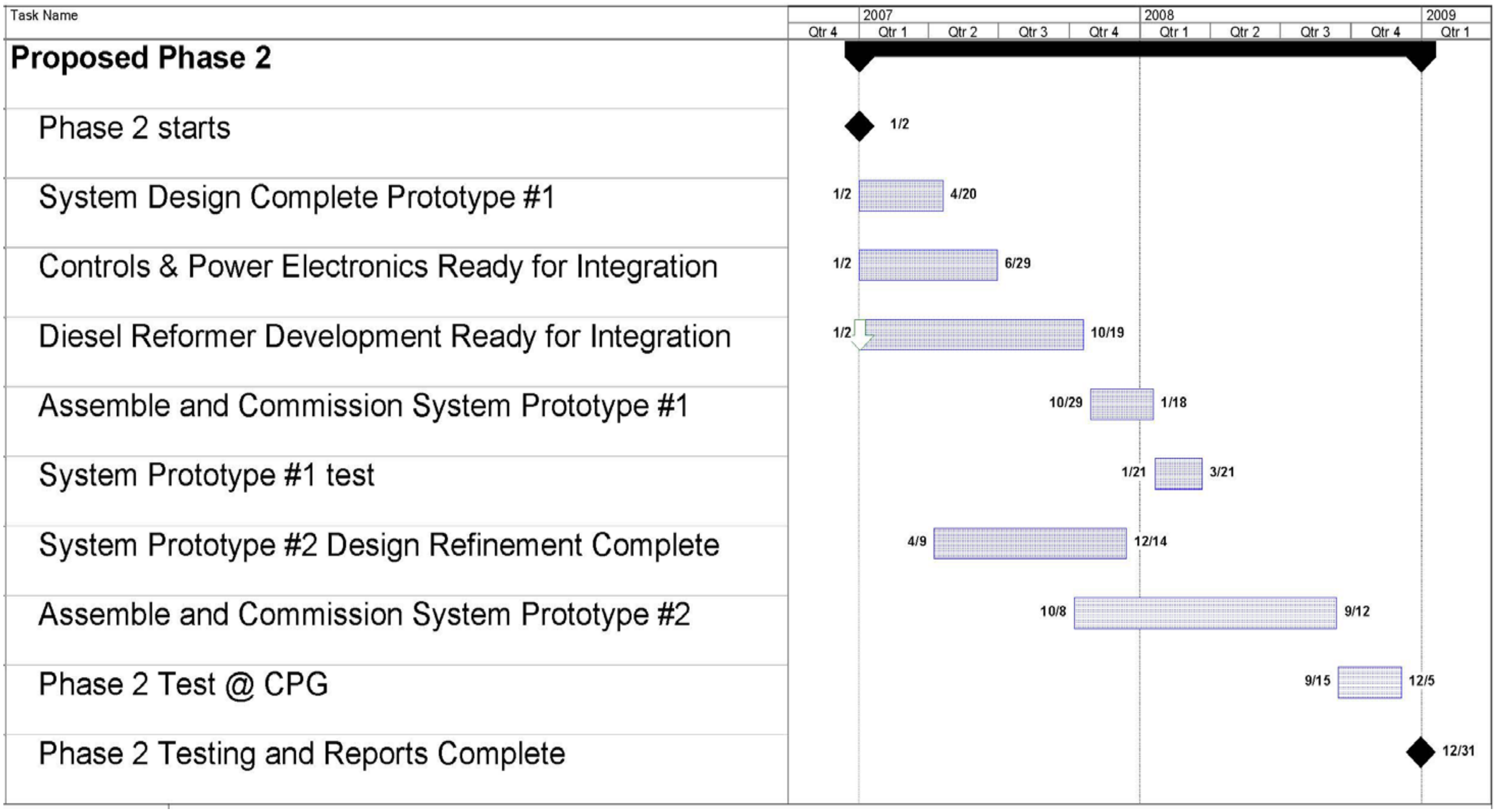
Plans Balance of Phase 1

- CPG/VP Phase 1 Proto Development and Testing
  - System Pre-test at VPS completed 09/05/2006
  - Phase 1 Performance Test at CPG



Phase 2 Plan Overview

- CPG/VP Phase 2 Development and Testing



Phase 1 Evolution Reduced Direct Internal Reforming (DIR)

- Low levels of DIR provide flexibility to operate with a wide variety of fuels, reforming technologies and operating conditions
- Reduced DIR shifts stack heat rejection to other cooling means
- VPS integrating low DIR capability into the latest stack technology

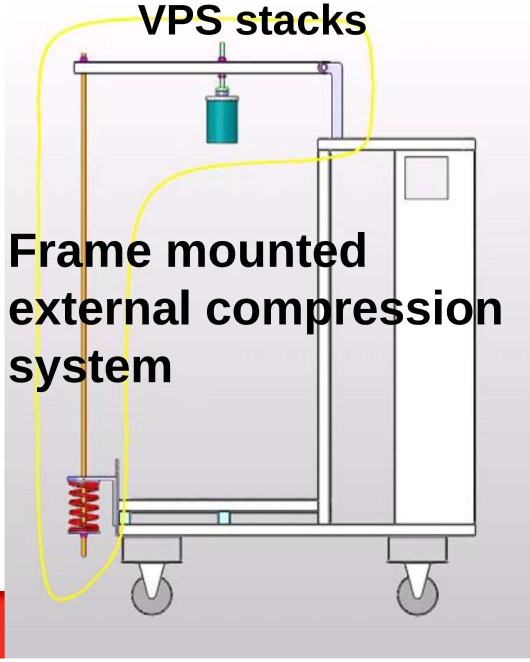
Phase 1 Evolution Reduced Direct Internal Reforming (DIR)

- Stack testing with no methane slip is the new baseline for stack testing in test stands
- Stack design modified to reduce thermal gradients in VPS' baseline platform for operation with low DIR reformate
- System reformer modifications completed to increase natural gas conversion to H_2 and CO
  - Increased heat transfer in the afterburner / reformer design

Phase 1 Evolution
Internal Stack Compression

- Internal compression replaces cold external system components with integrated in-stack clamping (hot)
- Internal compression
  - Reduces system volume and weight
  - Reduces system part count and complexity
  - Is more suited to mobile applications with shock and vibration environment
- Internal compression utilizes differing thermal expansions between the stack and compression member design

Early generation internal compression in VPS stacks



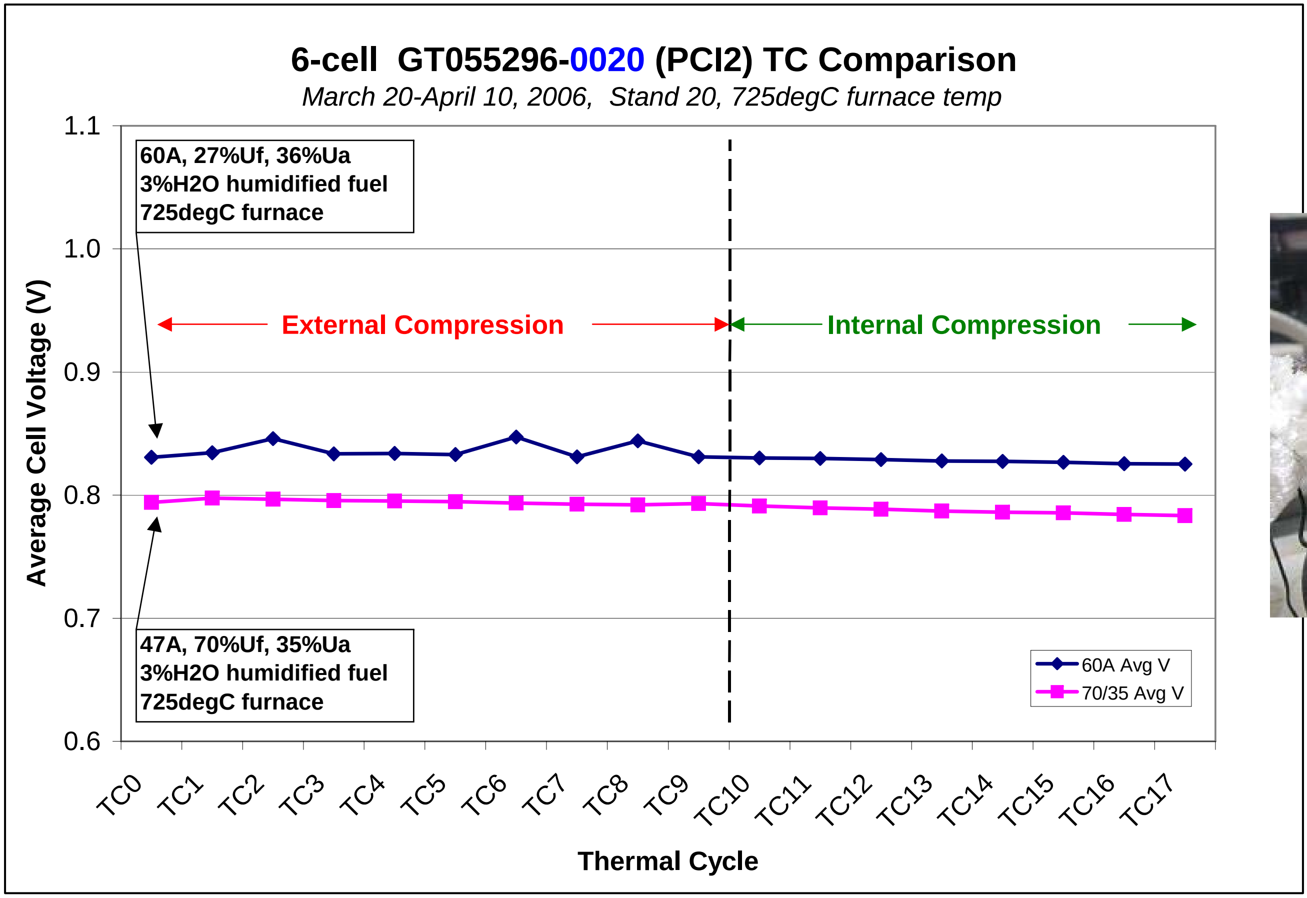
Frame mounted external compression system

Phase 1 Evolution
Internal Compression

- Internal compression materials selected and parts fabricated and implemented in test stacks at 6 cell and 28-cell level
- Thermal cycle testing of external and internal compression 6-cell stacks found no distinguishable performance difference
- Phase 1 SECA test will run with external clamping, system will be converted to internal clamping post-test

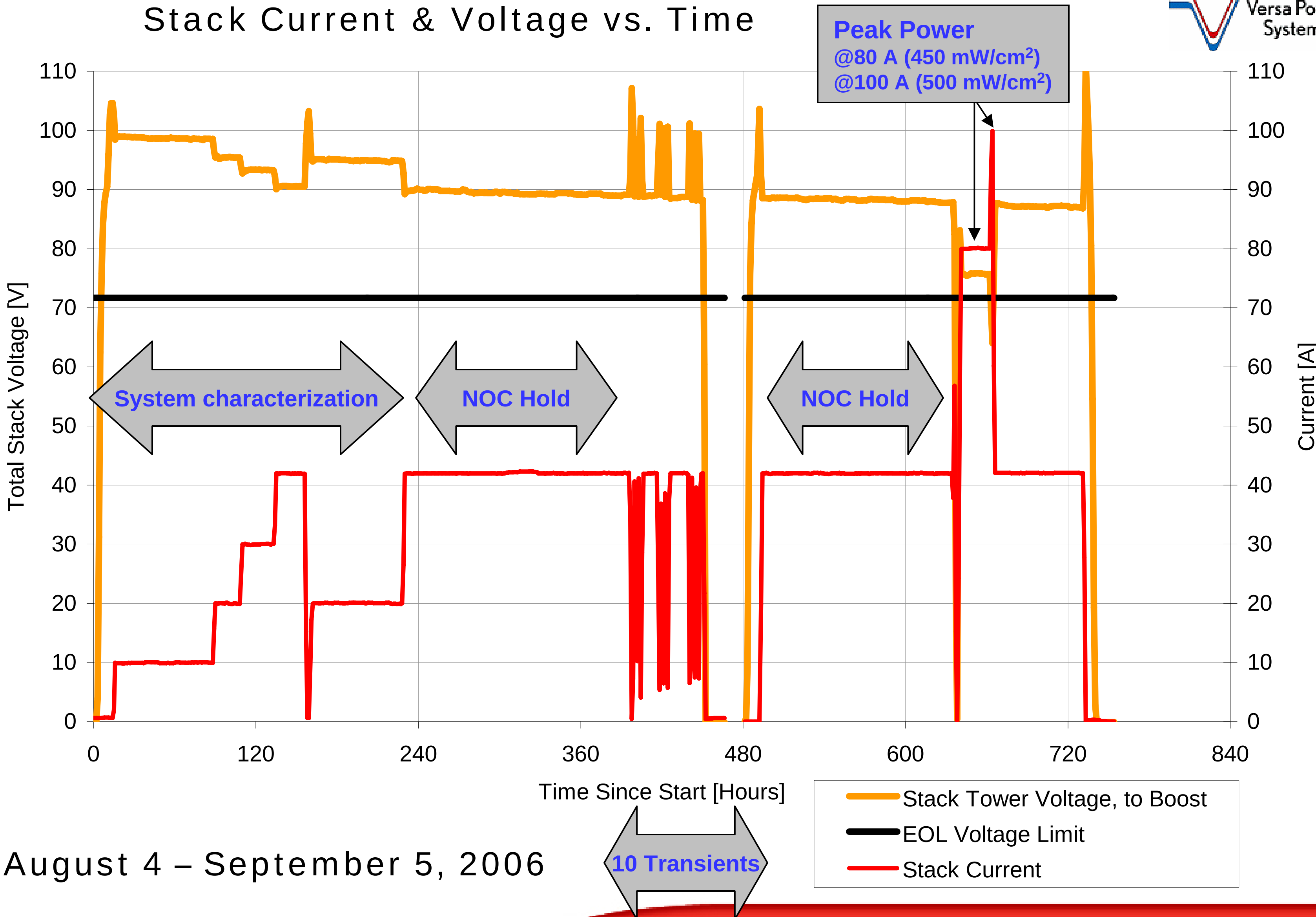
Phase 1 Evolution
Internal Compression

- Test Results (121 cm^2 active area):



Initial Phase 1 System Testing:

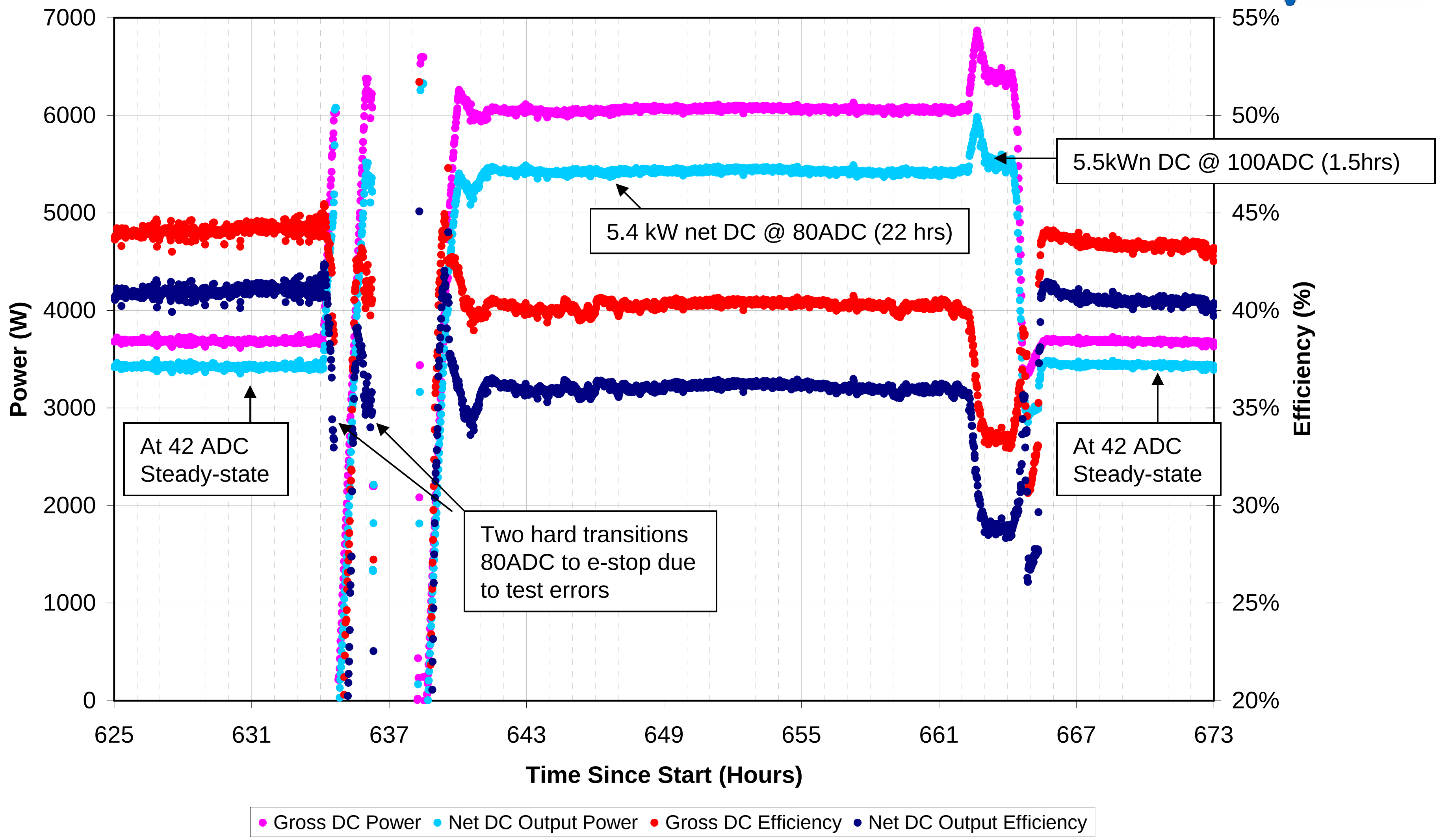
Stack Current & Voltage vs. Time



August 4 – September 5, 2006

Initial Phase 1 System Testing:

Peak Power



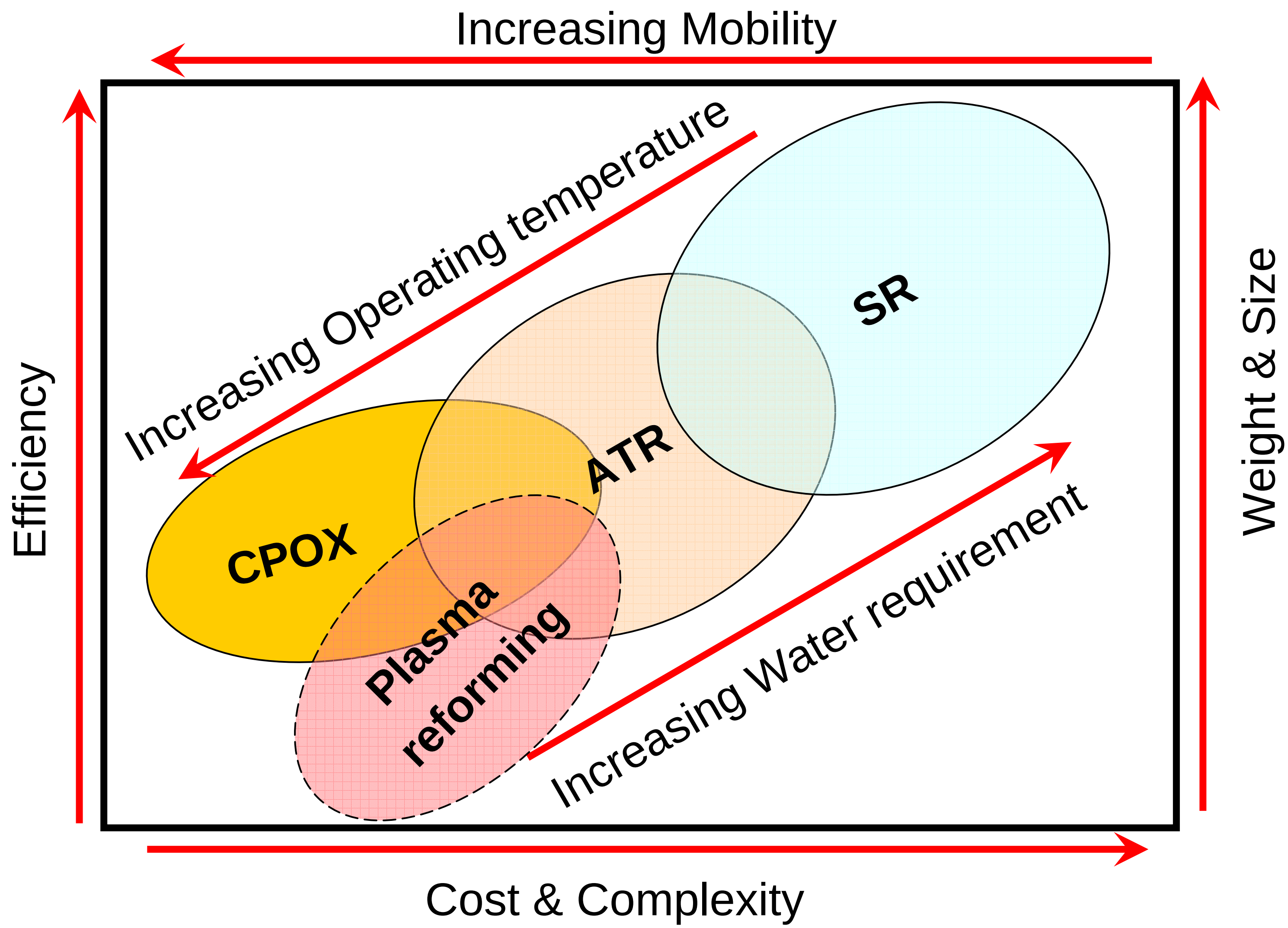
Phase 2 Preparation
ULSD - Fuel for Mobile SOFC Commercialization

- CPG's SECA work to date based on LPG and Natural Gas
- Market studies strongly indicate ULSD (< 15 ppmw sulfur) is critical to successful commercialization of CPG Target Markets
- US EPA on Highway Emission requirements mandate transition to ULSD beginning in 2007 (some regions have already begun transition).

"Zero Net Water" for Mobile SOFC Commercialization

- Water simplifies fuel reformation
  - Source of additional hydrogen
  - Reduces carbon formation
- Higher S/C ratios mean water requirement can exceed the fuel requirement
- Carrying significant amounts of water on mobile applications undesirable
  - Space
  - Weight
  - Availability
- Mobile system water *requirement = Zero Net Water*
- Other factors favor desirability of *waterless system*
  - Cost
  - Complexity
  - Storage requirements

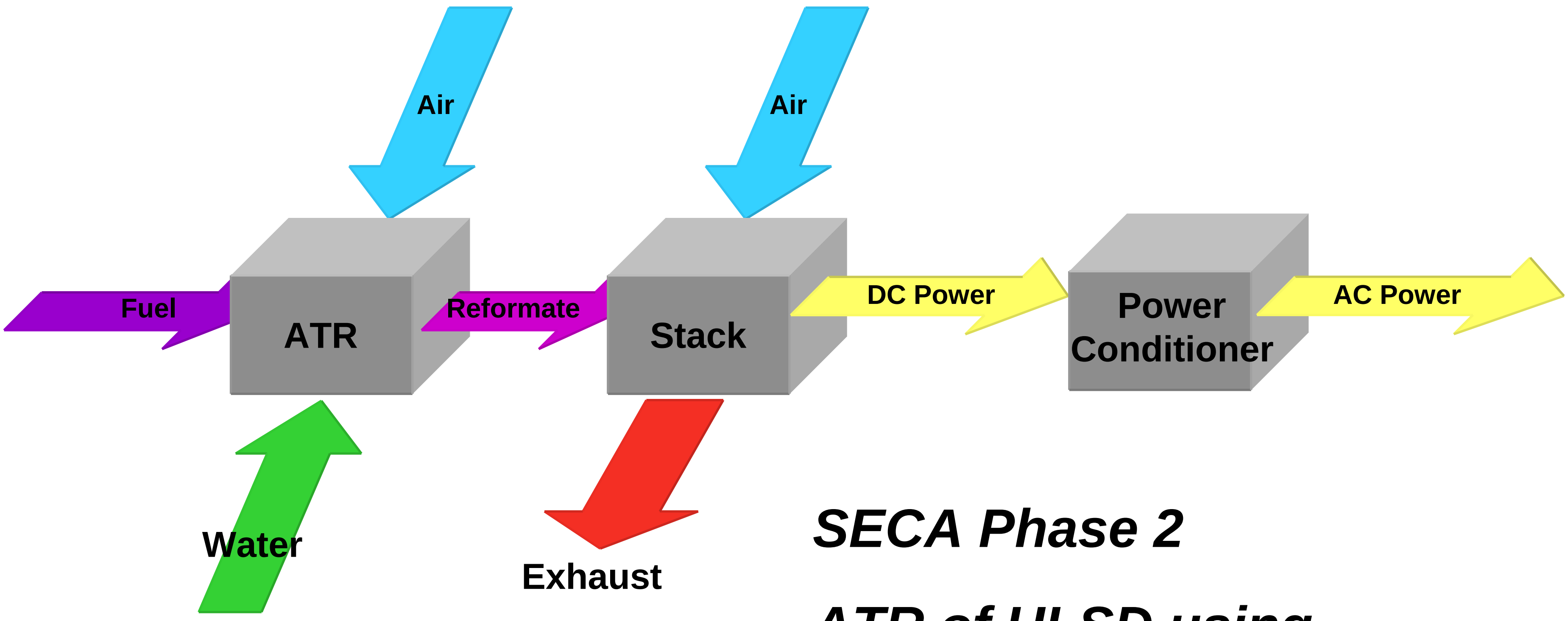
Diesel Reforming Technologies Compared



Diesel Reforming Technology
Preliminary View for Mobile Products

	Efficiency	Simplicity	Cost	Reformate stability (Carbon formation)	Freeze Resistance (Long Term Storage)	Transient Performance	Size & Weight	Electrical Parasitic Power Consumption	Maintenance
Steam Reforming	Green	Orange	Orange	Green	Orange	Orange	Orange	Yellow	Orange
Autothermal Reforming									
Supplemental water	Yellow	Green	Green	Green	Orange	Green	Orange	Yellow	Orange
Anode Gas Recycle	Yellow	Yellow	Yellow	Green	Green	Yellow	Yellow	Yellow	Yellow
Water Condensation	Yellow	Yellow	Yellow	Green	Orange	Green	Yellow	Yellow	Yellow
Catalytic Partial Oxidation Reforming	Orange	Green	Green	Red-orange (large)	Green	Green	Green	Green	Green
Plasma Reforming (dry)	Orange	Green	?	Orange	Green	Green	Green	Orange	?

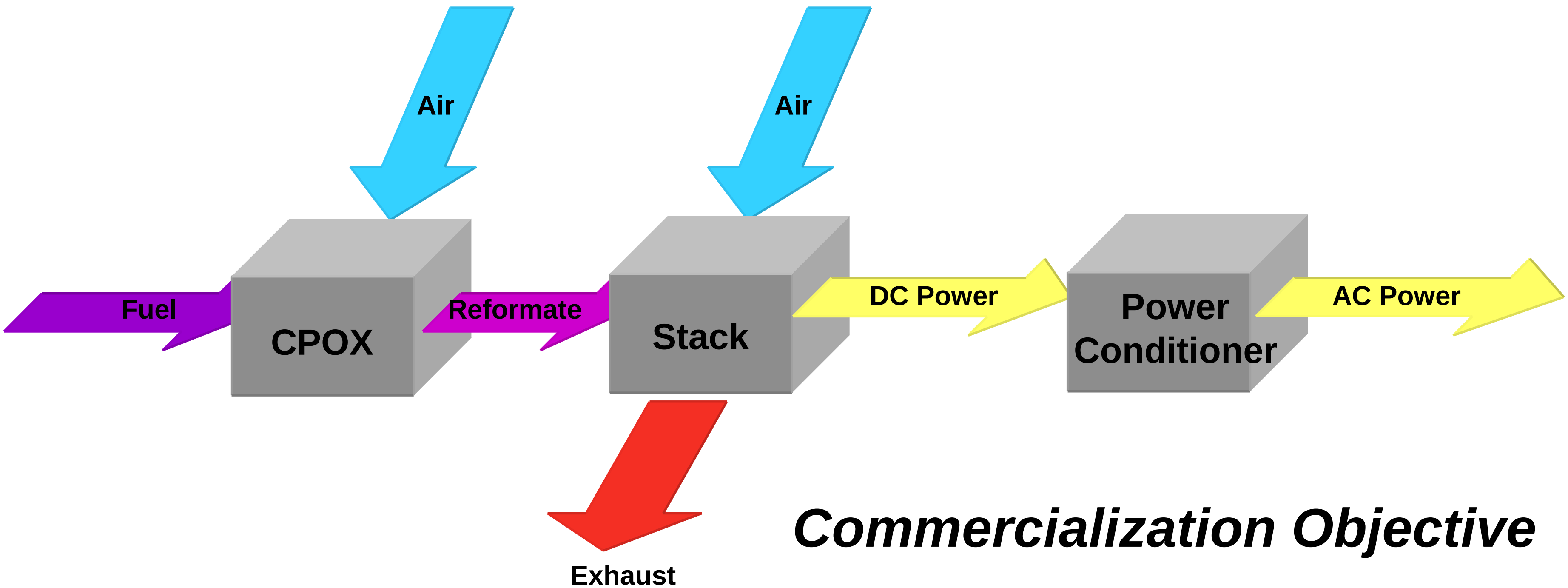
Evolution of SOFC Fuel System Form Mobile Applications



SECA Phase 2

ATR of ULSD using supplementary water

Evolution of SOFC Fuel System Form Mobile Applications

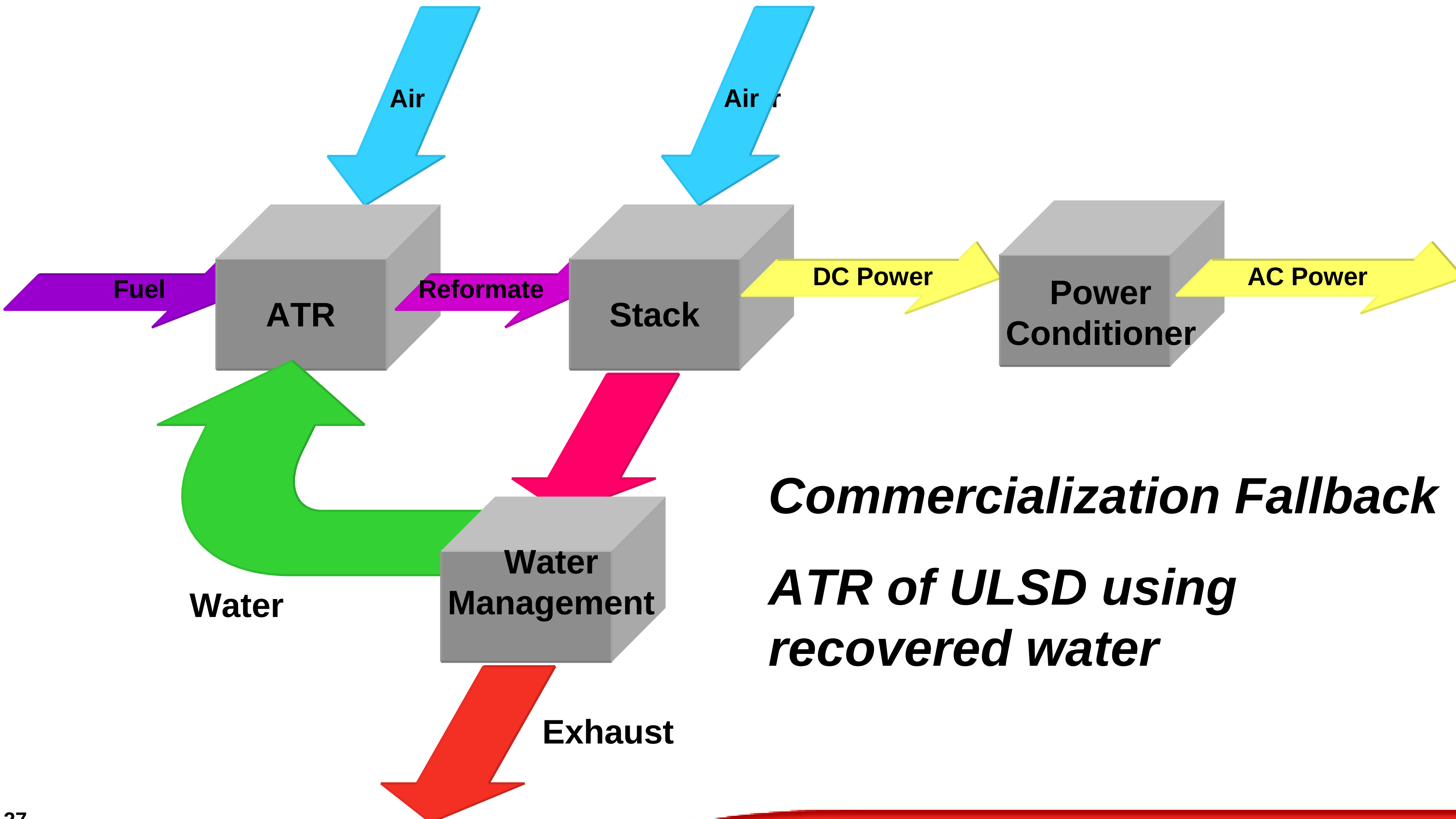


Commercialization Objective

CPOX of ULSD using NO water

Power Generation

Evolution of SOFC Fuel System Form Mobile Applications

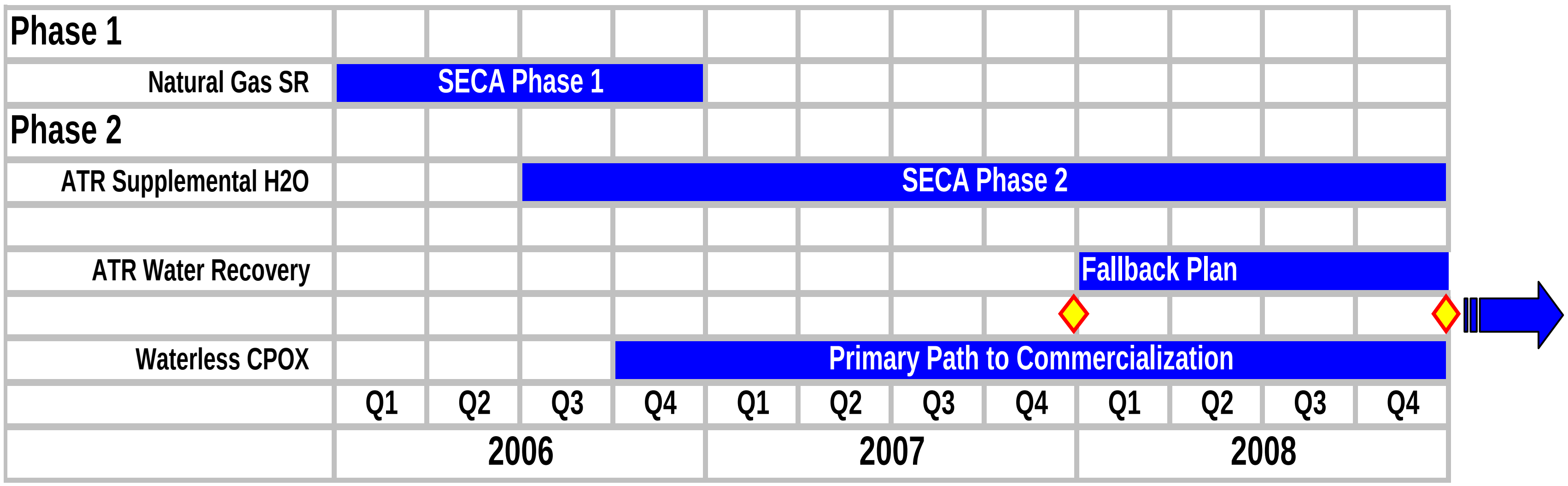


Commercialization Fallback

ATR of ULSD using recovered water

Parallel Reformer Development Paths

- ATR for SECA Phase 2
- CPOX Primary Path for commercialization
- ATR w/H2O Recovery Fallback



Optimizing Air Supply System Cost

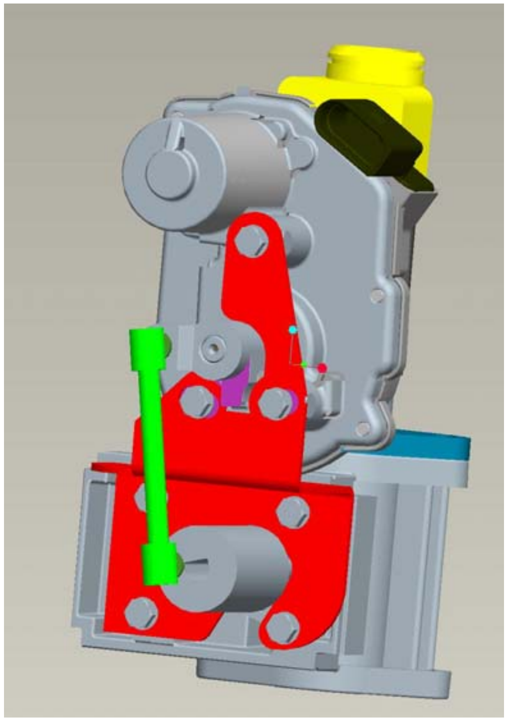
Power Generation

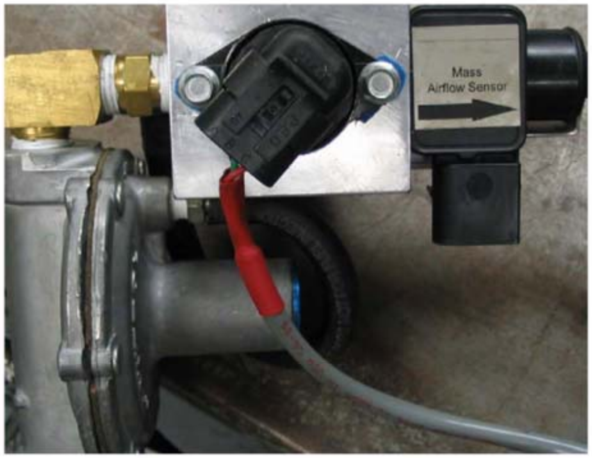
- Low Cost Air Supply Subsystem Design -- Primary Tasks
  - Optimize flow levels and pressure losses
  - Minimize the number of control elements/streams
  - Avoid hot side valving
  - Incorporate low cost (industrial / automotive) sensors and actuators
  - Design with components derived from production supplier base and consumer product experience.
  - Achieve costs consistent with high volume production components
  - Develop robust control algorithms derived from system characterization

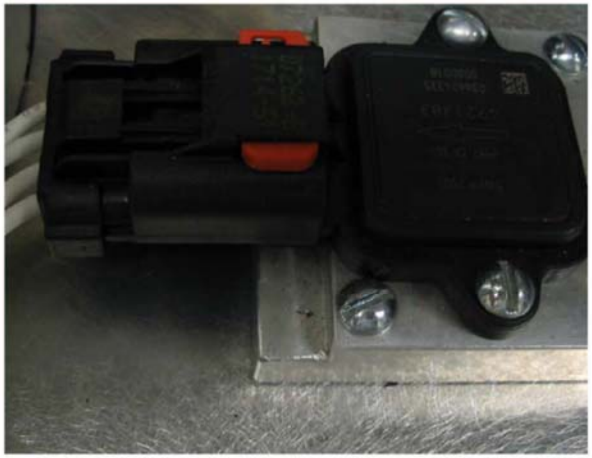
Reduced cost air supply

Butterfly Control Actuator Assembly with Integrated:

- Mass Flow Meter
- DC Servo Actuator
- Butterfly Valve Assembly
- Mechanical Linearization







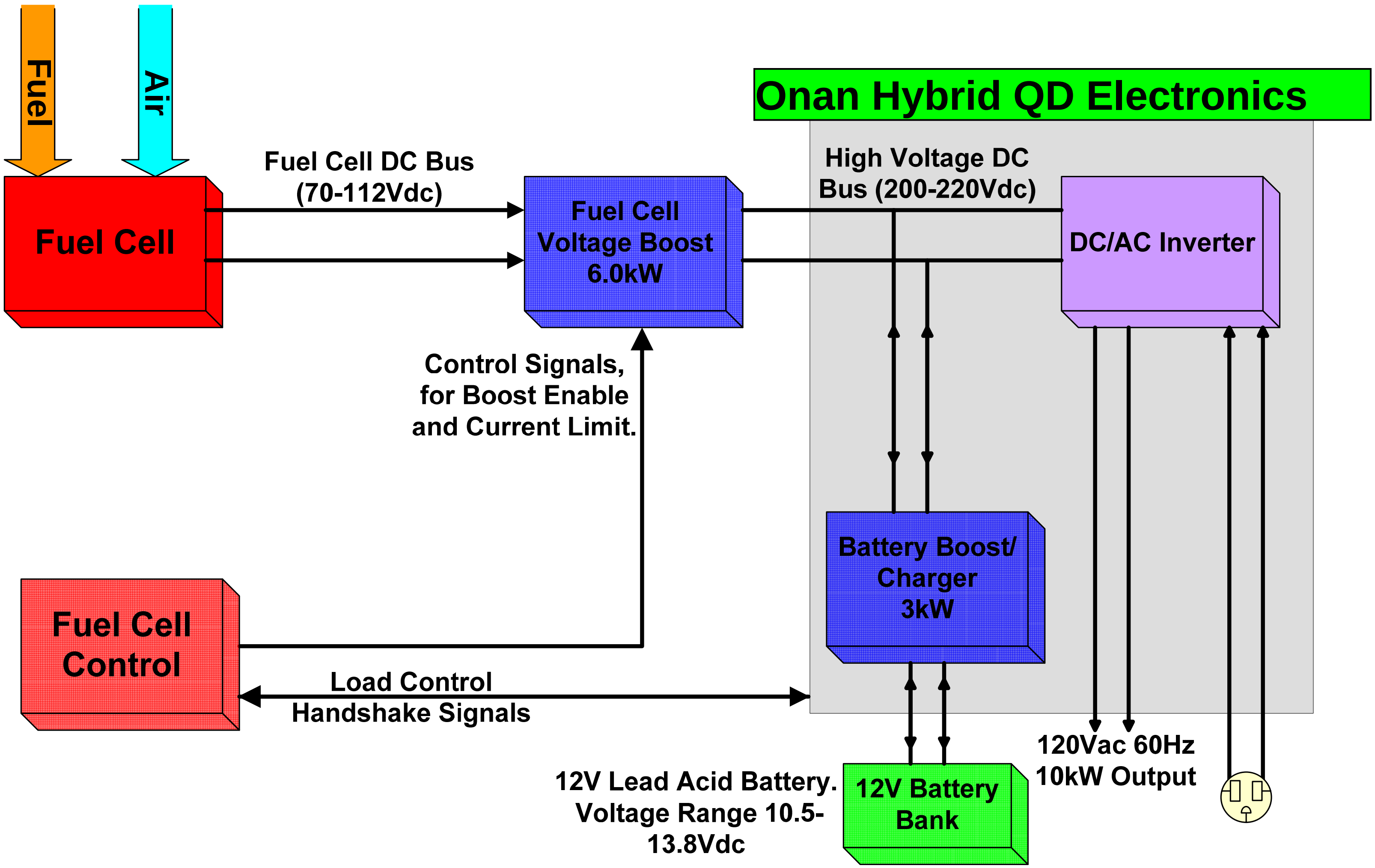
Components Included in previous Prototype:

- Mass Flow Meters from Cummins 2007 B Series
- Stepper Motor Actuator
- Low Cost, ~40% Eff., Cathode Blower

Air Supply

CPG Designed Field Replaceable Unit (FRU)

Fuel Cell Power Electronics

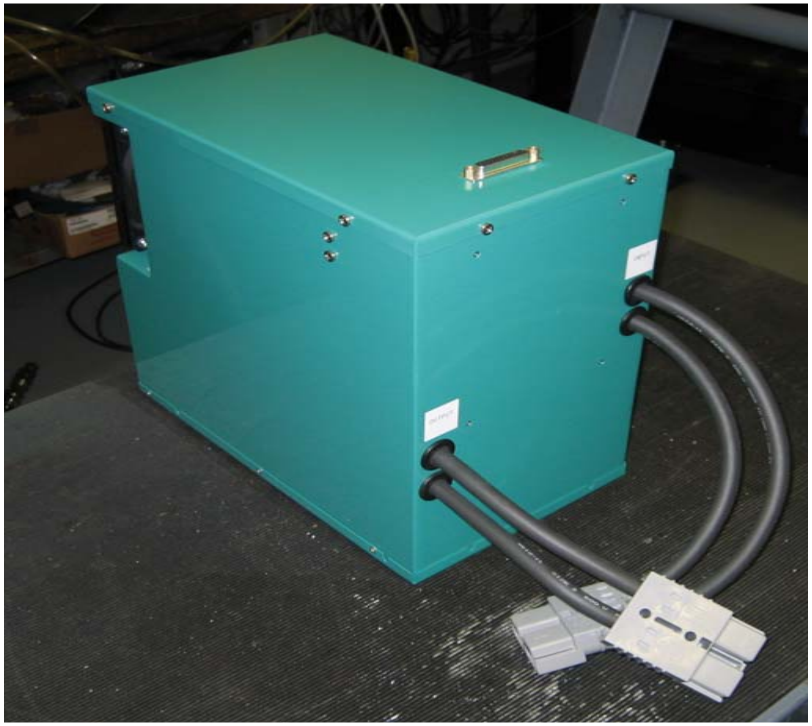


Phase 1 Fuel Cell Boost

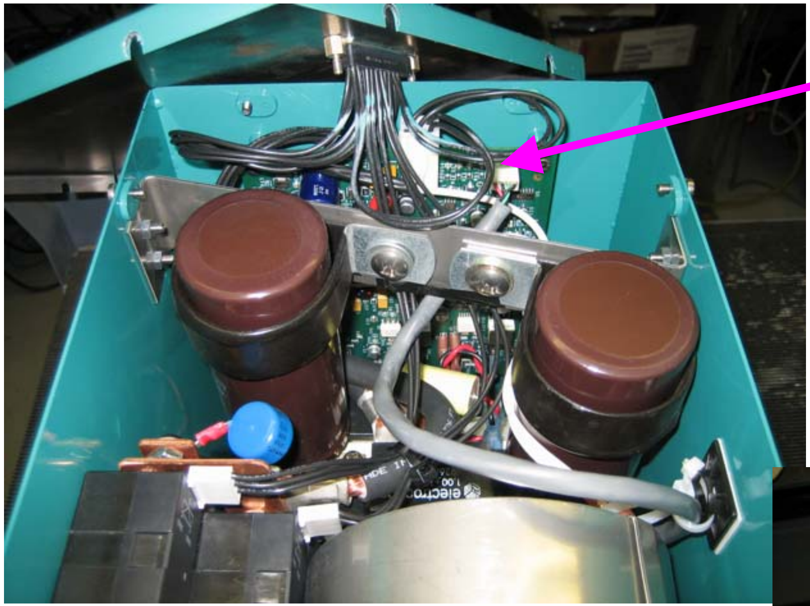
Cummins Power Generation

- Fuel Cell Boost
  - Boosts and Regulates Fuel Cell Voltage
    - Input Voltage Range 57-200Vdc
    - 6kW output power.
    - Output Voltage 200Vdc
  - Current Limit Control for Stack Protection
    - Limits Stack Current During Transients
  - Soft-Start and Enable Feature
  - Very Low Cost Design
    - 6kW for <$200 Total manufacturing cost

The Fuel Cell Boost

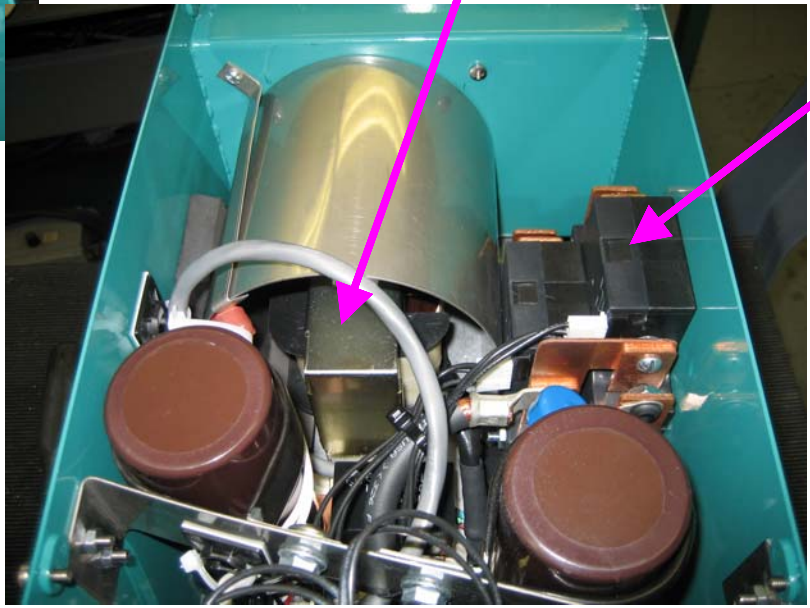


The Fuel Cell Boost



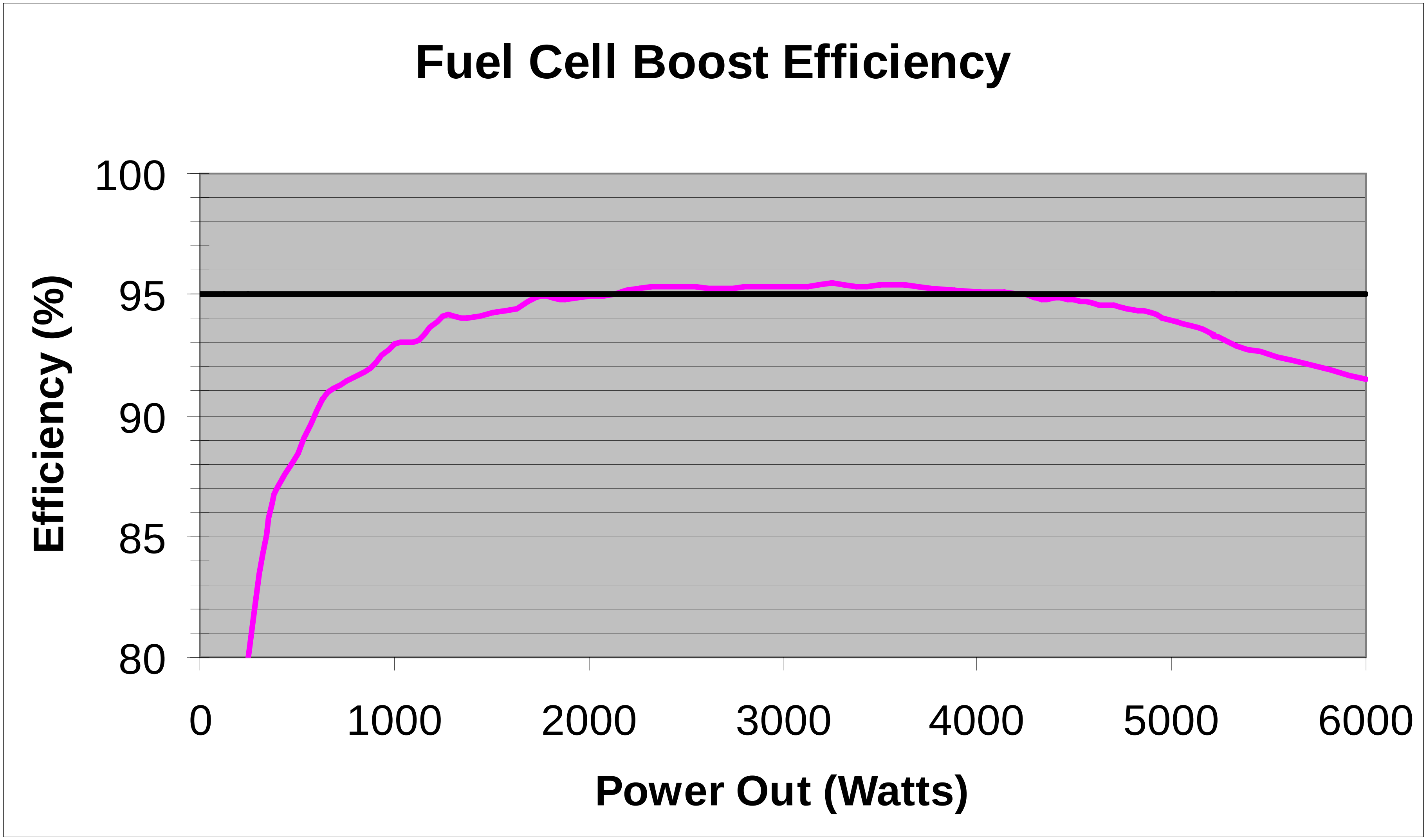
Control Board

Inductor

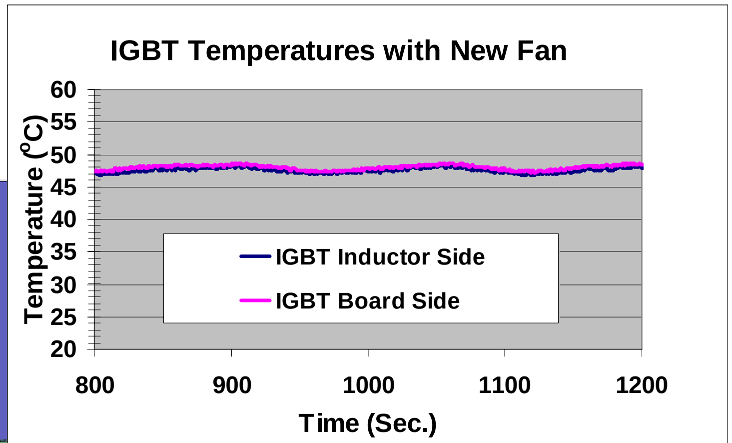


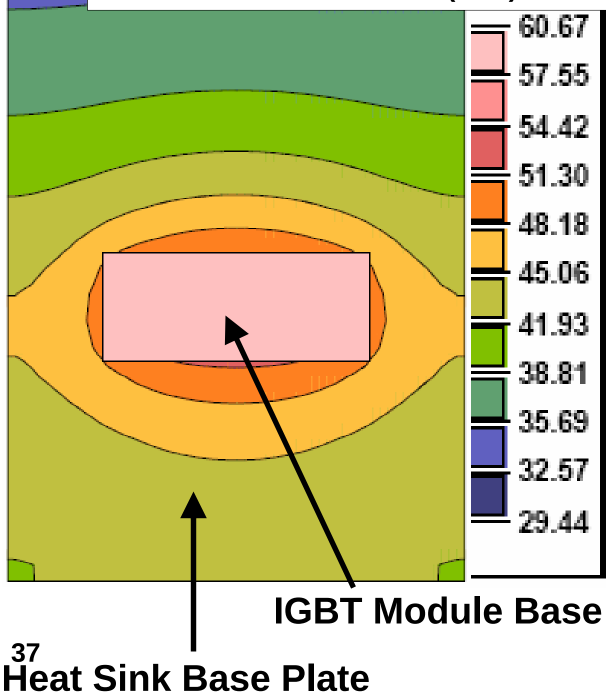
Soft Start Relays

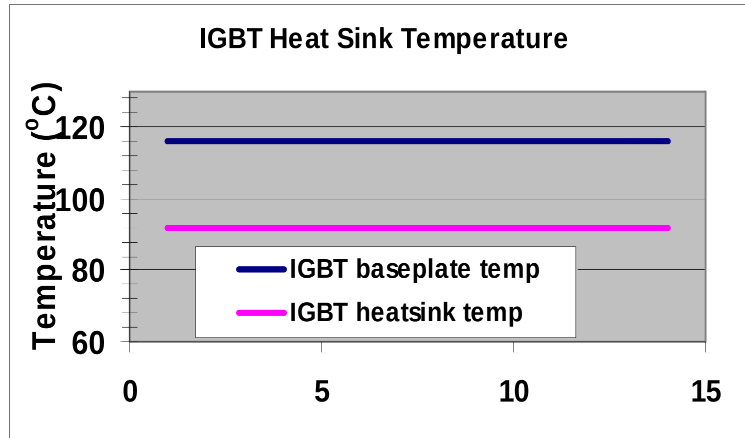
Fuel Cell Boost Efficiency vs Load



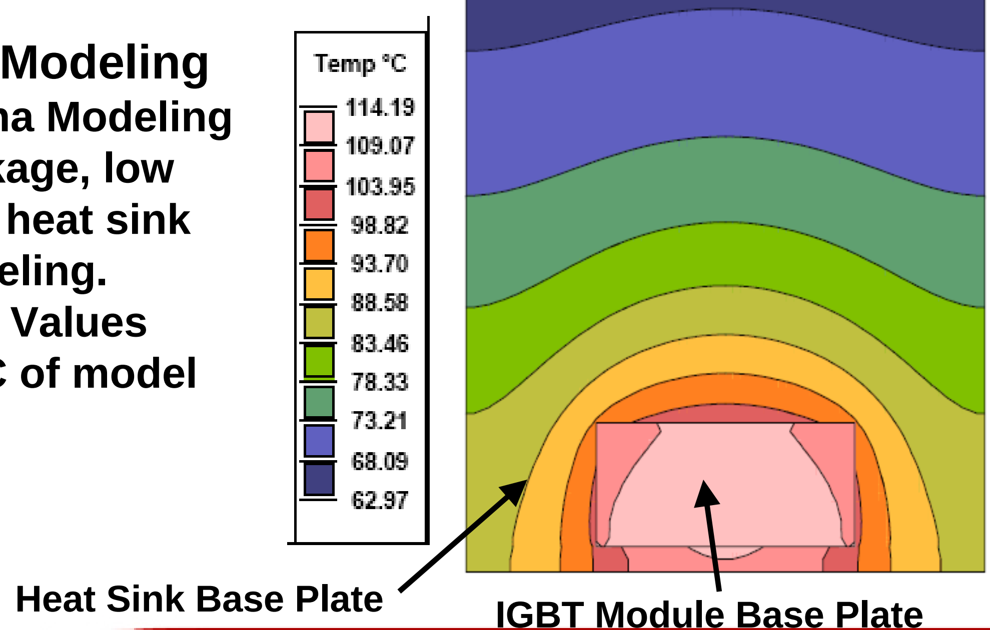
Boost Heat Sink Modeling with Sauna





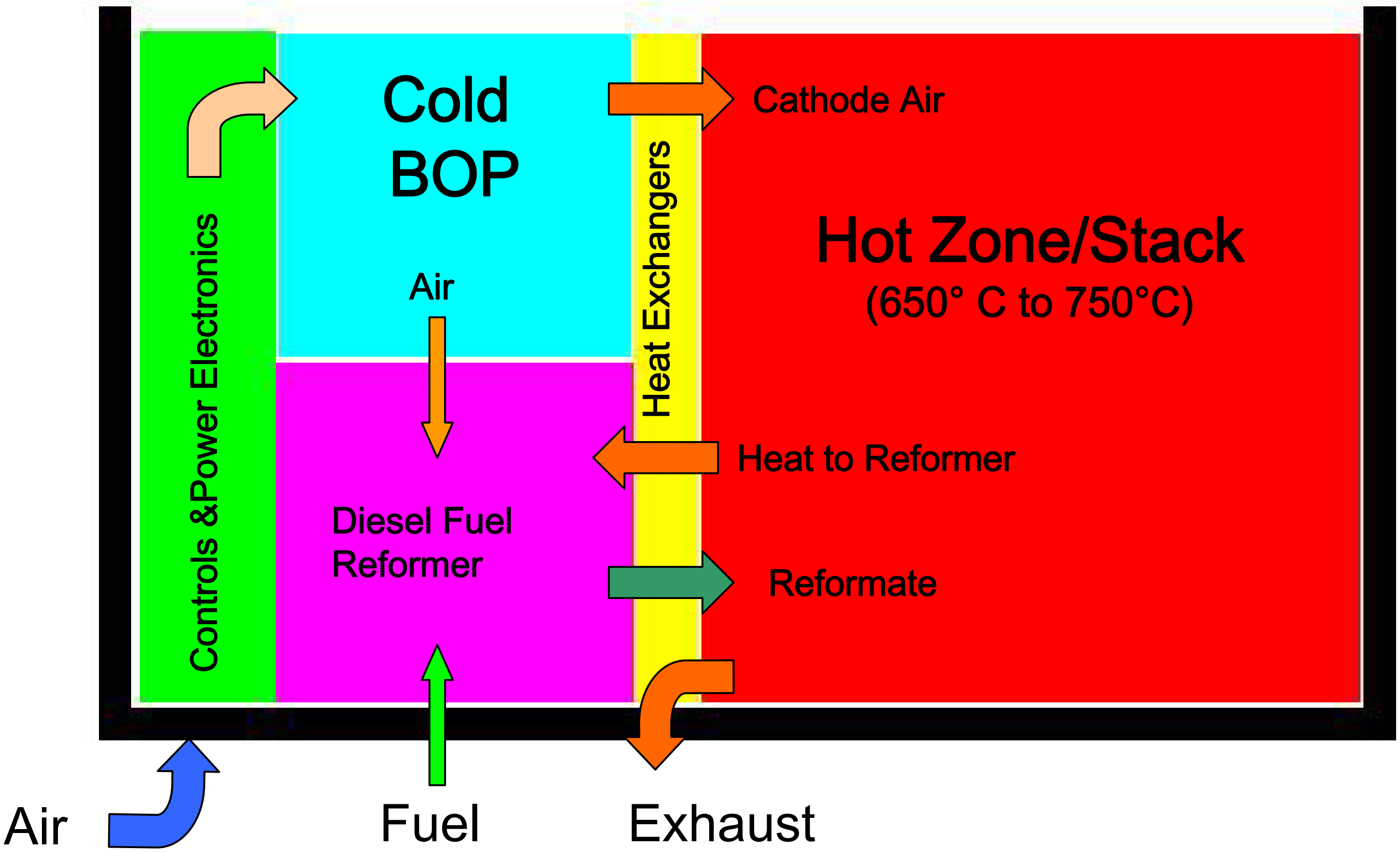


- **Thermal Modeling**
  - **Sauna Modeling Package, low cost heat sink modeling.**
- **Measured Values within 3°C of model**



Phase 2 Packaging

- Thermal Integration
- Compact
- Close Coupling

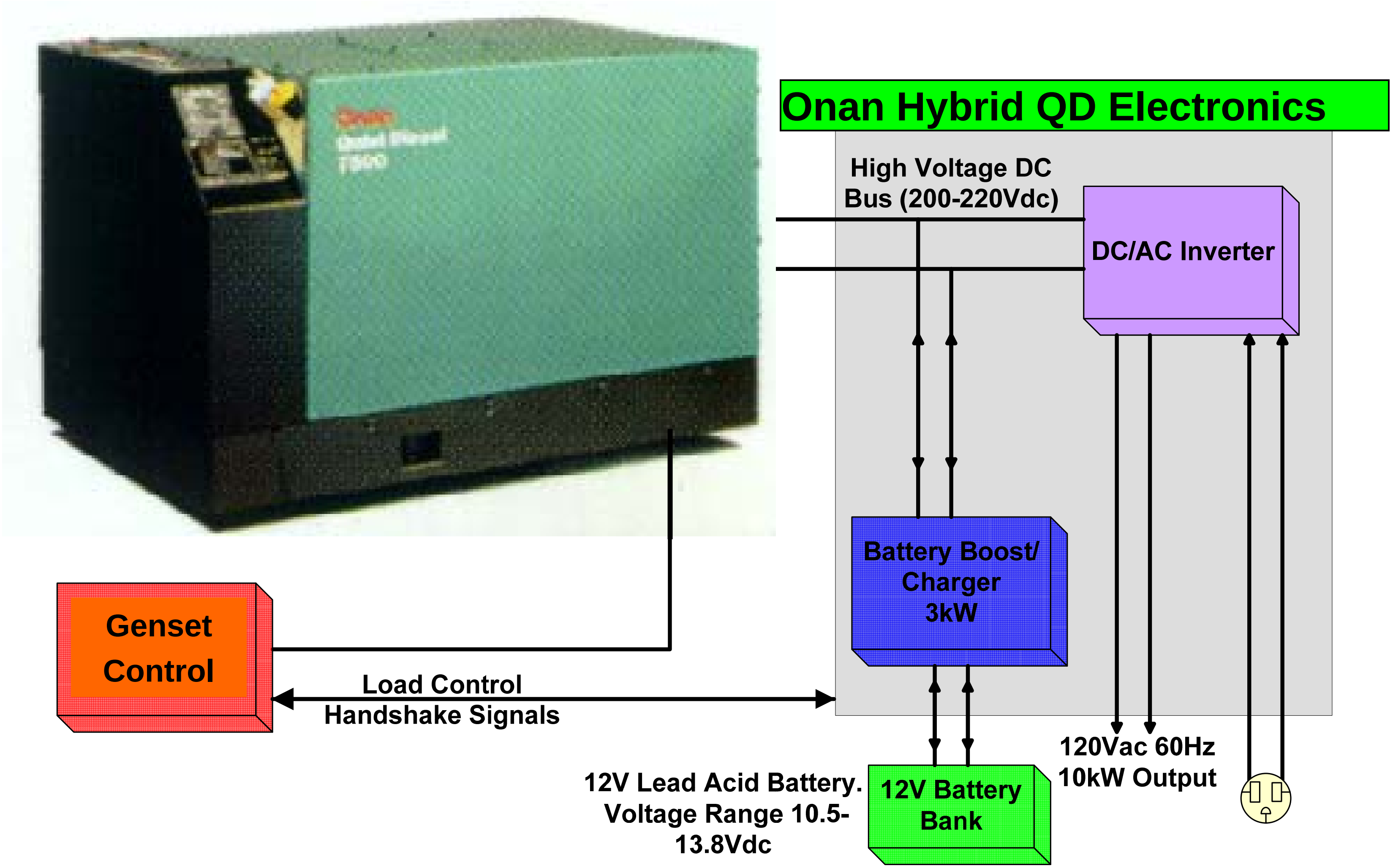


Packaging

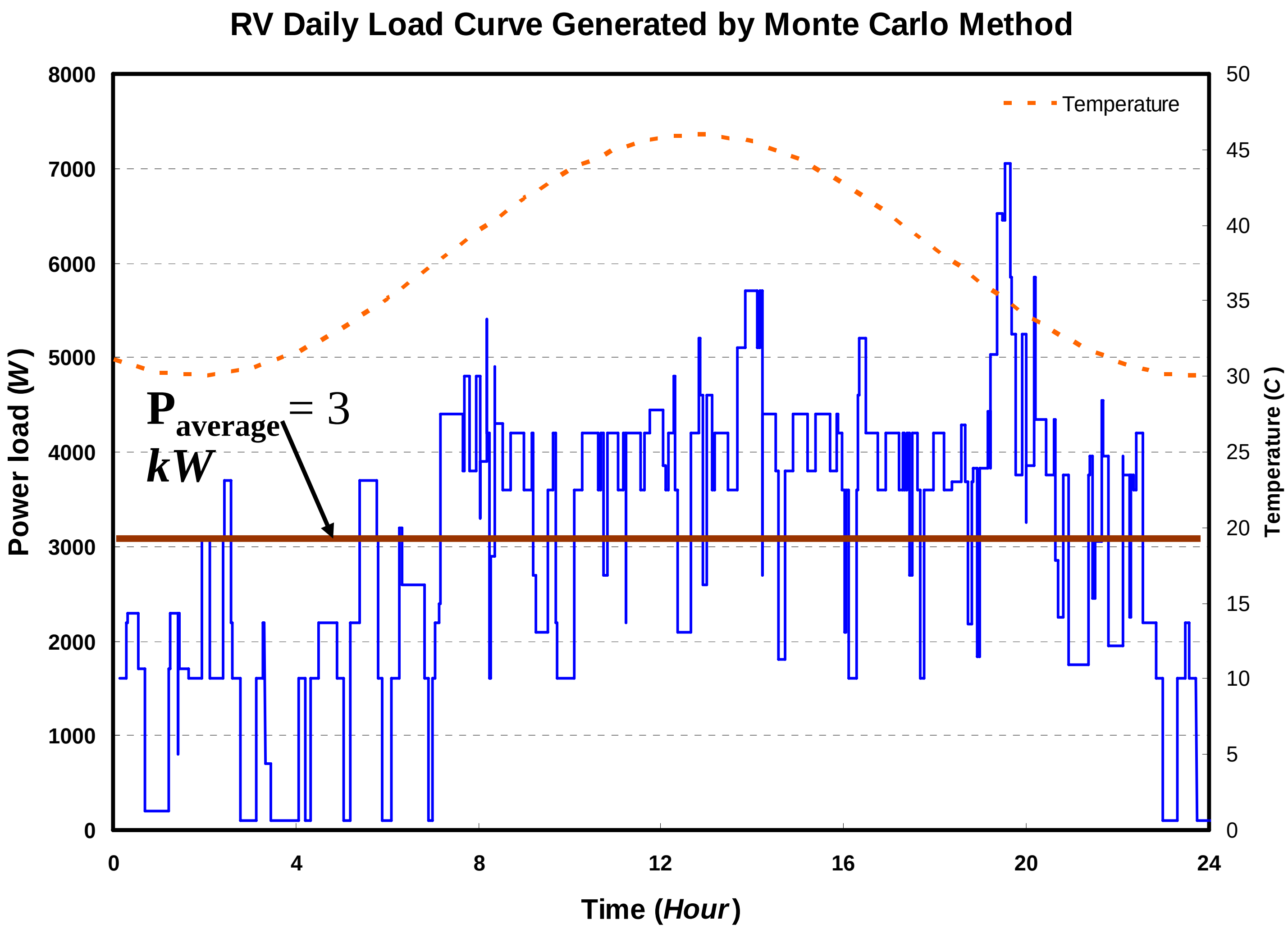
Power Generation

- Target for Phase 2 system: 400-450 L
- Replaces Diesel engine powered genset in hybrid system

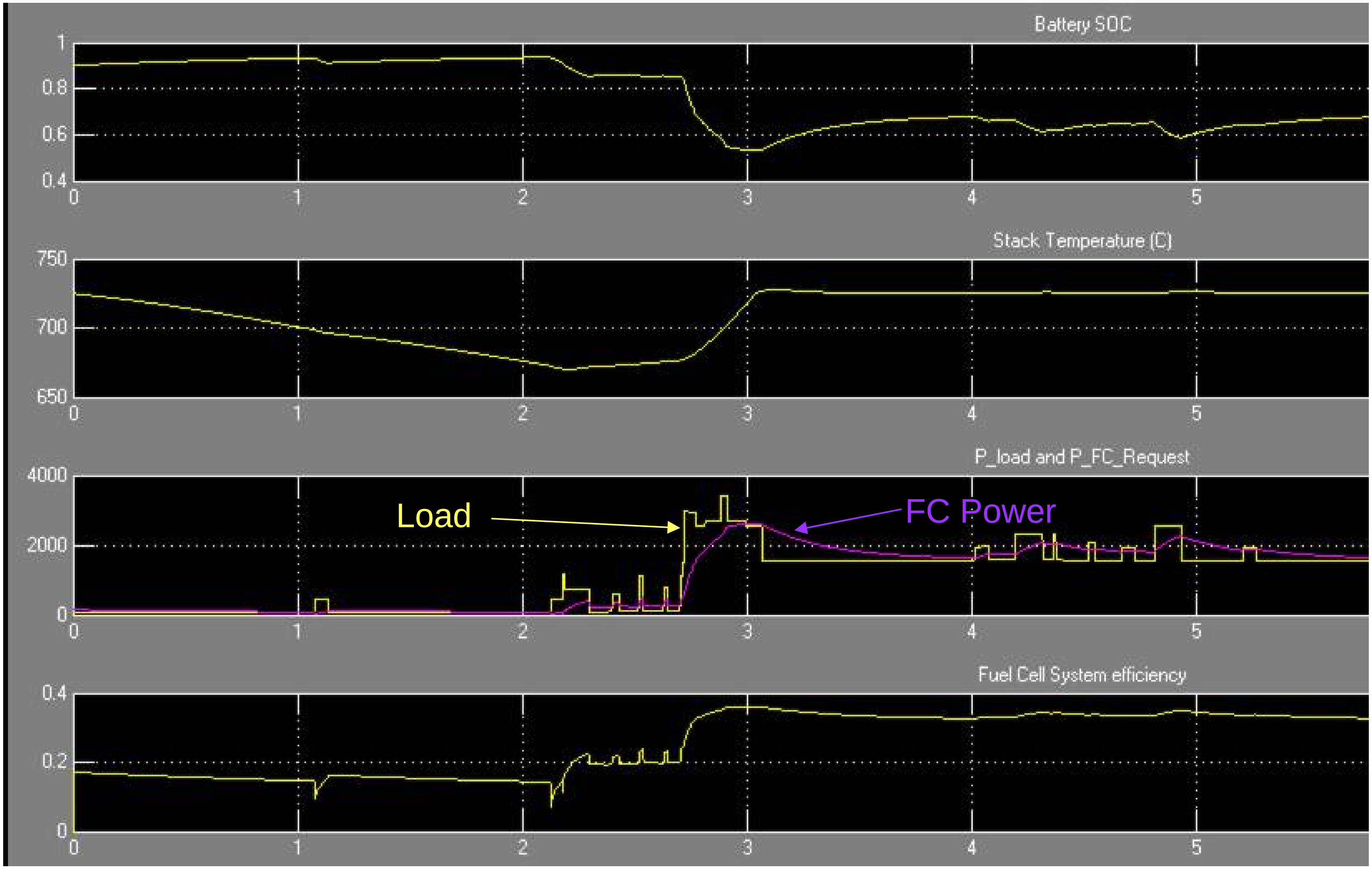
Common System Architecture



Dynamic Output for a Specific Input Condition



Sample System Model Run



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