Fuel Cell Power Pack for 24V Scrubber

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ABSTRACT

Tennant Company, a leader in commercial and industrial cleaning equipment, wishes to modify one of their most popular floor scrubbers, the T3, to operate on a fuel cell rather than lead-acid batteries. In addition to environmental concerns raised by use of lead-acid batteries, Tennant's wishes for longer run time and quicker refueling motivated the choice of a NEXA PEM fuel cell for this application. It is our objective to research alternate methods of onboard hydrogen storage and power transfer between the fuel cell and the T3 scrubber, design and build necessary mechanical and electrical interfaces and power management systems, fabricate a proof-of-concept prototype, and quantify performance characteristics of our prototype.

1 INTRODUCTION

Tennant Company is a leader in commercial and industrial cleaning equipment, controlling an estimated 10% of the commercial and industrial cleaning equipment market and doing nearly $600 million in business during the year of 2006 [1]. As a leader in the industry, Tennant is striving to be the first to offer a green alternative to current deep-cycle lead-acid batteries used to power their floor scrubbers. These lead-acid batteries present environmental concerns if disposed of improperly, have a limited lifetime, and long recharge times; Tennant believes these problems can be alleviated with an alternate energy source.

Tennant, with the help of a ME 450 Winter '07 team, selected the Ballard NEXA PEM fuel cell to power their scrubber because of its many advantages over lead-acid batteries. The main improvement over lead-acid batteries is that the fuel cell generates electricity with water and heat as the only by-products. Using a fuel cell to power floor scrubbers could also decrease the refueling time and increase the run time of the scrubbers, leading to more efficient cleaning. There are no corrosive materials in the NEXA fuel cell system, so scrubber operation and maintenance is safer for the user. The NEXA system does not produce a significant amount of noise compared to the current battery system, so the user will not be disturbed by the new power system.

The purpose of our project is to successfully integrate the Ballard NEXA PEM fuel cell with a Tennant T3 floor scrubber while making minimal modifications and maintaining the original functionality to the T3 itself. The scrubber must be powered by commercially available hydrogen. We will design all mechanical and electrical interfaces and power management system, install the components, and test and debug the T3. Tennant wishes our team to document power output, run time, fuel efficiency, operating temperature, and any design issues that occur.

2 INFORMATION SEARCH

Currently, Tennant Company powers their scrubbers, including the T3, with lead-acid batteries. Not only do these batteries give the scrubbers limited run time (about 2.5 hours) and require long recharging periods, but their disposal presents environmental concerns. Tennant Company wishes to eliminate lead-acid battery use in favor of a more efficient and environmentally friendly power source. Our investigation of solutions to these problems began with researching available fuel cell technologies, hydrogen storage methods, and then comparing our application of fuel cells to similar commercially available applications.

2.1 Fuel Cell Technologies

Our engineering team looked into five different types of fuel cells: polymer electrolyte (also known as proton exchange) membrane fuel cells (PEM), direct methanol fuel cells (DMFC), alkaline fuel cells (AFC), phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), and solid oxide fuel cells (SOFC). The difference between each type of fuel cell is the electrolyte used in the chemical reaction, the type of hydrogen fuel required, and the operating characteristics of the fuel cell itself such as emissions, temperature, and noise [2]. A comprehensive comparison of each fuel cell type is available in Appendix A.

The previous team who worked on this project selected a PEM fuel cell as the best choice for a T3 scrubber. The only by-products of a PEM fuel cell are heat and water, and the fuel cells contain no hazardous materials, making them safe for indoor applications. Additionally, PEM fuel cells operate at a relatively low temperature and can therefore be safely enclosed within the plastic housing of a T3. These fuel cells are available in a variety of power ratings, and the T3 requires approximately 1kW of power which is easily achievable with a PEM fuel cell. Through extensive market research, the previous team chose a Ballard NEXA PEM fuel cell; this is a proof-of-concept project, and since we do not wish to incur additional costs to Tennant, we will be using this fuel cell.

Manufacturer	Model	Length (m)	Width (m)	Height (m)	Power Output (kW)
Ballard	NEXA	0.56	0.25	0.33	1.2
Intelligent Energy	Power System	0.58	0.25	0.14	1.3
ReliOn	T-1000	0.60	0.48	0.32	1.2

Table 1: Alternate PEM Fuel Cells Compared Against the NEXA [1, 3, and 4]

Since fuel cells are a rapidly advancing technology, even in the six months since the NEXA PEM was selected significant improvements have been made. Smaller packages are available that deliver the amount of power necessary for the T3; Table 1, above, lists some of these alternate PEM fuel cells. Successful integration of a fuel cell into a T3 will be easier to achieve as the technology improves; by the time Tennant is ready to produce fuel cell-powered T3s, it will be much less challenging to fit a fuel cell in the available space.

2.2 Hydrogen Fuel Storage

There are many methods of hydrogen fuel storage; they include compressed hydrogen gas, liquefied hydrogen, metal hydride lattice storage, carbon nanotube storage, and extraction from a storage material via chemical reaction.

The simplest of these methods is compressed gas storage. Since hydrogen is less dense than air at standard temperature and pressure, a very large container would be necessary to hold a significant amount of fuel [5]. As such, hydrogen is stored in pressurized cylinders, allowing more hydrogen by mass to be stored in the same volume. While a relatively large tank (approximately 1 m high and 0.2 m in diameter) would be necessary to power a fuel cell for the desired amount of time, this is one feasible option for the T3 scrubber [6].

Following the same principle as compressed hydrogen gas, liquefied hydrogen is both compressed and cooled. This makes the hydrogen much denser, and therefore, allows more hydrogen to be stored in the same volume. Liquefied hydrogen needs to be stored at 20K [7]. The low temperature necessary to store hydrogen in liquid form makes it impractical for use as an onboard fuel source, as keeping the fuel source the proper temperature would require much more energy than powering the scrubber itself.

Some metal alloys can absorb and store hydrogen through chemical reaction; the metal hydride storage method takes advantage of this property. A hydrogen storage alloy is allowed to react with hydrogen to form metal hydride, facilitating the storage of large amounts of hydrogen in a small tank that need not be pressurized. The hydrogen can be released without compromising the structure of the alloy meaning it can be used repeatedly. A tank using one of these alloys will consist of only 1 to 2% hydrogen by weight when fully charged [7]. Even still, it is possible to store as much as eighteen times the fuel in a tank that is only slightly bulkier than the standard compressed gas tank discussed above. This storage capacity to tank volume relationship makes this a very feasible option for our application; however, it may be a challenge to find an appropriately dimensioned tank.

Other forms of hydrogen storage are still in the developmental stages and are not yet widely available. The process of nanotube storage shows a great deal of promise but is not commercially available at this time [7]. Hydrogen can also be "cracked" from fossil fuels such as coal or gasoline. GM is currently developing an onboard system for automobiles that extracts hydrogen from gasoline to power a fuel cell [8]. This system has been heralded as a method to help the auto industry convert to a hydrogen economy as an infrastructure capable of producing large quantities of more cleanly produced hydrogen is developed. However, this system's root dependence on fossil fuels makes it undesirable for our application.

2.3 Product Benchmarking

As fuel cell technology develops, those seeking to integrate them into existing products are presented with obstacles such as cost, manufacturing processes, fuel selection, and fuel storage. Car companies have been attempting to overcome these difficulties but thus far have been unsuccessful. Automobiles that run solely on fuel cell technology are currently enormously costly and fuel cells capable of powering an automobile are not commercially available. Recent developments, however, have allowed for practical application of fuel cells in smaller vehicles such as utility trucks and forklifts; these applications have characteristics similar to the T3 floor scrubber.

Table 2, on page 4, compares two currently available products to our targets for the T3. This comparison not only helps our team determine whether or not our targets for the T3 are feasible but also shows where a fuel cell powered floor scrubber would fit into the rapidly growing market of fuel cell powered products. For the comparison we chose a utility truck, made by the European company H2 Logic, and a forklift, made by a joint venture of several companies. The H2 Truck is intended to be used for applications such as luggage carriers at airports and mobile work stations for janitors. Its major features include harmless emissions, longer operating times than battery powered vehicles, and an innovative refueling station [9]. The previously mentioned forklift was developed to reduce the harmful emissions of propane powered forklifts and the inherent hazards associated with swapping and charging heavy battery packs [10]. Specification sheets for both of these products can be found in Appendices C and D respectively.

Design Criteria	T3 Scrubber Targets [1]	H2 Truck [9]	Hydrogenics HyPM™ Forklift [10][11]
Power Usage (kW)	0.9	1.2	10
Voltage (V)	24	24	39 to 58
Current (A)	30	-	350
Temp (°C)	< 120	-	65
Weight (kg)	177	450	-
Size (cm)	109x128x76	205x90x120	-
Commercially Available Fuel	Yes (99.99% pure gaseous hydrogen)	No (99.999% pure gaseous hydrogen)	Yes (99.99% pure gaseous hydrogen)
No Lead-Acid Batteries	Yes	Yes	Yes (no batteries)
No Hazardous Emissions	Exhaust is Water	Exhaust is Water	Exhaust is Water
Fuel Cell/Battery Runtime	Fuel Cell ≥ Battery	4hrs/2hrs	8 hrs/Less than Fuel Cell
Type of Fuel Cell	NEXA (PEM)	Hybrid PEM	Hydrogenics HyPM™ (PEM)
Easy to Operate	No Functional Changes	Drives like a Golf Cart	Same or Better than Battery Powered

Table 2: Product Benchmarking with Similar Fuel Cell Applications

3 CUSTOMER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

Since this project was initially started by a team in the ME 450 Winter '07 class, many of the customer specifications were already defined. During our first conference call with our contact at Tennant, Fred Hekman, we discussed and defined the additional customer specifications for the continuation of this project. We then combined the new customer requirements with those of the previous team into a QFD chart.

3.1 Customer Requirements

Our customer requirements are based upon the restrictions given to us by Tennant and the progress that the previous project team made. Tennant's overall purpose for this project is to further their goal of having environmentally friendly products. For the T3 scrubber this means eliminating potentially harmful lead-acid batteries. Since the company chose to replace the batteries with fuel cell technology, emissions must be considered; Tennant required that the system be free of all hazardous by-products because the T3 will primarily be operated indoors. Additionally, Tennant gave us requirements pertaining to the functionality and operation of the T3. Our team is to only modify the power source; all other components of the T3 should remain the same, with exception to minor changes to the casing if necessary. Also, our team is to ensure that the T3 is still safe, easy to operate, easy to maintain, and easy to refuel. Finally, the fuel cell that is to be integrated with the T3 is the NEXA unit created by Ballard. This constraint comes from the previous team's research on different types of fuel cells currently available on the market. Table 3 at the top of page 5 illustrates these requirements.

	Customer Requirement
Winter '07 Req	Commercially available hydrogen
	Easy to operate
	Does not overheat
	No hazardous by-products
	Comparable run time
	Easy to refuel
	Safe
	Easy to maintain
New Req	T3 functionality unchanged
	No lead acid batteries
	Uses NEXA fuel cell

Table 3: Customer Requirements in Order of Importance

3.2 Engineering Specifications

Our team developed appropriate engineering specifications based on the requirements from Tennant. Using values from the T3 product specifications we produced target values for the new power system (power, voltage, and current). The remaining target values were estimated based upon the optimal conditions for operating the T3. These specifications and target values are available in Table 4 below.

Engineering Specification	Target Value
Power Output	900 W
Voltage	24 V
Current	30 A
Operating Temperature	<120 °C
Operating Time	2 hr
Weight	177 kg
Size	1.06 m^3
Additional Parts	<10 parts

Table 4: Engineering Specifications and Corresponding Targets

3.3 QFD Chart

Combining our customer requirements, engineering specifications, and the benchmarking data from our information search, we put together a quality function deployment (QFD) chart, available in Appendix B. This chart helps us identify which engineering specifications have the most effect on our customer's satisfaction by rating the specifications according to their importance. Our analysis has shown us that we should be focusing our attention on minimizing additional parts, operating temperature, and physical dimensions to make a product that best suits Tennant's wishes. In addition, the QFD was used to compare the T3 to other indoor-operating fuel cell powered vehicles. Comparing our targets and customer requirements to similar products gave us a better idea of how our fuel cell-powered T3 will fit into this emerging industry. Our QFD showed that the T3 scrubber is an appropriate application for a fuel cell, as there are other commercial products that implement a fuel cell in a similar way.

4 CONCEPT GENERATION

In order to ensure our team selects the optimal method of implementing the NEXA fuel cell with the T3 scrubber, we utilized a variety of design techniques to qualitatively compare concepts. We created a FAST diagram to break the fuel cell implementation process into sub-functions, and then used a morphological chart to compare possible ways to perform these sub-functions. Each of these possible solutions to sub-functions is described in its appropriate section below. Using this analysis, we were able to generate multiple concepts and choose the best solution for our prototype as well as recommending an alternate solution which would be better suited for eventual mass-production.

4.1 FAST Diagram

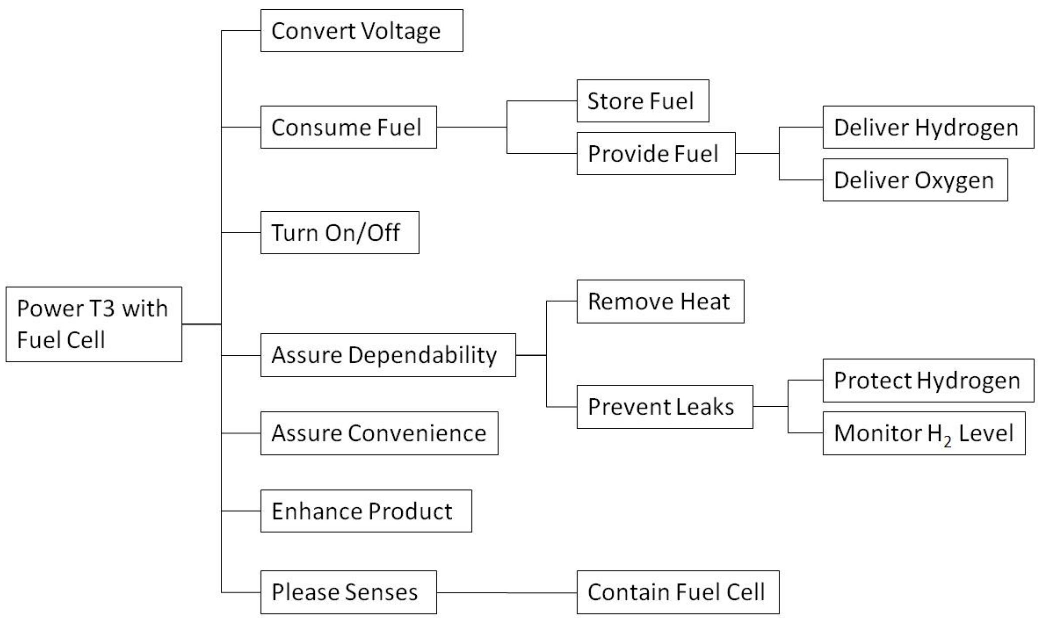

Figure 1: FAST Diagram

Our team produced a FAST diagram, Figure 1, above, in order to define the functions and sub-functions of our overall task. We were sure to define function, not form, so we did not discount any ideas or concepts prematurely. We used the functions from the FAST diagram to construct a morphological chart of the various options for implementing the sub-functions.

4.2 Morphological Chart

In order to easily compare the various options for implementing the sub-functions necessary to operate the fuel cell within the scrubber, a morphological chart was constructed. We took each sub-function and generated as many different possibilities as we could, laying them out next to each other so we could analyze them. The morphological chart proved to be an invaluable tool in generating our high-level concepts, as discussed in section 5. The details of each option considered for different sub-functions are listed in the appropriate subsections and organized in Table 5 on page 7.

Function	Option 1	Option 2	Option 3	Option 4
Convert Voltage	Commercial DC/DC converter	Hybrid fuel cell/battery system		
Store Fuel	Commercially available compressed gas tank (welding supplies)	Customized compressed gas tank	Metal hydride lattice storage	Solid H_2 storage
Deliver H_2	Compressed gas delivery system (pressure regulator)	Pressure regulator designed for metal hydride storage		
Deliver O_2	Free-flowing ducting system	Ducting with forced air system	Open to environment	
Remove Heat	Free-flowing ducting with heat shield	Ducting with heat shield and forced air system	Open to environment (no heat shield)	
Protect Hydrogen	Protective frame around container (esp. delivery system)	Store hydrogen off of scrubber	Store hydrogen inside the scrubber body	
Monitor H_2 Level	H_2 detector within fuel cell area	H_2 detector built into fuel cell		
Contain Fuel Cell	Adjust shroud upward to fit in the fuel cell	Extend shroud outward to fit in the fuel cell	Re-arrange fuel cell components	Exterior addition to scrubber to hold fuel cell

Table 5: Morphological Chart

4.2.1 Convert Voltage

In order to use the NEXA fuel cell to power the T3, its output voltage needs to be converted to a constant 24 volts. Our team came up with two options: using a commercially available DC/DC converter or creating our own hybrid fuel cell/battery system.

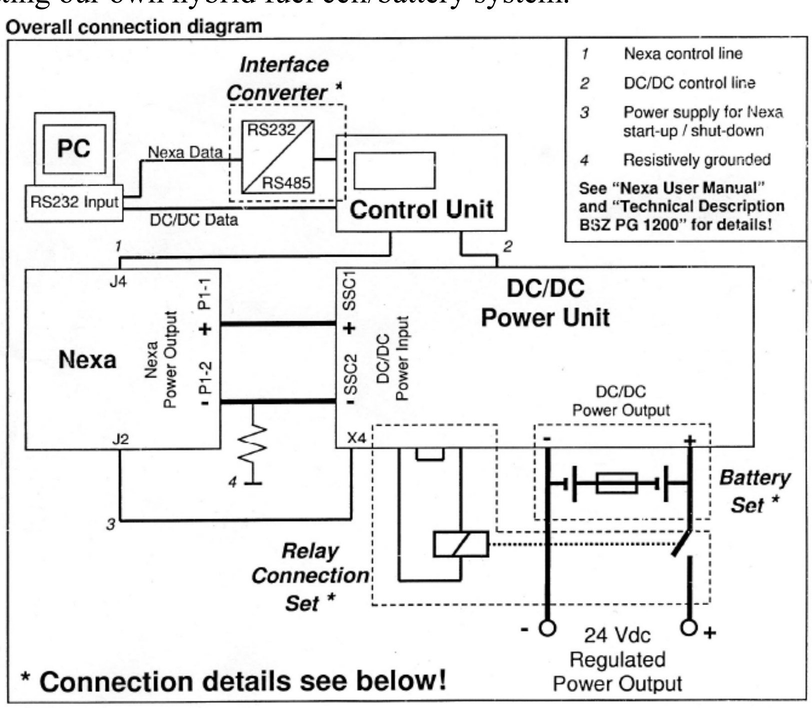

Figure 2: Heliocentris 24V DC/DC Converter Diagram

The commercially available DC/DC converter we would use is made by Heliocentris and is designed to be compatible with the NEXA fuel cell. This DC/DC converter works by using the NEXA to constantly recharge 24V of batteries. These batteries provide power to the consumer's application; in our situation this would be the T3. In addition to using the batteries as a buffer between the NEXA and the T3, this DC/DC converter provides additional control features that prevent the NEXA unit from over-charging the batteries. Please see Figure 2, on page 7, for a detailed schematic on how the DC/DC converter provides power at 24V to the T3.

4.2.1.1 DC/DC Converter Battery Considerations

As discussed above, in order to use the NEXA system to power the T3, some type of rechargeable battery must be used in conjunction with the DC-DC converter. We have generated multiple battery implementation concepts that take into account both customer requirements and the technical specifications of the scrubber itself.

To power the scrubber successfully DC power must be delivered at 24 Volts, therefore all battery concepts must be configured to have a total effective voltage of 24V. The most widely available and highest capacity batteries at the appropriate voltage are sealed lead acid batteries. However, as stated in the customer requirements, the elimination of lead acid batteries is a goal of this project. Recent advancements in rechargeable battery technology provide a few alternate technologies that could be used in place of the lead acid batteries.

Battery Chemistry	Positive Aspects	Negative Aspects
NiMH	• Available in increments of 6V • Available in higher capacities than Li+	• Most not designed for high current applications • Slow recharge time • Bulky at capacity and voltage necessary
Li+	• Smaller and lighter than NiMH for a given capacity • Designed for high current applications • Longer recharge cycle lifetime than NiMH	• Only available in 3.7 V increments • More expensive than comparable NiMH • High current drain produces heat

Table 6: Battery Technology Comparison

In generating different battery design concepts we varied the chemical technology, voltage, and number of the batteries to try to find the most favorable combination of capacity, size, and cost that meet the required voltage while not utilizing lead-acid batteries. The two main chemical technologies considered were nickel metal hydride (NiMH) and lithium ion (Li+). Single 24 V batteries as well as combinations of two 12 V or four 6 V batteries were considered. The strengths and weaknesses of each concept are discussed in Table 6, above.

When the battery voltage drops below a certain level, the DC-DC converter turns the fuel cell on, charges the batteries, and then turns the fuel cell off. In order to assure uninterrupted scrubber operation, the selected battery technology, at a bare minimum, must be capable of powering fuel cell startup and shutdown while simultaneously powering the scrubber for the combined time of these startup and shutdown operations, which means they must last 70 seconds. The batteries must not run down before the fuel cell can begin recharging the batteries after first shutting down and subsequently restarting. This requires a battery capacity of at least 0.7 Ah when 30 A are being drawn.

A larger than necessary battery capacity would limit the frequency with which the fuel cell would need to be turned on and off as well as the battery recharge cycles. Larger battery capacity is desirable to reduce wear and tear on the batteries and fuel cell. However, the trade-off is that higher capacity batteries tend to be larger and more expensive, and given the limited space inside the scrubber, battery size is an important concern.

4.2.1.2 Required Battery Specifications

Given the nature of our battery and DC-DC converter system, our battery will be simultaneously charged and discharged. Ideally, this would be a steady-state process, with the batteries charging and discharging at the same rate. More realistically, given the specifications of the fuel cell and the power requirements of the scrubber, the fuel cell will provide more power to the battery than the scrubber requires. It is acceptable if the battery charges faster than it discharges, since when the battery is fully charged the fuel cell could be temporarily shut off without interrupting scrubber operation.

Engineering Specification	Target	NiMH	Li-Poly Battery
Technology	Not lead-acid	Met	Met
Charge Rate	30 A	Not Met	Not met
Capacity	Minimum 0.70 Ah @ 30 A (46 C)	Not Met (cannot provide 30A)	Met
Operating Voltage	21-24.5 V	Met	Met
Size	Less than 1.3×10^6 mm^3	Met	Met

Table 7: Battery Concepts Compared with Engineering Target Values

An acceptable battery solution will need to be able to supply a steady 30 A to the scrubber while simultaneously charging with slightly more than 30 A of current. Our research did not find any single battery which is capable of meeting the battery specifications listed in Table 7, above. Existing lead-acid batteries meet the performance characteristics needed, but fails to meet our customer requirements. Typical nickel-cadmium and nickel-metal-hydride batteries are not designed for high current applications and do not meet the charge or discharge requirements. Lithium polymer batteries designed for high current applications seem to show the most promise, as there are commercially available batteries that meet all characteristics except for the required charge rate. One viable solution could be to connect several lithium polymer batteries in parallel and charge them all simultaneously such that their total charge rate sums to 30A. The most promising lithium polymer battery has a charge rate of 5A; to obtain a 30A charge rate, we would need six of these batteries. However, cost and space within the scrubber are both prohibitive factors with this solution.

4.2.2 Store Fuel

Our information search yielded many different methods of storing hydrogen fuel, and from these we selected the three most appropriate for our application. These methods of hydrogen storage were a standard compressed gas tank, a customized high-pressure gas tank, and metal hydride lattice storage.

There are many reasons why compressed gaseous hydrogen storage would be a feasible option for use with the NEXA fuel cell. Since it is such a well established and readily available form of storage, there are many commercial retailers which could provide us with a standard tank and the hydrogen necessary. The use of a standard compressed gas tank is very cost efficient, and would not be excessively heavy for use on the T3 scrubber. This compressed gas tank would also be a good method of storing the hydrogen because at room temperature the tank would be able to deliver the appropriate amount of hydrogen flow at the correct pressure for the NEXA system. These compressed gas tanks could be swapped out with each other, and this would greatly reduce refueling time; refilling the tanks themselves is also a quick process, taking much less time than charging the T3's current battery system.

The use of compressed gaseous hydrogen presents some safety concerns as well as having some drawbacks. Hydrogen gas is extremely flammable and precautions need to be taken to ensure safety of the user; T3 operators would need to be trained on the basic dangers of compressed gas and hydrogen. Compressed hydrogen in a standard tank has the lowest amount of hydrogen per unit volume of the storage methods so a larger tank is required for equivalent runtimes. To achieve the desired 4 hour run time, the tank would need to be pressurized to approximately 15 MPa; while tanks are available to withstand this pressure, care must be taken to protect the tank and the hydrogen delivery system. A tank of this nature would weigh approximately 7-10kg, making it a reasonable option for T3 onboard storage.

Another alternative to using a standard compressed gas cylinder is using a custom-built high-pressure hydrogen tank. This has the benefit of using readily-available gaseous hydrogen and while fitting more hydrogen per unit volume (up to 30 kg/m^3), but has the drawback of using a high-pressure tank. This custom-built high-pressure tank would utilize techniques such as carbon fiber wrapping to achieve pressures as high as 80 MPa, a pressure much higher than a standard tank could withstand. Any gas stored at this pressure requires tanks with not only thicker walls but stronger materials to contain it; this leads to a higher tank weight of 110kg [14]. As mentioned previously, this allows for more hydrogen per unit volume of storage, however, this high-pressure tank is even more dangerous than a standard cylinder. Great precautions and care would need to be taken when handling the tank and its pressure fitting system, and the tank would need to be very well protected. The cost of a custom-designed tank is also prohibiting, as we would need to have it fabricated for us.

The third method of hydrogen storage is metal hydride lattice storage. The details of this storage mechanism are described in section 2.2, above. In order to prevent the buildup of contaminants in the metal hydride lattice, 99.99% pure hydrogen fuel is necessary; this is the fuel purity the NEXA requires for operation, so this purity of hydrogen is appropriate. Since any impurities that enter the hydride lattice are essentially trapped in there, the tank's capacity would slowly decrease over its lifetime. The benefit of metal hydride lattice storage is that it is capable of storing much more hydrogen per unit volume (150 m^3/kg) than compressed gas, and it is stored at atmospheric pressure [15]. This removes much of the danger associated with hydrogen delivery. While care must still be taken with the tank, if it were to rupture it would not be as catastrophic as with compressed gas.

Despite its advantages, metal hydride lattices are not widely commercially available at this time. The technology is still in development, and largely in the test phase. The tanks themselves are also extremely heavy; an appropriate capacity tank would be approximately 100 kg. There is also no established infrastructure for recharging metal hydride lattices, and the cost of purchasing a one-of-a-kind tank for our uses would be extremely prohibiting. Metal hydride lattice tanks also require complicated thermal regulation and flow control to successfully deliver hydrogen fuel, and we would need to purchase this system in order to implement one of these tanks.

4.2.3 Deliver Hydrogen

After choosing a method of storing hydrogen fuel, we need to develop a system for delivering the hydrogen to the fuel cell. The system we use must ensure hydrogen does not escape during delivery, as hydrogen is a flammable gas; Tennant wishes the T3 to be operable indoors, and in order to satisfy our customer requirements we must eliminate hazardous by-products. Since hydrogen is flammable, it would be extremely hazardous for the fuel supply to ignite; our team must implement a safety mechanism against fuel supply combustion.

In addition to meeting these two safety requirements, the hydrogen delivery system must conform to the fuel intake specifications for the NEXA fuel cell. The NEXA accepts dry, gaseous hydrogen between pressures of 70 to 1720 kPa, and contains a safety pressure relief valve set to 2400 kPa. Care must be taken to not exceed this pressure and release hydrogen gas into the T3's operating environment. The gaseous hydrogen must be between 5 to 80 °C, so if the fuel source is changing pressure the resultant change in temperature must be considered. Under maximum load, the NEXA requires 18.5 slpm of hydrogen; our hydrogen delivery system must be capable of achieving this flow rate.

4.2.4 Deliver Oxygen and Remove Heat

In order to successfully operate the fuel cell within the scrubber, we need to consider its air flow requirements. Intake air into the fuel cell serves two purposes: providing oxygen for the electricity-generating reaction and cooling the fuel cell itself. Both of these incoming air streams must also exit the scrubber, and we must address exhaust concerns as well. Each of these needs were considered, and we have generated possible concepts to address these requirements.

The NEXA fuel cell system requires oxygen-rich air to react with the hydrogen and generate electricity. This air enters the fuel cell through an inlet on the top of the fuel cell. From here, the air goes through the fuel cell stack, reacts with the hydrogen fuel, and is exhausted out of the fuel cell. Since the air goes directly through the fuel cell stack, intake air needs to be cool, fresh air at atmospheric pressure. Intake air also needs to be free of contaminates, however, the NEXA fuel cell system has a built-in air filter to remove particles down to 10 microns. The NEXA manual recommends that the air intake system be easy to disconnect, as the air filter will need periodic maintenance. The oxygen-hydrogen reaction within the fuel cell produces water as a by-product, and this water will be present in this exhaust air stream as either a vapor or a liquid. A 16 mm OD tube stub allows for connection of an exhaust hose. Operating at maximum power, the NEXA system requires 90 slpm of intake reaction air.

The NEXA fuel cell system also requires air for cooling purposes. The NEXA has a built-in fan which directs air from the bottom of the fuel cell stack to the top, maintaining its temperature at 65° C. The NEXA manual also recommends that this incoming air be separated from the exhaust air streams to prevent recirculation of hot air which could potentially cause overheating and ultimately a safety shutdown. Operating at maximum power, the cooling air intake system requires 3600 slpm.

After the intake reaction air and coolant air circulate through the fuel cell, they must be exhausted from the scrubber's body. The intake reaction air exhausts through a 16 mm OD tube stub, as mentioned above. Care must be taken with this exhaust stream, as it will contain both water vapor and liquid water. The cooling air exhausts through the top of the fuel cell stack itself, and should not have any concerning by-products present.

A number of different methods of directing air into the scrubber's body itself were considered during concept evaluation. The top three methods considered were an opening in the side of the scrubber's body, drilled holes in the side of the scrubber, and a metal grating with the majority of its area available for airflow. The positive and negative aspects of each of these possibilities are summarized in Table 8, below.

Air Direction Method	Positive Aspects	Negative Aspects
Open to outside	• Simple • Maximum air flow • Allows for maximum heat transfer	• Unattractive • Foreign objects could enter intake system
Holes in side of body	• Prevents foreign objects from entering • More attractive than open to outside	• Minimum air flow • Restricts heat transfer
Grating on side of body	• Most attractive • More air flow and heat transfer than holes in side	• Grating may be hot if metal • Small foreign objects could enter intake system

Table 8: Air Direction Method Comparison

Once air is inside the scrubber, it needs to be directed to the appropriate places. We considered multiple methods of directing airflow, and given the necessary flow velocity, a ducting system will need to be employed. Direct air intake with no ducting was considered, but was determined infeasible because of the NEXA's requirements for cool, fresh air for proper operation. Between the reaction air intake and cooling air intake, 3700 slpm of ambient air is necessary. The intake air needs to be divided, with approximately 100 slpm going to reaction intake and the rest being used for cooling. Our project is not yet at the stage where we would determine the exact method of achieving this necessary flow velocity, but this basic analysis has raised the issue and it will soon be determined.

4.2.5 Protect Hydrogen

Once the type of hydrogen storage is chosen, special care must be taken in order to ensure the storage mechanism's safety in both operating and storage conditions. The two methods of protecting the hydrogen source are storing it inside the scrubber's body itself, or fabricating a frame around the hydrogen tank and attaching it to the exterior of the scrubber.

Due to space restrictions, we concluded that an appropriate hydrogen storage vessel for our use would not fit within the scrubber body unless a significant extension to the scrubber body was made. Since we already need to increase the available space within to the scrubber to fit the NEXA fuel cell and its subcomponents, this option may not be realistic.

A fabricated frame which protects the hydrogen source would allow for easy tank swapping and refueling while still providing the protection we require. As long as the hydrogen delivery system is also protected by this frame, we minimize the risk of a catastrophic failure even if the scrubber were to tip.

4.2.6 Monitor Hydrogen Level

The use of hydrogen fuel presents a number of safety concerns, especially since our fuel cell will be operating indoors. Hydrogen is extremely flammable, as well as being odorless and tasteless. Since the operator of the T3 would not be aware of unsafe hydrogen levels, we have determined it is necessary to monitor the hydrogen level and have safety mechanisms to prevent against possible dangerous operating conditions.

One option considered is a custom built hydrogen detection system. This system would incorporate a hydrogen level detector and a safety shutoff for the fuel cell. This safety shutoff system could be wired to send the NEXA a shutdown signal when hydrogen levels are unsafe, and it could warn the user when hydrogen levels are increasing. In order to do this, we would need to purchase a hydrogen detector to place in the T3 housing as well as design a control circuit to operate the warning and shutdown system. A custom built hydrogen detection system would have the benefits of allowing us to define the safe hydrogen levels and allow us to decide where to measure the hydrogen level, but has the drawback of being expensive and not as reliably built as the NEXA's integrated hydrogen detection system.

As mentioned above, the NEXA contains an integrated hydrogen detection system. The NEXA's hydrogen detector is placed in the reaction exhaust stream and contains both a warning signal and a forced shutoff at 8,000 ppm and 10,000 ppm of hydrogen, respectively. This reaction exhaust stream is also the location where the pressure relief valve releases hydrogen to, so if excessive pressure were to occur in the H_2 intake stream it would be immediately detected. The only concern with using the NEXA's integrated hydrogen detector is the possibility of hydrogen leak in the intake system going undetected; if a leak of this nature were to occur, the hydrogen would be used as cooling intake air and would be eventually detected.

Given our time and budget constraints, we determined it best to use the NEXA's integrated hydrogen leak detector. It is the simplest, most reliable way to detect excessive hydrogen and with other precautions taken with our hydrogen delivery system will lead to safe operating conditions.

4.2.7 Contain Fuel Cell

In order to keep the fuel cell operational, maintain a safe operating environment, and make our scrubber aesthetically pleasing, the fuel cell needs to be contained. Functionally, this will allow us to control the operating conditions of the fuel cell, allowing us to dictate temperature, fuel intake, where the exhaust goes, as well as separating the fuel cell from potential spark sources. Visually, the T3 will look more like it was designed to operate on a fuel cell if it is contained rather than exposed.

Fuel Cell Integration Method	Positive Aspects	Negative Aspects
Adjust shroud upward to fit fuel cell height	• Allows fuel cell to remain in factory configuration • Will not significantly alter scrubber functionality or visual appeal	• Could affect prototype scrubber stability
Extend shroud outward to fit fuel cell height	• Scrubber is more stable	• Unsightly shroud extension
Modify interior cavity to fit fuel cell length	• Allows fuel cell to remain in factory configuration • Will not alter exterior scrubber appearance	• Would reduce scrubber tank volume slightly
Re-arrange fuel cell components	• Could allow fuel cell as well as necessary batteries and voltage converter to fit in scrubber without modification	• Difficult to reconfigure fuel cell in a way that maintains safe operating conditions
Exterior addition to scrubber to hold fuel cell	• Simple • Allows for customized container geometry and composition	• Wasted space inside the scrubber • Decreases visual appeal

Table 9: Fuel Cell Integration Method Comparison

While volumetrically comparable to the lead acid batteries it will replace, the dimensions of the NEXA make it challenging to orient within the scrubber. The fuel cell is too long and too tall for the current cavity although there is ample room in the width dimension. This width could be utilized to house the batteries the DC-DC converter requires. This problem has, in simplified terms, three basic solutions: we can make the fuel cell smaller, make the cavity in the scrubber larger, or simply not put the fuel cell in the scrubber cavity at all. While we cannot actually make the fuel cell smaller, we can reconfigure the fuel cell components so that the whole assembly is shorter in length and height, but wider thereby making it fit within the scrubber cavity. It would be simple to make the shroud containing the scrubber cavity taller without changing the overall scrubber footprint; we could widen the shroud, but this would yield an unsightly protrusion at one side of the scrubber. However, it is worth noting that the cavity is not of uniform length along its height. In fact, the length of the fuel cell can be accommodated by removing more material from inside the cavity without having to add to the length of the shroud housing this cavity. We could also create a container for the fuel cell and attach that container to the exterior of the scrubber. The positive and negative aspects of each of these concepts are compiled in Table 9, above.

4.3 Possible Concepts

After reviewing our morphological chart and the requirements of the NEXA system, our team developed eight possible concepts for integrating the NEXA fuel cell into a T3 scrubber. Since we are limited by a budget and time constraints we placed our high-level concepts into two categories. These categories are concepts for a prototype and concepts for production. An example of each type is given below, while descriptions and sketches of the other six are available in Appendix F and G respectively.

4.3.1 Prototype Concepts

For our prototype, the concept we choose must be something we can fabricate/purchase all components and successfully install them on the T3 scrubber. This means that expensive, emerging technologies such as metal hydride lattice storage will not be effective since we are only building one prototype and the cost of a single custom-designed component would be astronomical. An example of a good concept for our prototype is concept A, as all of its components are either commercially available or can be fabricated by our engineering team.

4.3.2 Production Concepts

For eventual mass-production of a T3 scrubber with a fuel cell, our constraints on what technology we can use are a little more relaxed. Since Tennant would be building many of these scrubbers, it is possible to get custom-designed components such as a high-pressure hydrogen tank at a much lower price per unit than we could if we only purchased one. Tennant could also redesign the scrubber's body itself in order to accommodate the new components, leading to a more aesthetically pleasing scrubber than our prototype. An example of a good concept for production would be concept D. This concept features metal hydride lattice storage, which would be extremely expensive for our prototype but could be feasible in a production situation. It also extends the scrubber's body outwards rather than upwards, something Tennant could design and manufacture themselves with their rotational molding facilities. This customized body would be a poor choice for our prototype as we could not fabricate an entire new scrubber housing, but is appropriate for mass-production.

5 CONCEPT EVALUATION AND SELECTION

After diverging and generating as many concepts as possible, we needed a method to select the best one for our prototype. Below, we outline the process we used for this selection. We discarded designs which were infeasible or impractical given our time and budget constraints, and selected the 5 concepts most likely to be successful. These were then compared using a Pugh analysis and the optimal prototype concept was selected.

5.1.1 Top 5 Concepts

We distilled the concepts listed in Appendix F down to the top 5 which are most feasible. To narrow down our choices, we considered cost of each prototype, time it would take to design necessary subsystems, commercial availability of parts, safety of each prototype, and how well they satisfied customer requirements. Based on these criteria, our top 5 concepts for a prototype are concepts A, B, C, D, and G.

We chose concept A as one of our top 5 because the fuel storage system is readily commercially available, it is simplest to adjust the shroud upward, and the protective frame around the hydrogen source will ensure safety of operation. One of concept A's limitations is that by adjusting the shroud upwards, we are making the T3 scrubber less stable than it originally was and it raises concerns of stability during operation. Another of concept A's limitations is that the protective frame around the hydrogen source is not aesthetically pleasing, something Tennant does not wish to happen.

Concept B is similar to concept A in that the majority of its parts are commercially available. One area where it differs is in its hydrogen fuel storage mechanism. Concept B has a custom-fabricated high-pressure hydrogen tank. Essentially, by storing the hydrogen at a higher pressure, we are able to store more fuel for the scrubber in a smaller volume, leading to longer run times. A serious limitation of this concept is our ability to fabricate this pressure vessel; it would need to be custom-made and would be extremely expensive. It also raises safety concerns with using an unproven tank design compared to welding cylinders which have been in use for years. Concept B adjusts the scrubber's shroud outward to accommodate the extra components. This would lead to a more stable floor scrubber, but increases the size of the footprint and makes it more difficult to maneuver in tight spaces.

Concept C features metal hydride lattice storage rather than a compressed hydrogen tank. As discussed in section 4.2.2, on page 9, this promising technology is able to contain much more hydrogen per unit volume than a compressed gas tank. However, the metal hydride containers are very heavy, and this weight will affect the way the scrubber operates. Another limitation of metal hydride lattice storage is their commercial availability; they are not yet widely commercially available, and there is limited infrastructure to support recharging them. Concept C also adjusts the shroud upward rather than outward; as stated in the description of concept A, this would make the scrubber less stable than it originally was. The positive aspect of adjusting the shroud upward is keeping its original footprint, not hampering the operator's ability to fit in tight spaces.

Concept D is a combination of concept C and concept B, featuring metal hydride lattice storage with the additional components for the fuel cell encapsulated by moving the scrubber shroud outwards. As with concept B, this increases the scrubber's footprint while increasing stability.

Concept G is essentially the same as concept A with the exception of moving the shroud outwards instead of upwards to accommodate the additional parts. If we selected concept G, our prototype would be more stable but it would come at the cost of footprint size. Again, the loss in maneuverability needs to be considered against the additional stability.

5.1.2 Pugh Analysis

In order to qualitatively compare our top 5 concepts, we performed a Pugh analysis. The Pugh analysis gave us a numerical correlation between the design specifications, their weight with the customer, and the attributes of each concept.

	Customer Requirement	Weight	Concept A	Concept B	Concept C	Concept D	Concept G
Winter '07 Req	Commercially available hydrogen	8	S	-	-	-	S
	Does not overheat	1	S	S	S	S	S
	No hazardous by-products	10	S	S	S	S	S
	Comparable run time	7	S	+	-	-	S
	Easy to refuel	4	S	-	-	-	S
	Safe	3	S	S	+	+	S
	Easy to maintain	11	S	-	+	+	S
	Easy to operate	2	S	-	S	-	-
New Req	Uses NEXA fuel cell	6	S	S	S	S	S
	No lead acid batteries	5	S	S	S	S	S
	T3 functionality unchanged	9	S	-	S	-	-
		Total +	0	1	2	2	0
		Total -	0	-5	-3	-5	-2
		Total	0	-4	-1	-3	-2
		Weighted Total	0	-27	-5	-16	-11

Table 10: Pugh Analysis of Top Concepts

6 SELECTED CONCEPT

As the Pugh chart above indicates, concept A is our best concept for the prototype. Concept A has the following features: a commercial DC/DC converter to convert the fuel cell's voltage, a standard compressed gas tank to store the hydrogen fuel, a pressure regulator designed to work with standard compressed gas tanks to regulate hydrogen delivery, a ducting system with forced air and a heat shield to both bring in fresh oxygen and provide cooling air to the fuel cell, and a protective frame to protect the hydrogen supply. The hydrogen level will be monitored by the NEXA's built in hydrogen detector, and the T3 scrubber's shroud will be adjusted upwards to accommodate the new components.

Figure 3, on page 18, shows the components that will be used for our prototype installed on a T3 scrubber. The drawing shows the hydrogen gas tank with its protective cage as well as the pressure regulation system. By using the box-shaped frame depicted here, we allow for easy access to the hydrogen tank from the side while providing protection in case a scrubber was to tip. This allows us to satisfy Tennant's wishes for refueling to be quick and easy while not compromising the safety of operation. Also depicted is a riser which will raise the top tank of the scrubber vertically upwards by approximately 12 cm. This addition allows us to successfully package both the NEXA fuel cell itself as well as the DC-DC converter within the scrubber housing, while providing room for ducting to be installed. Shown on the side of concept A is a metal grating for the ducting system. This metal grate will prevent foreign objects from entering the intake while still allowing an appropriate amount of air flow and heat transfer for fuel cell operation.

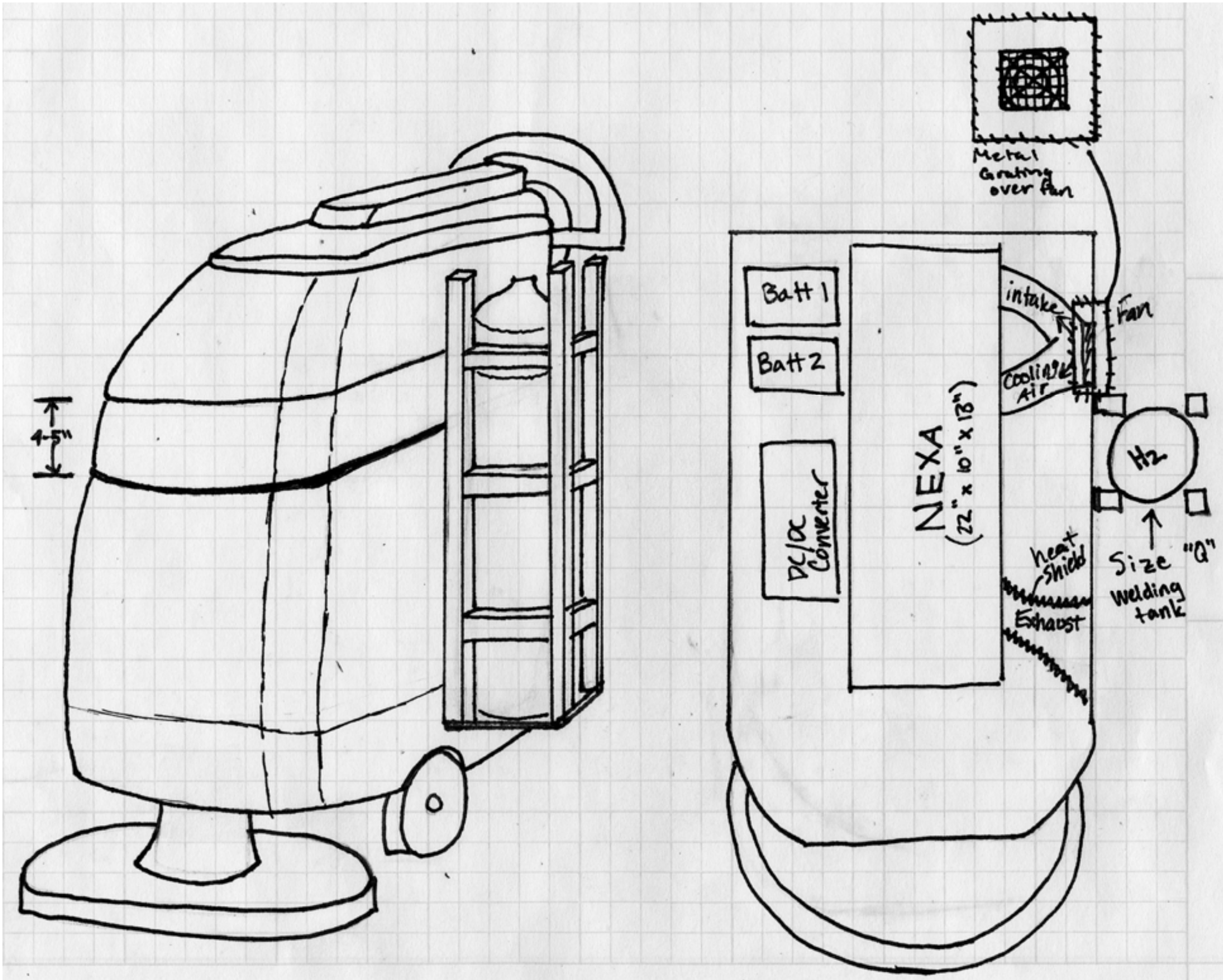

Figure 3: Selected Concept A, with Known Dimensions

At this point in our project, we have selected the best way to perform each sub-function required for operation of the fuel cell but have not yet detailed all of these sub-functions. This is due to the fact that we must operate the fuel cell on a lab bench before implementing it with the T3. Design of the particulars of these sub-functions will occur simultaneously with lab testing of the fuel cell. For instance, we now know that a ducting system with forced air is necessary due to the fuel cell's air flow requirements. The selection of a ducting material as well as calculation of the necessary air velocity and duct diameter is yet to be performed, since even if this were done at this time we would not yet be ready to fabricate and install the system.

While we know we will be using the Heliocentris DC-DC converter, we have not yet purchased the batteries it requires for operation. As mentioned above, we have found a Li+ battery which could be appropriate for our application, but we require sponsor approval before purchasing due to the price.

A size Q welding gas tank has been ordered, as well as the hydrogen, appropriate pressure regulator and safety mechanisms for hydrogen delivery.

7 ENGINEERING ANALYSIS

In order to create a successful prototype, we employed various engineering analysis techniques. We used stress and heat transfer analysis to ensure that our prototype would operate without causing damage to itself. We also analyzed our hydrogen system to calculate our prototype's expected run time.

7.1 Component Engineering Analysis Descriptions

7.1.1 Riser

During the design process for the riser we determined that there were two critical dimensions, the height of the riser and the thickness of the top and bottom plates. In order to determine the necessary height of the riser, meaning there is no concern of contact with the NEXA, we used CAD to place the NEXA appropriately and measured the height, 10 inches. Since the most likely way for the riser to fail is from stress due to bending between two of the upright supports, we performed the following beam bending analysis for the longest distance between uprights.

First of all we needed to determine the force per unit length applied to the upper plate. We know that the recovery tank holds V=0.04 m^3 of liquid and that the tank itself has a mass of m=18.144 kg. Additionally, the length around the contour of the top plate was measured to be L=2.34 m.

$$\frac{V\rho_{H_2O} + mg}{L} = 244\,\tfrac{N}{m} \qquad \text{Eq. (1)}$$

Next we used this force distribution in the following beam bending analysis and found the minimum thickness of the "beam" between two supports to be 2y = 1.40 mm. From the "Mechanical Engineers' Handbook" we know that the yield strength of 6061 T6 aluminum is 275 MPa [17]. Therefore, we concluded that for our design sheet metal 1/8 inch thick top and bottom plates would be sufficient to hold the weight of the recovery tank and also be easy to acquire for manufacturing purposes.

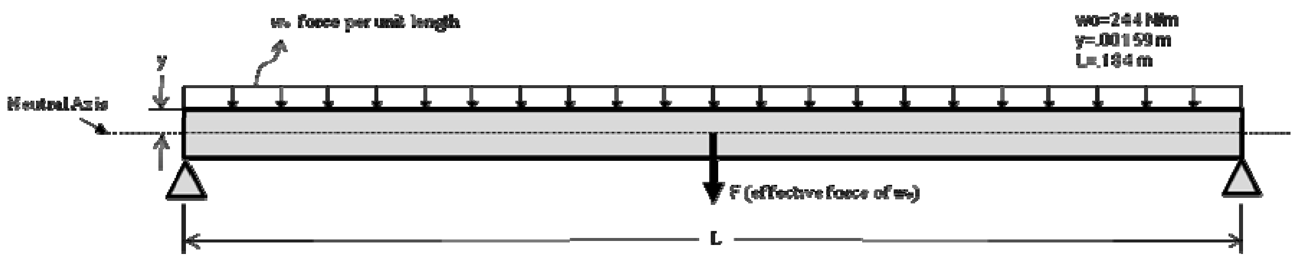

Figure 4: Beam bending Analysis for Riser

$$-\frac{\sigma}{L} = \frac{M}{I} = \frac{E}{R} \quad \text{Beam Bending Equation} \qquad \text{Eq. (2)}$$

$$y = \sqrt{\frac{3w_oL}{\sigma_y}} \qquad \text{Eq. (3)}$$

7.1.2 Hydrogen Storage

When operating at maximum power, the NEXA fuel cell unit requires 18.5 slpm of hydrogen fuel from a suitable hydrogen source. Our method of hydrogen storage must be capable of achieving these flow rates while also storing enough hydrogen to achieve the desired run time. In order to determine the necessary amount of fuel to run 2 hours we performed a volumetric flow analysis.

From the NEXA manual we learned that at maximum power the NEXA draws 18.5 slpm of fuel. Since the NEXA does not run at maximum power all the time, we reduced the fuel intake to 10 slpm, a value that we felt better represented our application of the fuel cell. Using this information, we calculated the necessary amount of fuel to power the scrubber for 2 hours, equation 4 below.

$$120\,\text{min} \cdot \frac{10\,\text{liters}}{\text{min}} \cdot \frac{\text{ft}^3}{28.3\,\text{liters}} = 42\,\text{ft}^3 \qquad \text{Eq. (4)}$$

In selecting a hydrogen tank, we wanted to minimize the increase in the scrubber's footprint while storing at least the amount of fuel we determined was necessary to run for 2 hours. This led to selection of a size "Q" pressure tank, provided by Cryogenic Gases, Inc., which is capable of storing approximately 2.27 m^3 (80 ft^3) of 99.99% pure gaseous hydrogen at a pressure of 13.8 MPa (2000 psi). This tank measures 609.6 mm (24") in height and 177.8 mm (7") in diameter and these relatively small dimensions make it ideal for our project. When mounted on the T3 scrubber, the tank and its protective frame are short enough to not interfere with the opening of the scrubber's recovery tank. The diameter is also small enough so that the tank does not interfere with the cleaning path of the scrubber; this is further explained in 7.1.3, the hydrogen protection section of this report.

7.1.3 Hydrogen Protection

When storing a pressurized hydrogen source onboard the T3 floor scrubber, we must consider the dangers associated and how we will protect the tank from these damages. We must accommodate a tank 177.8 mm (7") in diameter and 609.6 mm (24") in height that weighs 60 lbs. The protective frame for this tank will measure 240 mm by 220 mm by 700 mm (9.5" by 8.75" by 27") to completely enclose the tank. The pressure regulator extends above the top of the frame; it will not be enclosed by the frame to allow the gauges to be oriented for easy user viewing.

From our design we determined that the weakest point of the frame would be where the bracket was attached to the base plate. We wanted to make sure that our material choice could withstand the concentrated stress on each of the bolts at this point. To determine the stress applied at each bolt head we first needed to determine the force transmitted through each bolt. We did this using a conservative moment analysis (assuming that the caster did not support any of the load) in Figure 6, on page 21. Here F_p is the force applied by the frame's support post, F_t is the force applied by the hydrogen tank, F_w is the weight of the base plate, and F_b is the force that will be distributed across the four bolts.

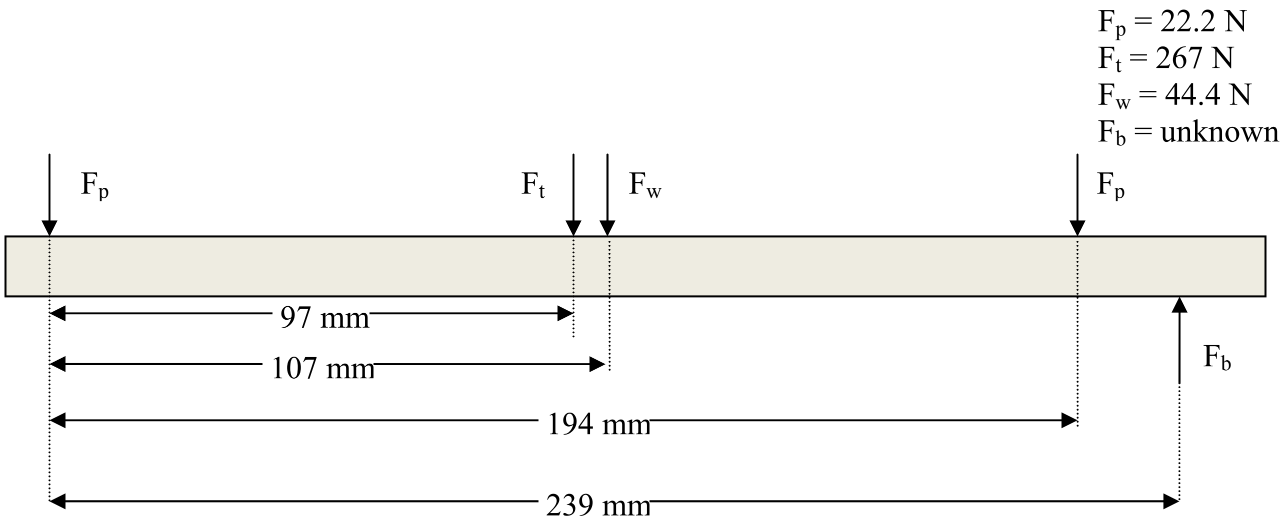

Figure 5: Moment Analysis for Force Distributed over Bolts

$$\sum M_o = 0 = (267 \cdot 97) + (44.4 \cdot 107) + (22.2 \cdot 194) - (F_b \cdot 239) \qquad \text{Eq. (5)}$$

Solving for F_b,

$$F_b = 146\ \text{N}$$

After calculating the force distributed over the bolts (F_b = 146 N) we then found the stress at each bolt head using Equation XX below, where A_b is the area of contact between the base plate and a bolt head. Since the stress at each bolt is so low (σ_b = 0.56 MPa) we decided to choose a material that provided a significant safety factor, could be welded, was lightweight, and was easily obtained. This led us to the choice of 6063 aluminum which has a yield strength of 215 MPa [17]. Additionally, this aluminum is readily available as sheet and bar stock, and is easily welded. 6063 aluminum also has a density of 2700 kg/m^3, and using this alloy allows us to keep the frame's weight to a minimum.

$$\sigma_b = \frac{F_b}{4 \cdot A_b} = \cdot \frac{146}{4 \cdot 6.53 \cdot 10^{-5}} = 0.56\ \text{MPa} \qquad \text{Eq. (6)}$$

We also needed to calculate the load that will be supported by the caster. Assuming the caster will support the entirety of the frame and hydrogen tank's weight, our caster must support 80 lbs. Our sponsor provided us with the casters used on the T3 itself; these casters are designed to carry 250 lbs, so we found these to be acceptable. This allows for a safety factor of 3 against caster failure by loading.

7.1.4 Ducting System

In the process of generating electricity from hydrogen, the NEXA fuel cell generates heat and in order to prevent damage to the scrubber's body we must account for this heat. The engineering team who previously worked on this project performed an extensive heat transfer analysis of the NEXA fuel cell system [16]. They modeled the NEXA as a rectangular prism and assumed the ends were ideally insulated, as shown in Figure 6, below. The remaining heat is distributed between the exhaust exit on the top of the fuel cell and its three sides.

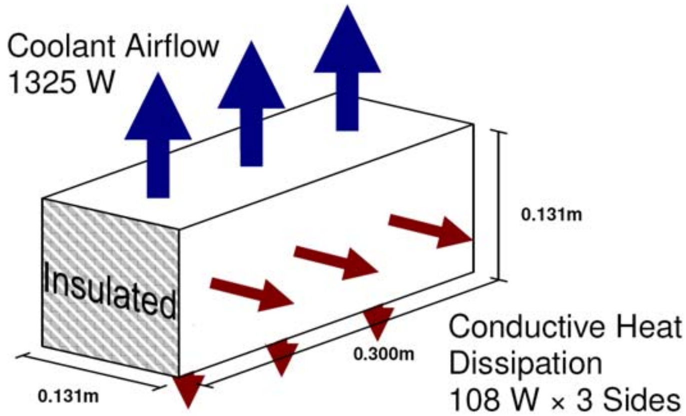

Figure 6: Thermal Model for NEXA Fuel Cell [16]

According to the NEXA manual, at peak power, the NEXA will generate 1650W of heat. In order to calculate the amount of heat which flows through the top of the fuel cell, a mass transfer analysis was performed. Equations 8 and 9, below, show how the 3600 cfm of airflow generated by the NEXA's cooling fan lead to a heat transfer rate of 1325W of heat transfer from the fuel cell's top surface. This leaves 325W to be distributed between the front, back, and bottom surfaces of the NEXA; assuming that each surface distributes an equal amount of heat due to their approximately equal areas, this leads to 108W coming from each of these faces.

$$\dot{m} = \rho\dot{\forall} = 1.293\,\tfrac{kg}{m^3}\cdot 0.06\,\tfrac{m^3}{s} = 0.0776\,\tfrac{kg}{s} \qquad \text{Eq. (8)}$$

$$q_{top} = \dot{m}c_p\Delta T = 0.0776\,\tfrac{kg}{s}\cdot 1.005\,\tfrac{kJ}{kg\cdot K}\cdot 17K = 1325W \qquad \text{Eq. (9)}$$

In the equations above, $\dot{m}$ represents the mass flow rate, ρ is the density of air, $\dot{\forall}$ is the volumetric flow rate, q_{top} is the heat flux from the top surface of the fuel cell, C_p is the specific heat of air, and ΔT is the difference in temperature between the exhaust stream inlet and outlet temperature. The volumetric flow rate and temperature difference between the inlet and outlet of the NEXA's cooling system were found in the NEXA manual to be 3600 cfm and 17°C, respectively; these were converted for our application.

Our ducting system takes the 1325W of heat coming from the top of the fuel cell and directs it outside of the scrubber body. The remaining 325W will heat the interior of the scrubber body, but since the NEXA's cooling fan draws directly from the inside cavity of the scrubber this heat will eventually be exhausted through the duct to the ambient. This system will lead to an increase in temperature of the scrubber's interior cavity compared to the ambient, however, this temperature difference is not high enough to negatively impact the NEXA's performance or compromise the integrity of the scrubber's body.

7.2 Design for Manufacturability

Throughout the design process we kept in mind the need for simple manufacturing techniques. Below is a bulleted list of the steps we took to make our prototype possible to manufacture.

- Raw materials, such as bar stock and sheet metal, all standard sizes
- Fasteners, such as screws, bolts, and nuts, all standard sizes
- Purchased/donated parts, such as casters, all standard sizes
- In the riser, replace welding with screws
- Electrical components mounted with screws to a removable plate of aluminum
- All materials used are readily available, such as PVC and aluminum

By adhering to these guidelines, we were able to reduce the complexity of our manufacturing considerably. The majority of our raw materials were chosen so that they would be readily available in the GG Brown machine shop; this includes the sheet aluminum to make the riser and the mounting for the electrical components, aluminum bar stock to make the H_2 protection frame, and square PVC to make the NEXA's mounting feet. The machine shop has English fasteners available for use, so all custom-fabricated components use standard English sizes. Some of our components, such as the caster used to support the H_2 protection frame, were donated from our sponsor. These components are metric sized and we did not have a metric tap available for use, so we simply purchased the corresponding metric nut instead of threading the caster into a tapped hole. This allowed us to reduce the manufacturing cost of our prototype.

We took care when designing our components to make them easy to manufacture. Originally, we had thought the best way to make the riser would be to weld support posts to two profiles; after some consideration, we decided it would make manufacturing simpler if we were to replace the welds with screws. This allowed us to avoid the manufacturing difficulties associated with welding thin sheet aluminum, such as preventing heat stress from warping our components. Our team had considered mounting the electrical components necessary for NEXA operation on the floor of the recovery tank with an epoxy. We decided to change this design, and instead incorporate a sheet aluminum plate with holes in appropriate places to screw the electrical components down. This made our design simpler to manufacture, as we will not need to epoxy critical components in a difficult to reach space, and allows us to easily remove the electrical components when necessary.

Rather than choosing to use exotic materials which could give us higher strength and lower weight, such as carbon fiber, we chose to use standard materials such as aluminum and PVC. The lower cost of these materials allowed our team to meet our engineering goals within our budget requirements.

7.3 Design for the Environment

Since our sponsor for this project is dedicated to their products being environmentally friendly, our team also wanted to design our prototype so that it had no adverse effects on the environment. In order to design our prototype so that it was environmentally friendly we followed to following five guidelines.

- Reduced the amount of lead-acid batteries
- Fuel cell does not produce hazardous by-products
- Used aluminum for prototype parts so that it could be recycled
- Amount of material reduced for each subsystem
- Fuel cell’s life time is longer than batteries

First of all, by using the fuel cell and DC/DC converter we replaced the large lead-acid batteries with much smaller sealed lead-acid batteries. Our original intensions were to completely replace the lead-acid batteries but we found that this would be beyond our allowed budget. Secondly, we chose a type of fuel cell that does not produce any hazardous emission. This is important for the health of the environment as well as the consumer. Third, we are using aluminum for as many applications as possible. These aluminum parts can easily be recycled once the project is finished. Fourth, in designing each subsystem of the prototype we tried to reduce the amount of material that was used, for example the riser consists of two plates and several uprights instead of being a solid piece. By doing this we reduced the amount of mass that the scrubber would need to move and thus decreased the amount of power necessary for it to run. Finally, through proper maintenance of the hydrogen tanks and the fuel cell, the lifetime of the power unit itself can be much longer than the batteries. Also, disposing of the fuel cell is less hazardous than disposing of lead-acid batteries.

7.4 Failure Mode Effect Analysis

Failure mode effect analysis allows our engineering team to predict possible ways our modified scrubber will fail and take measures to prevent these failures. This is done by calculating, on a scale of 1 to 10, the probability of each failure mode, the severity of the failure, and how detectible each mode of failure is. These numbers are then multiplied together to find the risk priority number (RPN); a high RPN indicates a failure mode which should be carefully considered and addressed in the design stage. Table 11, below, contains the two most significant failure modes for our scrubber. Our full failure mode effect analysis is available in Appendix I.

Part # & Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes/ Mechanism(s) of Failure	Occurrence (O)	Current Design Controls/Tests	Detection (D)	Recommended Actions	RPN	new S	new O	new D	new RPN
7-Hydrogen Tank	Hydrogen leak while unattended	flammability, asphixiation	10	operator leaving a tank connected improperly when leaving the worksite, a leak in the hydrogen tank, bad or broken seals, loose fittings, or a leak in the hose or regulator	3	External hydrogen detection before reaching flammable level	3	Storage of scrubber in a room with hydrogen detection; A wireless external hydrogen detector could be used to detect hydrogen leaks and send alerts to a reciever up to 75 feet away	90	10	3	2	60
5-Voltage Conversion	power insufficint to run scrubber	scrubber shuts down, poor performance	7	fuel cell malfunction, out of fuel	6	Scrubber has minimum voltage detection. Visual voltage detection on scrubber. Gauge on fuel tank.	2	Routine preventative maintence of fuel cell compononents; Limit on pressure drop of fuel tank	84	7	4	2	56

Table 11: FMEA, Top 2 Failure Modes

The primary failure mode for our fuel cell-powered scrubber is a hydrogen leak while the scrubber is unattended. Under normal operation, the NEXA’s onboard hydrogen detector would detect any leaks within the NEXA and the scrubber body and consequently power down the fuel cell if unsafe hydrogen levels were reached. However, when the NEXA is not turned on, its hydrogen detector does not operate and a leak could possibly go undetected. The best method for dealing with a leak of this nature would be to provide hydrogen detection in the area where the scrubber will be stored when not in use or to attach an independent hydrogen detector to the inside of the scrubber itself. This would provide hydrogen detection at all times, ensuring that hydrogen's lower flammability limit is never reached and there is no danger of combustion.

The secondary failure mode for our scrubber is insufficient power to operate the scrubber. This could happen due to either a fuel cell malfunction or depleting the hydrogen fuel source. The NEXA does perform self-diagnostic tests on startup and shutdown, and the users of the floor scrubber should perform routine maintenance on the NEXA to check if the NEXA is reporting a problem. The hydrogen source is connected to a pressure regulator; this gives a visual indication of the amount of hydrogen fuel remaining in the tank in the form of a pressure reading. The operators of the scrubber should monitor this pressure gauge's reading and when the hydrogen fuel source drops below a pressure of 100 psi the tank should either be refilled or switched with a full hydrogen tank in order to continue cleaning.

8 FINAL DESIGN

In this section, we detail our final design. All components have been modeled in CAD, with detailed dimensioned drawings of critical components available in Appendix J. We have also prepared a bill of materials for our prototype; this is available in Appendix K.

8.1 CAD/Engineering Drawings

Figure 7, below, shows the CAD drawings of our designed components attached to the T3 scrubber. The riser and hydrogen storage systems are clearly visible, while the ducting, mounting, and electrical subsystems are hidden within the body of the scrubber. The full CAD assembly serves to give a visual representation of how the necessary components will be attached to the scrubber. Top and side views of the full assembly are available in Appendix J.

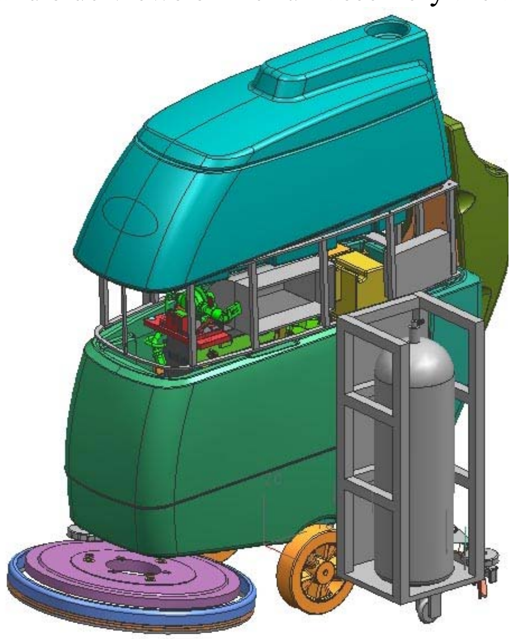

Figure 7: CAD Drawing of Full Assembly

8.1.1 Riser

Shown here, as Figure 8 on page 26, is an isometric view of the riser which will allow us to place the NEXA fuel cell and necessary electrical components within the body of the T3 scrubber. The riser has the exact profile shape of the outside rim of the T3's protective shroud in order to provide the maximal surface area for the recovery tank to sit on. It raises the recovery tank 220 mm vertically; this ensures that the recovery tank will not touch the fuel cell, even when the recovery tank is full of water.

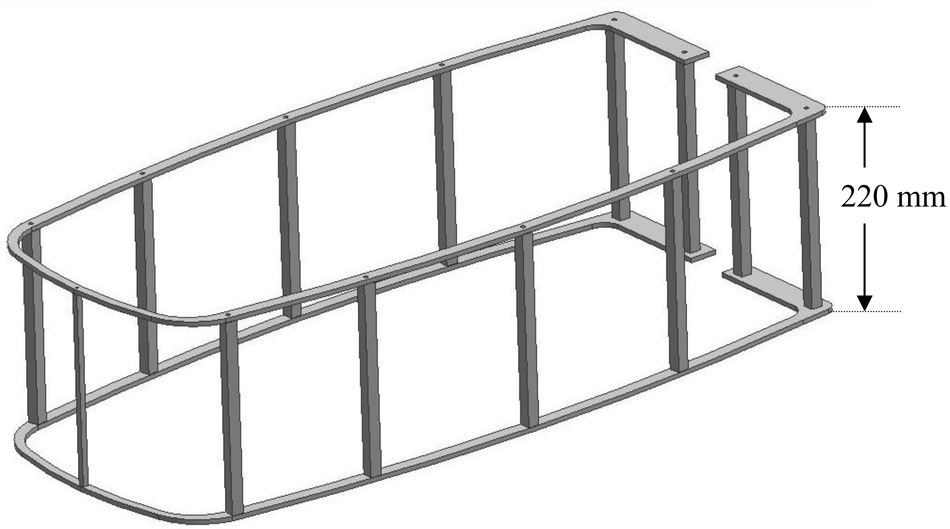

Figure 8: Riser

8.1.2 Hydrogen Storage

Shown here, as Figure 9, is an isometric view of our selected hydrogen storage tank. The key dimensions for this component are the height and diameter of the tank; the tank measures 610 mm in height and 178 mm in diameter.

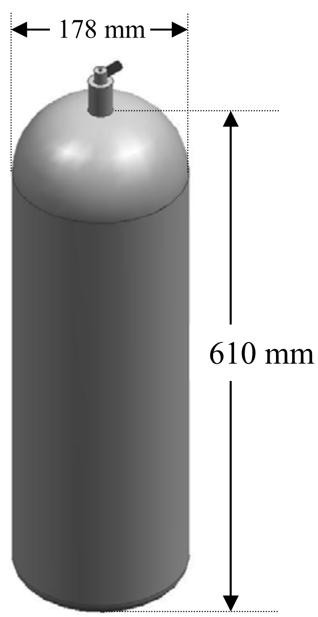

Figure 9: Hydrogen Storage Tank

8.1.3 Hydrogen Protection

Figure 10, on page 27, is an isometric view of our hydrogen protection solution. The aluminum frame was designed to provide adequate room for our hydrogen tank, allow the tank to be easily removed from its position on the T3 scrubber, and keep the hydrogen tank safe from damage while minimizing the addition to the overall width of the scrubber. The hydrogen protection frame is 800 mm in height and adds 220 mm to the width of the scrubber.

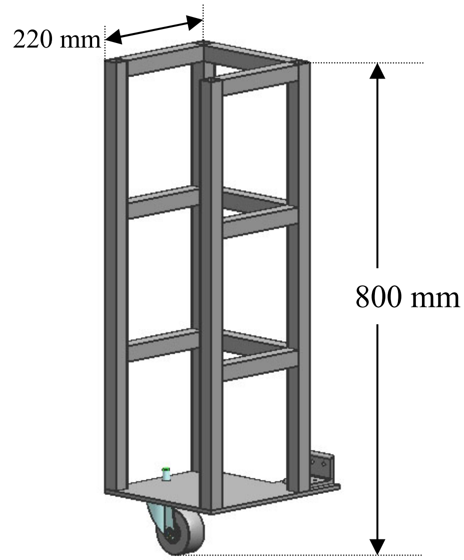

Figure 10: Frame for Hydrogen Protection

8.1.4 Mounting System

Shown here, as Figure 11, is an isometric view of the mounting system for the NEXA within the T3 scrubber. Its primary purpose is to elevate the NEXA off the bottom of the inside cavity of the T3 while keeping the NEXA in place during operation. The mounting system raises the NEXA 200 mm off the bottom of the inside cavity within the scrubber.

The NEXA's four feet each sit in a PVC block designed to hold the NEXA steady during operation. The two front feet sit on the recovery tank, while the two back feet are press fit into a 25.4 mm square aluminum bar. This aluminum bar is anchored to the scrubber's shroud. This design allows us to safely and securely hold the NEXA while not needing to fasten it to a critical water-holding component of the T3.

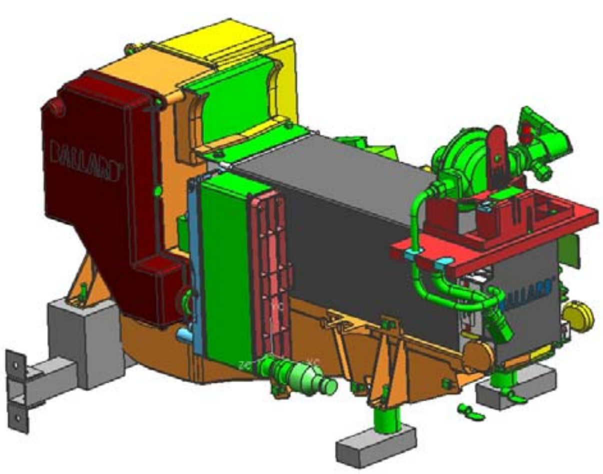

Figure 11: Mounting System with Fuel Cell

8.1.5 Electrical Component Placement

Shown here, as Figure 12, is an isometric view of where the electrical components will be placed within the T3's inside cavity. The components are oriented so that the cooling air drawn by the NEXA's cooling fan will pass over these components, allowing for convection heat transfer, keeping the operating temperature of the electrical components low and preventing any damage to the T3.

The electrical components sit directly above the T3's cleaning water tank. In order to secure these electrical components without drilling into this tank, we constructed a plate which has the profile of the T3's interior cavity. This plate rests on the scrubber floor, and allows positioning of electrical components to be changed by simply adding holes where necessary. Currently, the DC/DC power box and the NEXA's load relay are positioned as shown. No dimensioned engineering drawing is provided because the position of these components is meant to be adjustable and easily changed.

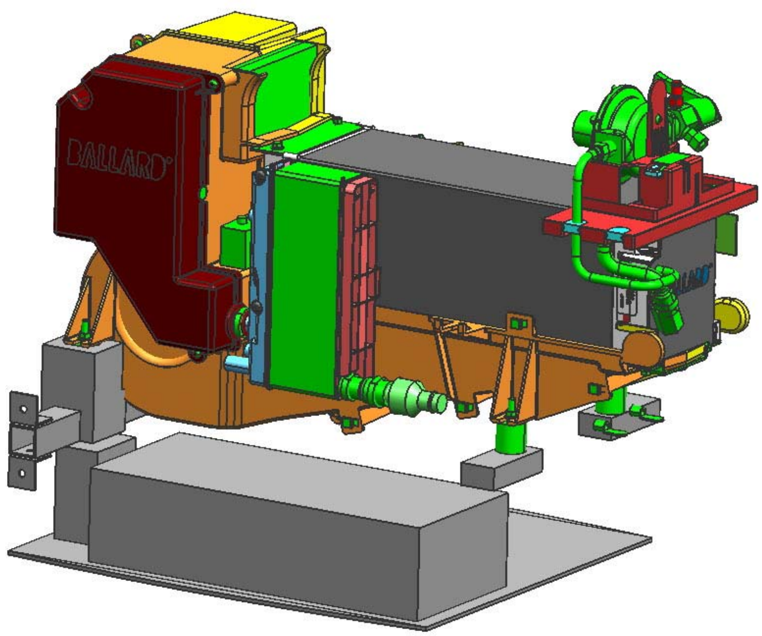

Figure 12: Electrical Components' Orientation within Scrubber

8.1.6 Ducting System

The ducting system, shown in Figure 13 on page 29, serves to bring cool, oxygen-rich reaction air to the NEXA while providing a direct route for the hot air to exit the scrubber's inside cavity. The key dimensions for this component are the areas the NEXA uses for reaction air intake and cooling air exhaust. Reaction air is drawn through a 90 mm by 58 mm opening while the hot exhaust air is expelled through a 240 mm by 113 mm opening on the top of the fuel cell.

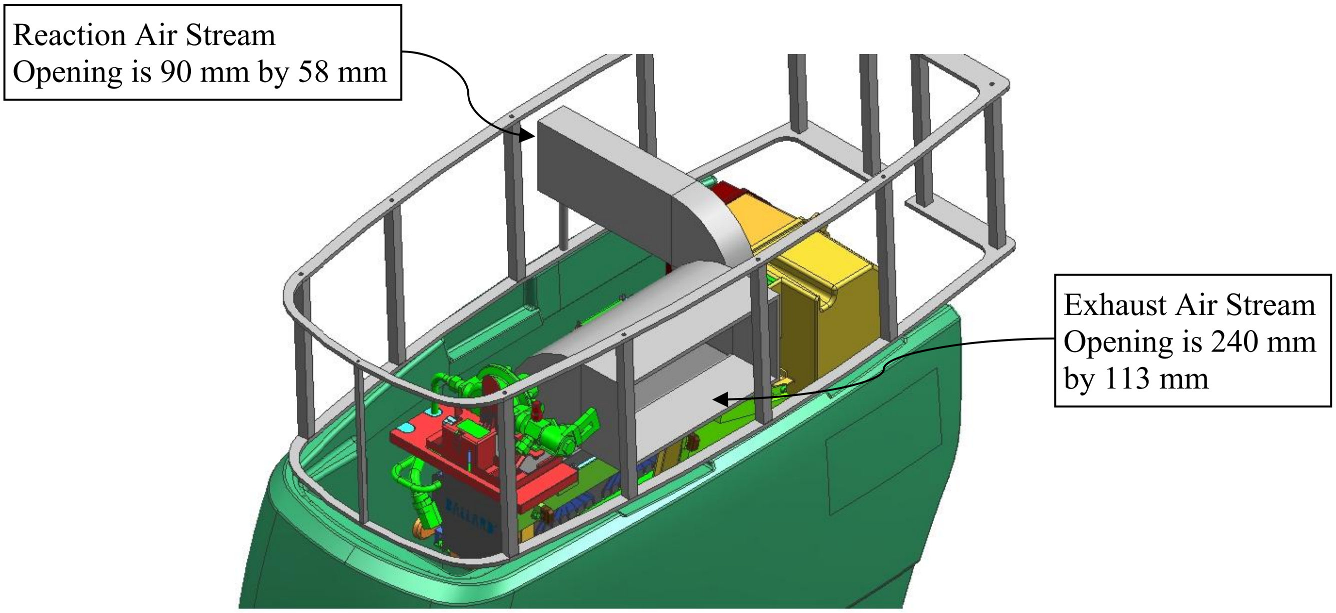

Figure 13: Ducting Isometric View

8.2 Bill of Materials

Our bill of materials, found in Appendix K, gives details regarding where supplies were purchased and how much they cost. For the most part our raw materials were donated by the G.G. Brown machine shop and used to create the main portions of our subsystems. Most of the components that were purchased came pre-made and ready to attach to the prototype. Overall, we are estimating a final prototype cost of $127.

9 MANUFACTURING

The purpose of this section is to detail the processes that we employed to fabricate the components necessary for our project. We created process plan sheets for parts that were machined in house, and specified where the remaining components came from.

9.1 Riser

The riser was manufactured in the G.G. Brown machine shop. All raw materials were acquired at the machine shop and cut to the appropriate initial size. The basic process consisted of cutting out the riser profiles from 3.175 mm (1/8 inch) thick aluminum sheets and bolting them onto the top and bottom of 13 square aluminum uprights. After assembly, the top and bottom of the riser were cleaned with rubbing alcohol so that the adhesive on the rubber gasket could stick. The full process plan sheet for the manufacturing process is available in Appendix L.

9.2 Hydrogen Storage

We will be renting a size Q tank from Cryogenics Gases Inc. This is the same company that the University of Michigan uses for their compressed gas needs. By renting the tanks we are reducing a large portion of our budget. Essentially, the tank comes pre-manufactured and pre-filled.

9.3 Hydrogen Protection

The protective frame for the hydrogen tank was manufactured in the G.G. Brown machine shop. We used hollow 6063 aluminum bar stock to make each member of the frame and then welded these to the 0.5” thick sheet aluminum base plate using the TIG welding method. The caster and angle bracket were then attached using ¼”-20 bolts and nuts. The frame itself is then attached to the scrubber. As a final step, foam pipe insulation was installed on the bars which will support the frame in order to ensure a tight fit. The full process plan sheet for the hydrogen protection solution can be found in Appendix L.

9.4 Fuel Cell Mounting

The fuel cell mounting system was manufactured in the G.G. Brown machine shop out of available stock materials. 25.4 mm (1 inch) square hollow aluminum bar stock, 25.4 mm (1 inch) aluminum angle brackets, 25.4 mm (1 inch) thick PVC plate, and 50.8 mm (2 inch) square PVC bar stock were used. The aluminum bar stock and angle brackets were used to construct the rear foot support bar, and the PVC was used to construct the feet which the NEXA sits on. The bar was secured to the scrubber by the brackets with ¼”-20 bolts and nuts. With the bar in place the grooves of the rear feet were press fit onto the aluminum bar at the proper width to accept the fuel cell. The front feet were positioned on the solution tank, and the scrubber was ready to house the fuel cell.

9.5 Electrical Component Placement

The electrical component mounting plate was constructed out of 3.175 mm (1/8 inch) sheet aluminum. The plate was cut to match the profile of the scrubber cavity to ensure a snug fit and prevent the electrical components from moving during operation. We then positioned the electrical components where they best fit our needs and drilled holes to mount them. #10-24 bolts and nuts were used to secure the electrical components to the plate, and the plate was then placed inside the scrubber.

9.6 Ducting System

To make the ducting we started with a sheet of 30 gauge galvanized steel sheet metal, similar to the material used for ducts in housing. We traced the layouts shown in Figures 14 and 15 on pages 31 and 32 onto the sheet of metal. Using tin snips the shapes were cut out appropriately. Finally, the layouts were bent along the appropriate lines and taped into place with aluminum foil tape.

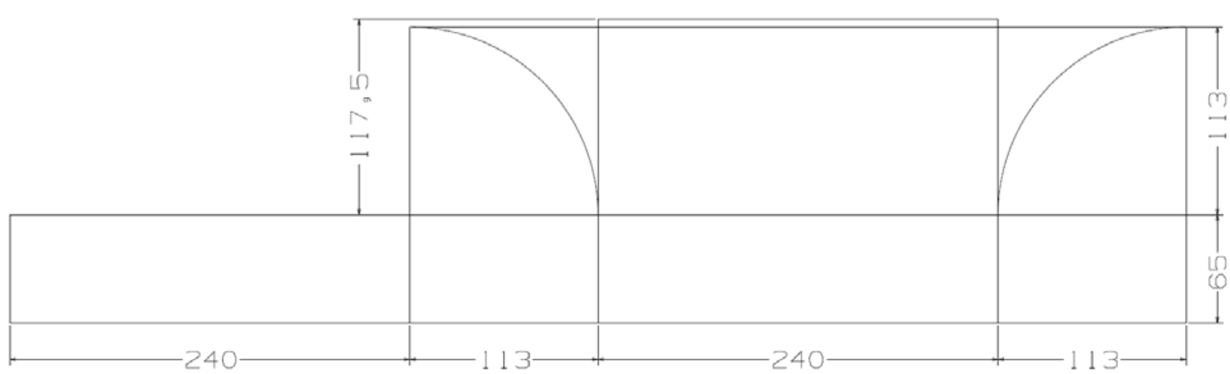

Figure 14: Layout for Hot Air Duct

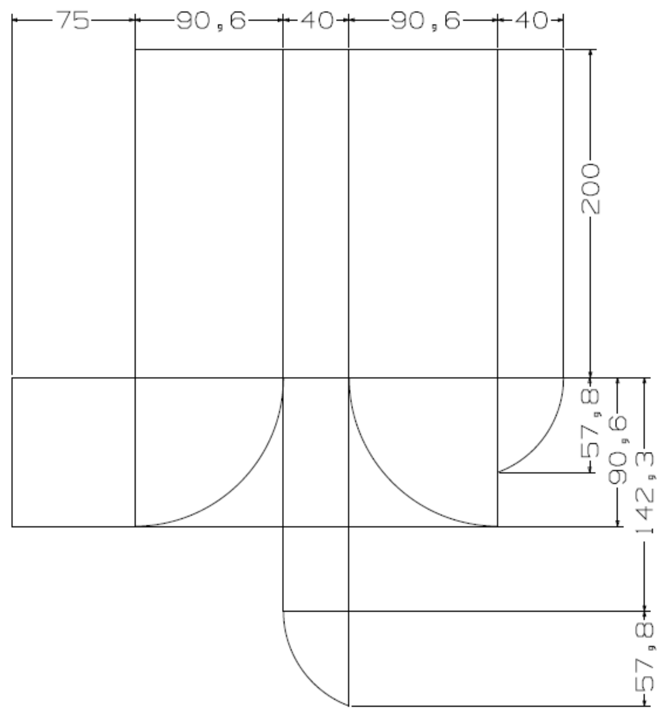

Figure 15: Layout for Cold Air Duct

10 TESTING

In order to test our prototype, we needed to test both the NEXA fuel cell and the floor scrubber itself. The purpose of this section is to describe the process we used and the tests performed.

10.1 Fuel Cell Testing

Before we placed all the fuel cell components into the scrubber we set up the fuel cell and DC/DC converter components on a test bench beneath a fume hood. Our intensions were to trouble shoot issues with the fuel cell reported by last year's team and also to ensure that the fuel cell was working properly. After setting up the NEXA according to the manual, our first attempt to turn the system on failed. The fuel cell system did not indicate that it was receiving power at all, and the DC/DC converter's LCD screen did not turn on.

Steven Frank of Heliocentris helped troubleshoot the NEXA system startup issues. Ultimately he concluded that one of the power boards on the DC/DC converter had gone bad and arranged for new parts to be sent to us. Once these parts arrived we were able to successfully start up the NEXA system and connect it to a laptop to monitor it.

10.2 Prototype Testing

As a final test of the NEXA fuel cell's capabilities, we used it to power the T3 floor scrubber on the test bench. We used the same test setup described above, using the large hydrogen tank, lead-acid batteries, and new DC/DC converter to operate the NEXA fuel cell. The leads coming from the NEXA were attached to the T3 floor scrubber's leads which usually go to its lead-acid batteries.

The NEXA was then used to operate the T3 floor scrubber. Once the NEXA was turned on, it immediately began powering the T3's vacuum motor. This motor is what sucks water off of the floor and deposits it into the recovery tank during cleaning, and runs continually during operation. We then engaged the T3's scrubbing brush and powered it; the brush operated as expected, scrubbing the lab floor as we held the scrubber in place next to our lab setup. The DC/DC control unit was used during this time to monitor the voltage. We saw the voltage supplied to the scrubber remain between 24.0 and 23.9 V during all times of operation, including directly after the scrubbing brush was engaged. We were very pleased with this result, as this means scrubbing will not be interrupted by changing the amount of power the NEXA must provide.

Upon installation of the components we fabricated for the T3 floor scrubber, we wanted to test the T3's functionality. With the additional components, we tested the T3's ability to maneuver and found it to be as effective at cleaning as it originally was. We wanted to be sure that the addition of the hydrogen protection frame would not interfere with the squeegee's operation. Normally, the squeegee has a large range of motion, moving from the left to right side of the scrubber as the operator turns. Allowing the squeegee to move freely is important to ensure that all dirty water is collected from the floor and returned to the recovery tank; leaving water on the floor would be unsightly as well as creating a slipping hazard. During our testing, we found that the hydrogen protection frame did not interfere with the squeegee's motion. We also wanted to test the cleaning range of our prototype; with our components installed, we want to ensure that the T3 could maneuver and clean against a wall. In testing, we found that our additional components did not interfere with the T3 scrubbing against a wall.

The final step in our testing would have been using the NEXA with our mobile hydrogen source with our non-lead-acid batteries, but we were unable to complete this. In order to receive approval to use our hydrogen supply outside of the fume hood, we would need to fill out a new risk assessment for OSEH. This would also most likely involve our team being directly supervised by an OSEH representative while operating our prototype. We did not have time to prepare this risk assessment or make arrangements with an OSEH representative, and we were not able to complete this prototype testing.

11 FUTURE IMPROVEMENTS

The purpose of this section is to discuss known shortcomings of our prototype and possible ways to address these issues.

11.1 Battery Selection

As discussed in section 4, we were unable to find a battery solution that was economically and spatially feasible. Our recommendation would be to focus the search on lithium based technologies, as our research indicates that they tend to allow for higher currents in both charging and discharging compared to nickel-metal-hydride batteries. At this point in time, we were unable to find a commercially available lithium based battery that met our charge rate requirements; the possibility of using multiple lithium batteries in parallel should be considered. While this would be expensive, it may currently be the only way to obtain the necessary charge rates without using lead-acid batteries.

11.2 Recovery Tank Mounting

One area where our prototype could be improved is in the mounting of the recovery tank. In the original T3 design, the recovery tank bolts onto the main scrubber body via two angle brackets along the side of the scrubber. Currently, these angle brackets are attached to two aluminum pieces which are the height of the riser; these aluminum pieces attach to the bottom of the scrubber as well as the recovery tank. The riser itself and these aluminum pieces are completely separate components. This leads to the recovery tank being stable when it is in the operational position, but unstable when the recovery tank is raised to the side.

One way to improve this design would be to attach the recovery tank directly to the top of the riser. This could be accomplished with an angle bracket, but precautions must be taken. The riser was not designed to support the weight of the full recovery tank when the recovery tank is in its "open" position. When the recovery tank is tilted to the side, it creates a large unbalanced force on the riser. This force could cause the latches which secure the riser to the bottom of the scrubber to fail and allow the riser to come off. Any future work done on this component should include analysis of the strength of the riser and its latches when the recovery tank is in this position.

11.3 Control Box Mounting

Our prototype could also be improved by adding a mount for the DC/DC converter's control unit within the space of the riser's profile. The control unit could fit entirely behind the riser, ensuring that it will not be damaged during operation under any circumstances while still being accessible to the user. A small aluminum mounting system could be fabricated to attach to the riser and position the control unit as desired.

Another possibility would be mounting the control unit near the place where the scrubber operator stands. This would make it very easy to monitor the NEXA and DC/DC converter's operating parameters while scrubbing the floor. This would also require a mounting system of some kind; one consideration if this were to be attempted is the recovery tank needs to be able to rotate for access to the inside of the scrubber. The control unit would need to be positioned in such a way that it does not interfere with this motion.

12 CONCLUSIONS

Tennant Company wishes to power their T3 floor scrubber with a more environmentally friendly and efficient power source than currently used lead-acid batteries. Hydrogen-powered fuel cells are appropriate for their application. Tennant's T3 requires approximately 1kW of power, needs to be safe to operate indoors, and operate at a temperature low enough to not compromise the T3's plastic housing. This project is a continuation of a previous ME 450 team's work, and their team selected and purchased the Ballard NEXA PEM fuel cell system. This fuel cell is appropriate for the operating requirements and conditions of the T3 scrubber, however, the previous team had difficulty getting their proof-of-concept prototype operational.

It was our team's goal to successfully build this proof-of-concept prototype and improve upon it. We were able to design and build a riser, hydrogen storage frame, fuel cell mounting system, and a plate to hold the electrical components within the scrubber. With these pieces, our proof-of-concept prototype would operate successfully if a battery solution could be found. Our team was unable to find a battery which meets the required charge and discharge rate in our budget constraints while not containing lead-acid.

If a battery solution could be found, the battery would simply need to be attached to our prototype and scrubber operation could begin. A computer could then be used to gather performance data regarding the operation of the NEXA fuel cell and its subsystems.

With a suitable battery, our prototype reduces refueling time of the T3 while increasing its run time. The T3 floor scrubber's cleaning performance is unchanged; it has its full range of mobility it originally had and can clean against a wall with ease. The only by-products our prototype produces are water and heat; we have succeeded in creating hydrogen-powered cleaning without using environmentally hazardous materials.

13 ACKNOWLEDGEMENTS

We would like to thank Fred Hekman of Tennant Company for his continual support. He has provided invaluable assistance in defining our customer specifications, familiarizing us with the T3 scrubber, and helping us understand Tennant Company's mission to move towards green products. Our team would also like to thank Fred for inviting us to Tennant Company's design and manufacturing facility in Holland, MI and allowing us to see the rotational molding process which creates the T3 scrubber.

Our team would also like to thank Professor Kazuhiro Saitou. In addition to providing specifics on project deliverables, Professor Saitou has helped a great deal to define the scope of our project.

We also thank Dr. Chang Hwan Kim of the Chemical Engineering department for his assistance in both receiving appropriate training to work with hydrogen and understanding how the NEXA fuel cell works. He has volunteered a great deal of his time to help our team succeed.

Thanks to Steven Frank of Heliocentris, we were able to successfully operate the NEXA fuel cell. Without his help, we would not have been able to diagnose our dead control board and obtain a replacement in time for the design expo.

Bob Coury of the ME Department's machine shop also deserves our thanks. He has helped us create designs which are feasible to manufacture with the equipment and materials available to us. He also provided us with welding training, and assistance in the welding necessary for our project.

Thanks to Kathy McCrumb of the Mechanical Engineering department for assisting us in purchasing hydrogen gas and obtaining proper OSEH approval to use hydrogen in a lab.

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15 TEAM BIOS

Theresa DeVree

Theresa is originally from a small suburb of Grand Rapids, MI. She attended Grandville High School and acquired her interest in engineering by participating on the school FIRST Robotics team. On that team she experienced designing and fabricating four separate robots. Through discussions with engineering mentors, she decided to attend University of Michigan's College of Engineering where she quickly decided to major in mechanical engineering. Upon graduating Theresa plans to find a career in the fields of space flight or robotics.

Michael Grenier

Michael is from Rochester Hills, MI. He went to high school at Adams High School where his classes in CAD, math, and physics gave him an interest in mechanics. He decided to attend University of Michigan because of its excellent engineering program combined with close location to his home town. Michael has been interested in mechanics since elementary school where students programmed Lego robots with computers. He is unsure what direction he wants to go after graduation, but is certain that experience and knowledge gained in alternative energy from this project will be invaluable.

Ryan Kotenko

Ryan is from Macomb, MI. He went to high school at Lutheran High School North and enjoyed math, chemistry, and physics. Ryan decided to study mechanical engineering at the University of Michigan, which he saw as an opportunity to receive a world class education in an interesting field, gain a variety of career opportunities, and see some pretty good football games. While still interested in the field of engineering, Ryan has decided to pursue a career in ministry and hopes to begin Master of Divinity studies Concordia Lutheran Seminary in St. Louis in the fall of 2009.

Andrew Olive

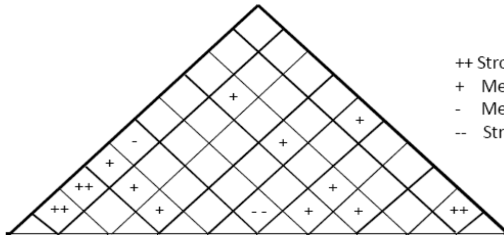
Born overseas in Rome, Italy, Andrew actually spent most of his life in Washington, D.C. proper. He graduated from Gonzaga College High School with the hopes of studying mechanical engineering at the highly-acclaimed University of Michigan College of Engineering. He was attracted to the field due to his interest and awareness in automobiles and their need to increase fuel efficiency in the depleting fossil fuel market. He hopes to complete his degree and go into industry supporting hybrid and alternative technologies, namely fuel cells. This is one reason why this ME450 project was so appealing to him. Other than class work, he enjoys rooting for the Wolverines on the football field, playing golf, and being outdoors.

APPENDIX A FUEL CELL TYPE COMPARISON [12]

Fuel Cell Type	Electrolyte	Operating Temperature	Power Output	Electrical Efficiency	Advantages	Disadvantages
Polymer Electrolyte Membrane (PEM)	Solid organic polymer polyperfluorosulfonic acid	50-100 °C	10W-250kW	53-58%	• Solid electrolyte reduces corrosion and electrolyte management problems • Low temperature • Quick start-up	• Requires expensive catalysts • High sensitivities to fuel impurities • Low temperature waste heat
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90-100 °C	10-100kW	60%	• Cathode reaction faster in alkaline electrolyte, higher performance	• Expensive removal of CO_2 from fuel required
Phosphoric Acid (PAFC)	Liquid phosphoric acid soaked in a matrix	150-200 °C	50kW-1MW	32-38%	• Large amount of power • High tolerance to impurities in hydrogen	• Requires expensive platinum catalysts Relatively low current and power for size • Large size/weight
Molten Carbonate (MCFC)	Liquid solution of lithium, sodium, and/or potassium carbonates, soaked in a matrix	600-700 °C	<1kW-1MW	45-47%	• High efficiency • Fuel flexibility • Can use a variety of catalysts	• High temperature speeds corrosion and breakdown of cell component • Slow start-up • Complex electrolyte management
Solid Oxide (SOFC)	Solid zirconium oxide to which a small amount of yttria is added	650-1000 °C	5kW-3MW	35-43%	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte reduces electrolyte management problems	• High temperature speeds corrosion and breakdown of cell component • Slow start-up • Brittle ceramic electrolyte with thermal cycling

APPENDIX B QUALITY FUNCTION DEPLOYMENT (QFD)

Quality Function Development (QFD)



++ Strong Positive
+ Medium Positive
- Medium Negative
-- Strong Negative

Key:
9 => Strong Relationship
3 => Medium Relationship
1 => Small Relationship
(blank) => Not Related

		Weight	Power Output	Voltage	Current	Operating Temperature	Operating Time	Weight	Size	Additional Parts	Carbon Monoxide/Dioxide Emissions	Hydrogen Purity	Benchmarks: *H2 Truck*	Benchmarks: *Hydrogenics HyPM™ Forklift*
Winter '07 Req	Commercially available hydrogen	8						3	3	1		9	2	5
Winter '07 Req	Easy to operate	1	1				1	9	9	1			5	5
Winter '07 Req	Does not overheat	10	1	1	1	9	3	1	1	1			5	5
Winter '07 Req	No hazardous by-products	7	1							3	9	3	5	5
Winter '07 Req	Comparable run time	4			1		9	1					5	5
Winter '07 Req	Easy to refuel	3					1	1	3	9		3	5	4
Winter '07 Req	Safe	11	1	1	1	3		1	1	9	3		5	5
Winter '07 Req	Easy to maintain	2				3			1	9			5	5
New Req	T3 functionality unchanged	6				1	3	1	3	9			N/A	N/A
New Req	No lead acid batteries	5	1	3	1			1		9			5	5
New Req	Uses NEXA fuel cell	9	9	9	9	9	3	9	9	3	3	3	1	1
													43	45
	Measurement Unit		W	V	A	°C	hr	kg	m^3	#	ppm	%		
	Target Value		900	24	30	<120	4	177	1.06	<10	0	99.99		
	Importance Rating		**6**	**6**	**6**	**2**	**6**	**4**	**3**	**1**	**6**	**5**		
	Total		115	117	111	216	115	153	164	310	123	129		
	Normalized		0.09	0.09	0.09	0.17	0.09	0.12	0.13	0.24	0.09	0.10		
	H2 Truck		1200	24	-	-	4	450	2.21	-	0	99.999		
	Hydrogenics HyPM™ Forklift		10000	39 - 58	350	65	8	-	-	-	0	99.99		

1 = doesn't satisfy at all
2 = satisfies "slightly"
3 = satisfies "somewhat"
4 = satisfies "mostly"
5 = satisfies perfectly

APPENDIX C HYDROGENICS HYPM™ FORKLIFT SPECIFICATION

NACCO MATERIALS HANDLING GROUP, INC.

HYDROGENICS CORPORATION

Fuel Cell Powered Forklift

Hydrogenics' fuel cell forklift initiative involves outfitting two 5000 lb. Class I sit-rider electric forklifts manufactured by NACCO Materials Handling Group **with fuel cell propulsion systems. Hydrogenics** is supplying its fuel cell hybrid power solution for the forklifts, while **Deere & Company and NACCO Materials Handling Group** are assisting Hydrogenics in the integration of the fuel cell systems into the vehicles. The funding also supports the provision of a HyLYZER™ hydrogen refueling station that will serve to refuel both forklift vehicles. This refueler is designed and built around Hydrogenics proprietary PEM (Proton Exchange Membrane) stack technology. Working demonstrations of the forklifts and refueler will take place at **GM** and **FedEx** operations within the Greater Toronto Area, and potentially other locations, throughout the fall and winter of 2004/2005.

Assistive funding for this initiative is provided by Sustainable Development Technology Canada and the Canadian Transportation Fuel Cell Alliance.

Hydrogenics HyPM 10 Power Module, H_2 Storage, and Ultracapacitors Power Pack power the forklift.

VEHICLE AND POWER PACK OPERATING SPECIFICATIONS

Power Source:	Hydrogenics HyPM™ 10
Power Configuration:	Fuel Cell – Electric Hybrid
Power Pack Dimensions: [1]	33"(L) x 40" (W) x 24" (H)
Regenerative Braking Capable:	Yes
Lifting Capacity:	5000 lbs
Wheels:	4
Tire Type:	Cushion Tire
Operating Time:	8 hours
Refueling Time:	< 2 minutes
Hydrogen Storage Capacity:	1.8 kg

FUEL CELL OPERATING SPECIFICATIONS

Hydrogenics HyPM™ 10 Power Module	
Low pressure PEM fuel cell stack:	< 20kPa, gauge
Rated Net Continuous Power:	10 kW
Voltage range: [2]	39 to 58 VDC
Max. System Efficiency: [2]	56%
Dimensions: (H x W x L)	310 x 560 x 900 mm
Volume:	156 L
Fuel type:	Direct hydrogen
Zero emissions	✓
Quiet indoor operation	✓

(1) Includes fuel cell, electrical storage device, hydrogen storage, power electronics and thermal management system

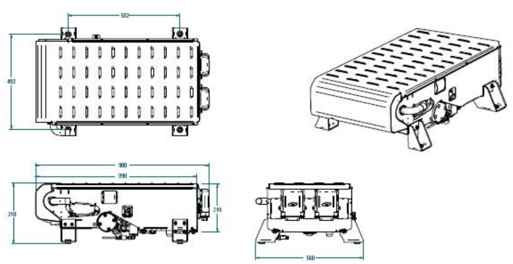
(2) Beginning of Life

(3) Lower heating value basis, excluding radiator fan

SPECIFICATIONS

Fuel Cell Technology	Proton Exchange Membrane (PEM)
Performance	
Rated net continuous power	10 kW
Peak power	12 kW
Voltage range[1]	37 to 57 VDC
Rated current	350 A
Max. system efficiency[2]	53 %
Operational lifetime	>1000 hours
Fuel	
Type	Gaseous Hydrogen > 99.99% purity
Gas supply pressure	310 to 710 kPa, gauge
Stack operating pressure	≤ 20 kPa, gauge
Consumption	≤ 150 std L/min
Operating Environment	
Stack operating temperature	65°C
Ambient temperature	15 to 30°C
Ambient pressure	101.3 kPa, absolute
Cooling Sub-system (supplied by user)	
Coolant	De-ionized water
Physical	
Dimensions (height, width, length)	310 x 560 x 900 mm
Mass	88 kg, dry

1) Beginning of life
2) Lower heating value basis, excluding user-supplied radiator fan



HYDROGENICS CORPORATION

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Waterless Printing Process

HYDROGENICS CORPORATION

HyPM™ 10

Fuel Cell Power Module

- Power output: 10 kW net
- High performance and efficiency
- Rapid dynamic response
- Compact lightweight design
- Onboard system controller and diagnostics
- Comprehensive safety features
- Modular/scalable design for a range of applications

H2 Truck KONCEPTET

H2 Truck Konceptet

H2 Truck projektet blev opstartet i 2003, og efter intensiv udvikling og test er resultatet blevet et brint og brændselscelle drevet køretøj, der kan bruges til intern transport på sygehuse, i lufthavne, gågader og andre steder hvor benzin-, gas- og el-trucks anvendes.

H2 Trucken er CE-godkendt og sammen med den tilhørende H2 FillingStation (fyldestation) fungerer H2 Trucken som et komplet demonstrationskoncept for brint og brændselscelle transportsystemer.

H2 Truckens fordele

Driftstiden er fordobbelt i forhold til batteridrevne el-trucks og H2 Trucken kan optankes på under 2 minutter, mod 10-12 timer opladning af batterier. Udstødningsproduktet er 100% rent vand.

I udviklingen af H2 Trucken er der i høj grad taget hensyn til ergonomi og brugervenlighed. Genopfyldningen af brint sker således let og simplet ved at udskifte H2 Canisters (brintbeholdere).

The H2 Truck Concept

The H2 Truck concept is build upon the thoughts of a sustainable society based on renewable energy and hydrogen as energy carrier.

The H2 Truck project was started in 2003, and the result after intensive development and continuous test is a hydrogen fuel cell powered truck, that can be used in airports, hospitals, inner cities and other applications where gasoline and battery powered truck's are used today.

The concept, also includes a H2 FillingStation where the replaceable H2 Canisters inside the H2 Truck can be refilled with hydrogen. The H2 Truck concept is CE approved and ready for commercial demonstration.

The H2 Truck is superior in any ways compared to battery powered trucks. The operation time is twice as long on a H2 Truck, and it can be recharged in less than 2 minutes, compared to the normal battery recharge time of 10-12 hours. On top of this, the only exhaust from the H2 Truck is pure water.

Easy replace and fill system™ muliggør hurtig og sikker skift af H2 Canisters på under 2 minutter.

Easy replace and fill system™ enables quick and safe replacement of H2 Canisters in less than 2 minutes.

H2 Truck SPECIFIKATIONER

H2 Truck™ 	Drivsystem	Hybrid PEM brændselscelle system	Power System	PEM Fuel Cell hybrid system
	Brændstof	99,999% Brint	Fuel type	99,999% Hydrogen
	Driftstid	4 timer kontinuerligt, 12-16 timers normal drift	Operating time	4 hours continuously, 12-16 hours normal operation
	Trækkraft / Lastevne	2000kg / 750kg	Tractive power / Load limit	2000kg / 750kg
	Tophastighed	15 km/t	Max. speed	15 km/h / 9,3 mph
	Effekt	2kW DC motor	Power	2kW DC motor
	Styring	Mikroprocessor med LCD touch screen til betjening af H2 Truck™ og H2 PowerUnit™	Control system	Microprocessor with LCD touch screen operation of H2 truck™ & H2 PowerUnit™
	Dimensioner	205x90x120 (LxBxH)cm	Dimensions	205x90x120 (LxWxH)cm / 790"x 35"x47"
	Vægt	450 kg	Weight	450 kg
H2 PowerUnit™ 	Udgangseffekt	0-1,2kW 24V DC (peak 2kW) 0-1,0kW 230V 50Hz AC (peak 2kW)	Power Range	0-1,2kW 24V DC (peak 2kW), 0-1,0kW 110/230V 50/60Hz AC outlet (peak 2kW)
	Energi-forsyning	2 x H2 Canisters™	Fuel supply	2 x H2 Canisters™
	Driftstid	4 timer kontinuerligt ved 1,2kW	Operating time	4 hours continuously at 1,2kW
	Sikkerheds-system	2 uafhængige sikkerhedssystemer brintdetektorer, automatisk nedlukning..	Safety system	2 separated safety systems, hydrogen sensors, automatic shutdown..
	Dimensioner	60x55x40(LxBxH)cm	Dimensions	60x55x40(LxWxH)cm / 24"x22"x16"
	Vægt	90 kg (uden H2 Canister™)	Weight	90 kg (uden H2 Canister™)
H2 Canister™ 	Lagringstype	Metalhydrid brintlagring	Storage type	Hydrogen hydride storage
	Kapacitet	Kapacitet 1900 L H2 / 10,6kWh(LHV)	Capacity	Capacity 1900 L H2 / 10,6kWh(LHV)
	Max. Lagringstryk	20 bar	Max. storage pressure	20 bar (290 PSIG)
	Dimensioner	43x11x22 (LxBxH)cm	Dimensions	43x11x22 (LxWxH)cm / 17"x4"x9"
	Vægt	15 kg	Weight	15 kg
H2 FillingStation™ 	Påfyldnings flow	Gennemsnitlig 65 L H2/min	Net storage rate	Average 65 L H2/min
	Tilslutningstryk	mellem 15-200 bar	Inlet pressure	15-200 bar (218-2900)PSIG
	Renlighed	99,999+%	Purity	99,999+%
	Opfyldningstid	30-60 minutter*(2 stk. H2 Canister *Afhænger af udetemperatur	Refilling time	30-60 minutes*(3800L 2 unit H2 Canister) *Depending on environment temperature
	Installation	Udendørs plan overflade og 230V AC tilslutning	Sitting location	Outdoor level with 230/110V AC outlet
	Dimensioner	80x46x90 (LxBxH)cm	Dimensions	80x46x90 (LxWxH)cm / 32"x19"x35"
	Vægt	85 kg (tørvægt uden H2 Canister™)	Weight	85 kg (dry weight without H2 Canister™)

Hybrid brændselscellesystemet på H2 Trucken sikrer øjeblikkelig start og optimal udnyttelse af brændstof. H2 Trucken har et unikt vandbehandlingssystem, hvorved vand fra udstødning på brændselscellen opsamles. Brint lagres ved lavt tryk i metalhydrider, hvilket sammen med sikkerheds-systemer i H2 PowerUnit gør H2 Trucken til et sikkert og pålideligt køretøj. På LCD touch screen displayet vises bl.a. brændstofniveau, effektforbrug m.v.

The H2 Truck hybrid drive system enables immediate startup and optimizes efficiency. The H2 Truck features a unique water recirculation system from the exhaust water of the fuel cell.
Hydrogen is stored in low-pressure hydride storage, combined with safety features in the H2 PowerUnit, makes the H2 Truck a safe and reliable vehicle. The digital fuel indication in the LCD touch screen display ensures reliable monitoring of the system and a precise indication of the fuel level. The display also gives the driver an easy control of the electronic system of the truck.

Integreret 230V udtag på H2 Trucken gør den ideel til anvendelse som vækstedsvogn eller renovationsvogn, hvor der ofte er behov for mobil strøm.

The H2 Truck features a 230/110V power outlet, which makes the H2 Truck ideal for use in workshops, warehouses or as small refuse truck for use in inner cities or parks.

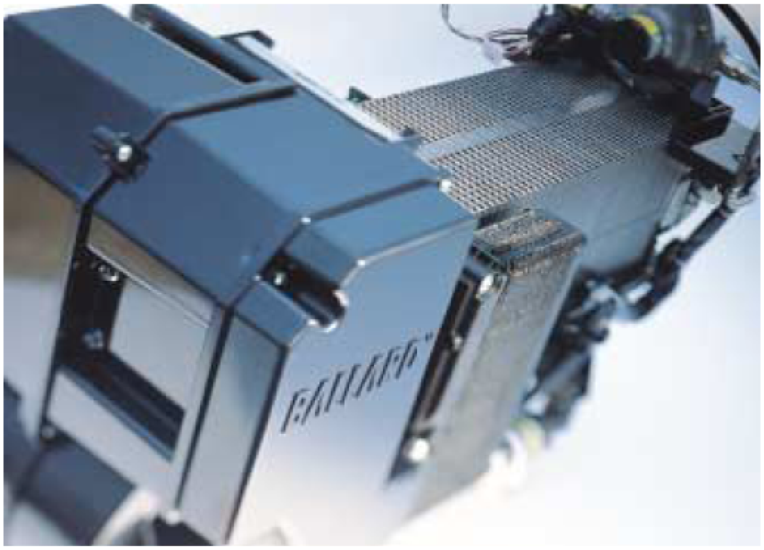
APPENDIX E BALLARD NEXA PEM FUEL CELL SPECIFICATION

Ballard® fuel cell power module

Nexa®

power generation

BALLARD®
power to change the world®



NEXA®

Ballard Power Systems introduces the Nexa® power module, the world's first volume-produced proton exchange membrane (PEM) fuel cell module designed for integration into a wide variety of stationary and portable power generation applications. Using Ballard's PEM technology, the Nexa® power module converts hydrogen fuel and oxygen (from air) in a non-combustive electro-chemical reaction to generate up to 1200 watts of unregulated DC electrical power.

Emitting heat and water as by-products of power generation, the Nexa® power module allows original equipment manufacturer products to be used in indoor environments and other locations not possible with conventional internal combustion engines. The Nexa® power module's quiet operation and compact size make it ideal for integration into uninterruptible power supply systems, emergency power generators, and recreational and portable products. And unlike battery technology with limited run-times, the Nexa® power module is capable of providing full extended run backup or intermittent electrical power for as long as fuel is supplied to the unit.

Brought to you by Ballard—the world leader in PEM fuel cell technology. The Nexa® power module is backed by over 15 years of experience in the development of premium fuel cell products for transportation, stationary and portable applications.

Specifications

Performance :	Rated net power	1200 watts[1]
	Rated current	46 Amps[1]
	DC voltage range	22 to 50 Volts
	Operating lifetime	1500 hours
Fuel :	Composition	99.99% dry gaseous hydrogen
	Supply pressure	10 to 250 PSIG
	Consumption	≤ 18.5 SLPM[2]
Operating Environment :	Ambient temperature	3°C to 30°C *(37°F to 86°F)*
	Relative humidity	0% to 95%[3]
	Location	Indoors and outdoors[4]
Physical :	Length x width x height	56 x 25 x 33 cm *(22 x 10 x 13 in)*
	Weight	13 kg *(29 lbs)*
Certification :		CSA, UL
Emissions :	Liquid water	0.87 liters *(30 fluid oz.)* maximum per hour[2]
	Noise	≤ 72 dBA @ 1 meter
Integration :	Fuel interface	45° flared tube fitting for 1/4" OD tubing – metallic
	Electrical interface	#8 AWG electrical wire
	Control interface	Full duplex RS 485

[1] Beginning of life, sea level, rated temperature range.
[2] At rated net power.
[3] Non-condensing.
[4] Unit must be protected from inclement weather, sand and dust.

Specifications and descriptions in this document were in effect at the time of publication. Ballard Power Systems Inc. reserves the right to change specifications or to discontinue products at any time (10/03).

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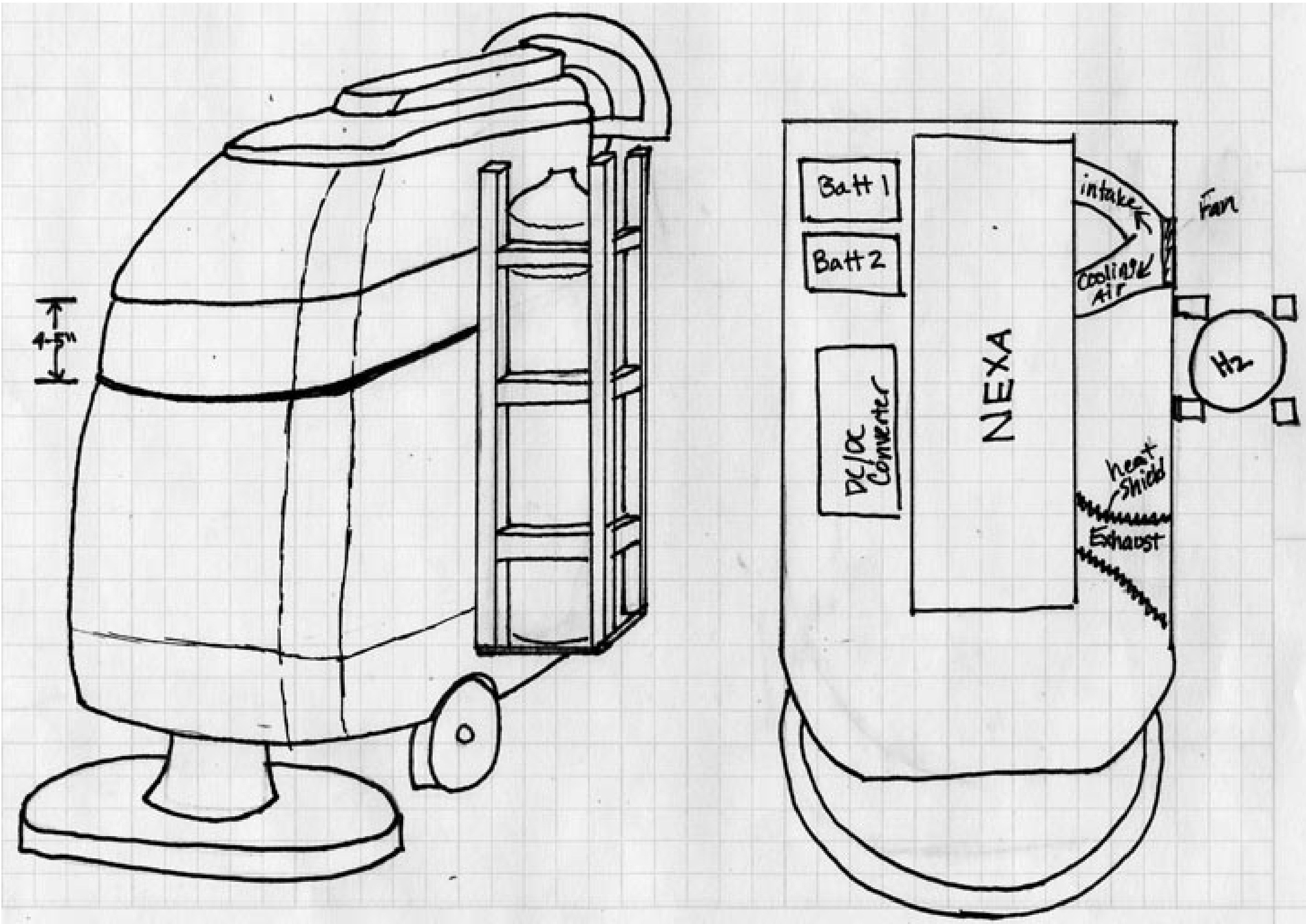
Burnaby, British Columbia
Canada V5J 5J9

APPENDIX F HIGH-LEVEL CONCEPTS

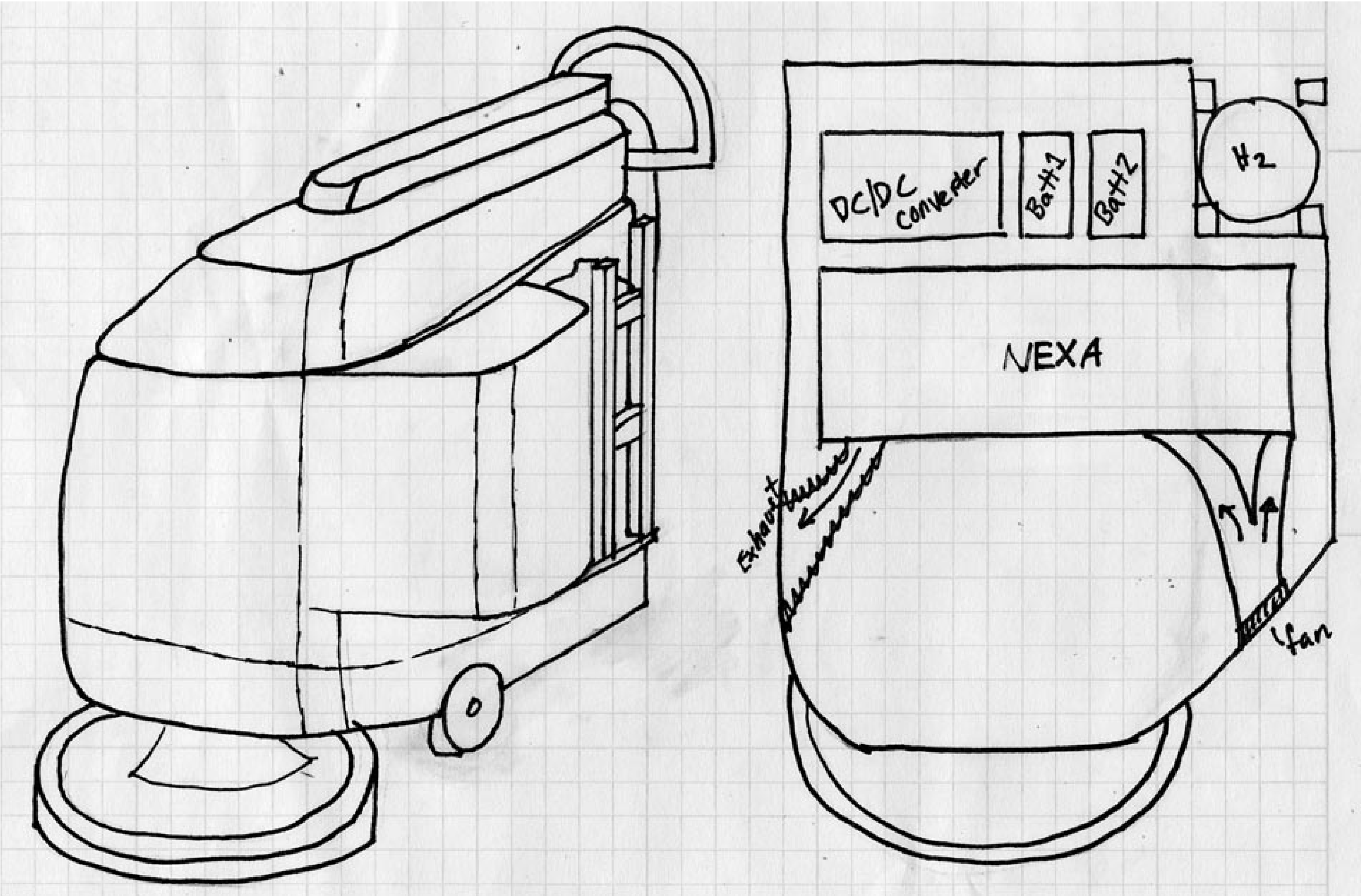
Function	Concept A	Concept B	Concept C	Concept D	Concept E	Concept F	Concept G	Concept H
Convert Voltage	Commercial DC/DC converter	Commercial DC/DC converter	Commercial DC/DC converter	Commercial DC/DC converter	Commercial DC/DC converter	Commercial DC/DC converter	Commercial DC/DC converter	Commercial DC/DC converter
Store Fuel	Commercially available compressed gas tank (welding supplies)	Customized compressed gas tank	Metal hydride lattice storage	Metal hydride lattice storage	Metal hydride lattice storage	Customized compressed gas tank	Commercially available compressed gas tank (welding supplies)	Customized compressed gas tank
Deliver H_2	Compressed gas delivery system (pressure regulator)	Compressed gas delivery system (pressure regulator)	Pressure regulator designed for metal hydride storage	Pressure regulator designed for metal hydride storage	Pressure regulator designed for metal hydride storage	Compressed gas delivery system (pressure regulator)	Compressed gas delivery system (pressure regulator)	Compressed gas delivery system (pressure regulator)
Deliver O_2	Ducting with forced air system	Ducting with forced air system	Ducting with forced air system	Ducting with forced air system	Ducting with forced air system	Ducting with forced air system	Ducting with forced air system	Open to environment
Remove Heat	Ducting with heat shield and forced air system	Ducting with heat shield and forced air system	Ducting with heat shield and forced air system	Ducting with heat shield and forced air system	Ducting with heat shield and forced air system	Ducting with heat shield and forced air system	Ducting with heat shield and forced air system	Open to environment
Protect Hydrogen	Protective frame around container	Protective frame around container	Protective frame around container	Protective frame around container	Store hydrogen inside the scrubber body	Store hydrogen inside the scrubber body	Protective frame around container	Protective frame around container
Monitor H_2 Level	H_2 detector built into fuel cell	H_2 detector built into fuel cell	H_2 detector built into fuel cell	H_2 detector built into fuel cell	H_2 detector built into fuel cell	H_2 detector built into fuel cell	H_2 detector built into fuel cell	H_2 detector built into fuel cell
Contain Fuel Cell	Adjust shroud upward to fit in the fuel cell	Extend shroud outward to fit in the fuel cell	Adjust shroud upward to fit in the fuel cell	Extend shroud outward to fit in the fuel cell	Exterior addition to scrubber to hold fuel cell	Exterior addition to scrubber to hold fuel cell	Extend shroud outward to fit in the fuel cell	Adjust shroud upward to fit in the fuel cell

APPENDIX G **HIGH-LEVEL CONCEPT SKETCHES**

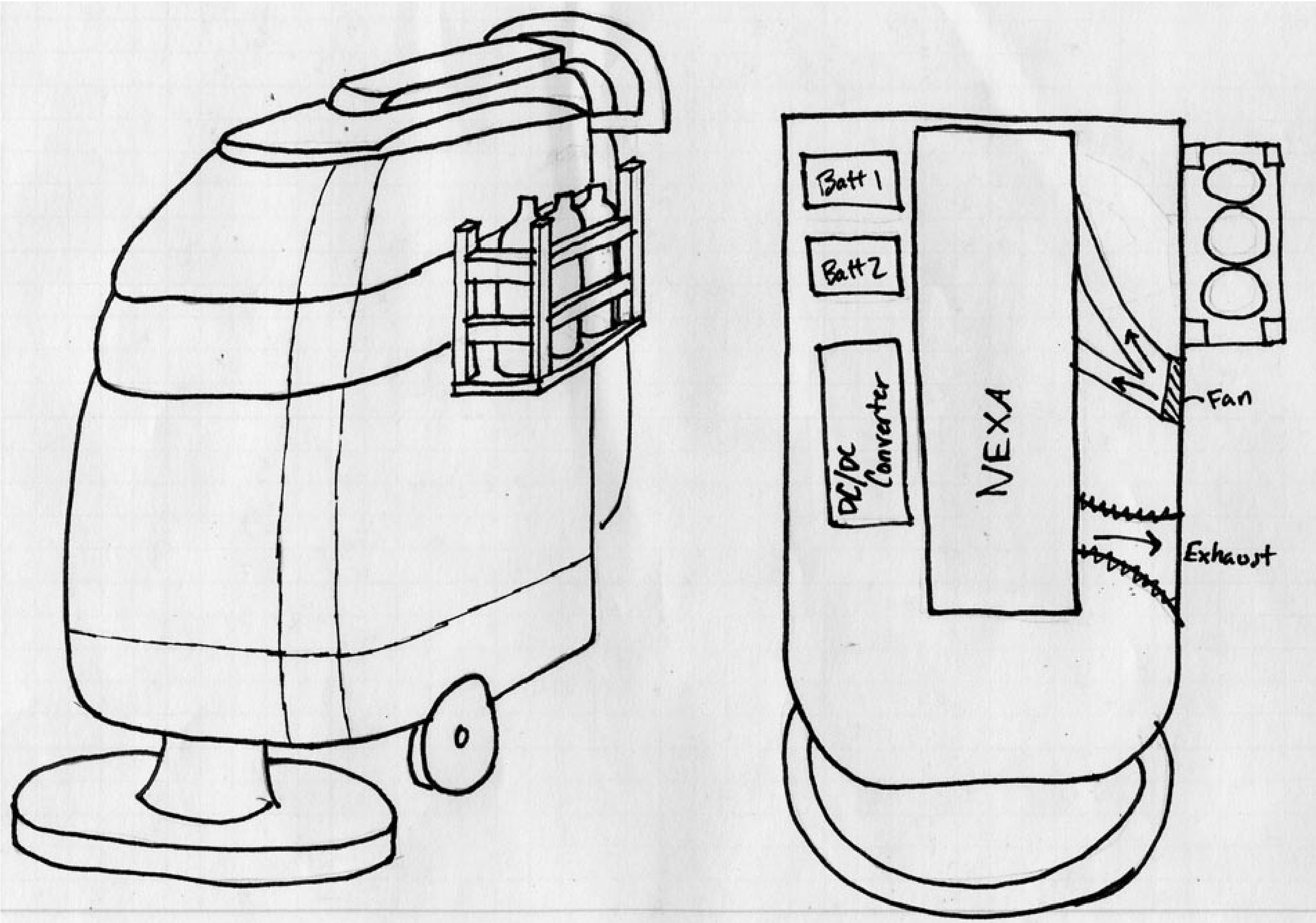
G.1 Concept A



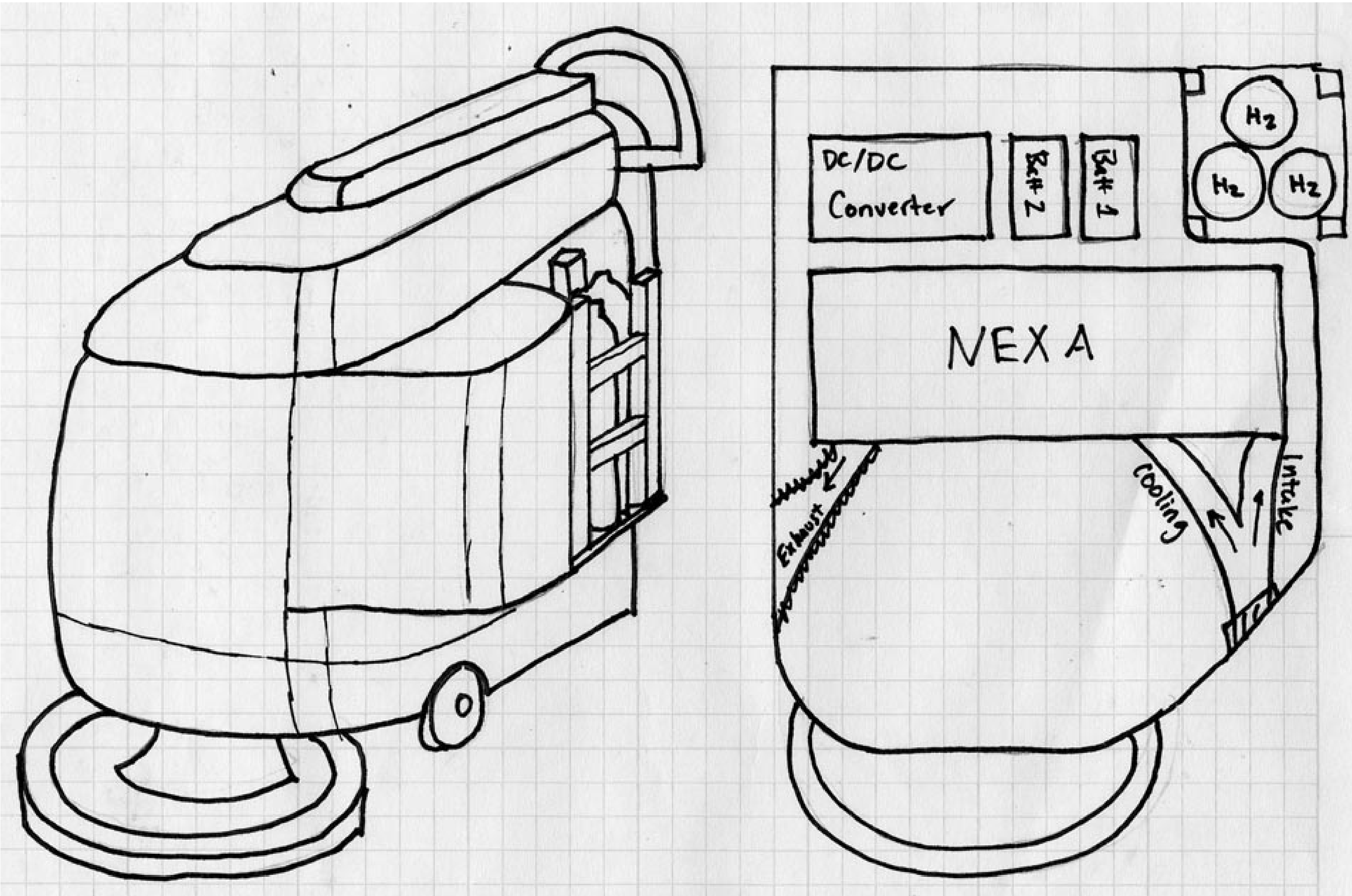
G.2 Concept B



G.3 Concept C

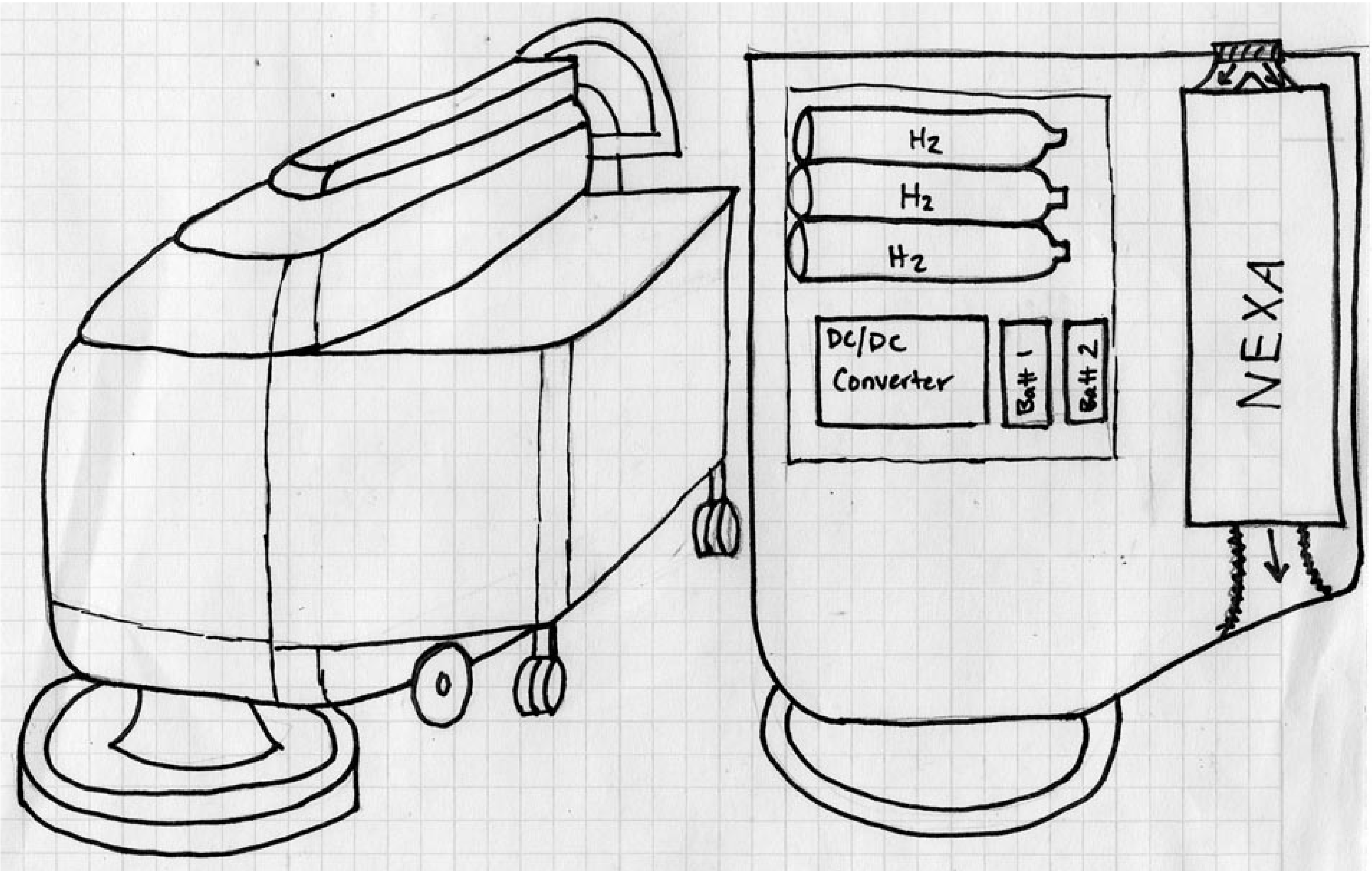


G.4 Concept D

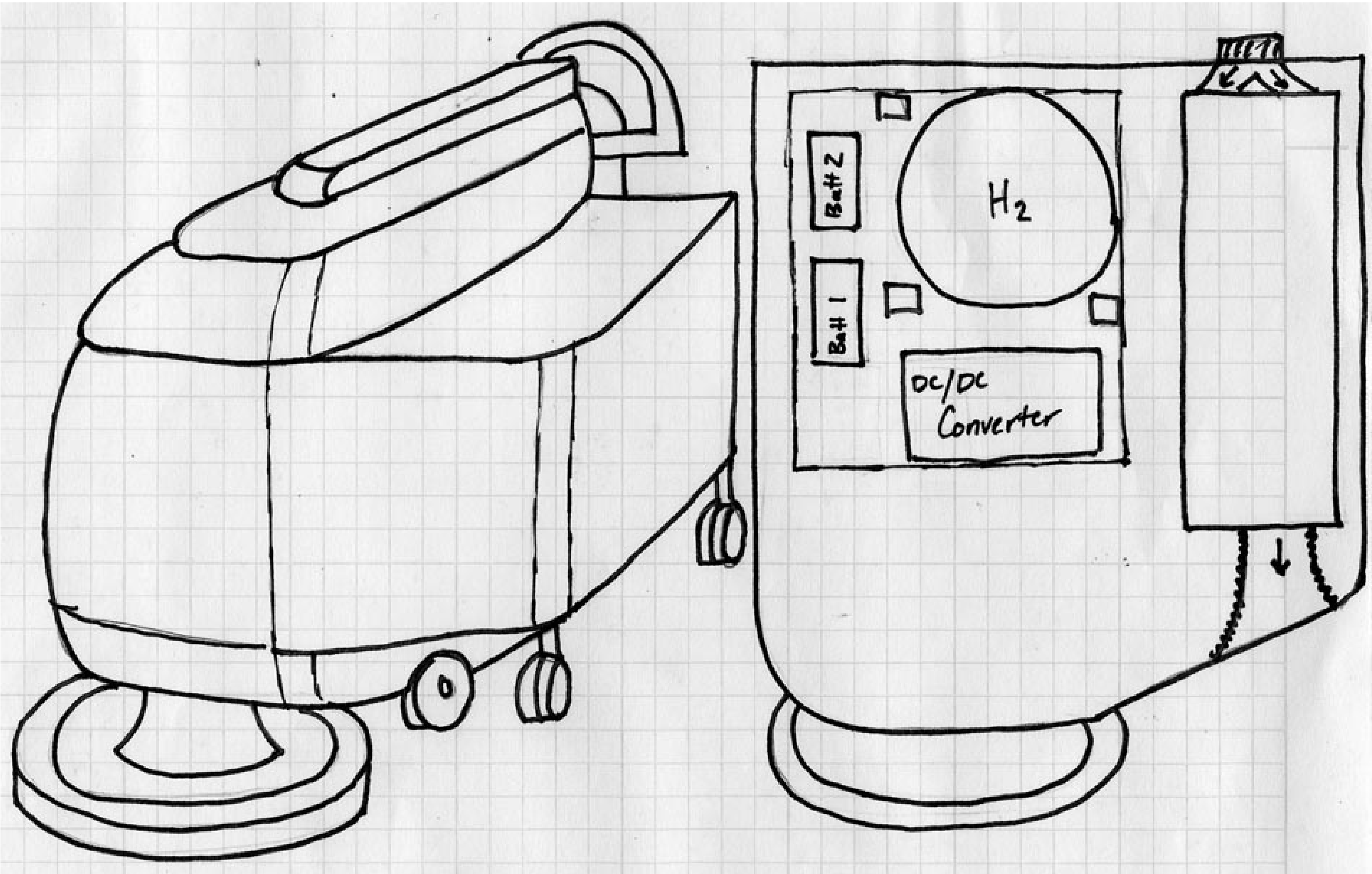


DC/DC Converter
Batt 2
Batt 1
H2
H2
H2
NEXA
Exhaust
Cooling
Intake

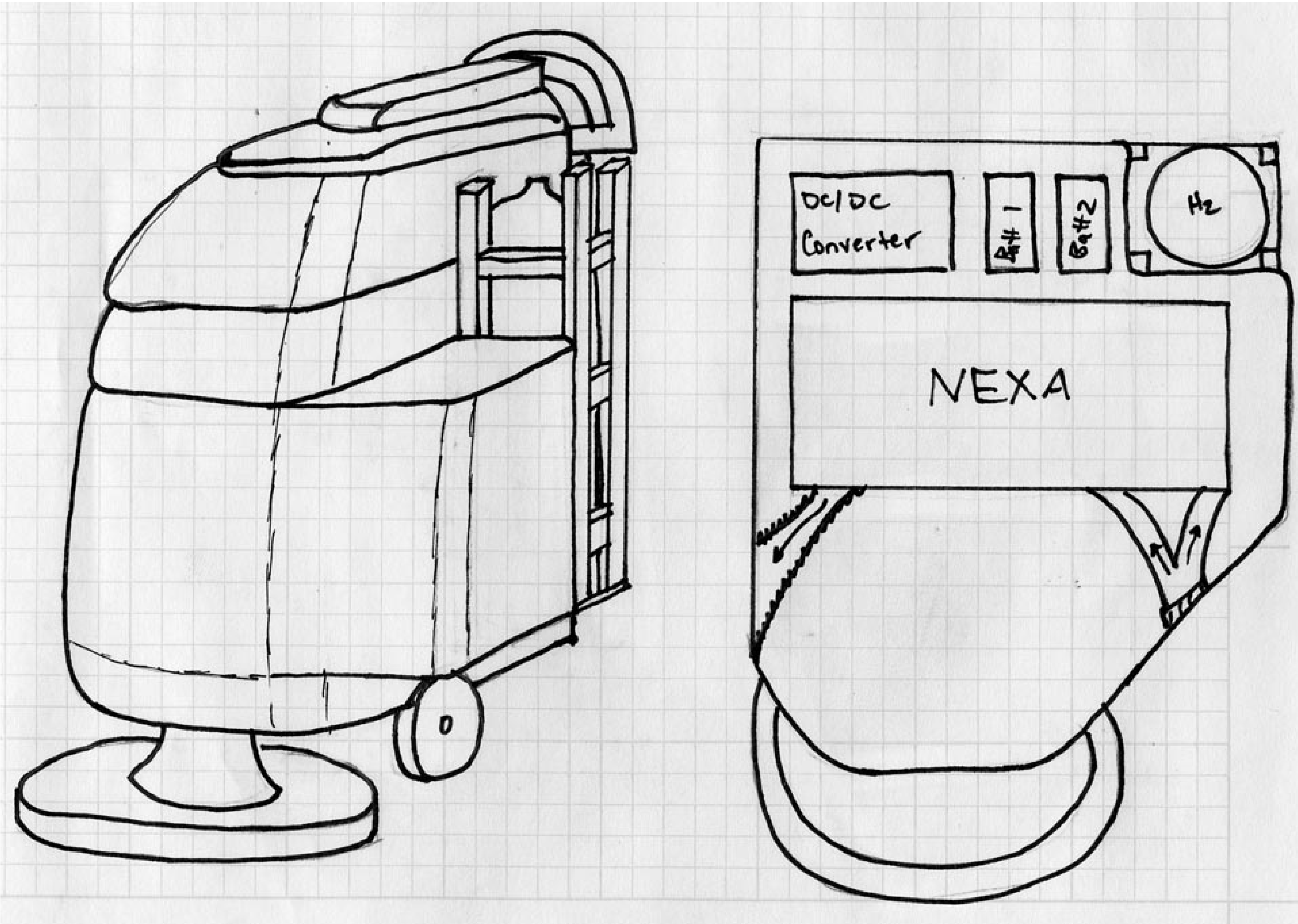
G.5 Concept E



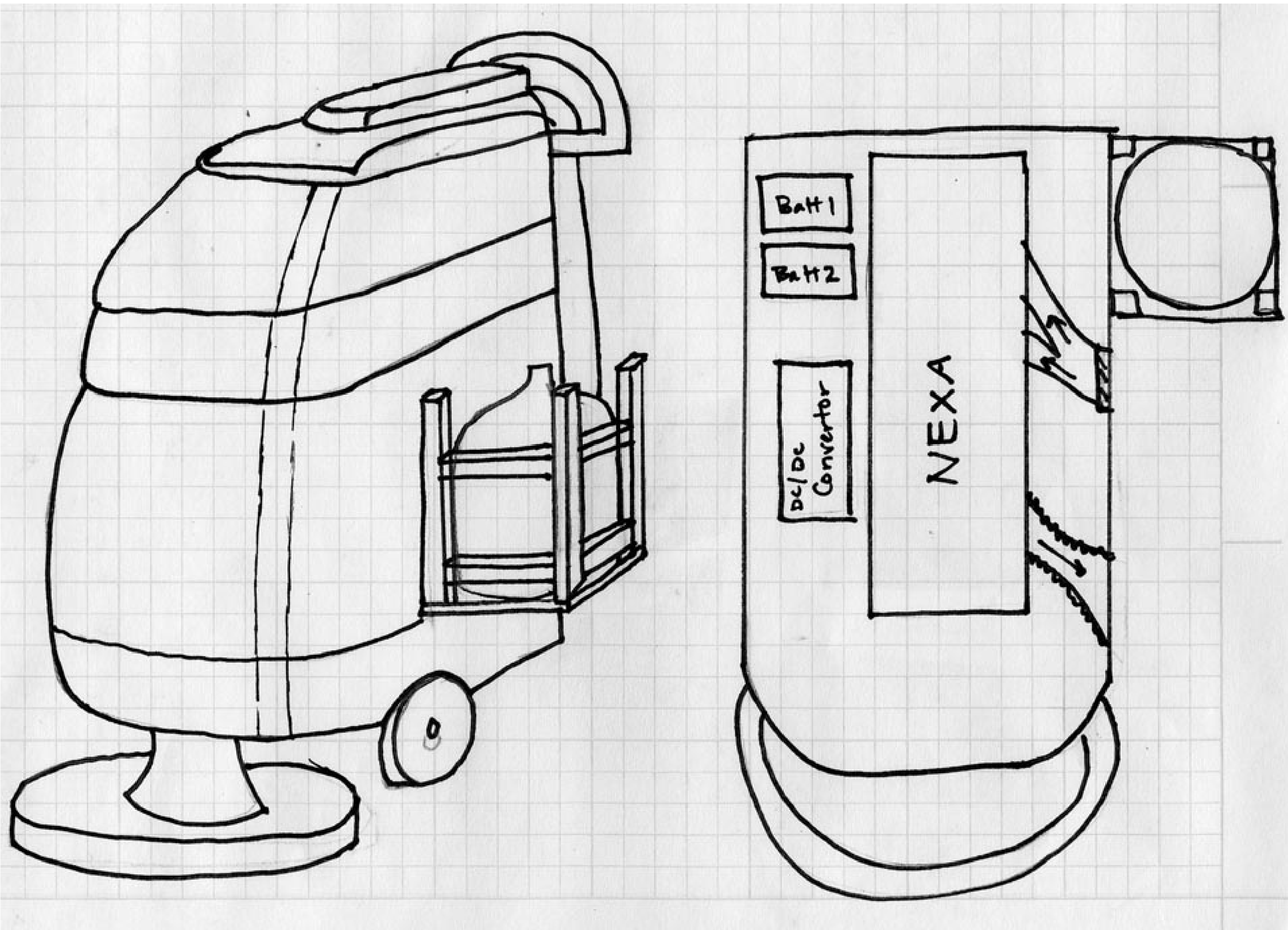
G.6 Concept F



G.7 Concept G

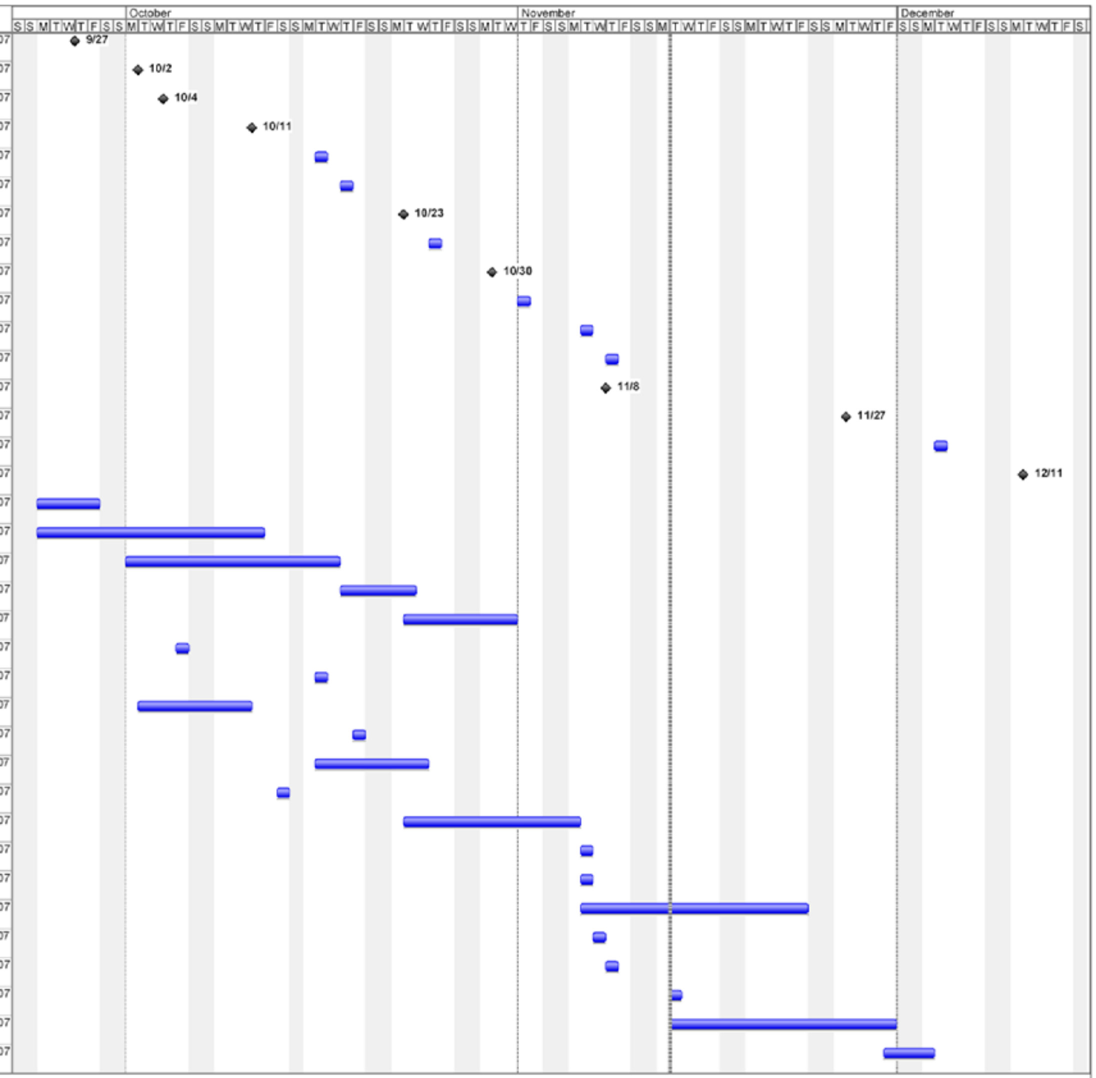


G.8 Concept H



APPENDIX H GANTT CHART

ID	Task Name	Duration	Start	Finish
1	Design Review 1	0 days	Thu 9/27/07	Thu 9/27/07
2	Design Review 1 Feedback Emailed	0 days	Tue 10/2/07	Tue 10/2/07
3	Send Kazu Update Ppt	0 days	Thu 10/4/07	Thu 10/4/07
4	Send Kazu Update Ppt	0 days	Thu 10/11/07	Thu 10/11/07
5	Fall Study Break	1 day?	Tue 10/16/07	Tue 10/16/07
6	Informal Chat	1 day?	Thu 10/18/07	Thu 10/18/07
7	Design Review 2	0 days	Tue 10/23/07	Tue 10/23/07
8	Informal Chat	1 day?	Thu 10/25/07	Thu 10/25/07
9	Design Review 2 Feedback	0 days	Tue 10/30/07	Tue 10/30/07
10	Informal Chat	1 day?	Thu 11/1/07	Thu 11/1/07
11	Short Presentation	1 day?	Tue 11/6/07	Tue 11/6/07
12	Informal Chat	1 day?	Thu 11/8/07	Thu 11/8/07
13	Design Review 3	0 days	Thu 11/8/07	Thu 11/8/07
14	Design Review 4	0 days	Tue 11/27/07	Tue 11/27/07
15	Design Expo	1 day	Tue 12/4/07	Tue 12/4/07
16	Final Report Due	0 days	Tue 12/11/07	Tue 12/11/07
17	Preliminary Information Gathering	5 days	Mon 9/24/07	Fri 9/28/07
18	Investigate/characterize NEXA Fuel Cell	14 days	Mon 9/24/07	Thu 10/11/07
19	Research possible solutions to power transfer problem	14 days	Mon 10/1/07	Wed 10/17/07
20	Propose subfunction solutions to get scrubber running	4 days?	Thu 10/18/07	Tue 10/23/07
21	Determine specific solutions to subfunctions to get scrubber	7 days	Tue 10/23/07	Wed 10/31/07
22	Meet with Dr. Chang to discuss safety concerns, NEXA fuel c	1 day?	Fri 10/5/07	Fri 10/5/07
23	Obtain hydrogen safety training w/ Dr. Chang	1 day?	Tue 10/16/07	Tue 10/16/07
24	Locate suitable hydrogen source for testing in lab	7 days	Tue 10/2/07	Wed 10/10/07
25	Obtain lab space	1 day?	Fri 10/19/07	Fri 10/19/07
26	Get approval to use hydrogen in lab	7 days?	Tue 10/16/07	Wed 10/24/07
27	Purchase necessary electronic components	1 day	Sat 10/13/07	Sat 10/13/07
28	Entire team in lab, attempting to run fuel cell on bench	10 days	Tue 10/23/07	Mon 11/5/07
29	Discovered DC/DC converter does not power on	1 day	Tue 11/6/07	Tue 11/6/07
30	In lab, hooked up all hydrogen and electrical connections	1 day	Tue 11/6/07	Tue 11/6/07
31	Attempted to power on fuel cell; nothing happened	14 days	Tue 11/6/07	Fri 11/23/07
32	Finalized CAD of all components	1 day	Wed 11/7/07	Wed 11/7/07
33	DR3 Presentation	1 day?	Thu 11/8/07	Thu 11/8/07
34	Talked with Fred and Heliocentris about solutions to DC/DC	1 day?	Tue 11/13/07	Tue 11/13/07
35	Fabrication of components	14 days?	Tue 11/13/07	Fri 11/30/07
36	Installation of components	2 days?	Fri 11/30/07	Mon 12/3/07



APPENDIX I FAILURE MODE EFFECT ANALYSIS

Product Name: T3 Scrubber with NEXA Fuel Cell
_______ System
_______ Subsystem Name: _________
_______ Component

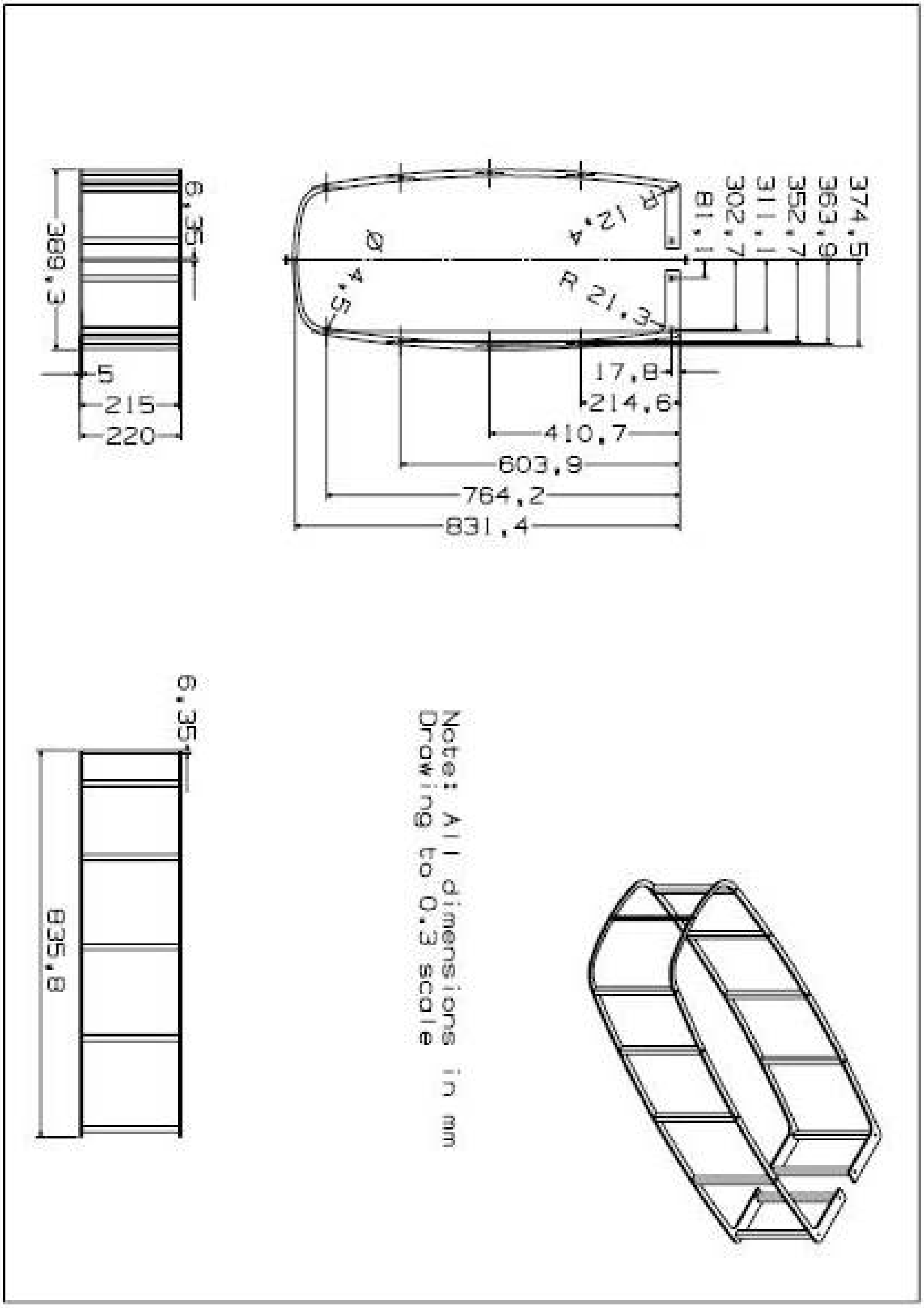
Devel Team: Theresa DeVree, Michael Grenier, Ryan Kotenko, and Andrew Olive
**Adapted from Winter '07 Project Team

Page No. 1 of 1
FMEA Number 1
Date: 11/6/07

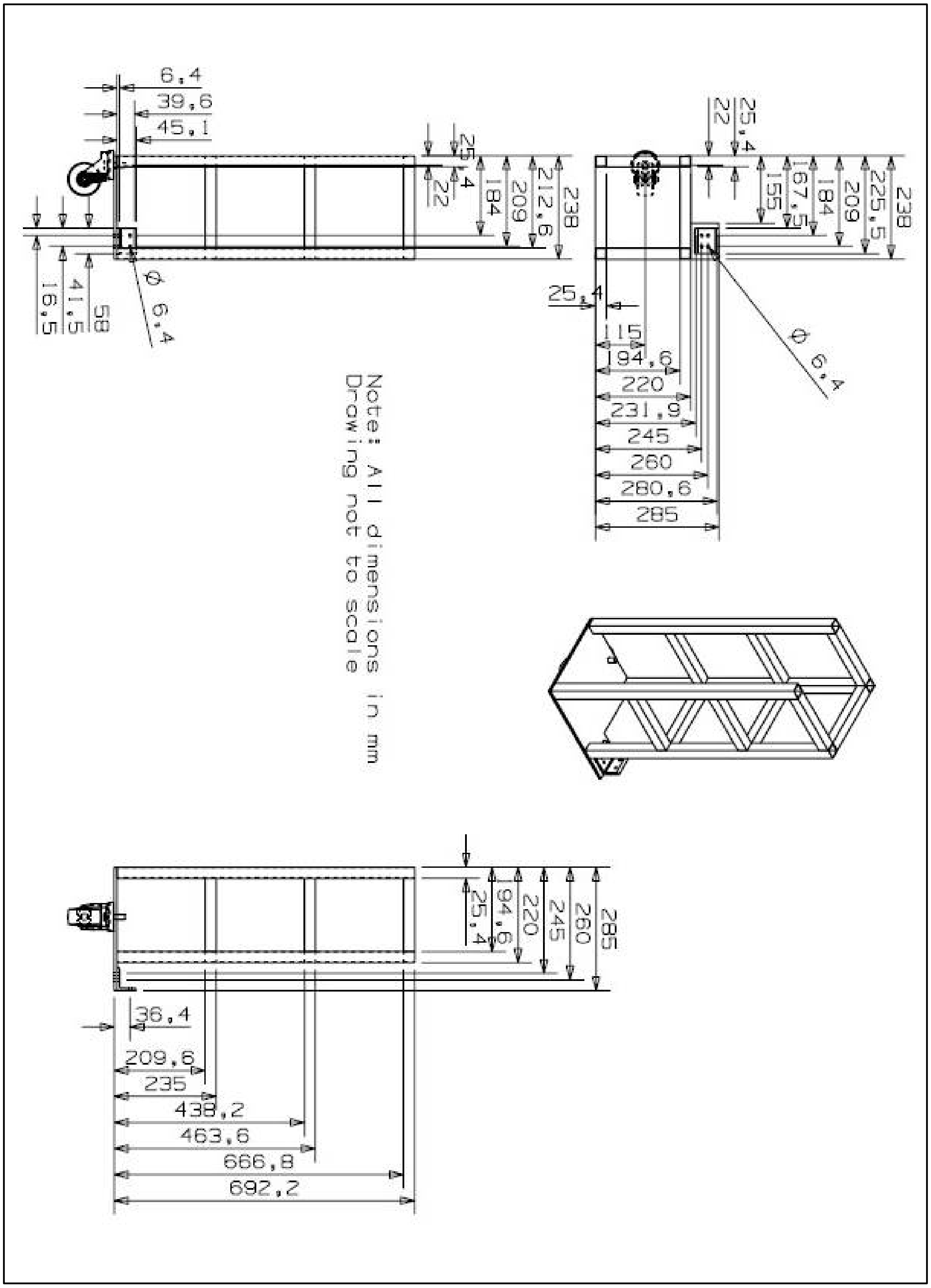
Part # & Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes/ Mechanism(s) of Failure	Occurrence (O)	Current Design Controls/Tests	Detection (D)	Recommended Actions	RPN	new S	new O	new D	new RPN
2 -NEXA	Hydrogen leak while operating	flammability, asphixiation	9	fuel cell stack leak, loose fittings, broken seal, non-functioning solenoid valves	1	Internal hydrogen sensors in NEXA exhast system will shutdown fuel cell if too much hydrogen is detected	1	Routine preventative maintence of fuel cell compononents; Hydrogen detector in scrubber shell	9	9	1	1	9
2 -NEXA	Hydrogen leak while not operating	flammability, asphixiation	9	non-functioning hydrogen solenoid and purge valve	1	External hydrogen detection before reaching flammable level	3	Storage of scrubber in a room with hydrogen detection; Hydrogen detector in scrubber shell	27	9	1	3	27
7-Hydrogen Tank	Hydrogen leak while attended	flammability, asphixiation	9	a leak in the hydrogen tank, bad or broken seals, loose fittings, or a leak in the hose or regulator	2	External hydrogen detection before reaching flammable level	3	Routine preventative maintence of hydrogen lines; Special hydrogen installation hook-up	54	9	2	3	54
7-Hydrogen Tank	Hydrogen leak while unattended	flammability, asphixiation	10	operator leaving a tank connected improperly when leaving the worksite, a leak in the hydrogen tank, bad or broken seals, loose fittings, or a leak in the hose or regulator	3	External hydrogen detection before reaching flammable level	3	Storage of scrubber in a room with hydrogen detection; A wireless external hydrogen detector could be used to detect hydrogen leaks and send alerts to a reciever up to 75 feet away	90	10	3	2	60
5-Voltage Conversion	electrical overload of scrubber parts	motor damage, control board damage, overheat, loss of control	9	Power regulation failure or fuel cell malfunction	1	Fuses break. Burning odor.	2	Routine preventative maintence of fuel cell compononents	18	9	1	2	18
5-Voltage Conversion	power insufficint to run scrubber	scrubber shuts down, poor performance	7	fuel cell malfunction, out of fuel	6	Scrubber has minimum voltage detection. Visual voltage detection on scrubber. Gauge on fuel tank.	2	Routine preventative maintence of fuel cell compononents; Limit on pressure drop of fuel tank	84	7	4	2	56
8-Hydrogen Frame	tank frame failure	injury, hydrogen leak, cylinder damage, regulator damage	8	improperly secured, fastener malfunction, mounting breaks, shock load	3	Visual inspection for loose parts. Listen for rattling.	1	Routine preventative maintence of fuel cell compononents; built tank as part of scrubber frame	24	8	2	1	16
4-Ducting	thermal damage to scrubber	polyethelene structure melts, burning	9	improper ventilation or insulation, obstruction of air flow	2	Odor, visual inspection	3	Routine preventative maintence of scrubber components; NEXA set to turn off if insufficient flow	54	9	1	2	18
2-NEXA	fuel cell system fails	scrubber doesn't receive power	5	high stack temp due to operating above rated power, high abent temp, cooling fan or cooling exhast obstruction, cooling fan/motor failure, air exhaust leaking into fan intake. High or low pressure due to low fuel or low fuel delivery pressure	5	NEXA has internal system of controls and sensors. It will automatically shut down when operating out of desired range. If the system experiences a self test of software fault it will enter a non-restartable mode.	2	Routine preventative maintence of fuel cell compononents; design for ease of removing fuel cell to replace	50	5	5	2	50
5-Voltage Conversion	auxilliary battery failure	fuel cell won't start	4	Battery not charged or defective	1	Confirm battery voltage	4	Routine preventative maintence of voltage convertor compononents, set DC/DC Converter to not let charge fall below certain level	16	4	1	2	8
2-NEXA	component freezing	fuel cell won't start while frozen	2	Ambient temp too low	1	Measure ambient temp	1	Store and operate scrubber at room temperatures	2	2	1	1	2

APPENDIX J DIMENSIONED CAD DRAWINGS

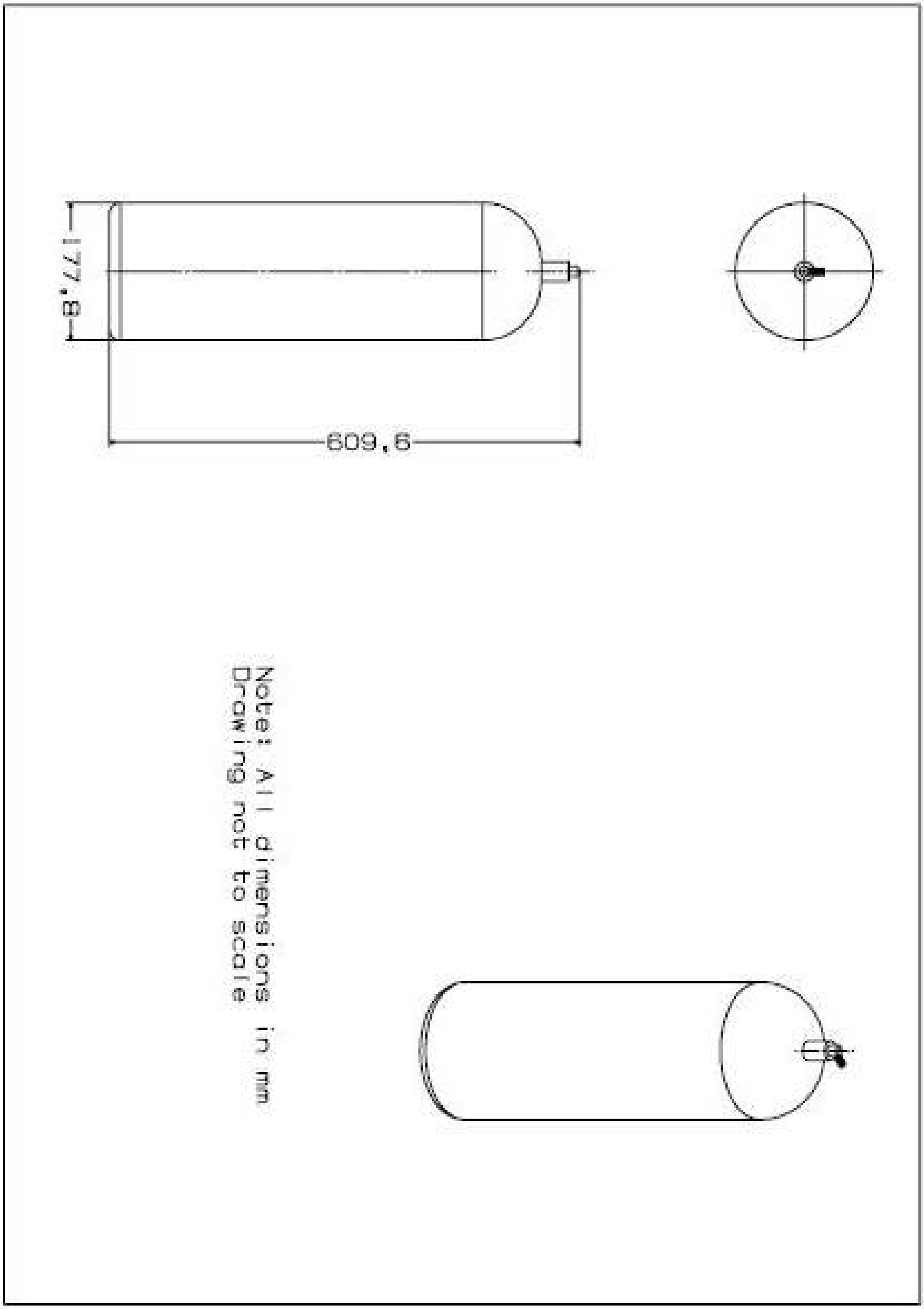
J.1 Riser



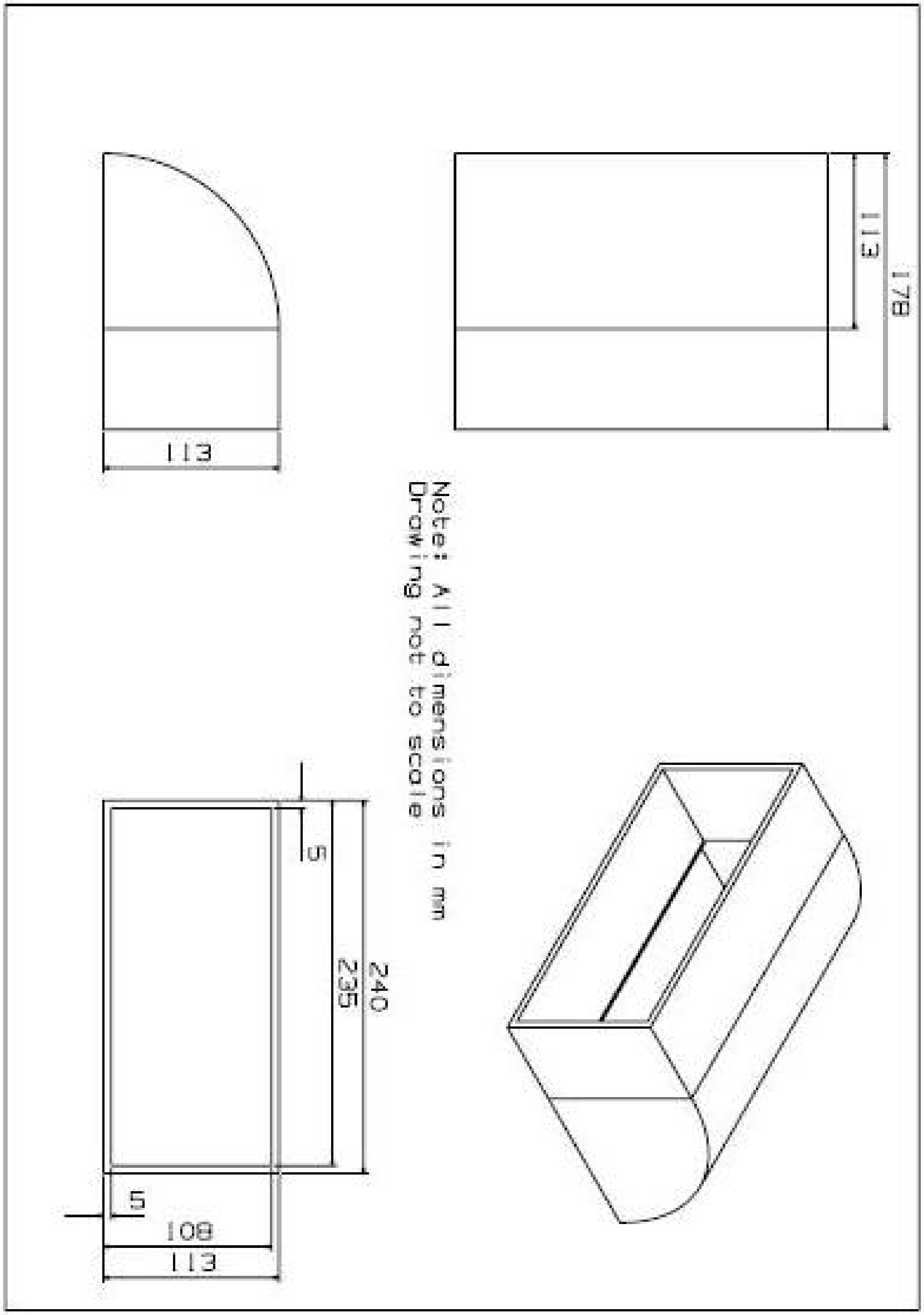
J.2 Hydrogen Frame



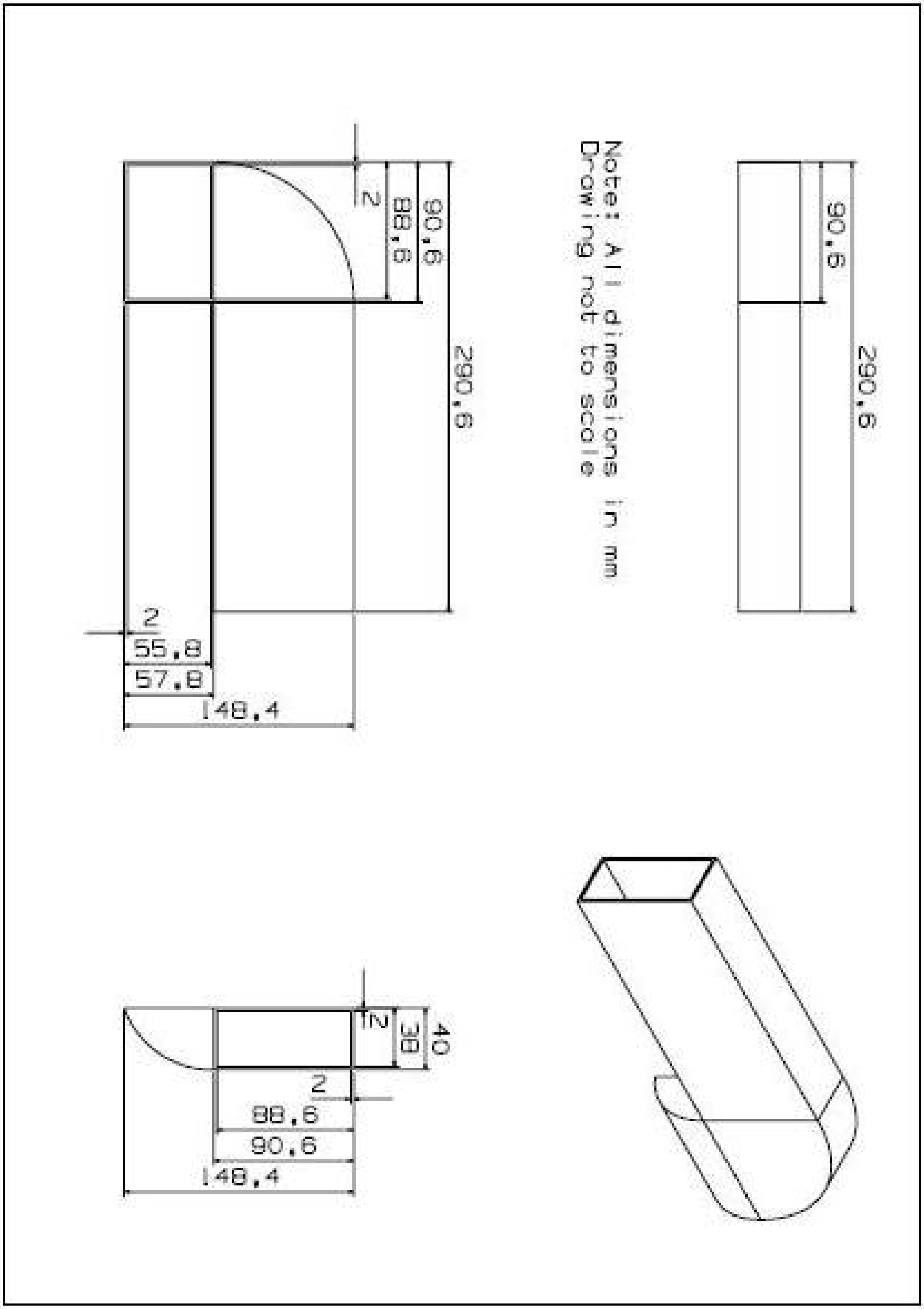
J.3 Hydrogen Tank



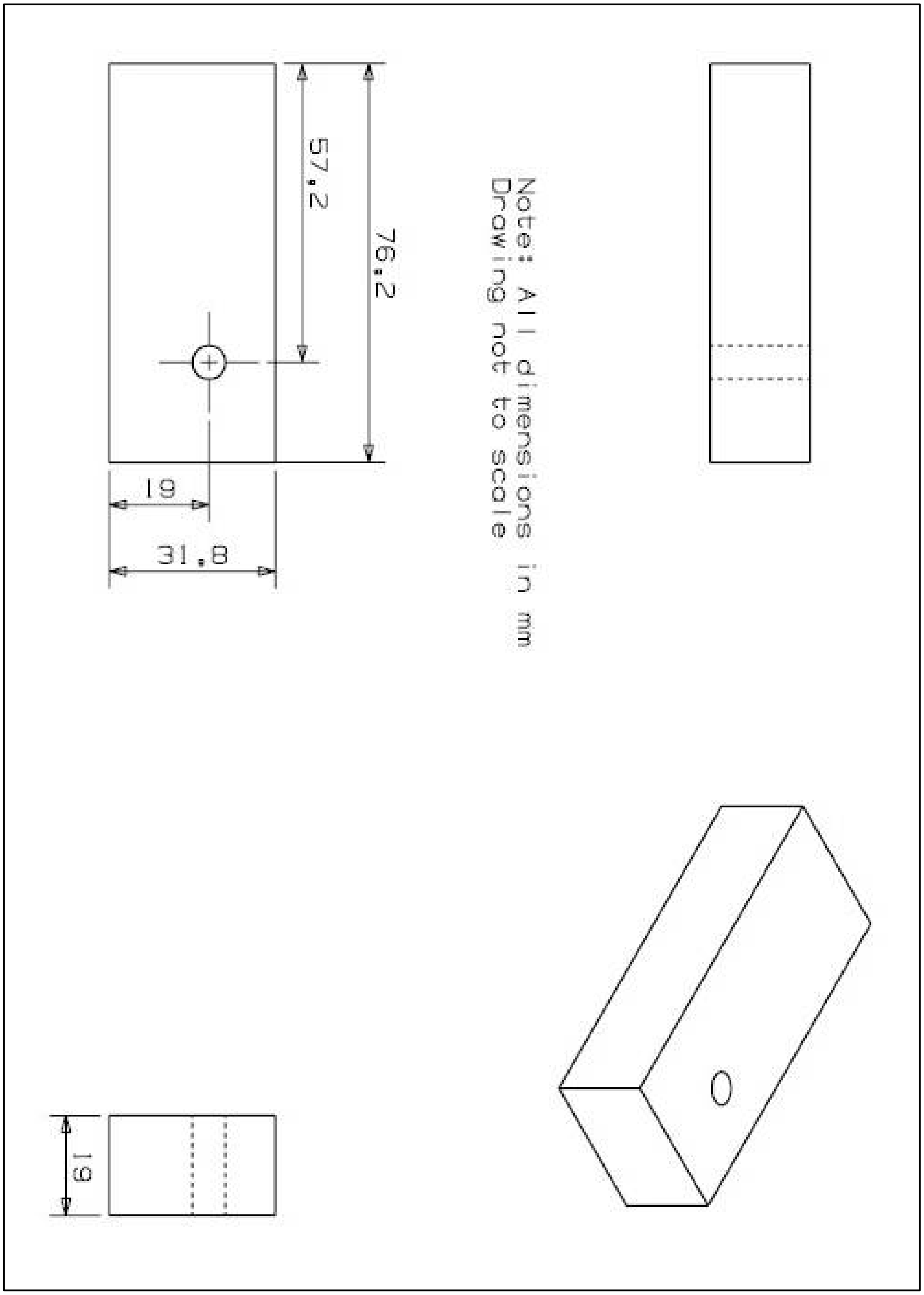
J.4 Hot Air Duct



J.5 Cold Air Duct

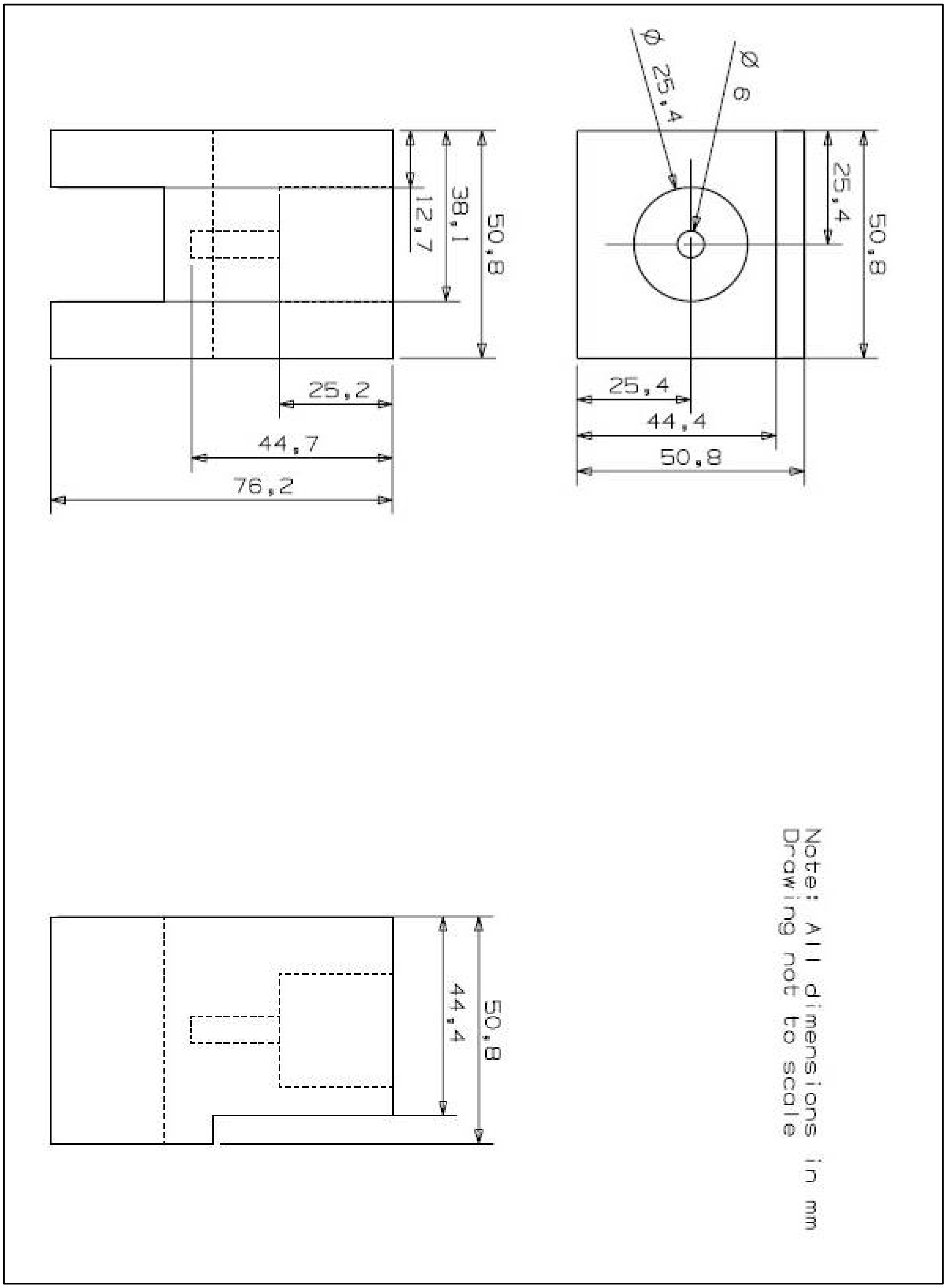


J.6 Front NEXA Support

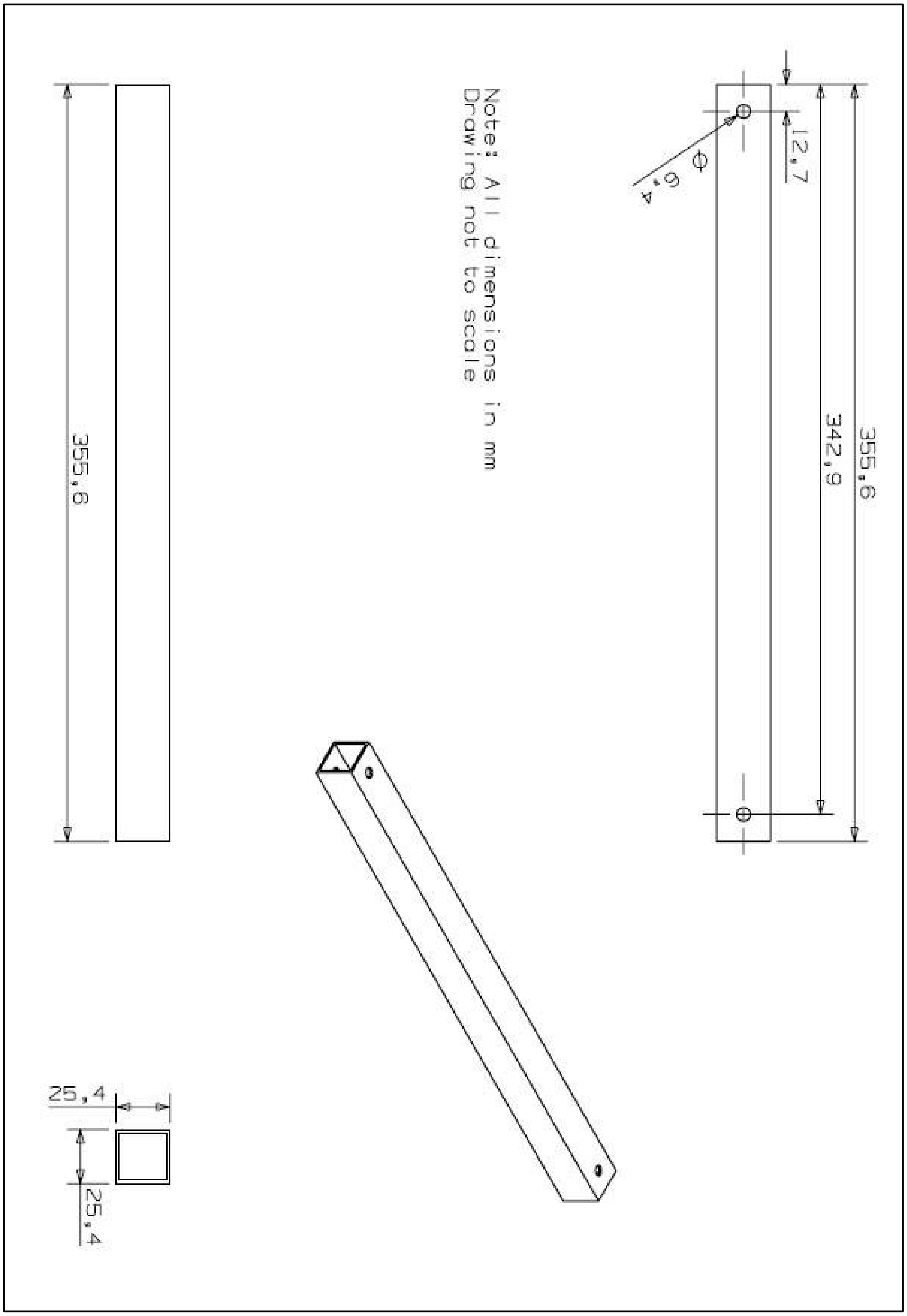


J.7 Rear NEXA Support

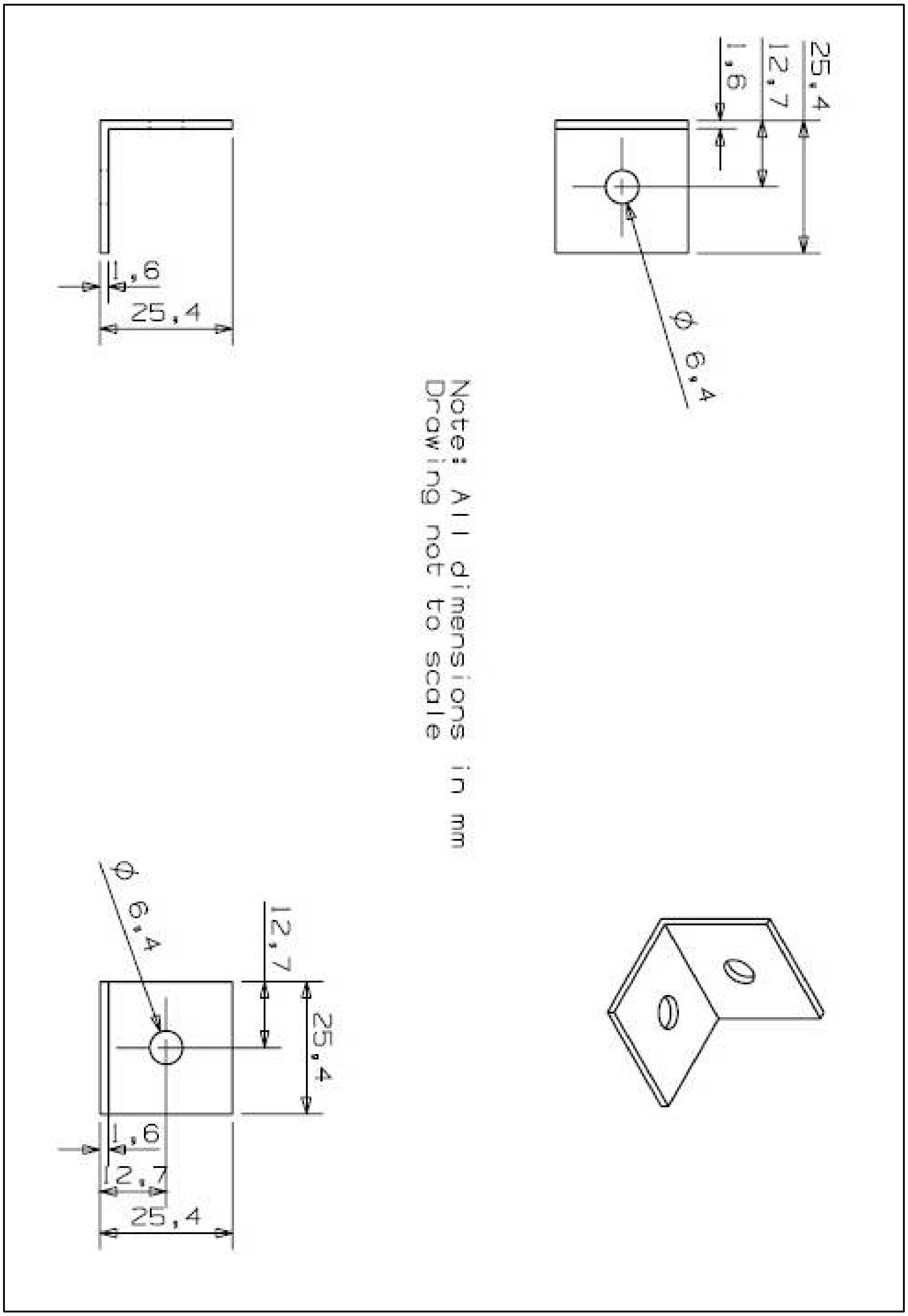
J.7.1 Back Foot



J.7.2 Back Bar


Note: All dimensions in mm
Drawing not to scale
12,7
Φ 6,4
342,9
355,6
355,6
25,4
25,4

J.7.3 Back Bracket



APPENDIX K BILL OF MATERIALS

Level	Part No.	Description	Make/Buy/Given	Supplier	Quantity	Cost	Unit	Total Cost
A	***1***	***T3 Scrubber***	***Given***	***Tennant***	***1***	***$0.00***	***Ea***	***$0.00***
B	***2***	***NEXA***	***Given***	***Tennant***	***1***	***$0.00***	***Ea***	***$0.00***
C	***3***	***Internal Mounting***	***Make***					
	3-1	*2" square PVC Bar stock*	Given	ME Machine Shop	4	$0.00	Ea	$0.00
	3-2	1" square hollow bar stock - 355 mm long	Given	ME Machine Shop	1	$0.00	Ea	$0.00
	3-3	10-24 x 1/2" bolts	Buy	Carpenter Bros	6	$0.12	Ea	$0.72
	3-4	1/8" thick aluminum sheet	Given	ME Machine Shop	1	$0.00	Ea	$0.00
D	***4***	***Ducting System***	***Make***					$0.00
	4-1	30 gauge galvanized steel sheet (16"x35")	Buy	Home Depot	1	$7.11	Ea	$7.11
	4-2	Foil Tape	Buy	Home Depot	1	$2.79	Ea	$2.79
E	***5***	***Voltage Conversion***	***Buy***					
	5-1	*DC/DC Converter*	Given	Heliocentris	1	$0.00	Ea	$0.00
F	***6***	***Riser***	***Make***					
	6-1	1/8" thick aluminum sheet	Given	ME Machine Shop	2	$0.00	Ea	$0.00
	6-2	1/2" square bar stock - 2880mm long	Given	ME Machine Shop	1	$0.00	Ea	$0.00
	6-3	1/4" square bar stock - 240mm long	Given	ME Machine Shop	1	$0.00	Ea	$0.00
	6-4	10-24 x 1/2" bolts	Buy	Home Depot	24	$0.16	Ea	$3.84
	6-5	4-40 x 1/2" bolts	Buy	Home Depot	2	$0.49	Ea	$0.98
	6-6	Treasure chest style brackets	Buy	Carpenter Bros	4	$2.50	Ea	$9.98
	6-7	Weatherstripping	Buy	Murray's	3	$7.95	Ea	$23.85
G	***7***	***Hydrogen Tank and Gas***	***Buy***					
	7-1	Fill size Q compressed hydrogen tank	Buy	Cryogenic Gases, Inc	1	$12.00	Ea	$12.00
	7-2	1 size Q compressed hydrogen tank	Rent	Cryogenic Gases, Inc	2	$2.77	Month	$5.54
H	***8***	***Hydrogen Frame***	***Make***					
	8-1	6'L x 3/8" T x 1" ID foam pipe insulation	Buy	Home Depot	1	$1.94	Ea	$1.94
	8-2	1" square hollow bar stock - 4400 mm long	Given	ME Machine Shop	1	$0.00	Ea	$0.00
	8-3	1/2" aluminum sheet (230x250 mm)	Given	ME Machine Shop	1	$0.00	Ea	$0.00
	8-4	1/4" aluminum L Bracket	Given	ME Machine Shop	1	$0.00	Ea	$0.00
	8-5	1/4-20 x 1/2" Bolt	Given	ME Machine Shop	4	$0.00	Ea	$0.00
	8-6	1/4-20 x 1" Bolt	Given	ME Machine Shop	4	$0.00	Ea	$0.00
	8-7	1/4-20 Nut	Buy	Carpenter Bros	8	$0.12	Ea	$0.96
	8-8	Rubber Washer	Buy	Carpenter Bros	12	$0.25	Ea	$3.00
	8-9	Chain	Buy	Carpenter Bros	2	$0.69	Ft	$1.38
	8-10	Eye hook	Buy	Carpenter Bros	2	$2.42	Ea	$4.84
	8-11	Carabenier	Buy	Carpenter Bros	1	$1.09	Ea	$1.09
	8-12	1/4-20 x 4" Bolt	Buy	Carpenter Bros	2	$1.50	Ea	$3.00
	8-13	M12 Standard Thread Nut	Buy	Carpenter Bros	1	$1.30	Ea	$1.30
	8-14	Caster	Given	Tennant	1	$0.00	Ea	$0.00
Prototype Total (discounting cost of donated items)								$84.32
G	***9***	***Misc Items***						
	9-1	D-sub 9 crimp style connector	Buy	Radioshack	2	$1.99	Ea	$3.98
	9-2	22 Gauge wire	Buy	Radioshack	1	$4.99	Ea	$4.99
	9-3	D-sub to USB Converter	Buy	Newegg.com	2	$13.34	Ea	$26.68
	9-4	4 Gauge Wire	Buy	Home Depot	6	$1.28	Ft	$7.68
Project Total								$127.65

APPENDIX L PROCESS PLAN SHEETS

L.1 Riser

Process Plan Sheet for Riser *Stock: 1/8" Aluminum Sheet Metal, 1/2" square Aluminum Bar Stock, and 3/8" square Aluminum Bar Stock*			
Operation	**Tool**	**Parameters**	**Fixture**
Trace outline onto sheet metal	Marker	-	-
Mark holes on cut-out	Center Punch	-	-
Drill 4-40 clearance holes	Drill Press: #32 (.116 in) Drill bit	300 RPM	Clamps
Drill 10-24 clearance holes	Drill Press: #9 (.196 in) Drill bit	300 RPM	Clamps
De-burr holes	De-burring tool	-	-
Cut out traced objects (rough)	Bandsaw	600 RPM	-
Finish edges on cut-out	File	-	-
Cut 12 1/2" bars to 215 mm long	Bandsaw	-	Vice
Cut 1 3/8" bars to 215 mm long	Bandsaw	-	Vice
Set Bar in vice so that both ends can be milled	Mill	-	Vice
Face off one end of bar	Mill: Planar	1200 RPM	Vice
Move 210mm + end mill dia to other end of bar	Mill	-	Vice
Face off other end	Mill: Planar	1200 RPM	Vice
Repeat until all bars are faced off	-	-	-
Place Bar into Lathe and center	Lathe	-	1/2" Square Collet
Center drill end of part	Lathe: small center drill	600 RPM	Tail Stock, 1/2" or 3/8" Square Collet
Drill tap hole	Lathe: Large Holes = #16 drill Small Holes = #43 drill	600 RPM	Tail Stock, 1/2" or 3/8" Square Collet
Repeat lathe operations until all holes are drilled and tapped	-	-	-
Tap holes	Large Holes = 10-24 tap Small Holes = 4-40 tap	-	Hand tap

L.2 Hydrogen Frame

Process Plan Sheet for H_2 Frame *Stock: 13.625 ft of 1" x 1" 6063 series aluminum bar stock, 0.5" thick sheet metal*			
Operation	**Tool**	**Parameters**	**Fixture**
Cut bar stock into 4 pieces 27" long	Bandsaw	600 RPM	vice
Cut bar stock into 6 pieces 6.75" long	Bandsaw	600 RPM	vice
Cut bar stock into 3 pieces 7.5" long	Bandsaw	600 RPM	vice
Cut 1/2" sheet metal into correct shape	Bandsaw	600 RPM	vice
File edges smooth	File	-	vice
Drill a 0.375" clearance hole in base plate	Drill Press	600RPM	vice
Drill four 3/16" holes in the extrusion on the base plate	Drill Press	600RPM	vice
Weld 6" x 6.75" bars to 4" x 27" bars, 8"apart	TIG Welder	-	vice
Weld 2" x 7.5" bars to welded assembly in previous step	TIG Welder	-	vice
Weld assembly at the 4 corners of 0.5" base plate	TIG Welder	-	vice
Cut 3" long aluminum L bracket	Bandsaw	600RPM	vice
Drill four (3/16)" holes on one side of the L bracket and two (3/16)" holes on other	Drill Press	600RPM	vice

L.3 Mounting System

Process Plan Sheet for Rear Mounting Feet *Stock: 2" square PVC*			
Operation	**Tool**	**Parameters**	**Fixture**
Measure lengths of PVC stock	Ruler/Marker		-
Cut posts (rough)	Bandsaw	1200 RPM	-
Face off posts (both ends)	Mill: Planar	-	Vice
Drill narrow, deep holes	Drill Press: 1/4" deep drill bit	depth 1.75" 1000 rpm	Vice
Mill wide, shallow holes	Mill: 1" ballnose end mill	depth 1.0" 500 rpm	Vice
Cut press-fit slots in feet	Bandsaw	1200 RPM	

Process Plan Sheet for Rear Mounting Bar *Stock: 2" square PVC*			
Operation	**Tool**	**Parameters**	**Fixture**
Measure lengths of aluminum bar stock	Ruler/Marker		-
Cut length (rough)	Bandsaw	1200 RPM	-
Face off bar (both ends)	Mill: Planar	1200 RPM	Vice
Drill holes	Drill Press: 1/4" drill bit	600 RPM	Vice

Process Plan Sheet for Front Mounting Feet *Stock: 2" square PVC*			
Operation	**Tool**	**Parameters**	**Fixture**
Measure lengths of PVC stock	Ruler/Marker		-
Cut outline (rough)	Bandsaw	1200 RPM	-
Face off blocks (both ends)	Mill: Planar	-	Vice
Drill hole for NEXA foot	Drill Press: 1/4" drill bit	600 RPM	Vice