2005 DOE Program Hydrogen Review

Diesel Fueled SOFC for Class 7 / Class 8 On – Highway Truck Auxiliary Power

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Working Partners: International Truck and Engine, and SOFCo-EFS Holdings LLC

This presentation does not contain any proprietary or confidential information

Project ID #: FCP31

Cummins Power Generation

2005 DOE Hydrogen Program Review

SOFC APU for Class 7 / Class 8 Trucks

Project Overview

Timeline

Project start date 9/01/2004
Project end date 8/31/2007
Percent complete 15%

Budget

Total project funding
- DOE share $3,225,611
- Contractor share $1,564,298

Funding received in FY04

Funding for FY05

Barriers

Barriers addressed (2006 Targets)

Specific Power	70 W/Kg
Power Density	70 W/L
Effcy @ Rated Power	25% LHV
Cost	<800 $/Kw
Cycle Capability	40 cycles
Durability	2,000 hrs
Start up Time	30 to 45 mins

Partners

Cummins Power Generation
International Truck & Engine Corp
SOFCo-EFS Holdings LLC

Background for interest in Truck APUs

Studies indicate that approximately 500,000 class 7/8 trucks currently travel more than 500 miles from base on their daily trips

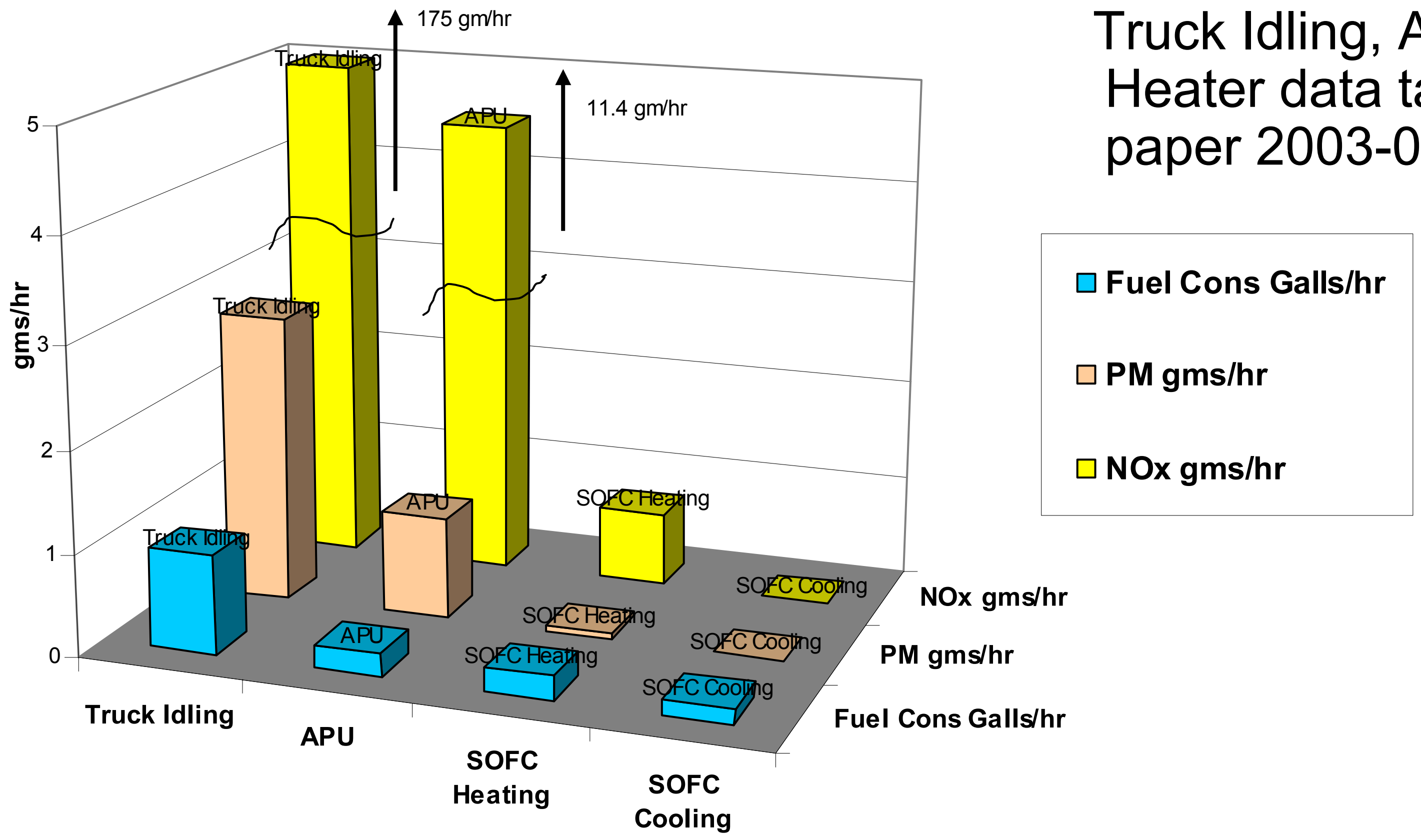
It is estimated that these trucks may spend up to 300 days per year idling for 8 hours per day at overnight rest stops to provide heat and power for the sleeper cab

Under these conditions idling trucks would consume, at 0.8 gals of fuel per idling hour, 960 million gallons of diesel fuel while idling

Significant amounts of NOx, CO_2 and PM are produced under these engine idling conditions

Elimination of truck engine idling by providing heat and power in a more efficient manner, (such as a truck mounted APU), has the potential to conserve large amounts of diesel fuel and significantly reduce exhaust emissions

Comparison of Idling Truck, APU & SOFC Emissions



Truck Idling, APU, and Diesel Heater data taken from SAE paper 2003-01-0289

Program Objectives

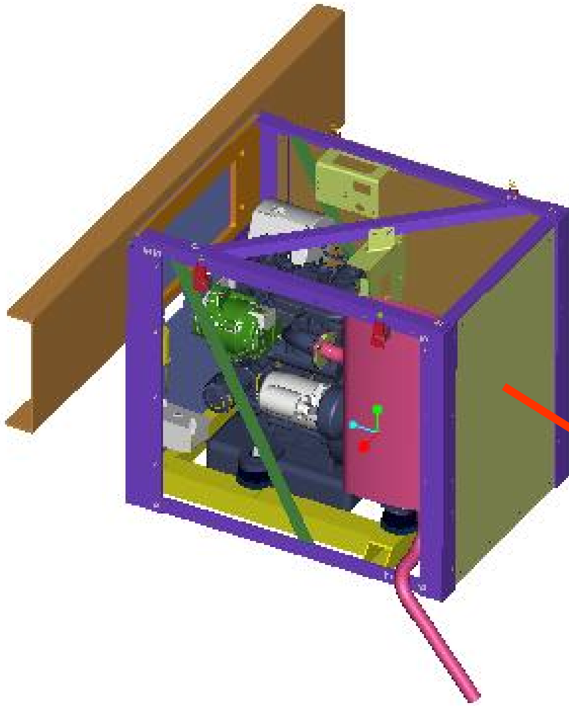
- On-vehicle demonstration and evaluation of a SOFC APU with integrated on board reformation of diesel fuel
- Develop transparent methods of water management for diesel fuel reformation
- Develop controls to start, operate and shutdown SOFC APU in a transparent manner
- Harden the SOFC APU to enable it to operate reliably in the on-highway environment
- Develop overall system to deliver performance, cost and reliability targets

Approach

- Develop System Technical Profile to define SOFC APU output requirements and operating environment
- Analyze Truck electrical and thermal load profile
- Utilize SOFC technology developed in parallel SECA program
- Conduct bench testing to evaluate suitable diesel reformer catalysts
- Identify and evaluate potential solutions for internal water management concepts
- Obtain and analyze real world truck vibration data to support suitable analysis and design of SOFC APU isolation system
- Design and evaluate separate subsystems
- Integrate and evaluate overall system in laboratory and on truck

Comfortguard

Diesel APU Prototype



*Mission Requirements for APU

- Maintain warm main vehicle engine during cold weather to ensure reliable starting
- Provide cab and sleeper heat during cold weather to maintain operator comfort
- Provide cab and sleeper cooling during hot weather to maintain operator comfort
- Provide electrical power to maintain battery charge and to power required electrical accessories, e.g., TV, refrigerator, microwave etc
- Save fuel and reduce vehicle operating costs

* More than an electrical power supply

Why Solid Oxide Fuel Cells (SOFC's)?

Advantages

- Simplified fuel reformation for HC fuels (CO is fuel constituent, some Sulfur tolerance, thermally matched)
- No water management in stacks
- Potential for low / no precious metals (cost)
- No external cooling required
- High quality waste heat stream
- High efficiency

Challenges

- Thermal management (start up, shut down, transients) – startup time
- Degradation
- Seals
- Zero net water Diesel Reforming
- Cost, cost, cost

Basic APU Economics

- Cost of Fuel √
- Idling Time √
- Delta Fuel Consumption, Truck – APU √
- Service Costs √
- APU Installed Cost √

Economics are critical to encourage enthusiastic adoption of anti-idling solutions

Payback Period !

Technical Profile Development

Technical Profile broken down into 5 sections:

- Performance
- Product Integrity
- Environmental
- Liquid Coolant Loop
- Interface Definition

Thermal vs. Electrical Loads

The Load Profile developed for the SOFC APU shows:

- Peak electrical load during summer = 4.4 Kwe
- Avg electrical load during summer = 1.5 Kwe
- Peak electrical load during winter = 3.4 Kwe
- Avg electrical load during winter = 0.5 Kwe
- Peak thermal load requirement during winter
  = 17,000 BTU/hr = 5 Kw

ie. Thermal load *greater* than electrical load

Thermal vs. Electrical Loads

Avg electrical load during winter = 0.5 Kwe

Assume SOFC LHV fuel in to watts electrical out = 30% efficiency

Thermal energy in SOFC exhaust approx 1 Kw

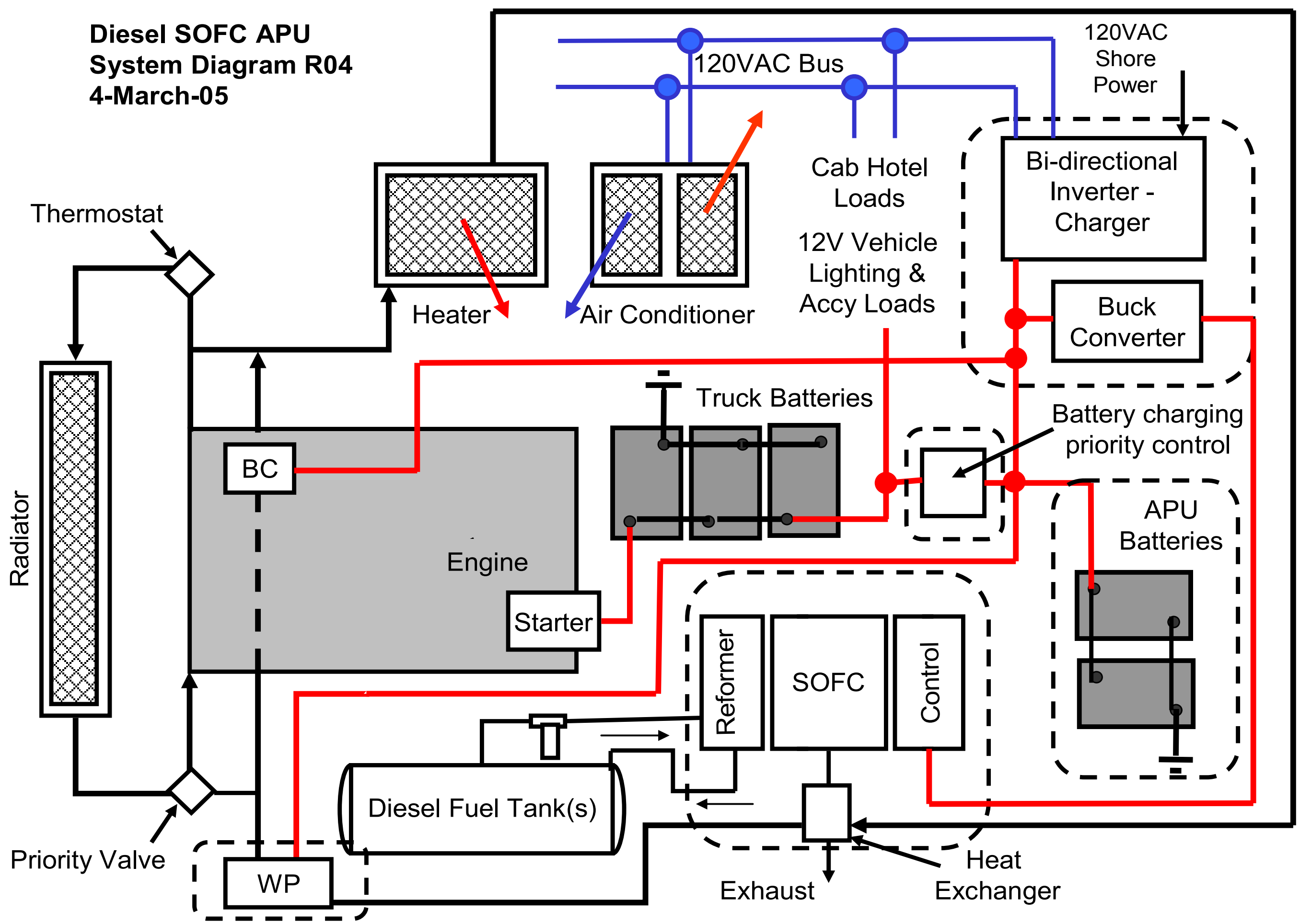
If harness the bulk of this energy

How best to provide additional 4+ Kw of thermal energy?

Exploring three approaches to provide heat for the sleeper cab and maintain vehicle engine coolant temperatures

- Use electric coolant heaters to provide thermal coolant energy
- Use electric coolant heaters in combination with SOFC exhaust energy recovery via heat exchangers to extract heat to coolant
- Use a separate diesel fueled coolant heater to provide the balance of the thermal energy required by the sleeper cab and truck engine during cold weather

APU System Diagram



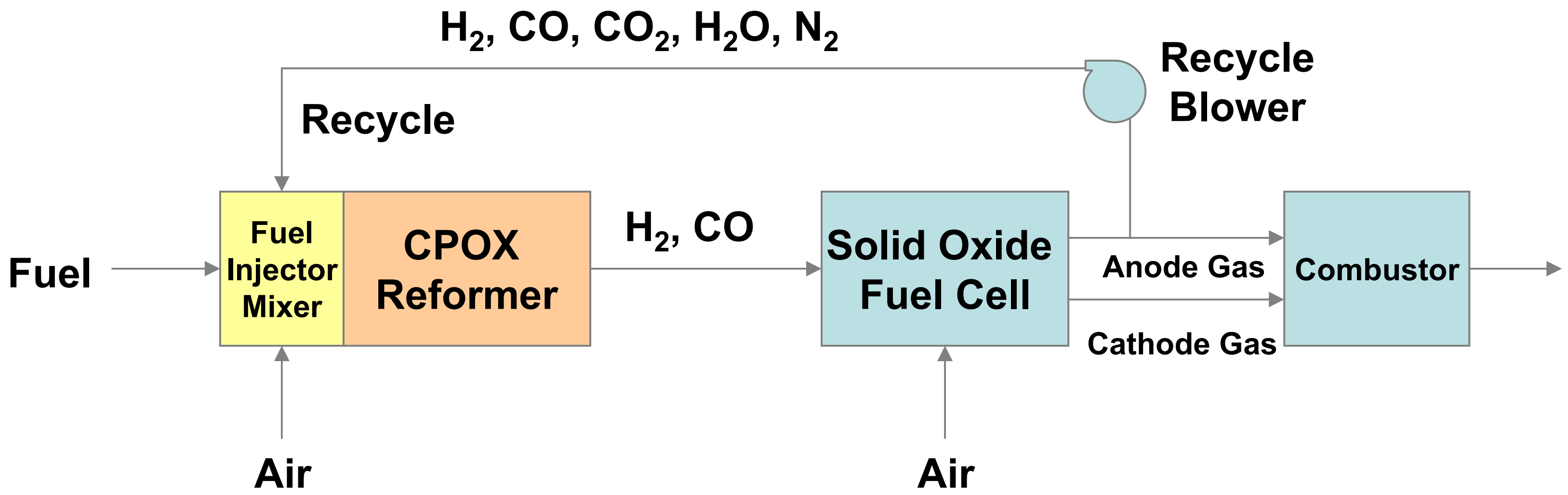
Water Management

Reforming of Diesel fuel requires water to moderate temperatures and suppress carbon formation

Possible sources:

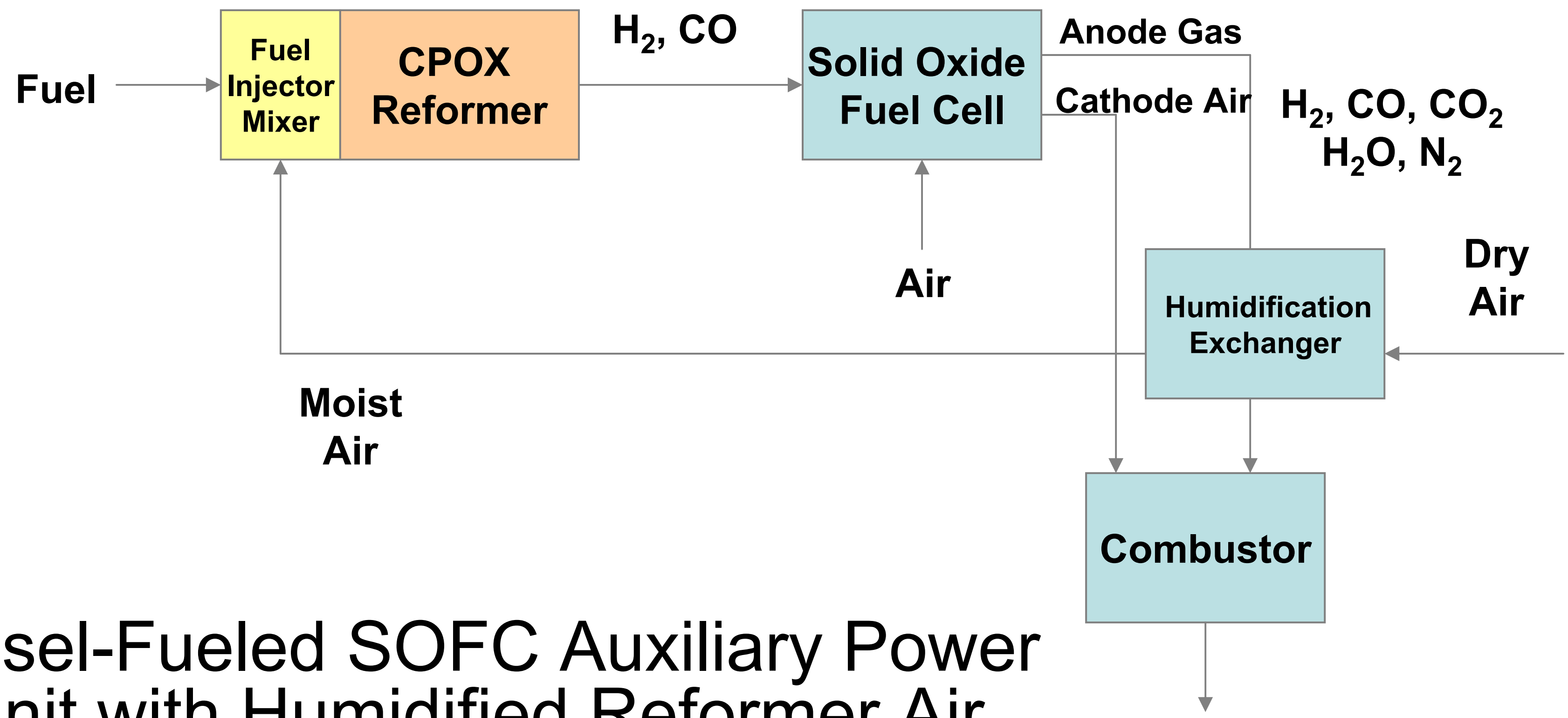
- Separate on board water supply (less desirable)
  - Availability, added weight, something else to worry about
  - Purity, contaminates could damage catalyst
  - Freezing when truck not in use. Will freeze depressants damage catalyst?
- Recycle of moisture rich Anode Gas (more desirable)
  - How to start unit without water addition?
  - Alternative concepts to evaluate
  - Aspen Modeling and testing underway to evaluate best concept

Internal Water Management - Concept 1



Diesel-Fueled SOFC Auxiliary Power Unit
with Anode Exhaust Recycle

Internal Water Management – Concept 2



Diesel-Fueled SOFC Auxiliary Power Unit with Humidified Reformer Air

Some Unknowns

- Anode Gas Recycle
  - Impact of combustibles (H_2 + CO) and diluents (CO_2, N_2) on reforming
  - Range of acceptable operation
- Air Humidification
  - Membrane performance
  - Effect of trace contaminates
  - Durability
- Impact of each approach on system efficiency and hardware design

Impact of water recovery approach on system performance and design

- Aspen system models
- Basis for comparison
  - Same fuel flow & cell area (same cost basis)
  - Nominally 2.5 kW stacks
  - Recycle ratio of 50%
  - Steam/carbon ratio of 1.0 (membrane)

Summary of System Analysis

- Although recycle approach requires larger components it allows significantly lower reformer temperatures than humidification approach.
- Lower reformer temperatures expected to improve catalyst life.

Summary of Anode gas recycle testing

Initial bench-scale evaluation of anode gas recycle indicates:

- No negative impact of recycle on performance
  - no operational issues observed (P, T)
  - there may be a slight improvement in efficiency
- The impact of steam/carbon ratio on performance appears to be reduced when anode gas is recycled

Humidification membrane testing

Purpose: Evaluate the membrane's mass transfer performance using simulated anode exhaust gas and air

- Anode exhaust gas produced by CPOX of natural gas with post reformer oxygen injection to simulate the SOFC
  - Determine increase in air's moisture content due to membrane by using humidity sensors
  - Determine stability of membrane's performance

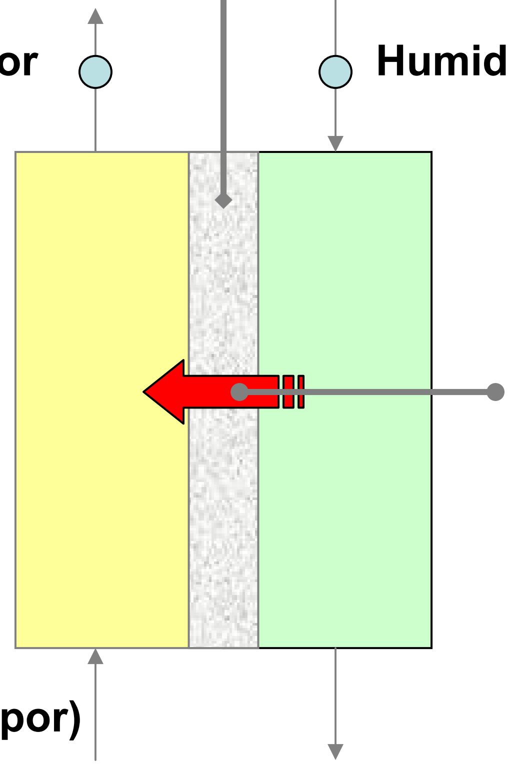


Illustration of humidification membrane

Summary of humidification membrane testing

- Only half the target water was recovered
- Membrane performance sensitive to contaminates
  - Carbon (soot)

Conclusion:

- Use Anode exhaust gas recycle for internal water recovery

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Analysis of Truck Load Profile

- IT&E loads identified
- Developing profiles for modeling
- Winter and Summer
  - Extreme Cold
  - Extreme Heat
  - Moderate Cold
  - Moderate Heat
- Monte Carlo Analysis
- Very important to understand history of average load against peak loads over the entire "no idle" period
- This impacts fuel cell size vs energy storage media size which leverages total system cost

Season	Summer
Sky Cover	Clear
Precipitation	Rainy
Day or Night	Night
Engine Running?	No

Peak DC Current (amperes)	129.28	Peak AC Current (amp)	23.22
Average DC Current (amperes)	18.15	Average AC Current (amp)	10.35
Peak DC Power (watts)	1615.99	Peak AC Power (watts)	2786.40
Average DC Power (watts)	226.88	Average AC Power (watts)	1242.15
DC Energy (watt-hours)	2268.80	AC Energy (watt hours)	12421.52

11000 **Averages are over a ten-hour period.**

T LOADS
acter to include electrical load

	Peak Current	Ave. Current	Peak Power	Ave. Power	Energy
Halogen headlamps	0.000	0.000	0.000	0.000	0.000
Daytime running lights	0.000	0.000	0.000	0.000	0.000
Fog lights	0.000	0.000	0.000	0.000	0.000
Side marker lights - Front	0.600	0.600	7.500	7.500	75.000
Clearance lights - Cab	1.100	1.100	13.750	13.750	137.500
Trailer - Clearance & Marker	4.500	0.150	56.250	1.875	18.750
Identification lights - Cab	1.700	0.283	21.250	3.542	35.417
9000i cab	0.810	0.093	10.125	1.156	11.563
Spot Lights	2.300	0.004	28.750	0.048	0.479
Mirror Lights	1.000	0.033	12.500	0.417	4.167
Dome Lights - cab	1.900	0.063	23.750	0.792	7.917
Cigar Lighter - cab & bunk	6.900	0.058	86.250	0.719	7.188
Luggage Lights	0.600	0.015	7.500	0.188	1.875
Accessory Lights - Bunk	1.900	0.048	23.750	0.594	5.938
Instrument Panel Lights	3.000	0.050	37.500	0.625	6.250
Control Identification Lights	0.100	0.002	1.250	0.021	0.208
Taillights	5.500	0.183	68.750	2.292	22.917
Dome Lights	2.100	0.070	26.250	0.875	8.750
Accessory Lights - Bunk	1.900	0.063	23.750	0.792	7.917
Magnetic Switch	3.000	0.025	37.500	0.313	3.125
Hold-In Coil	22.000	0.183	275.000	2.292	22.917
A/C Blower Motor	22.000	11.834	275.000	147.919	1479.188
Bunk Blower Motor	0.000	0.000	0.000	0.000	0.000
Sleeper Fan	3.600	1.434	45.000	17.919	179.188
Defroster Fans	0.000	0.000	0.000	0.000	0.000
Fuel Solenoid	0.000	0.000	0.000	0.000	0.000
Fuel heater	0.000	0.000	0.000	0.000	0.000
Ether Start Solenoid	0.000	0.000	0.000	0.000	0.000
Windshield Wiper	0.000	0.000	0.000	0.000	0.000

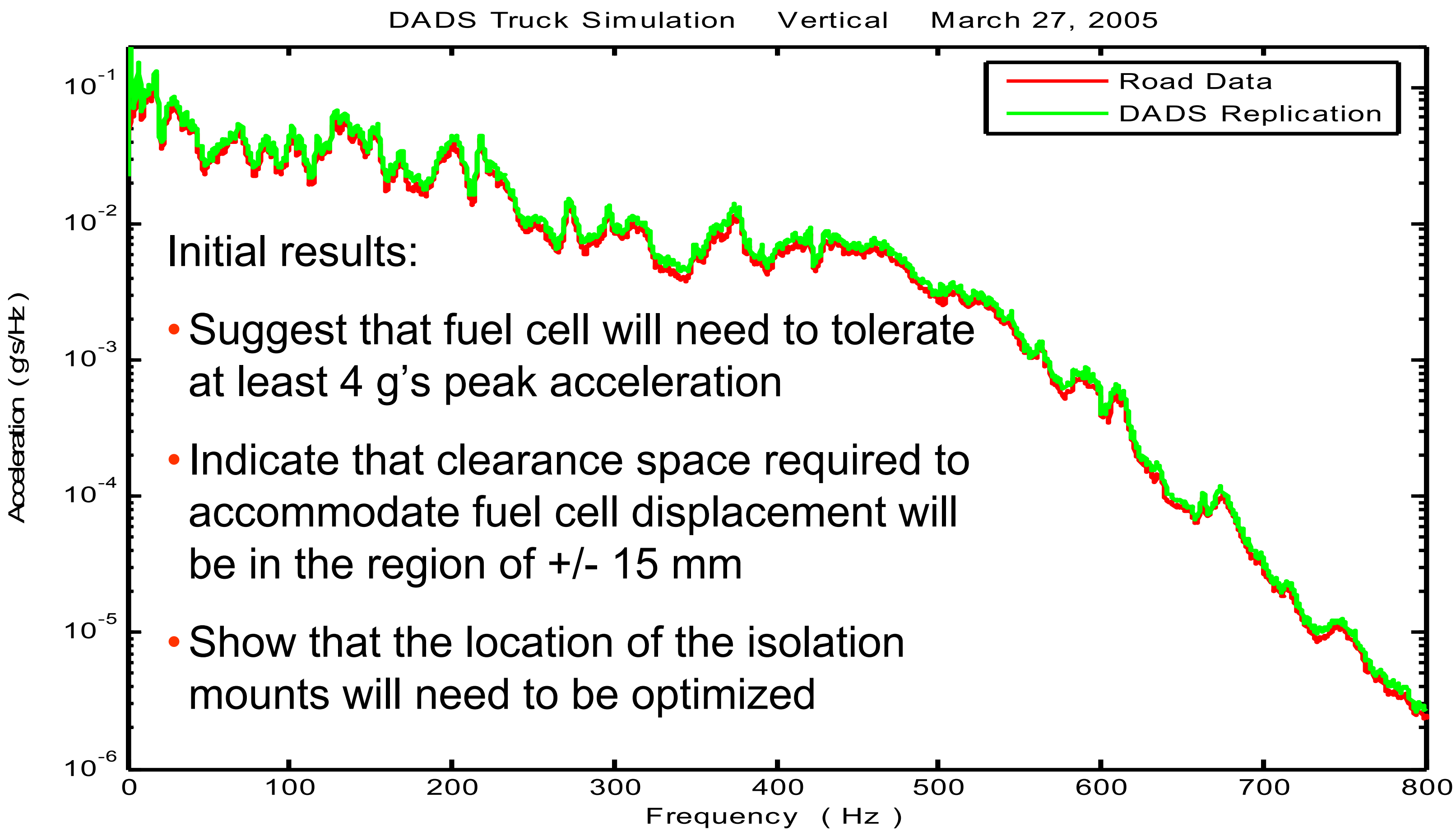
Vibration Isolation of SOFC Stack

- Reverse problem from normal IC engine APUs
- Normally concerned about isolating APU IC engine from main vehicle to avoid operator discomfort
- With SOFC APU need to isolate APU from truck shock / vibration
- Use on highway truck vibration data to enable modeling of system
- Use representative shaker testing to evaluate vibration tolerance of stack elements

Vibration Isolation of SOFC Stack

Vibration signature in vertical plane on drivers side truck frame with unloaded trailer

Vibration Isolation of SOFC APU



Initial results:

- Suggest that fuel cell will need to tolerate at least 4 g's peak acceleration
- Indicate that clearance space required to accommodate fuel cell displacement will be in the region of +/- 15 mm
- Show that the location of the isolation mounts will need to be optimized

Summary of Accomplishments

- Technical Profile
- Analysis of Truck Electrical and Thermal load profile
- Micro reactor testing underway to support reformer catalyst evaluations
- Alternative internal water management concepts have been evaluated and an approach has been selected
- Suitable truck vibration signatures identified to aid in SOFC isolation and design and test

Future Work for 2005

- Complete truck load profile analysis against time vs fuel cell output to optimize SOFC stack size vs battery capacity (efficiency / component sizing / cost tradeoffs)
- Complete analysis and selection of best overall approach to providing thermal output
- Complete reformer catalyst evaluation
- Continue with vibration analysis and design and determination of vibration tolerance of fuel cell stacks
- Commence sub-system design

Acknowledgements

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This support does not constitute an endorsement by DOE of the material expressed in this presentation.

Publications and Presentations

Presentation given at the:

21st Century Truck Idling Reduction Projects Merit Review – March 16, 2005, Washington DC.

"Diesel Fueled SOFC for Class 7 / Class 8 On-Highway Truck Auxiliary Power"

Hydrogen Safety

The most significant hydrogen hazard associated with this project is:

Information to follow

Hydrogen Safety

Our approach to deal with this hazard is:

Information to follow