Cummins Power Generation SECA Phase 1 Review

Dan Norrick
Manager Advanced Development
Cummins Power Generation

August 7, 2007
San Antonio, TX

Agenda

- Introduction
- SECA Phase 1 Results
- Phase 1 Development Progress
- Application of 6S Design Tools to fuel reforming strategy
- Some Remaining Challenges
- Acknowledgements

Agenda

Power Generation

- **Introduction**
- SECA Phase 1 Results
- Phase 1 Development Progress
- Application of 6S Design Tools to fuel reforming strategy
- Some Remaining Challenges
- Acknowledgements

Power Generation

Power of One

The Engine Business:

The Power Generation Business:

The Components Business:

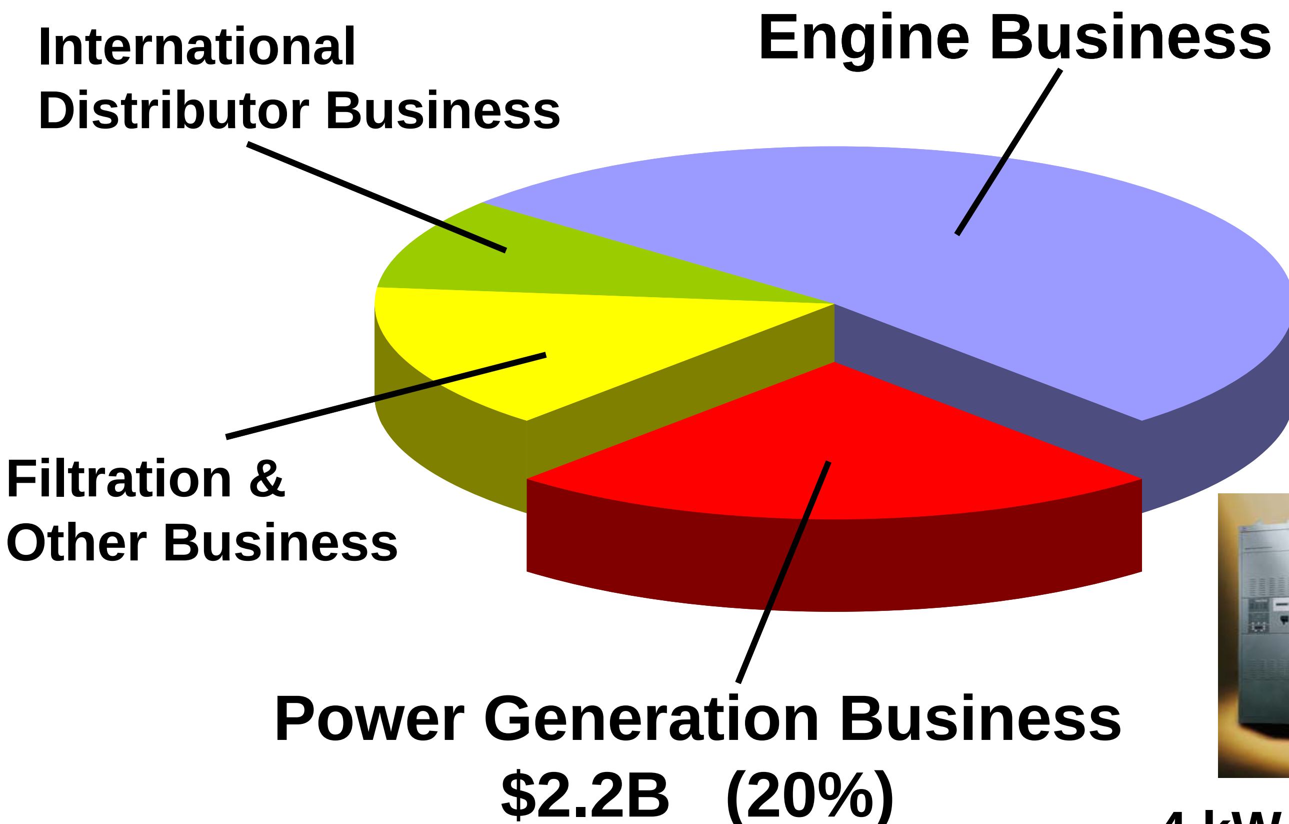
Global Operations - 2007

- Factories (26)
- Technical Centers (16)
- Parts Distribution Centers (15)
- Distributors (550)
- Sales and Service (5,587)

160 Countries
33,500 Employees
US$ 11.4 Billion in Sales
US$ 278 Million in R&D

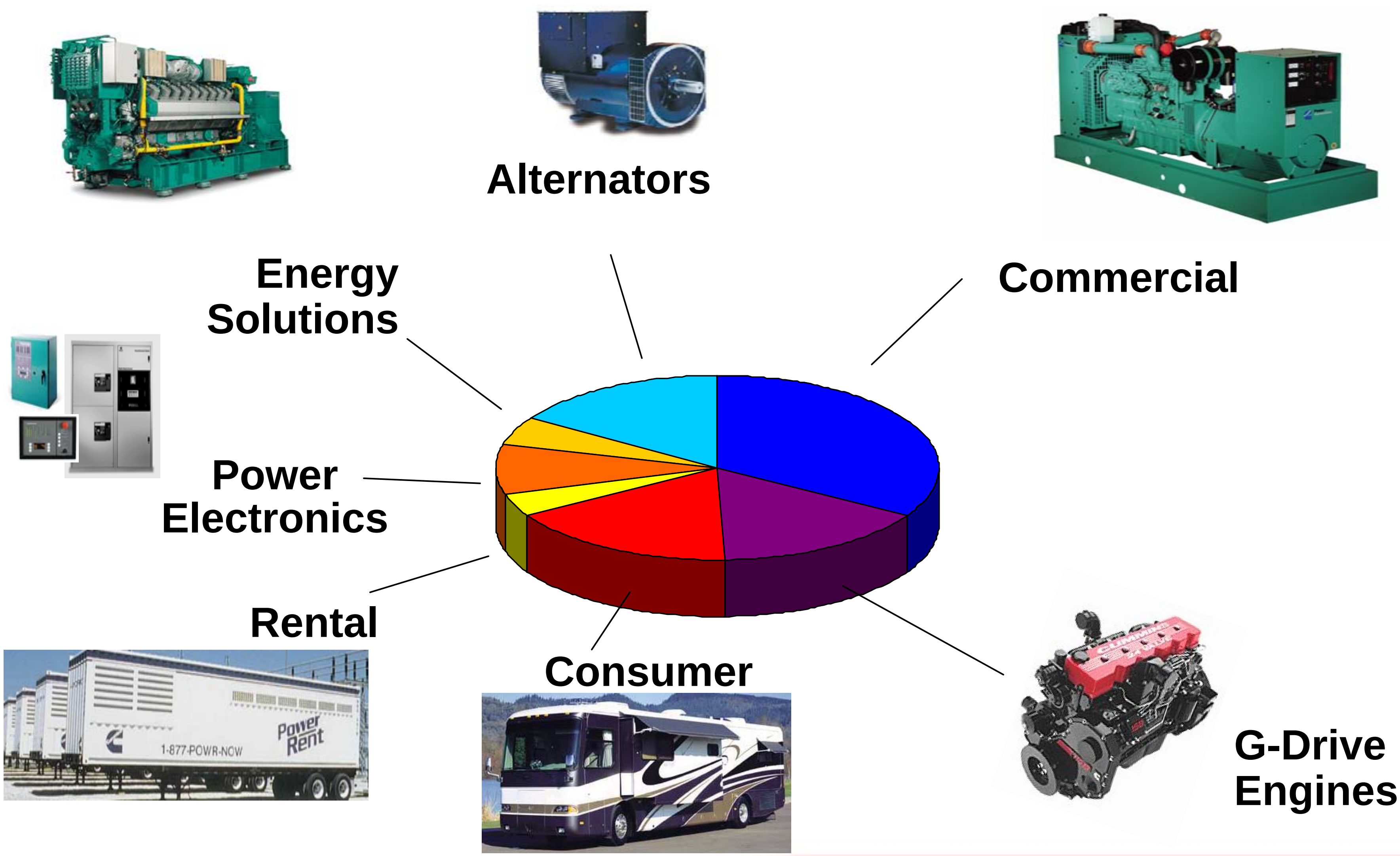
Cummins - Revenues

$11.4 Billion in 2006



4 kW to 2.5 MW gensets

Cummins Power Generation Revenue by Business Group



Cummins Power Generation

Typical Applications

Recreational Vehicle

3- 20 kW

Commercial Mobile

3 – 15 kW

Marine

3 – 95kW

Residential Standby

12 – 45 kW

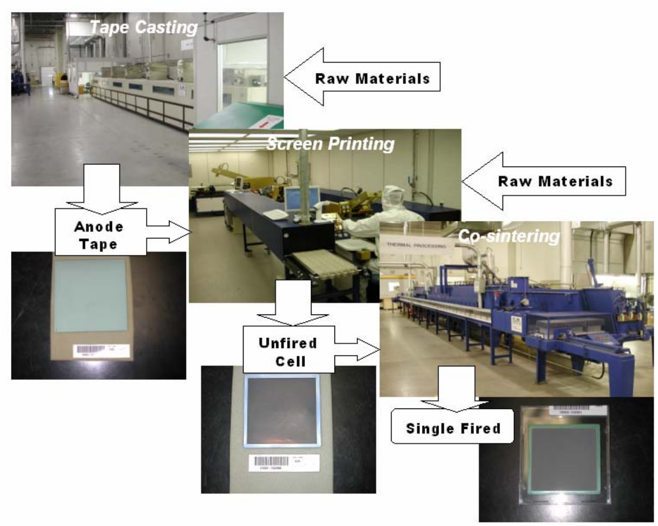
Diesel Commercial Standby & Prime

8 kW – 2.7 MW

Rental

Versa Power Systems (VPS)

- Focused on SOFC commercialization
- Demonstrated cost-effective SOFC ceramic cell manufacturing technology
- Developed a highly competitive state-of-the-art SOFC stack technology
- Built and operated multiple generations of complete, integrated SOFC systems



Agenda

- Introduction
- **SECA Phase 1 Results**
- Phase 1 Development Progress
- Application of 6S Design Tools to fuel reforming strategy
- Some Remaining Challenges
- Acknowledgements

CPG-VPS SECA Team

Cummins Power Generation

Versa Power Systems

Cummins Power Generation
Versa Power Systems Teaming Plan

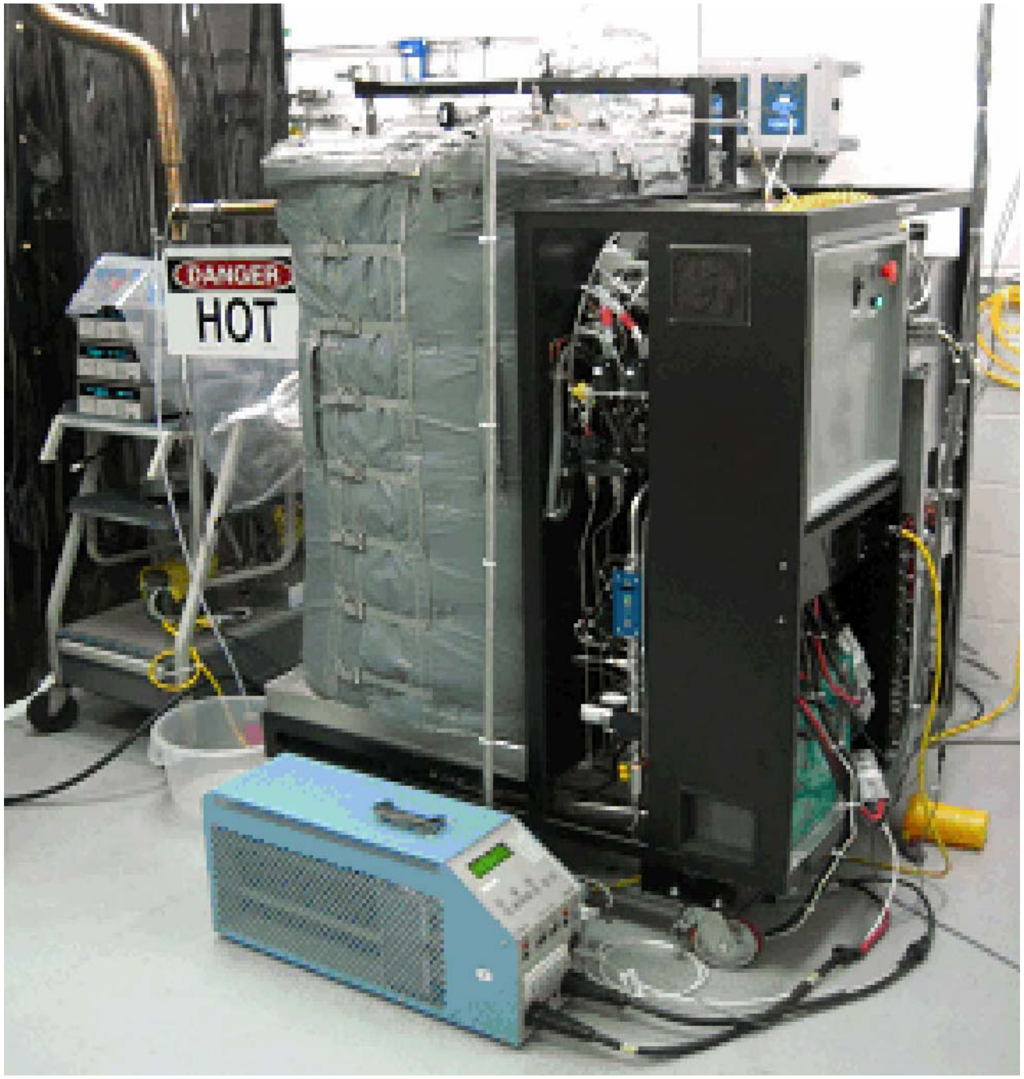
- Reformer development
- Electronic controls
- Power electronics
- Fuel systems
- Air handling systems
- Noise and vibration
- Power system integration
- Manufacturing
- Marketing, sales, distribution

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

CPG-VPS Team Phase 1 Accomplishments Overview

- Successfully delivered 3kWe nominal fully-integrated, automatically-controlled SOFC system called Mission 1 (or M1) system meeting SECA Phase 1 metrics.
- Developed a system concept & development plan for a Mission 2 (M2), mobile APU system.
- Developed, engineered, and prototyped a Mission 2 (M2) stack and hot module.
- Advanced core SOFC materials technology towards CPG's Value Package Introduction (VPI) goals in the area of sulfur tolerance and alignment to ultra-low sulfur diesel (ULSD).
- Identified low-cost BOP components applicable to SOFC and implemented in demonstration air supply system.
- Initiated application of 6S design tools to system optimization.

CPG – VPS SECA Phase 1 Test Unit in Cell 137 at CPG



- Unit startup
  - Oct 2, 2006
- SECA Test Start
  - Oct 15, 2006
  - 319 hours
- SECA Test Completed
  - Jan 4, 2007
  - 2250 hours
- Unit shut down
  - Jan 23, 2007
  - 2700 hours
  - 99% Availability

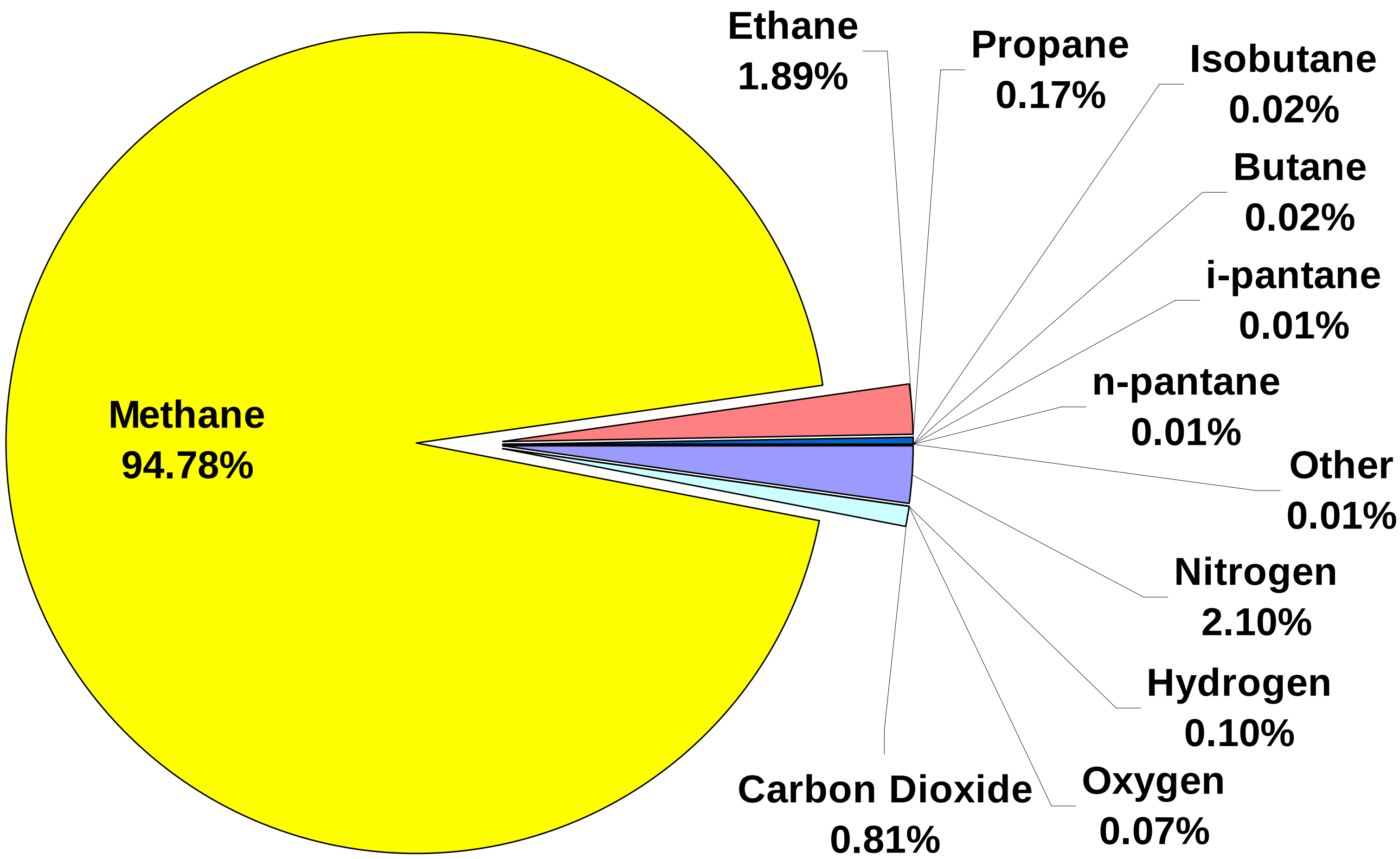
CPG – VPS
SECA Phase 1 Test Results

Cummins Power Generation

Versa Power Systems

RESULTS AGAINST PHASE 1 METRICS				
REQUIREMENT	***TARGET***		***Actual***	
Power Rating (Net DC@ NOC)	**3 – 10**	**kW**	**3.2**	**kW (4pt. Ave.)**
Efficiency Mobile (Net DC/LHV)	**25**	**%**	**37.1**	**% (4pt. Ave.)**
Steady State Degradation	**2% / 500 hrs**		**1.7**	**% / 500 hrs**
Transient Degradation	**1% / 10**		**1.1** **0.5**	**% / 10 (Full system)** **% / 10 (Stacks)**
Total Degradation - ref (1500h + Tran.)	**7 %**		**6.3** **5.7**	**% (Full system)** **% (Stacks)**
Availability	**> 80 %**		**99**	**%**
Peak Power (Net DC)			**4.6**	**kW**
Fuel Type	**Commercial Commodity**		**Commercial Pipeline (local utility) NG**	

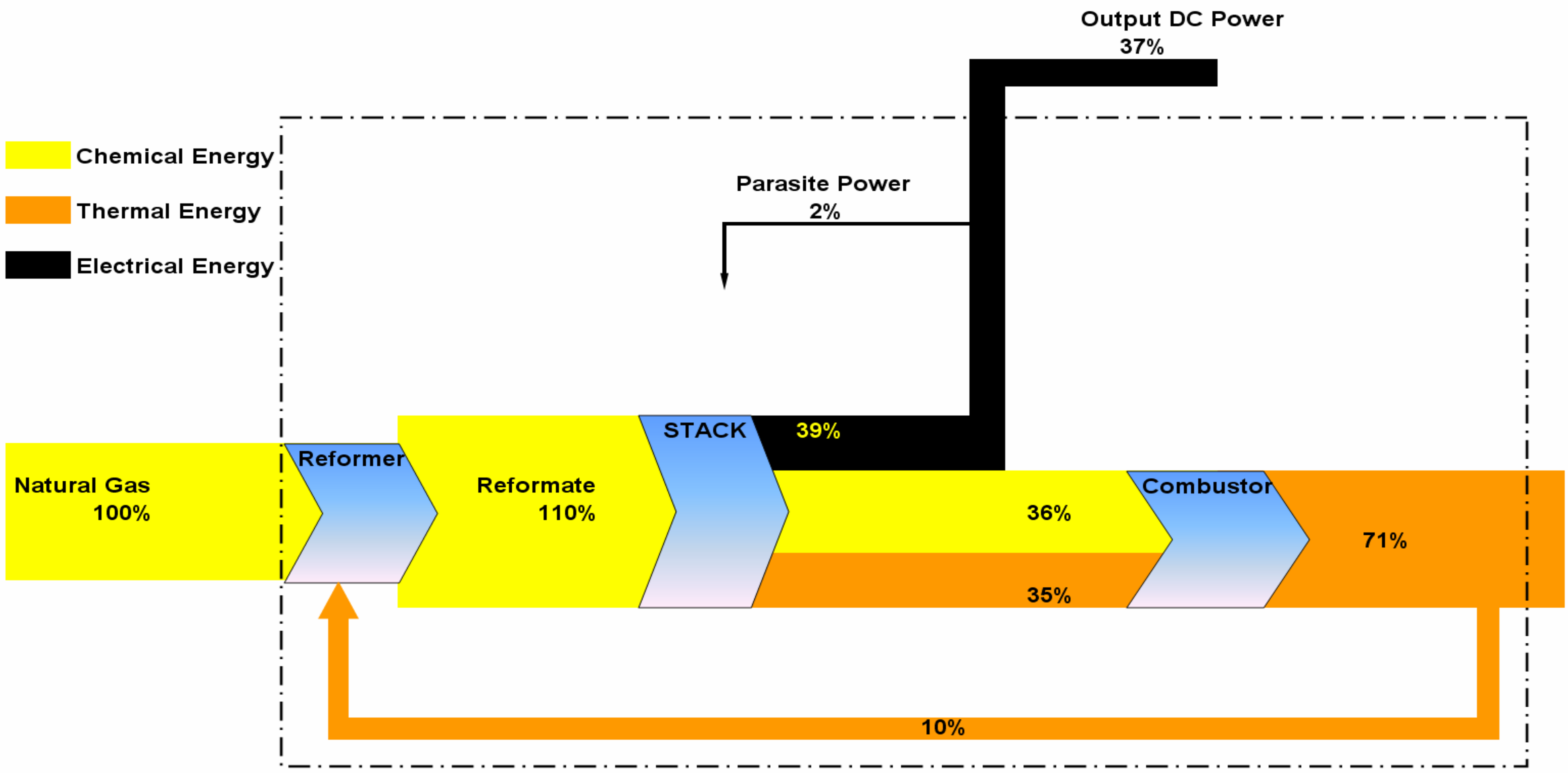
Gas Composition @ Desulfurizer Outlet



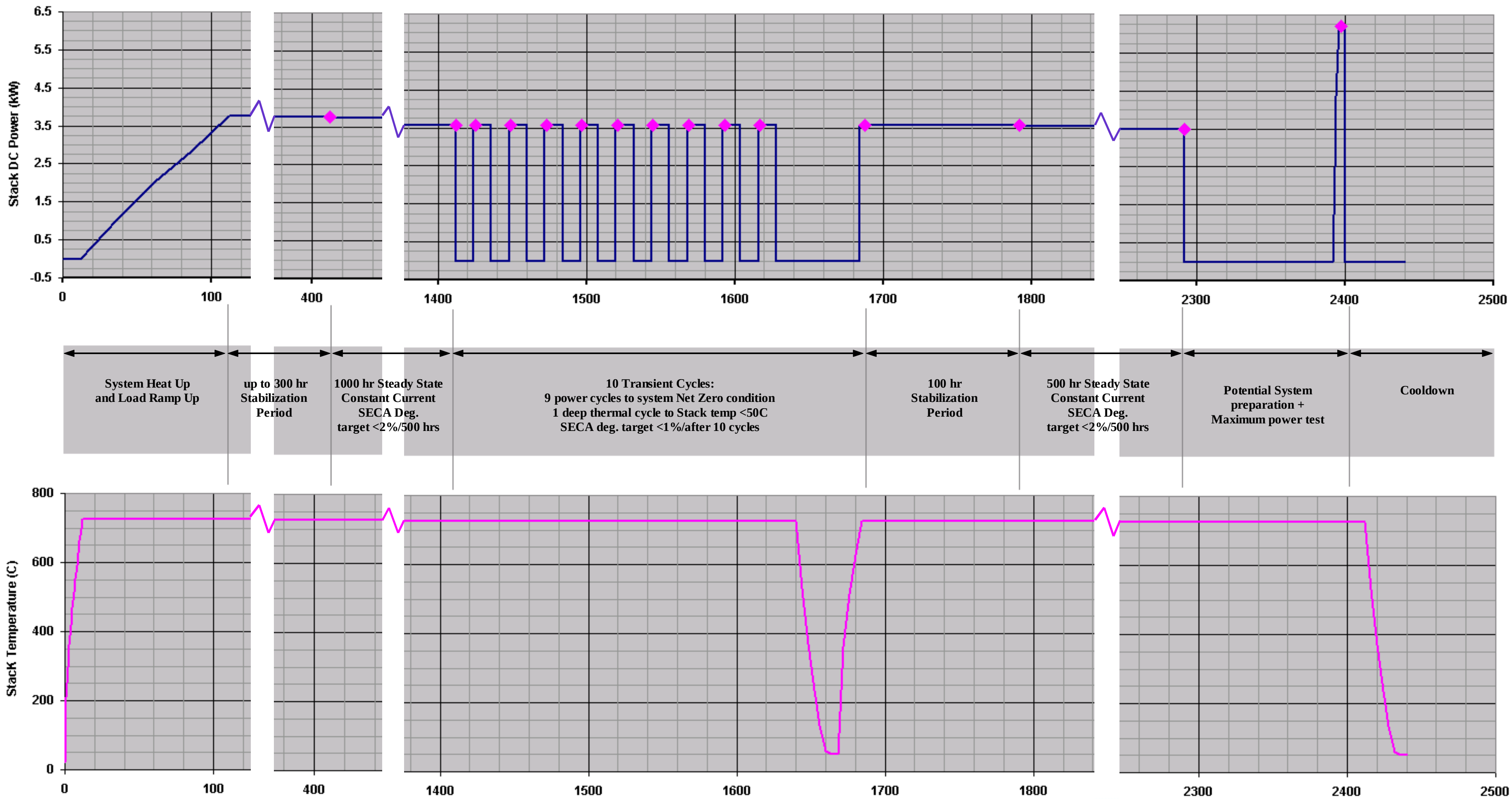
System Parameters @ NOC & Peak Power

	Unit	NOC	Peak Power
Power Density	mW/cm^2	268	402
Current	A	42	85
Voltage	V	86.7	64.1
Fuel Utilization	%	57.6%	56.9%
Net DC Efficiency	%	37%	26%

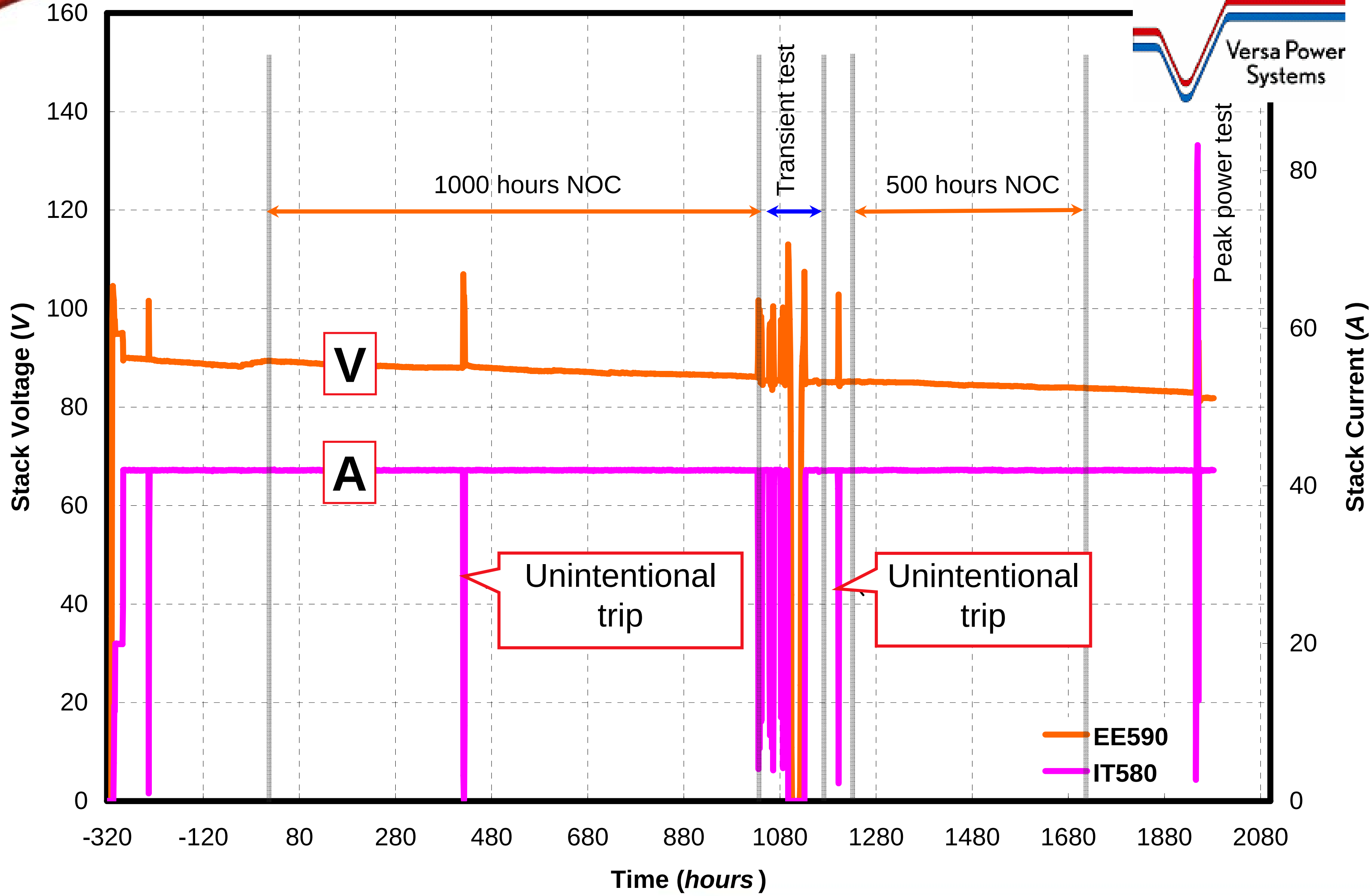
Sankey Diagram



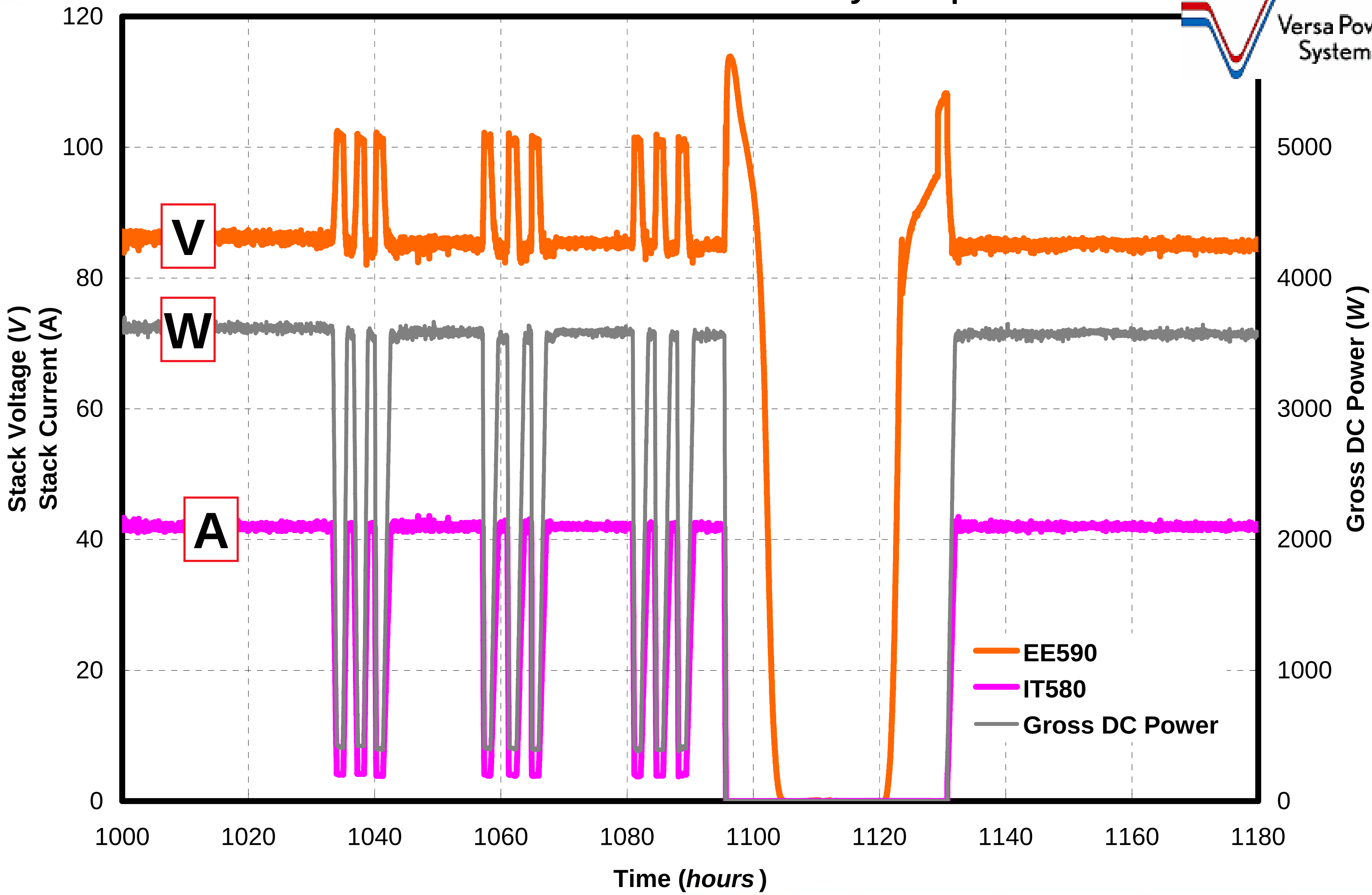
Phase 1 Test Plan



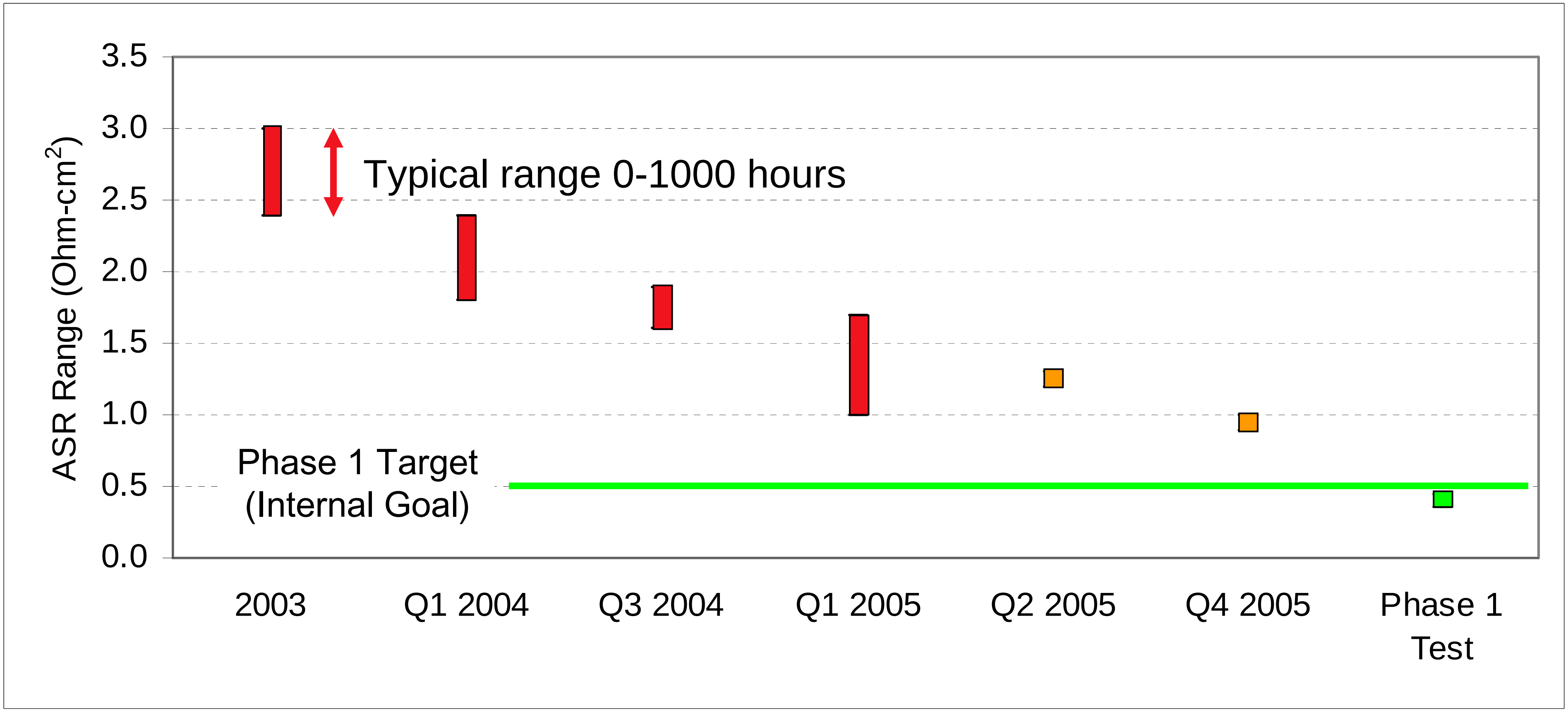
Stack Current & Voltage



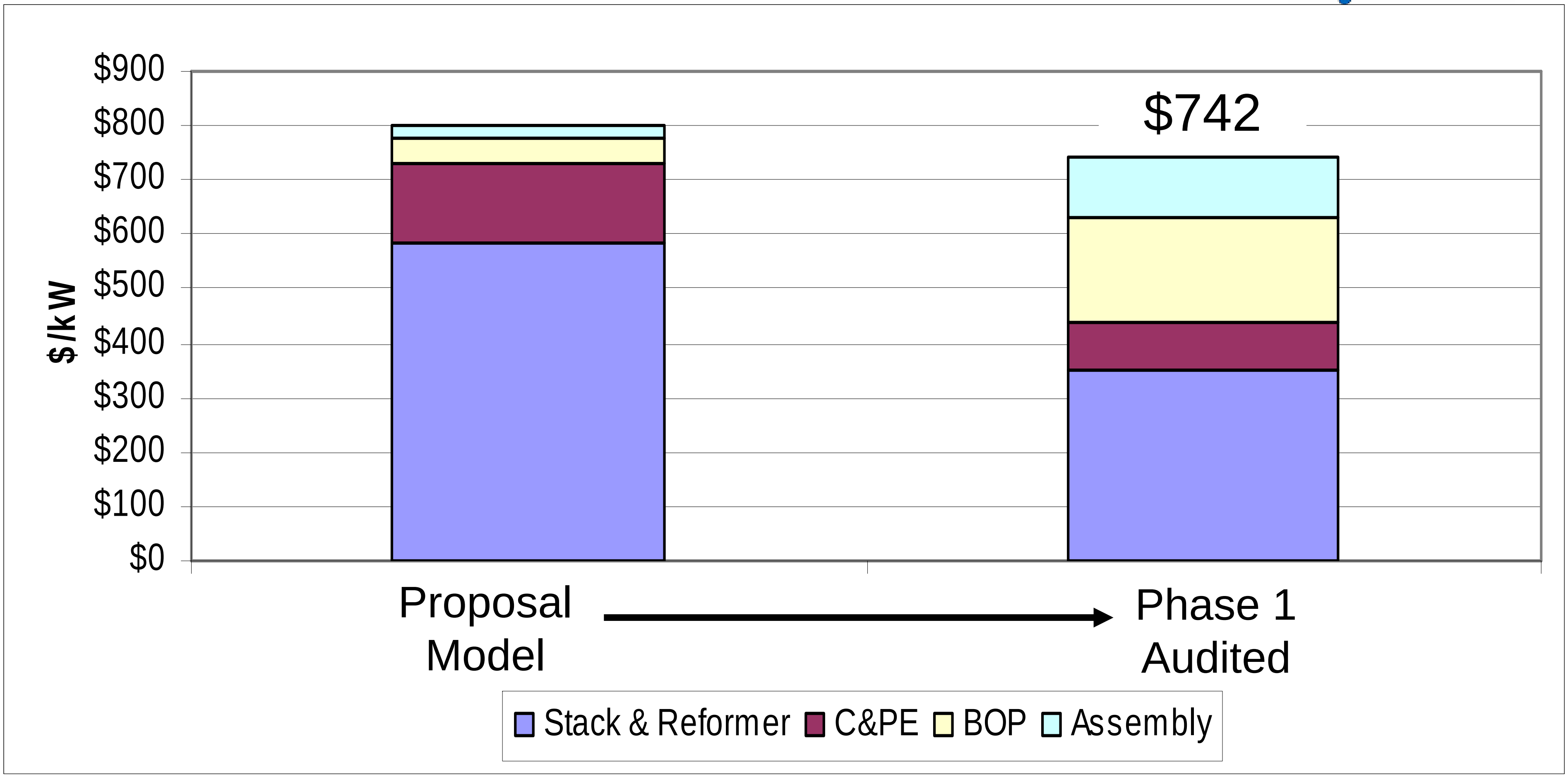
Stack Voltage, Current & Gross DC Power at the 10 transient cycle period



Phase 1 ASR Progress



SECA Phase 1 Cost Targets
Audited Cost Comparison



Agenda

- Introduction
- SECA Phase 1 Results
- **Phase 1 Development Progress**
- Application of 6S Design Tools to fuel reforming strategy
- Some Remaining Challenges
- Acknowledgements

VPS Technical Advances

Reduced Direct Internal Reforming

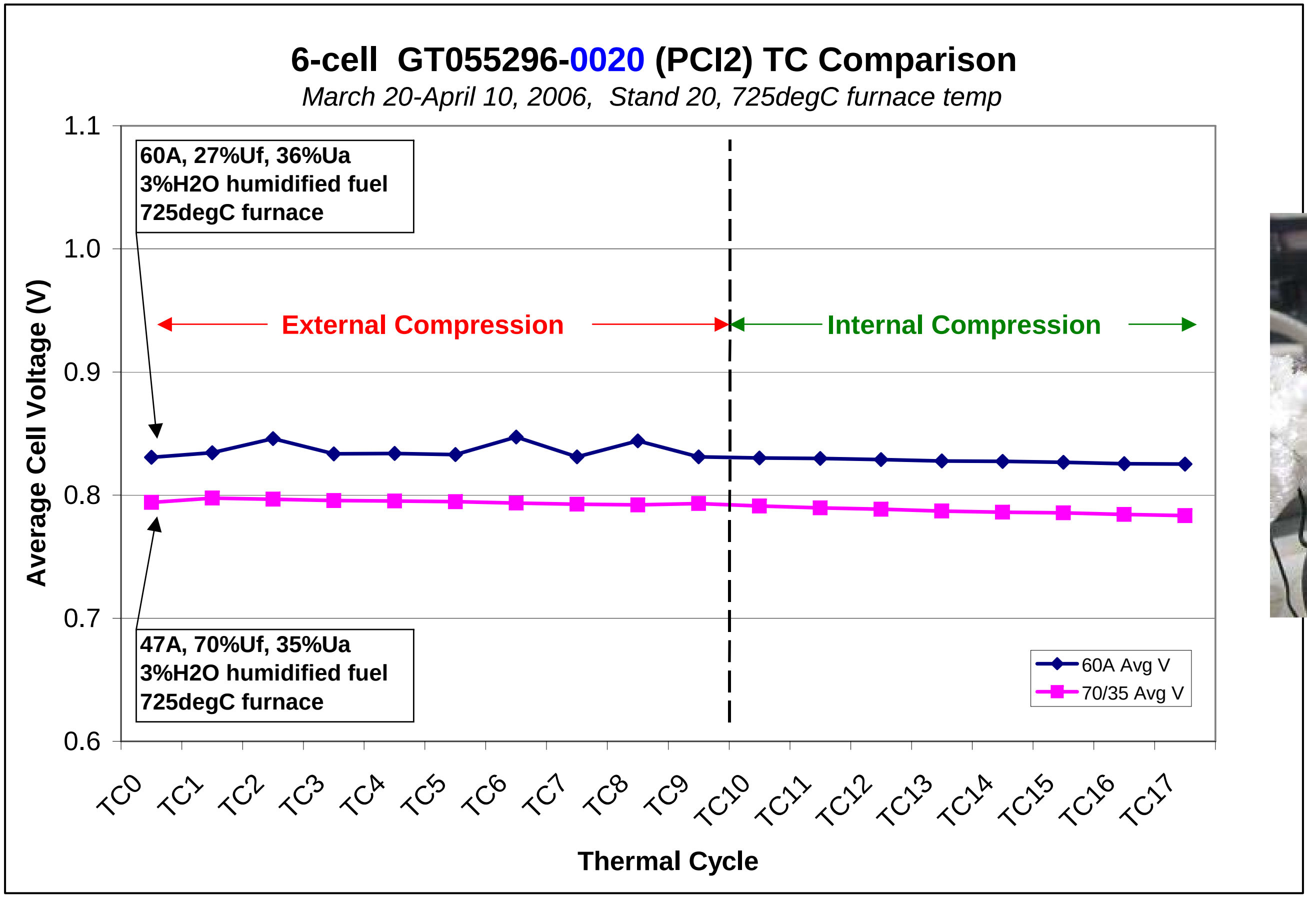
- Provides flexibility to operate with a wide variety of fuels, reforming technologies and operating conditions
- Shifts stack heat rejection to other cooling means
- Reduced DIR capability integrated into Phase 1 stack technology
- System reformer modifications completed to increase natural gas conversion to H_2 and CO; increased heat transfer in the afterburner / reformer design

Internal Compression

- Better suited to mobile applications with shock and vibration environment
- Replaces cold external system components with integrated in-stack (hot) clamping
- Reduces system volume and weight
- Reduces system part count and complexity

VPS Internal Compression Thermal Cycling Performance

Test Results (121 cm² active area):



VPS M2 APU Stack: Highlights

- **VPS developed the Mission 2 (M2) stack in response to CPG's mobile APU system / stack Requirements**
- **M2 APU-stack development objectives:**
  - **Preparation for SECA Phase 2**
  - **Advancement towards commercialization program goals at CPG**
  - **Form factor**
  - **Diesel reformate**
  - **Accelerated start protocol**

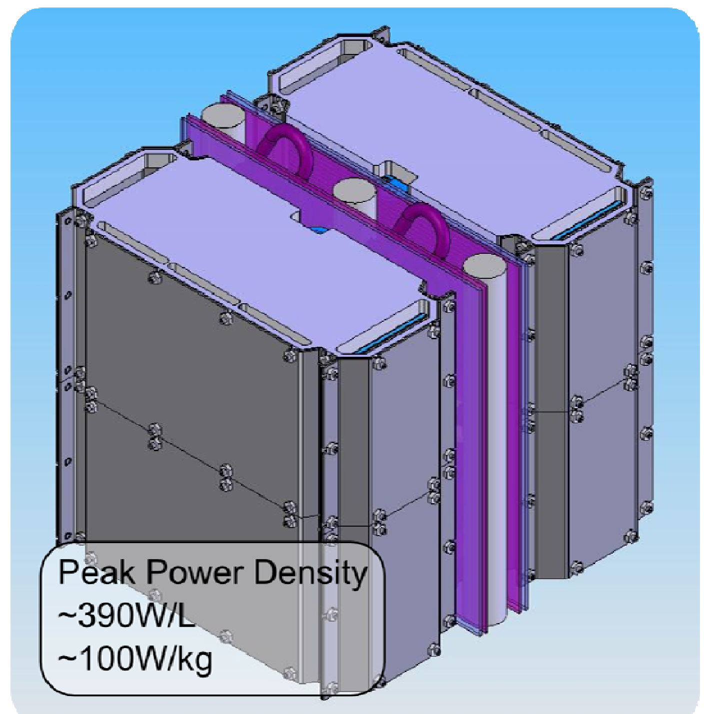
VPS M2 APU Stack

Power Generation

Versa Power Systems

Baseline layout

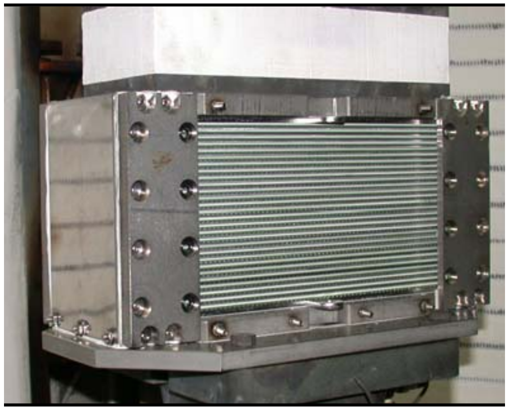
- 112 cells - 200cm^2
- 4 stacks
- 6.5kWe gross (NOC)
- 11kWe gross (Peak)
- 12” x 12” x 12” overall
- Close-coupled central cathode preheat
- No internal reforming
- External manifold



M2 APU Stack: Status

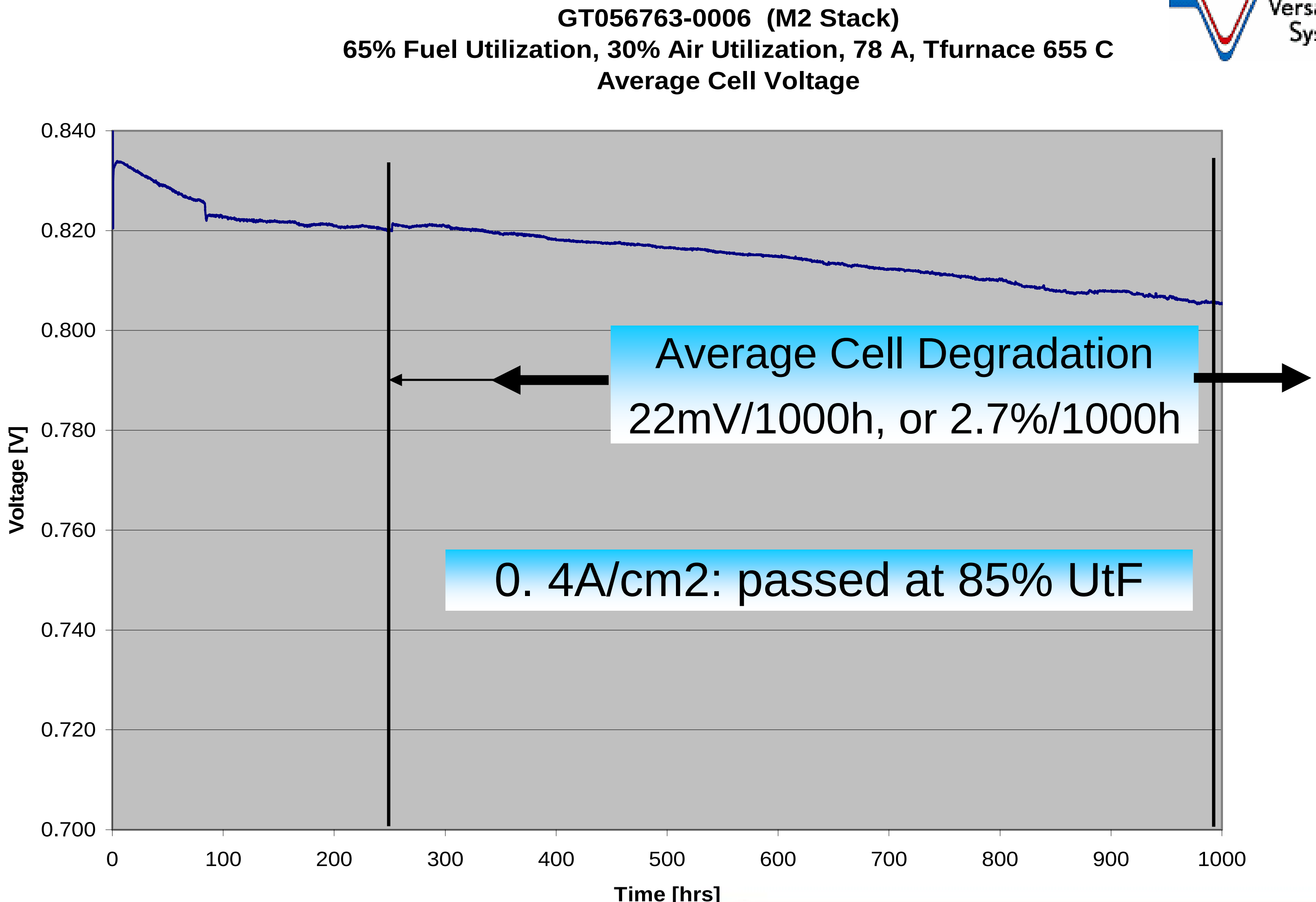
- M2 stack progressed from requirements and idea stage through engineering/testing of two stack iterations.
- Demonstrated: Cell Manufacturing scaleup, and stable manufacturing development
- The M2 stack is a technical fit for CPG's future APU development
  - custom-engineered to meet mobile APU product requirements.
- 17 x 28 cell stacks were built and tested
  - 9 stacks of REV00
  - 8 stacks of REV01
- A compact air heat exchanger was taken from concept through completion of proof of concept component testing for integration into the APU hot module

M2: REV00

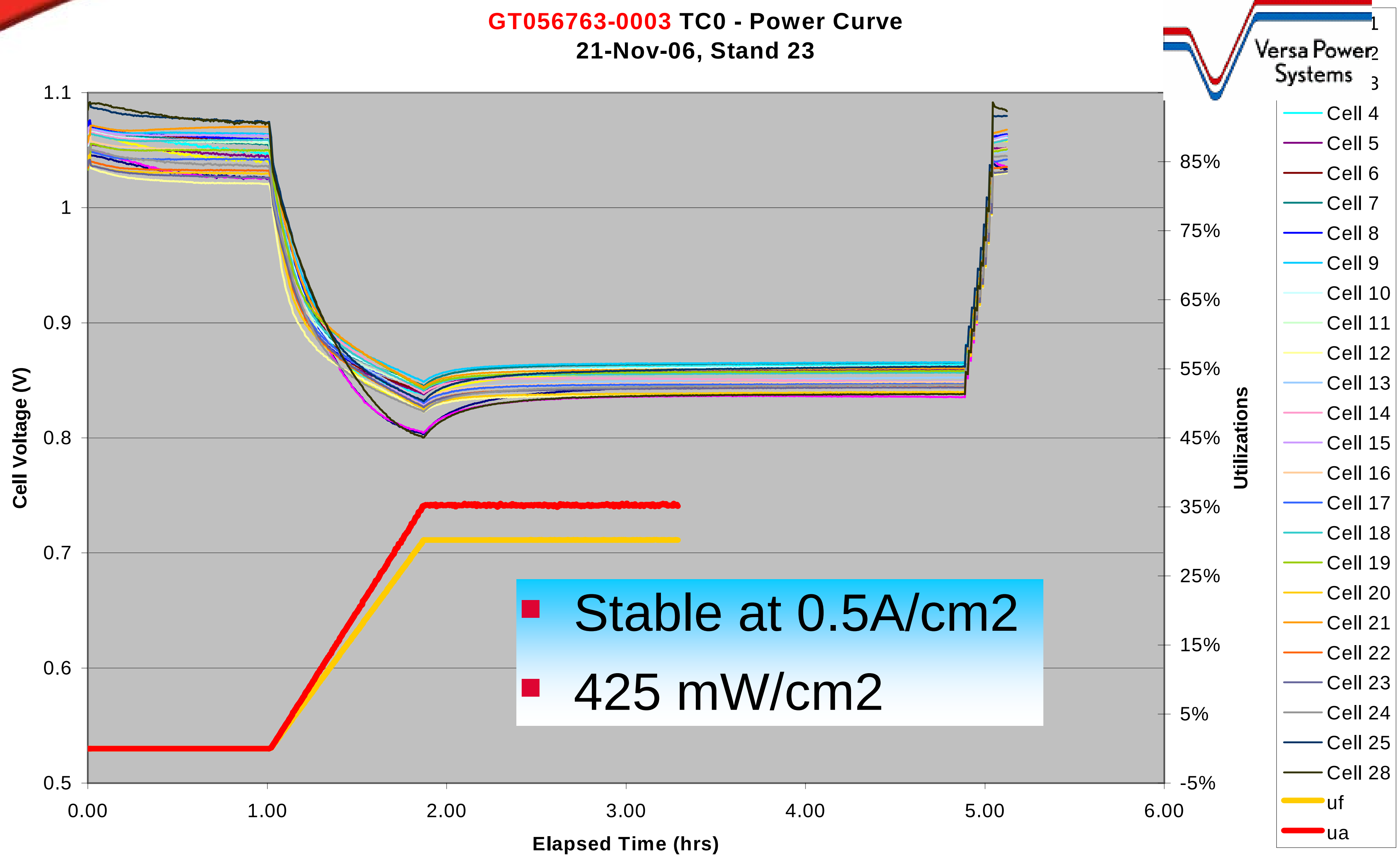


M2: REV01

VPS M2 Stack REV00: Performance at 0.4 A/cm2



M2 Stack REV00: Power Curve

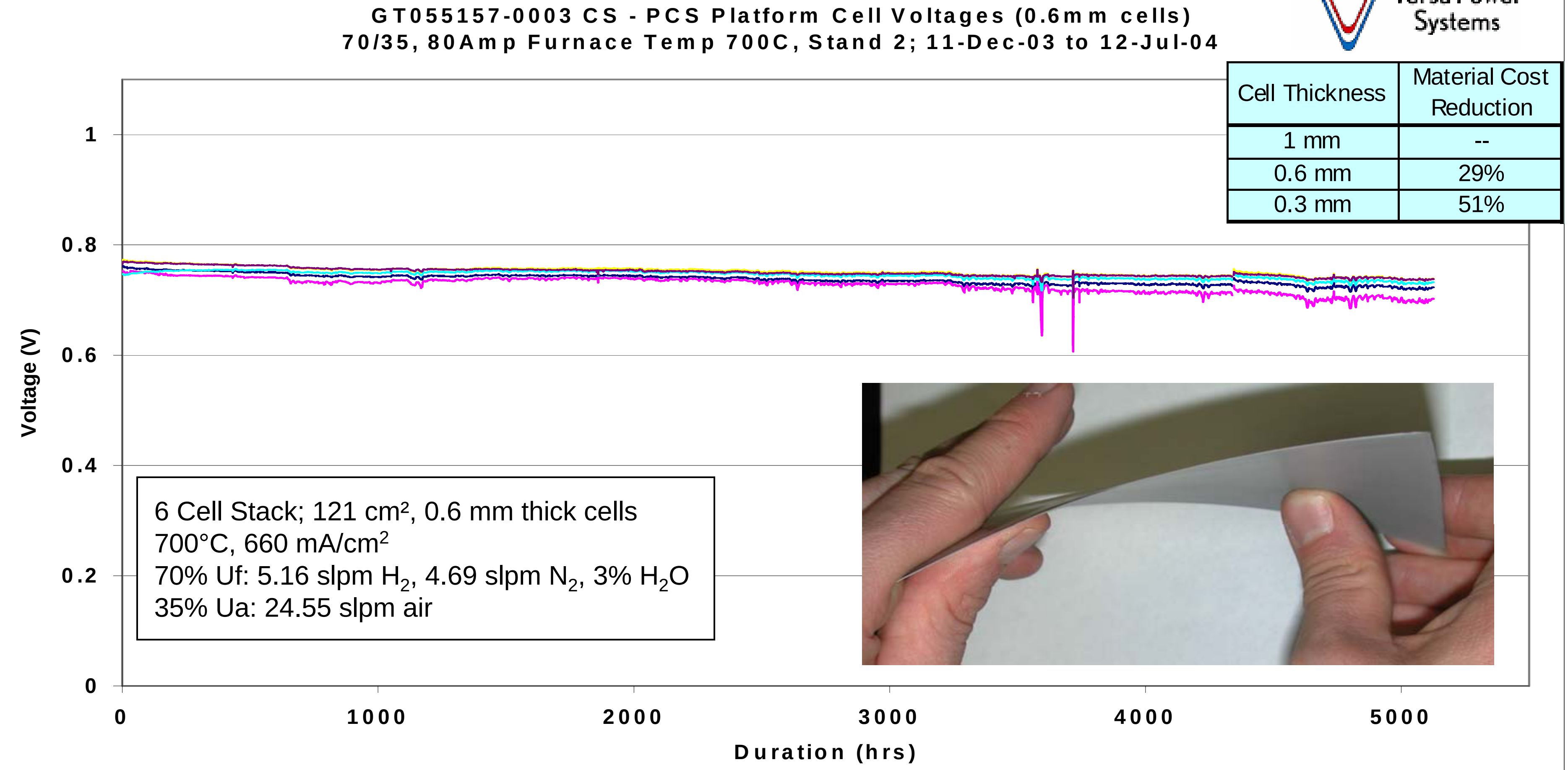


Cost Reduction: Thin Cell Development

Cummins Power Generation

Versa Power Systems

Cell Thickness	Material Cost Reduction
1 mm	--
0.6 mm	29%
0.3 mm	51%



6-cell thin cell stack operated for more than 5,000 hours at 0.49 W/cm² (80 Amps) and 70% fuel utilization.

- Degradation rate 0.74% per 1000 hours (<6 mV per 1,000 hours per cell) -

Agenda

- Introduction
- SECA Phase 1 Results
- Phase 1 Development Progress
- **Application of 6S Design Tools to fuel reforming strategy**
- Some Remaining Challenges
- Acknowledgements

Diesel Diesel Reforming 6S Technology Evaluation

SR with WCR – Steam Reforming (SR) with Water Condensation Recycle (WCR)

SR with WMR – SR with Water Membrane Recycle (WMR)

ATR with HAGR – AutoThermal Reforming (ATR) with Hot Anode Gas Recycle (HAGR)

ATR with WAGR – ATR with Warm Anode Gas Recycle (WAGR)

ATR with WCR

ATR with WMR

ATR with supplemental water

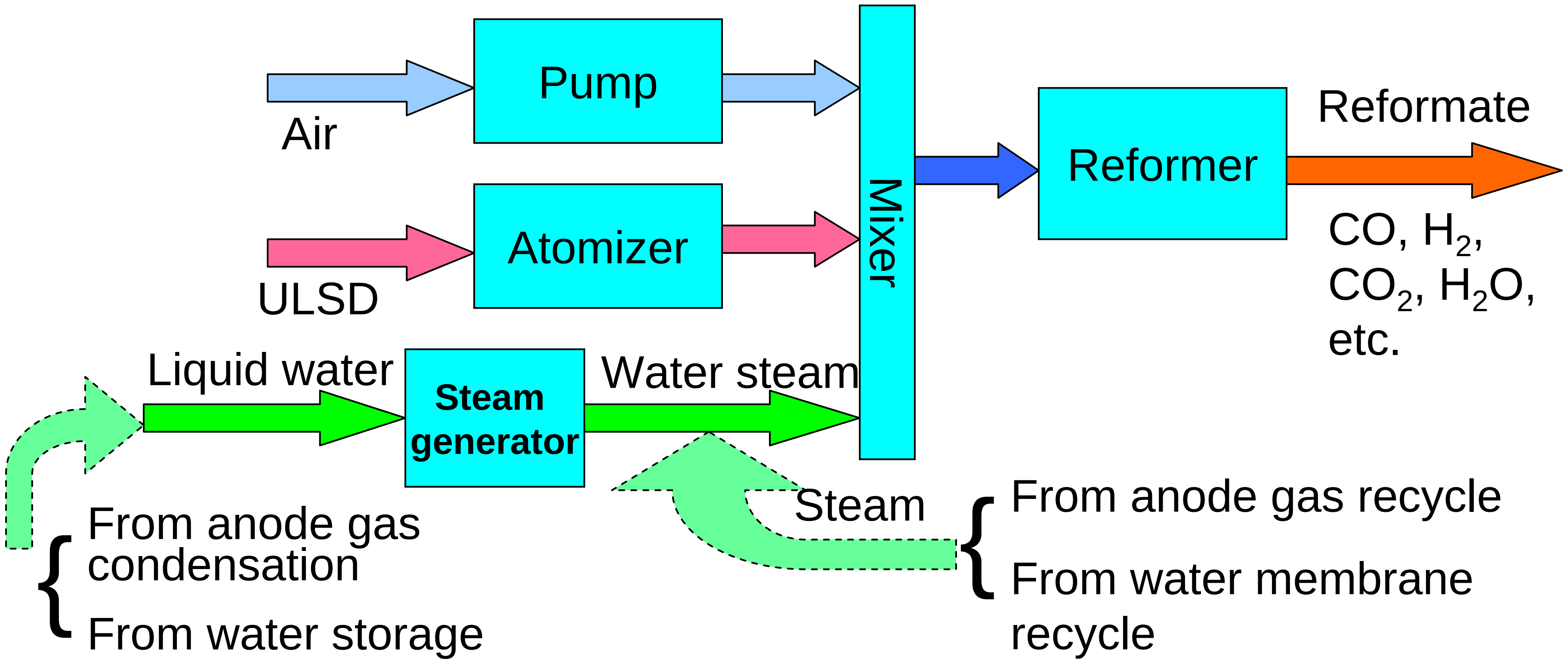
CPOX – Catalytic Partial OXidation (CPOX)

CPOX with downstream WCR injection

CPOX with downstream storage water injection (with water tank)

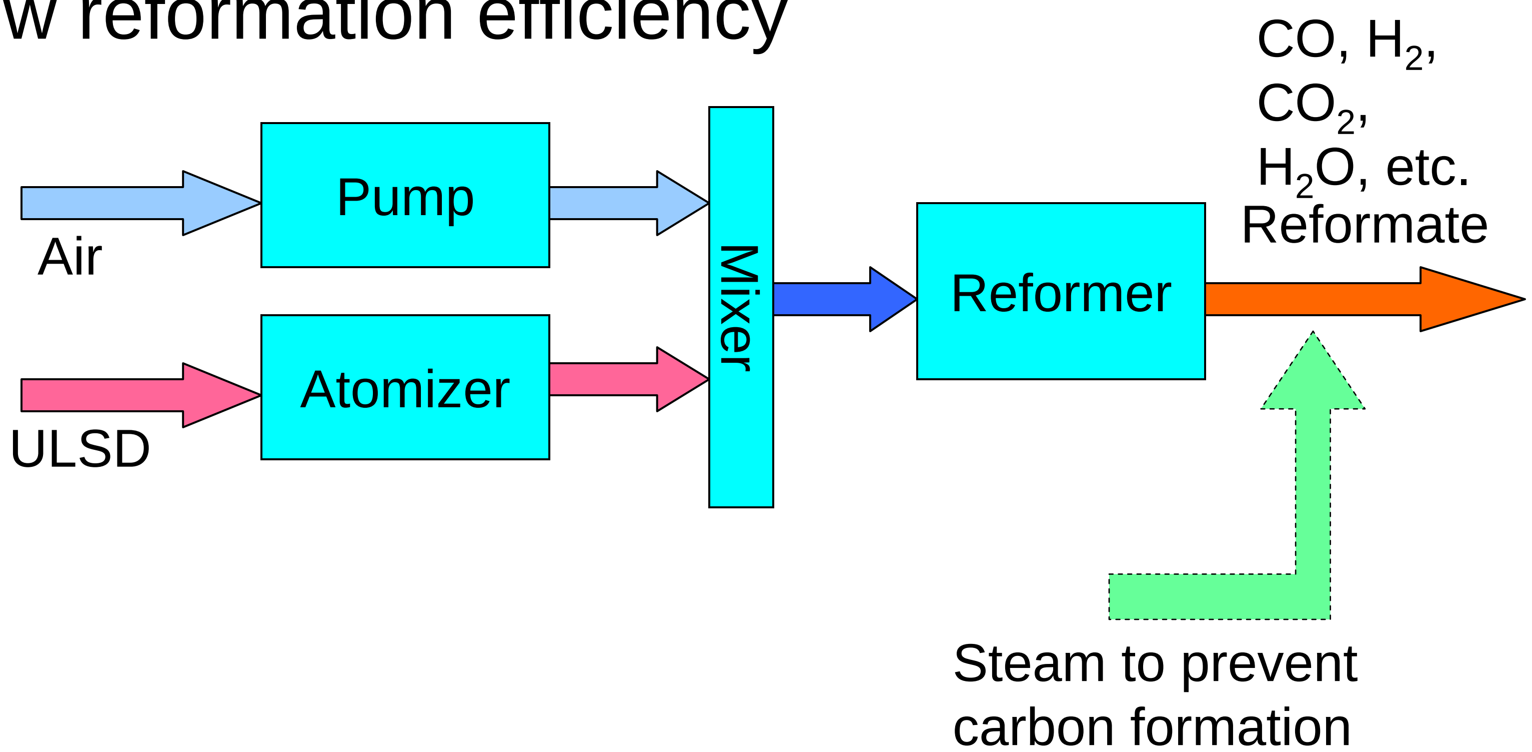
Auto-thermal Reformer (ATR)

- Lower carbon formation risk
- Higher reformation efficiency



Catalytic Partial Oxidation (CPOX) Reformer

- High carbon formation risk
- Low reformation efficiency



SR vs. ATR vs. CPOX (3 kW net DC)

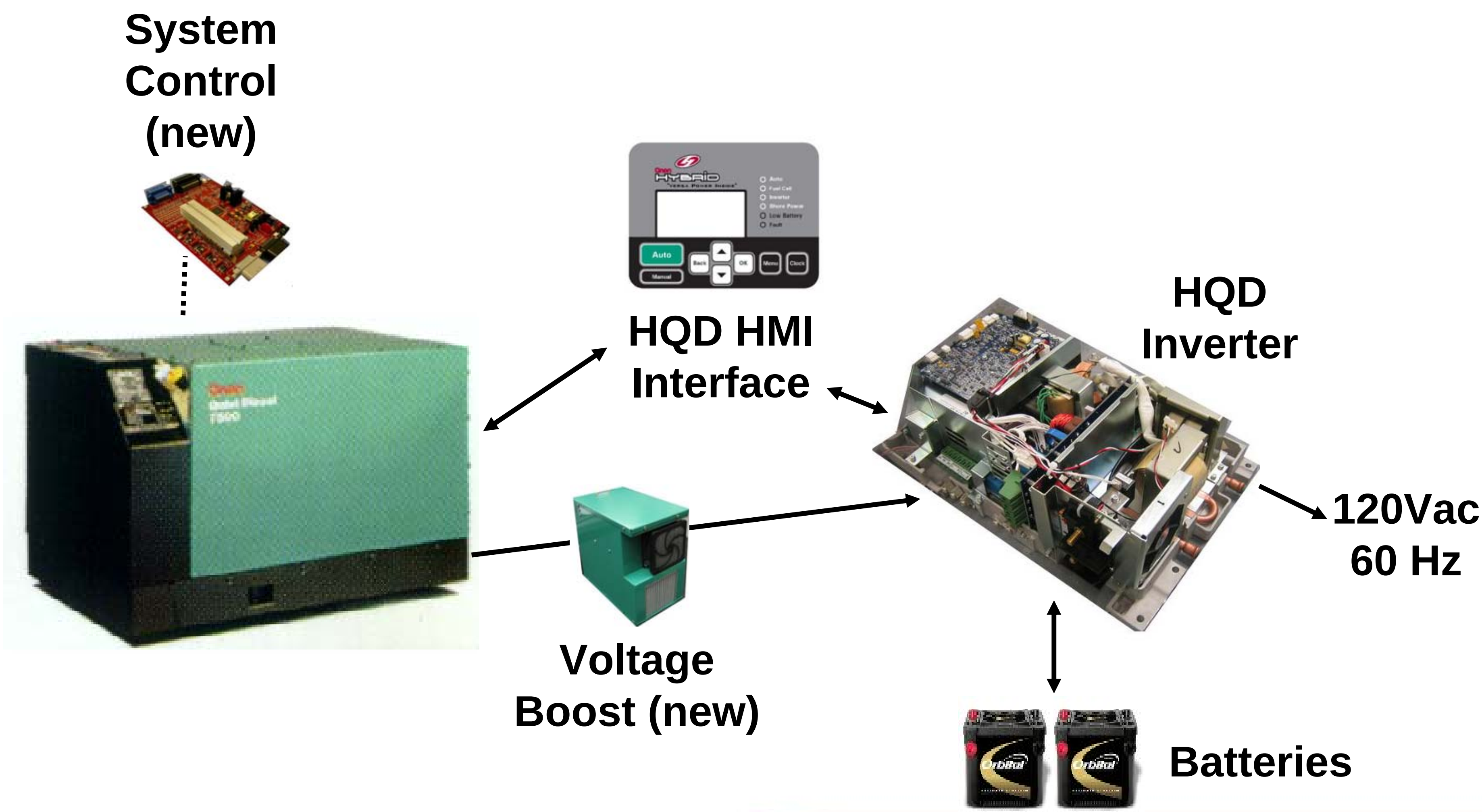
	SR	ATR	CPOX
S/C	3.0	1.1	0
Parasitic Power (kW)	0.50	0.45	0.40
Stack Efficiency	43.5%	43.5%	43.5%
DC Boost Efficiency	95%	95%	95%
Reformer Efficiency	110%	85%	70%
Overall System Efficiency	39.0%	30.5%	25.5%
Diesel Consumption (GPH)	0.20	0.26	0.31
Water Requirement (GPH)	0.67	0.31	0

Ranking of Reformation Technologies

Ranking	C&E Matrix	Pugh Matrix
1	~~CPOX~~	~~CPOX~~
2	ATR with HAGR	ATR with HAGR
3	ATR with WAGR	ATR with WAGR
4	~~SR with WCR~~	~~ATR with supplemental water~~
5	~~SR with WMR~~	~~ATR with WMR~~
6	ATR with WCR	ATR with WCR
7	~~CPOX with downstream WCR injection~~	CPOX with downstream storage water injection
8	CPOX with downstream storage water injection	~~CPOX with downstream WCR injection~~
9	~~ATR with supplemental water~~	~~SR with WMR~~
10	~~ATR with WMR~~	~~SR with WCR~~

Common Electronics Architecture

Cummins Onan Hybrid QD™



Agenda

Power Generation

- Introduction
- SECA Phase 1 Results
- Phase 1 Development Progress
- Application of 6S Design Tools to fuel reforming strategy
- **Some Remaining Challenges**
- Acknowledgements

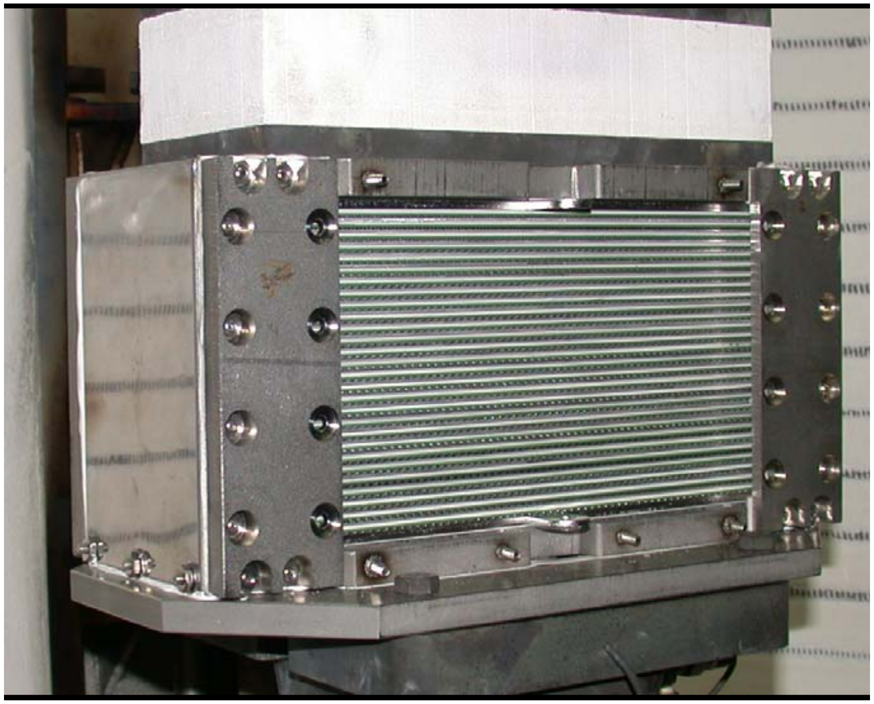
Challenges remain…

- SOFC stack evolution
- Zero net water diesel fuel reforming
- Sulfur (ULSD)
- Transient operations
  - Start-stop without purge gases
  - Load pickup / variable load operations Hibernation
- Degradation
  - Steady state (life) degradation
  - Transient degradation
- Mechanical robustness
- Controls
  - Autonomous control of all transient operations
  - Dynamic load sharing with stored energy (hybrid mode) – recalibration to fuel cell time constants

VPS M2
Mobile APU Stack

- New form factor, HX arrangement
- Additional M2 stack development is needed to:

  - Stabilize the platform
  - Attain statistical confidence to integrate into mobile APU systems with full product capability
  - Characterization over full operating range



M2: REV01

Fuel / Reforming

- Fuel
  - CPG's SECA work to date based on LPG and Natural Gas
  - On-highway ULSD (< 15 ppmw sulfur) is critical to successful commercialization of CPG Target Markets
  - ULSD transition underway in supply system
- Reforming
  - Exploring zero net water alternatives for commercialization
  - Examining water management strategies (recovery vs. recycle)
  - Strategic partner for co-development

Sulfur Tolerance

CPG expects 15ppm by weight sulfur in ULSD to result in ~ 3-5ppm by volume in reformate (ATR or CPOX)

Two pronged approach:

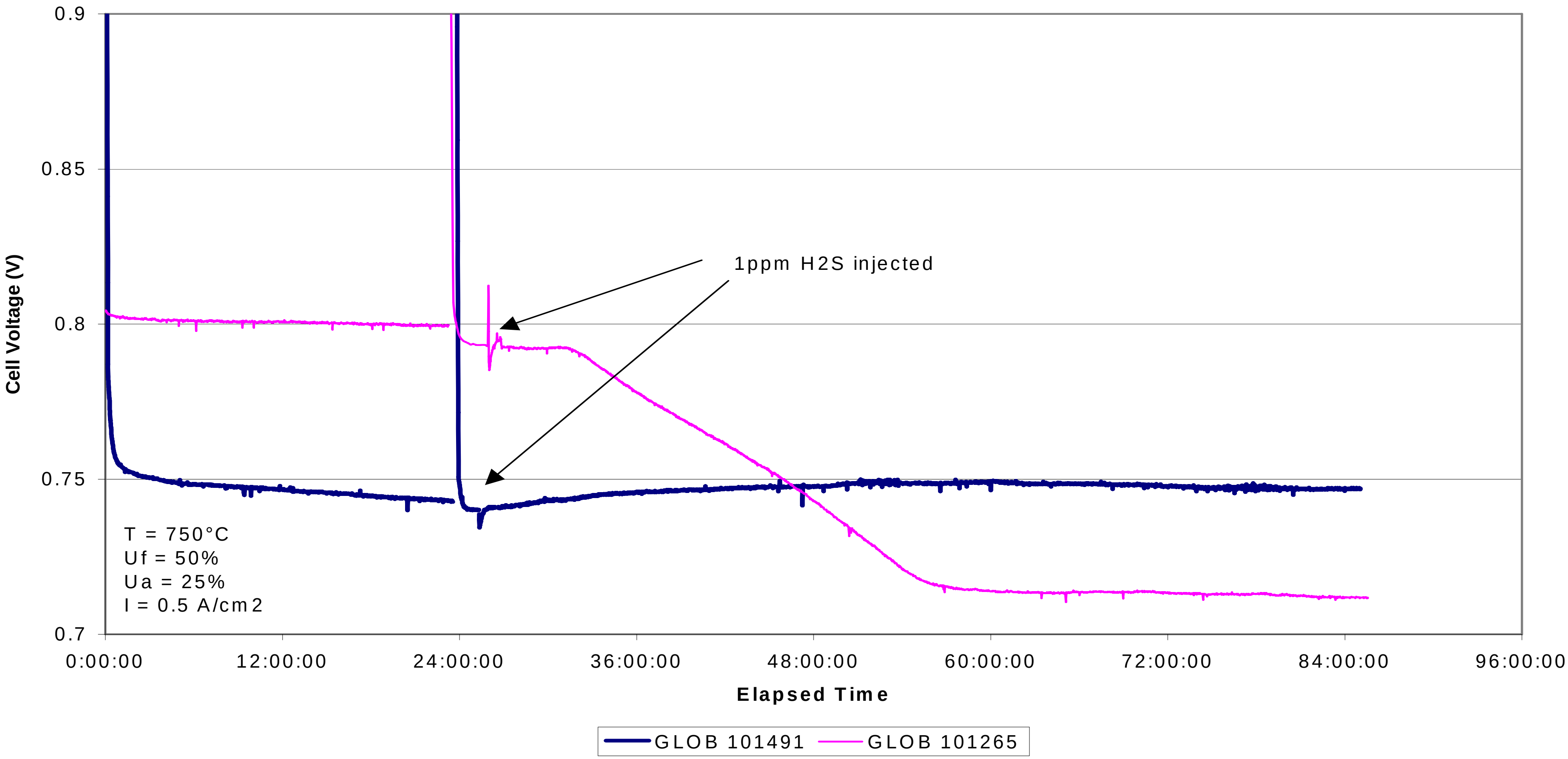
- Identification and development of sulfur tolerant anode materials (preferred approach, cell and stack selection factor)
  - Cost, size, weight, maintenance of desulfurizers
  - Anticipate need for recovery from temporary sulfur spikes
- Incorporate de-sulfurization (backup plan)
  - Liquid phase
  - Gas phase

Sulfur Tolerance

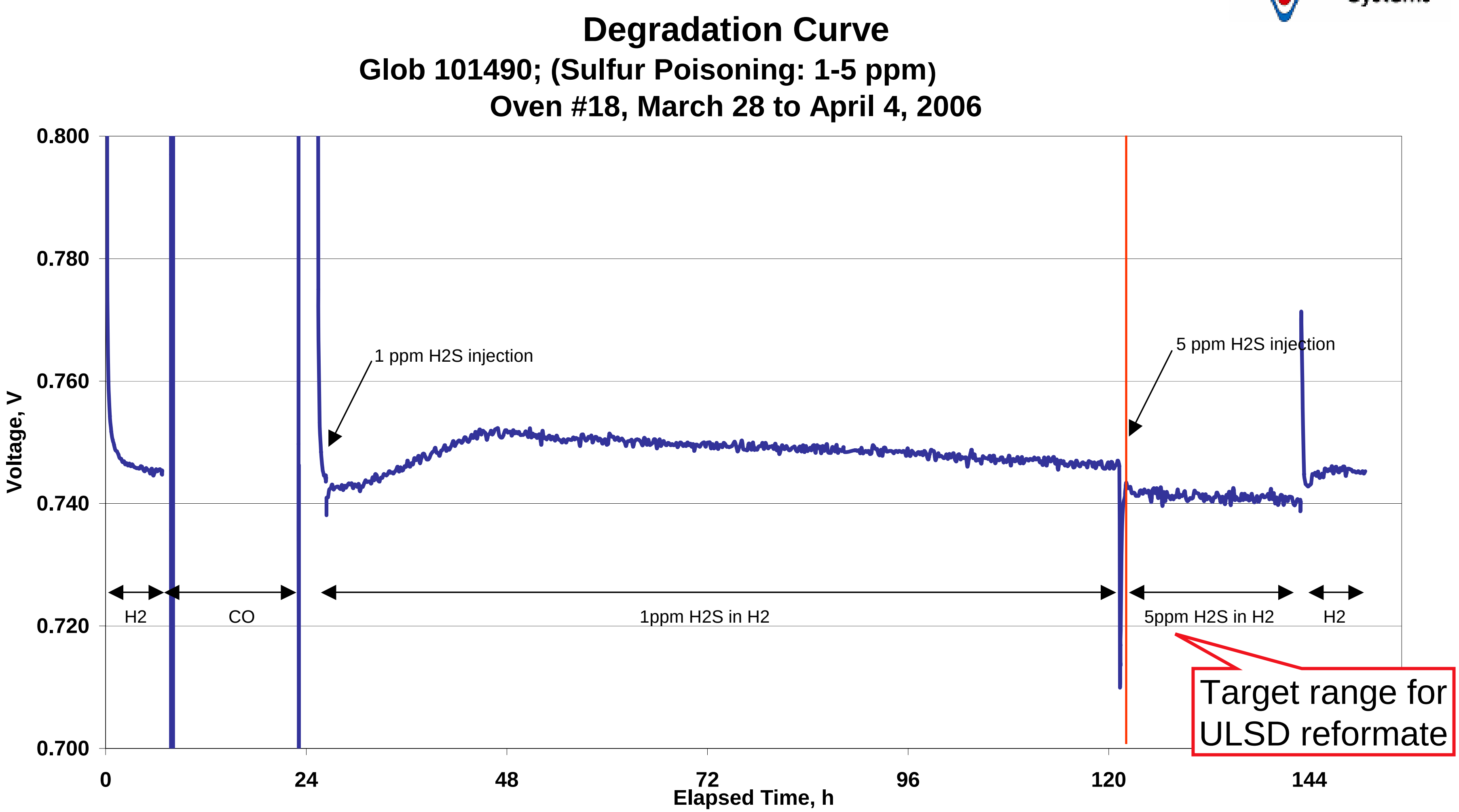
- Novel anode material system
- Improved performance and stable operation to at least 1000 hours compared to VPS standard TSC2 cell
- Tested H2S concentrations of 1-5 ppm in humidified H2 fuel
- Next stage of development will move to single cell and extended stack durability testing

VPS APU Advanced Anode Enhances Sulfur Tolerance

GLOB 101491: 1ppm H2S Poisoning Cell Comparison With GLOB 101265, Standard TSC-2 Cell



VPS APU Advanced Anode Enhances Sulfur Tolerance

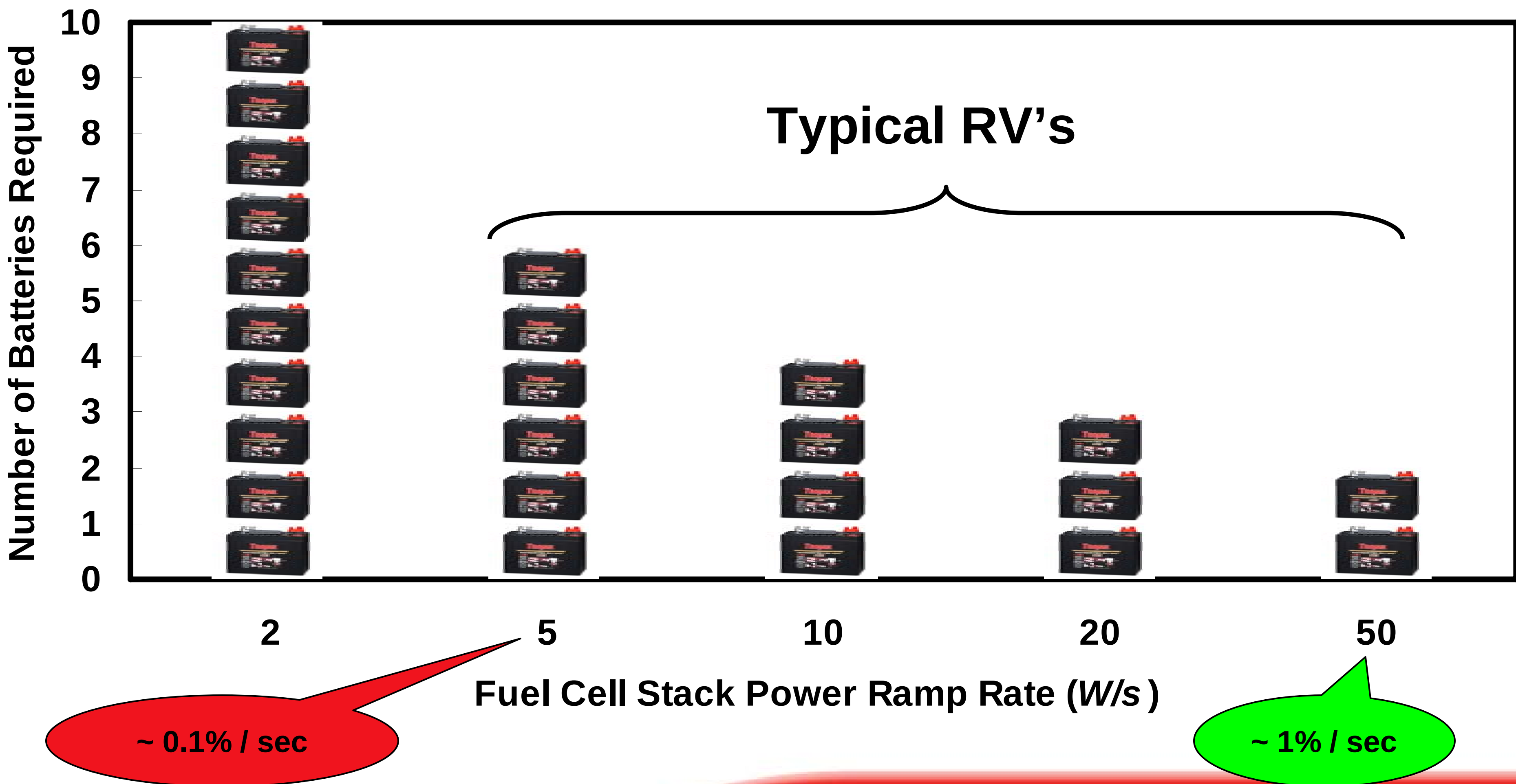


Transient Response

- Stack transient response robustness will be a selection factor for non-base load applications like APU's
- System effects of slow response are
  - Increased energy storage requirements
  - Higher system losses with energy transport into/out of storage

Power Generation

Example: Influence of transient response on energy storage requirements for RV's



Real World Durability

Transient

- Ability to sustain start / stop cycles without excessive degradation
- Ability to enter and recover from state of “hibernation” without degradation
- Ability to start consistent with loads and manageable energy storage requirements

Operational life time

- Interrelated with start time, transient degradation
- Varies by market but expected to be substantially greater than current technology (gensets)

Low Start Time

Extended Start Time

Low Operating Hours

High Operating Hours

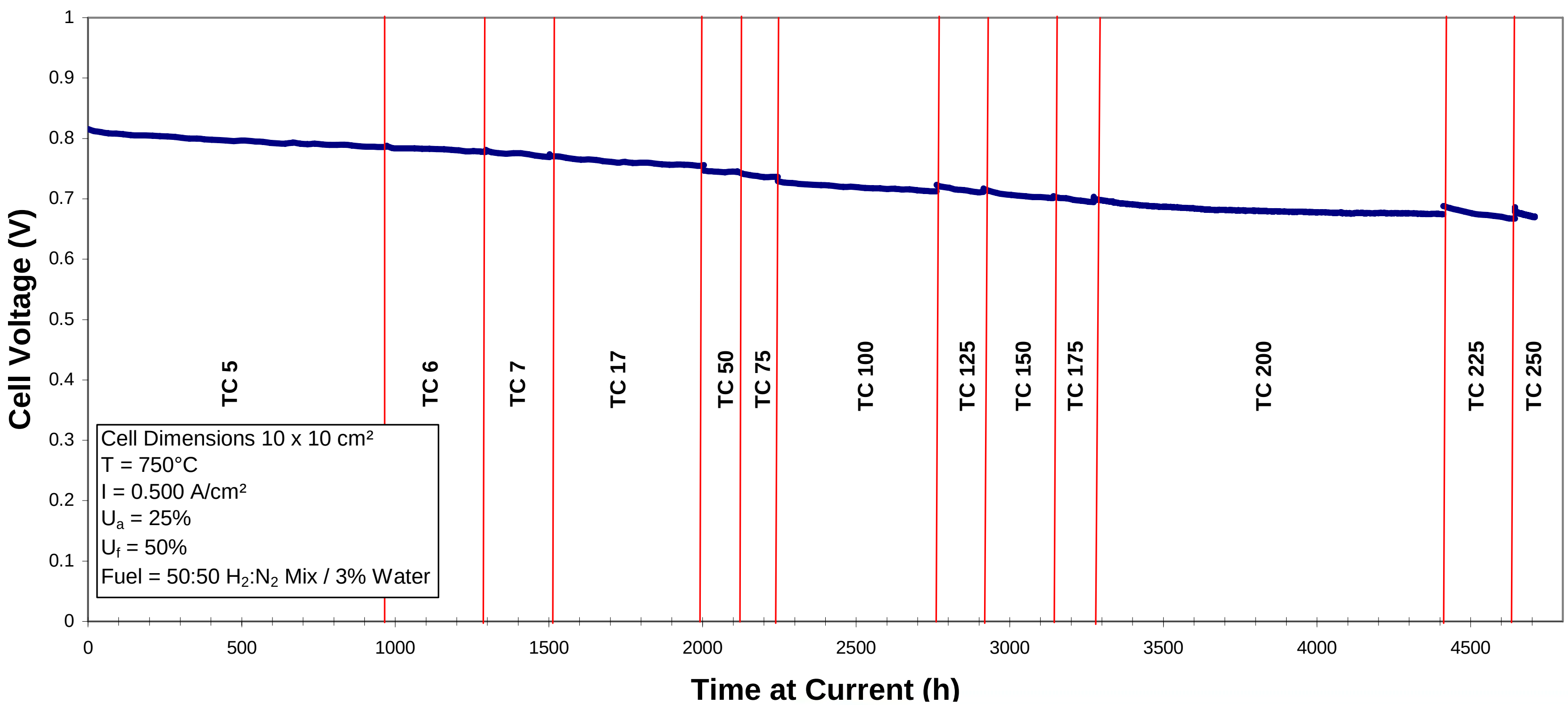
Low Cycle Degradation

Hi Cycle Degradation

Thermal Cycling

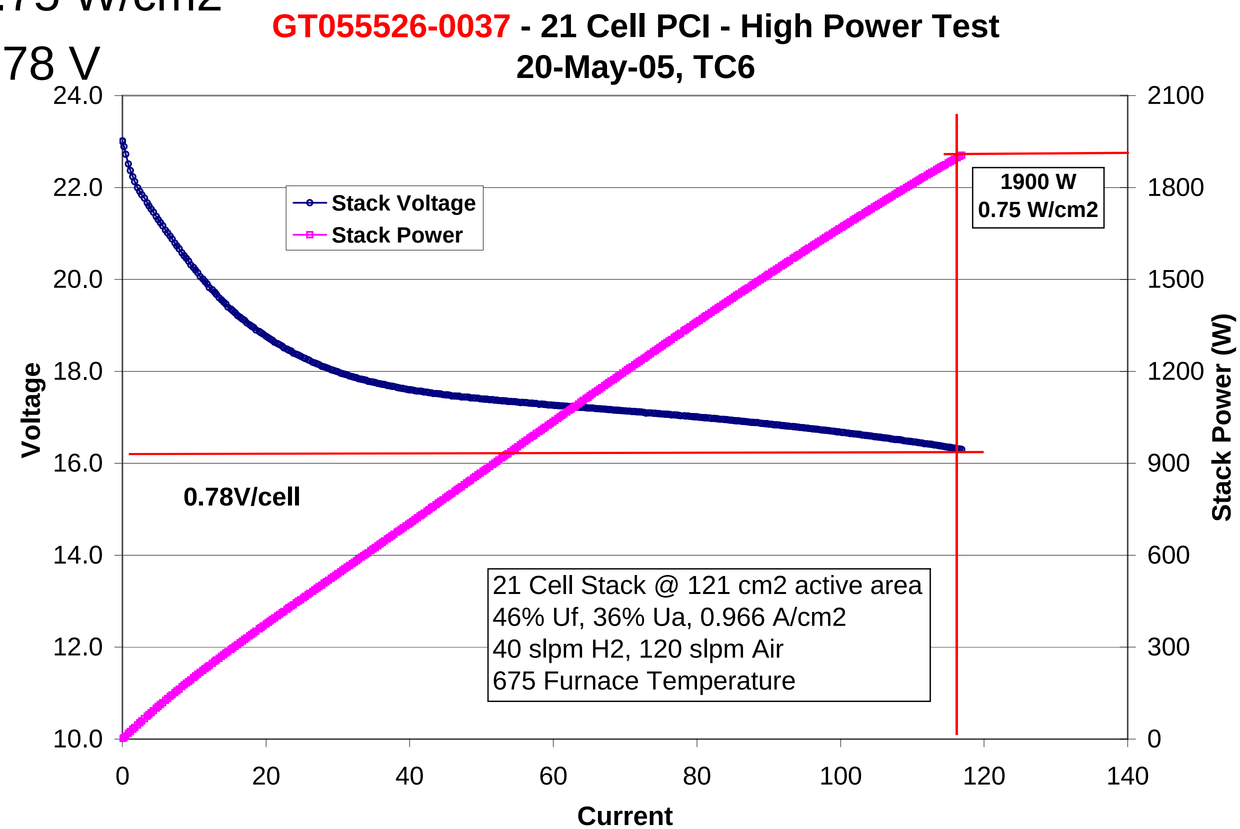
- Cell Level
  - 250 thermal cycles and 4500 hours proven at the single cell level
  - Degradation corresponds to 0.05%/Thermal Cycle
  - No sealing loss as shown at 85% Ut

Test 101406: Steady-State Cell Voltage Degradation Over 250 Thermal Cycles



Thermal Cycling

- Stack Level
  - 40 thermal cycles on 21 cell stack segment
  - Following 3000 hours & 6 thermal cycles in-system, this stack segment was operated at 0.966 A/cm2
  - Produced >1900W, at 0.75 W/cm2
  - Average cell voltage ~0.78 V



Shock & Vibration

- Much speculated, some modeling, little data
- Limited, anecdotal experience is positive
- Engineering issues
  - Planar SOFC stacks require controlled clamping load to maintain seals, electrical contact
  - Coefficient of Thermal Expansion mismatch and creep must be controlled
- Two pronged approach to evaluation and design:
  - Modeling (ALD)
  - Sub-system testing

Shock and vibration

Shock & Vibration: As part of a separate, Imperial College, automotive engine effort

- The Advanced Battery Solid Oxide Linked Unit to maximize Efficiency (ABSOLUTE) Hybrid,
- VPS supplied 300 W stack for testing
- VPS stack was pre-conditioned and performance documented at VPS prior to shipment to England
- ***During shipment from Versa Power to London, the stack experienced shocks as high as 14.4 G***
- Post-shipment testing at Imperial College indicated no apparent degradation / damage from shipping shocks (stack operated within 1% of rated power)

Cummins Power Generation Teaming for Commercialization

Power Generation

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

- Reformer development
- High temperature thermal integration
- Specialized SOFC components (e.g. HT blowers, HT HX)

- High performance SOFC stacks and manifolds
- Application engineering expertise and data to support integration of stacks

Acknowledgements

US DOE SECA DE-FC26-01NT41244

Cummins Power Generation	Versa Power Systems	DOE / NETL
Xin Li	*Sofiane Benhaddad*	*Dave Berry*
Jie Luo	*Brian Borglum*	*Don Collins*
Dennis Otremba	*Casey Brown*	*Heather Quedenfeld*
Brad Palmer	*Jake Kelsall*	*Crystal Sharp*
Jamal Thompson	*Michael Pastula*	*Travis Shultz*
Charles Vesely	*Randy Petri*	*Wayne Surdoval*
	Mark Richards	
	Eric Tang	
	Tony Wood	

SECA Program
Cummins Power Generation
SECA Phase 1 Review
San Antonio, TX
August 7, 2007

This presentation was prepared with the support of the U.S. Department of Energy, under Award no. DE-FC26-01NT41244. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the author(s) and do not necessarily reflect the views of the DOE.

Power Generation