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
Project Overview

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

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

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

Funding received in FY04
Funding for FY05

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, CO₂ 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

<table>
<thead>
<tr>
<th></th>
<th>PM</th>
<th>NOx</th>
<th>Fuel Cons Galls/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck Idling</td>
<td>25</td>
<td>175</td>
<td></td>
</tr>
<tr>
<td>Diesel Heater</td>
<td>11.4</td>
<td>175</td>
<td></td>
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<tr>
<td>SOFC Heating</td>
<td>11.4</td>
<td>175</td>
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<tr>
<td>SOFC Cooling</td>
<td>11.4</td>
<td>175</td>
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</tr>
<tr>
<td>APU</td>
<td>11.4</td>
<td>175</td>
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</tbody>
</table>

**Legend**
- **Fuel Cons Galls/hr**
- **PM gms/hr**
- **NOx gms/hr**
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
2005 DOE Hydrogen Program Review
SOFC APU for Class 7 / Class 8 Trucks

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
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

Diesel SOFC APU
System Diagram R04
4-March-05
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 contaminants
  - 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

- Membrane tube
- Moist Air to CPOX (30% water vapor)
- Moist Recycled Anode Gas (35% water vapor)
- Dry Air (<1% water vapor)
- Water vapor transfer through membrane tubes
- Humidity sensor
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
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
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

Over the Road Truck Vibration Data

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

Acceleration (g's)

Time (sec)
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.
Presentation given at the:


“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*
Our approach to deal with this hazard is:

*Information to follow*