

Feasibility of Fuel Cell APUs for Automotive Applications

By Chris Spangler, Eric Sattler, and Heather McKee

AET5110 Fuel Cell Fundamentals

Professor Simon Ng

Due 12/05/05

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 07 DEC 2005		2. REPORT TYPE Journal Article		3. DATES COVERED 29-08-2004 to 30-11-2005	
4. TITLE AND SUBTITLE Feasibility of Fuel Cell APUs for Automotive Applications				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Chris Spangler; Eric Sattler; Heather McKee				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army TARDEC, 6501 East Eleven Mile Rd, Warren, Mi, 48397-5000				8. PERFORMING ORGANIZATION REPORT NUMBER #15383	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army TARDEC, 6501 East Eleven Mile Rd, Warren, Mi, 48397-5000				10. SPONSOR/MONITOR'S ACRONYM(S) TARDEC	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) #15383	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Fuel cells are currently being evaluated for many applications, including portable power transportation, and large stationary systems. The US military is looking at fuel cells to help reduce its use of fuel in the battlefield, and to more adequately address the vehicle electrical power demands not being fulfilled by batteries and on-board generators. Hydrogen will not be used in the battlefield for a long time, if ever, and so the primary concern for introduction of military vehicle fuel cells is on-board fuel processing. Because of the military's decision to implement the Single Fuel Forward policy, JP-8 (and JP-5) is the primary fuel used in the battlefield. When acquired outside of the US where fuel quality is not necessarily regulated, this can lead to sulfur levels of up to 3000 ppm, which are several orders of magnitude above the tolerance of current fuel cell and reformer systems. The Army has several fuel cell programs for vehicle applications currently underway, ranging from successful processing of JP-8 to vehicle demonstration programs, with the hope that those two areas will eventually converge during the technology evolution process.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Public Release	18. NUMBER OF PAGES 67	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

ABSTRACT

Fuel cells are currently being evaluated for many applications, including portable power, transportation, and large stationary systems. The US military is looking at fuel cells to help reduce its use of fuel in the battlefield, and to more adequately address the vehicle electrical power demands not being fulfilled by batteries and on-board generators. Hydrogen will not be used in the battlefield for a long time, if ever, and so the primary concern for introduction of military vehicle fuel cells is on-board fuel processing. Because of the military's decision to implement the Single Fuel Forward policy, JP-8 (and JP-5) is the primary fuel used in the battlefield. When acquired outside of the US, where fuel quality is not necessarily regulated, this can lead to sulfur levels of up to 3000 ppm, which are several orders of magnitude above the tolerance of current fuel cell and reformer systems. The Army has several fuel cell programs for vehicle applications currently underway, ranging from successful processing of JP-8 to vehicle demonstration programs, with the hope that those two areas will eventually converge during the technology evolution process.

TABLE OF CONTENTS

Page 4	LIST OF FIGURES AND TABLES
Page 5	BENEFITS AND DRAWBACKS OF AUXILIARY POWER UNITS
Page 5	MILITARY VEHICLE MAIN ENGINE ISSUES
Page 6	SILENT WATCH AND COMMERCIAL VEHICLE IDLING REDUCTION
Page 7	BATTERY ISSUES
Page 11	SINGLE FUEL FORWARD
Page 11	CLEAN FUELS INITIATIVE
Page 14	REFORMING FUEL
Page 23	MILITARY JP-8 REFORMER
Page 25	HYDROGENICS MULTI-SERVICE REGENERATIVE ELECTROLYZER FUEL CELL
Page 29	DELPHI SOFC APU w/ REFORMER
Page 31	FREIGHTLINER TRACTOR WITH BALLARD PEM APU AND METHANOL REFORMER
Page 35	SUNLINE TRACTOR WITH HYDROGEN-FUELLED HYDROGENICS PEM APU AND VEHICLE ELECTRIFICATION
Page 37	CONCLUSIONS
Page 39	REFERENCES

LIST OF FIGURES AND TABLES

FIGURES LIST

Page 8	Figure 1 – 6TL Battery
Page 8	Figure 2 – 6TLFP Battery
Page 8	Figure 3 – 6TMF Battery
Page 9	Figure 4 – VRLA Battery
Page 10	Figure 5 – Battery graveyard from current use.
Page 25	Figure 6 – MREF Phase II: 3kW PEM
Page 26	Figure 7 – MREF Phase III: 7kW PEM
Page 26	Figure 8 – MREF Phase III: 7kW Stack
Page 27	Figure 9 – MREF Phase III: Electrolyzer
Page 27	Figure 10 – Metal Hydride Tanks
Page 29	Figure 11 – Delphi SOFC APU with integrated fuel processor. The picture on the right illustrates the volume compared to a typical battery.
Page 30	Figure 12 – Schematic layout of the current BFV powertrain.
Page 30	Figure 13 – Schematic layout of the current BFV battery and generator configuration.
Page 31	Figure 14 – Bradley electrical power requirements increasing over time (provided by the US Army TACOM Bradley PM office).
Page 32	Figure 15 – A graphical representation of the logistics burden of the military.
Page 33	Figure 16 – Freightliner Class 8 tractor with the Ballard integrated APU.
Page 33	Figure 17 – APU installed on the side framerails of the tractor. The fuel tank is mounted on the opposite side of the truck.
Page 33	Figure 18 – The Ballard module assembly. The stack is on the top, the air system is on the bottom right, and the fuel processor is on the left.
Page 34	Figure 19 – Graphical representation of the fuel processor.
Page 35	Figure 20 – Data generated by the DOE NREL ADVISOR model, comparing the idling of a main diesel engine to this APU configuration.
Page 35	Figure 21 – The SunLine tractor after its cross-country trek from southern California to Washington, DC, in 2005.

TABLES LIST

Page 10	Table 1 – 6TMF/VRLA Comparison of Technologies
Page 24	Table 2 – Comparison of Usage of JP-8 and Cost per 12.5 kWh
Page 24	Table 3 – Comparison Usage of Cost to Charge Battery
Page 24	Table 4 – Scenario: 100 Charge Cycles (JP-8 reformer and fuel cell APU \$28,500 estimate 2010)
Page 26	Table 5 – MREF Stack Specifications
Page 27	Table 6 – MREF Electrolyzer Specifications

BENEFITS AND DRAWBACKS OF AUXILIARY POWER UNITS

Fuel cell auxiliary power units (APU) offer many benefits over the performance of a vehicle's main engine, whether it is for engine idling reduction in the heavy-duty commercial vehicle world or Silent Watch of military vehicles. APUs have significantly improved fuel economy; reduced tailpipe emissions; and reduced thermal, visible smoke and noise signature. Even in the situation in which one requires a fuel reformer, to process a hydrocarbon fuel such as diesel into hydrogen, the emissions would be less because the amount of fuel consumed is decreased.

Some of the drawbacks to APUs, whether they are engines or fuel cells, are their added cost, weight, and maintenance burden. Issues also arise regarding the packaging space they claim, as well as mechanical and electrical integration. Few, if any, military tactical vehicles have engine APUs. Combat vehicles such as the Bradley Fighting Vehicle and the M113 Armored Personnel Carrier also usually lack APUs, but many M1 Abrams tanks have had small diesel generators retrofitted. Retrofitted APUs are not easily designed to be protected, as is other integrated hardware on the vehicle. [1] [2]

MILITARY VEHICLE MAIN ENGINE ISSUES

The typical diesel propulsion engine of military vehicles is not well suited for idling over long periods of time, even though that is one of the most common operating modes in the battlefield. During extended idle, poor diesel combustion and over-fueling in cold weather conditions can occur. This can result in diluted oil and engine damage. Engines are also typically extremely inefficient at idle speeds, on the order of 25% efficiency, or approximately one to three gallons diesel fuel per hour for trucks. Armored vehicles may consume up to eight gallons per hour due to greater engine fan power requirements and larger engines. The Abrams M1 tank, with the propulsion gas turbine engine, has an especially poor consumption of over twelve gallons per hour, depending on its idling speed. [1]

SILENT WATCH AND COMMERCIAL VEHICLE IDLING REDUCTION

Silent Watch mode is when a military vehicle and crew are alert and actively monitoring the battlefield in a scouting or ambush mode. The vehicle batteries provide electrical power until they reach minimum capacity, and the diesel engine is restarted to recharge those batteries. If the battery discharge is too low, a risk is run of not being able to restart the engine at all. Repeated deep discharges will also wear out the batteries. Two other alternatives for standby electrical power in military vehicles include idling the main engine continuously and/or using a diesel or gasoline internal combustion engine APU. These options, in addition to battery usage with repeated engine start-up, are considered poor choices. Since deep discharging dramatically decreases the life of the batteries and the earsplitting idling engine noise defeats the purpose of Silent Watch, and thus the motivation for fuel cell APUs, with their better efficiency and fuel processing capability of the aviation Single Battlefield Fuel. Full-time engine idling is still currently the dominant means of ensuring electrical power for the communications equipment. [1] [3]

In the commercial trucking and transit bus world, there is increasing emphasis in eliminating unnecessary idling, such as when long-haul semi-trucks idle overnight at a truck rest stop. Although this is in a commercial application, the needs are similar to that of Silent Watch: minimize exhaust emissions, minimize the fuel wasted when idling, and minimize noise/vibration of the vehicle, all while providing power for hotel loads, such as heat and air conditioning. The most important requirements are that a technology(s) has a payback period of less than two years, and that the hardware has a seamless integration, to minimize changing their habits (other than unnecessary idling). DOE's Argonne National Laboratory estimates that around 500,000 long-haul trucks idle between three and sixteen hours per day, with an associated annual fuel cost of around \$3000-4000 per vehicle. There is also a strong cultural belief in the industry that idling overnight is necessary for ease of cold start-up. Inconsistent regulations; inconsistent enforcement of the regulations; variability of drive cycles, drivers and applications; and lack of education of the anti-idling options available to drivers and fleets have, until recently, prevented progress from being made in this area. In 2004, several government agencies, including the DOE, EPA, DOT, and DOD, joined forces to work with industry

to address these issues, moving idling reduction technology into the policy mainstream, and are currently finalizing a comprehensive action plan.

Idling reduction technology(s) can be mass-produced at reasonable cost through the competition and high-volume of the industry. The extremely high mileage accumulation of typically 100,000 miles per truck per year provides quick durability results. The larger fleets turnover vehicles every five to ten years, depending on the current market resale value for used trucks. However, the typical Army truck travels only about 3,000 miles per year, and the vehicle is typically kept for 20 years or more-this low mileage accumulation and vehicle turn-over leads to slow or no technology growth. This is a prime example of the US Army's National Automotive Center's mission of helping develop dual-use technology for both military and commercial vehicles, and some of these programs are outlined below. [1]

BATTERY ISSUES

Batteries are an integral part of today's society. While it is not immediately evident, batteries are used by people multiple times every day. Examples of this include the latest portable devices, children's toys, and even most wrist watches. The US Army has utilized battery technology to power its forces since the early 1950's. There have been five different battery types used: 6TN, 6TL, 6TLFP, 6TMF, and VRLA.

The first battery to be used was the 6TN battery. This battery was a lead-acid chemistry with antimony used as the hardening alloy for the lead. This battery technology was able to sustain the US Army until 1982. Some of the major disadvantages of this battery were the time required to maintain the battery, and the need to add water on an almost constant basis. Water was needed in a lead-acid battery to charge the battery. Even though the battery also creates water, the efficiency of the reaction was not high enough to generate enough water for the battery to continue to operate properly. [4]

The 6TL battery was introduced in order to alleviate these primary concerns. Between the 6TN and 6TL, there was no increase in storage capacity or battery life. Chemistry advances were made to increase the efficiency of the reactions which lessened the demand for water to a great extent. The need to “top off” the battery only occasionally with water became the common practice, instead of every time the battery was cycled. Another advantage was a decrease in the maintenance. With the added efficiency of the battery, there were fewer failures of individual cells. One of the driving forces behind the added efficiency was the use of less antimony in the cell. [4]

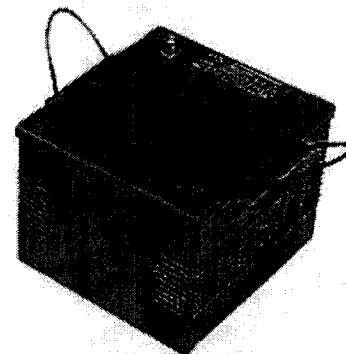


Figure 1 – 6TL Battery

In 1996, the US Army began to transition into calcium instead of antimony to support the lead in the battery. Antimony is a very toxic material, and along with the acid already

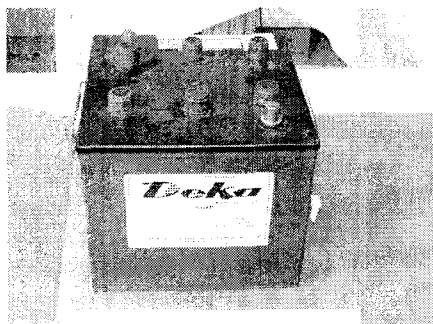


Figure 2 -- 6TLFP Battery

present in the battery, the US Army wanted to utilize a material that would be safer for the soldier. The 6TLFP was introduced, offering multiple advantages to the 6TL predecessor. One major issue with the 6TL and 6TN battery was the self-discharge effect, or the phenomenon of a battery to lose its charge while not in use. Since the self-discharge rate was lower

than before, the 6TLFP had a greater shelf life and required less maintenance than the 6TL. One of the largest breakthroughs was the ability now for the battery to not require any water to be added to the system, which further decreased the amount of maintenance needed. [4]

In 1999, a minor advancement was made in battery technology allowing the US Army to move to the 6TMF. The overall chemistry was the same as the 6TLFP; however the chemistry had been optimized giving the 6TMF a greater overall capacity. This

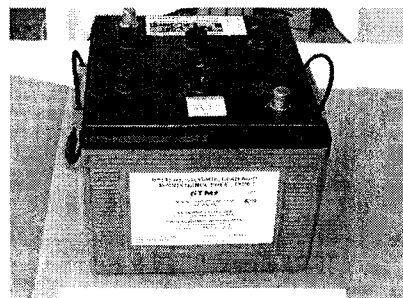


Figure 3 – 6TMF Battery

increased capacity was thought at the time to give the soldier enough power to complete missions. One of the few ways to tell the difference between the batteries was the color of the casing: a 6TLFP was green, while the 6TMF is brown. Currently, this is the official battery that is used by the US Army. [4]

In 2004, an update was made to the specification for the battery that the US Army uses in the field. This update was made to allow competition to the archaic flooded lead acid battery. This move forward has allowed not only the advances in lead acid technology, but other battery chemistries to be able to compete for the US Army's business.

The leading candidate at this moment is the Valve-Regulated Lead Acid (VRLA) battery. One of the major developments was the use of Absorbed Glass Mat (AGM) technology,

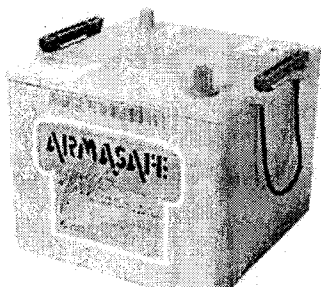


Figure 4 – VRLA Battery

which utilizes a thin fiberglass felt which holds the electrolyte in place like a sponge. VRLA batteries are held at a constant pressure (one to four psi), which promotes the recombination process of the hydrogen and oxygen during the charge cycle. This technique uses advances in technology to give the soldier higher starting power, longer

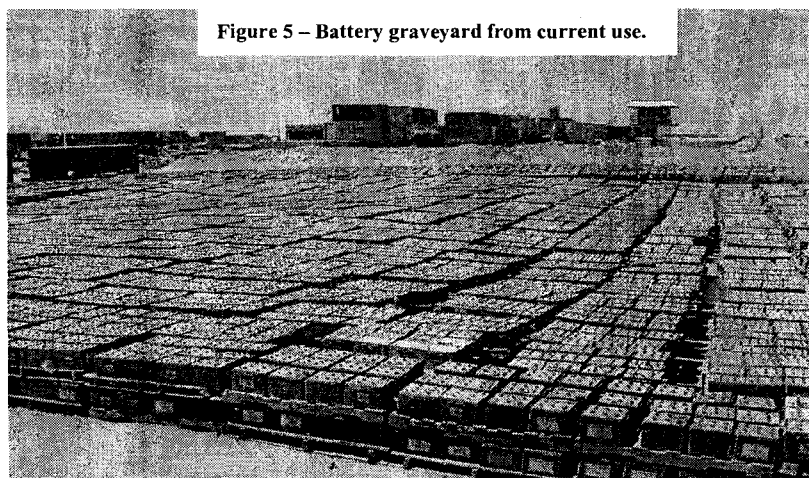
shelf life, extended life, deep discharge capacity, lower life-cycle costs, among others.

Below is a table comparing the 6TMF with the VRLA:

Table 1 – 6TMF/VRLA Comparison of Technologies [5]

	6TMF	VRLA
Voltage (V)	12	12
Cold Cranking Amps	650	240
Reserve Capacity (min)	200	240
Usable Reserve (DoD)	30%	70%
Shelf Life (months)	3	30
Battery Type	Flooded Lead Acid	Sealed, maintenance free
Cycle Life	235	350
Life (months)	13	48
Technology	Lead Calcium flooded	AGM, sealed recombinant
Internal Resistance (ohms)	0.009	0.0017
Transport Class	Hazardous	Non-spillable
Environmental Design	Hazardous	Non-hazardous
Weight (kg)	34	40
Size (l x w x h) (mm)	256 x 269 x 227	256 x 269 x 227

Even with the battery advancements made to date, there is still an issue with capacity and depth of discharge (DoD). Below is a figure showing a “battery graveyard”. This is a

**Figure 5 – Battery graveyard from current use.**

recent picture of dead batteries from the field. When used by the soldier, they do not always pay close attention to the DoD during usage. To complete their missions, a need

to utilize more capacity is desired, thus taking the discharge down below its recommended levels. This poses a major issue with logistics. A change needs to occur to prevent this from happening.

SINGLE FUEL FORWARD

In earlier times, the US military had used a combination of fuels to power their arsenal. Passenger cars used motor gasoline (MOGAS). Tactical and combat vehicles used diesel fuel (DF-2). Aircraft used aviation fuel (Jet A, Jet A-1, and others). Ships used Diesel Fuel-Marine (DF-M) and Bunker Fuels. Logistically, this was becoming unacceptable. Conditions arose in which some vehicles became stranded due to the unavailability of the correct fuel.

The Single Fuel Forward policy was developed for all military vehicles, ground and air; at least, for those not having a spark-ignition engine requiring gasoline. The fuel chosen was JP-8. [6] JP-8 is a kerosene-like aviation fuel consisting of hundreds of hydrocarbons ranging from C_{10} – C_{16} . The hydrocarbons that make up JP-8 can be broken down into four distinct classes; paraffins (e.g. dodecane), naphthenes, aromatics, and bicyclics (e.g. tetralin). It has a sulfur level comparable to on-highway DF2 in the US of around 300 ppm, but the fuel quality can not be controlled in other countries, where the military specification must be flexible to allow up to 3000 ppm sulfur. As a side note, it was discovered that the flash point of this fuel was too low for ship board fire safety. JP-5 was developed from JP-8 as a solution for this problem. Today, all vehicles are commissioned to use JP-8 / JP-5 as the single fuel for the US military. This has greatly reduced the logistical burden, as well as the cost of placing separate fuels into required locations.

CLEAN FUELS INITIATIVE

The cost of fuel has been increasing rapidly, especially the past few years. The increase is at least partially attributed to the cost of locating it and producing it from the wells. As domestic production slows, the United States is becoming increasingly dependent on imported sources of oil. Today, the US imports 57% of its oil requirements, and that is

expected to rise to greater than 70% by 2025. China, India, and Eastern Europe are all expected to increase their demand by 54%. The developing world will increase their demand for crude oil by 91% in a fierce competition with the Western nations. The world consumption is expected to rise from 70 to 121 million barrels per day by that time.[6]

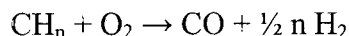
Compounding these problems is the fact that no new refineries have been built in the contiguous US in the last 25 years. Since 1985, 66 operating refineries have been shut down, leaving 148 still operating. The capacity of the state of California alone has decreased by 20% since 1985. Further, environmental laws and cultural considerations impose restrictions for building new refineries, such as the culture of “Not-In-My-Back-Yard”. Of the remaining refineries, 88% of the capacity is located in eight states on the Great Lakes and the East, Gulf, and West Coasts, including mega-refineries in Texas, Philadelphia, New Jersey, Los Angeles, and Louisiana. These complexes are potentially significant terrorist targets, not to mention being located in areas sensitive to the effects of extreme weather conditions. Fuel prices skyrocketed after Hurricane Katrina struck New Orleans in 2005, disabling the Gulf oil refinery industry.

Unfortunately, there is a risk associated with maintaining the status quo. World oil production will peak and reserves will fall. The US is currently on track to import 70% of its crude and 25% of its refined products. A coordinated terrorist attack on US refineries, ports, and marine terminals would place national security, public welfare, economic security, and public confidence at risk.

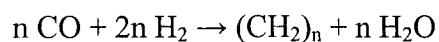
In 2004, the US Department of Defense developed the Clean Fuels Initiative. The goal of this initiative is to secure indigenous sources of energy, to use an environmentally sensitive Fischer-Tropsch process to produce fuels, and to produce better fuels (no sulfur, cleaner burning, bio-degradable), while using limited government funding and meeting existing government mandates.

The primary source of fuel for this initiative is coal. The US has more coal in reserve than any other country. In the central US alone, there are more than 250 billion tons of coal, which is equivalent to 500 billion barrels of crude oil. The secondary source of fuel is Petcoke. Petcoke is a carbonaceous residue produced by all refineries. Approximately 50 million tons per year are produced, equivalent to 100 million barrels of crude oil.

Converting these products into a useable fuel will require using an old, proven technology from pre-WW II, the Fischer-Tropsch (F-T) process. This process was developed by two German scientists to convert indigenous coal into a liquid fuel, because at that time, Germany's ability to secure petroleum fuel was severely disabled due to the war. The basic process is:



This is the conversion of a biomass fuel into carbon monoxide and hydrogen, the so-called synthesis gas reaction, which takes place in the presence of a catalyst. These materials are then converted, in the presence of another catalyst, into long chain paraffins through the reaction:



These paraffins are then converted into liquid fuels using cracking processes, which are standard in the industry. After the war, the technology was shelved as it was deemed too expensive to use, compared to inexpensive and plentiful petroleum. More recently, during their apartheid embargo period, South Africa used this technology to help them produce an F-T blending stock for jet fuels. Even today, the jet fuel at the Johannesburg airport in South Africa contains a significant portion of Fischer-Tropsch fuel from their local plant, SASOL.

Fischer-Tropsch fuels can be considered superior fuels for the following reasons:

- a) Non-detectable levels of sulfur, aromatics, or metals

- b) Higher cetane number than diesel fuel (> 74 vs. 45 – 50)
- c) Very low toxicity and is bio-degradable
- d) Produces lower emissions (NO_x, PM, and CO) and smoke when burned
- e) Completely compatible with the existing fuel distribution infrastructure
- f) Immiscible with water
- g) Can be a source of hydrogen

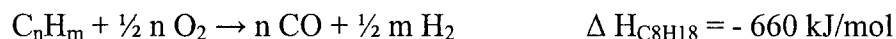
Industry currently plans on building eleven F-T coal plants and nine Petcoke plants to produce liquid fuel. This would supply 12% of the US energy needs, and will have a direct impact on the price of crude oil. The eleven coal plants will supply the US military with all of its worldwide requirements. The nine Petcoke plants will help current refiners to convert a waste product into a clean blending stock, allowing them to produce an extra 900,000 bbl / day of fuel, along with an extra 10.5 GW of new power from the associated co-gen plant.

REFORMING FUEL

JP-8 is a difficult fuel to reform, but due to the requirements of the Single Fuel Forward policy, it is a necessity for the US military. It comprises about 70% of the battlefield cargo stream. Highly efficient fuel cell APUs are being considered as a means to reduce fuel consumption in the field, but would require the use of hydrogen created from reformed JP-8.

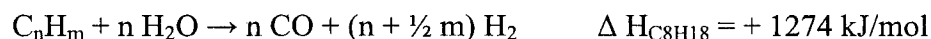
There are three common reforming chemistry options: Partial Oxidation (POX), Steam Reforming (SR), and Autothermal Reforming (ATR).[7]

Partial Oxidation (POX)



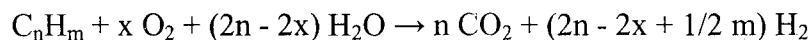
Low H₂ yield, exothermic reaction, mass transfer limited

Steam Reforming (SR)



High H₂ yield, endothermic, heat transfer limited

Autothermal Reforming (ATR)



Medium H₂ yield, tunable heat duty [8]

A project was recently completed by the US Army to develop a fundamental understanding of how major JP-8 components behave under ATR conditions. Previous work had shown that one of the biggest hurdles to having a successful JP-8-fuelled fuel cell was preventing the sulfur-laden JP-8 from poisoning the catalyst.[9] Specifically, it was decided to compare the reforming performance of JP-8 paraffins (dodecane) to JP-8 bicyclic aromatics (tetralins). The catalyst system was 10 wt% Ni / Ce_{0.75}Zr_{0.25}O₂ (Ni / CZO). This was chosen since it had previous success as a reforming catalyst for gasoline surrogates. The conclusions of this study were that:

- 1) Dodecane ATR was unstable for oxygen to carbon ratios less than 1.2
- 2) Tetralin ATR was unstable for O / C ratios less than 1.0
- 3) JP-8 surrogate compounds are much more difficult to reform than gasoline surrogates
- 4) JP-8 reformat was much more suitable for SOFC rather than PEMFC

The Army is currently initiating follow-up work. This study, “Assessment and Development of Advanced Fuel Processing Properties,” will provide an assessment of promising fuel processing options, including the development of novel approaches for reprocessing the Army’s logistics fuel, JP-8.[10] There are three main objectives for this program:

- 1) Develop reforming options for Solid Oxide Fuel Cell APUs
- 2) Investigate the feasibility of gas-to-liquid fuel processes for APUs and other Army relevant applications
- 3) Develop technical approaches for overcoming barriers to the success of SOFC APU demonstrations using JP-8 fuel

Objective number one involves investigation and research into two methods for reforming JP-8 logistics fuel—direct decomposition and step-wise reforming, as well as autothermal reforming for using JP-8 in SOFC APU applications.

The objective of the first sub-project is to demonstrate the feasibility of a simple, robust and lightweight fuel processor that can be used with complex hydrocarbon fuels, such as JP-8. The reformers that have been developed to date for mobile applications consist of three reactors and a large number of heat exchangers. The result is a relatively heavy and complex reformer that weighs significantly more than the fuel cell itself. This project will demonstrate the feasibility of a reformer that is dramatically different, less complex, and physically lighter. This approach to fuel processing is based on direct catalytic decomposition of the hydrocarbon fuel into carbon and hydrogen. Using a catalyst, this reaction is expected to occur around 600-800°C. A catalyst will be chosen on which the carbon is deposited in the form of carbon fibers. The catalyst surface will be regenerated by burning off the deposited carbon. The catalyst can also be regenerated by a mixture of steam and oxygen, in which case it is possible to produce CO and additional H₂, in addition to CO₂. In this regeneration approach, the catalyst bed will be heated to ~1000°C. The heat deposited into the catalyst bed during regeneration will then supply the energy needed to decompose the hydrocarbon fuel. The excess heat, carried away by the hot gases from regeneration, will be used to preheat and vaporize the liquid fuel. Overall, this process is conceptually similar to catalytic cracking used in petroleum refineries and in the material production of carbon fibers.

When estimating the size of the reactors and catalysts for this type of a fuel processor and comparing it to the three-component type (reforming, water-gas shift and preferential oxidation), it will weigh significantly less than the classical fuel processor because it eliminates the heavy water-gas shift and the preferential oxidation reactors. The number of heat exchangers will also be reduced to only one. The construction materials will be simpler and more robust, because reactors of this type are used in automotive exhaust emissions aftertreatment, such as ceramic honeycomb reactors. There will be no need for

extra heat exchangers because the catalyst beds will serve as the heat sinks (regeneration) and sources (decomposition).

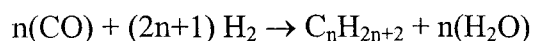
The second sub-objective is to study the effect of complex feed mixtures on the catalytic activity and durability of fuel reformers. For transportation fuel cell applications, it can be critical to be able to reform the current hydrocarbon fuels into hydrogen for onboard demands. Depending on the application, there are different specifications for the required hydrogen purity. Hydrogen for a low-temperature fuel cell, such as the polymer electrolyte fuel cell (PEMFC), must contain less than ten ppm of CO to eliminate anode poisoning. However, the purity requirements for a high-temperature, such as SOFC, are much less stringent, because the high temperature eliminates CO site poisoning concerns. Little is known of the effects of hydrocarbon mixtures on reforming catalysts' activity and durability. Diesel and JP-8 are both quite different from the commonly tested isooctane and methane. Not only do they consist of larger and more complex hydrocarbons, but they also contain fuel additives that could have detrimental effects on both catalyst durability and reforming chemistry.

Equally important to understanding the effect of complex feeds on state-of-the-art reforming catalysts, it is also necessary to develop novel catalysts that remain active over a wide variety of fuels. Preliminary research has shown that catalysts with ion conducting supports show an improved activity over traditionally supported catalysts. In this project, supports of interest may include, yttria-stabilized zirconia (YSZ), zirconia-doped ceria (CeZrO_2), gadolinia-doped ceria (GDC), and, $\text{Gd}_2\text{Ti}_2\text{O}_7$. These materials display oxygen mobility of some form, and are the subject of significant research. Many of these support materials are key components in SOFC construction. For example, YSZ is often used as both the electrolyte and the anode support material in a SOFC. While SOFCs have the ability to reform hydrocarbons directly, in practice, an indirect reformer is often placed upstream of the SOFC due to thermal management issues. Direct reforming would be ideal for SOFCs since it would greatly simplify the SOFC system. If novel catalysts could be developed that are functional for fuel reforming and have

attractive electrical properties, it is conceivable that they could be used for direct reforming inside an SOFC.

Objective number two is investigate the feasibility of gas-to-liquid fuel processes for APUs.

The first sub-objective is to conduct fundamental research and process development for the production of a reformer-friendly designer fuel, via advanced Fischer-Tropsch synthesis. The Fischer-Tropsch synthesis permits the conversion of carbon monoxide and hydrogen into a variety of organic compounds, as illustrated below:



An intriguing possibility is to use the F-T synthesis for production of a designer fuel, meeting exact specifications. The product distribution obtained is dictated by Anderson-Schulz-Flory polymerization kinetics, resulting in a product mix that is far from ideal for purposes of transportation fuels. Consequently, the products emanating from an F-T plant require substantial downstream processing to meet transportation fuel specifications. On the other hand, the process is attractive insofar as the resulting hydrocarbon mix is free of sulfur. This is of great importance for use of a fuel in on-board fuel processors for SOFC auxiliary power units.

There has been considerable effort, both in industrial as well as academic laboratories, to understand the factors contributing to positive or negative deviations from the product distribution of the Fischer-Tropsch synthesis by the Anderson-Schulz-Flory polymerization kinetics. To create this “designer” fuel, it is important to learn how to manipulate the product distribution. To date, there have been some observations of small deviations for the theoretically predicted product distribution, as well as illustrating that the paraffin/olefin ratio increases exponentially with increasing carbon number.[13] Several explanations for this phenomenon have been offered in the literature. One states that the catalyst sites produce olefins as primary products, and that olefins formed are re-

adsorbed on different sites on the catalyst, where they undergo hydrogenation.[14] Others have suggested that the increasing paraffin/olefin ratio as a function of hydrocarbon chain length is due to transport rate differences[15] or differences in solubility.[16]

The first strategy consists of manipulating the surface composition of advanced Fischer-Tropsch catalyst formulations on an atomic scale. Recent advances in combinatorial synthesis methods and high-throughput catalyst screening methods, along with advances in computational methods, will be explored for rapid optimization of multi-functional Fischer-Tropsch catalysts, capable of creating product distributions that are "reformer-friendly".

The second strategy involves novel catalyst formulations, where catalytically active metals will be supported on refractory support materials that exhibit fast ionic conductivities. Several fast ion-conducting solids that allow transport of various mobile ion species, such as H^+ , Li^+ , Na^+ , Ag^{++} , Cu^{++} , Pb^{+2} , F^- , and O^{2-} , are available (Agrawal,1999).[17] These crystalline solid electrolytes provide a rigid lattice framework throughout the bulk structure, which contains channels with unique and specific structural features in which one of the ionic species of the solid, such as oxygen ions, can migrate. Ionic transport involves site-to-site hopping along these conductive channels. There is reason to believe that catalyst supports with high oxide-ion mobility will permit the fine-tuning of Fischer-Tropsch product distributions, analogous to what can be accomplished with doping. The primary difference, however, is that electrochemical promotion is tunable, so that the promoter effect can be optimized to yield a "reformer-friendly" fuel. The revolutionary potential benefit of using solid ionic conductors in Fischer-Tropsch catalysis lies in the electrochemical promotion of activity. By applying a voltage across a monolithic support, ions, such as sodium, can be pumped to or from the working catalytic surface, producing changes in activity and product selectivity. This may lead to "tunable doping" where different product distributions can be achieved by changing the applied voltage.

The third strategy that will be evaluated is the use of modular reactor network systems with localized heating and multi-port, distributed feed. The product distribution leaving one reactor can be adjusted by co-feeding a second reactant into the input stream into that same reactor. An ideal process would achieve 100% selectivity towards desired products, thereby eliminating the need for product separation and purification. An important step in this direction is to move towards “smart” catalytic systems that are capable to respond to agile, localized control strategies. Utilizing "smart" catalytic modules instead of bulk catalysts opens exciting opportunities to explore agile, localized control strategies.

The second sub-objective is to improve the reforming characteristics of JP-8 by selective removal of aromatics. The difficulty in reforming JP-8 fuel for the production of H_2 is mainly due to its higher aromatic and sulfur contents. The presence of various additives is also known to have deleterious effects on the performance of steam reforming catalysts. Significant research effort is being directed to the development of suitable adsorbents to remove sulfur from JP-8 but little attention is being paid to the issue of aromatics. Those present in JP-8 are mostly alkyl-substituted naphthalenes and polyaromatic hydrocarbons[19]. Naphthalenes and other polycyclic aromatics have higher tendency toward coking than mono-aromatic compounds and, therefore, the currently available methane and gasoline steam reforming catalysts are not suitable for the processing of JP-8. In addition to developing better reforming catalysts for handling these aromatics[21], possible ways of pre-treating JP-8 should also be considered. These pretreatment processes can be based either on physical removal of aromatics or on catalytic conversion of these refractory compounds to the more easily reformed ones.

The aromatic compounds present in JP-8 fuel can be removed through solvent extraction processes, a common practice in refineries for removing aromatics from kerosene. Research is required to develop a suitable compact extractor for JP-8 applications. If properly developed, such a pre-treatment step could also partially remove the sulfur compounds as well as the additives that are present.

The transformation of polyaromatic hydrocarbons to monoaromatics and paraffins have recently created significant research interest for reducing aromatic content in diesel. The reactions generally take place under elevated pressure (about 100 bar) and temperature (300-400°C) in presence of H_2 over catalysts having both hydrogenation and cracking capabilities. Researchers are also studying catalytic cracking as a pretreatment step for converting the polyaromatics to monoaromatics. Further studies are required to develop improved versions of these processes or newer processes based on novel concepts for converting polycyclic aromatics to monoaromatics.

Objective number three is to develop a technical approach for overcoming barriers to the success of SOFC APU demonstrations using JP-8 fuel.

Examples of important problems associated with SOFCs are:

- (a) Carbon coking – For a hydrocarbon fuel, the state-of-the-art Ni/YSZ (Ni supported on yttria-stabilized-zirconia) anode material gets poisoned by graphitic carbon depositions, which limit its catalytic performance. Novel anode materials need to be developed that are more carbon-tolerant than Ni.
- (b) Over-potential losses – Almost any SOFC design has an over-potential problem. Activation losses are associated with slow inherent rates of catalytic electrochemical reactions. Novel anode materials that are inherently more active catalysts for electro-chemical oxidation reactions will be identified.
- (c) Sulfur poisoning – Almost any hydrocarbon fuels, such as methane, diesel, JP-8, and gasoline, have a certain content of sulfur containing molecules. These sulfur compounds tend to poison Ni anode catalysts and dramatically reduce their effectiveness. It is important to formulate anode catalysts that are more sulfur-tolerant than Ni anodes.

The first sub-objective will approach this issue by developing advanced catalysts for SOFC anodes and cathodes using density functional theory and laboratory experiments. The quality and economical feasibility of SOFCs will ultimately depend on efficient, robust, and affordable fuel cell electrode materials. There is a very limited understanding

of the molecular level chemical processes that govern electrode performances. This sub-objective proposes to use quantum Density Functional Theory (DFT) calculations and well-controlled surface science experiments to study molecular level mechanisms of the electrochemical reactions that take place on the SOFC anode.

The molecular-level mechanistic information will be used to search computationally, using quantum DFT calculations, for anode materials that are more resilient to carbon coking and sulfur poisoning, and that have lower over-potential losses as compared to Ni anodes. Any identified metal alloy will be synthesized and tested using an experimental setup designed for fuel cell testing. Subsequent optimization of these materials will then occur, specifically with respect to JP-8.

The second sub-objective is to make a determination of anode catalyst deactivation mechanisms during exposure to JP-8 reformat and identify counter-measures. SOFCs have several advantages over other fuel cells in APU applications. Internal reforming of hydrocarbon fuels in the cell anode compartment possible with an efficiency of forty to sixty percent, eliminating the need for external reforming because SOFCs operate at an elevated temperature higher than 600°C. One problem with using SOFCs is that during internal reforming of hydrocarbons, coke formation is possible, which has a negative impact on the anode catalyst life.

The purpose of this sub-objective is to conduct research into the possibility of internally reforming JP-8 fuel in SOFCs. A literature review indicates that current research is focused on the internal reforming of methane in SOFCs but there is a lack of knowledge on internal reformation of other hydrocarbon fuels, such as JP-8. The main challenge with methane internal reforming is coke formation. The Army is evaluating the feasibility of indirect internal reforming as a way of minimizing coke formation during the internal reforming of methane in an SOFC. This concept was proven to have problems, due to the mismatch between the thermal loads created by the rapid endothermic steam reforming reaction and the electrochemical reactions.

This sub-objective will be focused on attempting to optimize the performance of the anode material as an alternative to internal reforming of JP-8, without catalyst deactivation. The literature on methane reforming will be used as a guide to JP-8 reforming. The feasibility of using indirect internal reforming will be evaluated, as it is a way of internally reforming methane without causing coke deposition in the anode compartment of the SOFC. This analysis will lead to optimizing the performance of the anode catalyst as an alternative to internally reforming JP-8 without anode deactivation. If this research shows that internal reforming is not feasible for JP-8 reforming in SOFCs, then external reforming will be considered as a secondary option.

There is still much to be learned regarding reforming JP-8 into a useable fuel for SOFCs. The Army intends to pursue these multiple options for the advancement of converting JP-8, the logistical Single Fuel Forward, into a fuel that is useful for SOFCs.

MILITARY JP-8 REFORMER

Per the Single Fuel Forward policy, there may be a future need to make JP-8 and separate out the hydrogen. As stated earlier, JP-8 is a sulfur-rich, kerosene-like fuel that is difficult to reform. The three driving forces for this change include:

1. With its current capabilities and equipment the US Army cannot meet the objective of "Silent Watch".
2. With the continued advancement of vehicle electrical and electronic power requirements, vehicles are reaching critical levels to where decisions are made as to what electronics are operating at any given time to complete the mission.
3. Currently there is no power management system available for use to manage the power demand.[23]

Table 2 – Comparison of Usage of JP-8 and Cost per 12.5 kWh [23]

	\$ Required / 12.5 kWh	JP-8 gallons
Abrams	\$2470	99
Bradley	\$390	15.6
Stryker	\$312	12.5
Fuel Cell System	\$25	1

Table 3 – Comparison Usage of Cost to Charge Battery [23]

	Fuel Usage (gal/hr)		Total Possible Power (kWh)	Battery Power (kWh)	Gallons to charge at		Cost to charge batteries
	Basic Idle	Tact. Idle			Tact.	Idle (2 hr)	
Abrams	10.784	14.23	9	3.6	28.46		\$711.48
Bradley	0.899	1.498	6	2.4	3.00		\$74.89
Stryker	0.374	0.599	3	1.2	1.20		\$29.96

Table 4 – Scenario: 100 Charge Cycles (JP-8 reformer and fuel cell APU \$28,500 , estimate 2010) [23]

Cost 100 Charge Cycles 12.5 kWh/cycle		Savings / gallons conserved		Payback Time # Charge cycles
Abrams	\$247,000	\$244,500	9789 gal	12
Bradley	\$39,000	\$36,500	1460 gal	78
Stryker	\$31,200	\$28,700	1148 gal	99
Fuel Cell	\$2500			

Other benefits, besides cost savings, are a reduced engine operation/improve main engine life, reduced engine maintenance, maintenance schedules and logistics support, and reduced battery weight and space claim. Currently, this program is in the process of determining how many contracts to award from the proposals submitted to the US Army TARDEC Broad Agency Announcement (BAA).

HYDROGENICS MULTI-SERVICE REGENERATIVE ELECTROLYZER FUEL CELL

The Hydrogenics Multi-Service Regenerative Electrolyzer Fuel Cell (MREF) is a potential alternative for currently fielded APUs. Unlike some of the other initiatives, which focus on utilizing JP-8 as a source of hydrogen, the MREF system creates hydrogen from water through electrolysis, which can then be used in the fuel cell.

This is an on-going project that began back in 1999 with a paper study to determine the path forward for the Army. It is mandatory to have sufficient power for continuous Silent Watch for a specified amount of time. Silent Watch is a situation where the main engine is shutdown and the crew still needs to operate electronics and other equipment without being detected. Other application requirements include a unit that is quiet, cool, efficient, and that will supply enough power to complete the missions. The result of the study determined that a 5-10 kW Proton Exchange Membrane (PEM) Fuel Cell system would address the all-inclusive needs of the soldier.[24]

The second part of the program was to demonstrate a viable technology. In 2001, an agreement was signed and a contract was placed for this unit; the agreement included the US and Canadian militaries. The goal was to create a unit that would supply 3 kW of power, with the ability to run up to 5 kW for short periods of time, have 10 kWh of hydrogen storage, and operate at 28 volts DC. This unit was to be tested in a laboratory environment and be able to charge off a standard 300 A alternator. The vehicle that was chosen to support this effort was Stryker, the Light Armored Vehicle (LAV). To

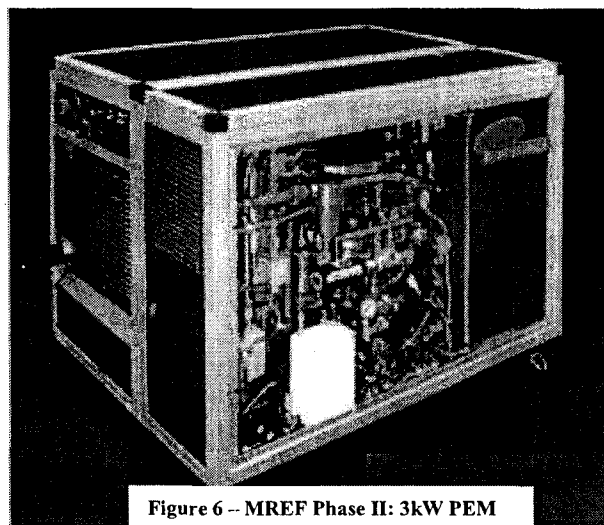
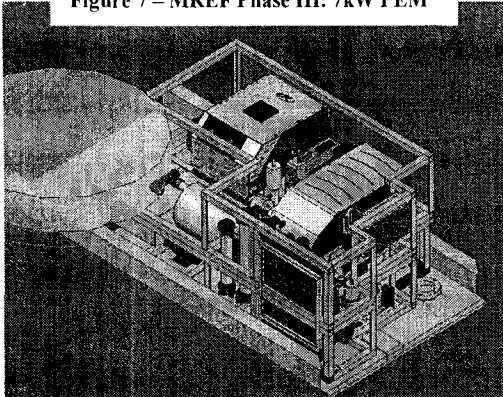


Figure 6 -- MREF Phase II: 3kW PEM

store the hydrogen, a metal hydride canister was chosen. Although compressed gaseous hydrogen was a proven storage method, the program went a step further to pursue the less

developed, and higher risk, high-pressure metal hydride storage. Successful demonstration and evaluation occurred in 2002 at the US Army TACOM.[24]

Figure 7 – MREF Phase III: 7kW PEM



The next phase of the project was a vehicle demonstration program. Multiple branches of the US and Canadian military were involved in the design process; there were increasingly more power and storage demands put on the unit. The new power requirement was 7 kW of power, with 9 kW for short durations, and 30 kWh of storage was specified. The three main components of this

system are the fuel cell stack, the electrolyzer, and the hydrogen storage.

Below is a listing of the technical specifications of the fuel cell stack:

Table 5 – MREF Stack Specifications[24]

Dimensions	cm	66.6 x 43.6 x 22.8
Mass	kg	60
Efficiency @ 50 amp	%	51
Operating Lifetime	hrs	1000
Net Rated Electrical Power	kW	7
Operating Current Range	Amp	0-140
Beginning of Life Voltage Range	V	53-75
Time from Off Mode to Idle	sec	< 15
Time from Idle to 7 kW	sec	<3
Gaseous Dry Hydrogen	%	99.99
CO	ppm	< 0.2
Sulfur	ppb	< 9
Supply Pressure	kPa	600-800
Stack Operating Pressure	kPa	< 125
Consumption (max)	slpm	< 90

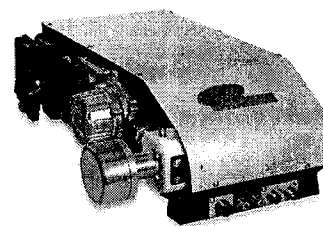


Figure 8 – MREF Phase III: 7kW Stack

Below is a listing of the technical specifications for the electrolyzer:

Table 6 – MREF Electrolyzer Specifications[24]

Wattage Demand at 28 VDC	4-6 kW
Hydrogen generation	20 slpm (2.5 kg/day)
Supply gas pressure	100 psig
Start-up time	1 minute
Time to Max Capacity	15 minutes
Purity of generated hydrogen	99.9%
Effective Electrolyzer on-time	3800 hrs
Equivalent hydrogen produced	3200 standard m ³ (282 kg)
System on-time	~6000 hrs
Operating voltage	28 V
Nominal current	150 A ~ 15 slpm of hydrogen
Number of on/off cycles	> 500

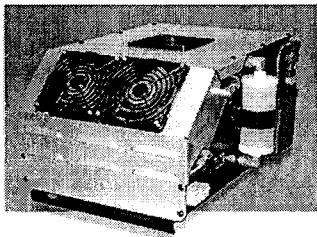


Figure 9 – MREF Phase III: Electrolyzer

The hydrogen storage is in three separate metal hydride containers. Each canister has dimensions of 14.0 cm diameter and 16.5 cm in length, a weight of 110 kg, and a hydrogen storage capacity of about 13 kWh. Even though these canisters have quite a bit of storage capacity, they are very heavy. Unfortunately, the military needs more production, with less volume and less weight.[24]

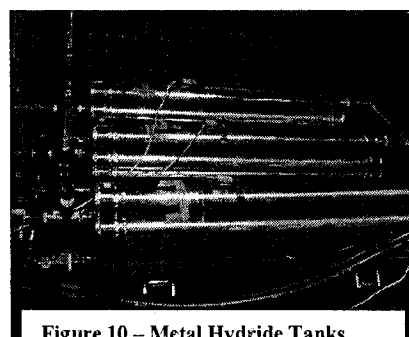


Figure 10 – Metal Hydride Tanks

Currently, testing is being done on this system to determine whether or not it is compatible with the electronic systems during a “Silent Watch” profile.

The next phase of the program is being developed. The initial goal was to demonstrate the ability of the system to operate in a military environment, but the system will have to be redesigned and integrated into a vehicle. Multiple tests will then be conducted to verify the durability and ruggedness of the system. At this time the decision has not been made whether gaseous hydrogen will be utilized, or if metal hydride will still be the hydrogen storage.

This system has several technological advantages for military applications. Most importantly, extending the period of continuous “Silent Watch” is a necessity. Along with the advancement of technology, there is a greater demand for power, and the MREF will be able to supply the power demands. Another advantage is the system’s ability to use water as the source of hydrogen, as opposed to JP-8 or other fossil fuel. With the ability to create hydrogen, store hydrogen, and produce power, the MREF has the advantage to “plug and play” on multiple vehicle formats without major redesigns. Since both the US and Canada are interested in reducing their dependence on fossil fuel, this collaborative effort is an appropriate stepping stone to a hydrogen economy.[24]

However with all emerging technologies, there are also disadvantages. Although water is a great and abundant resource, the greatest drawback is its relatively near-ambient freezing point. At 0°C, potential system damage needs to be minimized. In addition, for any dynamic condition, there are issues for the system. Vibration, dust, puncture, as well as temperature are all requirements that will be challenging for the MREF to pass. Another disadvantage of this system is the amount of space the MREF requires. In the current phase, metal hydride tanks are still utilized; these comprise a majority of the volume, as well as the weight. Optimization will reduce this footprint. Logistic optimization is another issue. Since water is being used as a fuel source, additional demands will arise for the water. There will also be a need for electrolyzers to operate at base camps. Further, there is a question as to whether there will be enough hydrogen produced inside the mobile units. Another issue will be whether the quality of water needed to operate this system is critical, or else will the system’s “water requirements” require a special water supply in the battlefield.

DELPHI SOFC APU w/ REFORMER

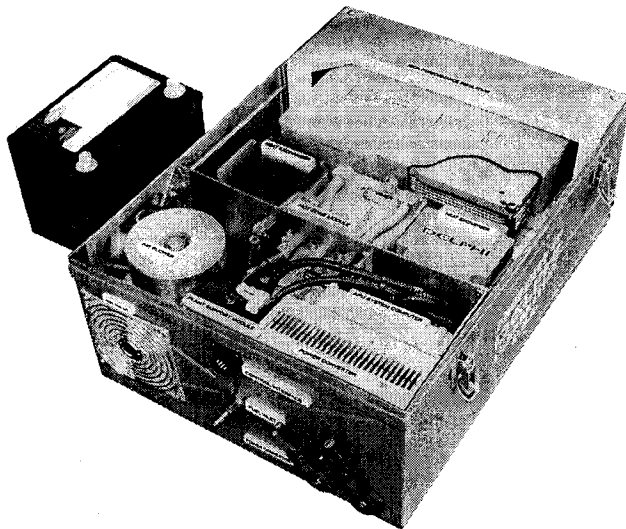


Figure 11 – Delphi SOFC APU with integrated fuel processor. The picture on the right illustrates the volume compared to a typical battery. [26]

As shown above in Figure 11, Delphi Corporation has been developing a five kilowatt solid oxide fuel cell (SOFC) APU, with integrated fuel processor, for use in military and commercial heavy-duty vehicle applications. A modeling effort, funded by the US Army National Automotive Center, was conducted to determine the estimated performance of this APU on a Bradley M2A3 Diesel Infantry Fighting Vehicle (IFV). The vehicle holds a crew of three (commander, driver, and gunner) and up to six infantrymen. The main engine is a diesel Cummins VTA-903T 447kW (600 BHP), and there are six 12V and one 24V batteries, as shown in Figure 12 and Figure 13 below. In addition to poor engine fuel economy at idle, the battlefield identification risks are increased for the soldiers in the vehicle, due to the main engine's heat rejection and visible exhaust smoke. [25]

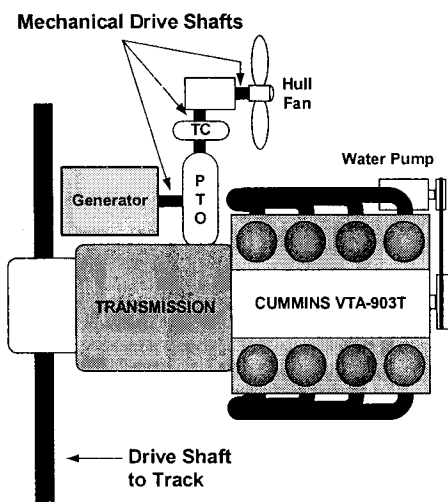


Figure 12 – Schematic layout of the current BFV powertrain.

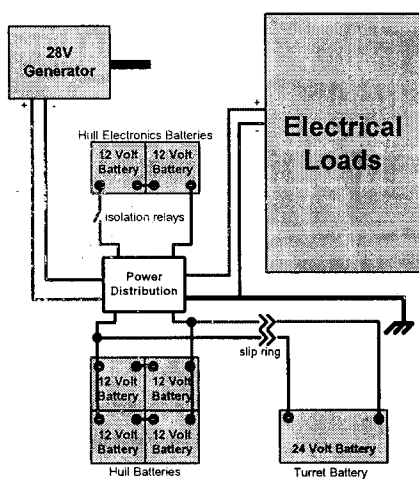


Figure 13 – Schematic layout of the current BFV battery and generator configuration.

During Silent Watch operation, in which an electrical load of 85A and 2.3kW are required, the fuel economy observed by using an APU was improved by 86% in comparison with the main engine, despite the efficiency loss of having a fuel processor. This extended the continuous Silent Watch capability from the baseline five days, when relying on the main engine, to over 36 days, when relying on the SOFC APU. As shown in Figure 14 below, the Bradley's electrical requirements are escalating quickly in power demand, and extending the Silent Watch capability with a more efficient APU is highly desirable. There were incremental vehicle efficiency improvements when modeling the engine hull fan and water pump, in which those electric engine accessories were powered

by the APU. Removing parasitic losses on an engine translates to more engine power being available for purely propulsion purposes; this provided marginal improvement in acceleration from 0-30 MPH. However, in the situation of the vehicle physically moving at a maximum speed of 2600 RPM and 75% load, the fuel cell did not prove to have a beneficial impact on fuel economy or vehicle performance. [25]

Bradley Electrical Generating Capacity

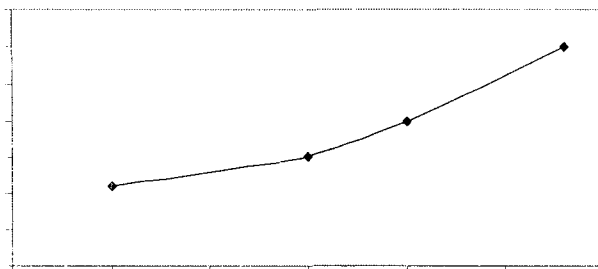


Figure 14 -- Bradley electrical power requirements increasing over time (provided by the US Army TACOM Bradley PM office).

FREIGHTLINER TRACTOR WITH BALLARD PEM APU AND METHANOL REFORMER

The Army Transformation Initiative has been providing direction to the organization to develop lighter combat vehicles, and therefore lightening its logistic infrastructure. As General Kern stated at the 2003 SAE World Congress, approximately two-thirds of the military's vehicles in the battlefield deliver fuel to the other one-third, and that approximately two-thirds of the fuel consumed in the battlefield is in the transport of that fuel, as illustrated below in Figure 15. There is also a rough estimate that the military spends \$100-500 in logistics cost for every gallon of fuel transported to the battlefield, so substantial improvements to fleet fuel economy are an absolute necessity. Reduction of fuel consumption can be achieved by minimizing the delivery, dispensing, and storage infrastructure needed through fuel economy improvements, as well as being able to reduce the combat assets needed to protect the fuel re-supply infrastructure. [3] [25]

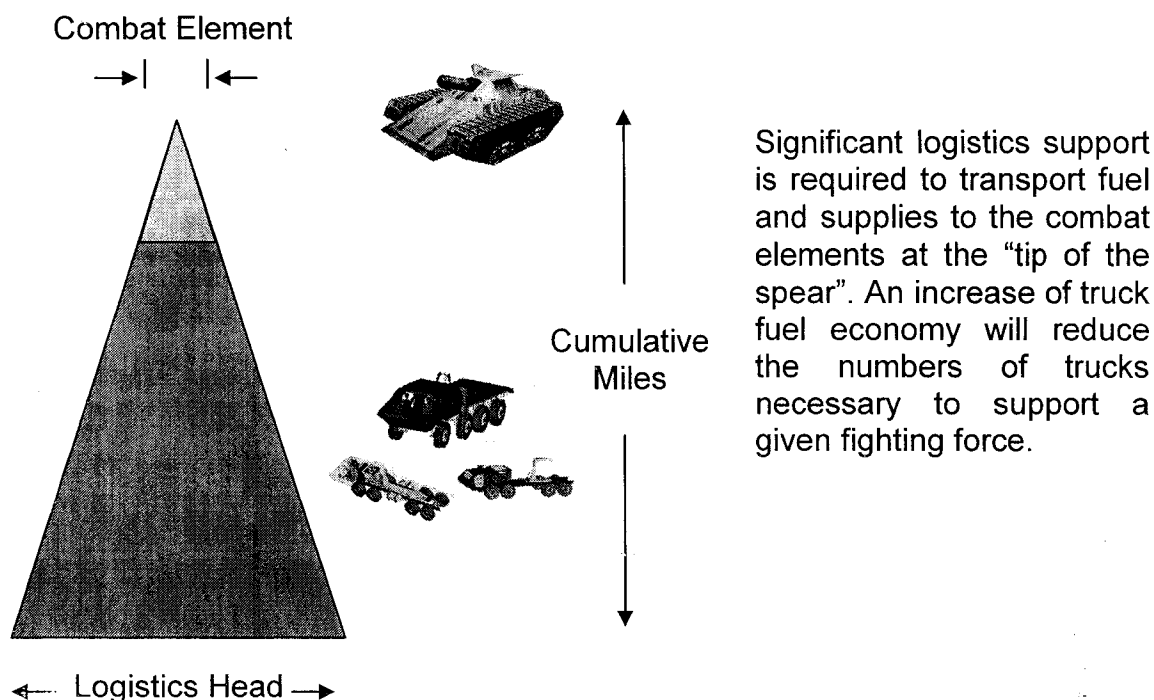


Figure 15 – A graphical representation of the logistics burden of the military.

A program between the NAC, Freightliner, Ballard, and the University of Alabama, integrated two Ballard 1.1 kW PEM fuel cells into an APU system, complete with its own balance of plant (BOP) and liquid-methanol reformer, on a commercial Freightliner Class 8 tractor, as shown in Figure 16. Methanol, CH_3OH (also known as MeOH), was chosen as a "more easily reformed fuel" and a stepping stone to reaching the military's ultimate goal of having a fuel processor capable of reforming the kerosene-like JP-8, which has potentially high sulfur content when acquired overseas. Although a diesel reformer-capable fuel cell APU makes the most sense for the commercial market, it will need to be compliant with military-grade JP-8. The next planned intermediate step was a fuel reformer capable of processing a synthetic low-sulfur diesel or military fuel, which was demonstrated on a brass board reformer system. [2] [3]

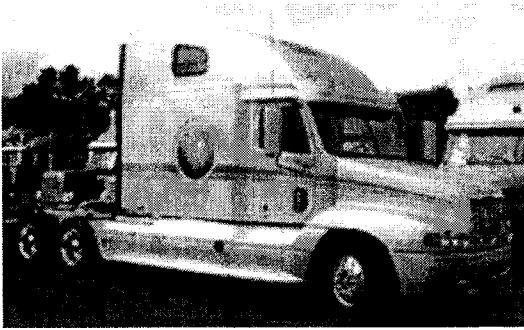


Figure 16 – The Freightliner Class 8 tractor with the Ballard integrated APU.

Risk analysis was performed regarding vehicle safety in the case of fuel leakage, and the safest APU location was determined to be behind the cab on the frame rails, as shown in Figure 17. The module itself is shown in Figure 18. [2] [3]

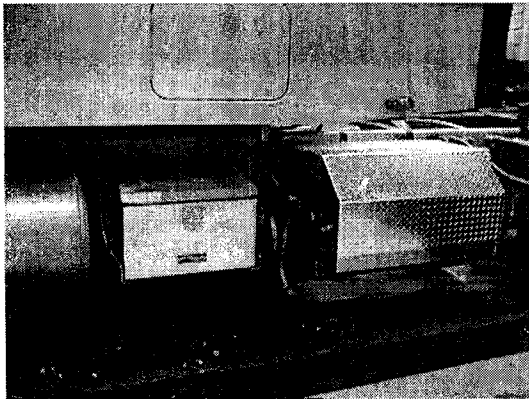


Figure 17 – APU installed on the side frame rails of the tractor. The fuel tank is mounted on the opposite side of the truck.

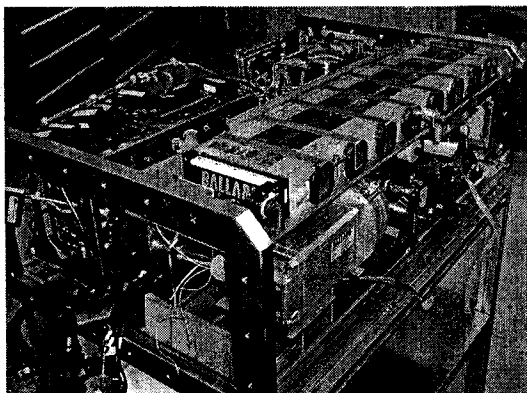


Figure 18 – The Ballard module assembly. The stack is on the top, the air system is on the bottom right, and the fuel processor is on the left.

The liquid methanol was actually a mixture of MeOH and water, and this was injected into the fuel processor. It was vaporized prior to the reformer, and then converted by a catalyzed reaction into a hydrogen-rich gas. The H_2 concentration at this point was over 50% by volume and that of CO was <1% (10,000 ppm). A final reforming stage reduced that CO level to <100 ppm; CO levels greater than that would have poisoned the fuel cell stack. The processing system is illustrated below in Figure 19, which illustrates the autothermal reforming (ATR) system with the ATR reactor, Shift reactors, the SeIOx, and the catalytic burner. The reformer was air-cooled, which was a critical issue for the APU's overall noise and vibration signature. In 2003, the fuel processor had successfully accumulated over 1,000 hours of full power operation (including transient) without an increase in CO concentration. CO concentration is a direct indicator of reformer degradation. [2] [3]

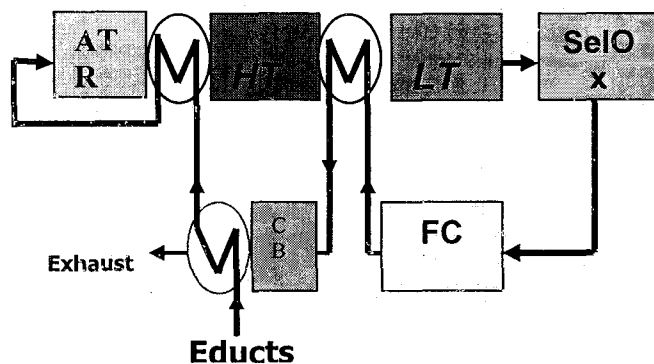
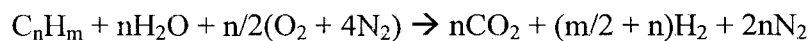


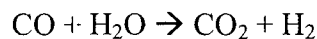
Figure 19 – Graphical representation of the fuel processor.

The theoretical equations for the fuel reformer above are:

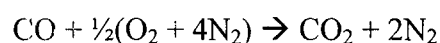
Autothermal reforming →



Water gas shift →



Preferential oxidation →



System efficiency, including the fuel processor, was found to be consistently greater than 30%. To meet the extremely fast transient response times necessary for a transportation application, the fuel cell system was hybridized with a battery, providing a dynamic response time of less than one second. As illustrated in Figure 20 below, the APU provided a 16-68% improvement in fuel economy over idling the main engine. [2] [3]

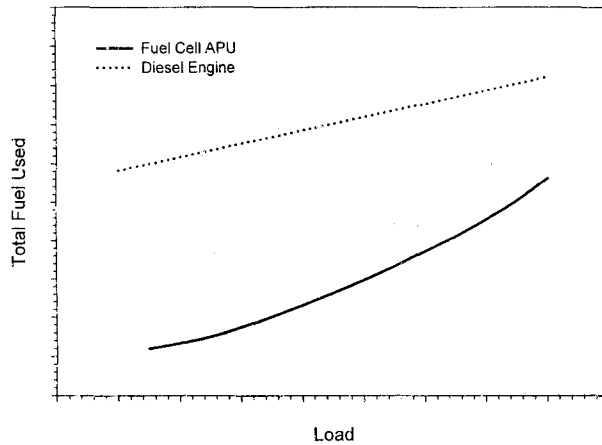


Figure 20 – Data generated by the DOE NREL ADVISOR model, comparing the idling of a main diesel engine to this APU configuration.

SUNLINE TRACTOR WITH HYDROGEN-FUELLED HYDROGENICS PEM APU AND VEHICLE ELECTRIFICATION



Figure 21 – The SunLine tractor after its cross-country trek from southern California to Washington, DC, in 2005.

The Delphi and Ballard programs outlined above show that there are fuel economy benefits obtained during Silent Watch mode in utilizing a fuel cell auxiliary power unit over main engine idling. To further employ those benefits when the vehicle is actually moving, the Army NAC wanted to determine other ways to gainfully employ a fuel cell APU. Otherwise, the fuel cell system (FCS) was “deadweight” on a moving vehicle. A program between SunLine Transit Agency, Southwest Research Institute, and the US Army NAC tackled this exact issue, and they are showing that vehicle electrification is a very complementary technological path to fuel cell APUs, utilizing the generated electrical power without the typical mechanical-to-electrical conversion losses, not to mention the primitive optimization. [27] [28] [29] [30]

Electrification offloads parasitic loads on the engine. This means removing an accessory, such as the mechanical engine radiator fan, and replacing it with a comparable electrical system. The accessory is longer tied to engine speed and load. Unnecessary excess accessory power demand is no longer going to waste, because of system control optimization through modulation. Heavy-duty vehicle systems that are electrified exist today include the engine fan, water pump, oil pump, air compressor, and cabin air conditioning system. [27] [28] [29] [30]

Although in its infancy stages of development for commercial vehicles, waste heat recovery can be another complementary electrification technology. By using electric turbocompounding and an integrated motor starter generator (ISG), waste heat can be recovered and converted into even more electrical power.

System electrification can be applied to anything from addressing commercial vehicle idling reduction to enhancing Silent Watch capability, not to mention fuel economy improvement. In controlled dynamometer testing of the SunLine vehicle (“pre-electrified” vs. the current configuration), a 14% improvement in diesel fuel economy was attained. Even when including the hydrogen consumption, the fuel economy benefit is still substantial, and is the primary reason that the heavy-duty vehicle industry is

quickly integrating this electrification technology into an industry standard. [27] [28] [29] [30]

Another vital role of electrification is as an enabling technology for fuel cells. Although fuel cell supporters would like to see them “replace” internal combustion engines in every application now, this will decidedly not happen immediately for the foreseeable future, primarily due to the lack of hydrogen infrastructure, as well as the exorbitant cost of the fuel cell systems themselves. Introducing smaller, less costly fuel cell APUs can help develop hydrogen refueling capability in a more realistic manner and provide a smoother transition.

The SunLine vehicle currently has two 10 kW Hydrogenics PEM fuel cells. The ultimate goal of the program is to have a liquid-fuelled fuel cell APU, but progress is very slow in developing a sulfur-tolerant fuel processor, mostly due to the decision by the auto companies and DOE a few years ago to pursue on-board hydrogen storage instead of on-vehicle fuel reforming. The vehicle has three 5000 psi Dynetek compressed gaseous hydrogen storage tanks, for a total of 5 kg of hydrogen storage. The electrified system components include an engine radiator fan, a water pump, air compressor, and air conditioning system. These are all 42V systems, due to the perceived evolution to that voltage a few years ago in the automotive industry. These electric accessories are all powered by the fuel cell APU, but there is also a 42V alternator set up to provide back-up power in case of fuel cell system failure (or if the vehicle runs out of hydrogen on the road). [27] [28] [29] [30]

CONCLUSIONS

Although the US military is still many years away from implementing fuel cells in the battlefield, they are working diligently to move the technology forward for dual-use applications in commercial and military vehicles. The most critical issue is desulfurization of jet fuel, since fuel cells are sulfur-intolerant and fuel quality can not be controlled outside of the boundaries of the US. Demonstrations of hydrogen-fuelled fuel

cell APUs are a stepping-stone to liquid-fuelled fuel cell APUs, when reformation reaches the level of maturity required for system integration and demonstration.

REFERENCES

- [1] SAE 2001-01-2792 "US Army Strategy for Utilizing Fuel Cells as Auxiliary Power Units," by Herb Dobbs Jr. (US Army RDECOM TARDEC NAC), Erik Kallio (US Army RDECOM TARDEC NAC, and James Pechacek (US Army RDECOM TARDEC NAC).
- [2] SAE 2003-01-0266 "Recent Results on Liquid-Fuelled APU for Truck Application," by Massimo Venturi (Ballard), Erik Kallio (US Army RDECOM TARDEC NAC), Scott Smith (Freightliner), J. Baker (University of Alabama), and P. Dhand (University of Alabama).
- [3] SAE 2003-01-0267 "Synthetic Hydrocarbon Fuel for APU Application: The Fuel Processor System," by Massimo Venturi (Ballard), Detlef zur Megede (Ballard), Berthold Keppeler (Ballard), Herb Dobbs Jr. (US Army RDECOM TARDEC NAC), Erik Kallio (US Army RDECOM TARDEC NAC).
- [4] Interview with Clarence Woodard, TARDEC Engineer, 4 October 2004.
- [5] <http://www.milbatteries.com/hawker/brochure.html>
- [6] US Energy Information Administration
- [7] University of Michigan, Dept. of Chemical Engineering, B. Gould, A Tadd, J. Schwank
- [8] University of Michigan, Dept. of Chemical Engineering, B. Gould, A Tadd, J. Schwank
- [9] J. Hu, Y. Wang, D. VanderWiel, C. Chin, D. Palo, R. Rozmiarek, R. Dagle, J. Cao, J. Holladay, E. Baker Chemical Engineering Journal, 4049, (2002), 1-6
- [10] University of Michigan, Advanced Energy and Manufacturing Technology, Phase III project
- [11] R. Fischer and H. Tropsch, Brennstoff-Chemie 4 (1923) 276.
- [12] G. A. Olah and A. Molnor, "Hydrocarbon Chemistry", John Wiley & Sons, Inc., pp.66 (1995).
- [13] E. Iglesia, S. C. Reyes, and S. L. Soled, in "Computer-Aided Design of Catalysts" (E.R. Beckes and C.J. Pereira, eds., Marcel Dekker, New York, pp. 199-259 (1993).
- [14] H. Schulz and H. Gokcebay, in "Catalysis of Organic Reactions", J.R. Kosak, Ed., Marcel Dekker, New York, pp. 153-169 (1984).

- [15] E. Iglesia, S. C. Reyes, R.J. Madon, *Journal of Catalysis* 129 (1991), 238.
- [16] E. W. Kuipers, C. Scheper, J.H. Wilson, I.H. Vinkernburg, and H. Oosterbeek, *Journal of Catalysis* 158 (1996) 288.
- [17] R. C. Agrawal, and R.K. Gupta, *Journal of Materials Science* 34, (1999), 1131.
- [18] Villiermaux, J. "Future Challenges in Chemical Engineering Research", *Trans. IChemE*, 73, p. 105 (1995).
- [19] T.J. Campbell, A.H. Shaaban, F.H. Holcomb, R. Salvani, M.J. Binder, *J. Power Sources*, 2004, 129, 81.
- [20] R. Coll, J. Salvado, X. Farriol, D. Montane, *Fuel Proc. Technol.*, 2001, **74**, 19; and X. Wang, R.j. Gorte, *Appl. Catal. A: Gen.*, 2002, **224**, 209.
- [21] B.N. Bangala, N. Abatzoglou, E. Chornet, *AIChE J.*, 1998, **44**(4), 927.
- [22] M. Freemantle, "Microprocessing on a large scale", *Chemical & Engineering News*, Oct. 11, 2004, pp. 39-43.
- [23] Presentation from 2005 Power and Energy Symposium "Fuel Reformation", Mike Berels, TARDEC Engineer.
- [24] Presentation from 2005 NATIBO Conference "MREF", Chris Spangler, TARDEC Engineer, June 2005.
- [25] SAE 2004-01-1586 "Logistics and Capability Implications of a Bradley Fighting Vehicle with a Fuel Cell Auxiliary Power Unit," by Joseph Conover (Delphi / EDS), Harry Husted (Delphi), John MacBain (Delphi), and Heather McKee (US Army RDECOM TARDEC NAC). Presented at the 2004 SAE World Congress.
- [26] http://www.delphi.com/pdf/ppd/energy/sofc_auto.pdf
- [27] SAE 2004-01-1478 "42-Volt Electric Air Conditioning System Commissioning and Control for a Class-8 Tractor," by Bapiraju Surampudi (SwRI), Mark Walls (SwRI), Joe Redfield (SwRI), Alan Montemayor (SwRI), Chips Ingold (Modine), Jim Abela (Masterflux).
- [28] SAE 2005-01-0016 "Electrification and Integration of Accessories on a Class-8 Tractor," by Bapiraju Surampudi (SwRI), Joe Redfield (SwRI), Gustavo Ray (SwRI), Alan Montemayor (SwRI), Mark Walls (SwRI), Heather McKee (US Army RDECOM TARDEC NAC), Tommy Edwards (SunLine Transit Agency), Mike Lasecki (EMP).

[29] SAE 2006-TBD “Accessory Electrification in Class 8 Tractors,” by Joe Redfield (SwRI), Bapiraju Surampudi (SwRI), Gustavo Ray (SwRI), Alan Montemayor (SwRI), Heather McKee (US Army RDECOM TARDEC NAC), Tommy Edwards (SunLine Transit Agency), Mike Lasecki (EMP).

[30] <http://www.swri.org/sunline>

Feasibility of Fuel Cell APUs for Automotive Applications

**Chris Spangler
Eric Sattler
Heather McKee**

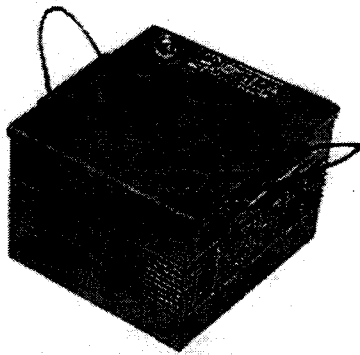
*Wayne State University AET5110
Professor Simon Ng
12/7/05*



Overview

- Vehicle batteries
- Single Fuel Forward Policy
- FC APU w/ JP-8 reformer
- FC APU benefits
- Demonstration programs
 - Delphi
 - Hydrogenics MREF
 - SunLine vehicle
 - Freightliner vehicle
- Clean Fuels Initiative
 - FT fuel
- JP-8 reforming

Battery History



6TN/6TL (1950/1982)

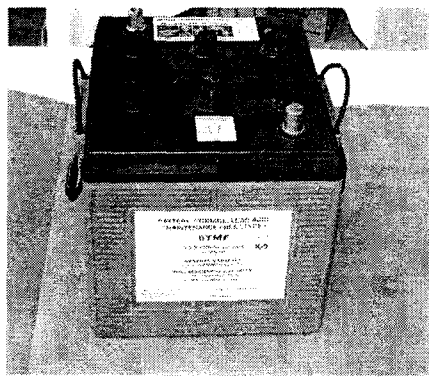
- Developed in 1950s for need
- Large water demand
- High maintenance cost



6TLFP (1996)

- Change from calcium to antimony
- Less self-discharge rate
- No additional water needed

Battery History



6TMF (1999)

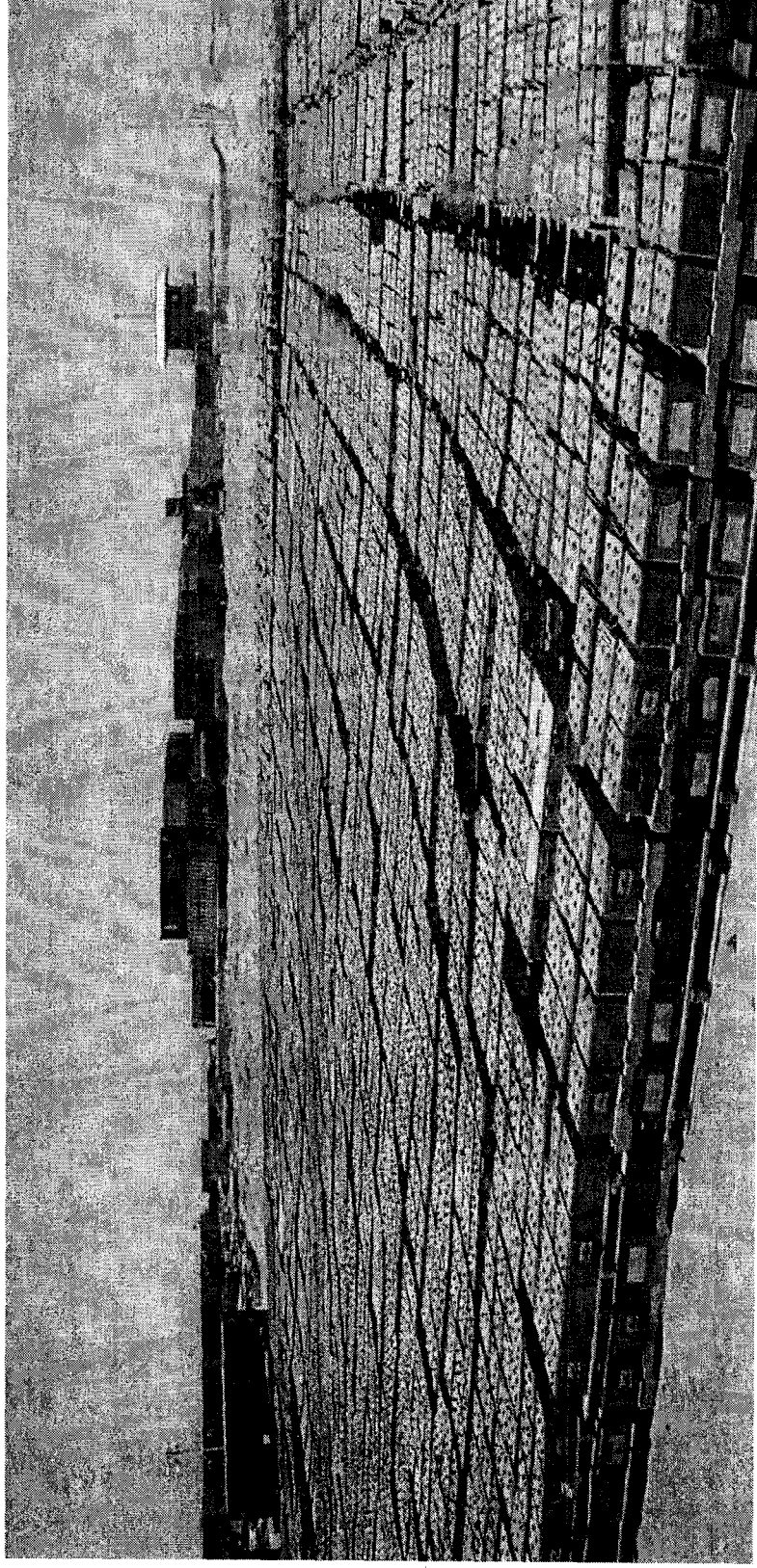
- Optimized chemistry
- Greater capacity
- Case color



VRLA (2004)

- Absorbed Glass Mat
- Sealed
- Deep discharge tolerant

Battery Graveyard



Motivation to supply an APU

Single Fuel Forward

- Previous times, various fuels
 - Diesel, gasoline, jet fuels
 - Incorrect fuel left vehicles stranded!
 - Caused logistical nightmare!
- All deployed vehicles “converted”
 - New fuel is JP-8
 - Works for compression ignition and turbine engines
 - Also suitable for ships as JP-5
 - Higher flash point for fire safety

Single Fuel Forward

- JP-8 constituents
 - Hydrocarbons ranging from C10 to C16
 - Paraffins, naphthalenes, aromatics, bi-cyclics
 - Spec limit for sulfur up to 3000 ppm!
 - Intolerant of reformation

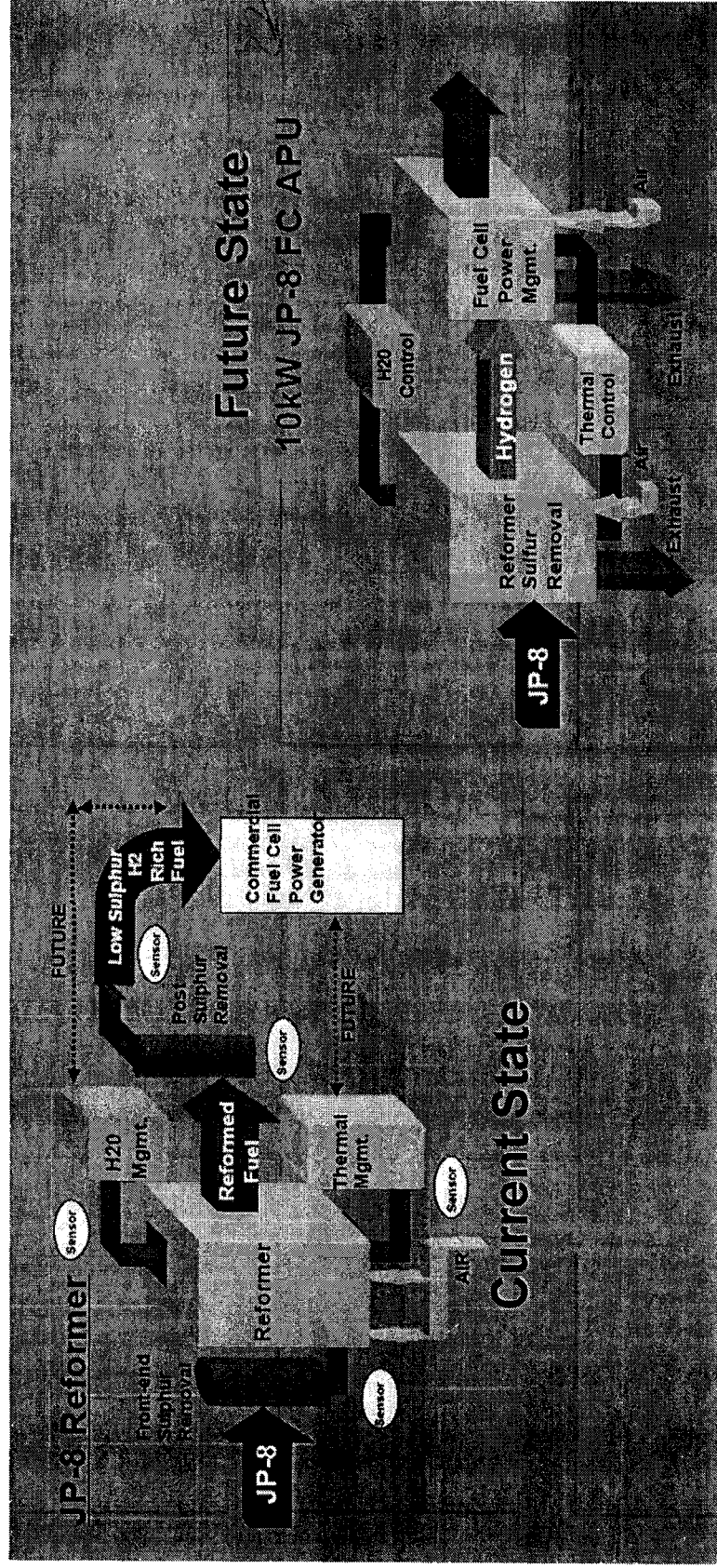
Military JP-8 Reformer

Challenges

- Not meeting objective of “Silent Watch”. - ?
- Electronic operation trade-offs
- No power management system available to manage the demand

Military JP-8 Reformer

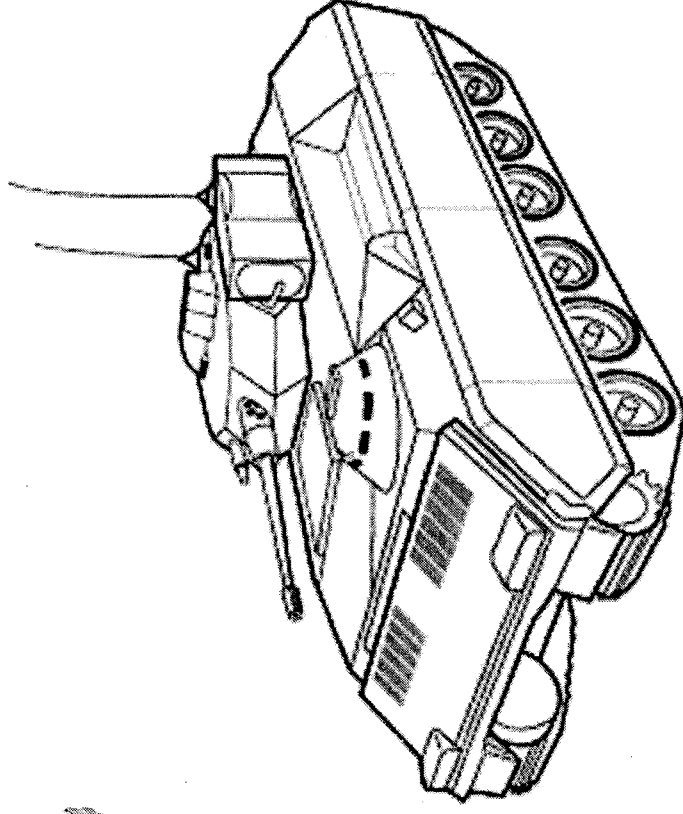
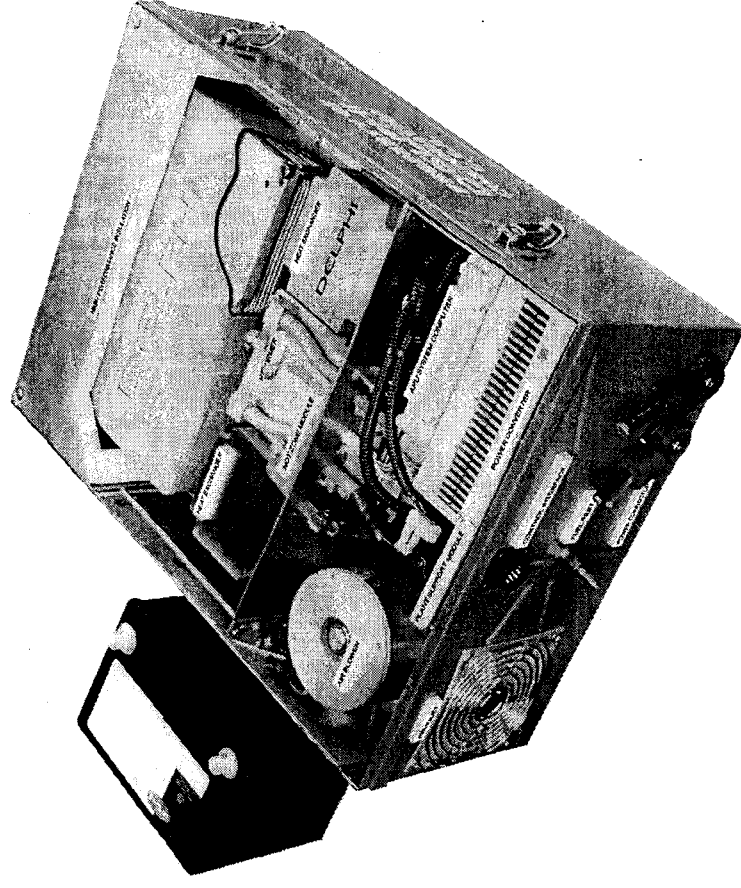
Military Vision Path Forward



Benefits of a FC APU

- Commercial vehicles - idling reduction
 - Quieter
 - Less/no exhaust emissions
 - Less vibration
- Military vehicles – Silent Watch 
 - Quieter
 - Less/no exhaust emissions
 - Less vibration
 - Increase continuous operation
 - Reduced thermal signature

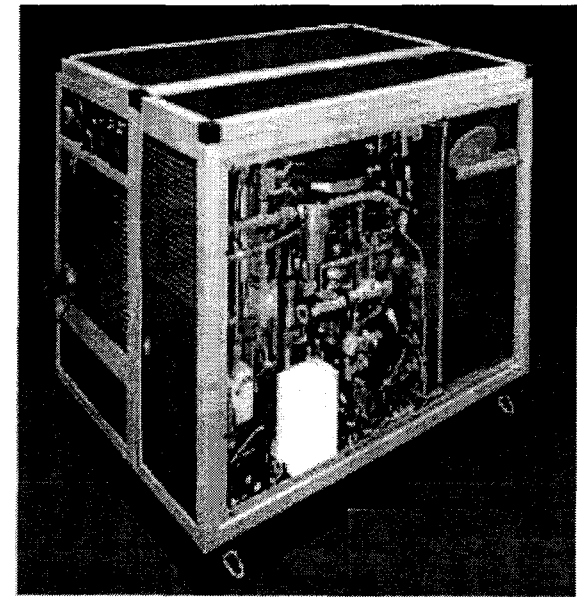
Delphi Bradley M2A3 Program



MREF Program

Phase II – Concept Demonstrator

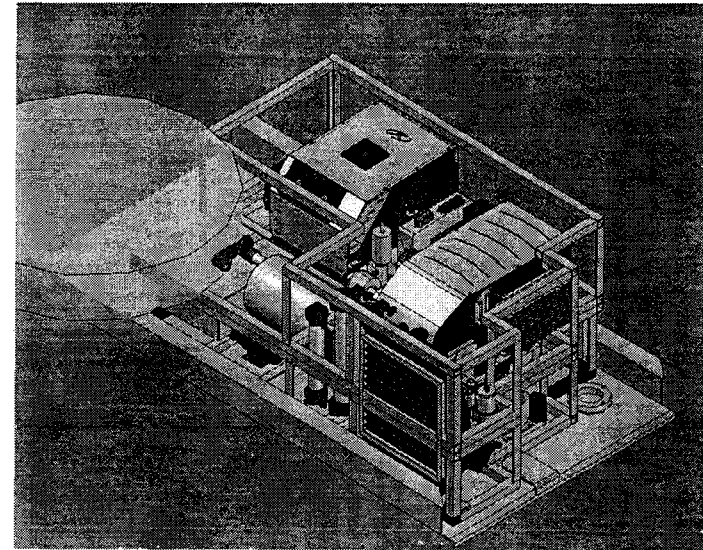
- 3 kW of Continuous Power
- 5 kW Peak Power
- 20 kW-hrs of H₂ storage
- 28 VDC format
- In a Laboratory Environment
- Std. 300A alternator



MREF Program

Phase III – Vehicle Demonstrator

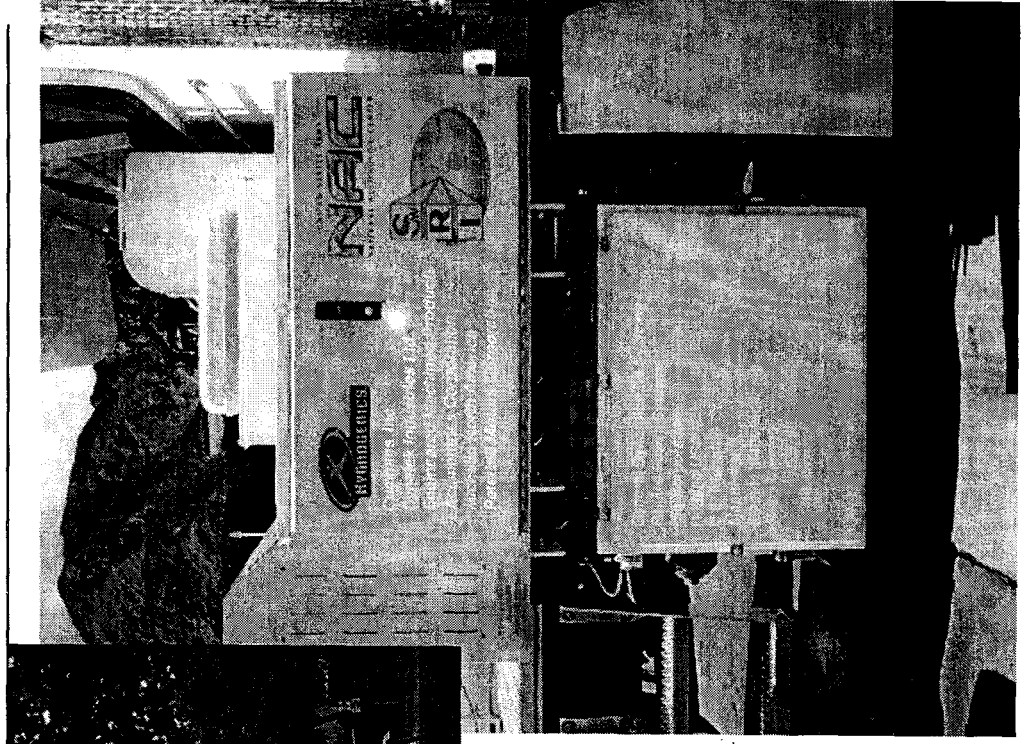
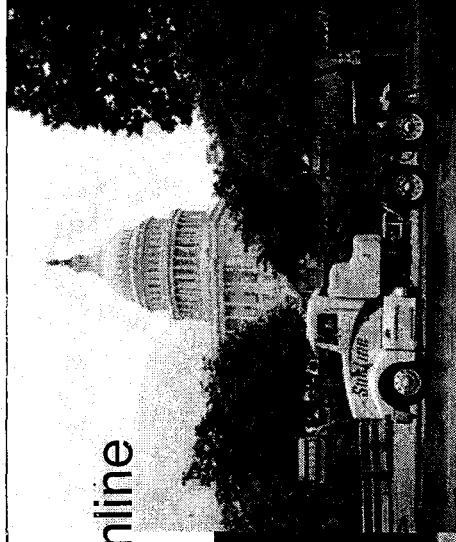
- 7 kW of Power
- 9 kW Peak Power
- 30 kW-hrs of H₂ storage
- 28 VDC & 120 VAC formats
- Standard alternator
- In/on a Light Armored Vehicle (Stryker)



— ?

SunLine Demo Program

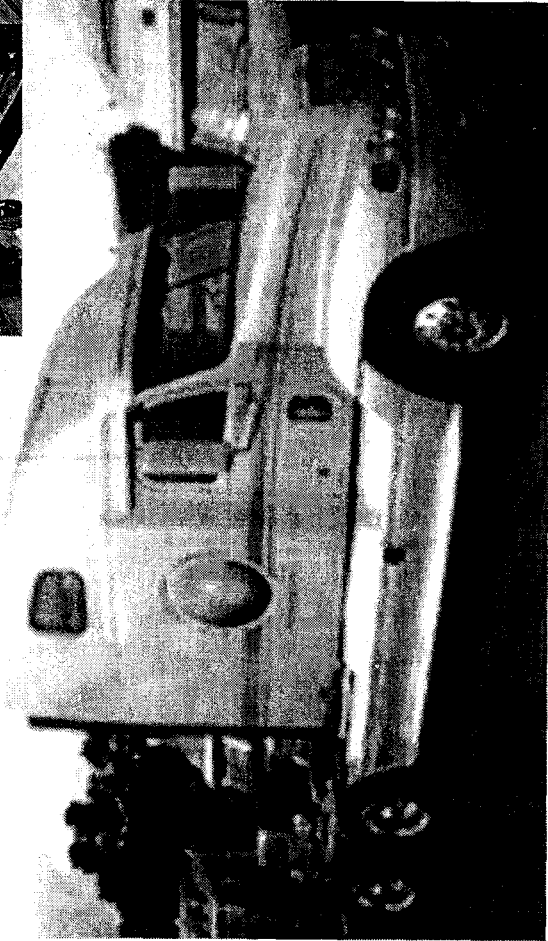
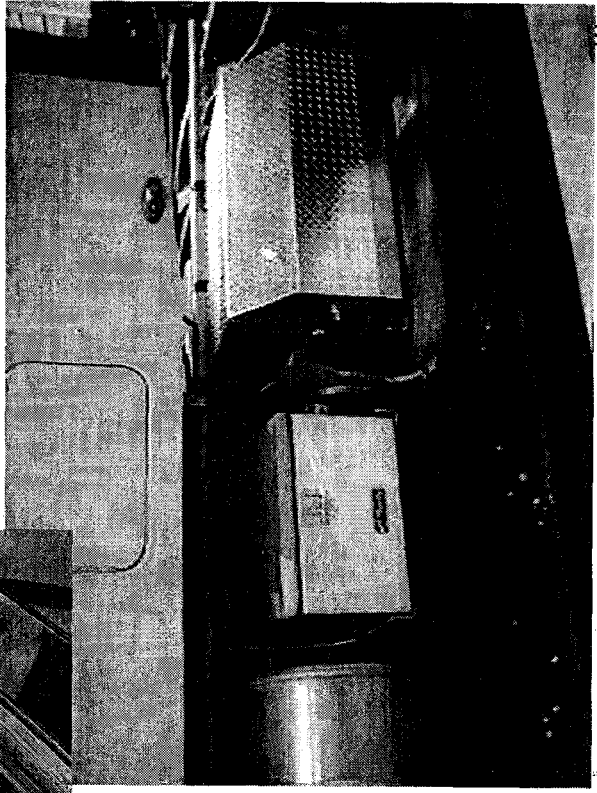
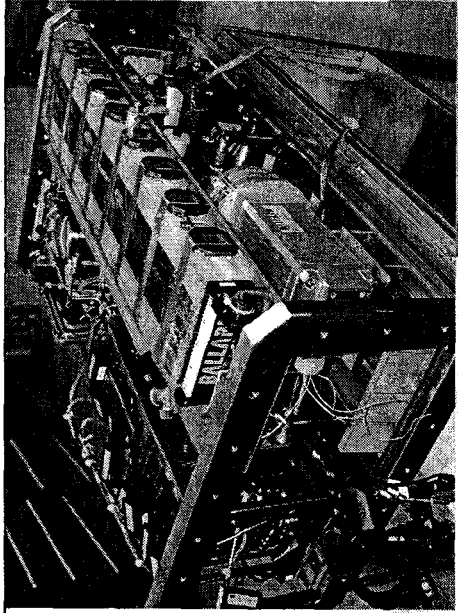
<http://www.swri.org/sunline>



SunLine Demo Program

- Contractors
 - SunLine Transit Agency
 - Southwest Research Institute
- Baseline vehicle
 - Peterbilt Class 8 semi-truck w/ Cummins ISL pre-2002 diesel engine (no EGR)
- Fuel cell APU
 - Two Hydrogenics PEM units (20 kW total)
- On-board hydrogen storage
 - Three 5000 psi Dynetek composite units (5 kg total)
- Electrified systems to date
 - Water pump, air compressor, engine radiator fan, air conditioning system
- Other systems that can be electrified include
 - Power steering, oil pump, integrated motor starter generator (ISG), electric turbocompounding

FL/Ballard Demo Program

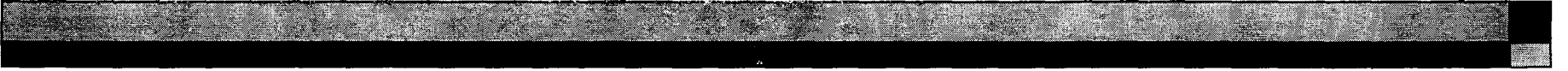


FL/Ballard Demo Program

- Baseline vehicle
 - Freightliner Class 8 semi-truck
- Fuel cell APU
 - Ballard PEM w/ on-board methanol reforming (2.2 kW total)
- On-board methanol storage

Clean Fuels Initiative

- Today US imports 57 % of oil requirements
 - Expected to rise to > 70 % by 2025
- China, India, and E. Europe increase = 54 %
 - Four times greater than production capability
- World consumption from 70 to 121 MM BPD
- No new CONUS refineries built in 25 yrs
 - No new US refineries expected to be built (NIMBY)
 - 88 % refining capacity in 8 states on Great Lakes, East, Gulf, and West Coasts
 - Mega-complexes in Texas, Philadelphia, New Jersey, Los Angeles, and Louisiana
 - These are all potential terrorist targets → ?
- Total supply exhausted in a few decades?
 - (data from US Energy Information Administration)



Clean Fuels Initiative

- Use secure indigenous sources of energy
 - Coal and petcoke
- Use an environmentally sensitive process to produce a better fuel
 - Fischer-Tropsch process
 - Use coal and petcoke as feed stocks

Fischer-Tropsch Fuels

- Non-detectable levels of Sulfur, Aromatics, or Metals
- High cetane number (> 74 vs. $45 - 50$)
- Very low toxicity / bio-degradeable
- Significantly lower emissions (NO_x , PM, CO)
- Compatible with existing fuel distribution infrastructure and legacy fleet
- Reduced visible smoke
- Great source of Hydrogen

JP-8 Reforming

Three common methods for reforming -

- Partial Oxidation (POX)
 - $C_nH_m + \frac{1}{2} n O_2 \rightarrow n CO + \frac{1}{2} m H_2$
 - Low H₂ yield, exothermic reaction, mass transfer limited
- Steam Reforming (SR)
 - $C_nH_m + n H_2O \rightarrow n CO + (n + \frac{1}{2} m) H_2$
 - High H₂ yield, endothermic, heat transfer limited
- Autothermal Reforming (ATR)
 - $C_nH_m + x O_2 + (2n - 2x) H_2O \rightarrow n CO_2 + (2n - 2x + \frac{1}{2} m) H_2$
 - Medium H₂ yield, tunable heat duty

JP-8 Reforming

- Biggest issue in using JP-8 for fuel cell is sulfur content
- JP-8 surrogate compounds are very difficult to reform due to molecule size
 - Dodecane and Tetralin are surrogates
- JP-8 reformatte better suited for SOFC rather than PEMFC
 - > 10 ppm CO not a problem for SOFC

JP-8 Reforming

Develop reforming options for SOFC APUs

- Direct catalytic decomposition of JP-8 into C and H_2 at 600 – 800° C
 - One reactor vs. three (reforming, WGS, PROX)
- Alternative, novel catalysts needed that will remain active over a wide range of fuels
 - Yttria-stabilized zirconia (YSZ), Zirconia-doped ceria ($CeZrO_2$), Gadolina-doped ceria (GDC), $Gd_2Ti_2O_7$
 - Others?

JP-8 Reforming

Investigate the feasibility of GTL fuel processes for APU's

- Develop a “designer” fuel from the F-T reaction which meets exact specifications
 - Results in an easy-to-reform fuel without pre-processing
- Develop a method to selectively remove aromatics as well as sulfur
 - Results in an easy-to-reform fuel

JP-8 Reforming

Develop technical approaches for overcoming barriers to the success of a JP-8 – fueled SOFC APU

- Use Density Functional Theory calculations to develop novel catalyst / electrode combinations
 - Find those material combinations that are resistant to coking and sulfur poisoning as well as having a lower overpotential loss than Ni
- Determine anode catalyst deactivation mechanisms
 - Coke formation is biggest challenge

Questions?

©2005, 10th Annual Mr. Plegge / 1057 by University Press Syndicate

Mr. Plegge

E: CLOSING@MILLER



A dramatic breakthrough in the world of alternative energy: canine tail power.