ALTERNATIVE ENERGY TESTBED ELECTRIC VEHICLE
AND THERMAL MANAGEMENT SYSTEM INVESTIGATION

A thesis presented to
the faculty of
the Russ College of Engineering and Technology of Ohio University

In partial fulfillment
of the requirements for the degree
Master of Science

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August 2007
This thesis titled

ALTERNATIVE ENERGY TESTBED ELECTRIC VEHICLE
AND THERMAL MANAGEMENT SYSTEM INVESTIGATION

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Abstract

GREGG, CHRISTOPHER B., M.S., August 2007, Mechanical Engineering

ALTERNATIVE ENERGY TESTBED ELECTRIC VEHICLE & THERMAL
MANAGEMENT SYSTEM INVESTIGATION (91 pp.)

Director of Thesis: Gregory G. Kremer

Methodology of and details on designing, constructing, and testing an efficient
low power electric vehicle for alternative energy testing purposes. Experimental analysis
of the drive motor operating temperature to determine feasibility of a thermal
management system to preheat ammonia for improved efficiency of an electro-chemical
reformer. Description of steps taken in preparation for the eventual inclusion of a
hydrogen fuel cell and ammonia electrochemical reformer.

Approved: ______________________________________________________________

Gregory G. Kremer
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# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>3</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>7</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>8</td>
</tr>
<tr>
<td>LIST OF ABBREVIATIONS</td>
<td>11</td>
</tr>
<tr>
<td>1) INTRODUCTION</td>
<td>12</td>
</tr>
<tr>
<td>2) LITERATURE SEARCH</td>
<td>16</td>
</tr>
<tr>
<td>2.1) EXISTING ELECTRIC VEHICLES</td>
<td>16</td>
</tr>
<tr>
<td>2.2) BATTERIES</td>
<td>18</td>
</tr>
<tr>
<td>2.3) DRIVE MOTOR TYPES</td>
<td>19</td>
</tr>
<tr>
<td>2.4) TEMPERATURE SENSORS</td>
<td>19</td>
</tr>
<tr>
<td>2.5) THERMAL MANAGEMENT SYSTEMS</td>
<td>20</td>
</tr>
<tr>
<td>2.6) AMMONIA AS A FUEL SOURCE</td>
<td>23</td>
</tr>
<tr>
<td>2.7) FUEL CELL OPERATING CONDITIONS</td>
<td>24</td>
</tr>
<tr>
<td>3) TESTBED VEHICLE DEVELOPMENT</td>
<td>25</td>
</tr>
<tr>
<td>3.1) VEHICLE SELECTION</td>
<td>25</td>
</tr>
<tr>
<td>3.2) AUTOBODY OPTIONS</td>
<td>27</td>
</tr>
<tr>
<td>3.3) PROPULSION MOTOR TYPES</td>
<td>28</td>
</tr>
<tr>
<td>3.4) MOTOR COOLING OPTIONS</td>
<td>30</td>
</tr>
</tbody>
</table>
7) CONCLUSIONS .................................................................................................................. 72

8) FUTURE WORK .................................................................................................................. 74

REFERENCES ....................................................................................................................... 78

APPENDIX A: ADVANCED VEHICLE SIMULATOR .............................................................. 81

APPENDIX B: BATTERY CHARGING AND BASIC VEHICLE OPERATION .... 83
# List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1</td>
<td>Battery Comparison</td>
<td>18</td>
</tr>
<tr>
<td>Table 2</td>
<td>Temperature (°C) vs. Time: for selected Heat Sources</td>
<td>43</td>
</tr>
<tr>
<td>Table 3</td>
<td>FMEA</td>
<td>44</td>
</tr>
</tbody>
</table>
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>The Aztec GT</td>
<td>17</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Effect of Temperature on Electrolysis</td>
<td>24</td>
</tr>
<tr>
<td>Figure 3</td>
<td>VW after body removal</td>
<td>27</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Potential fiberglass body kits</td>
<td>28</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Electric Drivetrain</td>
<td>33</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Coupler CAD model</td>
<td>34</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Coupler Prototype</td>
<td>35</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Commutation Sensors</td>
<td>36</td>
</tr>
<tr>
<td>Figure 9</td>
<td>Sensor Disk</td>
<td>36</td>
</tr>
<tr>
<td>Figure 10</td>
<td>Brass Bushing</td>
<td>37</td>
</tr>
<tr>
<td>Figure 11</td>
<td>Lubrication System</td>
<td>38</td>
</tr>
<tr>
<td>Figure 12</td>
<td>Accelerator Pedal</td>
<td>40</td>
</tr>
<tr>
<td>Figure 13</td>
<td>Thermal Management System (basic)</td>
<td>41</td>
</tr>
<tr>
<td>Figure 14</td>
<td>Thermal Management System (improved)</td>
<td>42</td>
</tr>
<tr>
<td>Figure 15</td>
<td>Drive Cycle 1 (Rapid Accelerations)</td>
<td>47</td>
</tr>
<tr>
<td>Figure 16</td>
<td>Drive Cycle 2 (Rapid Decelerations)</td>
<td>48</td>
</tr>
<tr>
<td>Figure 17</td>
<td>Drive Cycle 3 (Constant Velocity)</td>
<td>49</td>
</tr>
<tr>
<td>Figure 18</td>
<td>Infrared Thermometer</td>
<td>50</td>
</tr>
<tr>
<td>Figure 19</td>
<td>Sample Thermal Image</td>
<td>50</td>
</tr>
<tr>
<td>Figure 20</td>
<td>Thermocouple Options</td>
<td>51</td>
</tr>
</tbody>
</table>
Figure 21- Thermocouple Locations................................................................. 53
Figure 22- Error Correction ............................................................................... 55
Figure 23-Averaged Current Use................................................................. 56
Figure 24- Constant Velocity Power Use .................................................... 58
Figure 25- Acceleration Power Use .............................................................. 59
Figure 26- Deceleration Power Use ............................................................... 60
Figure 27- City Driving Power Use ............................................................... 61
Figure 28- Temperature Response with respect to Power .................. 62
Figure 29- Motor Temperature for City Driving ........................................... 65
Figure 30- Motor Temperature and Speed.................................................. 66
Figure 31- Motor Temperature for Constant Velocity ............................. 67
Figure 32- Motor Temperature for Hard Acceleration ............................. 68
Figure 33- Motor Temperature for Hard Deceleration ............................. 68
Figure 34- Motor Temperature After Shutdown ........................................ 69
Figure 35- Motor Temperature Rate of Cooling ......................................... 70
Figure 36- The AETEV ............................................................................... 72
Figure 37- Motor Controller Coldplate Concept ....................................... 75
Figure 38- Advisor Simulation Parameter ................................................... 81
Figure 39- Advisor Simulation Results ....................................................... 82
Figure 40- Lead-acid Battery & Charger ................................................... 83
Figure 41- Power Key .................................................................................. 84
Figure 42- Ni-MH ON/OFF Switch............................................................... 84
List of Abbreviations

EV – Electric Vehicle
AEYTEV – Alternative Energy Testbed Electric Vehicle
TMS – Thermal Management System
NEV – Neighborhood Electric Vehicle
PM BL DC – Permanent Magnet Brushless Direct Current (motor)
IMA – Integrated Motor Assist (Honda)
IC – Internal Combustion
BCM – Battery Condition Monitor
SOC – State of Charge
LED – Light Emitting Diode
PEM – Polymer Electrolyte Membrane (fuel cell)
VW – Volkswagen
FMEA – Failure Modes and Effects Analysis
AEC – Ammonia Electro-chemical Converter
1) Introduction

Although the first electric car was made in the 1830’s, automobile engines powered by inexpensive fossil fuels became far more popular in the early 1900’s and hindered electric vehicle (EV) development [1]. Recent increases in gasoline prices brought renewed interest in electric propulsion and spurred developments that improved both efficiency as well as performance. The most profound advances in electric propulsion are discussed in detail throughout this thesis.

Today, the need to develop new energy storage methods that can replace gasoline is paramount to reducing America’s dependence on foreign oil. New energy storage and production concepts require rigorous testing to become accepted for use in personal transportation vehicles. This testing should be done by third party research facilities without bias or ulterior motives. This need is addressed in this project with the development of a testbed vehicle to provide a means of collecting data from the use of alternative energy for propulsion.

The premise of this thesis is to describe the methodology used for designing and building the Alternative Energy Testbed Electric Vehicle (AETEV) including the conceptual design of a Thermal Management System (TMS) to transfer heat throughout the vehicle improving system efficiencies. As future work, a fuel cell and ammonia reformer are being prepared as the first energy system to be tested on the vehicle.

The proposed TMS will serve two roles; it will remove heat from one or more of the subsystems in need of active cooling and transfer this heat to the systems that will benefit from it. The term active cooling refers to real-time temperature monitoring and
continuous rate of cooling control. The TMS conceptual design is based on examples found in other heat removal systems and scaled proportionally from the thermal data collected in the feasibility study. The purpose of designing this system specifically for this vehicle is to ensure that it will be able to efficiently transfer as much of the available heat as possible. This process includes the following steps:

1) Develop a theoretical model of the system
2) Determine the availability of sufficient heat from the actual vehicle systems
3) Design a basic TMS with approximate component sizes and flow rates

Once the electric propulsion system is past the development stage and thoroughly road tested, the vehicle will be modified for testing new energy concepts. A 5 kW fuel cell stack and small hydrogen storage tank will be mounted in the vehicle to supplement the battery power. After the fuel cell has been integrated into the charging system, various hydrogen production and storage methods can be tested.

The first hydrogen production technology to be tested will be the Ammonia (NH₃) Electrochemical Reformer. This process uses electricity to reform Ammonia Hydroxide into gaseous Hydrogen and Nitrogen in the chemical reaction shown in Equation 1.

\[
2NH_3 \rightarrow N_2 + 3H_2 \tag{1}
\]

Where:

\(N_2\) = Gaseous Nitrogen
\(H_2\) = Gaseous Hydrogen
The goal of integrating this process with the fuel cell is to replace the inefficiencies of compressing or liquefying hydrogen with a more efficient chemical storage and reforming system.

In Chapter 2, the work done by others in the fields relating to electric vehicles, the use of ammonia as a fuel source, and thermal testing will be reviewed. The state of the art in EVs will be addressed to show that the testbed vehicle developed includes some of the latest technologies available. Drive motor technologies will be briefly discussed, including some of the pros and cons of each type. The state of the art in thermal testing equipment will be reviewed to justify the testing methods to be used.

In chapter 3, the electric drivetrain production and base vehicle modifications will be described in sufficient detail to ensure reproducibility. The components necessary for this conversion will be discussed in detail in this chapter. Chapter 4 details the methodology for the study of the available heat from the motor and controller to determine if cooling is necessary.

In Chapter 5, the vehicle performance and the results of thermal testing are discussed in detail. Chapter 6 is the feasibility review for the addition of a TMS to the vehicle. Chapter 7 contains the conclusions drawn from the testing and Chapter 8 focuses on future areas for development.
Former Ohio University Vice President of Research Jack Bantle, who initially approved funding for the project under the 1804 fund, set several goals at the start of the project. He specified that the initial prototype vehicle should be capable of traveling at 25 mph and look like a real car. The vehicle was also to look sporty in order to generate excitement. In order to meet performance goals with limited hydrogen fuel capacity, the team members were to make the vehicle perform as efficiently as possible. To this effect it should use efficient components and be very light and aerodynamic.

The AETEV project consists of three engineering subgroups of graduate students and professors separated by discipline: Chemical, Electrical, and Mechanical. Each subgroup was assigned specific tasks to bring the project to completion. The mechanical engineering tasks that form the basis of this thesis are as follows:

- Build an efficient electric testbed vehicle
- Measure heat from motor, battery, and controller during simulated driving
- Determine highest & average heat source temperatures
- Determine if need exists for a cooling system
- Develop theoretical model of the TMS
- Create a conceptual design of an effective TMS
2) Literature Search

Several key areas of interest were researched to review what has already been done in the following areas: electric vehicles, fiberglass body options, batteries, drive motors, temperature sensors, and thermal management systems.

2.1) Existing Electric Vehicles

Electric vehicles are increasing in popularity with the majority in a class referred to as Neighborhood Electric Vehicles (NEVs). Several of these NEVs were researched and found to satisfy the requirement for a low speed electric vehicle [2]. A search for used NEVs determined that they were cost prohibitive for two reasons: all were $5,000 to $10,000 more than the budget permitted and most of them were located 2000 miles away in California [3]. The Global Electric Motorcar was the one NEV that was available in Athens, as it was in the first year of use by Ohio University as a campus transport. This NEV was only used by OU for one year and quickly retired, as it was found to be prone to failure and expensive to repair and maintain. Upon determining that the NEVs were not the best choice for a starting platform, the next logical choice was to look for either a conventional car that had been converted over to electric or one that could be easily converted.
Extensive research on typical conversion vehicles indicated that the most likely candidates were either compact cars or light duty pickup trucks [4]. These options did not satisfy the primary goal of building an exciting vehicle to attract attention to the project and required further research to find additional solutions. The most promising option found was to build a lightweight and aerodynamic kit car based on the type 1 Volkswagen beetle.

Not only is this vehicle a very popular choice for EV conversion but it also offers a myriad of choices for fiberglass bodies, nearly all of which offer significant weight reductions in comparison to the original steel body [5]. The Aztec GT shown in Figure 1 is an example of an early electric kit car made by Electro Automotive and just one of the many exciting body styles possible.

Figure 1- The Aztec GT [5]
2.2) Batteries

For years the major problem for electric vehicles was limited driving range using lead acid batteries [6]. New battery chemistries such as nickel metal hydride (Ni-MH) and lithium ion (Li-ion) have improved the energy density and reduced the base vehicle weight [7]. Table 1 compares the energy density of the three main battery types. By using a battery with higher energy density and thus lower weight, the resulting vehicle will have better acceleration and travel longer distances between charging.

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Energy Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead acid</td>
<td>30 - 40 (Wh/kg)</td>
</tr>
<tr>
<td>Ni-MH</td>
<td>60 - 80 (Wh/kg)</td>
</tr>
<tr>
<td>Li-ion</td>
<td>120 - 150 (Wh/kg)</td>
</tr>
</tbody>
</table>

Table 1- Battery Comparison [7]

Taking advantage of these new developments, battery weight of the vehicle developed for this project could be lowered while maintaining the voltage potential required for the drive motor. As an example of how these batteries are revolutionizing the EV industry, two high performance electric sports cars are now being produced in California. The most noteworthy are the Tesla Roadster [8] and the Wrightspeed X1 [9], both of which can accelerate from 0 to 60 mph in 4 seconds or less! The Tesla Roadster is reported to have an estimated range of 250 miles per charge.
2.3) Drive Motor Types

Electric motors of the scale required to propel a vehicle are rather limited though several options do exist. Up until the 1980’s, series wound DC motors were the popular choice for EVs partly due to their simple control requirements [10]. As controller and inverter technology improved, AC motors gained popularity in the aftermarket EV community [11]. The two electric sports cars mentioned in section 2.2 are both propelled by AC motors. One of the newest types of electric motor, commonly referred to as brushless motors, combines features of both AC and DC and is currently used in several gasoline/electric hybrid vehicles [12]. These motor types will be discussed in more detail in section 3.3. Regardless of the type, the drive motor produces heat and will require cooling of one form or another. The options for maintaining optimal motor temperature will be discussed in section 3.4

2.4) Temperature Sensors

Temperature measurement devices can be classified into two groups: contact and non-contact. Thermocouples and thermistors sense change in temperature in their surroundings and must be in contact with a surface to give accurate readings [13]. Infrared temperature measuring methods measure the heat radiated from a surface [14]. Non-contact measurement offers a quick way to measure approximate temperatures of
many points in a large area. Both types were engaged to study the heat output from the

drive motor systems.

2.5) Thermal Management Systems

From the study of heat transfer and thermodynamics, equations 2 and 3 are used
to define the basic principles describing how heat moves through the materials that make
up the system. The standard conduction equation shown in equation 2 is used to
determine parameters such as insulation thickness and thermal contact surface areas [15].

\[
\dot{Q}_{\text{conduction}} = k_t \frac{A \Delta T}{\Delta x} \]

(2)

Where:

\( \dot{Q}_{\text{conduction}} \) = Rate of heat conducted through a solid [W]

\( k_t \) = Thermal conductivity of the solid [W/(m*K)]

\( A \) = Area normal to heat flow [m²]

\( \Delta T \) = Temperature difference [K]

\( \Delta x \) = Thickness of material [m]
The standard convection equation shown in equation 3 is useful for predicting how different fluids will behave in a conceptual model of the TMS. The theoretical model will use equation 3 to predict the behavior of various thermal fluids and liquid to liquid heat exchangers.

\[
\dot{Q}_{\text{convection}} = hA(T_{\text{surface}} - T_{\text{fluid}}) \tag{3}
\]

Where:

\(\dot{Q}_{\text{convection}}\) = Rate of heat transfer by convection through a thermal fluid [W]

\(h\) = Convection heat transfer coefficient of the thermal fluid [W/(m²*K)]

\(A\) = Wetted Surface area normal to the heat flow [m²]

\(T_{\text{surface}}\) = Temperature of the surface [K]

\(T_{\text{fluid}}\) = Temperature of the fluid away from the surface [K]

The effectiveness of a TMS in transferring heat from a source is defined in Equation 4. Typically the values determined through theoretical models can be unrealistically high due to unforeseen losses in the actual system. Careful consideration of the expected thermal effectiveness to be used in the modeling process can help reduce this error to better approximate experimental results.

\[
E_{\text{th}} = \frac{Q_{\text{lifted}}}{Q_{\text{available}}} \tag{4}
\]

Where:

\(E_{\text{th}}\) = Thermal effectiveness

\(Q_{\text{lifted}}\) = Heat lifted by the cooling fluid [W]

\(Q_{\text{available}}\) = Heat available from the heat source(s) [W]
To benchmark the proposed TMS, techniques were found to remove heat from sources in the 25°C to 100 °C range. Areas of interest include the cooling systems used for computer processors and motor controllers. Heat management systems that can operate effectively over a wide range of temperatures are also important. Such systems typically include real-time temperature monitoring to adjust cooling fan speeds as heat is produced.

An example of a lightweight TMS that can adjust to varying heat loads is a power electronics cooling system developed by SPARTA, inc. and the Air Force Research Laboratory [16]. Presented in a 1998 SAE technical paper, this TMS uses a phase change material, paraffin wax, to passively cool a motor controller at low heat levels and a conventional forced air heat sink to actively remove heat at peak loading. The methodology used by SPARTA inc. to design, model, build, and test the TMS is logical and effective. The influence of this and other studies on the development of the AETEV TMS will be discussed in chapter 4.

A passive cooling option known as a heat pipe was also investigated. A heat pipe consists of a sealed tube with a small amount of liquid inside and a porous lining. Heat pipes use the liquid-to-gas phase change of the fluid to lift heat from a source. The heated gas travels to a cooler region of the tube where it condenses releasing heat. The porous lining then transfers the fluid by capillary action back to the heat source to repeat the cycle. Several advantages to heat pipes over other cooling methods are that they use no power and are scalable for various applications.
2.6) Ammonia as a Fuel Source

Ammonia (NH₃) is a byproduct of life as it can be produced from the concentration of animal wastes. Dr. Botte, the chemical engineering professor collaborating with project, is investigating ways to convert NH₃ into hydrogen to be used as a fuel source. Apollo Energy Systems and Zap cars are currently developing a fuel cell car that will use an onboard high temperature thermal-reformer to convert NH₃ for the hydrogen needed to power the fuel cell [17]. This system differs from the one proposed by Dr. Botte that uses electrolysis to electrically reform the NH₃ at much lower temperatures. As previously stated in section 1, the focus of this thesis is to manage the heat rejected from the high temperature sources and use the heat to increase the efficiencies of other subsystems. The ammonia electrochemical reformer will use an ammonia solution that has been preheated in this manner, effectively reducing the energy required to electrolyze. The relationship for this endothermic reaction efficiency and temperature is based on research provided by the chemical engineers on this project. Figure 2, based on data collected by Dr. Botte, shows a significant reduction in the power required to reform NH₃ as the temperature increases to 50°C [18]. Notice that as temperature increases from 50°C to 60°C the change in power becomes negligible.
2.7) Fuel Cell Operating Conditions

The fuel cell selected for this project is of the polymer electrolyte membrane, PEM, type that has a normal operating temperature of 60°C [19]. Under normal operating conditions fuel cell stacks require cooling to prevent heat build up. The measured available heat from the PEM fuel cell stack will be investigated by the chemical engineers in future work.
3) Testbed Vehicle Development

The AETEV project is dependent on the efficiency and performance of the vehicle constructed. As a platform to showcase and validate the new technologies, the vehicle drive system must be fully assembled and tested in order to reduce future problems with the drivetrain or other base vehicle systems. The vehicle developed for this project also contains as many advanced components as possible in order to satisfy the design constraints. As previously stated in Chapter 1, the vehicle must:

- not look like a golf cart.
- be capable of speeds up to 25 mph
- be as light, aerodynamic, and efficient as possible.

3.1) Vehicle Selection

The first task in the vehicle selection process was a make vs. buy decision of the vehicle to use. This decision was based on cost and availability of EVs appropriate for this project. In chapter 2, NEVs were determined to be expensive, hard to find, and tend to look like golf carts thus failing to meet the requirements of the project. In section 2.1 the option of EV conversions was explored and found to be the most promising.

Many converted EVs were available across the country of all shapes and sizes. The typical example was a home conversion done by a hobbyist rather than a trained professional. These vehicles left too many unanswered questions and were not
appropriate for this project. The decision was then made to look for EV conversion kits and determine the cost and level of difficulty.

Several companies offer the components required to convert vehicles for electric propulsion. For example, the standard EV conversion kit offered by Electro Automotive was several thousand dollars more than the budget allowed and did not allow choice of components [20]. This leads to one of the main advantages of independently converting a car to use electric propulsion: the ability to choose the best possible motor, controller, and battery available. When selecting parts from suppliers for educational purposes, it is also possible to get major components discounted or even donated. For example, Advanced Motion Control donated the brushless motor controller used on this project, saving well over a thousand dollars. For these reasons a custom conversion was more advantageous than a standard conversion kit.

The vehicle selected for the conversion was a 1973 Volkswagen Super Beetle. As previously stated in Chapter 2, VWs have been a very popular choice for conversion [21]. This was the first year that Super Beetles came equipped with four-wheel independent suspension to provide better stability and response to road conditions [22]. To restore the vehicle, the following modifications were made:

- The entire brake system was replaced with new components
- Silicone brake fluid was substituted to prevent corrosion and evaporation
- The wheel bearings were greased with synthetic grease
- The transmission fluid was replaced with synthetic fluid
- The steel body was removed as seen in Figure 3
3.2) Autobody Options

Although the actual body kit installation will likely be completed as future work to follow up this thesis, the selection of the body to be purchased is essential to the packaging of the components and will be completed as soon as sufficient funds are available. The body kit selection process will take into consideration: location, availability, weight, manufacture, and aerodynamic shape. The body will be sectioned into front, mid, and rear compartments, to allow easier access to the subsystems without removing the entire body.
The most important factors that the body must satisfy are lightweight construction and low coefficient of drag. Figure 4 shows just a few of the body kits that were made for the VW beetle floor pan. The weight savings and reduction in wind resistance will improve the efficiency and performance significantly over the original steel body. As future work, the body will be reinforced with lightweight materials such as carbon fiber to improve the crash protection in case of an accident.

![Image of potential fiberglass body kits](image)

**Figure 4- Potential fiberglass body kits [5]**

### 3.3) Propulsion Motor Types

In order to select the most appropriate type of motor for this vehicle, all available motor types were researched. As previously stated in chapter 2, the two most common motor choices for electric vehicles are series wound type DC due to their high stall torque and simplicity [10] and squirrel cage type AC motors for durability [23]. To keep efficiency high, it is desirable to use a motor capable of regenerative braking, thus recovering a portion of the energy normally lost in braking.

Direct current (DC) motors run on the constant voltage supplied by a battery pack, thus avoiding the inefficiencies of inverting power required for AC motors. They are very
easy to control as the commutation is mechanically induced through carbon brushes contacting the rotor [23]. However, the friction of the brushes dragging against the commutator limits their potential efficiency. The carbon brushes wear down over time and if the motor is not ventilated properly, the dust can accumulate and create arc paths. When a series wound DC motor is run in no load conditions it can accelerate to dangerously high speeds and self-destruct, becoming “An Electromagnetic Bomb” [10].

On the plus side, series wound DC motors have very good torque and acceleration properties, making them a popular choice for electric drag racing [10]. For this particular vehicle, however, the low efficiency and safety concerns make this motor type unacceptable.

Induction motors are generally referred to as AC motors because they operate on alternating current as opposed to constant voltage DC motors. Squirrel cage AC motors are very durable, and if properly controlled, can be more efficient than DC motors despite inverter losses. Variable speed control involves real time motion control to vary the phase angle of the voltage in the stator. Regenerative braking is possible with AC motors, depending on the motor controller. It is accomplished by maintaining a lower voltage in the armature than in the field, thus effectively turning the motor into a generator [24].
Permanent Magnet Brushless (PM BL) DC motors are actually a type of AC motor, although they are coupled with an inverter that efficiently produces an alternating current from a DC power supply. This motor is one of the most efficient motor types in the required power range partly due to the reduced friction from sensor induced commutation [25]. Brushless motors require a special controller to monitor the signals sent by either Hall Effect sensors or encoders to determine rotor orientation [25].

3.4) Motor Cooling Options

To remove heat from the drive motor, two cooling methods were considered; convection to the surrounding air and conduction to a heat transfer liquid. The waste heat generated by the drive motor can be approximated using assumed values for efficiency and power consumption in Equation 5. Measured values for the heat produced will verify the approximations and determine the most appropriate method of removing this heat.
\[ P \times (1 - \eta) = x_{\text{heat}} + x_{\text{sound}} + x_{\text{vibration}} \]

Where:

\( P \) = Power Discharged through the Motor [W]

\( \eta \) = Motor efficiency

\( x_{\text{heat}} \) = heat losses [W]

\( x_{\text{sound}} \) = sound losses [\( \mu \text{W} \)]

\( x_{\text{vibration}} \) = vibration losses [\( \mu \text{W} \)]

*The energy lost in the forms of sound and vibration is several orders of magnitude smaller than heat and is thus assumed to be negligible.*

A cooling system will be designed in chapter 5 to efficiently remove waste heat from the drive system. The theoretical value for waste heat will be used for the assumed average heat load and verified against the heat values measured. A system with active cooling, as described in section 2.5 that adjust the rate of cooling based on the subsystem’s temperature, would be ideal as it would allow the vehicle to operate efficiently in a variety of conditions and environments. For example, if the vehicle were operating in extremely warm environments, where the heat produced by the drive system exceeds that of the typical conditions, the rate of cooling could then be increased to prevent overheating.
3.5) Simulations

The National Renewable Energy Laboratory (NREL) produced a vehicle simulator program named ADVISOR [26]. This software was used to compare components on a model of the vehicle. The model was based on measured values from the 1973 VW and virtual components modeled by the NREL and contributing research centers. The Honda IMA system was shown through simulation to be more than adequate to power the testbed vehicle when coupled with a 4 speed VW transmission. The feasibility of the drivetrain was shown with this and other methods including hand calculations.

The most important vehicle parameters - weight, height, frontal area, wheel base, and coefficient of drag - were approximated based on the expected final design. Complete simulation parameters and results can be reviewed in Appendix A.

3.6) Electric Drivetrain

Based on the information collected on motor types and the simulation results, the decision was made to find a used Honda Insight hybrid power plant. The main components were salvaged from a 2000 Honda Insight. The PM BL DC motor normally mounted to the crankshaft of the IC engine was the most important part of the system as this was the motor type determined to be best for this vehicle. This motor was also the only available brushless motor in the power range needed. It was modified for
replacement of the IC engine on the VW. Part of the modification process involved the removal of the approx. 30 lb. clutch to reduce rotational inertia losses. The motor was then directly connected to the transmission using a 3 lb. custom made coupler. The main components of drivetrain are labeled in Figure 5.

Figure 5- Electric Drivetrain
3.7) Motor Coupler

The motivating factors for designing the coupler to connect the rotor to the input shaft of the transmission were: reliability, ease of manufacture, and efficiency. As labeled in Figure 6, the coupler was made from three pieces: a rotor plate, a coupler shaft, and a splined hub.

![Coupler CAD model](image)

The rotor plate section was machined out of the section of the Honda clutch that mates to the rotor. The splined hub section was machined from the section of the VW clutch that mates with the splined input shaft of the transmission. The coupler shaft section was machined from steel cylindrical stock to mate with the inner diameter machined in the rotor plate and the outer diameter machined into the splined hub. The sections were connected by interference fit to avoid the problems associated with welding. The completed coupler is shown in Figure 7.
3.8) Commutation Sensor Disk Adapter

Replacing the clutch with a direct coupler reduces nearly thirty pounds of rotational weight from the Drivetrain but also removes the mounting point for the commutation sensor disk. The sensor disk has alternating protrusions that pass in front of the hall-effect sensors shown in Figure 8. The sensors communicate with the motor controller as to the phase of the rotor. To enable use of the hall-effect sensors to monitor rotor speed, an adapter plate, shown in Figure 9, was machined to attach the sensor disk to the coupler.
Figure 8- Commutation Sensors

Figure 9- Sensor Disk
3.9) Motor Bearings

The major limitation of the brushless motor used by Honda is that it must be supported by external bearings once disconnected from the crank shaft. Without proper alignment the motor will destroy itself very quickly. To solve this dilemma, modifications were made to support the rotor on both sides. On the font side of the rotor, an oil seal in the rear of the transmission was replaced with a brass bushing of very close tolerance to the input shaft to minimize the eccentricity of the shaft. Figure 10 is a CAD model of bushing. The inner and outer diameters are both approximately .002” over sized resulting in an interference fit with the transmission and a slip fit with the rotating input shaft.

![Figure 10- Brass Bushing](image)

The Honda IC engine was disassembled, cut apart, and modified to function as an end cap and main bearing for the rear side of the rotor. The rotor is attached to a short section of the crank shaft now serving as the main bearing. To facilitate oil circulation, an external electric pump was installed. To minimize the pump running time, a reservoir was made from half of the combustion chamber in the salvaged section of the engine. Figure 11 shows the oil circulation system.
An oil level sensor in the reservoir activates the pump timer circuit which then runs the oil pump for about twenty seconds to fill the reservoir halfway. The oil then flows down to the main bearing to maintain lubricity thus minimizing wear. Overflow channels were machined into the reservoir to allow the oil to flow down to the lower section when refilling.

### 3.10) Battery System

The Ni-MH battery pack used on the Insight was also important to this conversion as the 70 lb. battery produces the same voltage potential as 700 lb. of lead acid batteries. This is not a true energy-density comparison as the energy density of Ni-MH is only twice that of lead acid. For a direct comparison refer to Table 1 on page 14. Maintaining the voltage potential required for proper motor operation is the most important criteria in this discussion as reducing battery weight is paramount to achieving maximum
efficiency. The Insight also uses a DC/DC converter to step down the 144v to 12v to run the normal vehicle systems. Eventually this module could be used to charge the 12v lead acid battery that powers onboard computers, lights, displays, and other 12v accessories.

The Ni-MH battery pack provides 175v and 6.5A-h when fully charged. In order to safely recharge it, the battery chemistry was studied and several charge cycles were found. For the initial charging system a constant current of about 1.5 amp is be applied for about 4 hours to carefully bring the system voltage up to 170 volts.

The electrical engineering research team associated with this project is developing an on-board computer to safely charge the pack from the 48 volts supplied by the fuel cell stack. The amperage sent into and out of the battery pack will be regulated based on the temperature of the pack as sensed by thermocouples and a Battery Condition Monitor (BCM). To keep the driver informed of the State of Charge (SOC), an LED display will indicate a percentage of power left in the battery.

### 3.11) Motor Control

In order to efficiently control the drive motor, sophisticated controller chips were researched and experimented with to learn the intricacies of brushless motor control.

The brushless motor is typical in that it has three Hall Effect sensors, so a controller that utilized these inputs was necessary. It was also important for the controller to output a 3 phase signal that used Pulse Width Modulation. Another important feature of the controller was the ability to enable regenerative braking and convert the 3 phase energy
produced back into DC to store in the battery. After creating a university partnership with Advanced Motion Control, a brushless motor controller was located and donated to the project. The VW accelerator pedal in figure 12 was rebuilt to actuate a 50kΩ potentiometer using a four-bar linkage. The change in resistance in the potentiometer is the input used to vary the speed of the drive motor.

![Figure 12- Accelerator Pedal](image)
4) Feasibility Study of the Thermal Management System

To verify the ability of the vehicle subsystems to generate sufficient heat to necessitate liquid cooling, the temperature and its rate of change were examined. If a significant temperature gradient exists between the subsystems and the ammonia reformer, the Thermal Management System (TMS) concept will be developed in Chapter 7. Assuming that the motor will require active cooling, fluid can be used to lift heat from the motor and transfer some of that heat to the heat exchanger before being cooled and returned to lift more heat. Figure 13 is a system level diagram of the basic TMS. TH, TM, & TC refer to hot, medium, and cool temperatures respectively.

Figure 13- Thermal Management System (basic)

As explained in section 2.5 and 3.4, the heated fluid raises the temperature of the heat exchanger which then transfers the thermal energy to the ammonia. As stated in section 2.8, The Ammonia Electrolytic Reformer uses an endothermic process that has shown efficiency improvements with increasing NH3 temperatures up to 50° C [18]. The
increased internal energy reduces the electrical energy required to electrolyze the NH₃ for the production of hydrogen to power the fuel cell stack. Figure 14 shows how the fuel cell stack and motor controller can be added to the system if sufficient heat is generated in those components as well. Again, Tₜ, Tₘ, & Tₖ refer to hot, medium, and cool temperatures respectively.

4.1) Thermal Test Plan

Before a TMS can be designed it was imperative that the available heat from the drive motor be measured under various drive cycles and using multiple heat sensing technologies. The maximum unregulated motor operating temperature was determined from the insulation rating on the motor windings to be 130° C. If the motor had approached this temperature, the test would have been suspended until the motor cooled to ambient temperature. This would prevent damage to the motor during testing before a cooling system has been implemented.
To meet the objective of determining the feasibility of a TMS, the dominant factors must be defined and the heat available from the subsystems must be measured. The variable parameters for the test are the selected drive cycles and ambient temperature. The control parameters are the available power from a battery pack and all of the vehicle characteristics such as motor power and wheel size. The observable parameter that was of most importance is the time dependent temperature values for each localized region of the motor, battery, and controller. Table 2 is an example of the basic format that was used to collect temperature readings for each localized region at specific times to analyze the heat produced at each location throughout each drive cycle. The hot spots are points of interest locating regions of relatively higher heat on the drive system.

<table>
<thead>
<tr>
<th>Hot Spot</th>
<th>T&lt;sub&gt;ambient&lt;/sub&gt;</th>
<th>T @ 30 sec</th>
<th>T @ 1 min</th>
<th>…</th>
<th>T&lt;sub&gt;end&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>2</td>
<td></td>
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<td>3</td>
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<td>6</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Table 2- Temperature (°C) vs. Time: for selected Heat Sources
4.1a) Safety

One of the most important factors to the success of this project is safety. To ensure safety of those in or near the vehicle, the number of people present at the time of testing was at least two but no more than six. The technicians conducting the drive cycles did so in a professional manner. Safety glasses and hearing protection was required during operation. An emergency stop button on the dynamometer and the hydraulic brakes on the vehicle could have been used to abort the test if any potential problems had arisen during a drive cycle. Table 3 shows the Failure Modes and Effects Analysis (FMEA) that was used to address specific safety concerns.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Severity</th>
<th>Likelihood</th>
<th>Risk Priority Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Derailment</td>
<td>8</td>
<td>3</td>
<td>24</td>
</tr>
<tr>
<td>2) Fire</td>
<td>7</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>3) Electrocution</td>
<td>10</td>
<td>6</td>
<td>60</td>
</tr>
<tr>
<td>4) Flying Debris</td>
<td>5</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>5) Battery Explosion</td>
<td>7</td>
<td>4</td>
<td>28</td>
</tr>
</tbody>
</table>

Table 3- FMEA

(Ratings are between 1 and 10 with 10 being most severe or likely to occur)
The FMEA identified electrocution as a high risk and requires special attention to reduce the possibilities of occurrence as well as minimizing the severity of the operator being electrocuted. The high voltage cables were insulated and high voltage gloves were required by the operator when working on the system when activated. A high voltage contactor switch was installed between the battery pack and the motor to provide an additional emergency off switch for the operators. Extreme caution will be required from everyone present at the time of testing. Rubberized connections were added to further reduce electrocution hazards while charging the battery.

One mode of failure concerns the vehicle derailing from the dynamometer during use and colliding with the operators. To prevent this, the vehicle was be aligned to the dynamometer carefully each time it was loaded and secured with straps and chains to keep the tires centered. The tension on each strap and alignment of the vehicle was checked before and after each test. The loading on the straps to prevent lateral motion was well below the maximum loading of 3333 lbs.

The risk of fire was very low despite the high severity of such an accident. To minimize the dangers from fire, smoke detectors, a sprinkler system, and multiple fire extinguishers were on hand in the unlikely event of a fire.

The risk of battery explosion was of moderate concern and required special attention. To reduce the risk of injury from battery acid, a large sheet of Plexiglas was positioned between the batteries and the operators. A large container of baking soda was also on hand to neutralize any battery acid if such an accident had occurred.
Due to the nature of dynamometer testing, the tires contacting the rollers spin at a very high rate of speed. It is possible that foreign particles may become airborne if they come in contact with the spinning wheels. To reduce the risk of injury from flying debris, another large sheet of Plexiglas was positioned between the wheels and the operators.

### 4.1b) Testing Procedure

The vehicle was mounted to a chassis dynamometer to simulate traveling at speeds up to 30 mph determined by wheel speed and diameter. The motor was then run through a series of drive cycles to determine the highest temperature \(T_{th}\) that the motor will reach without active cooling. Each drive cycle simulated a different mode of driving conditions likely to be experienced by the motor. Although each drive cycle differed in the number and severity of accelerations and decelerations the power discharged in each was used as a basis for comparison. After each trial, the vehicle was allowed to cool to ambient temperature before beginning another test. Each drive cycle lasted approximately 20 minutes and was repeated a minimum of 3 times in varying order.

Upon completion of the testing, the data collected was used to form a maximum and average rate of temperature increase for each type of driving. These values for \(T_{th}\) and estimated values for the fluid flow rates can be used to determine the most appropriate heat exchanger type and size. One company that specializes in heat exchangers, Exergy LLC, provides a free tool to calculate the amount of heat transferred and output temperatures based on known input temperatures, flow rates, and a selected model of heat exchanger [27].
4.1c) Drive Cycles

Figure 15 shows the first drive cycle, characterized by repeated rapid accelerations with gradual decelerations. This studies the effect of excessive current loads on the motor temperature. After each gradual deceleration is a short interval to allow the heat generated to equalize before accelerating again.

![Figure 15- Drive Cycle 1 (Rapid Accelerations)](image)

Where:

A = time to accelerate to 30 mph

B = time to decelerate from 30 mph

C = time to allow heat to conduct through motor case
Figure 16 shows the second drive cycle, characterized by gradual accelerations with rapid decelerations. This studies the heat generated by the motor when used to slow the vehicle while capturing some of the energy dissipated in accelerations. The gradual accelerations are necessary to minimize the heat produced while not decelerating. A brief interval after each rapid deceleration again allows the heat generated to dissipate through the motor case.

![Figure 16- Drive Cycle 2 (Rapid Decelerations)](image)

Where:

A = time to accelerate to 30 mph

B = time to decelerate from 30 mph

C = time to allow heat to conduct through motor case
Figure 17 shows the third drive cycle, consisting of a gentle acceleration to a predetermined speed followed by a constant velocity output. This drive cycle ends when the amount of energy discharged through the motor is equal to that of the other two drive cycles. The purpose of this test is to determine the heat associated with a constant 30 ft-lb load simulating ascending a 5% grade at 10 mph in first gear.

![Figure 17- Drive Cycle 3 (Constant Velocity)](image)

**Where:**

- A = time to accelerate to 30 mph
- B = time that vehicle travels at 30 mph

**4.2) Temperature Measurement Devices**

The surface temperatures of the motor case and motor controller case are important in determining the best location to attach a heat transfer block. To help locate points of localized heat, i.e. hot spots referred to in section 4.1, a non contact thermal measurement device were used to survey the drive systems during an initial drive cycle.
The infrared temperature measurement device shown in figure 18 was used to take readings around the perimeter of the motor.

An infrared camera could also have been used to map the heat produced in the drive system had sufficient funds been available. This test would help visually locate the relatively warmer spots and that will require more cooling. An example of what the thermal image would have looked like can be seen in figure 19 [28].
The warm spots on the drive motor and motor controller were then fitted with more accurate contact thermal sensors such as thermocouples pictured in Figure 20 [29]. These sensors were used to record multiple surface temperatures accurately and simultaneously during the drive cycles. The use of this type of measurement reduced the error in the temperature measurement and improved the accuracy of the test. These sensors can even be used with the cooling system installed to verify that it is working properly and alert the driver of overheating in the event of a cooling system failure.

![Figure 20- Thermocouple Options](image)
4.3) Basic TMS Operation

Based on the assumption that a sufficient amount of heat is available, the following TMS would be developed. In order to lift the heat from the motor as efficiently as possible, a liquid interface will be designed based on the temperature sensor data. The liquid will most likely be ethylene glycol, based on its typical use as coolant in automobiles. The heated liquid will be pumped to a heat transfer section where an ammonia solution can be preheated. The heated liquid might also serve as cold weather protection to keep the fuel cell from freezing when operating in subzero climates. Typically though, the fluid will also be used to lift heat from the fuel cell as well to prevent the fuel cell from overheating. The battery pack, motor controller, and DC/DC converter were all designed to be air cooled so they will continue to be cooled that way unless it is determined that sufficient heat is available from these systems to justify the increased complexity of adding them to the fluid system.

4.4) TMS Preliminary Design

If the thorough analysis of the heat produced by the drive system had indicated that active cooling was required, a TMS would have been designed based on the required flow rates and available heat exchangers and radiators. The system would be designed to use the minimum volumetric flow rates needed transfer heat efficiently and simultaneously reduce the power consumed by the pump.
5) Vehicle Testing

5.1) Data Acquisition & Analysis

Knowledge of the interior and exterior motor temperatures was necessary to determine the feasibility of a Thermal Management System that would use heat from the motor to improve the efficiency of an Ammonia Electro-chemical Converter (AEC). Figure 21 shows the location of the two points on the motor selected to analyze how effectively heat moves through the case.

Figure 21- Thermocouple Locations
Using the infrared thermometer to survey the temperature profile of the motor during operation, the bolt on the lower half of the motor was observed to reach the maximum temperature before any other observable location. For this reason, this location was used to indicate the interior temperature. The exterior temperature location was observed to remain at room temperature temporarily as the internal temperature increased. This location also provided a recess to mount the thermocouple without damaging the insulated tip. By measuring this temperature difference and using case thickness and surface area measurements, the heat flux through the aluminum motor case was found to be about 100 watts during peak use.

Shielded K-type thermocouples were selected to monitor the motor temperature due to their accuracy of ±1°C in the required temperature range and insulation from electro-magnetic interference. The signals were amplified using isolated operational-amplifiers to increase the signal up to the input level required for the data acquisition system while filtering out unwanted electronic interference from the motor. The exposed ends of the thermocouples also had to be electrically insulated from the motor to minimize interference.
Despite every effort to reduce noise in the temperature data, interference from the drive motor EMF could not be completely avoided. For the experiments with a significant noise-to-signal ratio, error correction was used in the data analysis to remove outlying data points. For example, figure 22 illustrates the before and after effects of error correction in a worst-case scenario. Notice the much improved level of confidence value ($R^2$), or percent difference from the mean for the trend-line after removing the outlying data points.

![Figure 22- Error Correction](image)

The signals from the motor controller that were observed during testing were instantaneous current and motor rpm. The battery voltage was also monitored with a multi-meter but not the data acquisition system as it exceeded the input voltage capability. The instantaneous current signal indicates the current in the high-voltage motor leads. Figure 23 illustrates how the current signal was first modified using the root mean square approximation and averaged over two-second intervals to produce a nominal value identifying the command to accelerate. The value found using this method was verified using a clamp ammeter on the battery cable.
In the initial months of dynamometer testing, the data collected was plagued by interference and required the aforementioned efforts in noise cancellation to record data with a minimal interference from the drive motor. This early testing was still useful for calibration purposes, noise removal verification, and developing better testing techniques. After considerable effort, over 30 drive cycles with minimized interference were conducted and used to compile temperature response patterns for each type of driving conditions associated with low speed city driving.

The sampling rate selected was a compromise for the different types of signals recorded. The current and speed signals changed much faster than the temperature and hence required a much higher sample rate. Individualized sample rates were not possible with the data acquisition system so various sample rates were tested. Ten hertz was determined to be sufficient for capturing the responses of current and speed while minimizing the unnecessary data points for the temperature signals.
Response time was not critical for the thermocouples due to the low rate of change in temperature. The calibration for each thermocouple was conducted between 0-100°C to ensure that the measurements for the testing were accurate within the 25-50°C range.

5.2) Drive cycle specifics

During the drive cycles, there was a time lag of three to five minutes before an increase in motor temperature was observed, henceforth referred to as warm-up. For the first minute of temperature increase, the response was exponential in nature before approaching a near linear increase in temperature. The resulting increase in temperature was found to be the steady-state rate of change for temperature for the duration of the assumed vehicle operational distance. The normal operation of the vehicle includes city driving at speeds up to 25 mph for a distances of five miles.

The vehicle’s response to increasing torque loads was used to find the conditions for which the drivetrain is most efficient. When the motor controller is in the normal, hall-effect mode setting, the drivetrain has an unusual response to increased torque loads. For gradual torque loading up to 30 ft-lb the motor speed remained above 2,000 rpm. However, as torque increased beyond 35 ft-lb, the motor speed and efficiency immediately dropped by nearly half, indicating that there are motor controller issues yet to be resolved.

The constant velocity drive cycle had the highest average power consumption as indicated by the y-intercept value of 2.3 kW, on figure 24. Not surprisingly this drive
cycle also exhibited the highest increase in motor temperature. From these two factors it can be inferred that the source of heat is electrical in nature and not simply caused by friction. The vehicle was gradually brought up to speed before applying a 30 ft-lb load for the duration of test. The average amperage draw for this drive cycle was 20 amps, although in the city driving cycle the current draw was observed to be about 16 amps when traveling at a constant speed in second gear. Constant velocity driving produced the lowest rate of change in temperature with respect to power consumption of 0.27 (°C/min)/kW as shown in figure 28, due to the higher average power use.

![Power Consumed (const. vel.)](image)

**Figure 24- Constant Velocity Power Use**

The hard acceleration drive cycle produced a rapid temperature increase in the motor. This drive cycle was characterized by the highest instantaneous current values but relatively low average current and thus power values. As figure 25 shows, the average
power consumed during hard accelerations is shown to be 1.6 kW. For change in temperature with respect to power consumption hard accelerations had the most effect with a value of $0.66 \, (°C/min)/kW$ as indicated in figure 28.

![Figure 25- Acceleration Power Use](image)

The hard deceleration drive cycle had the least effect on motor temperature, which was expected. The power used during the hard deceleration drive cycle is shown in Figure 26. Hard deceleration produced second lowest rate of change in temperature with respect to power consumption of $0.28 \, (°C/min)/kW$ as shown in figure 28. There is a question as to if the regenerative braking actually passes current back into the batteries. A negative current flow was indicated by the controller although a secondary current
measuring device indicated that current was only flowing out of the battery. This could be verified by close monitoring of the controller temperature during braking to look for increased heat dissipation.

![Power Consumed (decel.)](image)

\[ y = 0.0282x + 1.1769 \]

**Figure 26- Deceleration Power Use**

The hard acceleration and deceleration drive cycles were initially tested on the dynamometer, but were also verified through actual on-road driving with on-board data acquisition. The city driving drive cycle consists of data collected during actual road use characterized by hard accelerations and decelerations as well as constant velocity driving. The average power used during this drive cycle, approximately 2 kW, is shown in figure 27. The rate of temperature change with respect to the electrical power used for city
driving, shown in figure 28, is 0.45 °C/kW. This value is reasonable as it is within the range of the drive cycles that it is a composite of.

\[
y = -0.0119x + 1.9959
\]

Figure 27- City Driving Power Use

In order to compare the drive cycles evenly, the average electrical power used in each was used a basis for comparison. Figure 28 shows the rate of change in temperature for each drive cycle per kW of power dissipated through the drive motor.
The problems experienced while attempting to use the dynamometer for some of the drive cycles were a result of the safety feature inherent to the dynamometer. The dynamometer has a minimum speed whereupon it instantly applies a very high torque load, stalling the motor. This led to inconclusive results and led to the development of the city drive cycle to collect data without interference from the dynamometer. The original plan to alternate the sequence of drive cycle testing turned out to be irrelevant as the time required to recharge batteries between drive cycles allowed the motor to cool back down to room temperature. It was also rare that more than two drive cycles could be completed in a day of testing.
5.3) Vehicle performance

Upon correcting the numerous problems with commutation sensors, the vehicle began reliable operation by the April of 2007. The maximum speed reached on level ground is 27 mph exceeding the performance goal of 25 mph. The vehicle range is about 5 miles on battery power alone, which is half the distance that the final version of the vehicle is to travel when converting ammonia into hydrogen for fuel. The maximum estimated drivetrain efficiency is 75%, taking into account a 10% loss from the motor and a 15% loss from the manual transmission. The chassis dynamometer rollers and belts and the use of truck tires to match the roller width resulted in an additional 15% loss in measured efficiency. These dynamometer losses are normally negligible for the power range that the dynamometer was designed for, but are significant for our maximum power output. The maximum electrical to mechanical efficiency recorded with the dynamometer was 40% for a 30 ft-lb load simulating ascending a 5% grade at 10 mph in first gear, equivalent to a system efficiency of 55%. The difference between the estimated 75% efficiency and the recorded 55% efficiency is partially a result of improper motor controller tuning. According to the controller manufacturer, under certain circumstances the controller may require soldering in new resistors for fine-tuning. This may be resolved in future tuning efforts but was determined to be too risky at this stage in the project. To remove the loss associated with the dynamometer the electrical to mechanical efficiency for the vehicle was determined experimentally with road testing. In first gear the electrical power required for the vehicle to accelerate from a stop to 10 mph in first gear with two occupants resulted in repeatable efficiency values of 65%. This
The estimate is conservative as it was calculated based on a mechanical power estimated by the acceleration force multiplied by the vehicle final velocity, neglecting rolling resistance and aerodynamic loads.

5.4) Temperature Measurement Results

The focus of the temperature measurements was on the steady state increase in temperature following the initial warm-up period. The graphs selected for each drive cycle show the typical temperature responses for each style of driving. On average the interior motor temperature increased at a rate approximately twice that of the exterior. The exterior temperature is increased by the conduction of heat through the aluminum motor case resulting in a lower rate of change for the time duration of normal use.

Figure 29 is based on the data collected on 5-18-07 for the temperature response to a random fluctuation in speed to simulate city driving on the dynamometer. The instantaneous rate for the change in temperature is shown by the slope value of each trend-line. The temperature response during the first five minutes of operation is non-linear and not relevant to the steady state increase in temperature. For the same reason, the y-intercept values are not relevant to this discussion as this is only an analysis for a small section exhibiting linear behavior.
Figure 30 is based on the data collected on 5-23-07 for the temperature response to constant velocity driving with short periods of inactivity. The rest periods give short durations for the temperature to equalize over the motor case as well as allowing temperature monitoring free from motor interference. This figure shows the relationship between operation of the motor and the resulting temperature increase.
The time rate of change in temperature for each drive cycle was verified by finding the slope of select data points in the regions of low noise while the motor was off. For the constant velocity drive cycle the values were within 10% of the instantaneous rate of change for the interior and exterior temperatures.
Figure 31 is a close-up of the temperature response over a three minute period of constant velocity on 5-23-07. Notice that the slope value of the internal temperature is nearly twice that of the external temperature. These formulas were used to make forward predictions into the regions without motor noise, resulting in values within 5% of the actual temperatures. This was true for all three drive cycles further validating the data.

![Motor Temperature vs Time](image)

**Figure 31- Motor Temperature for Constant Velocity**

Figures 32 and 33 are based on the data collected on 5-24-07 using the dynamometer to simulate repeated hard accelerations and hard decelerations respectively. Notice that the rate of change is greater during hard accelerations. This is as expected due to the higher amperage used and hence increased power consumed when accelerating.
quickly. These rates of change were verified to be within 15% of the rates for the entire drive cycles again using selected points without motor interference.

**Figure 32- Motor Temperature for Hard Acceleration**

**Figure 33- Motor Temperature for Hard Deceleration**
Figure 34 represents the temperature response during and after motor shut-down. Notice that the interior temperature decreases shortly after the motor stops as the exterior temperature continues to climb and remain at the elevated temperature 20 minutes after the motor is shut-down.

Figure 35 is a close-up of the last ten minutes of Figure 34, focusing on the negative rate of change associated with the motor returning to ambient temperature. The exterior rate of change is a measure of the heat radiated by the case to the surroundings. Notice that this rate of change is one order of magnitude smaller than the rate of temperature increase associated with normal operation.
Figure 35- Motor Temperature Rate of Cooling
6) TMS Feasibility Review

During normal operation, as characterized by an even distribution of hard accelerations, hard decelerations, and constant speeds, the temperature of the motor increases initially at an exponential rate followed by a near linear increase in temperature up to the max observed temperature of 50°C. It can be assumed that the motor will continue to increase in temperature if not cooled in some manner. Based on the data collected in over 20 experiments including both road driving and dynamometer tests, the average increase in motor temperature was 0.5°C/min ± 0.2°C/min and did not exceed 0.9°C/min.

For the assumed vehicle usage of ten miles at speeds of up to 20 mph, it is not feasible to add liquid cooling to the drive motor as it will not reach 50°C in this time. The motor should instead have finned heat sinks added to the case to improve the radiation of heat to the surroundings. If the vehicle role changes in the future to include a longer operating time then liquid cooling may prove feasible at that time.

The motor controller, on the other hand, reaches 51°C in the first seven minutes of operation, making it a decidedly a better candidate for liquid cooling. Although the temperature gradient is present, the motor controller should be the focus of a more thorough analysis of the heat capacity to determine the heat available. If sufficient heat is released from the motor controller a coldplate can be machined to replace the finned heatsink. This will allow the heat rejected to be used in conjunction with the Ammonia Electro-chemical Converter (AEC).
7) Conclusions

The goal of creating an efficient electric vehicle is nearly complete awaiting calibration information from the motor controller manufacturer. The vehicle satisfies the performance goal by reaching speeds in excess of 25 mph. The maximum recorded electrical to mechanical efficiency as of 7-27-07 was 65% during on road testing. Figure 36 is a picture of the AETEV operating in pure electric mode.

![The AETEV](image)

Figure 36- The AETEV

The rate of temperature change was measured for various driving conditions including actual road conditions. The motor temperature increased from 25°C to 50°C, although only after 50 minutes of operation. Starting with a five minute warm-up period, the temperature typically increased at a maximum rate of about 0.8°C per minute of operation. The motor controller was observed to heat up to 51°C within seven minutes of
operation and is thus a more readily available source of heat than the motor. The rate of temperature increase for the motor controller was found to be about 3°C/min up to 50°C when the cooling fan was turned on to prevent damage from overheating.

This concludes the research conducted thus far as the vehicle constructed is now ready for the next stage in vehicle development. All of the major goals for this thesis are now complete. To aid in the development of the TMS that will eventually be installed on the vehicle, specific design information has been included in the future work section.
8) Future Work

The following are a few areas of vehicle development that require attention. The front suspension needs to be replaced with a lowering kit to reduce frontal height. A frame connecting the shock towers needs to be designed with a goal of keeping vehicle weight low while incorporating a frontal impact zone. The fiberglass body kit selected requires minor repair and installation. The Ballard fuel cell purchased should be tested prior to installation including a 48v to 200v DC-DC converter to maintain the Ni-MH battery state of charge. After the fuel cell is installed and tested with a hydrogen supply, AEC integration can begin.

As it is not currently feasible to construct a TMS for this vehicle, the following information is to aid in the development for the TMS that is eventually installed.

The parts required for the TMS are as follows:

- Coldplate (9” x 10½” x 1½”) ~$50
- Pump with adjustable flow rate ~$50
- Heat exchanger with tube in shell design and counter flow ~$1000
- Connecting insulated copper pipes (½” dia. 10’ length) ~$30
- Radiator (12”x12”) ~$100
Figure 37 is a conceptual design of a motor controller coldplate with a single channel to avoid stagnant flow area and promote heat transfer to the thermal fluid. The operating temperature can be controlled by adjusting the flow rate of the thermal fluid passing through the coldplate.

![Motor Controller Coldplate Concept](image)

Figure 37- Motor Controller Coldplate Concept

The heat generated by the motor windings of the stator is conducted through the case where it can radiate to the environment. The motor has been observed to remain at elevated temperatures for a considerable amount of time following operation indicating that the radiation alone is not sufficient for removing the heat generated. Experiments seem to indicate that the temperature increases ten times faster than it can be dissipated by the motor through convection in its current configuration.
Several cooling options exist for the motor: exterior fins, exterior coldplates, and interior coldplates. Adding exterior cooling fins would increase the surface area and help radiate heat more effectively to the surroundings. This is the least expensive option and if properly installed will increase the heat transfer through the case and reduce the risk of overheating. One drawback of this cooling method is that the heat would be lost to the surroundings and not be available in the ammonia reformation process.

Utilizing a liquid cooling interface the heat lifted from the motor could be carried away by a thermal fluid, which could then in turn be used to heat ammonia, thus reducing the energy cost in electrolyzing it. An external coldplate is easier to install than an internal coldplate but still requires heat to conduct through the case before it can be lifted. Externally it would lower the motor case temperature and thus improve conduction away from the stator whereas an internal coldplate would remove heat directly from the stator.

Coldplates are inherently more complex than finned heat sinks because they require sealed pipes to transfer the thermal fluid between the hot and cold regions of the system and depending on flow require pumps or compressors. A heatpipe is a type of cooling device that does not need a powered device to move the thermal fluid. Instead, heatpipes use gravity or capillary action to return the condensed thermal fluid in liquid form back to the heat source where it can evaporate to lift more heat. In order to function properly, heatpipes require precise calibration to set the pressure at the liquid-gas phase change point for the operating fluid at the temperature of the source.

The motor and controller have been shown to require cooling for extended periods of use beyond current performance requirements. The motor internal temperature
increases at rates of up to 0.8°C/min while the case can only reject this heat at about 0.03°C/min. Without cooling, the motor will undoubtedly overheat during continuous operation. To allow the heat rejected by the controller to be used by the AEC, the finned heat sink should be replaced by a coldplate. The motor should also be modified to improve air-cooling through added heat sinks.
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Appendix A: Advanced Vehicle Simulator

The following is documentation for using ADVISOR software to verify the performance of the motor and battery pack from a Honda insight for the ammonia fuel cell car project. A test vehicle of higher than actual weight was configured to show performance under worst case loading conditions. The transmission was modified to represent the gears in the VW transmission. The wheel diameter was set to set to approximately 2 ft to represent the wheel on the vehicle. The accessory power was set to zero to reduce battery drain by accessories that will not be on the test vehicle. The first test was to verify the performance of an electric vehicle equipped with the 10 kW PMBL DC motor and the Ni-MH battery pack both from the Honda insight.

Figure 38- Advisor Simulation Parameter
The results show that after 1350 seconds, or about 22 minutes, of operation the battery pack is fully discharged. The max speed possible from this configuration is 43 mph and the distance traveled is 10 km. The simulation shows that the drivetrain is more than adequate to satisfy the project requirements of 25 mph.

Figure 39- Advisor Simulation Results
Appendix B: Battery Charging and Basic Vehicle Operation

Read and comprehend all instructions before attempting to charge the Ni-MH battery. The charging process must be continually monitored during the 3-4 hours required to charge the Ni-MH battery up to 170v from a completely discharged state of 140v. **A serious risk of electrocution exists whenever the Ni-MH battery is activated!** Avoid contact with any high voltage connections at all times. Do not allow unapproved personnel near the vehicle when activated. Read the Honda service literature for more details and precautions.

**Ni-MH Charging Procedure**

**Step 1:** Charge the lead-acid battery behind the passenger seat with the 12v battery charger to power fans during the Ni-MH charging process. When charged, the lead-acid battery should be about 13v.

![Lead-acid battery & Charger](Figure 40- Lead-acid battery & Charger)
Step 2: Remove the red plastic power key from the manual contactor on top of the Ni-MH battery to disconnect the controller from the power source. Ensure that the black ON/OFF switch on the Ni-MH battery is on.

![Figure 41- Power Key](image1.png) ![Figure 42- Ni-MH ON/OFF Switch](image2.png)

Step 3: Plug in the black 3-prong power cable from the battery charger into the outlet on the top right side of the Ni-MH battery. Plug in the resistor fan power cord to the 2-prong supply located on the top left side of the Ni-MH battery. Plug the battery charger into a normal 110v wall circuit.

![Figure 43- Ni-MH Battery Charger](image3.png) ![Figure 44- Ni-MH Battery and Charge Cables](image4.png)
Step 4: Use the digital voltmeter labeled ‘Battery Voltage’ on the dashboard to accurately monitor battery voltage during charging. The analog voltmeter is only for quick reference when driving.

![Analog Voltmeter](image1)

![Battery Voltage Meter](image2)

Figure 45- Analog Voltmeter

Figure 46- Battery Voltage Meter

Step 5: **Follow the arming sequence exactly to prevent damage to the contactors!**

Flip up only the red guard. Press and hold the black momentary switch. Flip up the toggle switch under the red guard. Release the momentary switch. The Ni-MH battery is now activated. The Ni-MH battery must be activated during the charging process.

(To deactivate the battery, simply flip down the red guard)

![Arming Switches](image3)

Figure 47- Arming Switches
Step 6: If the battery voltage is below 165v, charging is required. Turn on the ammeter connected to the battery charger. Set the variable resistance to **START** to reduce charge current prior to charger activation. **Failure to due so will result in fuse failure and possible damage to the charger.**

![Ammeter](image1.png)  ![Current Regulating Resistor](image2.png)

**Figure 48- Ammeter**  **Figure 49- Current Regulating Resistor**

Step 7: With the Ni-MH battery activated, turn on the silver toggle switch on the Ni-MH charger. Monitor the ammeter to limit the charge current at 1.5 amps. As the battery charges, the resistance value must be reduced to keep a charge rate of 1.5 amps until the battery voltage reaches 170v. **Overcharging the battery can result in explosion!**

Step 8: When battery voltage reaches 170v turn off the silver toggle on the Ni-MH battery charger. Turn off the red guarded toggle switch. Disconnect the battery charging cables.
AETEV Operation Procedures

The AETEV can only be driven with expressed written permission by Dr. Kremer for each instance and purpose. When fully charged the AETEV has a range of 5 miles or approximately 20 minutes. The transmission is typical to VW although the clutch has been removed. The motor speed must match the transmission speed when shifting or serious damage will result. For instance, when the vehicle is stopped the motor must be stopped in order to shift. To activate the controller the vehicle must initially be manually moved approximately 1” forward or backward with the transmission in 1st gear and the hand brake off.

Step 1: Ensure that the 12v battery behind the passenger seat is charged. Turn on the pump switch. Look for the flashing LED on the pump circuit box and steady oil flow into the oil reservoir.
Step 2: Insert the red plastic power key in the manual contactor on top of the Ni-MH battery and rotate CW 90° to power up the controller. A red LED will light up on the back of the controller.
Step 3: **Follow the arming sequence exactly to prevent damage to contactors!**

Flip up only the red toggle switch guard. Press and hold the black momentary switch.

Flip up the toggle switch. Release the momentary switch. The Ni-MH Battery is now activated. Verify that the voltage is above 165v.

![Arming Switches](image)

**Figure 56- Arming Switches**

Step 4: Press down on the foot brake, release the hand brake. Select 1st or Reverse gear.

(Press down, left, then back to select reverse gear).

![VW Transmission Shift Pattern](image)

**Figure 57- VW Transmission Shift Pattern**
Step 5: Rock the vehicle forward or backward slightly to activate the controller. This initiates the hall-effect sensors in the drive motor. A green LED will now light up on the back of the controller. Shift into neutral after the controller is activated to allow the motor to ‘idle’, thus maintaining proper hall-effect operation.

![Figure 58- Green LED](image)

Step 6: **Fasten seat belts.** In neutral, tap the accelerator gently to ensure proper operation. With motor at 0 rpm, shift into first gear and press down on the accelerator to travel forward. Accelerate with care. Upon releasing the accelerator, the motor automatically enters regeneration mode and slows the vehicle.
**Step 7:** Shifting procedure: After reaching 2500 rpm, simultaneously reduce pressure on the accelerator while shifting into neutral. Use the motor speed indicator to bring the motor to approximately 1200 rpm. Gently move the shifter into the next highest gear. When the motor speed matches the transmission speed, the transmission will shift effortlessly. **Do not force the shifter!**

![Figure 59- Battery Voltage and Motor Speed Indicator](image)

**Step 8:** Monitor battery voltage while driving the AETEV. When the battery voltage drops below 135v the Ni-MH battery is discharged. **Further discharging of the battery may result in irreversible damage.**

**Step 9:** After vehicle operation, set the hand brake and remove the red plastic power key. Leave the red guarded toggle switch on for ten minutes to help cool off the battery and controller prior to shut down. Wait for the battery to cool down to room temperature before charging again.