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Optimization of Hydrogen Storage/Generation for a Hybrid Battery/Fuel Cell Powered Unmanned Surface Vehicle

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Abstract

The focus of this project is to design and model the hybrid power system for an Unmanned Surface Vehicle (USV) performing an ISR (Intelligence, Surveillance and Reconnaissance) mission. A combination of diesel generator, lithium-ion battery pack and 5kW PEM fuel cell stacks were used to achieve the desired objective. The battery pack/5kW PEM fuel cell stack provides the power for the USV during the stealth mode of operation. The focus of the present work is the minimization of weight of onboard hydrogen storage. A solar-powered electrolyzer to generate hydrogen on board coupled with a reverse osmosis demineralizer to generate hydrogen from sea water has been considered. Additionally, relatively low pressure metal hydride storage has been incorporated into the design and will be compared to compressed gas hydrogen storage. Modeling work has also been accomplished in the Matlab-Simulink environment for an electrolyzer to be integrated into an existing USV model.

Keywords: Boat, Energy Storage, Fuel Cell, Modeling, PEM Fuel Cell (Proton Exchange Membrane), Vehicle Performance

1 Introduction

This research has been undertaken to further the development of an Unmanned Surface Vehicle (USV) project between Villanova University and The Naval Surface Warfare Center Carderock Division (NSWCCD) Philadelphia. USVs are positioned to play an integral role in the future of military and security. Potentially reducing the risk to humans, these autonomous ships will be able to perform tasks both possible and impossible to current manned crews.

The concept is nothing new. USVs were commissioned as far back as the post World War II days, where such vessels were used for minesweeping, battle damage assessment, and obtaining samples of radioactive water in the aftermath of the atomic bomb detonations [1]. Looking toward the future, new and more technically challenging mission guidelines will substantially increase their role and importance in the every day operations of the United States Navy.

2 Background

This collaborative USV effort between Villanova University and NSWCCD is being designed to conduct Intelligence, Surveillance and Reconnaissance Missions (ISR) powered by a unique hybrid system. The USV will utilize a diesel generator, lithium-ion battery pack, fuel cell stack, and a solar array to execute its missions. Also on board will be an electrolyzer powered by the solar array in order to generate more hydrogen from renewable resources, resulting in less fuel required to be carried on board from the outset of the mission. The diesel generator cannot be used during missions as the USV will be operating in stealth mode.
Hydrogen will be an essential fuel for the mission since the USV is meant to run for extended time periods at sea without human interaction. Thus, the generation of hydrogen from the electrolyzer will be essential to the longevity of the mission. Currently, the speed profile requires the USV to begin by running for 3 hours at 45 knots on diesel power, switching to the hybrid scheme, running for 336 hours at 5 knots while performing surveillance, and finally returning to

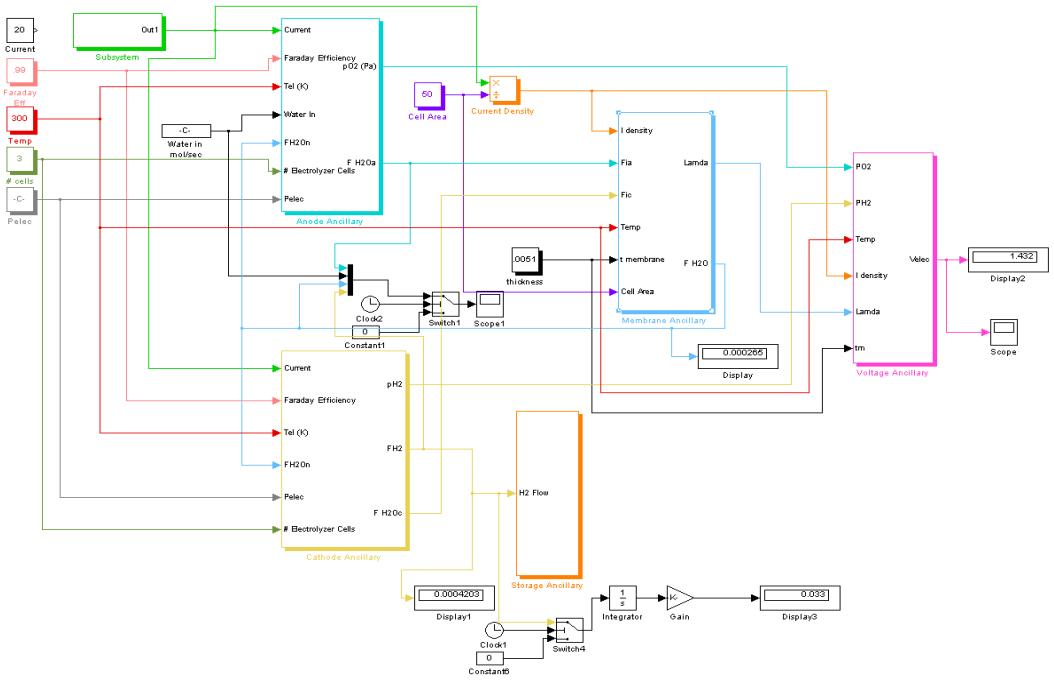

Figure 1: Full Electrolyzer System

the mother ship on diesel power running at 45 knots for 3 hours. Every aspect of this mission must be closely considered and properly sized so as to accommodate a mission of such substantial length.

The primary objective is to create models of each individual component of this power scheme in the Matlab-Simulink environment and integrate them into a full system design. These models will then be validated through a small scale lab setup. Each component will be optimized based on environmental conditions and mission profile.

USV research efforts in 2006 focused on the preliminary modeling of the vessel. A drag model was constructed in the Matlab-Simulink environment, closely following the parameters of previous research [2]. The modeling had been accomplished assuming a planing hull, and while that may not actually be the case, the low speed behavior of a planing hull simplifies to that of a displacement hull. The model inputs boat specifications such as dead rise, weight and beam, as well as the desired speed, and computes the power required from an electric motor to propel the vessel at the specified speed. Also accomplished during this year was work regarding the battery pack optimization. Since the boat's weight would increase with the addition of a battery pack, it was determined that the optimum battery pack size is 47 strings of 47 60Ah batteries, which should be sufficient to power the boat for 100 hours at 1.5 knots [3].

In 2007, ONR-sponsored research focused on incorporating Simulink models for 5 kW fuel cell stacks into the current model. This simulation allows estimation of the approximate range of the vehicle based on the amount of hydrogen stored on board in compressed gas cylinders.

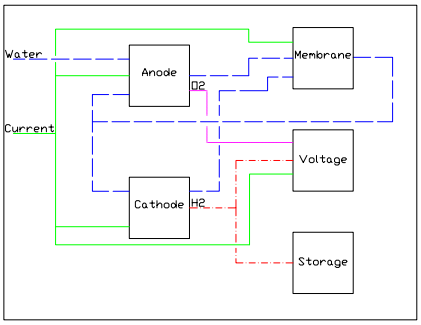

Figure 2: Major Actions Between Subsystems

This resulted in a reduction of the overall battery pack size to 18 strings of 18 60Ah batteries and utilized three 5 kW fuel cell stacks and thirteen 2,400 psi hydrogen storage tanks. Preliminary electrolyzer work also assumed that 20,000 Liters of hydrogen could be generated during the given mission. This hybrid configuration allows the vessel to travel on hybrid power alone for the expected 336 hours of operation at 5 knots [4].

Current research covered in this report evaluates the optimization of an electrolyzer and hydrogen storage unit, and endeavors to create models to integrate into existing simulations. The pros and cons of metal hydride storage versus compressed gas storage will be weighed and a decision will be made as to the best storage unit for the USV. It is important to recognize the role that the environment will play in the viability of a vessel expected to be mostly self-sustaining. It is also essential to consider the rate at which renewable technologies are growing, a rate that will

see many breakthroughs before this vessel is in the water. Therefore, this paper also strives to determine which technologies have the potential to promote further optimization and the points at which these components become legitimate options.

3 Electrolyzer

This report begins with the creation of a basic electrolyzer model which can be used as a template for many different commercially available PEM hydrogen generators. This research closely follows a previous published paper's methodology with some alterations [5].
The electrolyzer model designed can be broken up into four major subsystems. These models include the Anode Ancillary, Cathode Ancillary, Membrane Ancillary and Voltage Ancillary. Fig. 1 shows these main subsystems and how they interface with each other.

3.1 Anode Ancillary

Figure 3 shows a Simulink representation of the formulation of the Anode Ancillary.

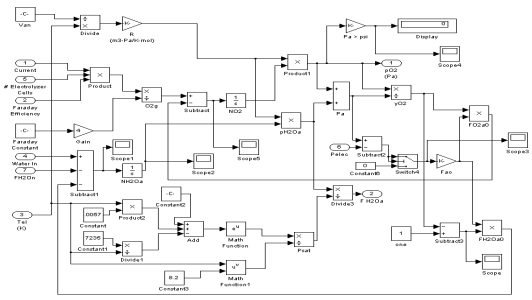

Figure 3: Anode Ancillary

Eq. 1 is the method used for interface models of the catalyst layer [6]. In this formula, n is the number of cells, I is the current, F is Faraday's Constant and η_f is Faraday's Efficiency. Faraday's Efficiency is defined as the actual quantity of material released to the theoretical quantity of material released, and is typically close to 100%.

$$O_{2g} = \frac{nI}{4F}\eta_f \tag{1}$$

As we can see in Eq. 2, in order to determine the total molar flow of oxygen, we must take steps to determine F_{O2ao}, the outlet molar flow rate of oxygen from the anode. This is done by calculating the partial pressure of both oxygen and water within the anode subsystem. Integrating the output of molar flow rate yields a value for total number of moles in the anode subsystem over a given time period.

$$\frac{dN_{O2}}{dt} = O_{2g} - F_{O2ao} \tag{2}$$

Eq. 3 details the partial pressure of oxygen in the anode where N_{O2} is the moles of oxygen just determined, R is the ideal gas constant, T is the stack temperature in Kelvin and V_a is the volume of the anode.

$$p_{O2} = \frac{N_{O2}RT}{V_a} \tag{3}$$

The total water flow rate, Eq. 4, is equivalent to the inlet water flow rate minus the following variables: electro-osmotic drag rate, diffusion rate, and outlet flow rate. Outlet flow rate will be determined in this model, and will now be known as F_{H2Oao}. Electro-osmotic drag and diffusion will be determined in the membrane ancillary and then be fed back into the anode ancillary subsystem. Once we have the total molar flow of water, we integrate the flow rate in order to yield the total moles for a given amount of time.

$$\frac{dN_{H_2O}}{dt} = F_{H_2Oai} - F_{H_2Oao} - F_{H_2Oeod} - F_{H_2Od} \tag{4}$$

Eq. 5 explains the components involved in the partial pressure of H_2O. The total anode pressure is described in Eq. 6.

$$p_{H_2O} = \frac{N_{H_2O}RT}{V_a} \tag{5}$$

$$P_a = p_{O_2} + p_{H_2O} \tag{6}$$

Next, we find the oxygen mole fraction, y_{O2}, which is simply the partial pressure of the O_2 divided by the total anode pressure. At the same time, the total anode pressure is subtracted by the electrolyzer pressure. The purpose of this calculation is to determine the number of moles that will escape from the anode layer. This process should occur when the pressure inside the anode is greater than the ambient pressure. This difference should be multiplied by k_{ao}, the anode outlet flow coefficient to return F_{ao}, the anode outlet flow.

$$y_{O_2} = \frac{p_{O_2}}{P_a} \tag{7}$$

$$y_{H_2O} = \frac{p_{H_2O}}{P_a} \tag{8}$$

$$F_{ao} = k_{ao}(P_a - P_{amb}) \tag{9}$$

By taking the anode out-flow, F_{ao}, and multiplying it by y_{O2}, the oxygen outlet flow rate is returned, F_{O2ao}. This is the value that is fed into the system and is subtracted from the O_2 generated in order to yield the total O_2 flow rate.

$$F_{O_2ao} = y_{O_2} \times F_{ao} \tag{10}$$

$$F_{H_2Oao} = (1 - y_{O_2}) \times F_{ao} \tag{11}$$

F_{H2Oa} is the anode water vapor activity, which is an input into the membrane ancillary and determines the electro-osmotic drag and diffusion.

In order to examine water vapor activity, we first examine the water saturation pressure in the anode, which is a function of temperature, found through Eq. 12 [7].

$$p_{sat} = \frac{e^{77.345+.0057\times T-\frac{7235}{T}}}{T^{8.2}} \quad (12)$$

$$F_{H_2Oa} = \frac{p_{H_2O}}{p_{sat}} \quad (13)$$

3.2 Cathode Ancillary

Fig. 4 is a diagram of the actions undertaken in the Cathode Ancillary. It is here where the chemical reaction will yield a hydrogen product. Also, one can notice upon quick inspection of the layout that it is very similar to the Anode Ancillary. One can use the same methodology as above for developing the Cathode Ancillary.

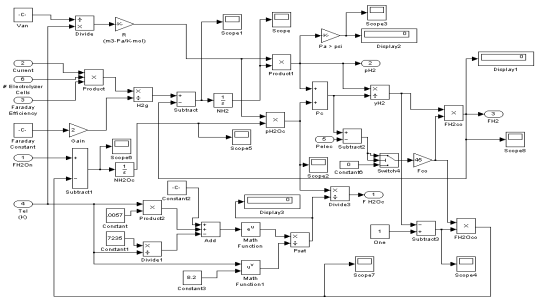

Figure 4: Cathode Ancillary

3.3 Membrane Ancillary

Fig. 5 shows a diagram of the Membrane Ancillary and its purposes as it pertains to this simulation. Mainly, this subsystem describes the water activity and flows exchanged between the anode and cathode. Water activity is essential in electrolysis models because water molecules are the vehicles for ion transport through the membrane. In this case, we are modeling Nafion 117.

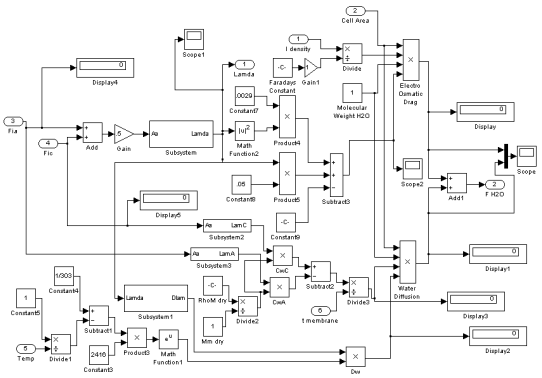

Figure 5: Membrane Ancillary

Electro-osmotic drag is the process that moves water from the anode to the cathode through the membrane interface. Eq. 14 describes the formula. In this equation, n_d is a flow coefficient that is determined from F_{H2Oa} and F_{H2Oc}. The variable i is the current density, F is once again Faraday's Constant, and A_n is the active membrane area.

$$F_{H_2Oeod} = n_d \frac{i}{F} A_n \quad (14)$$

Eq. 16 describes a relationship essential to the modeling of an electrolyzer. Of course, the membrane is always in a very delicate balance, where too much or too little hydration can spell disaster to a system. This balance is described by the moles of water per mole of sulfonic acid sites as an average hydration level, scaled between 0 and 22, where 22 is a fully hydrated membrane [8]. As Eq. 16 describes, λ is a function of the water vapor activity, a_{H2Ovap}, which is the average value of the cathode water vapor activity and the anode water vapor activity, F_{H2Oc} and F_{H2Oa} respectively.

$$n_d = 0.0029\lambda^2 + 0.05\lambda - 3.4 \times 10^{-19} \quad (15)$$

$$\lambda = 0.043+17.18\times a_{H_2Ovap}-39.85\times a^2_{H_2Ovap}+36 \times a^3_{H_2Ovap} \text{ for } a_{H_2Ovap} \leq 1 \quad (16)$$

$$\lambda = 14 + 1.4 \times (a_{H_2Ovap} - 1) \text{ for } a_{H_2Ovap} > 1$$

Water diffusion occurs due to build-up in water at one or both nodes, where the side with the higher concentration build-up will dissipate water to that of lesser build-up. The formula for water diffusion follows as Eq. 17.

$$F_{H_2Od} = D_w \frac{C_{wc} - C_{wa}}{t_m} A_n \quad (17)$$

In this formula, D_w equals the water diffusion coefficient, C_{wc} and C_{wa} are the water concentrations for the anode and cathode respectively, t_m is the cell thickness and A_n is the active membrane area. The water diffusion coefficient is a function of another variable, known as D_λ. The formula for both these variables is outlined in Eq. 18 and Eq. 19.

$$D_w = D_\lambda \times e^{2416(\frac{1}{303}-\frac{1}{T})} \quad (18)$$

$$D_\lambda = 10^{-6} \text{ for } \lambda < 2$$

$$D_\lambda = 10^{-6}(1 + 2(\lambda - 2)) \text{ for } 2 \leq \lambda < 3 \quad (19)$$

$$D_\lambda = 10^{-6}(3 - 1.67(\lambda - 3)) \text{ for } 3 \leq \lambda < 4.5$$

$$D_\lambda = 1.25 \times 10^{-6} \text{ for } \lambda \geq 4.5$$

Once again, λ is an essential piece of information in determining the water flow characteristics. It

is also essential in computing the water concentrations of the anode and cathode, C_{wa} and C_{wc}. The cathode concentration of Eq. 21 is only dependent upon the water vapor activity of the cathode, F_{H2Oc}, and the anode concentration of Eq. 20 is only dependent on the water vapor activity of the anode, F_{H2Oa}. Also, new variables have been introduced in Eq. 20 and Eq. 21. The dry density of the membrane is symbolized by ρ_m, and M_m is equivalent to the dry weight of the membrane.

$$C_{wa} = \frac{\rho_m}{M_m}\lambda_a \tag{20}$$

$$C_{wc} = \frac{\rho_m}{M_m}\lambda_c \tag{21}$$

3.4 Voltage Ancillary

Fig. 6 shows the Simulink model for the Voltage Ancillary.

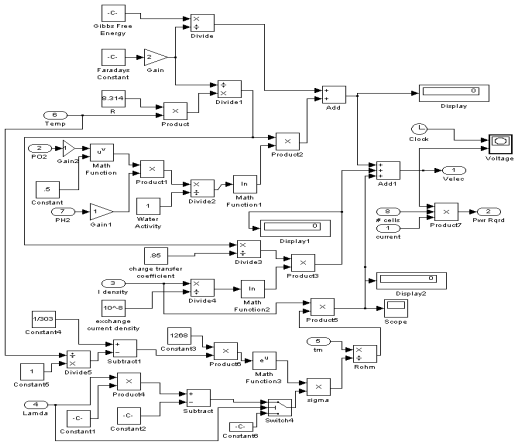

Figure 6: Voltage Ancillary

The first formula in this subsystem is the Nernst Equation, Eq. 22. This is a formula for finding either the equilibrium reduction potential of a half-cell or total voltage in an electrochemical cell.

$$E_{cell} = \frac{\Delta G}{2F} - \frac{RT}{2F}ln(\frac{p_{H_2}p_{O_2}^{0.5}}{a_{H_2O}}) \tag{22}$$

It is comprised of the Gibbs Free Energy of Formation ΔG, Faraday's Constant F, Universal Gas Constant R, and absolute temperature T. The partial pressure of oxygen is input from the Anode Ancillary and the partial pressure of hydrogen is input from the Cathode Ancillary. The water activity, a_{H2O}, is left at 1, which is considered acceptable for simple modeling.
Eq. 23 describes the activation polarization, where α is the charge transfer coefficient and i_o is the exchange current. The other variables in Eq. 23 have been previously defined.

$$V_{act} = \frac{RT}{2\alpha F}ln(\frac{i}{i_o}) \tag{23}$$

Finally, the ohmic polarization must be modeled. Eq. 24 details the first step in determining the ohmic resistance of the system. The inputs to this formula are λ and T. This formula determines the ionic conductivity, which is measured in S/cm. Eq. 25 yields the ohmic resistance, and finally Eq. 26 uses this information to determine the ohmic polarization from current density.

$$\sigma_m = (0.00514\lambda - 0.00326)e^{1268(\frac{1}{303}-\frac{1}{T})} \tag{24}$$

$$R_{ohm} = \frac{t_m}{\sigma_m} \tag{25}$$

$$V_{ohm} = i \times R_{ohm} \tag{26}$$

4 Hydrogen Generation and Storage Analysis

The proper storage of hydrogen poses a challenge for the USV project. Currently, the most economically sound and commercially available choice for hydrogen storage lies in compressed gas cylinders [9]. Preliminary USV research at Villanova assumed the vessel to carry (13) 2,400 psi hydrogen tanks at 49.6 Liters each. This becomes problematic because commercially available electrolyzers have relatively low outlet pressure, many at best reaching 200 psi [10] [11] [12]. Therefore, it is necessary in most compressed gas hydrogen generation and storage applications to implement a compressor. Unfortunately, this is not an option for a vessel engineered to run silently. Therefore, the USV would only be able to fill the tanks up to the head pressure sans compressor. Perhaps even more troubling, the cylinders will only be able to release hydrogen until the pressure inside and outside of the tank have equalized. When gaseous hydrogen is heavily compressed, this inefficiency becomes negligible, but in low pressure applications this poses a major threat. This paper therefore endeavors to find a better alternative.
Currently, fuel cell vehicles in the United States are in the ambitious early stages of commercialization. The vast majority of these vehicles are designed with compressed gas tanks, sacrificing volumetric energy density for gravimetric energy density. Among these, 5,000 psi hydrogen has been well established and utilized [13]. Therefore, gas compressed at 5,000 psi without onboard hydrogen generation will be considered as one possibility.
Perhaps the closest near-term competition to compressed gas hydrogen is metal hydride storage. Metal hydrides offer intriguing opportunities as they have been proven to run for thousands of sorption cycles, operate at much lower pressures, and have very strong volumetric energy densities. Unfortunately, current commercially available metal hydride alloys suffer from low gravimetric energy densities, making them too heavy for many applications. Since surface vessels must be light to run most efficiently, we have

analyzed the tradeoffs between various metal hydrides and compared them to 5,000 psi compressed hydrogen without an electrolyzer.

4.1 Generation System and Storage Weight Analysis

The USV is currently expected to run for 14 days. The longer the mission, the more effective an onboard hydrogen generation system will be to minimizing the initial vessel weight. Also, the electrolyzer is currently assumed to run from a solar array. Solar arrays have extremely variable outputs based on the environment, but 5 sun hours per day (1,000 Watts/m^2 for 5 hours/day) is a fair estimate for the average energy converted by the array. The final component is the minimum amount of hydrogen generated for the metal hydride/electrolyzer systems. As determined previously, an expectation of 20,000 Liters of hydrogen over a 14 day mission is within reason for the electrolyzers analyzed.

Table 1: Weight Specs

Boat	7,803.1	kg
HSM	306.2	kg/unit
FC	227.0	kg/unit
2400 psi Tank	115.7	kg/unit
Li-ion	486.5	kg
Dsal	32.0	kg
Dion	35.0	kg
Sanyo HIP200	15.0	kg/unit

Table 1 provides data previously determined for the weight of various system components [4]. By removing the 2,400 psi cylinders, the hydrogen storage modules (HSM) can also be subtracted, which are containment cabinets primarily used in stationary terrestrial applications, thus substantially reducing the overall system weight. After assuming a requirement of three 5 kW fuel cells, the total system weight before the inclusion of a solar array or hydrogen generation and storage system is 9,040 kg. This number is reduced in the case of the 5,000 psi hydrogen storage option, as there is no need for a desalination or deionization system. This is taken into account in future calculations. The solar module selected for the array is Sanyo's HIP-200BA19 for its high efficiency (17.2% module efficiency) [14]. Early estimates of available surface area on the 10.95 meter boat have determined that there is enough space for 5.8 kW of peak array power using the Sanyo HIP-200BA19 panels.
We will analyze three commercially available electrolyzers using basic information gathered from their specification sheets, HGenerators LM-2000, Heliocentris HG60, and Proton Energy System's Hogen S-20. The rough determination for the amount of hydrogen each will produce onboard versus the amount that must be stored from mission onset will be input into a metal hydride analysis where we will determine the total weight of the generation and storage system. This information will then be compared to data for a compressed gas storage system and results will follow.

4.2 Theoretical Weight Analysis

Metal hydride technology is expected to see vast improvements in the coming years. The goals set forth for the commercialization of metal hydride systems are ambitious and will require extensive advances. Nevertheless, for our analysis we will assume that some of these material advancements will be made by the time this vessel is deployed. Therefore, we will analyze the outset system weight based on different theoretical metal hydride storage weight percentages. Magnesium-based hydrides and complex hydrides have massive potential, among others, for increasing the gravimetric energy density of metal hydrides. Of course, this analysis is strictly reviewing systems based on weight percentage. There are many other factors that will affect the legitimate commercialization of these materials, such as operating temperatures and cost [15].
Since specific compositions are not considered for this study, hydride weight percentages will be input between 1% and 7% hydrogen by weight and the overall performance of the system will be evaluated. Other factors will also be considered. Since we assumed 5 sun hours per day earlier in our analysis, higher values for sun hours per day will be input to determine how this will affect system performance. We do this because the vessel may draw upon other power sources, such as wave energy, to power the electrolyzer. In such a scenario, more than 5 hours per day of operation can be assumed at the peak power level. The purpose of this study is to evaluate how longer electrolyzer operation will affect the performance of the system.
Finally, the result of this particular study will be understood best by determining the power required to run the vessel at full load. This result is a function of the vessel weight, as solved in a previous research report [3]. The information will clearly define the extra power necessary to run the vessel based on a metal hydride storage system, and determine whether the added safety and system flexibility is worth the added weight.

5 Results

5.1 Electrolyzer Modeling Results

The results have great promise as far as the accurate modeling of an electrolyzer system. This is first determined by reviewing the water flows in the system. As already described, the electro-osmotic drag provides the majority of transport to protons crossing from the anode to the cathode. The input water flow into the anode has been set as 100 mL/hour, or 1.542 x 10^{-3} mol/second. As can be seen in Fig. 7, within 2 minutes of operation the electro-osmotic drag model has reached a steady state value of about 4.72 x

10^{-4} mol/second. This suggests that a substantial amount of the water entering the anode will be transported across the membrane via electro-osmotic drag. These results assume the electrolyzer to be operating at 1kW.

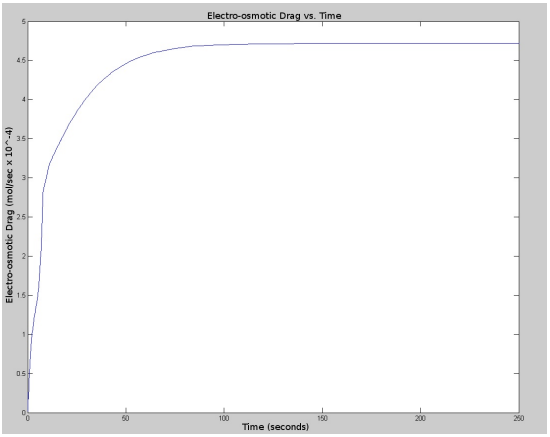

Figure 7: Electro-osmotic Drag (mol/sec) vs. Time (sec)

Depicted in Fig. 8, the water diffusion rate reaches a steady state position rather quickly, leveling out to around -7.7 x 10^{-5} mol/sec. A negative value for diffusion is expected since the reaction at the cathode produces water. Due to this build up, some water travels back through the membrane into the anode, creating back diffusion [6]. Therefore, the negative value suggests that instead of traveling in the same direction as electro-osmotic drag across the membrane, water diffusion will transfer from cathode to anode.

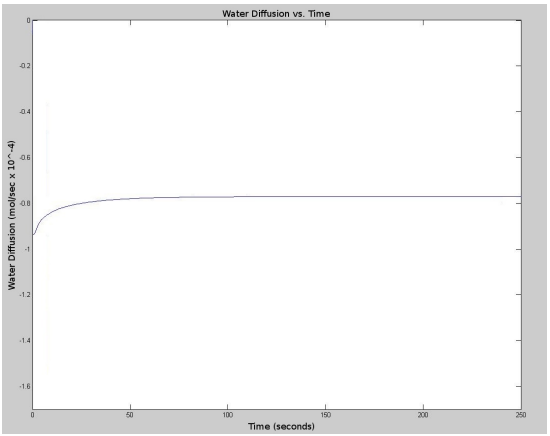

Figure 8: Diffusion (mol/sec) vs. Time (sec)

Through equations developed in the methodology, it is known that electro-osmotic drag and diffusion are a function of λ. Recall that λ is the variable for the moles of water per mole of sulfonic acid sites, and should be between 0 and 22, where 22 suggests a fully hydrated membrane. The simulation returns λ equal to 8.48, within the acceptable range but suggesting the membrane is not operating most efficiently. If the input current is lowered to 30 Amps for rated current conditions (up until now, results have been evaluated based on rated power; this will be explained later in the results), λ would represent an accurate 14.3 moles of water per mole of sulfonic acid sites.

The Voltage Ancillary, as presented in Section 3.4, is broken up into the Nernst Voltage, activation voltage, and ohmic polarization. The Nernst Voltage is accurately resolved as 1.482 V. The activation voltage, 0.94 V, may be too large, but when considering the charge transfer coefficient and exchange current density used, .3 and 10^{-8} respectively, it is within the realm of possible results. Fuel cell modeling supports these values [16]. Finally, ohmic voltage is modeled as 1.075 V. This value may also be somewhat large, but when considering the substantial thickness of the membrane, high ohmic losses are expected.

As alluded to earlier, these results are based on an electrolyzer power requirement of 1 kW. We expected to be able to model a very specific electrolyzer, the LM-2000 from HGenerators [11]. This electrolyzer is expected to require 1 kW for operation. Unfortunately, when rated current was input for this electrolyzer (30 Amps), the model only expects to require 315 Watts. This is because cell voltage is determined through the model as opposed to being an input to the model. Also, because of this error, the resultant hydrogen output from the system is lower than expected at 30 Amps of current. The LM-2000 is expected to output 10.75 g/hour of hydrogen gas. Instead, our model outputs 4.45 g/hour. This is, of course, a substantially lower rate. When the input current is adjusted to 72 Amps, the power required by the system is 1008 Watts, a very close approximation to rated power. Under this condition, the hydrogen output is accurately modeled and returns 10.70 g/hour. Still, the LM-2000 is expected to require 30 Amps of current and 1kW of power, and has been optimized to run most efficiently at this maximum power point. It is therefore necessary for us to find a way to model an electrolyzer based on a given input voltage and current, as opposed to only current. This will allow us to accurately model a system based on both the rated current and rated power. Future research on our modeling of electrolyzers should concern this problem.

5.2 Weight Analysis Results

Table 2 details the methodology presented above for determining the weight of the vessel with respect to different hydrogen storage options. Current metal hydride options do not measure up to high pressure cylinders in terms of a weight analysis, even for such long trips. Other factors must be considered, however, such as safety and mission flexibility. This is not to suggest that high pressure cylinders are unsafe, but on a Navy Vessel, the possibility of rupturing a 5,000 psi cylinder is much more devastating than a metal hydride canister which only reaches 150-250 psi. The metal hydride storage also allows the mis-

Table 2: Weight Analysis Spreadsheet

Mission Info

Duration (days)=	14	Sun Hrs/day=	5	Total H2 Req'd (L)=	116840	Min Generated (L)=	20000	Boat Weight (kg)=	9039.9			
Solar Module=	Sanyo HIP	Power=	200	Watts	Weight=	15	kg					

Electrolyzer Analysis

Electrolyzer	H2 Output (L/hr)	Outlet Pressure (Psi)	Unit Weight (kg)	Power Required (kW/unit)	H2 Generated (L/unit)	Units Required	Gen Weight (kg)	Total Power (kW)	Sol Array Weight (kg)	Total H2 Generated (L)	Total H2 Stored (L)	
Hgenerators LM-2000	120	58	25	1	8400	3	75	3	225	25200	91640	
Heliocentris HG60	60	155	22	0.53	4200	5	110	2.65	210	21000	95840	
Hogen S-20	564	200	215	5.751	39480	1	215	5.751	435	39480	77360	

Weight Analysis

			Heliocentris HG60					Hogen S-20				
Hydride Composition	wt %	Storage Weight w/o Gen System (kg)	Hydride Weight (kg)	H2 Generated Weight (kg)	H2 Generator Weight (kg)	Gen/Store Weight at onset (kg)	Full Vessel Weight (kg)	Hydride Weight (kg)	H2 Generated Weight (kg)	H2 Generator Weight (kg)	Gen/Store Weight at onset (kg)	Full Vessel Weight (kg)
LaNi5	1.49	704.8	578.1	126.7	110	688.1	9938.0	466.7	238.2	215	681.7	10156.5
LaNi4.6Al0.4	1.44	729.3	598.2	131.1	110	708.2	9958.1	482.9	246.4	215	697.9	10172.7
LmNi4.96Al.04	1.2	875.1	717.8	157.3	110	827.8	10077.7	579.4	295.7	215	794.4	10269.3
Ti0.98Zr0.02V0.43Fe 0.09Cr0.05Mn1.5	1.5	700.1	574.3	125.8	110	684.3	9934.1	463.5	236.6	215	678.5	10153.4

Compressed Gas Analysis

	Pressure (psi)	Capacity (kg/tank)	Volume (L/tank)	Tanks Required	H2 wt %	Total H2 Volume Stored (L)	Total H2 Stored (kg)	System Weight at onset (kg)	Full Vessel Weight (kg)			
High Pressure H2	5000	4.1	45615.87	3	5	136847.61	12.3	246	9216.5874			

Note: High pressure hydrogen storage information taken from FCX Clarity Specs. 5000psi H2 wt% taken from F. Babir, et al (2005). Hydride composition wt% does not account for weight of casing. All metal hydride wt% composition information taken from Sandia Labs Hydride Database (http://hydpark.ca.sandia.gov/). kg to liter conversion assumes hydrogen density of .089881 grams/liter.

sion to become more flexible. For instance, a mission with a set amount of fuel can not be extended without a refueling procedure, but a mission with a hydrogen generation system powered by the sun can extend indefinitely under the right circumstances.

An analysis of the different electrolyzer options eliminates the LM-2000 from currently being a viable option for onboard hydrogen generation. Although the model is an excellent choice for certain projects, such as terrestrial based stationary applications where a compressor is used, the outlet hydrogen pressure of the electrolyzer is too low to allow suitable refilling of the metal hydride tanks. The other two electrolyzers were chosen purposely to detail the differences between a smaller scale and larger scale option. With the HG60, multiple small electrolyzers can be installed to satisfy the mission requirements. On the other hand, one large Hogen S-20 electrolyzer can be utilized to more than account for the 20,000 Liters of hydrogen required through onboard generation.

The results between these two options are clear. Based on the mission duration and expected 5 sun hours per day, the smaller electrolyzer unit is a better fit for this application. This is due to the fact that it will require substantially less power to run (3 kW versus 5.75 kW), and can be scaled up or down very easily by cascading multiple units. The Hogen S-20 is much larger, and although its higher hydrogen output will allow for less metal hydride tanks at the outset, too much weight is added to account for the electrolyzer unit itself and extra solar panels required to power the device.

It should be pointed out there is an advantage in using the Hogen S-20 as opposed to the HG60. The outlet pressure of the Hogen S-20 is 200 psi while the HG60 is only 155 psi. This equates to faster fill times and higher end result metal hydride weight percentage. However, this is not such an advantage for our specific application. Since hydrogen will be used faster than generated, 20,000 Liters will easily fit within the empty metal hydride tanks, whether the pressure (and therefore concentration of hydrogen) is slightly higher or lower. Ovonics series metal hydride tanks are designed for a fill pressure of 155 psi to 250 psi [17]. At 155 psi, the canister will be roughly 2/3 full. Therefore, electrolyzer fill pressure is not a primary concern as long as it is equal to or greater than 155 psi.

Table 2 allows us to quantify how large this gap is between the weight of a metal hydride and compressed gas tank. The metal hydride compositions chosen are those that have been well studied in the literature and are prevalent in commercial applications. These compositions each have drawbacks and positive points, but will not be covered in this report as it has been done thoroughly elsewhere [18]. Aside from weight percentage, knowledge of the P-C-T (pressure concentration temperature) curves, cycling stability, operating temperatures, and hysteresis among others are essential pieces of information to specific applications. Since our application requires low operating temperature, strong cycling stability and low fill pressure, AB_5 and AB_2 alloys are the best fit, and are therefore the focus of our hydride modeling.

It should be understood that the hydride compositions in Table 2 do not account for canister weight. This is acceptable since precise measurements are not required and the canister weight does not add too significantly to the overall weight percentage. The important point is that this basic analysis suggests implementing five

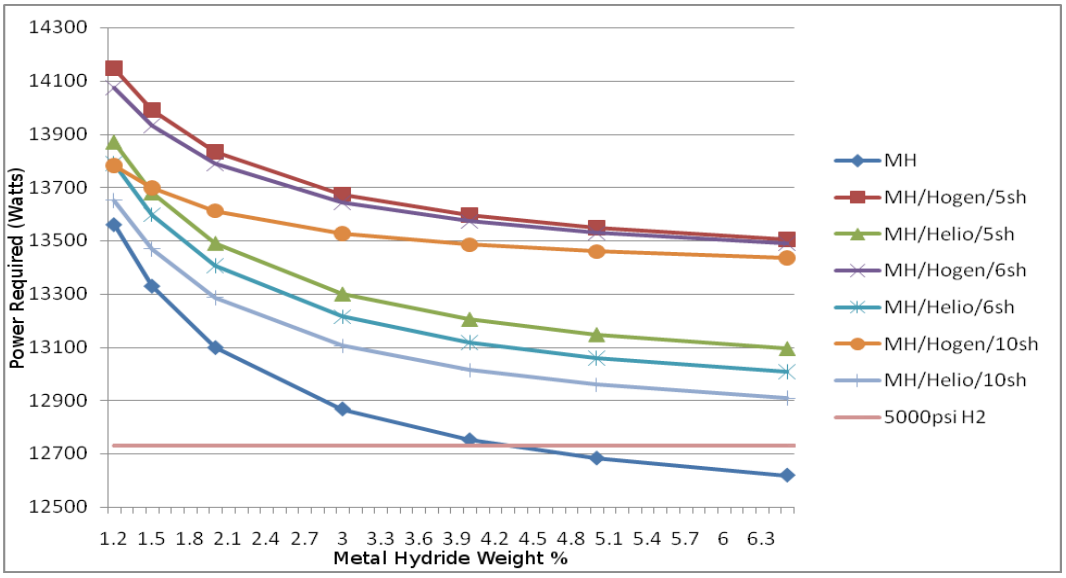

Figure 9: Power Required

HG60 electrolyzers with a 2.8 kW solar array to reduce the overall weight of the vessel by roughly 200 kg over a single Hogen S-20 electrolyzer powered by a 5.8 kW solar array. Also, this vessel has been optimized over the previous report's specifications, as the final expected weight has been reduced by roughly 1,400 kg from the original layout with 2,400 psi canisters and hydrogen storage modules to a metal hydride system with $LmNi_{4.96}Al_{0.04}$. Still, substantial technological improvements are required before the metal hydride tanks can be considered solely based on weight versus the much lighter 5,000 psi tanks, as the overall system will weigh over 800 kg more with the metal hydride. These results are listed in Table 3.

Table 3: Total System Weight

2,400 psi H_2	11,494	kg
MH w/ S-20	10,269	kg
MH w/ HG60	10,078	kg
5,000 psi H_2	9,217	kg

5.3 Theoretical Weight Analysis Results

Fig. 9 shows the results of the metal hydride analysis. Power, in Watts, required to run the vessel at 5 knots is along the y axis and metal hydride weight percentage is along the x axis. The power required to run the vessel with the 5,000 psi hydrogen tanks is included as a reference point.

The clearest result from this study is that over a 14 day mission, the Hogen S-20 electrolyzer is best suited for other applications, regardless of the number of hours per day it is running. The smaller scale electrolyzer is a valuable alternative to compressed gas storage, especially as the metal hydride percentage by weight increases. Still, the electrolyzer itself, strictly adhering to these results, is not as efficient as simply storing the required amount of hydrogen from the mission's onset.

6 Conclusions

We have demonstrated that a fairly basic Simulink electrolyzer model can be created and integrated into the existing system design. This allows us to run more precise, dynamic tests on our USV system for more accurate results and remove any ambiguities concerning the optimization of the final USV. Future work will concern the addition of similar metal hydride and solar Simulink models for a fully integrated USV system.

Changes will be made to the current electrolyzer model to better simulate the operation of commercially available electrolyzers based on their maximum power points.

Metal hydride storage systems have great potential in the USV application. Preliminary results show that the choice between metal hydride storage and compressed gas storage will be determined by quantifying the value of the added safety and flexibility granted by the hydrogen generation and storage system, since a simple side by side comparison details that compressed gas storage is the better option based solely on system weight. The other major factor is the inclusion of a compressor. In applications such as this one, where silent operation is essential, onboard-generated hydrogen must be stored without requiring a compressor. This factor eliminates compressed gas storage from viability in our study.

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