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Design Considerations for a PEM Fuel Cell Powered Truck APU

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ABSTRACT

In recent years interest has been growing in using fuel cell powered auxiliary power units (APUs) to reduce idling in line-haul trucks. Demonstrations of this technology have been constructed at universities and within industry, each with its own advantages and disadvantages. Invariably, in every design, tradeoffs need to be made and this has resulted in a multitude of different APU solutions that address different aspects of the problem.

This paper reviews some of the recent work related to fuel cell APUs for large trucks. The paper also examines what characteristics are important to consider in the design and integration of a fuel cell APU and outlines the strategy and methodology taken by the University of California Institute of Transportation Studies in designing and building a viable demonstration fuel cell APU.

INTRODUCTION

Currently large numbers of transport trucks idle during times when they are not actively transporting a load. Power demanded during these times has been called “hotel load” because it is the power necessary for the comfort of the driver while at rest. Earlier studies have indicated that trucks may idle anywhere from 6 to 16 hours out of the day and consume around a gallon of diesel fuel every hour that the engine is idling. The amount of fuel used and emissions produced during this time of inactivity is not insignificant. [1][2][3][4]

Policy making bodies, understanding the adverse effects of diesel emissions, noise pollution, and fuel consumption have started to pass legislation in an effort to curtail truck idling. At the local level many states as well as some municipalities have instituted idling bans, with many more considering anti-idling legislation. [5]

With idling reduction gaining more attention, the UCD ITS has designed and built a fuel cell demonstration APU for a Class 8 truck. The purpose of which was to demonstrate fuel cell APU technology and compare it to existing technology options.

RECENT FC APU DEMONSTRATIONS

Fuel cells are experiencing a period of renewed attention. In the last ten years federal and private funding for research into fuel cell technology and uses has been steadily increasing. As a result many fuel cell APU projects have been demonstrated.

Freightliner successfully demonstrated a PEM fuel cell APU on a Century Class Freightliner truck. [8] The APU incorporated two fuel cells that provided a total output of 1.4 kW of power. The system utilized a 52 gallon (197 L) compressed hydrogen storage tank at 2,500 psi. The system was able to provide 120 VAC power or 12 VDC power, however it was not able to supply both at the same time. Climate control was provided by a diesel fuel fired heater and a 120 VAC air conditioner described as a typical home, in-window air conditioning unit.

The authors examined the possible fuel and emissions savings that would be possible if engine idling were to be eliminated. The analysis assumed idling times of between 1,818 and 2,424 hours per year. In their calculations for economic payback period for a FC APU they also assumed 1 gallon of diesel fuel was consumed per hour on average for an idling engine running typical accessories. Using these assumptions it was calculated that between $3,127 and $4,169 was spent on engine idling alone per year. The paper also made some estimates as to the reduction in emissions that could be realized by using a FC APU.

Delphi Automotive Systems in cooperation with BMW has demonstrated a proof of concept SOFC APU. [9] This demonstration was built to power an electrical air conditioner and electrical loads in passenger vehicles. While not specifically designed for a Class 8 truck application the fuel cell APU shares many design characteristics that would make it easily adaptable to the truck market.

SOFC technology was chosen for the Delphi APU. Some of the reasons cited include the ability of the SOFC to utilize liquid hydrocarbon fuels, less expensive non-noble catalyst, a simpler reformer design, and elimination of the need for humidification or complex water management. Diesel fuel is readily available and would not require a new fueling infrastructure or a secondary fuel to be dispensed at the station.

The Sacramento Municipal Utility District (SMUD) built and tested a fuel cell APU. [10] Their demonstration project integrated a supercharged, water cooled, 5kW fuel cell with a Class 8 truck. The system used 5.3 kg of compressed hydrogen storage as the fuel source. Special attention was given to durability and the ability to operate in temperature extremes from -40C to 50C. The completed FC APU underwent track testing for environmental tolerance including both high and low temperatures and road dirt.

FC APU DESIGN CONSIDERATIONS

In order to better understand the market for FC APUs and the features that would be required for a desirable FC APU many sources of information where considered. The UCD ITS conducted a survey of 365 truck drivers at locations nationwide soliciting responses to questions involving trucker idling behavior, usage of idling reduction technologies, and preference for APU features. The results from previous studies, measurements taken from a stock test vehicle, and survey results were used to guide development of the demonstration fuel cell APU.

CUSTOMER REQUIREMENTS

The purpose of a truck APU is to provide the user with climate control and electrical power necessary in order to eliminate the need to idle the main engine that is normally used to provide these services. Beyond simply replacing the services provided by the main engine, the APU must provide a superior user experience. In the absence of regulation, the adoption of APU technology will proceed only if the APU design provides a better user experience at a lower cost than what is currently available by idling the main engine. It is very important to understand what compromises the user is willing to make in terms of performance and price in order to design an APU that is useful and marketable.

Venturi and Martin [11] examined the APU market in three regions; North America, Europe, and South America (using Brazil as a representative country). They concluded that the North American market was driven by high truck comfort and estimated its size at some 10,000 units. The European and South American market, due to shorter distances traveled and higher fuel prices, placed a higher value on fuel efficiency. They also published estimates for expected auxiliary loads from various truck appliances that might be used on a long haul truck.

Lutsey and Broderick also did work to estimate the power requirements of various appliances, and conducted multiple surveys to understand the distribution of these appliances and the use profiles among a representative set of line-haul truck drivers. [14][15] For line-haul trucks they estimated the size of the market at 100,000 trucks annually plus retrofits. They also estimated target parameters for a fuel cell powered APU that would be acceptable for this market. [16]

Truck Auxiliary Power Unit		
Peak Power	3 - 6	kW
Approximate APU Cost	4,000 - 8,000	$
Target System Cost	500 - 1,000	$ / kW
Target Weight	50 – 100	W / kg
Target Volume	30 – 50	W / l

Table 1 – Truck APU Market Parameter Targets [16]

Climate Control

In a stock truck, heating is provided by the idling engines coolant system. Cooling is provided by an engine driven refrigerant compressor. In each instance there is a thermal / mechanical load associated with the heating or cooling plus an electrical load associated with the fans to circulate the temperature controlled air through the cab. In comparison to anticipated electrical loads, climate control loads are much larger and are an important consideration when specifying the peak power capacity of the APU.

An APU climate control system can be sized smaller than the peak capacity for the stock system because the APU system is designed to provide climate control over a smaller set of operation conditions than the stock system. The stock HVAC system is designed to provide climate control for the entire cab and sleeper. The APU system needs to be sized only for the sleeper compartment which is much smaller. The stock system must be sized to bring the entire cab area to a desired temperature in a short amount of time, a process called “pull-down”. The APU will primarily be operated after the cab has already been brought to the desired temperature, usually after the operating truck has reached it’s destination for the night. If needed the truck could be idled for a short period of time to provide pull-down without negating the advantage provided by the APU. Finally, during APU operation the truck will be parked, putting less of a thermal load on the system due to reduced convective losses to the outside air stream and reduced thermal losses due to drafts and air leakage.

Cooling

The American Trucking Association publishes recommended engineering practices for the OEM truck manufacturing industry. They have developed recommended practices and testing criteria for APU climate control systems as part of RP 432. Table 2 shows the recommended performance and testing criteria for an APU cooling system.

ATA RP432 Cooling Recommendations		
Performance		
Sleeper Temperature (max)	78	°F
Duration	10	hrs
Test Criteria		
Factory Curtains	Closed	
Initial Cab / Sleeper Temp	73	°F
Ambient Temperature	100	°F
Relative Humidity	50	%
Solar Load (Overhead Source)	600	W / m^2

Table 2 – ATA RP432 APU Cooling [17]

In order to better estimate appropriate APU system sizing, stock HVAC system measurements were taken on the Freightliner test truck. Tests consisted of measuring the difference between ambient air temperature and the air temperature within the truck. A/C testing was completed under maximum HVAC settings with the engine idling at 1000 RPM.

Air conditioning systems in stock trucks are designed with capacities of up to 24,000 BTU/hr. This capacity is sufficient for cooling the entire cab, driver area and sleeping compartment under all operating conditions. The Freightliner Century class test truck came standard with a factory installed Sanden SD7H15 compressor. This compressor is driven mechanically by a belt off the engine, and may require from 1.5 – 6 kW of engine power depending on idling speed and ambient temperatures. At a condenser temperature of 52°C this compressor is capable of providing more than 10,000 BTU/hr cooling capacity at idle speeds, with greater compressor speeds the capacity approaches 24,000 BTU/hr. Results from stock cooling system tests are shown in Table 3.

Stock Cooling Performance		
Max Rated Vent Airflow	425 (250)	m^3/hr (CFM)
Max Rated Capacity	7.0 (24,000)	kW (BTU/hr)
Vent Temp Delta [Vent – Sleeper]	13.0 (23.4)	°C (°F)
Sleeper Temp Delta [Exterior – Sleeper]	7.8 (4.3)	°C (°F)
ATA RP432 Delta	*15* *(27)*	*°C* *(°F)*

Table 3 – Stock Cooling Performance

Heating

The ATA also publishes recommended practice for engine-off HVAC heating performance shown in Table 4. As a rough comparison of the different duty requirements for heating and cooling the temperature differences that must be maintained can be compared for each task. For the cooling system the testing criteria calls for a 27 °F temperature difference (plus additional solar load) to be maintained for a period of 10 hours, in the winter a 68 °F temperature difference must be maintained.

ATA RP432 Heating Recommendations		
Performance		
Sleeper Temperature (min)	68	°F
Duration	10	hrs
Test Criteria		
Factory Curtains	Closed	
Initial Cab/Sleeper Temp	73	°F
Ambient Temperature	0	°F
Solar Load	0	W / m^2

Table 4 – ATA RP432 APU Heating [17]

Heating is provided by waste heat from the engine cooling system. The engine on a large diesel truck has more than enough waste heat to supply all that is needed to the heating system. Unlike the cooling system, the heating system requires no additional mechanical input energy, except that needed in order to run low power auxiliary pumps and fans. In order to better estimate appropriate APU system sizing, stock HVAC system measurements were taken on the Freightliner test truck.

Benchmark testing was also performed on the stock heating system. Tests consisted of measuring the difference between ambient air temperature and the air temperature within the truck. Heating system testing was completed under maximum HVAC settings with the engine idling at 800 RPM. These tests are for the sleeper cab only, the main cab climate control system was not used. Measurements where taken after the sleeper compartment temperature reached steady state. Table 5 shows the results for the heating performance on the stock test truck.

Stock Heating Performance		
Max Rated Vent Airflow	425 (250)	m^3/hr (CFM)
Max Rated Capacity	8.8 (30,000)	kW (BTU/hr)
Vent Temp Delta	49.7	°C

[Vent – Sleeper]	(89.4)	(°F)
Sleeper Temp Delta	41.6	°C
[Exterior – Sleeper]	(74.8)	(°F)
	37.8	*°C*
ATA RP432 Delta	*(68)*	*(°F)*

Table 5 – Stock Heating Performance

Electrical Power

The electrical power needed for an APU system can be broken down into different needs. Low voltage DC power to run onboard truck integrated accessories such as dome lights, dash radios, CB radios, and other DC accessories. The other need, made possible by the APU, is for high voltage 120V AC to power electrical air conditioners, refrigerators, televisions, VCR's, computers, and other household appliances.

12V DC Power

Measurements were taken on devices powered by the 12 VDC system on board a representative line-haul test truck. The loads from accessory devices, such as lights and the dash radio, were found to be very small. The power consumption by the climate control fans was found to be 100W– 200W; however these fans are not used during APU operation because these functions are performed by other devices. The numbers in parenthesis for the blowers in Table 6 indicate fan speed setting.

12V Truck Loads	
Truck State	Ave. Power [W]
Off	7
Run	72
Climate Control	
Cabin Air Blower (1)	153
Cabin Air Blower (2)	185
Cabin Air Blower (3)	215
Cabin Air Blower (4)	229
Sleeper Blower (1)	83
Sleeper Blower (2)	118
Sleeper Blower (3)	135
Accessory	
Dome Light	29
Reading Light	14
Radio	12
CB Radio	15

Table 6 – 12 VDC Accessory Loads

120V AC

Unlike the stock 12 VDC accessories that are present on nearly all trucks by the manufacturer (ie. lights, fans, radio), the number and type of 120 VAC accessories in use varies greatly from truck to truck. The results of a nationwide survey performed by the UCD ITS found that a significant number of truck drivers use 120 VAC appliances in their trucks, presumably by utilizing a small inverter run off the truck's 12 VDC power system. Even though most trucks lack APUs, surveys show that these accessories are being used in a large majority of trucks. Some trucks don't have any AC accessories, while other trucks have several.

120V Truck Appliances		
Entertainment	Present	Pk. Power [W]
TV	74%	100
VCR	53%	30
Stereo	66%	50
DVD Player	*	30
Game System	*	20
Communication		
Cell Phone	62%	10
Laptop Computer	23%	35
Comfort		
Air Conditioner	-	1200
Refrigerator	59%	160
120V Lamp	46%	100
Microwave	19%	1200
Coffee Maker	15%	1200
Hot Plate/Crock Pot/Grill	*	750
Other *	11%	-

* Survey lumped enumeration as part of the "Other" category

Table 7 – 120 VAC Electrical Loads

The survey, for the most part, did not distinguish between 120 VAC appliances and those that directly operated on 12 VDC. However, all the appliances that are listed in Table 7 could be operated on a 120 VAC power supply if it were available. This would most likely be preferable to the truck driver because 120 VAC appliances cost less and usually run more efficiently than their low voltage DC counterparts.

The majority of the electrical load on the APU comes from 120 VAC appliances and climate control devices. The most significant load is from the electrical air conditioning system, which demands a large amount of power that must be maintained for long periods of time. The remaining 120 VAC loads are much smaller and more intermittent.

Packaging and Integration

Size and weight are important to truck drivers because the drivers are usually limited in how much they can haul by one of these two constraints. A truck that is loaded to its full weight capacity is said to be "grossed out", a truck loaded to it maximum storage capacity is said to be "cubed out".

The UCD ITS survey asked a sample of line-haul truck drivers how heavy and how large of an APU they would be willing to purchase. The survey found that about 40% of the respondents would find an APU that is less than 249 pounds acceptable.

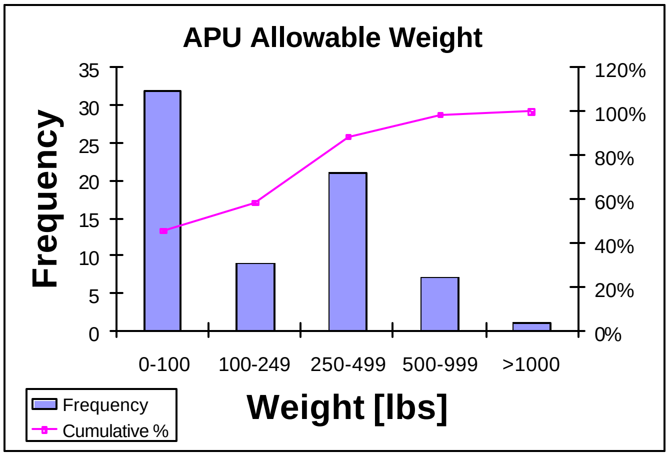


Figure 1 - Allowable Weight Response

It also found that about 80% of truckers are willing to accept an APU less than 16 cu. ft. in volume.

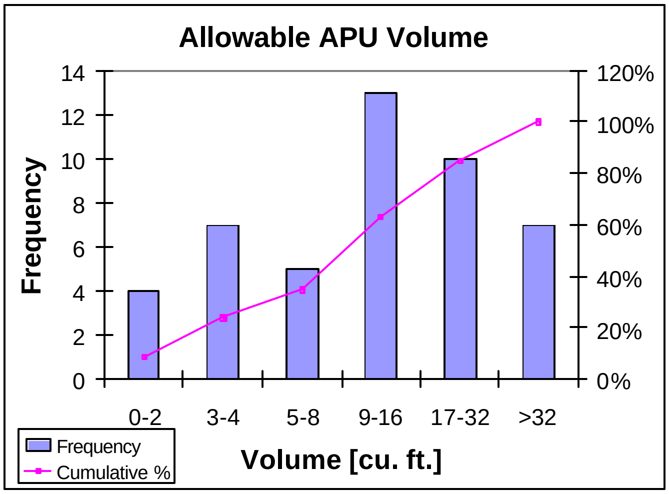


Figure 2 – Allowable Size Response

The opinion of the truck driver is useful in understanding what is acceptable in terms of APU size and weight, but it is not necessarily the best gauge of what is acceptable. It may be hard for a person to visualize what a complete system would look like based on numerical descriptions of size and weight. A well engineered and integrated system may be acceptable even if it is heavier and bulkier than the target audience reveals in a survey.

Cost and Economics

As part of the UCD ITS survey truck drivers were asked what factors are important in their decision to purchase an APU. The truck driver was given choices of different factors that might be important to them. Among these choices was the price of the APU. If the driver felt this was an important factor, he or she was then asked how much they would be willing to spend in order to purchase an APU. The results indicated a wide range of prices that the drivers were willing to pay ranging from $100 to $10,000. This indicates that some drivers value an idling solution highly while others are satisfied with the current solution. The drivers that put a low value on an idling solution may not idle that much, may not understand the benefits of using an alternative idling solution, or may not have been required to stop idling by regulations. When drivers where asked what payback period would be necessary for them to consider the purchase an APU the average answer was 27 months.

ENGINEERING CONSIDERATIONS

Based on the design guidance gathered from previous studies and directly from truck drivers, general engineering requirements for a fuel cell APU were established. The needs of the truck drivers were translated into engineering design requirements. These requirements were used to bound the design within practical limits and prioritize the importance of APU features and capabilities.

Power Output

Climate control power requirements have been found to far exceed the power requirements for auxiliary electrical appliances currently being use. The power requirements of the APU system will be largely dictated by the power requirements of the climate control system. Auxiliary electrical loads from small electrical appliances that a truck driver is currently likely to use will make up a small percentage of the total APU power used.

A few options are available for cooling a truck cab without using the main engine. There are auxiliary compressors powered by small diesel engines which consume considerably less fuel than the main engine. Pony Pack and Power Pak both make small, frame mountable auxiliary diesel engine APUs that have an A/C refrigerant compressor and auxiliary alternator. Webasto Thermosystems has developed a phase change chilled storage system in which a fluid is frozen while the truck is operating and later used to cool air when the engine is turned off. They have integrated this with a diesel fuel fired heater to supply both heating and cooling needs with a single climate control unit. There are also several companies that supply electrically powered air conditioning systems that are suitable for running off of 120 VAC power supplied from grid electric plug-in sources or an inverter.

Of these options the electrically powered vapor compressor cooling system makes the most sense for use with a fuel cell APU system. The system is very similar to the stock cooling system with the only difference being that the compressor is powered by an electric motor instead of being powered mechanically by the main engine.

Several electrically powered air conditioning systems exist in the 10,000 – 14,000 BTU/hr range that are purpose-built for mobile applications such as boats, RVs, and trucks. An air conditioning in this size range should be sufficient to cool the cab to the level specified by ATA's RP432 recommended practice. A unit with a 10,000 BTU/hr capacity consumes in the range of 1,200W of electricity at rated conditions but could require up to 3 times this amount for very short periods (about 1 second) at startup. This is a significant amount of power and must be supplied in addition to any power needed by other powered appliances.

Heating options for fuel cell powered APUs include electrically powered resistance heaters, fuel cell waste heat utilization, and fuel fired heating systems. After careful analysis the only system that made sense from an energy utilization standpoint was the fuel fired heater.

Heating requirements may be anywhere from 2 - 3.5 kW depending on the weather conditions and the quality of the truck's insulation. If a 2 kW heating requirement where to be provided by an electrical resistance heater the input fuel energy into the fuel cell would be 4 kW (assuming a 50% conversion efficiency). The total thermal efficiency of this configuration would be 50%.

The waste heat could in theory be recovered from the fuel cell and used to heat the cab. However, even if 100% of the waste heat from a fuel cell operating truck appliances of 500W was recovered, the total heat input into the cab would be only 1 kW. This would require extensive engineering, complicate safety considerations by introducing a direct path for hydrogen to enter the cab, increase complication by requiring extra heat exchangers, and shorten the usable life of the fuel cell by using high quality electrical power when only low quality heat is required. In any case, the amount of heat input to the cab is only half of the 2 kW required and would still need to be augmented by electrical resistance heating. Any conceivable heating system utilizing resistance heaters and recovered fuel cell waste heat results is an inferior solution to that of simply combusting the available fuel directly for heat.

Direct diesel fuel fired heaters are inexpensive, highly efficient, and currently exist. The units are over 90% efficient and can use diesel fuel directly from the trucks main tanks. They also use a small amount of electrical energy to power pumps and fans. End point emissions are very low, but if desired could be further reduced by combusting natural gas or hydrogen instead of diesel fuel. The direct fuel fired heater is the best option for supplying auxiliary heating needs for a truck.

Electrical power needs fall into two categories. 12 VDC power for onboard truck integrated accessories such as dome lights, fans, and dash radio and 120 VAC power for small household appliances that are operated on board the truck.

Having 120 VAC power available frees the on board 12 VDC system from many loads it might otherwise need to supply. Almost any appliance that a truck driver might want to use can be powered by 120 VAC current. Many appliances such as television, lamps, and refrigerators have been converted to accept 12 VDC power, however these appliances are more expensive and less efficient than their 120 VAC counterparts. It is expected that most of the electrical power needed will be in the form of 120 VAC. The remaining 12 VDC load that is not replaced by 120 VAC loads is estimated to be small in comparison to the amount of energy the batteries can supply.

The test truck has three batteries with about 130 Ah of capacity; this is typical for most line-haul trucks. This amount of battery capacity can supply a 100 W load for more than 39 hours. Based on this estimate, the UCD APU has made no provision for charging the on board battery bank. It is expected that the truck will be in use and the batteries recharged before they are depleted in real world driver applications.

APU Loads		
	Ave. Power [W]	Pk. Power [W]
12 VDC		
Auxiliary	100	200
Heating	25	50
120 VAC		
Auxiliary	300	1,000
Cooling	1,200	3,600

Table 8 - Power Requirement

There are many difficulties involved in estimating the amount of power that must be supplied by an APU. The average and peak power demanded will vary from application to application depending on the weather, the number and type of appliances in use, and the preference of the truck driver. Based on information about the type of appliances drivers tend to use, the power consumption of these appliances, and the revealed preference of the truck driver, Table 8 was compiled.

This table shows the electrical power requirement in four categories that is expected to be sufficient for the majority of truck driver needs. The estimated average power is used to size the fuel cell and fuel storage capacity. The peak power, in many cases, must only be supplied for very short periods of time during transients and power surges. The electric air conditioning compressor illustrates that the difference between average and peak power requirements can be quite different. These short periods of increased power demand can be handled by oversizing the fuel cell or by using power storage components such as batteries or capacitors. Because fuel cell efficiency tends to increase as power demand drops, using a fuel cell that is larger than necessary for average power usage has the advantage of increasing overall efficiency. However, the extra efficiency comes at the cost of having a bigger, heavier, and more expensive fuel cell. As fuel cell costs drop and power densities increase this will be of less concern.

Packaging and Integration

The packaging and integration of the APU is important in terms of customer acceptability as well as durability and safety. Consideration should be given to placing major components as close together as possible to minimize the transmission distance of high current electricity and fuel. The number of connections between the enclosure and the truck should also be kept to a minimum. This has the effect of increasing efficiency, and minimizing the size and weight of the APU. It also increases safety because there is less chance of fuel leakage and less of a chance of severing either high current wiring or fuel lines in the event of an accident.

In keeping with this design philosophy the number of joints and unions in the fuel lines should also be kept to a minimum. Longer unbroken lengths of tubing are preferable to many lengths of tubing teed or spliced together. Joints that are necessary should be in well ventilated areas or to the exterior of any enclosure if possible.

The size and weight of the fuel cell APU will dictate where the system can be integrated on the truck. The most obvious place is on the frame rails of the truck. Line-haul trucks are quite large and there is usually some unused space along the frame rails. As APU systems get smaller and lighter other possible mounting locations may become feasible. Many trucks have a wind deflector on top of the cab. This space has the advantage of being at the highest point of the vehicle and is well ventilated. Both of these characteristics help to make the APU installation safer. Another area to consider would be behind the cab near the step area between the truck and the trailer.

Durability

Fuel cells are not considered as robust as internal combustion engines. Fuel cells require clean air, clean fuel, and have not proven themselves in high vibration environments. Fuel cells also need to be protected from temperature extremes. A complete APU system will include an inverter, batteries, and other sensitive components that have their own environmental requirements. Protecting the fuel cell and other components from an adverse operating environment can have a profound effect on durability.

The APU enclosure should protect its components from extremes in temperatures and weather. The competing needs of protecting the components from rain, snow, dirt, and grime and the need to provide adequate ventilation and cooling during operation must be balanced. PEM fuel cells generally need to be kept between 0°C and 100°C. PEM fuel cells generally operate best at temperatures around 80°C. Excursions above boiling or below freezing can shorten the life or otherwise cause damage to the fuel cell, even if it’s not operating during these excursions. This requirement usually means that the enclosure needs to be insulated and some method of temperature monitoring and control must be provided. The need to provide adequate ventilation and access to the APU components tend to make the temperature control requirements more difficult to meet.

Extremely high temperatures damaging to the fuel cell are only likely to be experienced while the APU is operating and producing high levels of power. High temperatures extremes can usually be prevented by providing adequate ventilation to the fuel cells. Should temperatures rise too high, the APU can always be shut down or power output reduced before damage is done.

Preventing the fuel cell from freezing is a more challenging problem. Freezing can be a danger when the fuel cell is not in operation and not producing large amounts of power. Unlike extremely high temperatures, temperatures below freezing are common and likely to be encountered in real world situations. Protecting the fuel cell from freezing requires active monitoring of the environment and the ability to heat the enclosure should the temperature fall too low.

Extremely cold conditions are usually avoided by insulating the APU enclosure and providing some mechanism for temperature control. Should temperatures fall too low, the fuel cell can be turned on and the generated waste heat can be used to maintain enclosure temperatures at an acceptable level.

Isolation from vibration is also an important consideration. Trucks are subject to vibration and shock inputs from many sources; the road, the main diesel engine, engagement and disengagement of the trailer, and backing up against loading docks. Design actions must be taken to isolate the APU and the fuel cell from these damaging sources of shock and vibration while still providing for robust attachment that can restrain the APU in the event of an accident. Extensive work was performed by Mathuria, et. al. on a vibration mount system for a fuel cell APU system. [20]

Fueling

PEM fuel cells have been shown to operate using high purity gaseous hydrogen and methanol as fuels. Because trucks do not use either of these fuels additional fuel storage will need to be devised. Methanol has many advantages as a fuel. Methanol is a liquid, it has a high energy density, and it is currently used in many chemical and consumer applications. However, methanol is toxic, even in small amounts, and it is soluble in water. This combination of properties makes its safe distribution and storage a concern. It is not uncommon for underground gasoline fuel tanks to occasionally leak. A methanol leak could potentially cause much more environmental damage than a gasoline fuel leak. There are many examples of safe use and storage of methanol if care is taken. Consumer products such as stove fuel, racing fuel, and windshield washer fluid all contain methanol. Windshield washer fluid is interesting because it usually contains 35%-45% methanol and is currently safely distributed and used. A fluid very similar to windshield washer fluid could conceivably be used to power a fuel cell APU.

Hydrogen is the most commonly used fuel for PEM fuel cells. Hydrogen can be directly used by fuel cells but requires more complex methods of storage. Cryogenic liquid hydrogen storage is being considered by some automobile fuel cell manufacturers. Gaseous compressed hydrogen storage is a less complex method and its availability is much greater. Compressed hydrogen is available at all of the hydrogen fueling installations in the US and is also readily available in standard industrial cylinders.

The amount of fuel that must be stored depends on the expected fueling interval, the efficiency of the fuel cell APU and the expected average fuel cell APU load. Table 9 shows the estimated amount of fuel need for varying levels of average power required from the APU. The estimates where made for a fuel cell APU system with an overall efficiency of 45% powering the estimated load continuously over an 8 hour period. Note that the units for hydrogen are given in kg of gas, for gaseous storage the weight and volume of the system are usually much greater than the weight of the gas. Advanced compressed hydrogen storage systems have a weight storage efficiency of up to 8.5%, meaning that the complete storage system might weigh 12 times as much as the stored fuel. For methanol the units are given in liters; this does not include the likely additional volume that is needed for dilution water as direct methanol fuel cells generally use a methanol/water mixture for fuel.

Average Power	Hydrogen	Methanol
500 W	0.23 kg	1.12 L
1000 W	0.45 kg	2.23 L
1500 W	0.68 kg	3.35 L
2000 W	0.90 kg	4.47 L

Table 9 - Storage Estimates

Many times truck drivers do not stop at truck stops or other fueling stations to spend the night. In fact, one of benefits of the fuel cell APU is the ability for the truck driver to stop anywhere in order to sleep. The near silent and point pollution free operation of the fuel cell APU will open up new areas previously not available to the truck driver. Idling ordinances or noise ordinances are no longer a concern to the truck driver using a fuel cell APU. To maintain this freedom and to ameliorate the scarcity of fueling points, the on board storage system should be sized to allow operation for multiple days without the need to refuel. The exact number of days will depend on the number of fueling points the driver expects to be near in a given period of time. Initially fueling points may be located at major warehousing and distribution points. If one were to assume that the APU would be fueled once every three days, then the APU storage system would need to be capable of storing about 2 kg of hydrogen fuel or 10 L of methanol assuming an average nightly load of 1500W.

The industry is in the early stages of standardizing hydrogen fueling stations, fueling connectors, and storage systems. Some hydrogen connectors similar to those used for natural gas vehicles are being developed and standardized. Hydrogen fuel filling stations generally dispense fuel at pressures of 3,600 psi and 5,000 psi some stations are capable of 10,000 psi. The tank must be matched with the appropriate fuelling dispenser. Apart from industry standardization and self regulation the US DOT approves hydrogen storage systems for vehicle use. Any storage system intended for on-highway use must meet US DOT standards.

Safety

Safety precautions taken in the design of a fuel cell APU should take many forms. The APU should have an easily accessible emergency shutoff switch that can remotely stop fuel flow to the APU and electrical current from it. Any sources of high current electrical storage should be fused and sustained overload conditions to the truck should be protected for via circuit breakers.

In addition to precautions taken to avoid fuel leakage, a robust design should incorporate features that make the APU tolerant to leakage should a failure occur. As a first step the APU should employ passive ventilation strategies to assure that any fuel that does leak is vented to the surrounding atmosphere even when there is no power available to the system or monitoring is disabled. In terms of gaseous hydrogen this means incorporating venting at the high points of enclosures, placing tubing joints outside of any enclosure, and eliminating direct paths for fuel encroachment into the cab of the truck.

Apart from passive design features, active monitoring and forced ventilation using fans should also be used when possible. The lower flammability limit of hydrogen is 4% by volume. Sensors should monitor for hydrogen leaks and take action to dilute leaks through active ventilation strategies while simultaneously interrupting fuel supply and alerting the driver.

DEMONSTRATION FUEL CELL APU

The UCD ITS goal was to construct a functional FC APU suitable for public outreach and energy flow data collection and analysis. The capabilities and features of the APU were chosen with this goal in mind. Design for packaging and durability where considered secondary and compromises where made with the understanding that future advances in technology are expected to make these compromises unnecessary.

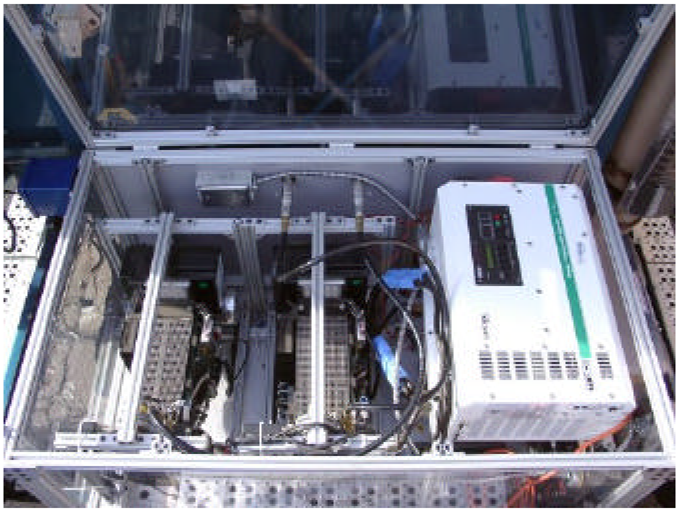
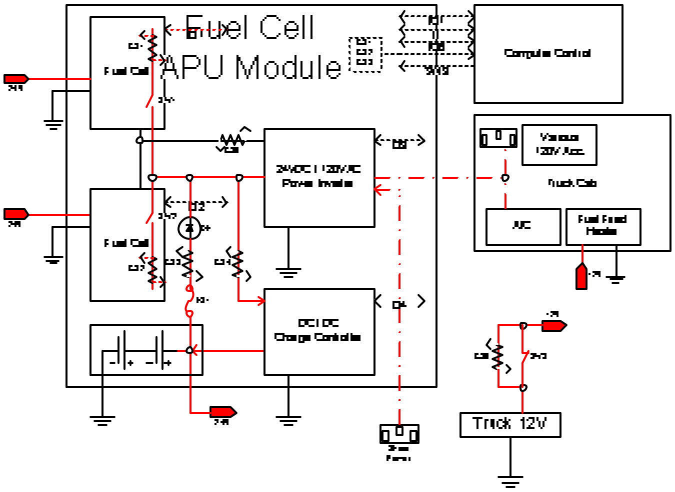


Figure 3 - UCD ITS Fuel Cell APU

SYSTEM DESIGN

Figure 4 shows a block diagram of the UCD ITS demonstration fuel cell APU system. The APU system consisted of two fuel cells connected in parallel, two lead acid batteries, a power inverter, a battery charger, and associated power distribution and safety components.



A fuel cell APU designed with a very large continuous power output large enough to handle the maximum possible load that is ever expected would result in a very large APU with excess capacity during most of its operational period. A better strategy is to size the average power output of the APU to match the expected average power requirement of the appliances likely to be used, and to provide sufficient power for peak intermittent loads.

Examining the expected appliances and usage profiles it was found that the requirements of the air conditioning system would dictate the sizing of the APU in terms of both average power output and peak power output. Based on estimated cooling loads an air conditioning system with a capacity of 10,000 BTU/hr was chosen. This air conditioning system had an average power requirement of 1.2 kW. Based on appliances that were expected to be used and the usage profile of these appliances another 600 W of power was expected to be used on average, for a total expected average load of 1.8 kW. This requirement dictated that the fuel cells powering the APU must be capable of continuously supplying this average load of 1.8 kW.

Parallel FC Stack Design

The fuel cell industry is small and currently few choices exist for complete fuel cell systems. To provide the primary power for the APU the Nexa series fuel cell built by Ballard Power Systems was chosen. The Nexa system is rated at 1.2 kW and has output characteristics similar to that of a battery, although over a much increased range of voltage. Under open circuit conditions the system voltage is 42V. The output voltage steadily drops as it approaches its 1.2 kW full load output of 50A at 25VDC.

In order to supply the 1.8 kW average power requirement it was necessary to use two Nexa fuel cells. The fuel cells were connected in a parallel configuration to maintain an operating voltage range of 42 - 25 VDC with 100A available at full load. A series configuration was considered because of its inherently more efficient higher voltage and lower current characteristics. This configuration was ultimately rejected because the higher 84 – 50 VDC voltage range of operation would have been more difficult to integrate with common off the shelf (COTS) components and more stringent higher voltage safety considerations.

Hybrid System Design

The peak power required by the air conditioner was found to be about 3 times its average power consumption during startup. This higher transient power requirement is known as “locked rotor” load. This load was expected to be the most extreme peak load that the APU would be required to power. The 10,000 BTU/hr air conditioner system contained an electric motor that required around 30 amps for about 1 second during startup. The APU therefore needed to be able to provide 3.6 kW for at least 1 second. From these estimates it was found that average APU power demand would be about one half the peak power demanded.

The large difference in peak power demand to average power demand suggested that a hybrid APU design might be advantageous. By using load leveling energy storage components in the APU design the peak capacity of the fuel cell could be reduced from the full 3.6 kW to 1.8 kW. The decision to build a hybrid APU allowed the APU to use two fuel cells instead of the three that would have been required to provide 3.6 kW of power. If custom built fuel cells optimized for these requirements were used, a single 1.8 kW fuel cell would have been sufficient.

In a hybrid APU design, the storage element provides extra power during times of peak demand and recharges during times of lower power requirements. Battery and ultracapacitor load leveling elements were considered. It was determined that ultracapacitors could have easily provided the power necessary for all expected peak loads and would have been smaller and lighter then their lead acid battery counterparts. The final design, however, utilized a pair of small lead acid batteries connected in parallel with the fuel cells. Batteries were used because the inverter that was chosen required a constant DC input to maintain its parameter memory. Capacitors have a much smaller energy storage capacity than batteries and also have the tendency to “leak down”, or lose their charge over a period of hours if they are not recharged, making them less desirable in this configuration.

Passive Control Strategy

The APU incorporates a passive control strategy. The strategy used ensures that fuel cell capacity is fully utilized before the energy storage components are called upon. This has the effect of minimizing the number of charge discharge cycles on the batteries and increases efficiency. It also reduced the cost of the system by using simple components and eliminating the need for expensive computer control.

The key to the passive control system is careful matching of the fuel cells, batteries, and inverter. Because each of these components operate at different voltages, provisions had to be made to integrate them into the final design. The fuel cells operate in the voltage range of 42 – 25 VDC. If the fuel cell output voltage drops below roughly 24 VDC they open an internal contactor and shutdown. The two fuel cells alone have a rated output of 50A at 25VDC for a total of 2.4 kW. During times of peak power demand, such as when the air conditioner starts, the voltage required would be in excess of this amount causing system shutdown. To solve this problem, two 13Ah lead acid batteries were also integrated into the system to provide power during these peak demand periods.

Under charging conditions the two lead acid batteries, connected in series have a nominal voltage in the range of around 28 VDC. This is somewhat higher than the standard 12.4 VDC of a lead acid battery under steady state conditions and is due to the charge system maintaining a float voltage in the range of 14 volts per battery. Under sustained load the battery voltage would quickly fall to 12.4 VDC per battery. As implemented the batteries start to augment the power output by the fuels cells when the bus voltage falls below 28 VDC. As power demand rises and the bus voltages falls even lower the batteries start to increase their output. As the bus voltage approaches the fuel cells supply their maximum rated power, more than 100A at 25 VDC. To this the batteries are also supplying more than 100A at 23VDC. The total output available to the load is greater than 4.4 kW which is more than enough to supply the transient power needs for most components. This system works very well because power is instantly drawn from the batteries as it is needed without any active control.

Lead acid batteries tend to charge best at slow rates and are usually sustained at a voltage above their open circuit voltage after they have reached full charge. This voltage is called the batteries “float voltage” and for lead acid batteries is usually 14.7 VDC per battery. In this installation two batteries are connected in series resulting in an optimum float voltage of 29.4VDC. Recharging the batteries after a load has been drawn from them required some extra design effort. The batteries cannot simply be connected to the main bus because the fuel cells operate at voltages up to 42 VDC; this is much too high a voltage for the batteries to graciously handle. To solve this mismatch problem, a power diode was placed between the batteries and the main bus. This allowed the batteries to discharge power to the bus when the buses voltage fell below the battery voltage, but it prevented power from the bus from reaching the batteries when the bus voltage was above the battery voltage.

Charging of the batteries was accomplished by using a battery charge controller. The charge controller worked by modulating a current switch at high frequency to limit the current that the batteries could absorb. This device is sometimes termed a chopper because of the way it modulates the current from the power supply to the load. This arrangement allowed the battery to charge at voltages up to the 29.4 VDC float voltage even when the bus voltage was at higher voltages. The workings of the charge controller also prevented the batteries from charging when the bus voltage fell and both the batteries and fuel cells were providing power to the load, because the batteries would be at a higher potential than the bus due to the power diode.

Instrumentation

Instrumentation and data collection was accomplished using current shunts placed at various locations in the power distribution network. The shunt voltages were read and recorded by a 16 channel data acquisition system connected to a laptop computer by way of a USB bus. The information acquired with the system was used to monitor power flows and bus voltages.

Packaging and Integration

The APU enclosure was built using modular aluminum extrusions. The enclosure was mounted to the frame rails behind the cab and isolated from the truck by rubber mounts. The fuel cells where further isolated from the enclosure by a second set of rubber ring isolators. The truck was isolated from the road by its suspension system.

Weatherproof conduit was used to connect the APU to the truck cab. 120 VAC power was fed to the cab through a metal sheathed set of wires to a junction box located below the sleeper bunk. This junction box served to distribute power to a set of outlets located on the lower part of the bunk and to the air conditioning system. Controls for the air conditioning and for the fuel fired heater where also located on the lower bunk panel.

Fueling

The tank used was an earlier generation 150 liter composite wrapped hydrogen vessel rated at 3,000 psi. Because the rated tank pressure did not exceed the 3,600 psi fill pressure available at local hydrogen fill stations it was decided that filling would be performed from industrial hydrogen cylinders. The hydrogen cylinders were delivered at a pressure of 2,000 psi, well below the rated pressure of the hydrogen tank. After connecting the cylinder to the tank, the hydrogen pressure in the cylinder was allowed to equilibrate with the tank pressure. Because of the difference in volume between the cylinder and the tank, much of the hydrogen gas is transferred using this method provided that the tank pressure is kept low. The partially depleted hydrogen cylinders were then used elsewhere until fully depleted. This method of filling is not the most efficient, but it did allow for multiple demonstrations without the need to use a gas compressor. It was also very inexpensive.

Safety

The enclosure incorporated many passive and active ventilation and safety features to minimize the possibility of a fuel leak and mitigate a leaks impact should one happen. The bottom of the enclosure had large vents on either side and the top panel had spacers between the lid and the frame to allow any light hydrogen gas to escape. The fuel cells were positioned in the box so that the cooling fans would draw air from the bottom and expel it at the top, ensuring that during operation a continuous flow of fresh air was circulated through the enclosure. The fuel cell also had hydrogen sensors integrated into them that would shutdown the system should a leak be detected. Each of the two fuel cells had a hydrogen sensor thus giving the system an element of redundancy.

The hydrogen storage tank had a built in pressure relief device (PRD) that would vent excess hydrogen to a vent mast connected to the rear of the cab in the event of an overfill or if excessive heat, as from a fire, caused pressures to rise above the 3,000 psi rating of the tank.

An emergency stop was located on the exterior of the enclosure within reach of the fill port. This stop would interrupt both gas supply from the tank and DC power to the inverter. The fuel cells had many safety features built into them also. Safety startup self checks made sure that the fuel cells were operating properly and checked for fuel leaks and other abnormalities. The fuel cells also shutdown should the temperature get too high or the bus voltage fall too low. A high current fuse was placed between the batteries and the main bus to protect against a high current short circuit. The high voltage electrical system safety was primarily handled by the individual components. The inverter had an integrated circuit breaker that would trip if the output line voltage dropped too low or current draw became too high.

COMPONENTS

Freightliner Century Class Test Vehicle

The fuel cell APU was integrated into a 1994 Century Class test tractor. This tractor is representative of most line-haul class 8 trucks.

Figure 5 - Freightliner Century Class Truck

Ballard Nexa Fuel Cell

The fuel cells chosen for this project were Ballard Nexa fuel cells. As of this writing the Nexa fuel cell is the PEM fuel cell that is closest to being commercially available. The Nexa system has extensive control and monitoring systems integrated into the stack allowing for push button operation. This stack was chosen for its availability, ease of use, compact size, and consistent operation.

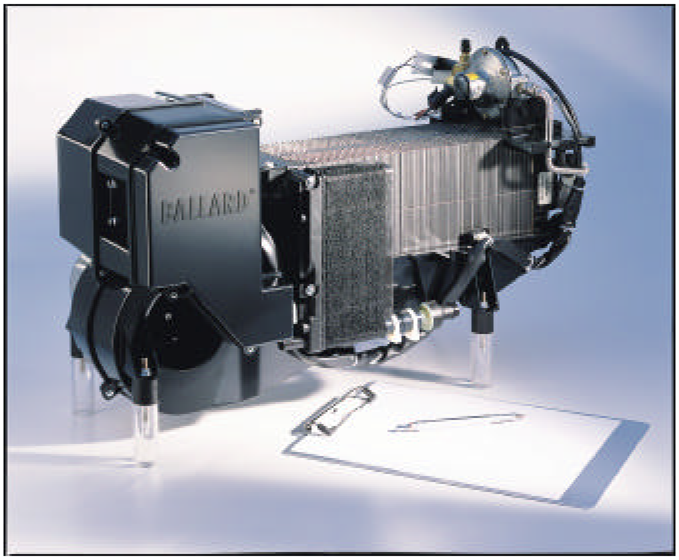


Figure 6 - Ballard Nexa Fuel Cell

Ballard Nexa PEM Fuel Cell		
Outputs		
Rated Power	1200	W
Rated Voltage	26	V
Mass	13	kg
Operating Life	1500	hrs
Inputs		
Fuel	99.99%	Hydrogen
Consumption	<18.5	SLPM
DC Startup Power	18 - 30	V
Environment		
Operating Temp. Range	3 - 40	°C
Storage Temp. Range	-29 to 70	°C
Storage Freeze Cycles	50	Cycles

Table 10 - Fuel Cell Specifications

Testing was performed at the UCD ITS Fuel Cell Lab to determine the performance of these fuel cells. Polarization curves and efficiencies curves were generated for single fuel cells.

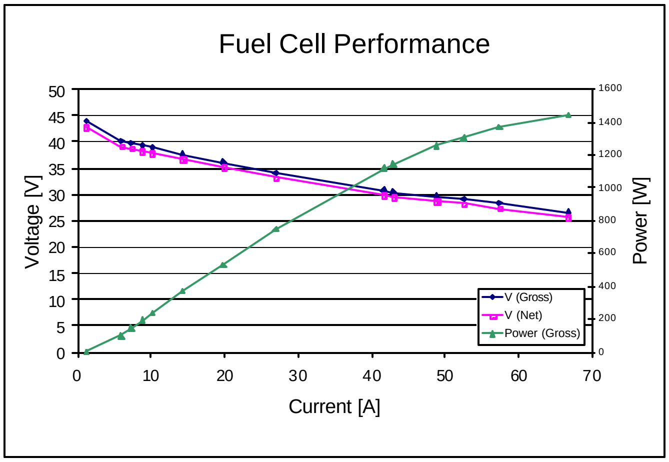


Figure 7 - Fuel Cell Polarization Curve

The fuel cell's power is greater than the rated output, approaching 1.4 kW at 65 amps. The fuel cells are rated for 50 amp output, so the 65 amp outputs represents output that is 30% in excess of rated output. The effects of operated the fuel cell in excess of rated output is not know, therefore the APU design was implemented so that the fuel cells would not exceed maximum ratings.

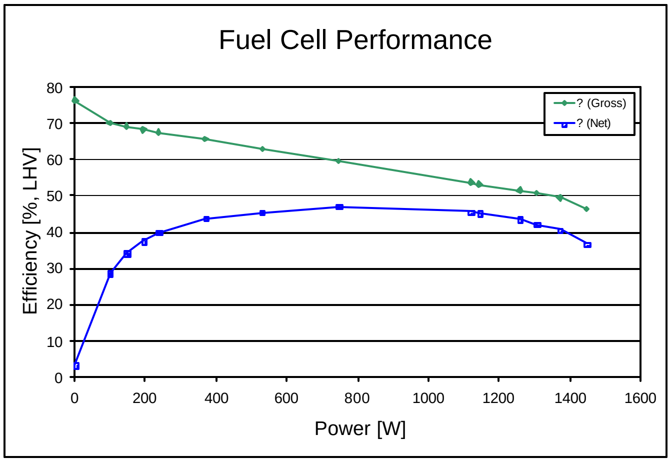


Figure 8 - Fuel Cell Efficiency Curve

The system efficiency of the fuel cells reaches a peak net of around 48%. At very low loads the net efficiency is poor because of the balance of plant components that must be powered in order to maintain operation.

Trace Xantrex Inverter

The inverter chosen was the Trace Xantrex SW4024. The SW4024 is primarily manufactured for home use, most often for homeowners who wish to power household 120VAC electrical needs without being connected to the grid. DC electrical power is supplied to the inverter unit generated by solar, wind or hydro sources. The generated power is stored in lead-acid batteries at 24VDC nominal and inverted to 120VAC as demanded.

The same characteristics that make this inverter a good choice for home power needs also make it a good choice for a fuel cell APU. The fuel cells have voltage and power output characteristics similar to a solar array or a turbine, and the unit is able to handle the fuel cell source with only minor modification. Modification to the inverter consisted of changing its allowable input voltage range to handle input voltages of 19 – 38 volts.

The inverter unit also has features that allow it to be tied to the grid power in order to supply 120VAC output electricity even when the primary power source is not available. It also produces a clean 120VAC sinewave that can be fed to the national electrical grid. For a homeowner these features allow power to be drawn from or sold to the grid based on the availability of the renewable energy source. For the truck APU these features allow the truck also to be easily connected to the grid, a feature generally know as "shore power". It also allows power to be resold to the grid from the fuel cell generated energy. This feature might be beneficial for distributed power generation.

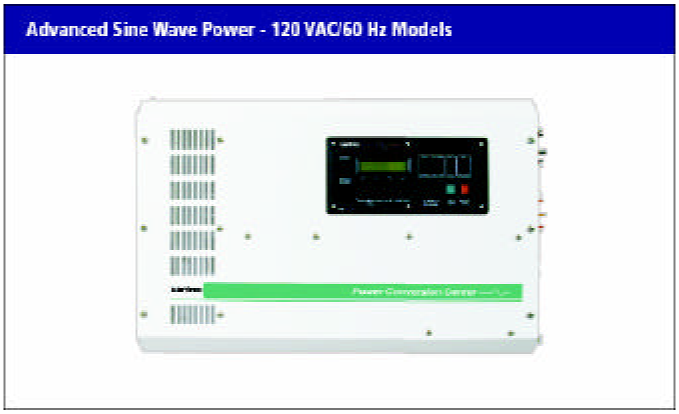


Figure 9 - Trace Xantrex SW4024 Inverter

Trace Xantrex SW4024 Inverter		
General		
DC Input Voltage	22 - 33	VDC
Output Voltage	120	VAC
Continuous Power	4,000	VA
Continous Output	33	A
Max Output	78	A
Efficiency (Peak)	94	%
DC Input		
Full Rated Power	200	A
Short Circuited Output	360	A
Input Range (Modified)	19 - 38	V
AC Output		
AC Output Wavform	Sinewave	
Voltage Regulation	+/- 3	%
Physical		
Size	15"x22.5"x9"	
Weight	105	lbs

Table 11 - Inverter Specifications

Taylor Made Air Conditioning Unit

The Taylor Made A/C is a self contained electrical air conditioner purpose-built for small area climate control. The unit can be installed into boats, RVs, campers, and trucks. Some trucks already use this A/C in combination with a diesel powered APU or when connected to shore power, as such no modification was needed to integrate the unit with the fuel cell APU.

Figure 10 - Cruisair ASC Air Conditioning

Cruisair ASC Air Conditioner		
Cooling Output	10,000	BTU/hr
	2.93	kW
Rated Voltage	120	VAC
Running Amps	10	A
Starting Amps	30	A
Power Consumption	1.2	kW

Table 12 - A/C Specifications

Webasto Fuel Fired Heater

The Webasto Air Top 2000 diesel fuel fired heater is also purpose built for small area climate control and truck use. The Air Top is powered by 12VDC from the trucks batteries and is integrated totally separate from the fuel cell APU. The unit draws very little power and analysis showed that the stock battery capacity of the truck could power the heater without danger of depletion.

Figure 11 - Webasto AirTop 2000

Airtop 2000 Specifications		
Heat Output	.9 - 2.0	kW
Fuel Consumption	.12 - .24	l/hr
Power Consumption	9 - 22	W

Table 13 - Heater Specifications

Dynetek Composite Fuel Tank

The Dynetek hydrogen fuel tank used is an earlier generation composite design. Current tank offerings achieve operating pressures of 10,000 psi. The tank is constructed out of an aluminum cylinder wrapped with carbon fiber and resin. This design makes the tank lightweight and strong.

Figure 12 - Dynetek Composite H2 Tank

Dynetek Tank		
Volume	150.0	L
Rated Pressure	3,000	psi
Capacity	2.6	kg

Table 14 - Tank Specifications

Hawker Genesis Batteries

The Genesis battery is a high performance lead acid battery. This battery is capable of high current discharges and is very robust to deep discharge and harsh charging cycles. These characteristics made it a very good choice for the fuel cell APU application.

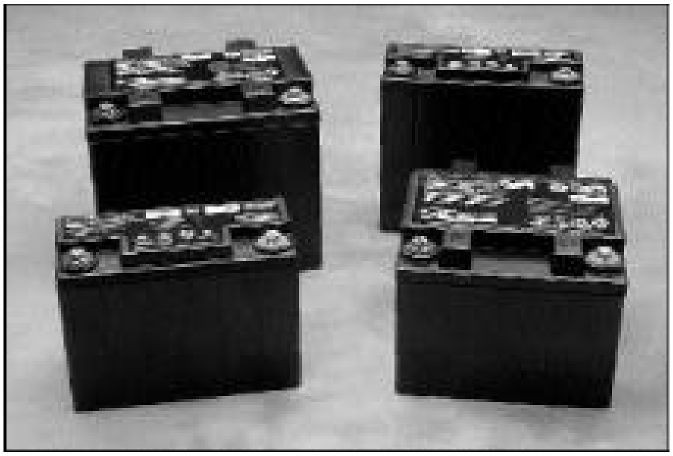


Figure 13 - Hawker Genesis Batteries

Hawker Genesis G13EP		
Mass	4.9 (10.8)	kg (lbs)
Capacity	13	Ah
Discharge (5 min rate)	70.8	A

Table 15 - Battery Specifications

Instrumentation

The NI DAQPad data acquisition system was used to gather energy flow data on the FC APU. The system has 16 single ended analog inputs and transmits collected data to a laptop computer running LabView where the data was analyzed and stored.

Figure 14 - National Instruments DAQPad-6020E

DAQPad-6020E		
Bus	USB	
Analog Inputs	16SE / 8 DI	
Input Resolution	12	bits
Sampling Rate	100	kS / s
Input Range	+/- .05 to 10	V

Table 16 – Data Acquisition Specifications

Current shunts were used to measure energy flows from the fuel cells, batteries, and to the inverter. Typical voltage drops across the shunts were 100mV at rated amperage, which was 100A for the fuel cells and batteries and 200A to the inverter.

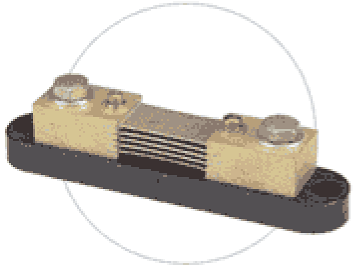


Figure 15 – Empro Shunt

Electrical Distribution

An International Rectifier HFA180NH40 rectifier diode was used to protect the batteries from over voltage. The diode has a high forward current capability allowing it to handle power transients from the batteries during peak demand.

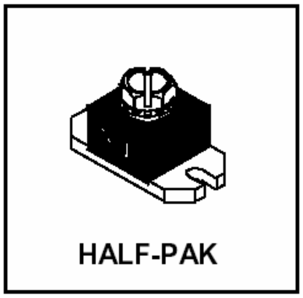


Figure 16 – Rectifier Diode

International Rectifier HFA180NH40 Diode		
Cathode to Anode Voltage	400	V
Forward Voltage	1.1	V
Forward Current (100°C)	160	A
Max Power Dissipation	625	W

Table 17 – Rectifier Diode Specifications

To provide safety shutdown protection to the fuel cell APU system a Kilovac EV200 contactor was used. Typically this component is used as a motor switch and is able to connect and disconnect high current loads reliably and robustly. This contactor can accept coil voltages from 9 to 36VDC making it compatible with the 24VDC battery backup power included in the design.

Figure 17 - Kilovac EV200

Kilovac EV200 Contactor		
Contactor		
Carry Current	250	A
Break Current (1 Cycle)	2,000	A
Contact Resistance (max)	0.4	mOhms
Close Time	15	ms
Mechanical Life	1,000,000	cycles
Coil		
Coil Voltage	9 - 36	VDC
Hold (min)	7.5	VDC
Hold (avg @ 24VDC)	0.07	A

Table 18 – Contactor Specifications

SYSTEM PERFORMANCE

Climate Control

Climate control tests were performed on the Freightliner test tractor. The Freightliner tractor was parked and allowed to come to temperature equilibrium. The climate settings on the APU powered HVAC systems were set to maximum (either heating or cooling) and the temperature was recorded after the interior sleeper temperature reached equilibrium, usually around 3 hours. The temperatures are expressed as temperature deltas. For the vent temperature delta this is the difference in temperature between the vent outlet and the sleeper cab. For the sleeper temperature delta this is the difference between the exterior temperature and the sleeper temperature. Tests procedures were not conducted in the exact manner as dictated by the ATA recommended practices due to resource limitations, however results obtained here are expected to be close to those that would be obtained with the stricter test procedures.

Heating

APU Heating Performance		
Rated Vent Airflow	110	m^3/hr
Rated Capacity	2.0	kW
Vent Temp Delta	> 82.9	°C
(Vent – Sleeper)	(149.2)	(°F)
Sleeper Temp Delta	36.2	°C
(Exterior – Sleeper)	(65.2)	(°F)
	37.8	*°C*
ATA RP432 Delta	*(68)*	*(°F)*

Table 19 - FC APU Heating Performance

Tests performed on the APU heating system indicated that the system was very nearly able to achieve performance as recommended by the ATA for APU heating systems, if the temperature difference was still achievable at ATA test conditions. In order to improve performance increased sleeper cab insulation or a slightly larger heating system could be used.

Cooling

APU Cooling Performance		
Rated Vent Airflow	552	m^3/hr
Rated Capacity	2.93	kW
Vent Temp Delta	8.6	°C
(Vent – Sleeper)	(15.4)	(°F)
Sleeper Temp Delta	10.9	°C
(Exterior – Sleeper)	(19.6)	(°F)
	15	*°C*
ATA RP432 Delta	*(27)*	*(°F)*

Table 20 - FC APU Cooling Performance

Tests performed on the APU cooling system showed that it also was not able to achieve the recommendations as stated by the ATA recommended practices. It should be noted however that strict testing conditions were not kept in regards to ambient temperature and solar load, indeed it is suspected that the solar load was greater than what was specified. To improve performance better insulation or a slightly larger air conditioning unit could be utilized. The fuel cell APU as implemented would be able to power an air conditioning unit that is 50% larger. This increase would most likely be enough to meet recommendations.

System APU Power

Testing was performed on the DC portion of the APU system. These tests were used to better understand the interaction of the fuel cells, batteries, and the passive control system and what effects the design had on power output and system efficiency.

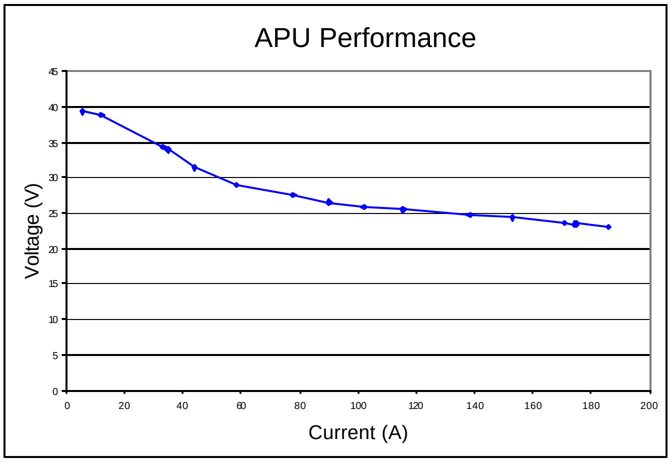


Figure 18 - APU Polarization Curve

The polarization curve of the system was similar to the behavior seen with a single fuel cell stack. The voltage initially drops rather quickly as current is drawn from the system. As more current is demanded the curve seems to flatten out and the voltage drop per amp demanded decreases. A look at the current being supplied by each individual component shows why this is happening.

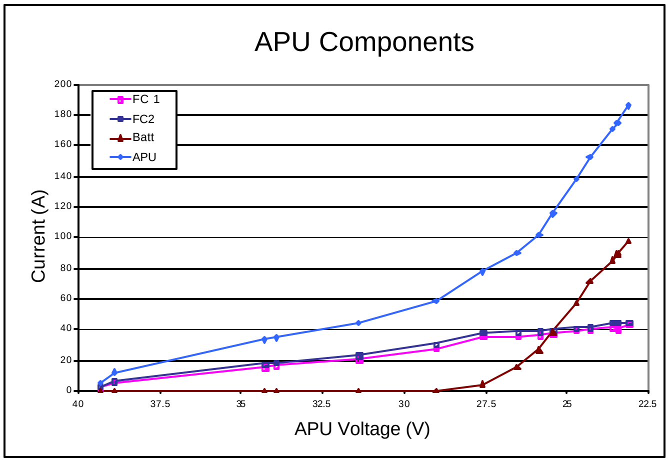


Figure 19 - APU Component Power Output

Figure 19 shows that the fuel cells supply all the power demanded until the bus voltage drops to around 27.5 volts. As the bus voltage falls from this point power is drawn from the battery pack. It is apparent that the batteries are a much more rigid source of current as compared to the fuel cells. That is, while a voltage drop of 15 VDC from 42 to 27 VDC will cause about 40 amps (2.66 A/V) to be drawn from the fuel cells, a 5 VDC drop will cause around 100 amps (20 A/V) to be drawn from the battery pack.

Transient Performance

The APU system was designed to handle high transient power needs without shutting down. This characteristic was especially important for the A/C compressor startup. During startup the electric motor that runs the compressor draws around 3 times the amount of current needed for steady state operation. To supply this large amount of current, batteries were integrated into the system.

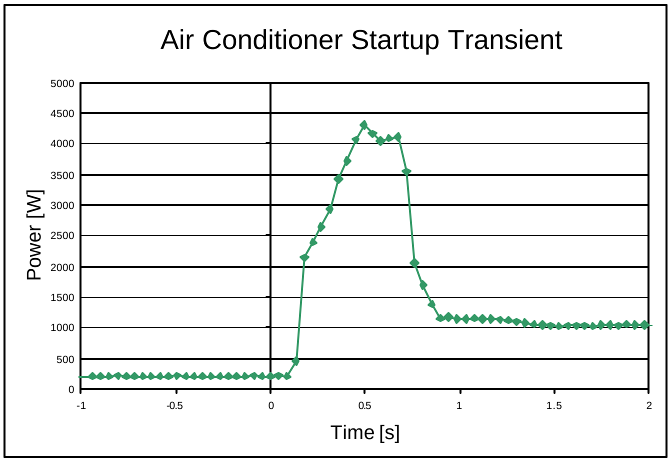


Figure 20 - A/C Power vs. Time

During A/C compressor startup high levels of power are needed in excess of 4kW. These high levels are only needed for a fraction of a second, after startup 1 – 1.2 kW are needed depending on temperature conditions and fan settings.

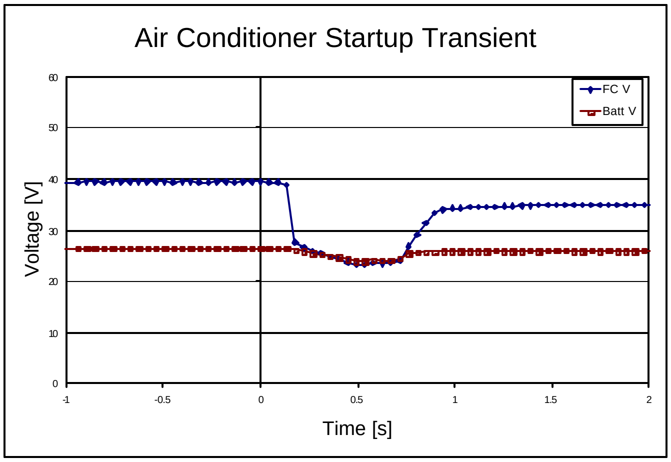


Figure 21 - A/C Startup Voltage vs. Time

Figure 21 shows the relationship between fuel cell and battery voltage levels. Due to the way that these components where implemented the fuel cell voltage is allowed to be higher than the battery voltage, however the battery voltage is not allowed to exceed the fuel cell voltage.

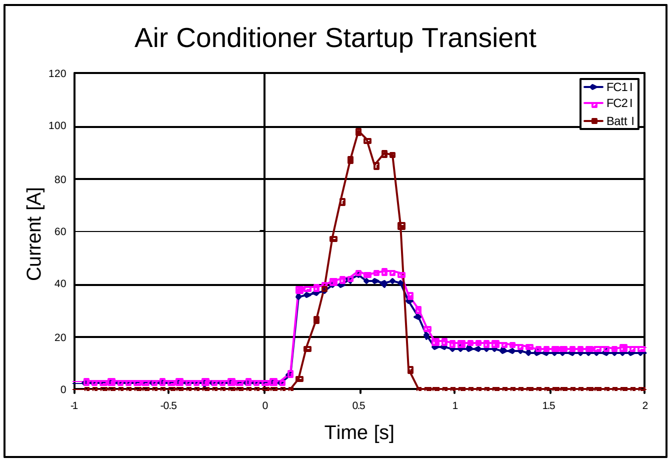


Figure 22 - A/C Current vs. Time

The final figure shows the current draw from the batteries and the fuel cells during the air conditioner startup transient. As is expected, the batteries provide much of the power needed during the transient.

CONCLUSION

System Performance			
	Stock	APU	Units
Heating			
Max Rated Vent	425	110	m^3/hr
Airflow	(250)	(65)	(CFM)
	8.8	2.0	kW
Max Rated Capacity	(30,000)	(6,830)	(BTU/hr)
Vent Temp Delta	49.7	82.9	°C
(Vent – Sleeper)	(89.4)	(149.2)	(°F)
Sleeper Temp Delta	41.6	36.2	°C
(Exterior – Sleeper)	(74.8)	(65.2)	(°F)
Cooling			
Max Rated Vent	425	570	m^3/hr
Airflow	(250)	(335)	(CFM)
	7.0	2.9	kW
Max Rated Capacity	(24,000)	(9,900)	(BTU/hr)
Vent Temp Delta	7.8	8.6	°C
(Vent – Sleeper)	(4.3)	(15.4)	(°F)
Sleeper Temp Delta	13.0	10.9	°C
(Exterior – Sleeper)	(23.4)	(19.6)	(°F)
Electrical 12 VDC			
Average Power	1.2	.25	kW
Peak Power	12	12	kW
Electrical 120 VAC			
Average Power	n/a	2.4	kW
Peak Power	n/a	4.0	kW

Table 21 – System Performance Comparison

The University of California Institute of Transportation Studies has performed a study on PEM fuel cell APUs. Based upon previous studies and truck driver input, a set of performance targets were established that would satisfy a majority of truck drivers needs. These targets were used to guide the design of the fuel cell APU system. The system was built at the UCD ITS fuel cell lab and integrated with a class 8 tractor. Testing was performed on the tractor with the integrated APU to determine the performance of the APU as compared with the stock system.

Testing has revealed that satisfactory APU performance can be achieved by using off the shelf components, however many challenges remain in the effort to commercialize FC APUs. As research continues, technical barriers are being removed and regulations are starting to be adopted that may encourage the adoption of this technology in the coming years.

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