NASA/CR—2003-212539

Initial Design and Construction of a Mobil Regenerative Fuel Cell System

Anthony J. Colozza and Thomas Maloney
Northland Scientific, Inc., Olmsted Falls, Ohio

September 2003

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Prepared under Contract NCC3–70731–K

National Aeronautics and
Space Administration

Glenn Research Center

September 2003

The Propulsion and Power Program at
NASA Glenn Research Center sponsored this work.

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Introduction

The goal of this project is to construct a stand-alone, mobile, regenerative fuel cell power system. Fuel cell technology has increased significantly over the last decade. It has progressed from isolated applications to a viable commercial product. The advantages of a fuel cell over other energy production and storage mechanisms are its high efficiency, scalability and environmental benefits. A fuel cell takes hydrogen and air (oxygen) and combines them to produce electricity. The only by-product of this energy production is water. Unlike a battery, the fuel cell reactants (hydrogen and oxygen) are stored in tanks external to the system. The energy producing capacity of the system is directly related to the size of the reactant tanks. The watt-hour capacity of the system can be increased by increasing the tank volume.

Aside from increasing the tank size, the watt-hour capacity of the system can also be increased by reusing the water produced by the fuel cell during power generation. This water can be broken down into the original reactants through the process of electrolysis in an electrolyzer. If the energy used for the electrolysis comes from a renewable source such as a PV array, then the energy capacity or watt-hours of the system can be infinite.

In order for the system to operate in this manner, the PV array, fuel cell and electrolyzer must be well integrated. The environment in which the system will operate (such as time of year and latitude) as well as the power loads it will support need to be well understood. These are critical aspect of the system design and will determine whether the system can operate effectively as a stand-alone power source.

The objective of the mobile regenerative fuel cell (RFC) development is to provide a testbed for future RFC research and development as well as providing a means for demonstrating the capabilities of a fuel cell system. The RFC system will be assembled on a trailer. The trailer allows the system to be easily moved and enables it to be set up at various locations for display purposes. Each component of the system is clearly marked as to its function and an operational display is used to provide information on the workings of the system.

Mechanical design

The mechanical design consists of the trailer buildup, the solar array mounting, the fuel cell placement and assembly, and the overall layout of the system components. One goal of the design was to keep the operation and deployment of the system as easy as possible. Another of the goals of the mechanical design is to eliminate the need for tools during deployment and stowage. Since the system has to be mobile and operate in public places, safety as well as durability were main goals in the trailer modifications and layout design.

Trailer

The RFC system is to be housed on a standard landscape trailer modified to be used with the RFC system. The trailer purchased for this project is a landscape trailer manufactured by International Trailer model 6X12. It measures 12 feet in length and 6 feet in width. The base trailer is steel framed with a wood floor. The modifications to the structure of the trailer are as follows:

- The floor is covered with 1/2" outdoor plywood.
- On top of the plywood is placed a 1/8" grooved rubber mat. The mat is glued down and attached along the edges using aluminum angle.
- A box frame is constructed off of the base of the trailer. The frame runs the length of the trailer and is 4' high. It is used as the support for the solar arrays and to cage in the remaining components of the RFC system. The frame is made out of 2" X 2" T6061 square tube aluminum.
- Stainless steel wire mesh is mounted to the inside of the box frame. The wire mesh has diamond shaped holes 1.5" X .75" and the wire thickness is 0.125". The wire mesh is attached to the box frame with 1", T6061 flat aluminum stock that is 1/8" thick.
- A set of access doors are located on the hitch end of the trailer. The access doors are made of a T6061 aluminum frame with the stainless steel mesh mounted on the inside. The access doors are each 3' in width and 4' high.
- A storage box is mounted on the back of the trailer underneath the array panels.
- The box frame is to be fitted with a canvas cover to protect the system from dust and weather during travel. The cover is custom-made to fit over the box frame and snaps are used to secure it for easy attachment and removal.

The wire cage was used to allow observers to view the system during operation while maintaining a level of safety for both the observers and the system itself. The access doors are also capable of being padlocked to secure the system if it is unattended. A diagram of the trailer with the modifications listed above is shown in figure 1. A photo with some of the modifications installed is shown in figure 2.

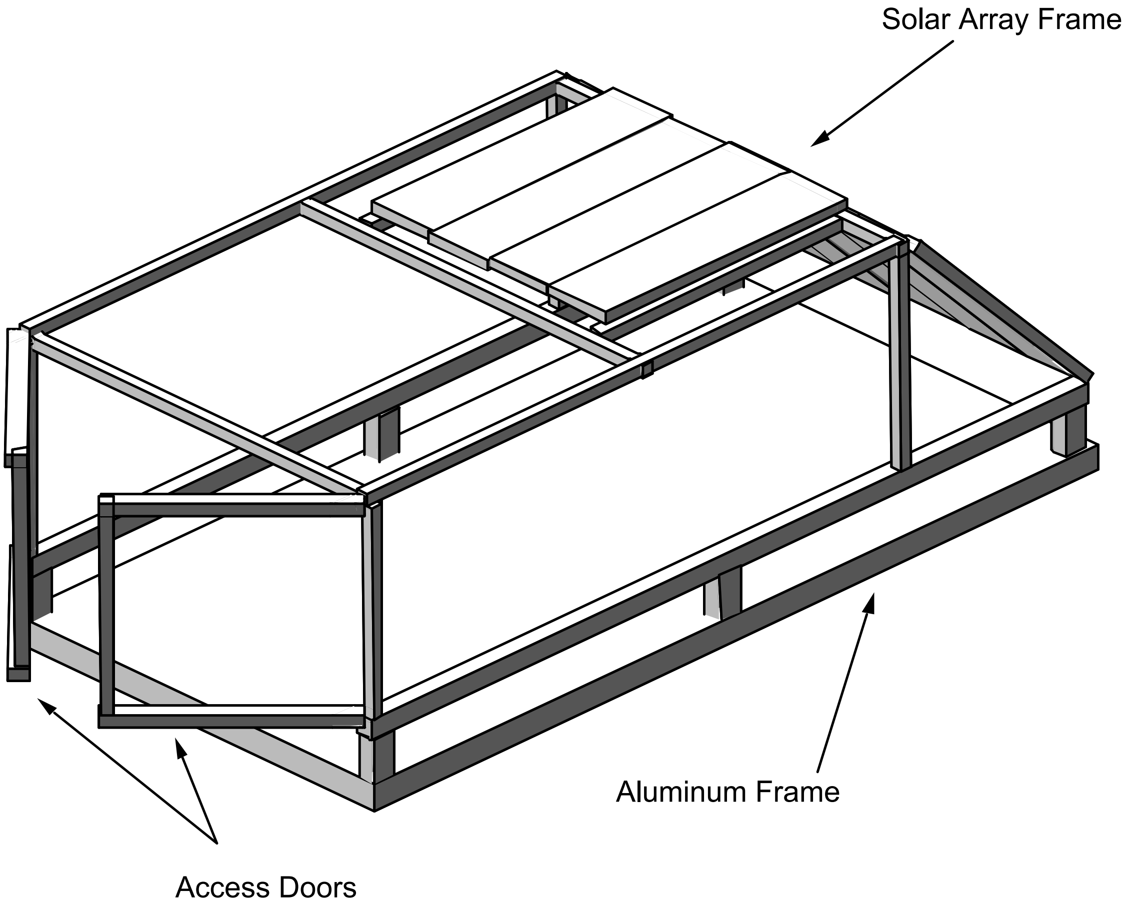

Figure 1 Trailer Structural Diagram

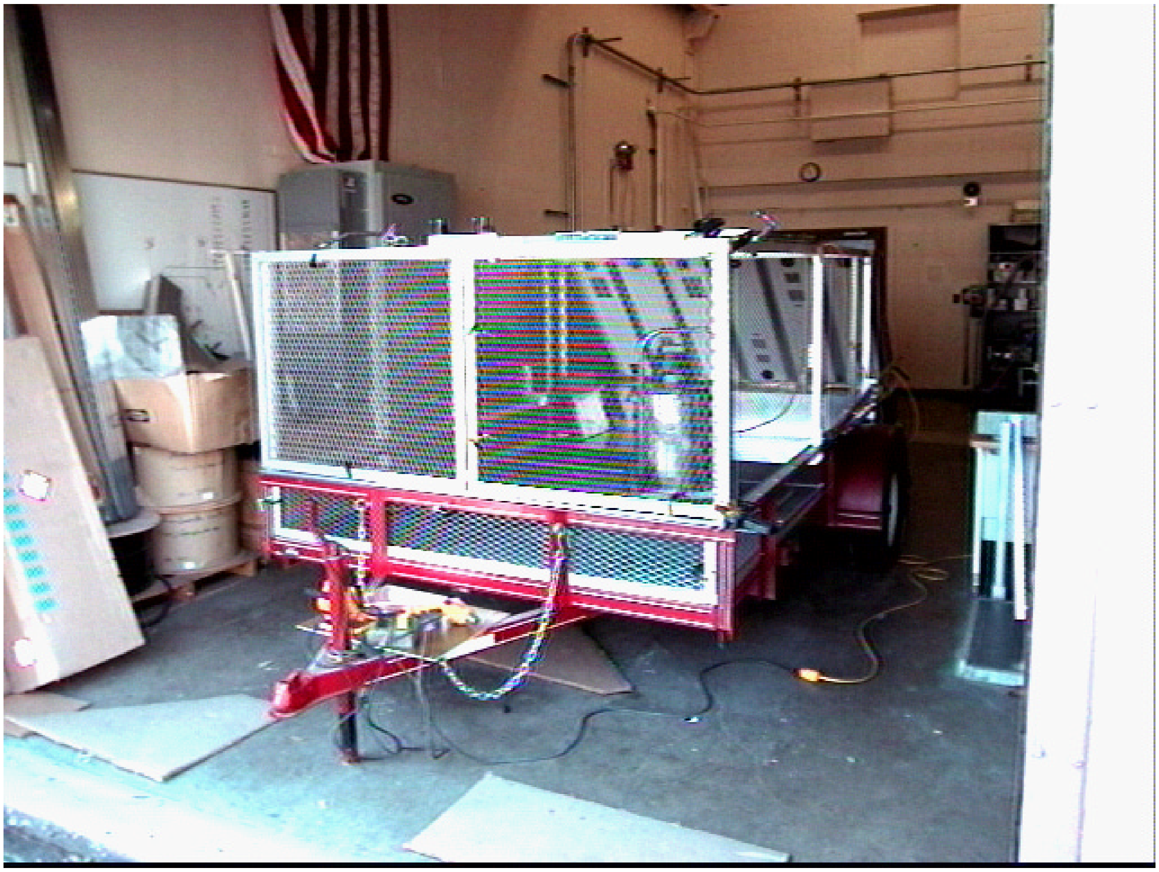

Figure 2 Photo of the RFC trailer with the box frame and cage installed.

Photovoltaic Array

The RFC system uses a photovoltaic array consisting of 20 Siemens M55 panels [1]. The panels are mounted in an aluminum angle, T6061 frame. The frame is oriented 45° to the horizontal when deployed. The array is configured into two levels.

The lower level consists of 12 panels, 6 central panels are mounted in a fixed frame and on either side of the central panels there are three panels mounted in a hinged frame. The hinged frame is attached to the central frame with a stainless steel piano hinge. The outer panels fold over the central panels when in the stowed position. When opened each outer panel is secured in position with a tubular stainless steel support. The stainless steel support is fixed with a rotating joint hinge to the frame of the trailer.

The upper level consists of 8 panels. There are 4 centrally mounted panels housed in a frame and two outer panels on each side also housed in a frame. These outer panels are hinged to the central panels with a stainless steel piano hinge. The bottom of the central panel is hinged to the top of the box frame. The outer panels fold over the central panel and the central panel is laid flat on the top of the box frame when in the stowed position. When opened the central panel is raised to a 45° angle and supported with two stainless steel tubular supports. These supports are attached to the trailer box frame with a rotating joint hinge. Once the central panel is raised the outer panels are opened. They are held in their opened position with tubular stainless steel rods attached to the box frame with a rotating joint hinge.

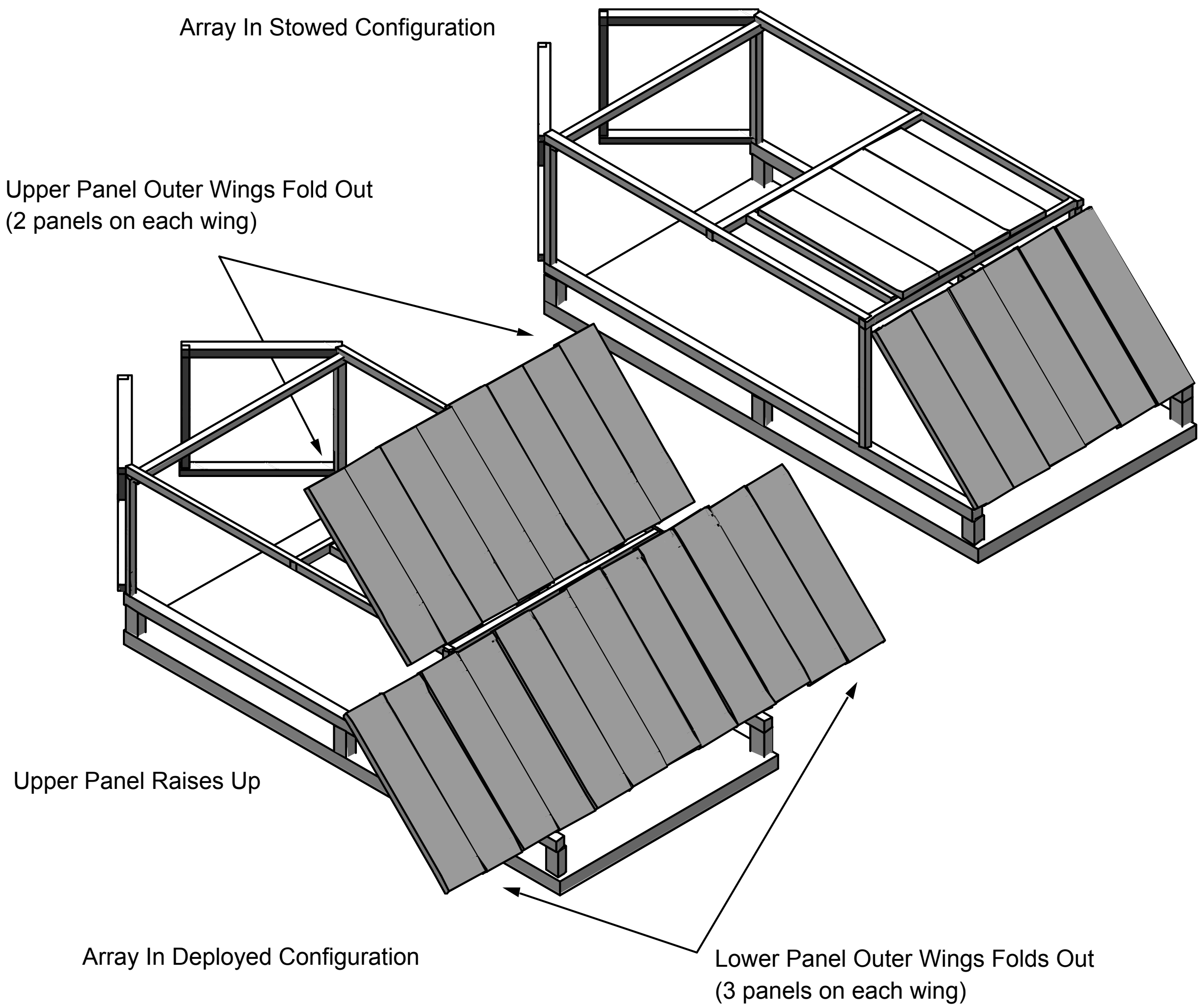

Figure 3 Stowage and Deployment Scheme for the Photovoltaic Array

The array panel frames are secured into position, both while deployed and stowed, using locking pins. These locking pins are T handled, 3/8" diameter, stainless steel pins. The use of these pins eliminates the need for any tools during deployment and stowage of the array. During deployment the pins are passed through holes in the end of the support rods and through special attachment blocks on the array frame to secure the array in place. When stowed, the pins are used to secure the array panels from opening. A diagram of the array stowage and deployment scheme is shown in figure 3. Photos of the array in both stowed and deployed configurations are shown in figures 4a and 4b.

Figure 4a Photo of Array in the stowed Configuration

Figure 4b Photo of the Photovoltaic Array in the Deployed Configuration

System Layout

The complete RFC system will be housed on the trailer. The system will include the following items listed below. The goal of the system layout is to provide a complete self contained, mobile RFC system.

- Solar Array
- Fuel Cell
- Electrolyzer
- Power Management Electronics
- Operational Display and Meters
- All Ancillary Equipment

The layout is designed to make the RFC system easy to operate while maintaining a level of safety for any observers of its operation. All breaker switches and cutoff controls will be located near the access doors of the trailer. This is to enable any component of the system to be shut down quickly in the event of an emergency. The remaining components will be positioned so that they can be accessed easily from the trailer entrance.

A major objective of the trailer's operation is to display both the components as well as information on the system performance during operation. Because of this requirement the various components of the system are arranged so that they are visible from at least one side of the trailer during operation. Also a display panel will be placed on the side of the trailer to shows key information, such as voltage and current flow for the main components, during operation. The display panel will also show a diagram of the system operation. All components within the trailer will be clearly marked with signs to indicate what they are.

A top view of the system layout is shown in figure 5 and a right and left isometric view is shown in figures 6a and 6b.

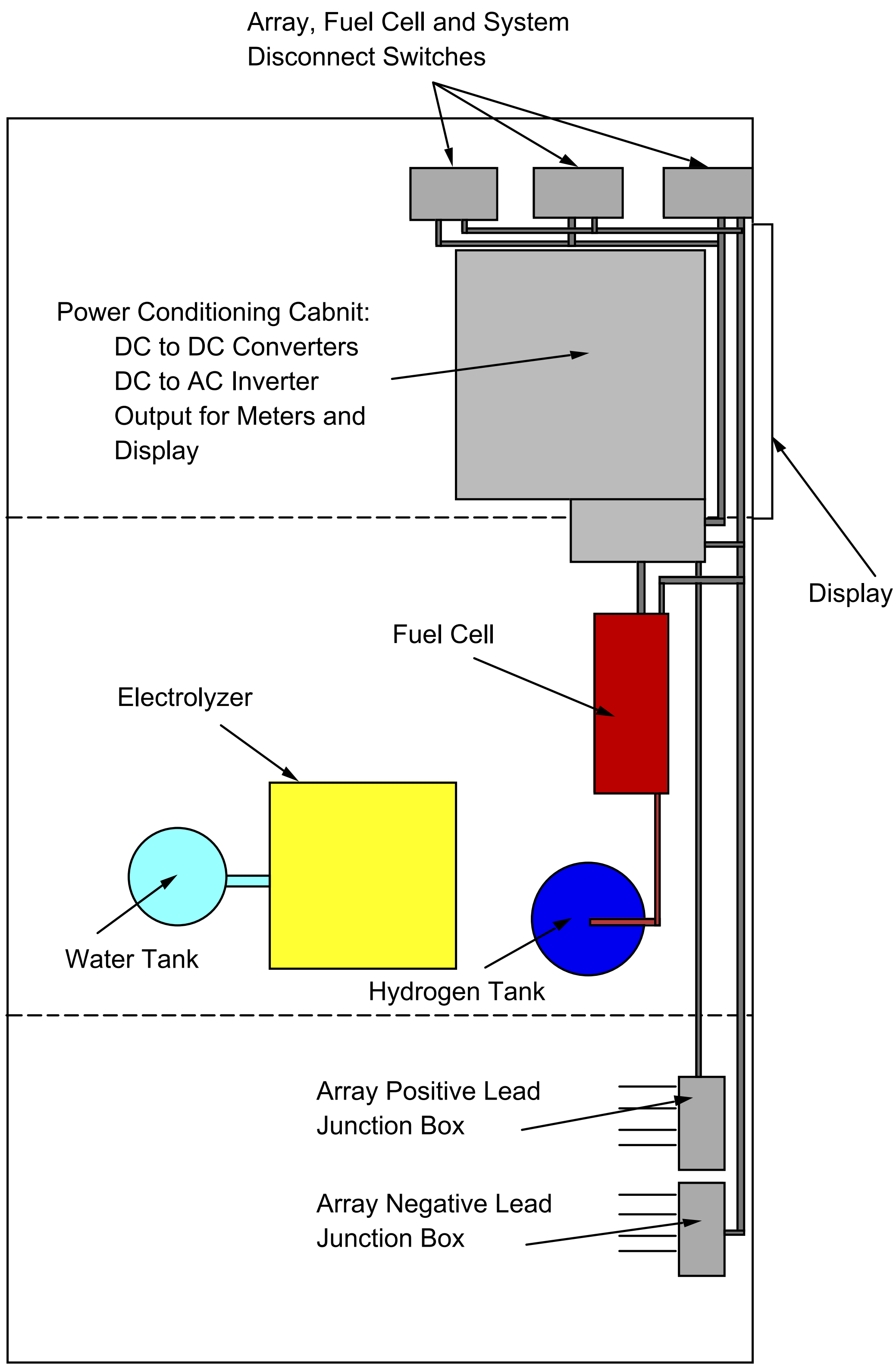

Figure 5 Top View of System Layout

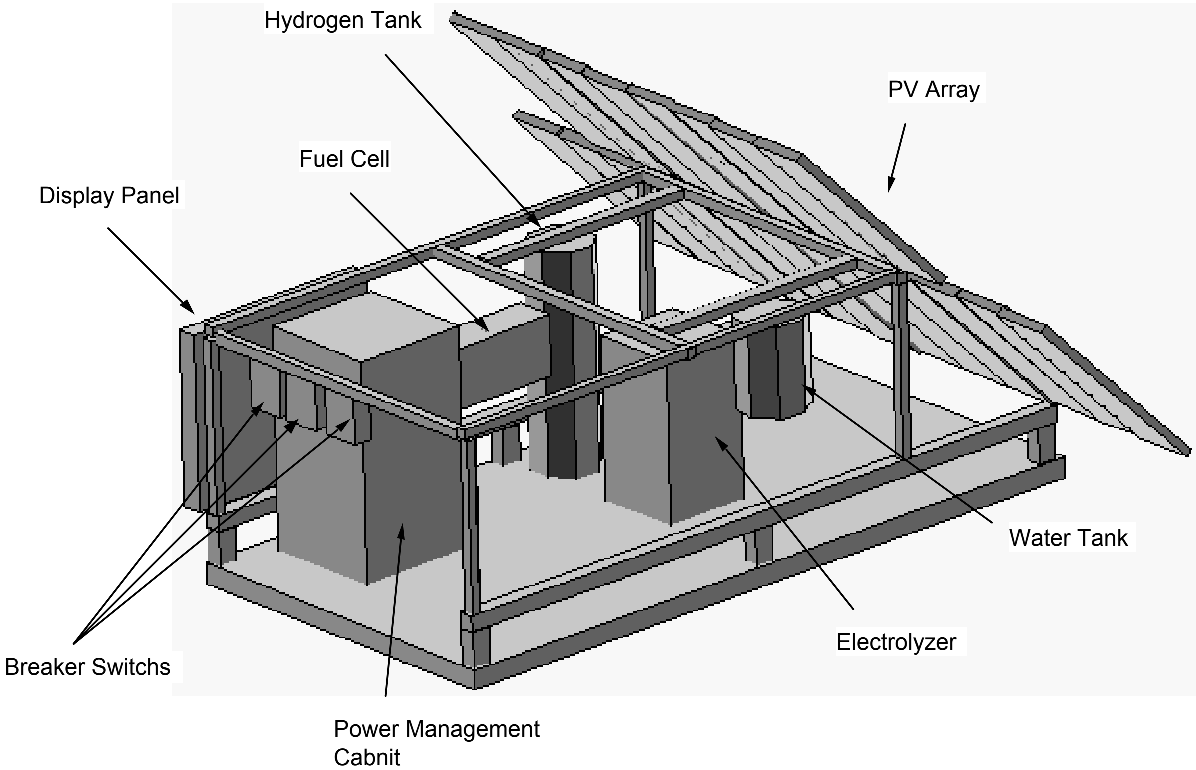

Figure 6a Right Isometric of System

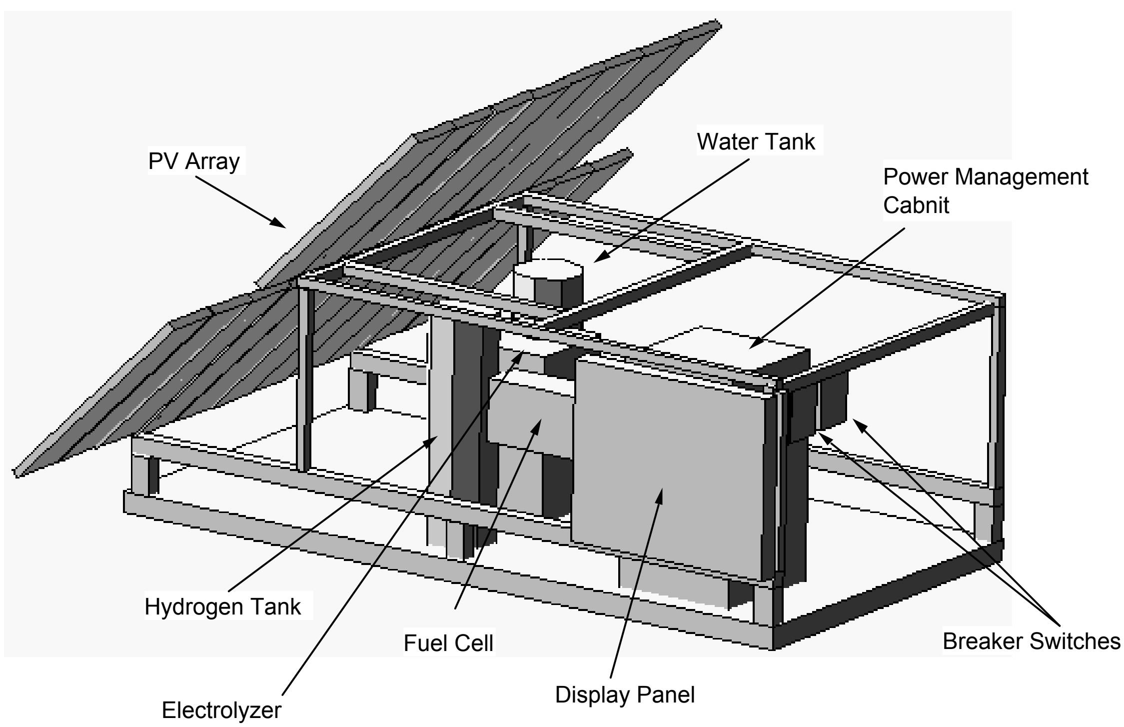

Figure 6b Left Isometric of System

Operational Design

The operational design of the system determines how the various components of the system work together. The design consists of integrating the PV array, fuel cell and electrolyzer into a working power plant. The output of the system is a standard 110V AC outlet and a 12V DC source. Another product of the operational design is the operational display. This display is integral to the trailer design since one of the main goals of this project is to further the understanding of how an RFC system operates. The goal of the operational design is to make the subsystems of the trailer work together as seamlessly as possible while minimizing the complexity of the system. Various power management equipment will also be used in order to turn the DC output from the PV array and the fuel cell into usable AC power. A diagram of the overall system operation is shown in figure 7. A detailed description of the different subsystems as well as the control scheme for the system operation is given in the following sections.

Photovoltaic Array Design

The voltage and current output combination of the solar array depends on the power required by the load and the incident solar radiation. As seen in figure 8, as the solar load demand increases, the output voltage of the array will drop from a maximum of 21.7 volts, in the no load or open circuit condition, to zero volts, in the short circuit condition. The current will also vary, under the same conditions from zero amps to 3.35 amps. Therefore, the current and voltage output of the array can very greatly depending on the loading condition.

The output of the array is also affected by the sun angle to the array and the solar intensity. If the array is left in a fixed position, the incident angle will vary throughout the day as the sun moves from east to west. Also for a given latitude, the variation of incident angle throughout the day will change depending on the time of year. This variation in incident angle throughout the day and year is shown in figure 9 for a south facing array at 41° N latitude (Cleveland Ohio). For this project, the elevation angle for the array was set to 45° up from horizontal. This was done to maximize the output of the array at the Cleveland Ohio location. This optimization can be seen in figure 10. This figure shows the variation in output power for a south facing array with different elevation angles for 41° north latitude.

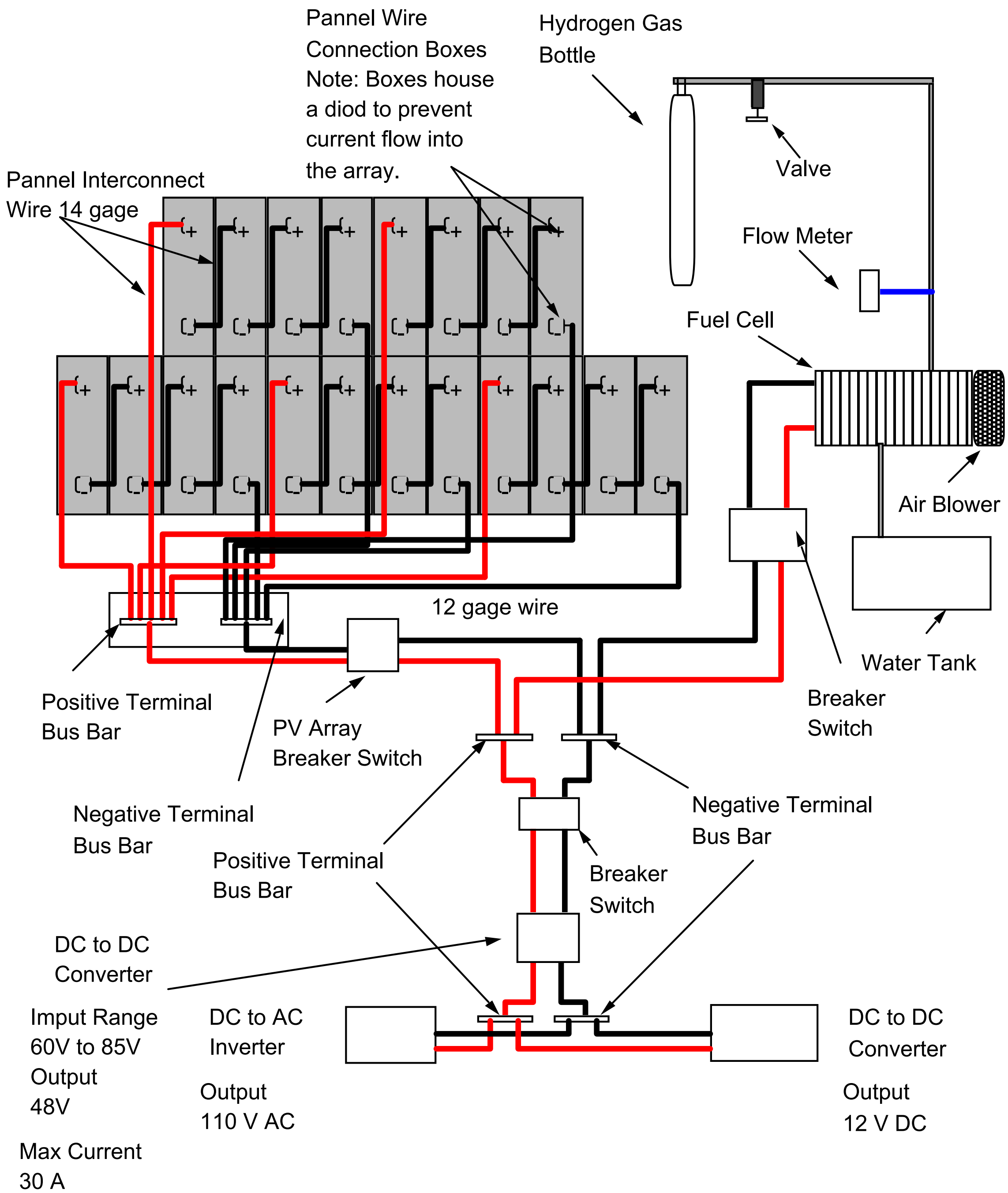

Figure 7 System Operational Diagram

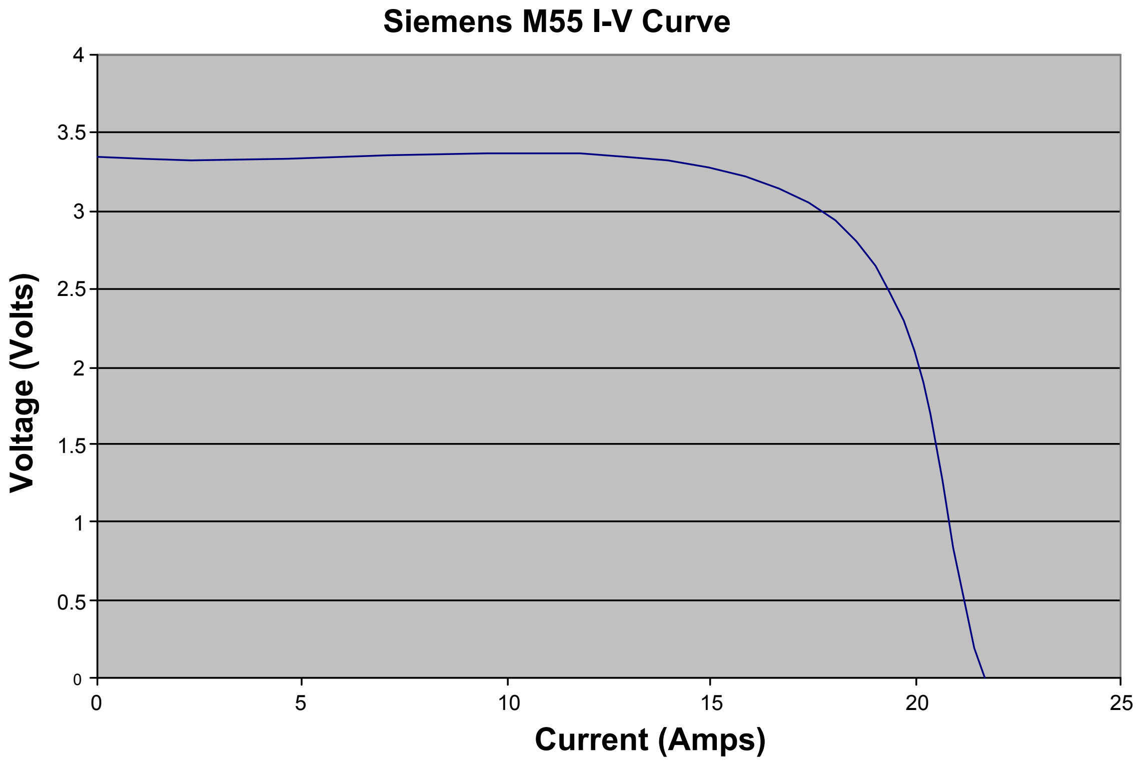

Figure 8 IV Curve for Siemans M55 Solar Panel [1]

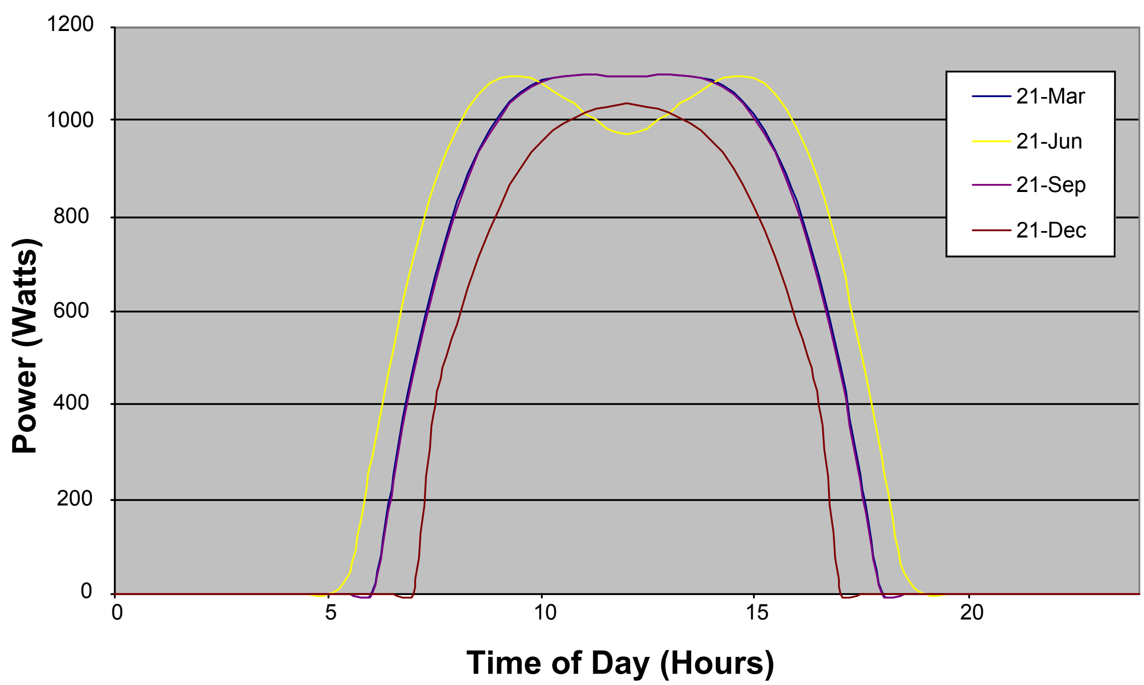

Figure 9 Variation in Output power for a 45° Fixed Array at 41° N Latitude

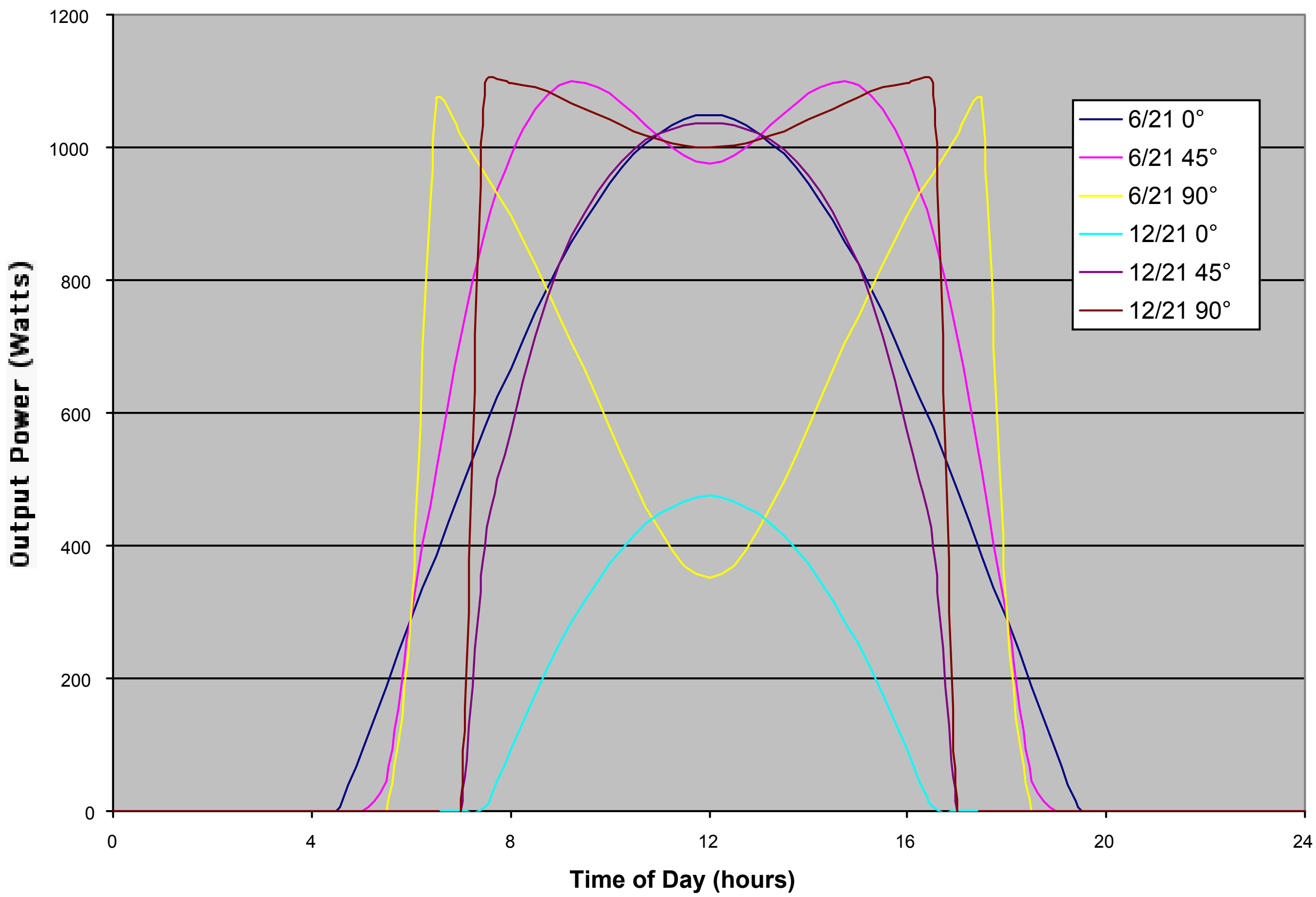

Figure 10 Array Output with Various Panel Elevation Angles for June and December

The photovoltaic array consists of 20 Siemens M55 panels. The panel specifications are given below in Table 1. The IV curve for the panel is given in figure 8.

Solar Cell Type	Single Crystal Silicon
Operating Efficiency	14.2%
Short Circuit Current	3.35 A
Open Circuit Voltage	21.7 V
Maximum Power Current	3.05 A
Maximum Power Voltage	17.4 V

Table 1 Specifications for a Siemens M55 solar array panel [1]

Groups of four panels are wired together in series, there are five such groupings in the array. Each grouping has a peak power output of 212 watts with a maximum current of 3.05 Amps and a voltage of 70 V. Fourteen gauge wire is used to connect the individual panels together. The positive leads from each grouping are brought to a junction box where they are connected to a single bus bar. The negative leads from each grouping are also connected together in a similar manner. Twelve gauge wire is then used to connect the positive and negative junction boxes to the rest of the system. There is also a manual breaker box on the positive lead out of the junction box. This breaker box is used as a means of electrically disconnecting the array from the system.

Since the solar panels will produce power whenever light is incident on them, there is no direct method for turning the panels off. However, the design of the deployment scheme for the array provides a means of turning the panels off. When the array is in the stowed configuration, the outer panels on both the upper and lower portion of the array are folded over the center panels. This can be seen in figure 4a. In this configuration, the cell side of the outer and central panels are facing each other. This effectively shuts the panels off, since little or no light will be able to reach the photovoltaic cells. This ability to effectively turn the array panels off adds significantly to the overall safety of the system.

This wiring scheme for the array can be seen in figure 7.

The Fuel Cell Subsystem

The fuel cell subsystem will deliver electrical power to the user loads when needed, that is when there is insufficient solar power available to supply to the user loads. The main requirements for the fuel cell subsystem are that some initial start-up power must be available to initiate fuel cell operation and that hydrogen fuel must be available. It is obviously desirable to implement a robust fuel cell subsystem that requires a minimum amount of ancillary components and parasitic power. The baseline fuel cell for the system is an 80-cell H_2-air De Nora fuel cell stack [2]. The characteristics of the fuel cell are a driving factor in the integration and capabilities of the complete system. This hybrid mobile power system incorporates a fuel cell subsystem design based upon the projected performance characteristics of the 80-cell De Nora stack, as shown in Figure 11.

The mechanical schematic for the fuel cell subsystem with the De Nora stack is shown in Figure 12. Note that the fuel cell subsystem requires no external humidification and no reactant recirculation. These two features are highly advantageous in terms of low parasitic power requirements, maintenance, and ease of operation. If another fuel cell stack is implemented in the system, then some process equipment, such as humidifiers and gas recirculators, must be added and other equipment may have to be replaced, depending upon the flow and pressure requirements of the new fuel cell stack. It is emphasized here that this fuel cell subsystem design is valid only for the 80-cell De Nora fuel cell stack which was baselined for this project.

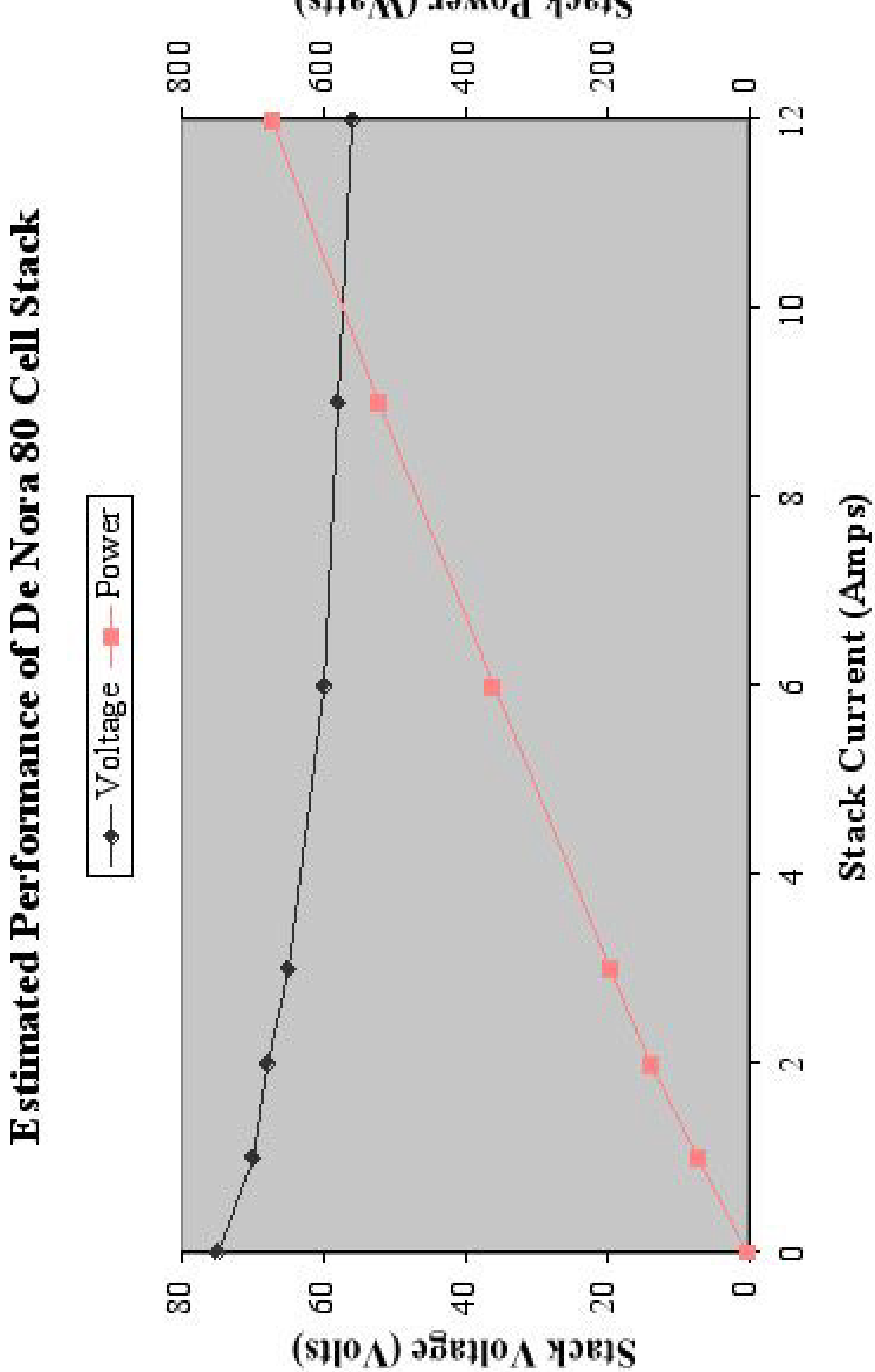

Figure 11 Fuel Cell Performance Estimate [2]

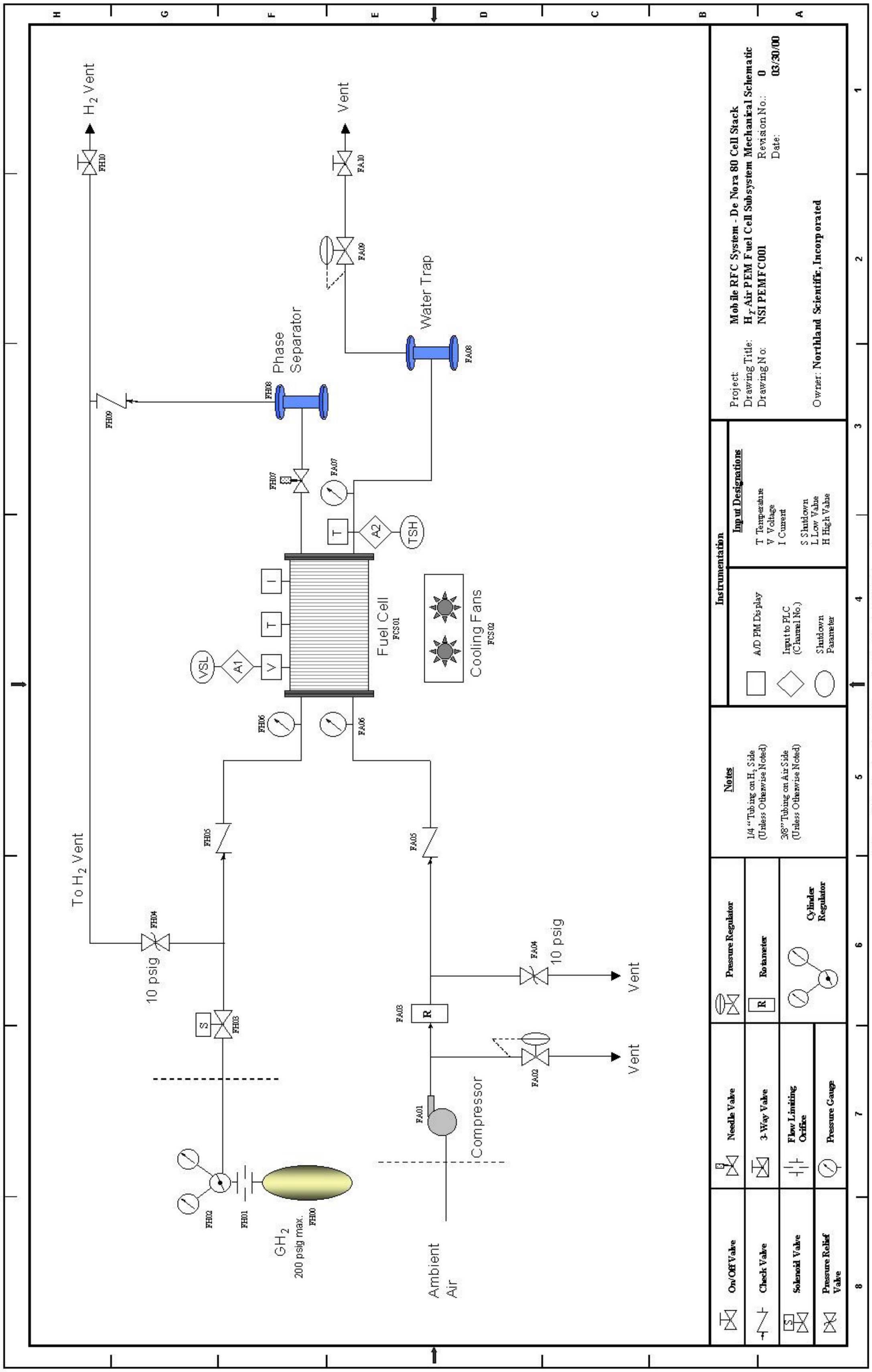

Figure 12. Mechanical Schematic for Fuel Cell Subsystem

Hydrogen-side Gas Flow

Hydrogen, regulated to 7–10 psig, will be introduced into the stack by actuating a solenoid valve. The solenoid will open and close based upon a digital signal from the process controller. Dead-ended H_2 feed is specified by De Nora for their fuel cell stack, qualified by intermittent purges. The purge interval has not been defined but will be based upon the stack voltage drop over a certain time period. The process controller implements the purge by opening and closing a solenoid valve on the hydrogen exit stream of the fuel cell stack. Alternatively, a slow but constant bleed can take the place of an intermittent purge. The baseline design therefore incorporates a needle valve, installed downstream of the hydrogen exit port of the fuel cell stack, to achieve a very slow bleed of H_2 through the stack. If it is determined through actual testing that the slow bleed is not necessary, the needle valve will simply be closed. A water/gas phase drop-out tank will be installed downstream of the needle valve to collect and measure any water that may be present on the hydrogen side of the fuel cell system. The amount of water in the hydrogen exit stream is expected to be negligible unless there is a problem with the fuel cell stack. The water level in this H_2/water phase separator will serve as one diagnostic measure of the integrity of the fuel cell stack.

Air-side Gas Flow

Fuel cell reaction air will be supplied by a compressor/fan that operates on a 12–24 Volt DC bus. Since the fuel cell can require anywhere between 2 and 60 seconds for start-up, an external power source will be needed to initiate operation of the fuel cell air feed compressor/fan. Once the fuel cell is operating, the fuel cell can power the compressor/fan in addition to powering the other ancillaries and the user loads. The fuel cell will consume about 202 normal liters (liters at 0 °C and 1 atmosphere pressure) per hour of oxygen at the 12 amp rating. The air-side supply system must deliver between 1440–1920 normal liters per hour of air at the 12 amp rating, corresponding to 50 to 100 percent excess air flow. De Nora recommends at least 50 percent excess air flow.

Air-cooling for the Fuel Cell Stack

In addition to reaction air, the De Nora fuel cell stack requires a separate air cooling function. De Nora specifies that the temperature of the central bipolar plate should not exceed 50 °C and the cathode exit stream should not exceed 60 °C at any time during fuel cell operation [2]. It was suggested by De Nora that cooling fans (flow rate not specified) must be implemented and the air flow must travel from the bottom of the stack to the top of the stack. “Walls” must be placed along the sides of the fuel cell stack to force the cooling air to flow across and in between the bipolar plates, which also serve as the cooling fins. Since the bipolar plates and the endplates of the fuel cell stack are electrically “hot” care will be taken to insure that those components are electrically isolated from all other components of the hybrid power system, including the cooling air flow “walls”. There are three options for implementing the air cooling function. The first option is to activate the cooling fans and to keep them operating at full capacity whenever the fuel cell is operating. This is the simplest option and is recommended as the baseline for the hybrid power system. The disadvantage to this approach is that excessive parasitic power may be consumed, although it is estimated that less than 10 watts is required for a 100 cubic feet/ minute (cfm) fan. The second option is to implement on/off control of the cooling fans. When any fuel cell subsystem temperature exceeds a predetermined value (i.e., 50 °C for the central fin or 60 °C for the cathode exit stream), the fans will be activated. The cooling fans would continue to operate until all monitored temperatures are cooled to acceptable levels. The third option is to implement proportional or proportional-integral-derivative control to change the air cooling fan speed based upon the fuel cell stack operating point. The fans would move more air when more current is being delivered by the fuel cell and the fans would move less air at low currents. This third option is most likely the most energy efficient approach but will require more complicated and expensive electronic controls than the first two options. In addition, comprehensive experimental data must be obtained before the control parameters can be determined. Option one was selected for the initial baseline because it is the simplest and most inexpensive to implement and the option could be changed at any later time. In all cases, for safety purposes, the fuel cell subsystem will be shut down based upon high temperature readings for the cathode air exit stream (60 °C) and for the temperature of the central fin (50 °C). A fuel cell stack operating voltage less than 56 volts will also induce a shutdown.

Hydrogen Storage and Hydrogen Safety

The stringent NASA safety standards must be followed when operating the fuel cell subsystem and when handling hydrogen. The fuel cell subsystem is compatible only with compressed gaseous hydrogen fuel, with storage pressures up to 2,265 psig. A wide variety of pressure vessels will be suitable for the mobile application but it is recommended that only vessels with a safety factor of at least four (4) be implemented. One standard Matheson “1A-bottle” [3], containing about 500 grams of hydrogen at 2,200 psig when full, will provide roughly 13.8 hours of fuel cell operating time at the rated gross stack electrical output of 672 watts. A two-stage pressure regulator, a flash arrestor, and a flow-limiting orifice will be attached to the outlet port of the hydrogen storage vessel. This is intended to eliminate the possibility of allowing high pressure hydrogen gas to be vented (or to enter the fuel cell stack) and to eliminate the possibility of a hydrogen tank explosion or fire due to mixing with air.

The tare weights of some standard commercial hydrogen storage vessels, such as Matheson “1A-bottles”, exceeds 120 pounds, so change-out of even modestly sized hydrogen tanks will not be practical [3]. The baseline hydrogen storage subsystem specifies one “1A-bottle”, secured to the floor of the trailer in a horizontal position. Nominal dimensions of the “1A-bottle” are 9 inches (23 cm) in diameter and 51 inches (130 cm) in length [3]. When filled to 200 psig pressure, the “1A-bottle” will allow for a little over 1 hour of fuel cell operation at the gross stack rated power of 672 watts.

It is especially important that the hydrogen supply subsystem be protected from the elements and that the cylinder shut-off valve and the two-stage regulator adjustment knob be easily accessible. Several commercial gas suppliers can be selected for procuring the hydrogen vessel, including Matheson, Scott, and Air Products. The suppliers’ regulations and guidelines must be strictly adhered to for all aspects of handling the hydrogen gas and storage vessel. In addition, all Department of

Transportation (DOT) guidelines must be satisfied, even if other tank vendors, such as those that make lightweight composite tanks, are selected. Most importantly for standard, commercial cylinders, the DOT regulations do not permit vendor owned cylinders to be refilled without the owner's permission [4]. Hence, if the hydrogen storage vessel is not owned by NASA, then vendor permission for refilling via electrolysis operation must be obtained.

The low pressure hydrogen supply that exits the two stage regulator that is attached to the hydrogen storage vessel will lead to the fuel cell stack. An intrinsically safe solenoid valve will be used for on/off control of the hydrogen flow into the stack itself. The solenoid valve will be mounted on the equipment rack that houses the fuel cell stack, so the hydrogen piping run from the hydrogen storage vessel to the fuel cell stack should be unobstructed and it should be as short as possible. A check valve and a pressure relief valve will be sited between the solenoid valve and the fuel cell stack. Aside from the intrinsically safe solenoid valve, all other electronic equipment will be separated from the hydrogen subsystem and the fuel cell stack to minimize all ignition sources. If any electronic equipment is absolutely required in the vicinity of hydrogen (such as the solenoid valve) the proper intrinsically safe (or explosion-proof) classifications must be invoked.

Fuel Cell Subsystem Construction and Operation

As already mentioned, the stringent NASA safety standards must be followed when constructing and operating the fuel cell subsystem. Swagelok™ tube fittings are recommended for construction [5]. The schematic shown in figure 9 and the parts list shown in Table 2 serve as the basis for fuel cell subsystem construction and only qualified personnel should implement and oversee construction and operation of the fuel cell subsystem. It is highly recommended that the fuel cell stack be operated in a controlled laboratory environment to establish performance parameters prior to testing in the fuel cell subsystem for the mobile RFC trailer.

The entire fuel cell subsystem, including the fuel cell stack, must be leak-tested before the system can be deemed operable. De Nora already supplied, with the stack, an operating manual that includes pre-operational leak tests. These tests must be conducted as per De Nora's specifications. In addition, all mechanical piping/components must be leak-checked and all instrumentation must be properly calibrated. Normal and emergency fuel cell subsystem shutdown procedures must be in place prior to operating the fuel cell subsystem in the RFC trailer. At a minimum, the fuel cell subsystem must be capable of self-shutdown due to low stack operating voltage (under 56 volts), high cathode exhaust temperature (above 60 °C), high center fin temperature (above 50 °C), or by personnel induced emergency shutdown (via "mushroom type " shutdown button). A log book must be kept with the fuel cell stack to document all elements of handling and operation of the stack. When possible, single cell voltages or group voltages should be recorded, in addition to the stack voltage at noted process conditions, as one measure of stack performance degradation.

Control Scheme and Operations

The system operation is designed to be as simple as possible and to limit the controls and electronics needed for the system to operate. In order for the system to operate, the main power generating components, the solar array and the fuel cell, have to be able to supply the required power to the load. The main issue is that the output of both the solar array and fuel cell can vary significantly during operation, as seen in Figures 8 and 11. For the system to operate correctly the fuel cell would need to supply power when the array was not capable. This could occur in situations of high load demand, changing solar incident angle or cloud cover. The system was designed to passively turn the fuel cell on when needed. This passive operation was accomplished by matching the maximum output power point of the array to the open circuit voltage point of the fuel cell. The maximum output power of each solar array panel occurs at approximately 17.4 volts (or 69.6 volts for a grouping of 4 panels); the open circuit voltage for the fuel cell occurs at approximately 68 volts. This means that when the array is operating at or below its peak power point the output voltage of the array / fuel cell system will be above 70 volts. When the demand on the array increases the system voltage will drop. Once it drops below 68 volts the fuel cell will automatically begin to supply current to the system. This passive operation between the array and fuel cell allows these two components to operate together with no active controls.

One problem with this passive operation is that the system operating voltage will vary over a fairly large range (approximately 84 volts to 50 volts). This large range of output voltage is not usable by most devices. Therefore, the system output has to be conditioned before it is sent to the load. This conditioning is done by connecting the output of the array-fuel cell combination to a DC to DC converter. The converter can accept the wide input voltage range and produce a constant 48 V output. The 48 V output is then passed through a DC to AC inverter to get the desired 110 V AC output as well as another DC to DC converter that supplies a 12 V DC output. A diagram of the power conditioning components described above can be seen in figure 7.

Another issue with the system operation is electrical grounding. Because of safety concerns at the relatively high voltage and power level the system will be operating at, the trailer structure cannot be used as the grounding point for the system. An external ground must be used. This ground can be a water pipe or other metal structure imbedded in the ground. The system will be supplied with a grounding cable and a 1.2 m copper rod that can be imbedded into the soil and act as a grounding point for the system.

The electrolyzer supplied by NASA, which is used to separate water into hydrogen and oxygen, will be mounted on the trailer. This electrolyzer will operate manually as a load and will not be integrated into the system operation.

Display Design

One of the primary goals of the mobile RFC is to serve as an educational tool for demonstrating the operation of a regenerative PV-fuel cell system. In order to facilitate the goal of education, a display panel was designed to show key aspects of the operation of the RFC system during use. The display panel will be mounted on the box frame of the trailer, as shown in figure 5. The display will contain the following items:

- Meters indicating the current being produced by both the fuel cell and PV array.
- Meters indicating the current being used by the load and the electrolyzer.
- The operating voltage of key components of the system (array, fuel cell)
- A diagram showing the system operation and indicating what components are active.

The display layout is shown in figure 13 and the locations of the meters for the display is shown in figure 14.

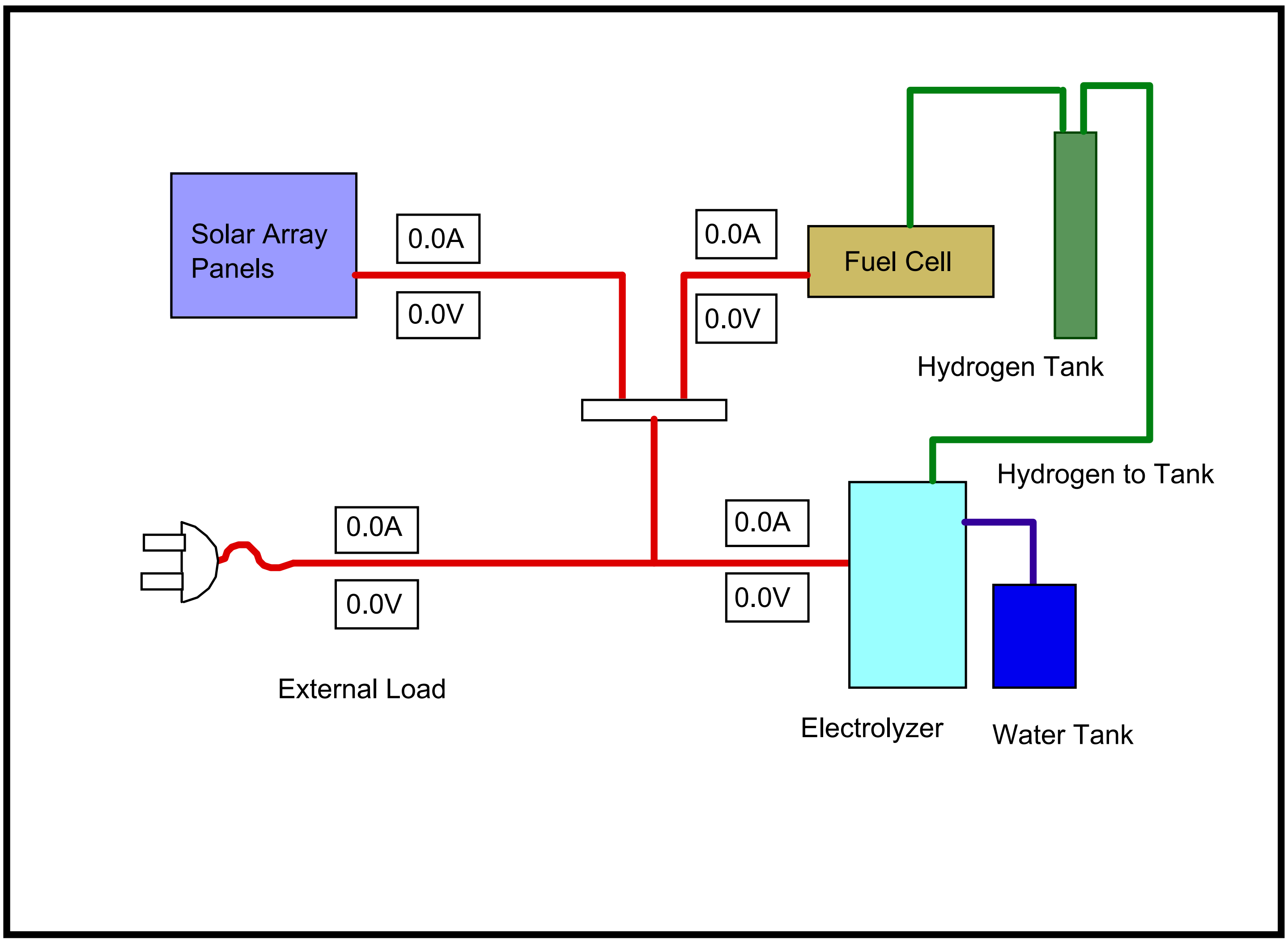

Figure 13 Operational Display Layout

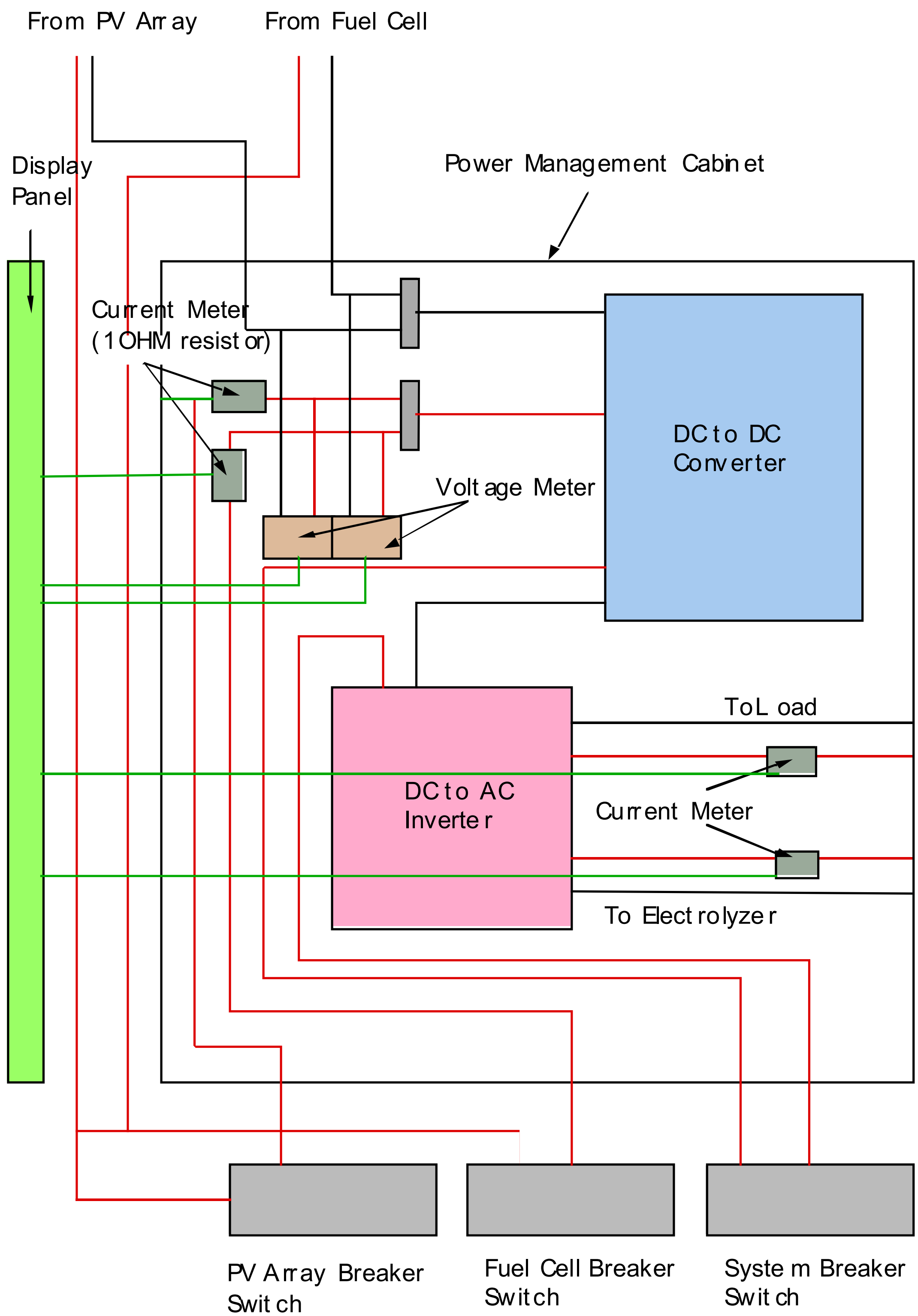

Figure 14 Display Meter Location within the System

Component Specification List

Part No.	Part Description	Vendor/Product No.
M55	Solar Array Panel	Siemens M55
TSC36x9	70V DC to 48V DC Converter	Tarco TSC36x9
TSC60x2	48V DC to 12V DC Converter	Tarco TSC60x2
MX2000-48	48V DC to 120V AC Inverter	Exeltech MX2000-48
NA	Voltage Meter Display	Datel Inc. DMS-40LCD-2/3-9B
NA	Current Meter Display	Datel Inc. DMS-40LCD-1/2-9B
200088 A	Electronics Rack	Electrorack 1-Bay NEMA 4 Aluminum Cabinet
FCS01	80-cell Fuel Cell Stack; 12A, 56V Rating	De Nora
FCS02	24 VDC Brushless Cooling Fans (two total)	Comair/Rotron/MC24B3
FH00A	Hydrogen Storage Tank	Matheson/1939101-0
FH00B	Hydrogen Tank Valve Outlet	Matheson/CGA No. 350
FH00C	Flash Arrestor (not shown)	Matheson/6104
FH01	Two Stage Pressure Regulator	Matheson/3102C
FH02	Restrictive Flow Orifice (integral with CGA connection, not as shown)	Matheson/Consult Sales Rep.
FH03	24VDC, Low Pressure, Intrinsically Safe Electronic Solenoid Valve	Skinner Valve/ 71215SN2MN00 encl/coil N0H111C2
FH04	¼” Pressure Relief, set to 10 psig	Swagelok™
FH05	¼” Check Valve, 1/3 psig cracking pressure	Swagelok™
FH06	3” diameter Pressure Gauge	Ashok/0-15 psig
FH07	¼” Needle Valve	Swagelok™
FH08	H_2O/H_2 Water Drop-out Tank; 1 liter with high pressure fixture and ¼” Swagelok™ fittings	Savillex/1000-4-3; 1000-PF
FH09	¼” On/Off Valve	Swagelok™
FA01	24VDC Air Compressor	GAST/1531-107B-G578
FA02	Back Pressure Regulator	Fairchild/10222BP
FA03	Rotameter	Brooks/1355EHA7ADA1A
FA04	3/8” Pressure Relief, set to 10 psig	Swagelok™
FA05	3/8” Check Valve, 1/3 psig cracking pressure	Swagelok™
FA06	3” diameter Pressure Gauge	Ashok/0-15 psig
FA07	3” diameter Pressure Gauge	Ashok/0-15 psig

FA08	H_2O/Air(O_2) Water Drop-out Tank; 2 liter with high pressure fixture and 3/8” Swagelok™ fittings	Savillex/2000-4-3; 2000-PF
FA09	Back Pressure Regulator	Fairchild/10222BP
FH10	3/8” On/Off Valve	Swagelok™
N/A	24 VDC Temperature Meter	Newport/INFCDT-411 A/E
N/A	Digital (Panel) Voltmeter	Newport/

Table 2 System Component List

Performance Estimate

The operational performance of the system is based on the amount of power available to run a given load (or loads) for a period of time. This power availability is dependent on the individual component characteristics as well as operational issues such as location and time of year. The system performance was determined by performing an energy balance on the system and determining the maximum load power it could sustain throughout a day period. A number of component specifications were used in the energy balance. These specifications are listed in table 3. As test data is gathered on the system's performance, the values used in the various component specifications may need to be updated.

Solar Cell Efficiency (η_{sc})	14%
Solar Array Area (A)	7.74 m^2
Fuel Cell and Electrolyzer Combined Efficiency (η_{rfc})	67%
Power Conditioning Equipment Efficiency (η_{pmad})	95%
Atmospheric Attenuation (1- τ)	30%

Table 3 System and Operational Specifications

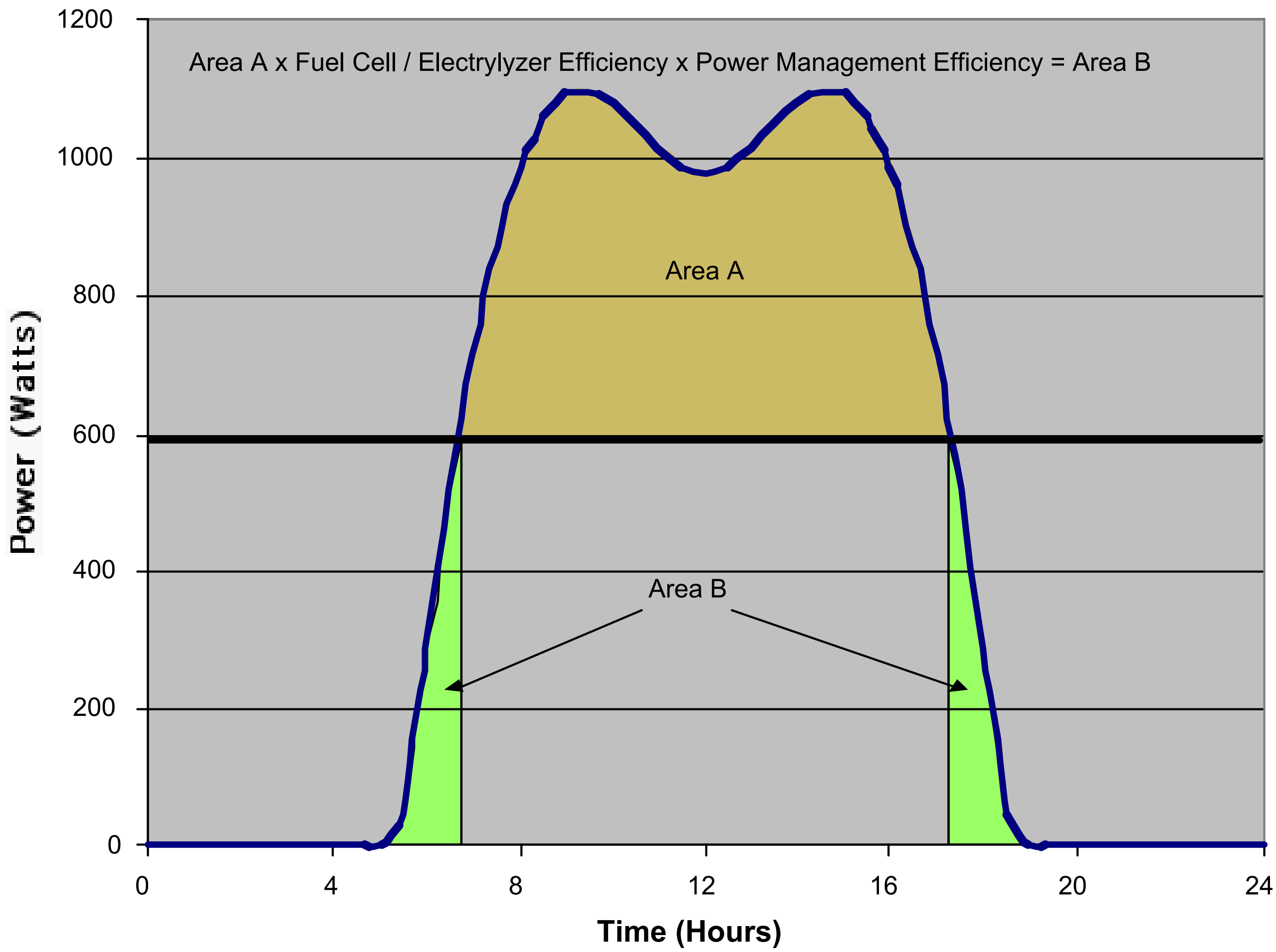

Figure 15 Energy Balance Diagram for June 21st

The energy balance was performed between the power produced by the solar array and that used by the electrolyzer to regenerate hydrogen for the fuel cell. The mean system operating power, established by the energy balance, is the amount of continuous power available from the system over a day period. This operating power level is obtained from the output power curve of the solar array, as shown in figures 9 and 10, by selecting a power level and integrating the array power curve above and below the selected power level. For the energy balance to work the area under the curve which is above the selected power level (area A) multiplied by the turn around efficiency of the fuel cell & electrolyzer and the power conditioning equipment efficiency, must equal the area under the curve and below the power level (area B). This energy balance is express in equation 1 and is shown graphically in figure 15.

$$\text{Area B} = \eta_{rfc}\, \eta_{pmad}\, \text{Area A} \qquad [1]$$

For the solar array the output power curve (P) is determined by the following equations where τ is the attenuation due to the Earth's atmosphere and is assumed to be 0.15 and A is the area of the solar array in m^2.

$$P = SI\,(1-\tau)\,\eta_{sc}\,A\,Sin(\alpha + \theta) \qquad [2]$$

The solar intensity (SI) is the solar flux at a given point in the Earth's orbit. It is given in (W/m^2). This quantity varies throughout the year. It is determined from the following equations.

$$SI = SI_m\,(r_{orbm}^{\;2} / r_{orb}^{\;2}) \qquad [3]$$

Where the mean solar intensity (SI_m) is 1352.8 W/m^2 and the mean orbital radius (r_{orbm}) of the Earth is 1.496E8 km. The actual orbital radius (r_{orb}) is given by the following equation.

$$r_{orb} = (1-\varepsilon^2) / (1+\varepsilon\,Cos\,(\omega)) \qquad [4]$$

The orbital eccentricity (ε) of the Earth's orbit is 0.017 and the day angel (ω) is defined as 0° on January 4th (perihelion of Earth's orbit) and increases by 0.98° per day.

The solar elevation angle (α) as a function of time of day in hours (t) is given by the following equation.

$$\alpha = \pi / 2 - \cos^{-1}(f_1 - f_2\,Cos(2\,\pi\,t / 23.935)) \qquad [5]$$

The constants f_1 and f_2 are given by the following equations where γ and ψ are the latitude (41° for Cleveland, Ohio) and Earth's declination angle respectively. The declination angle, given by equation 8, is based on a day angle (ω_2) which has a value of 0° on the vernal equinox and increases 0.98° per day.

$$f_1 = Sin(\gamma)\,Sin(\psi) \qquad [6]$$

$$f_2 = Cos(\gamma)\,Cos(\psi) \qquad [7]$$

$$\psi = 0.4091\,Sin(\omega_2) \qquad [8]$$

The effective array elevation angle (θ) is a function of the time of day (t) in hours and is given by the following equation.

$$\theta = Tan^{-1}\,(Tan(\alpha)\,Cos(2\pi\,t / 23.935 - \pi)) \qquad [9]$$

As described by equations 2 and 3 the solar flux will vary throughout the year. This will have an effect on the overall system performance. Figure 16 shows a plot of this variation in solar flux. Based on the analysis described above, a performance estimate was made for the system. The analysis was run for the 21st of each month at 41° N latitude. operation. The results of the analysis are shown in table 4 and plotted in figure 17.

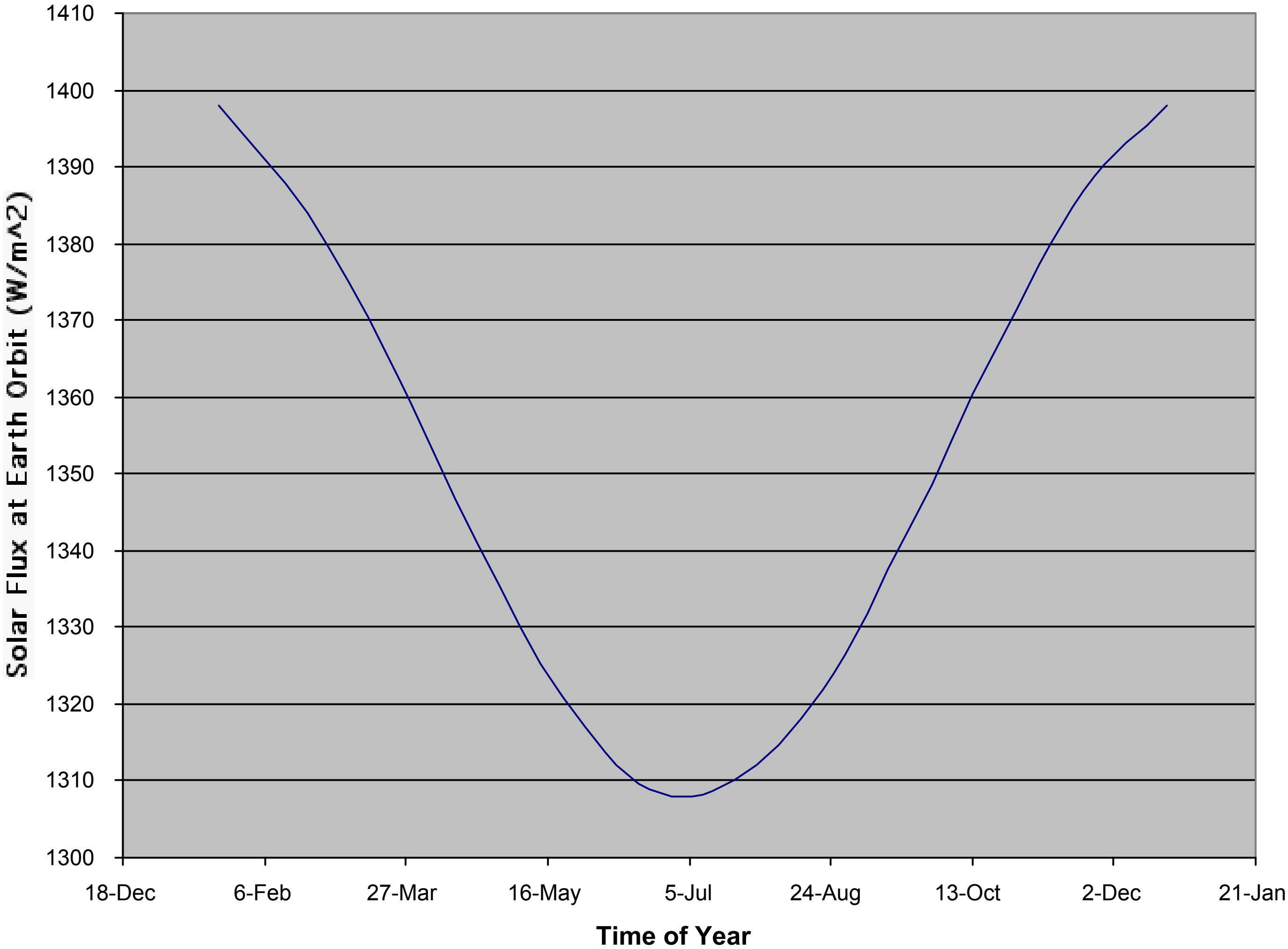

Figure 16   Solar Flux at Earth's Upper Atmosphere Throughout the Year

Time of Year	Operating Power (W)	Time Energy Balance is Achieved (hours)	Solar Flux at Orbit (W/m^2)	Solar Flux at Array (W/m^2)
January 21st	516	9:01 AM	1398	979
February 21st	606	8:42 AM	1384	969
March 21st	659	8:15 AM	1365	956
April 21st	653	7:42 AM	1341	939
May 21st	615	7:18 AM	1321	925
June 21st	595	7:08 AM	1309	916
July 21st	611	7:18 AM	1310	916
August 21st	645	7:44 AM	1322	925
September 21st	646	8:16 AM	1343	940
October 21st	587	8:45 AM	1366	956
November 21st	503	9:05 AM	1387	971
December 21st	469	9:12 AM	1398	979

Table 4 System Performance Results

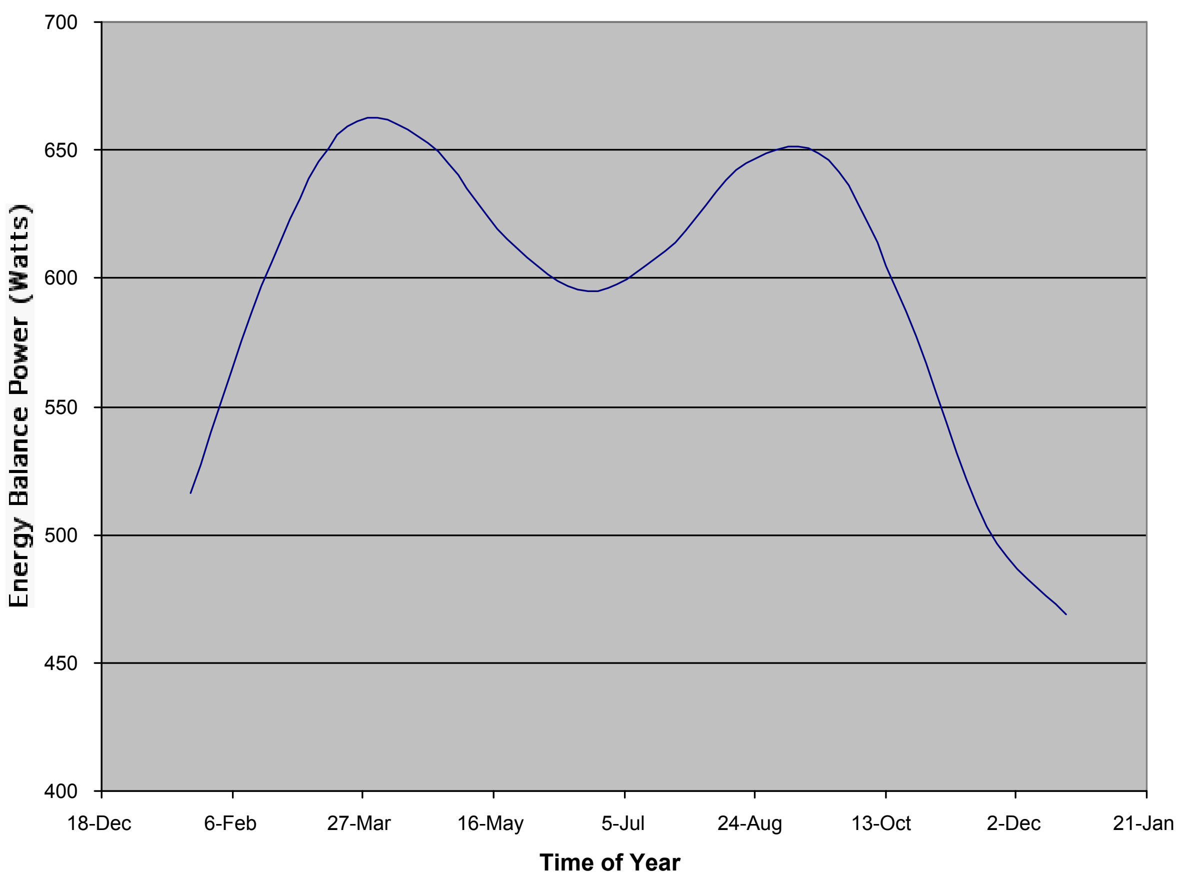

Figure 17 Continuous Available Output Power

Status

At the time of publication, the construction of the mobile RFC system was underway based on the design outlined within this report. The main components were procured including the trailer, solar array, fuel cell and the main electronic components and their housing. The installation of the system onto the trailer was begun. The structural elements were added to the trailer, the solar array was installed and wired and the main electronics enclosure was installed and its wiring was begun.

The next stage in the development of the system will be to install the fuel cell system and complete the electronics and control system installation. At this point testing of the system will commence. Once the array/fuel cell integration is operational, then the electrolyzer will be incorporated into the system. Subsequent testing of the complete system with the electrolyzer incorporated will be performed. Once the complete system has been tested and is operational, the display panel will be installed.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 2003	Final Contractor Report

4. TITLE AND SUBTITLE

Initial Design and Construction of a Mobil Regenerative Fuel Cell System

5. FUNDING NUMBERS

WBS–22–708–87–11
NCC3–70731–K

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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9970 Brook Road
Olmsted Falls, Ohio 44138

8. PERFORMING ORGANIZATION REPORT NUMBER

E–14105

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA CR—2003-212539

11. SUPPLEMENTARY NOTES

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Unclassified - Unlimited
Subject Category: 44 Distribution: Nonstandard

Available electronically at http://gltrs.grc.nasa.gov

This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

The design and initial construction of a mobile regenerative power system is described. The main components of the power system consists of a photovoltaic array, regenerative fuel cell and electrolyzer. The system is mounted on a modified landscape trailer and is completely self contained. An operational analysis is also presented that shows predicted performance for the system at various times of the year. The operational analysis consists of performing an energy balance on the system based on array output and total desired operational time.

14. SUBJECT TERMS

Regenerative fuel cells; Solar arrays; Fuel cell power plants

15. NUMBER OF PAGES

36

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	