PROJECT PROPOSAL AND FEASIBILITY STUDY
ATMOSPHERIC WATER GENERATOR
WATER FROM AIR:
TEAM 5

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Abstract
This senior design project is to design and prototype an atmospheric water generator. This is a device which produces drinkable water from humid air with an emphasis on energy efficiency and renewable energy sources.

This project is the culmination of the engineering program at Calvin College. It is conducted within the context of a two-semester course which covers all aspects of project development and management. The following report explores the feasibility of the proposed design. After careful research and analysis, Team 5 has concluded that wet desiccation is a feasible process for atmospheric water generation within the context of this project.
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<td>Project Proposal Feasibility Study</td>
</tr>
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<td>AWG</td>
<td>Atmospheric Water Generator</td>
</tr>
<tr>
<td>WHO</td>
<td>World Health Organization</td>
</tr>
<tr>
<td>CaCl2</td>
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1. Introduction

1.1. Background

Calvin College is a Christian Liberal Arts institution located in Grand Rapids, MI. It is one of the few Christian colleges in America that offers a full engineering major. Integrating Christian values and the Liberal Arts into engineering, Calvin’s program has a strong reputation for producing thoughtful and well-rounded engineers.

This senior design project is the capstone course for the Calvin Engineering program. Two courses, Engineering 339 and 340, are coordinated around the project, covering various aspects of project management and design.

1.2. Team Members

1.2.1. Ben Niewenhuis

Ben Niewenhuis hails from Battle Creek, Michigan, a product of St Phillip Catholic High School and the Battle Creek Area Math and Science Center. Active as a student and an athlete, Ben was particularly interested in the realms of math and science. He entered the Calvin College Engineering program in the fall of 2008, and has chosen Electrical Engineering as his field of study. He is an active leader of the Calvin Chess Club and has taken two summer research positions; one at Calvin College concerning polystyrene recycling and the other at Carnegie Mellon University on improvements in Monte Carlo analysis. He looks forward to continuing his studies at the graduate level in Electrical Engineering, with the eventual goal of entering into research.

1.2.2. Chris Shepperly

Chris Shepperly was born in Battle Creek, Michigan to Joel and Nancy Shepperly. He attended Harper Creek High School and the Battle Creek Area Math and Science Center. While in high school, Chris had a passion for math, science, and athletics. In school he was very involved in swimming as a captain and the National Honors Society as Vice President.

At Calvin, with Chris’s interest of math and science he chose to follow the path of engineering while also continuing his passion for swimming. Currently Chris is a senior mechanical engineering student and a two-year captain of the Calvin swim team. He has plans next year to work as a Mechanical Systems Engineer for Dematic Corp. in Grand Rapids.

1.2.3. Ryan Van Beek

Originally from Lansing, Illinois, a suburb a half hour south of Chicago, Ryan is the oldest of four children born to Randy and Ruth Van Beek. He is a graduate of Illiana Christian High School where he played sports and sang in choir. Ryan entered the Calvin College Engineering program in the fall of 2008. Being an Activities Coordinator in Beets-Veenstra, he developed a
wide social network and learned to manage his time to include both event planning for his dorm and the rigorous course load of the engineering classes he took.

During Ryan’s first two summers as a college student he worked for an asphalt paving and maintenance company called Site Services, Inc. in Highland, Indiana. In his two summers there, he developed the ability to survive sixty hour work weeks performing physical labor outdoors as well as a good sense of what needs to be finished to accomplish a task. This skill of understanding what needs to be done and working until it is completed helped Ryan to earn the respect and appreciation of his employer. Entering into his junior year of college, Ryan began his focused study of mechanical engineering primarily in the fields of machine design, thermodynamics, and heat transfer as organized by the engineering curriculum.

After spending the summer before Ryan’s senior year as a design engineering intern at Woodward, Inc., a company in the aviation and aerospace industry, he understood more completely how his engineering education will benefit him and enable him to go into many different areas. Through his three years of engineering and business coursework, sales engineering has emerged as the ideal field for Ryan to excel in because it would make use of his social and organizational skills in a context that also utilizes his educational background.

1.2.4. Eric Van Kooten

Eric Van Kooten is a native of the Grand Rapids Area. He was born and raised in Kentwood, Michigan and attended South Christian High School. While at South Christian Eric was active in sports playing football, baseball and basketball along with being involved in several student organizations including Student Senate. Eric was very involved academically and found his greatest joy in the sciences.

After South Christian Eric choose to follow the family path to Calvin College. At Calvin Eric declared Engineering and got involved immediately. Academics were a priority and student organizations were still a staple in his activities. He is involved in REO, EWB and ASME. After Calvin, Eric has a goal of continuing his education with a dream of obtaining his doctorate and someday becoming Professor Van Kooten.

1.3. Problem Statement

The initial problem statement for Team 5 was posed by Michael Harris, Executive Director of the Calvin College Enterprise Center. The original statement was as follows:

“Design and develop a prototype system for removing clean (potable) drinking water from air using a wind turbine. Use a wind turbine to generate electricity; use electricity to cool air (or increase pressure) resulting in condensation of water; capture water vapor from air that condenses into water. Self-contained system (no external connections required). Basic human need (especially valuable for remote areas).”
Upon adoption of this project, Team 5 adapted the problem statement to better reflect the realities of atmospheric water generation. Atmospheric water generators already exist as products on the market; thus there is a need for this design to differentiate itself, through some innovation or better utility in order to justify the expenditure of time and money on this project. Furthermore, atmospheric water generation is an energy intensive process. Existing implementations aren’t capable of producing significant amounts of water at a decent price. In light of these considerations, Team 5 formulated the following problem statement:

“To design and develop an innovative system for obtaining clean drinking water from air, focusing on improvements in the energy requirement with the end goal of powering the device with renewable energy.”

2. **Constraints**

2.1. **Requirements**

When designing the atmospheric water generator Team 5 identified three requirements they needed meet to ensure that the final project would effectively fulfill its intended purpose.

- **Potability of Water** - Water produced by the design must conform to the World Health Organization (WHO) drinking water quality standards.
- **Simplicity of Use** - Design must be operable by persons of limited technical experience.
- **Safety** - Design must not pose a hazard to users at any point during its normal operation.

The first requirement is that the water produced is safe to drink. This requirement is vital because engineers must be socially responsible and take precautions so that society is not harmed by any products they design. The World Health Organization (WHO) spends significant time working globally to keep people safe from disease and other illnesses. The WHO has established standards for clean water because it is easy for people to become sick consuming contaminated water. Team 5 plans to follow these standards so the end users are not harmed by the device they made.

The second requirement is that the design is simple for people with limited technical experience to use. We plan to design the interface to approximately the same complexity level as standard household appliances such as stoves, dishwashers, and washing machines.

In addition to the first two requirements, Team 5 will also design the AWG so that it is not hazardous to users at any point of its standard operation. This third requirement is similar to the first in that it seeks to protect the end users and society in general; however, this requirement focuses on ensuring safety across all aspects of operating the system.

2.2. **Design Objectives**

When starting the project Team 5 developed several goals or objectives that we hoped the AWG our design will meet.
The first objective is that this product is able to utilize a variety of power sources, including (but not limited to) solar, wind, and the traditional power grid. The targeted production output is one liter of drinkable water per day as defined by WHO standards, and since we want to maximize efficiency, the amount of energy needed to input to the device to generate this water should be minimized in every way possible. The objective of minimizing costs is related to both the energy usage and the selection of the system components. In the requirements section, it is mentioned that the design is intended to be easy to use by people with limited technical background. This goes hand in hand with the goal that the final product is designed for long-term operation with only low-cost and minimal repairs.

2.3. Deliverables

The final prototype of the atmospheric water generator is most importantly going to be a device that accomplishes the requirements Team 5 established at the onset of the project. Meeting the functionality requirements, the safety requirements, and communicating both the purpose of the project as well as the value proposition are the primary components requiring Team 5’s time effort. At the end of the project there will be several things that explain or demonstrate how successfully the goals were met. During the primary research and design phase Team 5 will spend time assembling the Project Proposal Feasibility Study to describe the plan to create the prototype and test it in conjunction with explaining the methodology behind all of the decision making and research findings.

During the second semester of Senior Design, Team 5 will work on constructing, testing, and optimizing a prototype based on the decisions made during the first semester design work. In addition to a working prototype, deliverables such as the website, design notebooks, and the final report will provide a comprehensive summary of the work involved with designing and constructing the atmospheric water generator. The design notebooks are going to enable people who did not work on the project to get a detailed explanation of the work performed by each one of the members on Team 5. Many of the deliverables such as the PPFS, the prototype details, and the final report will be posted on Team 5’s website\(^1\) to enable electronic perusal of the development of the final prototype. The final report will be a compilation of all project

\(^1\)http://www.calvin.edu/academic/engineering/2011-12-team5/?page=index
deliverables in a technical report form so people interested in the details of the project can find initial goals, process options, and final design results comprehensively explained in one location.

3. Design Norms

For this project, Team 5 kept several design norms in mind as they planned to create this wet desiccation system. This involved taking an honest look at the goals of the project and thought on how the final product should interact with the users and other people who would be affected by it.

3.1. Transparency

Throughout the design process we worked to make our process understandable, consistent, and reliable. Someone will be using this so we should make sure that users without a technical background can understand the process and make use of the product in everyday life.

3.2. Stewardship

The second design norm considered was stewardship. This norm is important for the project because in using the earth’s resources, we must remember to take care of the world God has given us. Using economic, environmental, and human resources in a manner that clearly demonstrates a high value on stewardship shows we care about the world we live in and the people we share it with.

3.3. Integrity

The design norm of integrity involves looking at the harmony between form and function, completeness, promotion of human values and relationships, and is pleasing and intuitive to use. Developing this AWG so that it accomplishes and reflects integrity in design meshes well with the other design norms of trust and transparency. Our goal is to accomplish all of these design norms to effectively make a better product that takes into consideration the rights of others.

3.4. Trust

The final design norm important for this project is trust. We want people to feel comfortable using our AWG so that they use it to its fullest potential and their maximum benefit. Our desire is to make a good product that is dependable and reliable. Making an unreliable product would drive up user costs for repair and maintenance, our goal is to have a trustworthy design, something that our customer can rely on.

4. Project Management

All four members of this team are well versed in the technical work required to complete this project adequately and on time. Each member is responsible for his work individually and is expected to contribute his expertise in whatever area they can. Organization plays a big role in the outcome of this project; several tools that Team 5 implemented were a detailed Work
Breakdown Schedule, weekly meetings, and a detailed budget. Advisors, mentors and consultants are important to the success of this project and are listed in Figure 1.

![Team Organizational Chart](image)

**Figure 1: Team Organizational Chart**

4.1. Meetings
Team 5 holds weekly meetings on Friday afternoons from 1:30-2:30 and various other times during the week as deadlines require. Meetings consisted of discussing milestones accomplished and goals for the coming week.

Records of each weekly meeting as well as several other class work days and impromptu meetings can be found in section 12.8 of the appendix. Agendas for several of the meetings were made in Google Docs as well and can be found in section 12.9 of the appendix.

4.2. Schedule
Team 5 created a Work Breakdown Schedule (WBS) at the beginning of the semester with all of the foreseen tasks the project required. This was updated weekly to reflect the project’s status. Each task was broken down into small sub-tasks that were manageable in a short period of time. The WBS can be found on the team website under the status section.

4.3. Budget
“Every project you ever work on will have a budget.” This quote is known to mechanical engineering students at Calvin as the Heun Postulate, named after Professor Heun of the Engineering department. For Senior Design projects, teams are given a five hundred dollar base budget with increased financial resources if the team presents justifiable need for it. Developing a detailed budget is important in order to maximize the funds allotted while obtaining all of the
components necessary for the system. It is important to factor in the cost of testing the prototype as well.

5. **Method of Approach**

5.1. **Design**

The design process has gone through three distinct stages. The first stage consisted of dehumidification brainstorming. Preliminary calculations on each idea gave us a better understanding of production capacity and energy efficiency. Ideas that showed significant promise in these two respects were researched further. All of this data and research was compiled and used to decide on the general dehumidification approach.

5.2. **Research**

Research was assigned to each team member for a certain set of topics, allowing for specialization and deeper investigation into the various aspects of our problem. Several topics have been kept universal: all team members are expected to understand and contribute to research on the basic operation of the device. Meeting with Mr. Glen Remelts of the Heckman Library was particularly helpful in keeping all team members on the same page concerning general design research.

5.3. **Team Communication**

Weekly team meetings and sharing of team emails are crucial in maintaining lines of communication between team members. Using Google Documents allowed for easy flow and modification of important documents between team members. All of this is in keeping with our desire to maintain transparency in our project, both among team members and between the team and our customers.

6. **Design Evaluation**

The system can be divided into four primary aspects: dehumidification, filtration, control, and power, each of which is discussed in detail below.

6.1. **Dehumidification**

When approaching the problem of atmospheric water generation it is clear that the heart of the system is dehumidification, which is the removal of water from a stream of air. In this application we seek to capture this water and utilize it for drinking purposes. Three common psychometric methods of dehumidification stood out during preliminary research; a temperature drop below the dew point (refrigeration condensing), pressure condensing, or a combination of the two. In addition to these three psychometric methods, the team came upon an alternative solution called wet desiccation.
6.1.1. Refrigeration

Traditional refrigeration cycle dehumidification remains the most prevalent method for generating water from atmospheric humidity. This method circulates air over cooling coils connected in a refrigeration cycle to bring the water in the air below its dew point. The dew point of the water is dependent on the vapor pressure and humidity and tends to be a relatively low temperature compared to the ambient conditions. To reach the dew point the air running through the unit will have to be cooled a considerable amount.\(^2\) This process requires a constant energy supply that is used as the maximum allowable energy demand for the system. This approach is expressed in Figure 2 below:

![Dehumidification by Refrigeration Cycle](image)

**Figure 2: Dehumidification by Refrigeration Cycle**

There are several advantages to this approach. First, it is founded on decades of technical work and innovation. Furthermore, it is a very direct approach and relatively simple to evaluate given psychrometric theory and the latent heat of condensation. A primary disadvantage to this approach is the magnitude of the heat transfer needed to generate a significant quantity of water. Virtually all commercial atmospheric water generators utilize this approach to dehumidification.

6.1.2. Pressure

It is possible to compress humid air so much that it will condense at the ambient temperature. As pressure increases the dew point rises; thus, enough compression will force the dew point above the ambient temperature resulting in spontaneous condensation; heat will transfer from the pressurized humid air to the ambient air. Compressing air to extract water could potentially require pressures up to five times the ambient pressure. This will require a very sturdy tank that can handle high amounts of stress in its walls. This method has great potential for low energy

demands, especially if one was able to recapture some of the energy in the compressed air using a turbine or piston. The energy efficiency of this design option has great promise but it is heavily dependent on compressor and decompressor efficiency and humidity. Figure 3 below is a representation of this approach.

**Figure 3: Dehumidification by Pressurization**

The primary advantage of pressure dehumidification is the low energy requirement; the only unavoidable loss is the pressure applied to the water vapor. However, any inefficiency in the compression/decompression cycle is amplified by the large volume of air processed per unit water produced. Additionally, the rate of production when driven by natural convection cooling to the atmosphere is too slow for significant production; some mechanism to speed up this heat transfer needs to be implemented, increasing the energy cost. No existing atmospheric water generators utilize this approach.

Pressure assisted condensation was the first idea investigated in this project. Team 5 saw potential in the alternate method of condensing because of the theoretical energy savings. Because the team saw such promise for this approach thorough energy calculations were used to evaluate the feasibility of the system. The system is deemed feasible if the energy per unit of water is less than the competition. Several assumptions were made for the base case feasibility calculations:

- The incoming air has a relative humidity of $1 \text{ kg}_{\text{water}}/\text{kg}_{\text{dry air}}$ ($\omega_1 = 1$) and the outgoing air has a relative humidity of $0 \text{ kg}_{\text{water}}/\text{kg}_{\text{dry air}}$ ($\omega_2 = 0$). This is a simplification because all air will not come in with a humidity of 1 nor will it leave with no water vapor left in the air, so this is an ideal humidity removal situation.
- The compressor has a constant volume that does not change. A standard home compressor has a volume of approximately 25 liters, which was used as the constant volume for the base case.
The mass of the water vapor removed from the air does not decrease the pressure in the system at all. This is not reality because when the water is condensed out and then it is pumped out of the control volume there will be less mass within the control volume and the gas will be less dense. Since we have a constant volume the pressure will decrease to account for the loss of mass.

The efficiency of the compressor was assumed to be 80%. This number is based on preliminary findings from the internet.

The efficiency of the turbine was assumed to be 80%. The turbine and compressor were assumed to be the same for simplicity but in reality they will vary.

The density of water is assumed to be 1000 kg/m$^3$ for all temperatures. This was assumed because the density variance over the small range of temperatures analyzed in this system was negligible. Likewise the density of air was assumed to be 1.2 kg/m$^3$ for all temperatures, for the same reasons.

Compression would not cause any change in temperature and the system would only have to remove the energy required to condense the water, the latent heat of condensation. It was also assumed that the heat could be removed in a perfectly efficient process.

For these assumptions Team 5 was able to calculate the amount of energy that was required per mass of water. This unit mass of energy was found using equation 1:

\[
q = \frac{e_{elec}}{m_w} = \frac{e_{out}}{\eta_{comp}} = \frac{\Delta PV}{m_a(\omega_1-\omega_2)} \tag{Equation 1}
\]

In $e_{elec}$ is the electrical energy required and $m_w$ is the mass of the water. The total energy required, energy recovered and the energy required from the grid are related in equation 2.

\[
q = q_{grid} + q_{recovered} \tag{Equation 2}
\]

With all of the assumptions, Team 5 found that for each gram of water produced the system would require 20,670 Joules from the grid which is more than the competition. Table 1 shows the values for the energy calculations of the pressure condensing system along with basic comparisons of the competitor’s energy requirements.

**Table 1: Energy Values from Compression Condensation Base Case**

<table>
<thead>
<tr>
<th></th>
<th>Total Energy Required</th>
<th>Energy Recovered</th>
<th>Energy Required from Grid</th>
<th>Ecoloblue</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>57416 kJ/kg</td>
<td>36747 kJ/kg</td>
<td>20669 kJ/kg</td>
<td>3500 kJ/kg</td>
</tr>
</tbody>
</table>
After the base case calculations were complete, Team 5 was able to vary several parameters to determine the minimum efficiency required in the compressor and turbine to equal the best competitor’s energy requirement. First by varying the efficiency of the compressor and turbine as one component, an average component efficiency of 92% is required to match Ecoloblue. When the final pressure is lowered the average efficiency decreases up until a certain point. This shows that there is an ideal pressure at which to operate the system. This ideal pressure is 190 kPa and requires a minimum average component efficiency of 85%, figure 4 shows the decreasing power requirements for increasing average component efficiencies. Calculations for the compression condensing system can be found in section 12.5 of the appendix.

![Figure 4: Block diagram of wet desiccation process](image)

6.1.3. Combination

The third alternative is a combination of compression and cooling. When humid air is pressurized the dew point of the water vapor is increased. This is beneficial for an atmospheric water generator because pressurizing the air a small amount so that less cooling is required could lower energy requirements. By combining the two approaches it minimizes the work needed for each to achieve the same desired result; however this will increase the system cost and complexity.

6.1.4. Wet Desiccation

The final design option considered is the most abstract, but has gained recognition recently as a valid design for atmospheric water generation. Wet desiccation is a process where a brine solution is exposed to humid air in order to absorb water vapor from that air. The solution is then sent into a regenerator where the water vapor is extracted from the solution. This method has

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grown in popularity because of its efficiency and the ease with which it can be adapted to renewable energy, particularly solar. Figure 5 below is a basic representation of this approach.

![Diagram of dehumidification by desiccation](image)

**Figure 5: Dehumidification by Desiccation**

A primary advantage to this approach is that the desiccant accomplishes the most difficult part of dehumidification, extracting the water from the air, without a direct expenditure of energy. The problem is thus recast into terms of regenerating the desiccant and capturing the resultant water. The main disadvantage of wet desiccation is the complexity that is introduced, both in terms of system and materials.

Actual implementation of wet desiccation dehumidification depends largely upon the desiccant used. Two atmospheric water generators that utilize desiccation have been identified, each of which utilizes a different material as its desiccant. The first is in development at the Interfacial Engineering and Biotechnology IGB in Stuttgart, Germany and uses a highly concentrated brine solution. The solution adsorbs water from humid air and is then cycled into the interior of the device, where the water is extracted under low pressure conditions. The other device uses a solid-state desiccant and a day-night cycle; by night humid air is circulated, by day solar heat is used to extract the water and regenerate the desiccant.

Wet desiccation originally appeared to be a daunting task, particularly for a team without any engineers in the chemical concentration. However, as more research was performed, wet desiccation became more appealing as a design alternative due to its potential for low energy operation and room for innovation. The biggest difficulty was establishing the feasibility of this approach, especially concerning the rate at which the water was absorbed by the desiccant. Research yielded several useful articles that described the performance and implementation of wet desiccation systems. Of these, one article in particular was best suited to our purposes. This article described a cross-flow liquid desiccant dehumidification system and reported the performance of the system across a variety of experimental conditions. The operation of the

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system under nominal conditions was highly encouraging, a state summarized in Table 2 below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solution Temperature</td>
<td>30°C</td>
</tr>
<tr>
<td>Solution Concentration (mass %)</td>
<td>43%</td>
</tr>
<tr>
<td>Solution Flow Rate</td>
<td>0.175 kg/s</td>
</tr>
<tr>
<td>Air Temperature</td>
<td>30°C</td>
</tr>
<tr>
<td>Air Relative Humidity</td>
<td>78%</td>
</tr>
<tr>
<td>Air Flow Rate</td>
<td>204.4 cfm</td>
</tr>
<tr>
<td>Water Absorption Rate</td>
<td>79.49 kg/day</td>
</tr>
</tbody>
</table>

Several observations can be made from these reported results. First, the rate of water production, almost 80 kg of water per day, translates into a volume much greater than our stated goal of 1 L per day. This is particularly encouraging considering the second observation: the operating points of the reported system are tailored to provide maximum dehumidification performance. Thus, in adapting the results of this system to our design one can only expect the absorption rate to fall as compromises are made to reduce energy cost and maximize the water produced in the regenerator system; the initial figure of 80 kg per day gives good reason to believe that the original goal can still be achieved in a similar system.

The next step was to construct a model using the relationships reported in this article between the various operating conditions and the water absorption rate. Four key factors were identified: the size of the contact surface, the rate of air flow, the concentration of the brine exposed to the air stream, and the temperature of the brine. Linear approximations were developed for each of these factors using the reported data. Additionally, it was assumed that each of these factors has an independent effect on the system. Figure 6 below is a representation of the resultant model:

![Figure 6: Research-Based Model](image)

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This model takes the four input variables noted above and returns a predicted rate of water absorption and a nominal brine flow rate (flow rates below this nominal value fall off due to incomplete wetting of the packing tower). This model was implemented in Engineering Equation Solver (see section 12.6 in appendix) and used to evaluate an operating condition representative of our system design. Table 3 below summarizes the results of this simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solution Temperature</td>
<td>30°C</td>
</tr>
<tr>
<td>Solution Concentration (w%)</td>
<td>32%</td>
</tr>
<tr>
<td>Packing Dimension</td>
<td>30cm</td>
</tr>
<tr>
<td>Air Flow Rate</td>
<td>93.5cfm</td>
</tr>
<tr>
<td>Water Absorption Rate</td>
<td>18.06kg/day</td>
</tr>
<tr>
<td>Nominal Brine Flow Rate</td>
<td>0.171kg/s</td>
</tr>
</tbody>
</table>

Table 3: EES Model Results for Representative Conditions

The critical change between the operating conditions and those used in the article is the solution concentration: we will be dehumidifying with a concentration much less than that used in the article. In this calculation 32% was the estimate used. Additionally, airflow was reduced to save energy and lower noise. According to this model, even with these changes, 18kg of water can be absorbed per day. Given that components supplying the required flow rates and packing dimensions are available within the budget range (see Table 8: Budget, p.25), it is concluded that this approach is feasible from a research perspective.

6.1.5. Decision

After careful consideration, Team 5 chose the wet desiccation system as the best option for atmospheric water generation. Teams 5’s initial inclination was to work with independent compression, but after doing initial energy calculations and going through careful consideration of the alternatives it no was no longer favored. A main difficulty with compression is that in order to make it competitive, in terms of energy usage, with the current market a high efficiency compressor is required which is expensive as shown above. Because of the pricey compressor Team 5 faced a tradeoff between either an energy efficient system or a relatively inexpensive system with pure compression, therefore it was passed up as the design of choice.

Another reason for the design decision is the fact that no patents or reports of an atmospheric water generator that runs only on compression could be found. Even though we had calculations to support that it is possible, the fact that no one uses that method made the team hesitant to pursue the process. We decided against cooling coils because currently every main stream atmospheric generator uses them. To achieve the goal of making this technology more available and to prepare for the future of this market, the technology designed needs to be new and
possibly better than the current competitors. All of these factors are quantified in a decision matrix located in the appendix in section 12.2.

6.1. Brine
In the desiccation process there are several different salts that will work in the brine solution. Lithium bromide (LiBr), lithium chloride (LiCl), and calcium chloride (CaCl2) are all common salts used in this process. To determine the best option, they were compared by several factors: corrosion, cost, and safety. Each of the considerations is explained below.7

6.1.1. Corrosion
Salt solutions can cause accelerated corrosion on many different materials. Because it is unavoidable for us to use a salt solution, corrosion must be minimized by choosing corrosive resistant components and choosing a relatively non-corrosive salt. All three of the salts that Team 5 is considering are fairly non-corrosive but the nature of a salt solution will cause accelerated corrosion compared to pure water.

To minimize corrosion, inhibitors can be added to the brine. Inhibitors are commonly used in both Lithium solutions in which the inhibitors are both effective. No matter how effective the inhibitor is, if it introduces toxic or harmful chemicals into the system Team 5 can’t use it (For more details refer to the safety section); unfortunately, most inhibitors are harmful to humans. CaCl2 does require inhibitors as frequently as the lithium-based brines but uninhibited CaCl2 is more corrosive than either LiBr or LiCL with inhibitors.

No matter which salt or which inhibitor is used, corrosion will occur with most metals. Because of this as many plastic components will be used as possible.

6.1.2. Cost
Cost is important when selecting the brine because the system will require a significant amount of brine in order to run. Cost prices for all three salts were found online and are reported in Table 4. Looking at the table it is clear that CaCl2 is the clear favorite. The design will require more than one kilogram or salt so using either of the lithium salts would take up the majority of our budget.

---

### Table 4: Salt Cost Comparisons

<table>
<thead>
<tr>
<th>Component</th>
<th>Price ($)</th>
<th>Amount (g)</th>
<th>Unit Price ($/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiCl⁸</td>
<td>19</td>
<td>100</td>
<td>190</td>
</tr>
<tr>
<td>LiBr⁹</td>
<td>59</td>
<td>100</td>
<td>590</td>
</tr>
<tr>
<td>CaCl₂¹⁰</td>
<td>23</td>
<td>22680</td>
<td>1.01</td>
</tr>
</tbody>
</table>

6.1.3. Safety

Team 5 is creating an AWG with the final goal of producing drinkable water. If this system is to be effective the final output must be safe for humans to consume and safe to operate. The brine solution has the potential to cause the design to be unsafe in both of these areas.

In this design the brine will be regenerated using evaporation; this means that no salt should remain in the water vapor because it will not evaporate out of the brine. However we do not want to bring water into contact with a compound that is harmful to humans if ingested. The general public would not understand that the design is safe and the resulting negative image would hinder any hope of having a marketable product. Of the three salts considered above, CaCl₂ is the safest. Both lithium based compounds are safe to minor ingestion and exposure but repeated exposure could cause harmful side effects. Because of this it is a great risk to use either LiCl or LiBr.

The brine can cause the design to be unsafe during operation if the brine mist gets out of the packed tower. Once in the air, it is hazardous if users inhale the mist or it comes into contact with their eyes. All three of the salts considered will cause irritation to the eyes and lungs if they exit the AWG apparatus. Since this is unavoidable with all three alternatives, Team 5 has decided to minimize the chance of escaped brine mist by putting air filters over the air intake and outlet of the packed tower. These filters have been chosen to minimize and eliminate the possibility of escaping brine mist.¹¹ ¹² ¹³

---

6.1.4. Decision
After considering the various factors for all three components, the chosen brine solution will be composed of CaCl2. The considerations are shown in Table 5. Although it was not the best option in all of the categories, CaCl2 is the safest and cheapest. If the design of the AWG is unsafe to use then it is worthless; using harmful brine is not an option on this project. The design must be cheap enough for customers to afford and with the amount of salt needed the lithium salts our design price would inflate quickly.

<table>
<thead>
<tr>
<th>Consideration</th>
<th>LiCl</th>
<th>LiBr</th>
<th>CaCl2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrosion</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Cost</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Safety</td>
<td>Poor</td>
<td>Poor</td>
<td>Good</td>
</tr>
</tbody>
</table>

Table 5: Brine Decision Summary

6.2. Filtration
Filtration takes place at three points in the atmospheric water generator: air intake, brine circulation, and water output. This is important for the cleanliness of the water and the safety of those consuming it.

6.2.1. Air Intake
Air filtration is required to eliminate large particulates, which will cause problems in the dehumidification apparatus. The biggest concerns in the air stream filtration are the maximum particulate size that can make it through the filter and the filter lifetime/cost. Maximum particulate size is more critical for the desiccation and pressure dehumidification schemes. There are several possible filtration technologies: paper filters, electrostatic filters, and oil bath air cleaners. Of these, the oil bath air cleaner is not only the most complex; it also introduces oil particles into the air stream, which is unacceptable for this application\(^\text{14}\). The electrostatic air filter has advantages in lifetime and airflow, but adds complexity and requires regular maintenance\(^\text{15}\). Finally, paper filters are simple and relatively effective, but need to be changed and can result in airflow penalties.

Oil bath filters introduce oil which is unacceptable in this application; hence they are not considered a feasible option. Electrostatic filters are an option but have been passed over because of the wish to maintain simplicity of design as well as decreasing cost and energy requirements. Paper filters are the best option because they are effective, simple, relatively cheap, and require


no extra power input and will be implemented into the design. Paper filters have the additional benefit of being able to trap and absorb into their material any escaping brine mist.

### 6.2.2. Brine Circulation

Brine filtration is necessary to ensure that contaminants and particulates do not accumulate in the brine stream and hamper the effectiveness of the desiccation. The options for filtration at brine circulation are much the same as those discussed above for water filtration, with one primary exception. UV sterilization is not necessary in the brine solution, as it will be too salty for any but the most extreme microorganisms to live in. Thus, the only concern is particulate and chemical contaminants. However, the brine salt itself can be thought of as a chemical contaminant; any chemically-oriented filter must be neutral to the brine salt, which limits the options. Thus, only particulate filters are both fully applicable and useful in filtration at this stage.

### 6.2.3. Water Output

Water treatment is crucial to ensuring drinking water quality. The goal is to reach WHO quality standards. The WHO guidelines deal primarily upon the microbial and chemical aspects of the water, with the additional constraint that water should also be “free of tastes and odors that would be objectionable to the majority of consumers”\(^\text{16}\). The process inherently produces relatively clean water; water treatment is thus implemented to guarantee quality. Once again there are several alternatives. We investigated UV sterilization, carbon filters, and ceramic filters. Of these, UV sterilization is the most costly in terms of price and energy, and it only focuses on the microbial aspect. Carbon filters remove both larger particulates and organic contaminants and are low cost and simple to implement\(^\text{17}\). Ceramic filters are good for removing microbiological contaminants, but do not remove organics. Although ceramic and carbon filters are both cheap, carbon filters are slightly less expensive and will provide the most appropriate coverage for the wet desiccation process. Because of its cost and coverage, a carbon filter would be most effective for the design.

### 7. System Architecture

The wet desiccation system can be divided into two over all sections, process and electronics. To help visualize the process portion of the design, please refer to Figure 7 which is a block diagram showing all of the necessary parts for the system.

---


7.1. Process

The process section is the mechanical and chemical methods that generate water. The process is divided into three subgroups; dehumidification, desiccant regeneration, and water capture.

7.1.1. Dehumidification

Dehumidification begins with the air inlet fan as ambient air is brought into the generator. As the air passes through the packing tower, the brine solution will absorb the water vapor out of the air. Brine will be circulated by the brine pump through the system of the packing tower and brine collector until the brine is “wet” enough to move to the next stage. Once the brine is “wet” enough by concentration, Flow Valve 2 will close and Flow Valve 3 will open leading the brine solution to the brine tank.

7.1.2. Desiccant Regeneration

Once in the brine tank, the solution will be heated until water vapor is separated from the brine. This step is carried out by the heating element which will have to be programed to only add heat when necessary to conserve energy. As this process continues, the “dry” brine will settle at the
bottom of the tank until the solution has been rid of its water vapor. A sensor will indicate that the drying process is complete and open Flow Valve 1. Gravity should provide enough energy to push the brine out of the tank and back through the packing tower. Thus continues the cycle of brine absorbing water, then having the water removed.

7.1.3. Water Capture
The last part of the process, water capture, deals with the water vapor after it has been drawn out of the brine solution in the brine tank. The first step is for the water vapor to be drawn out by a fan into the condenser. This condenser will condense water out and have it settle at the bottom of a small tank. Once this small tank is full a minor flow valve to run the water through a carbon filter and into the water storage unit. Since all of the water will not condense out on the first pass, the condenser loop will circulate continuously between the brine tank and the condenser.

7.2. Electronics
The electronic section covers power and controls.

7.2.1. Power
The device requires two distinct operating powers: low for the sensory and control circuitry and high for the pump and fan systems. While the hope is to be able to power the device using renewable energy sources, it is outside of the scope and budget of this project to implement this design consideration in our prototype. Instead, the prototype will utilize power from the electrical grid. In particular, both the pump and primary air blower will be fed AC power, allowing for simplification of the design and cost savings in the selection of the components. The control circuitry will still require a low DC voltage for operation, but transferring the larger power components to AC systems will allow for savings by scaling down the requirements for the AC/DC converter.

7.2.1. Control
The control systems for the device can be divided into two sections: sensory systems and decision systems. Both of these systems will work together to implement a series of control statements. Table 6 below lists the primary control statements with their sensor requirements and a basic summary of the required decision circuitry.

In terms of the sensors, the system will require three types: pressure, temperature, and humidity. Circuitry will be designed to take the outputs of each of these sensors and transform them into linearly-scaled voltages for the decision circuitry.
Table 6: Primary Control Statements for Design

<table>
<thead>
<tr>
<th>Control Statement</th>
<th>Sensor Inputs</th>
<th>Decision Circuitry</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Regenerator if Temperature Falls Below Threshold</td>
<td>Regenerator Tank Temperature</td>
<td>Comparator, Hold</td>
<td>Power to Heating Element</td>
</tr>
<tr>
<td>Stop Production if Atmospheric Conditions Unfavorable</td>
<td>Air Temperature, Air Humidity</td>
<td>2x Comparator</td>
<td>Power to Pump, Air Blower, Heating Element, Regenerator Fan</td>
</tr>
<tr>
<td>Return Wet Brine if Regenerator Runs Dry</td>
<td>Regenerator Humidity</td>
<td>Comparator, Hold</td>
<td>Signal to Valve Systems</td>
</tr>
<tr>
<td>Adjust Return Rates if Accumulation</td>
<td>Pressure at Regenerator Valve</td>
<td>Comparator</td>
<td>Signal to Valve Systems</td>
</tr>
</tbody>
</table>

The decision circuitry of our system is intended to be simplistic. Comparators will determine the need for control, as per the control statements in Table 6, while hold circuits will be implemented to allow time for the inherent delays while the system adjusts to the new operating conditions.

8. Testing

Testing and experimentation allow Team 5 to understand the relationship between different process variables and how the system reacts to environmental changes.

8.1. Process Experiments

In order to use desiccation it is essential to know the rate at which a brine solution can absorb water. Team 5 met with Mr. Glenn Remelts and Professor Vander Griend to answer this problem. Mr. Remelts helped lead the search for scholarly articles regarding brine absorption and experimental setups. Professor Vander Griend helped the team develop the set up for several experiments that will help to determine the absorption rate of a concentrated brine solution.

In the first experiment executed, a small mouth mug and a wide mouth mug (40% concentration of CaCl₂ by mass) were placed on a plate with water on it and covered with a larger pot. With both mugs under the dome the atmosphere would remain unchanged except when we made measurements. The water in the plate would evaporate into humidity which would then be absorbed by the brine in the mug. A picture of the experiment is included in Appendix 12.3. The water was held in a plate instead of a mug so that the test would not be limited by the speed at which the water came out of the mug but by the rate at which it could get into the brine. This test
took place from December 1, 2011 to December 5, 2011 with the two different sized mugs so we could obtain two different absorption rates based on each different mug. The data we collected is included in Appendix 12.4. The contact surface area between the brine solution and the controlled atmosphere for our small mouth mug was 0.00422 m\(^2\) and 0.00633 m\(^2\) for the wide mouth mug. For each mug we were able to develop a function for the change in mass over time. Looking at Figure 8 shown below this relationship is different for the different surface areas. The wide mouth mug has an absorption rate of 1.92 grams of water per day and the small mouth mug has a rate of 1.00 grams of water per day.

Because we had two different surface areas, each mug gained different amounts of water over the time of measurement, and so we calculated a mass flux rate to compare the two more accurately. Our wide mouth mug had a flux rate of 303.2 g/day-m\(^2\) and the small mouth mug’s flux rate was smaller at a rate of 235.8 g/day-m\(^2\). This comparison clearly shows that increasing the surface area increases the rate which water is absorbed.

In addition to our original experiment, we anticipate running several more experiments to further analyze the absorption process. One such expansion experiment involves repeating the original experiment with several other surface areas. Through the research we learned of a company who

![Figure 8: Brine solution mass gain over time](image)
made a similar device with a 16.4 m² absorption surface made of a cross corrugated cellulose pad. Since the original experimental surfaces were extremely small in comparison, running more experiments with greater absorption surface areas will enable better prediction results for the prototype. As seen already, the more surface area, the more water will be absorbed and consequently produced by the process.

Another way to increase the rate of absorption is by circulating air over the surface area of contact between the brine solution and the air. To simulate the effect moving air over the absorption surface we would like to develop an experimental setup moving a measureable quantity of air over the brine solution. Collecting the data for this experiment and determining the response of the absorption rate to different air flow rates will increase our understanding of this variable’s effect and thereby improve the accuracy of our model.

8.2. Prototype
The goal of our project is to generate water using the air surrounding the device. Temperature and humidity are key variables that influence the rate of water production and testing them in a measureable way is essential. Through Professor Harris we were connected with Steve Beukema who has access to a humidity-controlled room. Using this room for testing would allow us to subject our prototype to varying temperatures and humidity cyclically to simulate day and night conditions. Testing the AWG in this room will enable us to gather a much wider range of performance data to develop a model for predicting system performance given various atmospheric conditions. As a result, we will be able to optimize the prototype so that we can achieve maximum water production at a minimum cost.

8.2.1. Produced Water Quality
Team 5 will test the water generated in order to verify the design fulfills the requirement of drinkable water. The standard of drinkability established by the WHO is the measuring stick we will hold our water against. The most recently printed “Guideline for Drinking-Water Quality” was published in 2011 and is relevant to the water we will be producing. Further research into this document will determine specifically what concentration levels of various contaminants are acceptable, the target color of the water, and the desired taste. When we have determined the water is safe we will proceed to taste the water as well, starting with ourselves and possibly expanding to volunteers.

8.2.2. Power Requirements
The AWG we are designing will initially be operate using electricity from the local power grid, but because our goal is to design a sustainable process we will spend time optimizing it so that we could run our device off low cost solar panels. It is highly unlikely that we will have the budget to purchase any solar panels but we can do power tests on our prototype and compare the power requirements against rated panels. We will have access to extensive data on specific solar
panels through the Calvin College student branch of the Renewable Energy Organization and most other necessary data can be found online.

8.3. Control System

One of the critical areas of testing will be determining what manner of control the system requires for optimum operation. Current plans are to implement a series of control statements using simplistic analog circuitry. The first order of business will be to determine the thresholds required for good control on the system. From there, we will determine the most effective means of applying the control signals, beginning with an assessment of the delays inherent in the system process. Once these issues have been addressed, the overall performance of this type of control will be examined, and further improvements added as necessary.

9. Business Plan

9.1. Market Study

Virtually all atmospheric water generators currently on the market are luxury items. The designs stress water purity and convenience to the customer. Table 7 below is a quick summary of relevant design features for three prominent devices on the market.

<table>
<thead>
<tr>
<th>Device</th>
<th>Manufacturer</th>
<th>Production (L/day)</th>
<th>Power (W)</th>
<th>Water Filtration Stages</th>
<th>Unit Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ecoloblue 26</td>
<td>Ecoloblue</td>
<td>26</td>
<td>1050</td>
<td>11</td>
<td>$1,199</td>
</tr>
<tr>
<td>Dolphin1</td>
<td>Air2Water</td>
<td>22.8</td>
<td>500</td>
<td>5</td>
<td>$1,799</td>
</tr>
<tr>
<td>Atmos 28</td>
<td>Atmos H2O</td>
<td>28</td>
<td>500</td>
<td>5</td>
<td>$1,545</td>
</tr>
</tbody>
</table>

All three devices noted above use at least 5 water filtration stages. These filtration stages are being applied to water that has essentially been distilled out of the air; the only possible contaminants are those present in the air stream and those introduced in the condensation process.

The plan is to utilize this inherent process cleanliness and cut down on the number of filtration stages. A good air filter should be able to eliminate most contaminants present in the air stream, while two water filters and careful design should be enough to handle the contaminants.

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introduced in dehumidification. Such an implementation will be able to meet any relevant water quality standards. In this way we can simplify our design and cut down on costs compared to our competition, allowing us to sell our product at a lower price.

Additionally, desiccant dehumidification has the potential to provide better energy consumption as opposed to cooling dehumidification. This results in lower energy cost over the lifetime of the unit, an advantage which can be used as a major selling point.

9.2. Cost Estimates

All costs for the system components are estimates based on vendor information found online and in catalogs. Prices will vary depending on the capacity of the desired system.

9.2.1. Development

Table 8 contains the most up-to-date budget for the project. Components with an asterisk are the components that fit our current specifications

<table>
<thead>
<tr>
<th>Component</th>
<th>Manufacturer</th>
<th>Size</th>
<th>Total Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>*Mag Drive Pump</td>
<td>Iwaki America</td>
<td>110V 60Hz 5.3gpm</td>
<td>136</td>
</tr>
<tr>
<td>*265 CFMAir Blower</td>
<td>Dayton Fans</td>
<td>--</td>
<td>103</td>
</tr>
<tr>
<td>*CaCl₂</td>
<td>Dow</td>
<td>50lb</td>
<td>48</td>
</tr>
<tr>
<td>Ball Valve</td>
<td>Mueller Industries</td>
<td>2&quot; IPS</td>
<td>64</td>
</tr>
<tr>
<td>Resistance Heaters</td>
<td>Grainger</td>
<td>--</td>
<td>302</td>
</tr>
<tr>
<td>*Packed Tower</td>
<td>UMP</td>
<td>10&quot;x10&quot;</td>
<td>71</td>
</tr>
<tr>
<td>Brine Tank 1</td>
<td>Tamco</td>
<td>30 Gallon (1/4&quot; thick walls)</td>
<td>99</td>
</tr>
<tr>
<td>Brine Tank 2</td>
<td>Tamco</td>
<td>15 Gallon (1/4&quot; thick walls)</td>
<td>61</td>
</tr>
<tr>
<td>System Tubing</td>
<td>Apache</td>
<td>5/8&quot; x 25'</td>
<td>19</td>
</tr>
<tr>
<td><strong>Total System</strong></td>
<td></td>
<td></td>
<td><strong>902.06</strong></td>
</tr>
</tbody>
</table>

9.2.2. Production

Table 9 is an estimated cost breakdown of production over a three year period. This shows the costs and revenues of mass production of the wet desiccation system for three years, each year at a specified volume. Table 10 displays the income statement resulting from the revenues and costs produced in Table 9. This table shows the net income for the idealized company at the end of each fiscal year. Note that the parts and materials costs in Table 9 are based off of a mass production cost; the individual unit budget will differ.
Table 9: Estimated Cost Breakdown for Production

<table>
<thead>
<tr>
<th>Sales Volume Forecasts</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>600</td>
<td>800</td>
<td>900</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cost Breakdown</th>
<th>Total Value at Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Item</td>
<td>Year 1</td>
</tr>
<tr>
<td>Sales Revenue</td>
<td></td>
</tr>
<tr>
<td>Price</td>
<td>1050</td>
</tr>
<tr>
<td>Total</td>
<td>1050</td>
</tr>
<tr>
<td>Variable Costs of Goods Sold</td>
<td></td>
</tr>
<tr>
<td>Labor (5 hours)</td>
<td>125</td>
</tr>
<tr>
<td>Parts and Materials</td>
<td>239</td>
</tr>
<tr>
<td>Total</td>
<td>364</td>
</tr>
<tr>
<td>Fixed Costs of Goods Sold</td>
<td></td>
</tr>
<tr>
<td>Floor Manager</td>
<td>60000</td>
</tr>
<tr>
<td>Facility Rent/Utilities</td>
<td>80000</td>
</tr>
<tr>
<td>Total</td>
<td>140000</td>
</tr>
<tr>
<td>Variable Operating Costs</td>
<td></td>
</tr>
<tr>
<td>Shipping</td>
<td>80</td>
</tr>
<tr>
<td>Commission</td>
<td>120</td>
</tr>
<tr>
<td>Total</td>
<td>200</td>
</tr>
<tr>
<td>Fixed Operating Costs</td>
<td></td>
</tr>
<tr>
<td>Senior Engineer</td>
<td>80000</td>
</tr>
<tr>
<td>Director of Marketing</td>
<td>65000</td>
</tr>
<tr>
<td>Other Payroll</td>
<td>30000</td>
</tr>
<tr>
<td>Marketing Costs</td>
<td>20000</td>
</tr>
<tr>
<td>Warrantee Service</td>
<td>10000</td>
</tr>
<tr>
<td>Training</td>
<td>5000</td>
</tr>
<tr>
<td>Website Service</td>
<td>7000</td>
</tr>
<tr>
<td>Total</td>
<td>217000</td>
</tr>
</tbody>
</table>
10. **Conclusion**

After analyzing the different methods for use in an atmospheric water generator, Team 5 has determined that wet desiccation is a feasible method of dehumidification within the context of this project. Furthermore, Team 5’s analysis indicates that wet desiccation has the potential for greater energy efficiency and lower production costs than most existing atmospheric water generators.

By the end of the spring semester Team 5 will present a functional prototype, a comprehensive design plan, in-depth cost assessments, and an operational analysis of the system.

Through this project Team 5 hopes to further develop the wet desiccation technology. We believe that this technology can have a positive effect on world water issues as we move forward into the future.
11. **Acknowledgements**

**Professor Ned Nielsen**

Professor Nielsen was the faculty advisor for Team 5. He consistently took opportunities to teach each member through the different steps of the design process. He encouraged Team 5 to keep a realistic scope and reminded them that failure happens in the design process but it isn’t the end of the road. A change of direction occasionally leads to a better solution.

**Professor Michael Harris**

Professor Harris proposed the idea of designing an AWG to the senior design class. When Team 5 decided to take on this project he was valuable in offering preliminary insights and support, including putting the team in contact with Mr. Steve Beukema. He helped to define an initial scope and customer. With his help Team 5 was also able to get in contact with several other people that were willing to help.

**Mr. Ren Tubergen**

Mr. Tubergen is Team 5’s industrial consultant. He provided valuable insight and direction during the meeting he had with Team 5 as well as through emails. He encouraged the team to focus on specifying the absorption rate which is the “lynch pin” to designing the system. Without his honest evaluation we would not have produced the document being set forth.

**Professor Douglas Vander Griend**

Professor Vander Griend met with Team 5 on several different occasions and he helped design several experiments through which the absorption rate could be specified. He was instrumental in procuring some CaCl2 from the Calvin College chemistry department in order for the team to run the experiments. He set up room in one of the chemistry labs and allowed Team 5 to use some lab equipment. Without his willingness to help Team 5 would not have been able to perform these experiments.

**Mr. Steve Beukema**

Mr. Beukema provided valuable insight into the advantages and disadvantages of filter technology, particularly as compared to atmospheric water generators. He also offered encouragement to the team and raised the possibility of getting time in a humidity-controlled environment, a crucial resource in testing Team 5’s prototype in the spring semester.

**Class Advisors**

Professor Steven VanderLeest, Professor David Wunder and Professor Wayne Wentzheim all helped Team 5 through various assignments and were a vital asset throughout the senior design class.
12. **Appendix**

12.1. **Competitor Summary**

Table 11: Competitor Summary

<table>
<thead>
<tr>
<th>Model</th>
<th>Performance</th>
<th>Testing Conditions</th>
<th>Additional Features</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cost</td>
<td>Water (L/day)</td>
<td>Power (W)</td>
</tr>
<tr>
<td>Dolphin121</td>
<td>$1,799</td>
<td>27.5</td>
<td>500</td>
</tr>
<tr>
<td>Ecoloblue2622</td>
<td>$1,199</td>
<td>26</td>
<td>1050</td>
</tr>
<tr>
<td>AirJuicer401023</td>
<td>$1,499</td>
<td>19</td>
<td>500</td>
</tr>
</tbody>
</table>

12.2. **Decision Matrix**

Table 12: Desiccant Decision Matrix

<table>
<thead>
<tr>
<th>Weight</th>
<th>Key Factors</th>
<th>Complexity</th>
<th>Energy Use</th>
<th>Cost</th>
<th>Scale/Size</th>
<th>Safety</th>
<th>Innovation</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling</td>
<td></td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>27</td>
</tr>
<tr>
<td>Cooling &amp; Compression</td>
<td></td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td>Wet Desiccation</td>
<td></td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>29</td>
</tr>
</tbody>
</table>

---

12.3. Experiment Setup

Figure 9: Experimental Setup
### Finding the Brine Solution Absorption Rate of Water

**Date: 12/1/2011**  
**Experiment 1**

<table>
<thead>
<tr>
<th>Data Collection Information</th>
<th>Room Conditions</th>
<th>Pot 1</th>
<th>Pot 2</th>
<th>Data collected by:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date of Measurements</td>
<td>Time of Measurements</td>
<td>Time Elapsed (hr)</td>
<td>Room Temp (°C)</td>
<td>Room Wet Bulb Temp (°C)</td>
</tr>
<tr>
<td>12/1/2011</td>
<td>11:05</td>
<td>0:00:00</td>
<td>23.5</td>
<td>18</td>
</tr>
<tr>
<td>12/1/2011</td>
<td>12:00</td>
<td>0:55:00</td>
<td>23.5</td>
<td>19</td>
</tr>
<tr>
<td>12/1/2011</td>
<td>13:00</td>
<td>1:58:00</td>
<td>23</td>
<td>12.5</td>
</tr>
<tr>
<td>12/1/2011</td>
<td>15:04</td>
<td>3:59:00</td>
<td>23</td>
<td>18.5</td>
</tr>
<tr>
<td>12/1/2011</td>
<td>15:58</td>
<td>4:53:00</td>
<td>23</td>
<td>18</td>
</tr>
<tr>
<td>12/2/2011</td>
<td>13:45</td>
<td>26:40:00</td>
<td>23</td>
<td>15.5</td>
</tr>
<tr>
<td>12/2/2011</td>
<td>15:29</td>
<td>28:24:00</td>
<td>22.5</td>
<td>13.5</td>
</tr>
<tr>
<td>12/2/2011</td>
<td>17:00</td>
<td>29:55:00</td>
<td>22</td>
<td>18</td>
</tr>
<tr>
<td>12/5/2011</td>
<td>12:00</td>
<td>96:55:00</td>
<td>23</td>
<td>18</td>
</tr>
<tr>
<td>12/5/2011</td>
<td>13:10</td>
<td>98:05:00</td>
<td>23</td>
<td>16</td>
</tr>
</tbody>
</table>

**Initial Conditions:**

<table>
<thead>
<tr>
<th>Room Temp (°C)</th>
<th>Mass of Empty Wide Mouth Mug (g)</th>
<th>Mass of Empty Small Mouth Mug (g)</th>
<th>ID Wide Mouth Mug (WM) (in)</th>
<th>ID Small Mouth Mug (SM) (in)</th>
<th>Mass of Empty Wide Mouth Mug (g)</th>
<th>Mass of Empty Small Mouth Mug (g)</th>
<th>Surface Area (WM) (m²)</th>
<th>Surface Area (SM) (m²)</th>
<th>Brine Absorption Rate (WM) (g/day)</th>
<th>Brine Absorption Rate (SM) (g/day)</th>
<th>Flux Rate (WM) (g/day-m²)</th>
<th>Flux Rate (SM) (g/day-m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>526.87</td>
<td>409.14</td>
<td>3.535</td>
<td>2.887</td>
<td>526.87</td>
<td>409.14</td>
<td>0.00633</td>
<td>0.00422</td>
<td>1.92</td>
<td>1.00</td>
<td>303.2</td>
<td>235.8</td>
</tr>
</tbody>
</table>

**Surface Area (WM) (in²)**: 9.815  
**Surface Area (SM 1) (in²)**: 6.546  
**Surface Area (SM 2) (in²)**: 6.592
12.5. EES Calculations for Pressure Dehumification

\[
\omega_1 = \text{HumRat}(\text{AirH}_2\text{O}, T=28, r=0.8, P=P[1])
\]
\[
dp[1] = \text{DewPoint}(\text{AirH}_2\text{O}, T=28, w=\omega_1, P=P[1])
\]
\[
\omega_2 = \text{HumRat}(\text{AirH}_2\text{O}, T=28, D=28, P=P[2])
\]
\[
rh_2 = \text{RelHum}(\text{AirH}_2\text{O}, T=28, w=\omega_2, P=P[1])
\]
\[
\{ dp[2] = \text{DewPoint}(\text{AirH}_2\text{O}, T=28, w=\omega_2, P=P[2]) \}
\]
\[
dp[2] = 28[^\circ\text{C}]
\]
\[
P[1] = 101
\]
\[
{ P[2] = 150 * \text{convert(psi, kPa)} }
\]
\[
P[2] = 190
\]
\[
rho_{\text{water}} = 1000
\]
\[
\text{vol} = 25
\]
\[
rho_{\text{air}} = \text{density(air, T=20, P=P[1])}
\]
\[
\eta_\text{compressor} = 0.80
\]
\[
\eta_\text{turb} = \eta_\text{compressor}
\]
\[
\text{latent_heat_cond} = 2257[^kJ/kg]
\]

\[
e_\text{compress} = (P[2] - P[1]) \cdot \text{Vol} \cdot \text{convert(J, kJ)}
\]
\[
m_\text{air} = \rho_{\text{air}} \cdot \text{vol} \cdot \text{convert(m}^3, \text{L})
\]
\[
m_\text{water} = m_\text{air} \cdot (\omega_1 - \omega_2)
\]
\[
q = e_\text{elec} / m_\text{water}
\]
\[
\eta_\text{compressor} = e_\text{compress} / e_\text{elec}
\]
\[
e_\text{recovered} = \eta_\text{turb} \cdot e_\text{compress}
\]
\[
e_\text{elec} = e_\text{recovered} + e_\text{grid}
\]
\[
q_\text{grid} = e_\text{grid} / m_\text{water}
\]
\[
q_\text{recovered} = e_\text{recovered} / m_\text{water}
\]

\[
\text{Heat} = e_\text{compress} + \text{latent_heat_cond} \cdot m_\text{water}
\]
\[
q_\text{competitor} = 3500[^kJ/kg]
\]

Figure 10: EES Display for Pressure Dehumidification
12.6. EES Calculations for Desiccation Model

"Model for Peformance of Wet Desiccation AWG"

"Specified:"
- \( L = 0.3 \text{ [m]} \)
- \( C = 32 \)
- \( m_{\text{dot_air}} = 0.05138 \text{ [kg/s]} \)
- \( T_{\text{brine}} = 30 \text{ [C]} \)
- "Dimension of cubic packing tower"
- "Concentration of the brine solution"
- "Mass flow rate of air"
- "Brine temperature in packing tower"

"State Points"
- \( T[0] = 30 \text{ [C]} \)
- \( P[0] = 101.325 \text{ [kPa]} \)

"Assumptions:"
- \( m_{\text{dot_nominal}} = 0.00096 \text{ [kg/s]} \)
- \( j_{\text{brine_nominal}} = 1.9 \text{ [kg/m^2*s]} \)
- "Nominal mass flow rate"
- "Nominal flux rate"

"Calculations:"
- \( \text{Factor}_{SA} = \frac{(L^3)}{((0.3\text{[m]})^3)} \)
- "Surface area factor"
- \( \text{Factor}_{air} = 0.38 + \left(\frac{(0.5\text{[m^2*s/kg]}) \cdot (m_{\text{dot_air}} / L^2)}{L^2}\right) \)
- "Air factor"
- \( \text{Factor}_{C} = -1.02 + (0.042 \cdot C) \)
- "Concentration factor"
- \( \text{Factor}_{Brine} = (2.6 - (0.053 \cdot 1/C) \cdot T_{\text{brine}}) \)
- "Brine factor"

\[
\begin{align*}
\text{m}_{\text{dot_water}} &= \text{Factor}_{SA} \cdot \text{Factor}_{air} \cdot \text{Factor}_{C} \cdot \text{Factor}_{Brine} \cdot m_{\text{dot_nominal}} \\
\text{m}_{\text{dot_brine}} &= j_{\text{brine_nominal}} \cdot (L^2) \\
\text{m}_{\text{dot_waterperday}} &= \frac{\text{m}_{\text{dot_water}}}{\text{convert(s,day)}}
\end{align*}
\]

"Pump Work Calculations:"
- \( h_{\text{return}} = 3 \cdot L \)
- "\( h_{\text{return}} = \) height from pump to return valve"

\( W_{\text{dot_pump_in}} = m_{\text{dot_brine}} \cdot h_{\text{return}} \cdot g# \)

"Volumetric Flow Rate (air)"
- \( \rho_{\text{air}} = \text{density(air, T = T[0], P = P[0])} \)
- \( V_{\text{dot_air}} = \frac{m_{\text{dot_air}}}{\rho_{\text{air}}} \cdot \text{convert(m^3/s,cfm)} \)

![EES Display for Desiccation Model](image)

Figure 11: EES Display for Desiccation Model
12.7. Sketches

Figure 12: Hand sketch of theoretical pressure condensing design

Figure 13: Hand sketch of early desiccation design ideas
Figure 14: Hand sketch of three different dehumidification design alternatives
Figure 15: Hand sketch of theoretical desiccation design
Figure 16: Hand sketch of theoretical desiccation design
Figure 17: Hand sketch of detailed desiccation system
12.8.  Meeting Record

All Prior Meetings occurred before the semester began.

9/12/11, Monday
- Finalized team

9/14/11, Wednesday 1:30-2:30 PM
- Completed and submitted project proposal

9/26/11, Monday 1:30-2:30 PM
(Eric Absent-Big 10+ Grad School Expo at Purdue)
- Completed Project Requirements and Objectives

10/1/11, Saturday 11:30-1:00 PM
- Worked on PPFS outline
- Chris designated Webmaster
- Ryan designated Budget Master
- Eric designated Schedule/Secretary Master
- Discussed scheduling and future deadlines

10/3/11, Monday 1:30-2:30
- Turned in PPFS Outline
- Changed weekly meeting to Friday 1:30
- Started WBS
- Discussed industry mentor contacts
  - Harris for water/filtration/location of need
  - Nielsen for machine feasibility

10/5/2011, Wednesday 2:30
- Worked on WBS (completed)
- Moved Friday meeting to during class
- Begin Research
  - 3 sources by wed(10/12) for meeting with Librarian

10/7/2011, Friday 1:30-2:30
- Meeting was postponed due to WBS

10/14/2011, Friday 1:30-2:30

- Research delegated
- Set photo shoot for next Friday (10/21)

Upcoming work:
- Scheduled WBS: Ryan and Eric
- Industrial Consultant Project Brief: Ben and Chris

Brainstorm focus:
- Pressure Dehumidification
- Absorption Dehumidification (likely to be very complex and tricky)
- Cooling Systems
- We want to analyze the two separately and how we can combine them

10/14/2011, Friday 1:30-2:30

- 

10/21/2011, Friday 1:30-2:30
- Chris with Ben’s support work on Website and post
- Eric and Ryan work on PPFS

10/28/2011, Friday 1:30-2:30
- PPFS sections delegated:
  - Eric: Team Organization (11/4) and Calculations/ (11/11)
  - Ben:
  - Chris: PM Design Criteria
  - Ryan: Budget/Objectives and Requirements (11/4) and Testing (11/11)

11/1/2011, Wednesday 2:30-3:30
- Class work day
  - Each member worked on their section of the PPFS and compiling research

11/4/2011, Friday 1:30-2:30
- Picked up dehumidifier from Chris’ house
  - Reported on PPFS status

11/9/2011, Wednesday 10:00-
- Decision Matrix filled out (in some sense)
  - Ben theorized the cascading brine solution
- Set individual minimum of 4 hours of work per week to be reported on during our Friday weekly meetings

11/18/2011, Friday 1:30-2:30
- Consolidated and proofread PPFS
- Wrote Intro and conclusion
- Printed PPFS

11/21/2011, Monday 8:00-10:15 (In place of Friday this week per Thanksgiving Break)
- Updated WBS
- Preparations for Industrial Consultant Meeting
  - Prepared Agenda
  - Listed questions for Ren
- Planned projects for the rest of semester

11/28/2011, Monday 1:30-2:30
- Updated PPFS

11/30/2011, Wednesday 3:30-5:00
- Met with Professor Vander Griend
- Planned Rate Experiments

12/01/2011, Friday 1:30-2:30
- Updated PPFS
- Evaluated Experimental Results

12/05/2011, Monday 1:30-2:30
- Prepared for Class Presentation

12.9. Meeting Agendas

10/3/2011 Monday

1. Work Completed
   - Turn in PPFS Outline

2. Deadlines Approaching
   - Monday
   - PPFS Outline Submitted 1:43pm
   - Updated Resume - emailed to career@calvin.edu as word attachment
   - Friday
     - Work Breakdown Structure
     - Started and on the Scratch Drive

3. Roundtable
- We need to start researching
  - General Broad topics
  - Changed weekly meetings to Friday 1:30 per Chris

10/7/2011 Friday

1. Work Completed
2. Deadlines Approaching
   - WBS---- Due Friday

10/21/2011

1. PPFS
   - If you haven’t started already you are behind!
   - Need to do research!
   - Start focusing on expanding our outline
2. Website
   - Due up by Wednesday
3. Personal Journals
   - Everyone must be keeping one
4. Academic Advising
   - Should spend a significant amount of time getting ahead on deadlines
5. Devotions
   - November 7
   - Who wants to do it?
6. Presentation
   - Chris and Eric: practice run

11/4/2011

1. Devotions Monday
   - Who is doing this?
2. Picking up Dehumidifier from Chris’ house
3. Each member presents PPFS progress
   - Too many headings, too much info that should be in the sections and not headers
4. Look ahead to next week
   - PPFS sections to be worked on

12.10. Industrial Consultant
12.10.1. Brief

   Team 5: Water from Air
I. Team Members

Team 5 consists of three mechanical engineers and one electrical engineer. In the picture below, from left to right: Eric Van Kooten (ME), Ryan Van Beek (ME), Chris Shepperly (ME), Ben Niewenhuis (EE).

II. Project Description

Availability of clean drinking water is a major concern for humans both in the present and looking forward into the future. Our goal is to address this problem by tapping into the ambient air humidity. A secondary goal is to utilize renewable energy sources in order to create a monolithic device capable of operating independent of the traditional power grid.

III. Objectives and Requirements
**Objectives**

Efficiency: Maximize water per unit energy.

Maintenance: Minimize maintenance requirements over lifetime of device.

Cost: Minimize cost over lifetime of device.

Power Source: Allow for flexibility in power supply.

Baseline Production Volume: Should produce enough water for one person.

**Requirements**

Potability of Water Produced: Water must comply with WHO standards.

Simplicity of Use: Required training must be negligible.

Safety: Design must not pose a hazard to users at any point during normal operation.

**IV. Status**

The project design has been narrowed down to three primary alternatives: pressure driven, cooling driven, and desiccation dehumidification. One design alternative, pressure driven dehumidification, was rejected after calculations showed that its energy requirement was far greater than existing technology. Current efforts are focusing on theoretical analysis of desiccation and cooling dehumidification utilizing the Engineering Equation Solver (EES) program.

Research is an ongoing effort, particularly regarding the clarification of the theory behind wet desiccation. Geographic considerations, namely the average temperature and humidity as well as the availability of renewable energy, are also the subject of active research.

Finally, we have also acquired and dismantled a traditional dehumidifier in preparation for energy and efficiency analysis.

**V. Future Considerations**

Identification of the customer remains an area of crucial importance. Atmospheric water generators are marketed primarily as a luxury item in developed nations. Basic technological needs make it difficult to implement and justify in areas lacking significant technical infrastructure. Our idea is to split this gap with a high-efficiency and low-cost design; feasibility in this respect still needs to be determined via prototyping and theoretical analysis.
Design is also a significant area that is currently under scrutiny. We are in the process of developing the theory necessary to make concrete design decisions for the wet desiccation approach. Our goal is to have all parts ordered by the end of the semester.

12.10.2. Agenda

Industrial Consultation with Ren Tubergen

November 21, 2011

Meeting Agenda

Topics of Discussion:

I. Status Update
   A. Decided on wet desiccation for our project
      a. What is it?
         - Definition and picture of process (see below)
         - Why we chose it
      b. Difficulties we foresee/have
   B. PPFS
      a. Rough draft submitted last Friday
      b. Substantial amount of work remains to be done
   C. Other things that need to be done
      a. Extensive theoretical calculations to optimize our process variables and components
      b. Analysis of electrical system to develop a component order list
      c. Analysis of mechanical system to develop a component order list

II. Questions for Ren
   A. Putting together the system
      - Component selection methodology suggestions
      - Performing the analysis
      - Developing testable prototypes
   B. Budget estimates
      - Good practices to make sure that we minimize cost and include everything we need
Figure 18: Hand Sketch of the Wet Desiccation Process Presented at Industrial Consultant Meeting