Vaccine Refrigerator for Developing Nations

ME 481: Engineering Design Project
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1. Executive Summary

Nearly half of the vaccines in developing countries go to waste every year due to temperature spoilage, according to the World Health Organization. Current transportation and storage methods in remote regions rely on ice packs that last just a few days. In order to maintain the optimal temperature range of 2 to 8° Celsius for vaccine preservation, these regions need reliable long-term refrigeration where electricity is not available.

To solve this problem, the Appropriate Technology Design Collaborative student design team has developed an affordable, robust refrigerator that operates with heat generated by the sun. The vaccine refrigerator was designed with simplicity as a focus for manufacturing, maintenance and daily use. It uses widely-available alcohol as a refrigerant and has no moving parts. Manufacturing can be completed with common materials and simple assembly techniques. After the initial vacuum charging, the refrigerator is designed to work without maintenance for three to five years.

In an effort to make this solar refrigeration technology available around the globe, the team's final deliverable is a set of manufacturing plans that will be distributed for free on the Internet. This open-source distribution will allow the refrigerator to be built by governments, local businesses and nonprofit organizations throughout Latin America, Africa and Central Asia.

A robust refrigerator has been designed that will prove its worth by reducing the volume of spoiled vaccines. Testing has revealed the technology can achieve temperatures as low as 4°C and that the complete cycle works as expected. At a cost of approximately $1,100 per refrigerator, it is expected to be within reach of governments and nonprofits. However, reducing the cost could increase its availability, even making the technology available to families for food preservation.

The posting of the manufacturing instructions and technical reports on the Internet will not only spread the technology and knowledge, but could also lead to significant improvements in the design from global input on possible cost reductions and unique adaptations for each region.

2. The Appropriate Technology Design Collaborative

The Appropriate Technology Collaborative (ATDC), founded by John Barrie, is a non-profit organization with the goal "to design, develop, demonstrate and distribute appropriate technological solutions for meeting the basic human needs of low income people in the developing world." ATDC works in collaboration with clients and other nongovernment organizations) to create technologies that are culturally sensitive, environmentally responsible, and locally repairable in order to improve the quality of life, enhance safety, and reduce adverse impacts on their environment. The ATDC works hand-in-hand with the communities it is involved in, and promotes a healthy relationship with the people within those communities to aid them in harnessing the ideas and technologies that have been created through the ATDC. The ATDC has produced many successful technologies in the past including biofuels, energy systems, lighting replacements for common kerosene lamps, and water purification. All of the designs, which are created through the ATDC, are distributed freely online to anyone who wants to use or improve upon them.

The goal of this project is to create a source of refrigeration that will aid the billions of people without access to electricity and refrigeration. This project has many possible positive applications from cooling beverages for sale in remote areas to producing ice for commercial/medical use, with the main goal targeting the refrigeration of temperature sensitive vaccines. The Spring 2009 project was completed with the guidance of John Barrie, other members of the ATDC, and previous work completed by Michigan State design teams.

3. Design Review

3.1 Problem Statement

Many of the vaccines used to control diseases require cold temperatures for preservation. Without a reliable power infrastructure, developing countries often lack the resources for keeping these vaccines cool in the long-term, hampering the ability to adequately protect citizens. The Appropriate Technology Collaborative student design team has been charged with the task of developing a refrigerator to solve this problem. The team has created the following problem statement:

> *Design an adsorption refrigerator capable of maintaining a temperature between 2°C and 8°C that utilizes passive solar energy and can be built in developing countries. The team's final product will be a clear and comprehensive set of instructions for building the device.*

The problem statement provides a broad but complete perspective of the project's end goal. Beyond this description, the complexity of the design is defined by a number of requirements and restrictions.

3.2 Design Specifications and Constraints

The aim of the project is to build a low-maintenance and low-cost adsorption refrigeration unit which can be set up in areas that do not have an electrical infrastructure to support standard refrigeration systems. The primary goal of the refrigeration unit is to store vaccines in a temperature range of 2˚C to 8˚C, however the refrigeration will also be able to support low-level commercial use. Currently, vaccines are delivered in insulated boxes which are able to keep vaccines in the 2˚C to 8˚C range for a short period of time. The refrigerator will be able to store, cool, and extend the life of approximately 4 liters of vaccines delivered to these target areas.

Target regions have been identified as areas where an electrical infrastructure is nonexistent or unreliable, but sunlight is plentiful. Therefore, the refrigeration unit will rely solely on solar power generated from the sun for its energy supply. An adsorption refrigeration cycle allows for a space to be cooled by using heat from the sun. The performance of this cycle depends heavily on the adsorbent and adsorbate pair chosen, total pressure of the system, and the temperature difference experienced by the solar collector during one cycle.

The adsorbent and adsorbate pair chosen for this refrigeration unit was activated carbon and ethanol due to their performance and availability. Activated carbon can be obtained by using coconut shells and ethanol can be found in locally-available alcoholic beverages. Ethanol is a corrosive substance which can cause untreated metal to corrode over time, therefore the refrigeration unit will need to be made from materials which are resistant to corrosion. Activated carbon, in granulated form, can be very hard to handle and the design of the refrigeration unit will need to incorporate a subsystem which holds the carbon in one place. Since the adsorption refrigeration cycle depends on low pressure inside the system, the refrigeration unit will need to be leak proof. A low vacuum of about 29 inches of mercury will need to be pulled on the system and that vacuum will need to be held for the duration of the unit's life. Because the solar energy from the sun is used to add a certain amount of heat to the system, a solar collector will need to be designed such that it captures enough radiation and converts it into heat. The design of the solar collector will need to incorporate two additional factors. The adsorber needs to be heated during daytime to desorb the ethanol and must be cooled down during the night to adsorb the ethanol. However, activated carbon has poor heat conducting properties and an uneven distribution of heat inside the activated carbon will reduce the amount of space the refrigeration unit is able to cool.

The design of the refrigeration unit was finalized to the point where manufacturing drawings and instructions are published on the Internet for anyone to build the refrigerator and use in the target areas. With this in mind, the design integrates materials and processes that are domestically available in the target areas in order to reduce costs related with the build of the unit.

This task was a continuation of a two-semester project involving two design teams. In Spring 2009, the team built two prototypes, one in Guatemala and another at Michigan State University. These prototypes allowed the team to refine and test their design in two very different environments. While in Guatemala, the team members gained first-hand experience working in a developing country to understand the challenges of sourcing materials and fabricating products in a unique culture.

3.3 Identification and Evaluation of Design Parameters

The relevant design parameters for the solar adsorption refrigerator are:

1.) **Function/Performance**

The most important parameter, the design must be able to effectively cool and maintain a selected volume and its contents within a range of 2-8°C.

2.) **Product Cost**

A significant parameter for a product being produced in developing countries, the cost should be kept to a minimum. Ideally the cost would be under $400, to allow for an economically reproducible product.

3.) **Delivery Date**

A deadline of March 6, 2009 has been set for the project. At this time the project must be complete, this is imperative due to the group departure for Guatemala March 7, 2009.

4.) **Reliability**

The reliability of the final product is crucial. The product is to be used in areas where limited maintenance can be done. Additionally, the vaccines and perishables must be maintained within a strict temperature range of 2-8°C. The final product should be able to withstand the climate and effectively maintain the required conditions.

5.) Maintenance

The refrigerator is designed to be implemented in rural, undeveloped areas around the world. Here, there will not be technicians or advanced tooling available to perform complicated maintenance. Therefore any upkeep of the product should be kept to a minimum.

6.) Operating Costs

The product is to be implemented in poor countries and therefore must be inexpensive to build and to operate.

7.) Safety

The design will be used in emerging areas and around children; therefore it is important that it does not pose any potential threat to those in the area.

8.) Quality

It is important that the product be an effective and efficient design that can be the foundation for future development and distribution to other emerging areas around the world.

9.) Environmental Conditions

The environmental conditions that the design will be exposed to are an important parameter. The ambient temperature of the region will help dictate the cooling loads the system is subjected to, and the amount of energy that can be extracted from the system's surroundings.

10.) Energy Consumption

Energy consumption is of minimal concern; the refrigerator will be completely self-sufficient and use solar energy to complete the refrigeration cycle without use of electricity.

11.) Size

The final product does not have any direct size restrictions. Product limitations will be held to the cost, availability, and transportation of the necessary materials.

12.) Weight

The final product will not be mobile after installation, with proper support of the structure, there will not be a weight restriction.

13.) Service Life

A long service life is desired to help maximize the effectiveness of the vaccine storage capabilities and the return on investment.

14.) Operating Instructions

It is important that the design of the refrigerator be simple to operate, as locals with limited technical knowledge will have to manage the product on a daily basis.

15.) Transportation and Packaging

The final product will be immobile and installed in a permanent location. However, it is necessary that components of the system be kept to a size that can be easily transported.

16.) Mechanical Loading

The final product design must be able to withstand the initial pressurization of the system. The forces created by this process can become very large and should not be overlooked.

17.) Aesthetics

This parameter is not of great importance, but the design should attempt to be comparable to the aesthetics of the area.

18.) Personnel

The amount of training and attendance required for the final operating product should be minimal. This will require a simple effective design for implementation in developing areas.

19.) Noise Radiation

The system does not create excessive noise based on the refrigeration process implemented; in addition, the system should not be disruptive to its surroundings.

20.) Domestic Materials

This parameter is very important; the refrigerators are to be built locally with available materials. Therefore the necessary components should be readily available in the area.

3.4 Design Parameter Weighting

The relevant design parameters listed above have been rated on a scale from one to five, with five meaning the parameter is one of the most important factors in the design. These ratings will help the team choose a direction for the design with a decision matrix. Table 1 shows the parameter weighting of the 20 relevant categories in order of importance.

Table 1. Parameter Weighting

Function/Performance	5
Delivery Date	5
Reliability	5
Operating Costs	5
Product Cost	4
Maintenance	4
Operating Instructions	4
Mechanical Loading	4
Domestic Materials	4
Safety	3
Quality	3
Environmental Conditions	3
Personnel	3
Energy Consumption	2
Human Factors	2
Size	2
Weight	2
Service Life	2
Transportation and Packaging	2
Aesthetics	1
Noise Radiation	1

4. Design Recommendation from Previous Semester

Section 4 was written by the Fall 2008 Vaccine Refrigerator team.

Based on the design decision matrices (see below), a solar-powered adsorption refrigerator was selected for the design of the vaccine refrigerator. This refrigerator has no moving parts aside from a few valves. It uses no toxic materials, generally available materials, and should be simple to build and operate. The refrigerator has an intermittent cycle. It will “charge” during the day and remove heat from a cooling volume at night.

4.1 Research of Design Recommendation from Previous Semester

Some previously used adsorbent/refrigerant pairs used for solar adsorption refrigeration systems are zeolite and water, silica gel and water, activated carbon and methanol, activated carbon and ammonia, and activated carbon and ethanol. It has been determined that the performance of each pair depends greatly on the climate in which it is tested.

Zeolite and water has proven to be a successful pair in numerous designs, achieving solar COP in the range of 0.27-0.3. It has been proven to be the ideal pair for air conditioning applications, however is unable to produce evaporator temperatures below 5 °C, thus cannot be used in deep freezing or ice making applications. The required heat source temperature is approximately 200 °C, requiring advanced solar harnessing equipment and a hot climate.

Silica gel/water systems have been found to achieve solar COP in the range of 0.1–0.16. The required heat source temperature is generally in the range of 50 °C to 100 °C, allowing the pair to be used in a diverse range of climates. Silica gel and water are capable of producing low evaporator temperatures and can produce ice. The downside of this pair is its unavailability in remote regions and toxic nature.

Activated carbon and methanol have been found to achieve a solar coefficient of performance in the range of 0.1-0.18. The required heat source temperature is approximately 100 °C, allowing it to be used in a wide variety of climates. It has been tested to produce evaporator temperatures as low as -20 °C, and has been used in air conditioning and ice making applications. Activated carbon is available in most areas of the world and can be produced by burning other carbon sources. Methanol however, is generally unavailable in undeveloped parts of the world and toxic in nature.

Activated carbon and ammonia have been found to produce a solar coefficient of performance in the range of 0.1-0.2. The required heating source temperature is around 100 °C. The pair has been tested to produce temperatures as low as -20 °C, producing ice. Similar to activated carbon/methanol, the downside of the pair is the hazardous nature and unavailability of ammonia in remote regions.

The activated carbon and ethanol pair perform very similar to the carbon/methanol pair mentioned above, apart from the fact the ethanol has a lower heat of vaporization. It is this difference between the two refrigerants that results in methanol being preferred in most previous work in this area. However, since ethanol can be found in alcoholic beverages, it is believed that it will be easier to obtain in Africa than methanol and less toxic; so it is the refrigerant of choice for this application.

4.2 Conceptual Design from Previous Semester

The purpose of this section is to provide a more complete understanding of the refrigeration process and system operation of the design recommendation beyond what has already been discussed in earlier sections and identify some of the major subcomponents of the system.

Aside from valves to initially charge the system, the refrigerator has no moving parts. It consists of three major subsystems. They are as follows: an adsorbent bed/solar collector, a condenser, and an evaporator. Since adsorption systems are driven using heat, the energy input for the system will be heat converted from solar radiation. The cycle will be intermittent and likely only run once every 24-hour period. The system will be closed and will have to operate at a high vacuum pressure.

The basic operation of the system is described by the following: When the adsorbent is at an elevated temperature, its ability to retain adsorbed vapor is diminished, and vapor is rejected out of the adsorbent bed. This rejected vapor is forced into the condenser due to elevated pressure in the adsorbent bed due to the desorption of vapor. Heat is transferred away from the fluid in the condenser to the surrounds and the refrigerant returns to liquid form. At night, the adsorbent is allowed to cool. This increases its capacity to adsorb vapor. Once the adsorbent bed has reached nearly ambient temperature, the fluid in the condenser is permitted to flow into the evaporator. Now that the fluid is in the evaporator, the valve between it and the adsorbent bed is opened. Liquid refrigerant begins to evaporate in the evaporator, taking in heat from its immediate surroundings. This provides the cooling effect. Once the adsorbent bed has reached capacity, the cycle begins again.

The adsorbent bed/solar collector houses a bed of activated carbon. This subsystem collects and converts solar radiation to heat in order to heat the activated carbon it contains. The system also allows the activated carbon to cool when it is not being exposed to solar.

The evaporator is the element of the system that is contained within the cold volume. Good heat transfer between it and its surroundings are essential to its function. But most importantly, it must be designed such that it can withstand the vacuum pressures it will experience.

The condenser will be used to reject heat from the vaporized refrigerant to the surrounds. In conjunction with the raised pressure in the system after desorption, the condenser plays a crucial role in completing the cycle so the process can repeat.

5. Design Alternatives

Based on the research done by the first group of this two semester project, an adsorption refrigeration cycle was deemed to be the most effective process to deliver the project goal. Based on their performance in the cycle and availability in remote regions around the world, ethanol and activated carbon were selected as the adsorbent and adsorbate respectively.

Throughout the design process of the vaccine refrigerator, there were several design models considered. In the selection process, design alternatives were reviewed for the evaporator, condenser and solar collector, the three main components of the system. Material selection played a role in the selection process and thus should be considered as separate design alternatives.

5.1 Material Selection

Aluminum

Aluminum can effectively be used to construct each of the three main components of the refrigerator, the solar collector, condenser and evaporator. The good heat transfer characteristics, light weight, corrosion resistance, and machinability make aluminum a very desirable material. However, the availability of aluminum in remote regions is unlikely, as well as the necessary welding equipment and skilled trade worker to weld the material.

Steel

The vast availability of steel in various shapes and sizes in remote regions around the world makes steel a viable option for each component. The disadvantage of this readily available material is its relatively poor heat transfer properties. Therefore, steel use would be limited to a supporting structure, or possibly the solar collector.

Copper

Similar to aluminum, copper too, has very good heat transfer characteristics. Also, the availability of malleable copper tubing, and the ease of soldering copper joints would greatly simplify the construction of the evaporator and condenser in remote areas. This does leave the solar collector to be made out of an alternate material, based on the limited availability of sheet copper that would be necessary for construction.

5.2 Component Design

5.2.1 Evaporator Design

Evaporator Coil Design

The evaporator coil design utilizes soft, malleable copper tubing to create a large helix. The design will effectively increase the surface area of the evaporator to cool the designated space at a faster rate. With copper as the material and the larger surface area of a helix, the design provides good heat transfer properties, but lacks manufacturability. The formation of a helix for larger tube diameters can be difficult without precision instruments.

Figure 1. Copper coil

Evaporator Box Design

This evaporator design would be a box constructed of aluminum sheet metal, welded together to fit along the wall of the refrigerator cold space. The seemingly simple design would efficiently use the area of the cold space and allow for a large volume of ethanol. A disadvantage may be with the availability of aluminum and the ability to weld the aluminum in developing countries.

Evaporator Tube Design

An evaporator tube design would consist of a soldered bank of copper tubes, and fittings that are sized to the refrigerator cold space. This design is a hybrid of the coil and box designs; it utilizes the increased surface area and properties of the copper tubes, and minimizes the space taken up, similar to the box design. This design may be problematic due to the soldering of several joints. If these joints are not able to maintain vacuum pressure the system will not complete the necessary cycle.

Figure 2. Tube evaporator

5.2.2 Condenser Design

Evaporator Coil Design

The condenser coil design, very similar to the evaporator coil design, would utilize a larger diameter copper tube to create a helical shape. Again, the disadvantage of this design is the formation of a helix for larger tube diameters, where the process can be difficult without precision instruments. Also, if necessary, the application of fins to the helix to increase the surface area would be very difficult.

Condenser Tube Design

This condenser design would be constructed of a soldered bank of copper tubes and fittings, similar to the evaporator tube design. The design would give a large surface area, as well as allow for easy attachment of any number of fins. The disadvantage of this design is the soldering of several joints, and the possible inability to hold a vacuum.

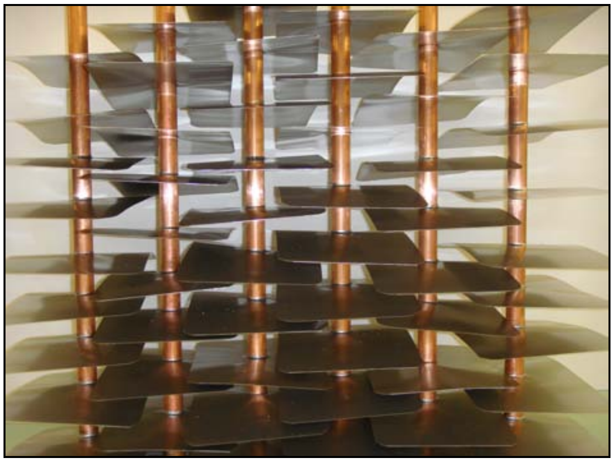


Figure 3. Tube condenser with fins

5.2.3 Solar Collector Design

55-Gallon Drum Design

This solar collector design would utilize the wide availability of 55-gallon steel drums throughout developing areas. The cylindrical drum would deliver a large surface area and allow for a simplified manufacturing process. The downfall of this design is the difficulty in distributing activated carbon evenly throughout the cylindrical drum.

Figure 4. 55-gallon drum

Flat Plate Design

A flat plate solar collector would be constructed of sheet steel and welded together to create a box to the required dimensions necessary for the activated carbon volume. A potential problem with this design would be the structural integrity of a large box. For a large volume of activated carbon, the box would have to be equally as big, and may collapse under the immense force created by the vacuum.

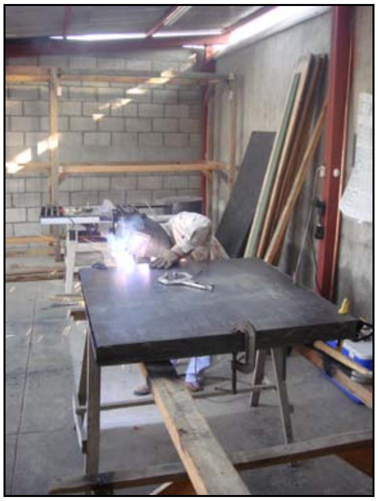


Figure 5. Flat plate solar collector

Flat Plate & Solar Reflector Hybrid Design

Utilizing the flat plate design, a solar reflector would be added around the structure. This addition will reflect the solar radiation to affect a larger surface area of the collector and allow it to achieve higher temperatures necessary for the activated carbon. The disadvantages of the design are the availability to source a highly reflective material in remote regions and the difficulty of accurately manufacturing an effective reflector.

Figure 6 Solar reflector

Flat Plate & Greenhouse Hybrid Design

Also utilizing the flat plate design, a greenhouse could be constructed around the structure. The greenhouse design would allow the solar collector to heat up, as well as prevent the warm air from rising, effectively increasing the temperature of the solar collector. The disadvantage of this design may be in the ability to find glass or Plexiglas in developing countries.

5.3 Subjective Evaluation of Design Alternatives

The design alternatives for each of the components of the system were subjectively evaluated to determine the best design parameters. A design was evaluated as being functional if it is able to perform the task, and nonfunctional if it is not able to perform the task. Those designs that are functional were evaluated as either being satisfactory or unsatisfactory based on the allowed design constraints.

5.3.1 Material Selection

Aluminum - Functional and Unsatisfactory

Aluminum was the first choice for the design of the major components of the refrigerator. This was due to the material properties that allowed for aluminum to have good heat transfer characteristics and corrosion resistance to ethanol. However, aluminum would not be ideal for developing nations based on the difficulty in finding the material. Guatemalan sources listed aluminum as extremely difficult to find. Aluminum also requires expensive welding equipment and skilled craftsman for manufacturing. Therefore, aluminum should be avoided for any portion of the refrigerator.

Steel - Functional and Unsatisfactory

Steel is a functional choice based on the worldwide availability of the material in several shapes and sizes. It is therefore cheap in comparison to aluminum and copper, thus significantly lowering the production cost. However, steel is unsatisfactory for several reasons. Using steel requires expensive welding equipment and skilled craftsman for manufacturing. It also has relatively poor heat transfer properties when compared to that of aluminum and copper. Therefore steel should be used in limited quantities where heat transfer properties are not essential for success.

Copper - Functional and Satisfactory

Copper was also considered a functional material with similar properties to that of aluminum. The material is corrosion resistant and also has functional heat transfer properties for use with our proposed designs. Copper is a satisfactory choice based on availability in developing nations and for ease of manufacturing. Copper is easily cut and soldered together requiring little skill and no costly equipment.

5.3.2 Component Design

Evaporator Coil Design - Functional and Unsatisfactory

The coil design is unsatisfactory based on consumption of space and manufacturability. In order to contain a liter of ethanol in a 0.75 inch diameter tube the copper tube needs to be 11.5 feet long. It was determined that an 18 inch diameter spiral was the tightest that was possible to manufacture by hand, therefore roughly 2.5 spirals would need to be constructed. This coil would consume a large portion of the available cold space leaving very little left for vaccines. Repeated hand manufacturing of a copper coil would result in inconsistent results.

Box Design - Functional and Unsatisfactory

A box evaporator is unsatisfactory for several reasons. First, such a box would need to be constructed out of either aluminum or steel, both previously mentioned as unsatisfactory materials. Secondly, a box design would be subject to very strong vacuum pressure; therefore, additional internal supports would need to be constructed to prevent collapse. Lastly, a box design would reduce the active surface area, allowing ethanol to evaporate further from a surface and reducing the cooling efficiency. Depending on the box dimensions the active surface area (area that is not in contact with a cold space wall) would roughly be between 70 and 180 square inches.

Evaporator Tube Design - Functional and Satisfactory

A tube design manufactured from copper is a functional and satisfactory design. The design is easily constructed with minimal manufacturing experience. This design also increases the active surface area because a very small portion of the evaporator will be against the cold space wall compared to that of a box design where one whole side would be in contact with a wall. A tube design is capable of increasing the surface area anywhere between 80 percent and 340 percent based on the box dimensions used. The increased surface area means that ethanol will evaporate closer to the copper wall and has a better opportunity to remove heat from the cooler, rather than from the liquid ethanol.

Condenser Coil Design - Functional and Unsatisfactory

A coiled condenser is unsatisfactory for several of the same reasons as the coiled evaporator. In order to obtain the required surface area for cooling purposes a very large and long coil would need to be manufactured by hand. It is possible to reduce the length by adding additional fins. However, the coil design would prove problematic for the addition of such fins. Therefore, a copper coil design proves an unlikely and unsatisfactory choice.

Condenser Tube Design - Functional and Satisfactory

The construction of a tube condenser similar to that of the tube evaporator is a satisfactory design. The design allows for the addition of fins to increase the surface area for cooling. The tube design is compact compared to the coil design. The easy manufacturing and assembly of the tube condenser is an additional plus.

55-gallon Drum Design - Functional and Unsatisfactory

A solar collector made from the remains of a 55 gallon drum was found to be unsatisfactory. Even though large drums are readily available in developing nations, manufacturing would be difficult. It was also proven that the surface area in contact with the sun is not enough to provide the required parameters. Other problems arise when trying to evenly distribute the activated carbon within the inside of the 55 gallon drum. The structural integrity of the drum also came into question with the addition of a strong vacuum.

Flat Plate Design - Functional and Unsatisfactory

A flat plate solar collector is beneficial because it can be manufactured at any size. However, the larger the flat plate collector, the greater risk of collapse under a strong vacuum. It was also determined through on-site testing in Guatemala that the surface temperature does not reach the maximum efficiency target temperature. Additional designs that incorporate the flat plate are better suited to meet required temperatures.

Flat Plate & Solar Reflector Hybrid Design - Functional and Unsatisfactory

A flat plate design that incorporates a solar reflector would also be considered unsatisfactory. The addition of a solar reflector would raise the temperature levels but would, in return, add additional problems. The additional problems are in connection with the difficultly in manufacturing a solar reflector. Therefore, a solar reflector, though functional, is highly unsatisfactory for the application and location.

Flat Plate & Greenhouse Hybrid Design - Functional and Satisfactory

To achieve the temperatures that are required, a greenhouse can be built around the flat plate. This design captures and prevents heat from escaping and can be easily manufactured for relatively little additional cost.

5.4 Objective Evaluation of Design Alternatives

The objective evaluation of the design alternatives was accomplished using a design matrix. The design matrix is used for an unbiased numerical representation of the previously mentioned design alternatives. The parameter weights shown are taken from the Table 1 design parameter weights.

Table 2. Design Matrix For Evaporator

Parameter	Parameter Weight	Coil Design	Box Design	Tube Design
Function /Performance	5	5	3	5
Reliability	5	4	3	4
Product Cost	4	3	2	3
Maintenance	4	3	3	3
Mechanical Loading	4	4	3	4
Domestic Materials	4	4	3	4
Safety	3	3	3	3
Size	2	1	2	5
Service Life	2	3	3	3
Transportation /Packaging	2	2	2	4
Avg. Weighted Score		3.49	2.77	3.83

From the design matrix for the evaporator, the tube design had the best average weighted score. Therefore, due to the subjective and objective design evaluations it was determined that the evaporator tube design should be implemented. The same tube design will be utilized in the condenser, as determined from Table 3 below.

Table 3. Design Matrix For Condenser

Parameter	Parameter Weight	Coil Design	Tube Design
Function /Performance	5	4	5
Reliability	5	4	4
Product Cost	4	3	3
Maintenance	4	4	4
Mechanical Loading	4	4	4
Domestic Materials	4	4	4
Safety	3	4	4
Size	2	2	5
Service Life	2	4	3
Transportation /Packaging	2	2	4
Avg. Weighted Score		3.66	4.03

Table 4. Design Matrix For Solar Collector

Parameter	Parameter Weight	55-Gallon Drum	Flat Plate	Flat Plate & Solar Reflector	Flat Plate & Greenhouse
Function /Performance	5	3	4	3	5
Reliability	5	3	3	3	4
Product Cost	4	5	3	2	4
Maintenance	4	2	5	2	4
Mechanical Loading	4	1	3	3	3
Domestic Materials	4	5	4	2	4
Safety	3	2	4	3	4
Size	2	3	3	3	3
Service Life	2	2	4	1	4
Transportation /Packaging	2	2	3	2	4
Avg. Weighted Score		2.91	3.63	2.49	3.97

The subjective and objective reviews have additionally determined that the solar collector will consist of a flat plate with an additional greenhouse. This was in large part due to the ability of such a set up to reach the desired temperature range.

5.5 Design Recommendations

The team decided to build a system that uses a tubular copper evaporator, tubular copper condenser with fins, and a steel flat plate solar collector. These elements provide excellent heat transfer properties while simplifying construction and keeping cost reasonable. Cost was a lower priority, as the team was primarily working to build a functioning system. With a working refrigerator, future groups may focus on reducing cost.

The solar collector box was built from sheet steel of 0.059-inch thickness. This allows for the minimum amount of weight and maximum heat transfer while still supporting the extreme forces created by the internal vacuum. Inside, the box is split at mid-height with a perforated sheet. The activated carbon will sit on top of this sheet, while the perforations allow the ethanol to reach the carbon and adsorb into it. Circular feet support the perforated metal from below, while long fins are welded to the inside of the top plate, acting as support and helping in heat transfer to the activated carbon.

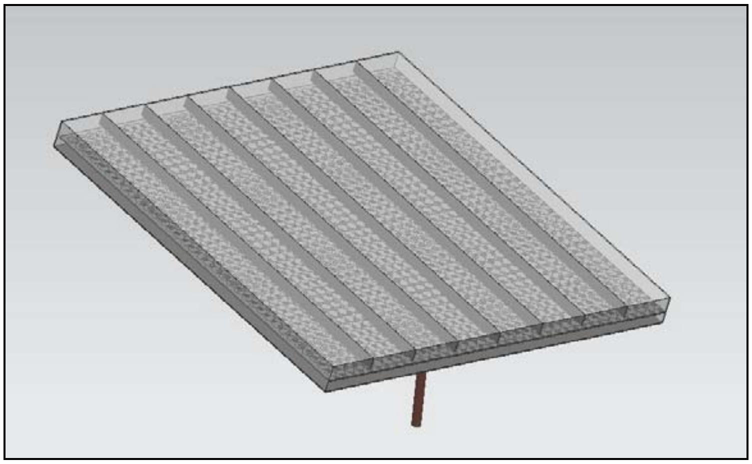


Figure 7. Solar collector design

The team has decided to design the system with a greenhouse over the solar collector. This will aid the system in collecting solar radiation to heat the activated carbon and promote desorption. Where glass or Plexiglas is not available, the system can be built with a semi-transparent plastic. The design features a simple plywood box with 2-inch foam insulation on every side except the top. The top surface is sealed with a transparent material.

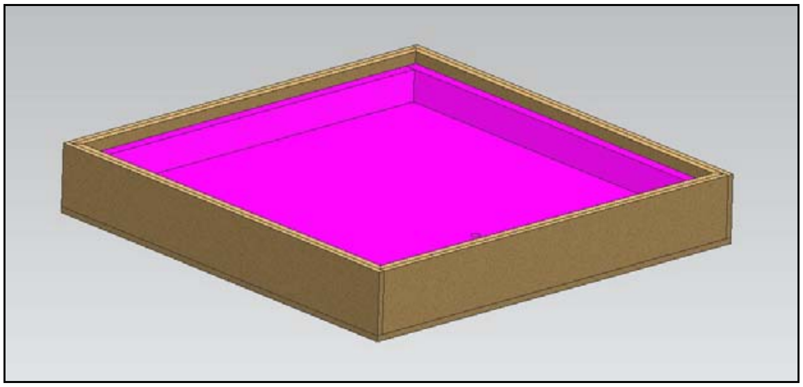


Figure 8. Greenhouse design

The structure for the entire refrigerator is shown in Figure 9. While the team used wood for both prototypes, it is possible to build a similar structure out of steel or similar metal. The structure consists of four posts and a platform capable of holding the solar collector. This platform is angled to optimize the sun exposure to the solar collector. The angle can be set equal to the line of latitude where the refrigerator will be used. Guatemala is located near the 15th parallel; therefore, our prototype utilizes a 15 ^{o} angle.

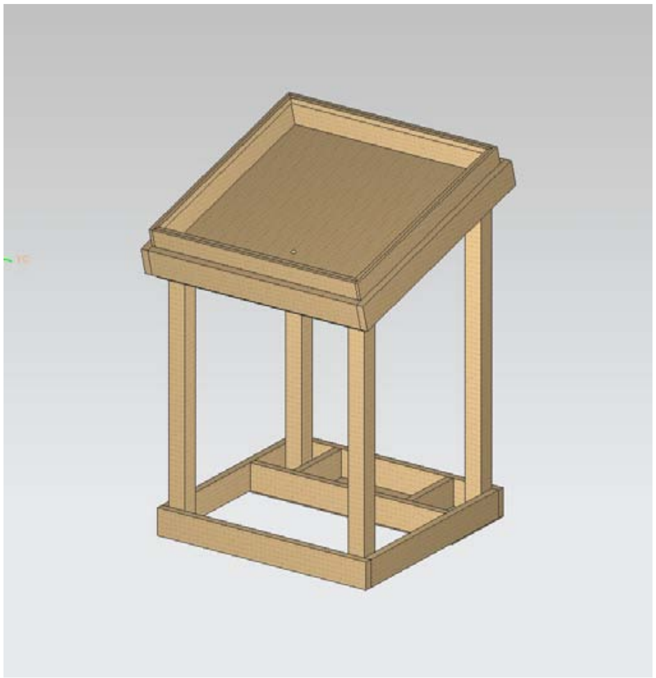


Figure 9. Structure design

Because the system requires such a large area for the condenser, the team has added additional fins to the condenser. These 6-inch by 10-inch fins made from aluminum flashing add significant convective area without the expense or bulk of additional copper piping.

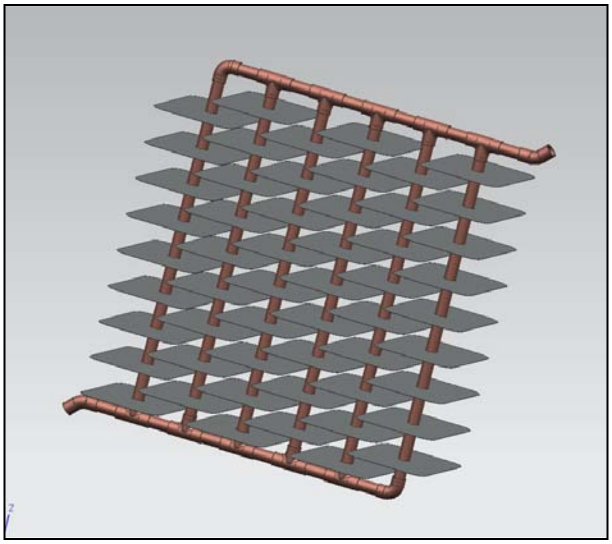


Figure 10. Condenser design

The use of copper tubing for the evaporator allows for easy assembly and excellent heat transfer due to the material properties and amount of surface area. The vertical elements are connected at the bottom so that the entire evaporator fills evenly as the ethanol condensates.

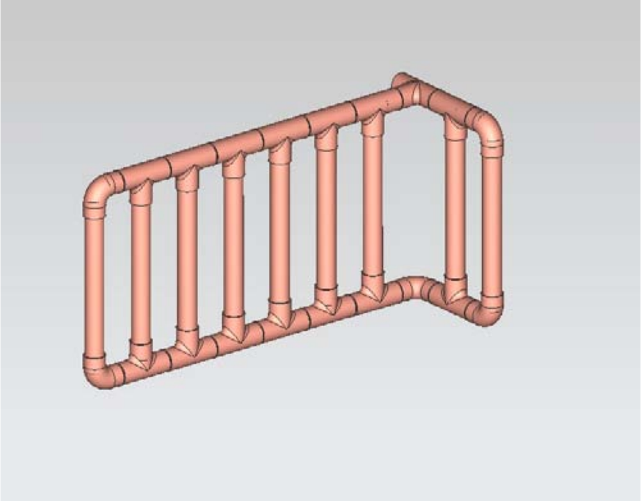


Figure 11. Evaporator design

The complete design of the system is shown in Figure 12. The condenser and cooler with evaporator are positioned under the solar collector to shade them from the direct sun. However, as the sun rises to its noontime peak, the cooler will inevitably receive some sunlight. To minimize heat loss, the cooler should be shaded, perhaps by using fabric sheets on the sides.

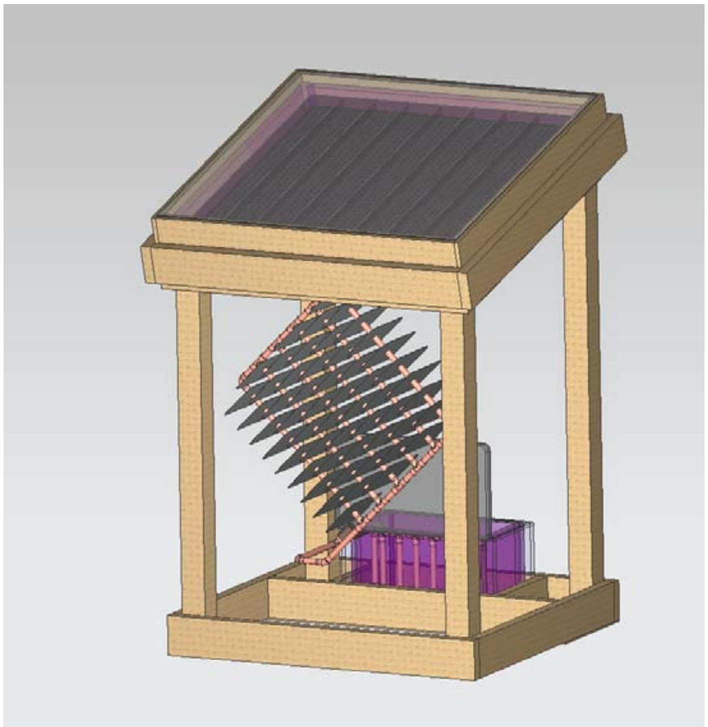


Figure 12. Complete refrigerator design

The appendix contains a list of all 49 available engineering drawings for re-producing the student designed refrigerator. The appendix also shows the main assembly drawings which include: Evaporator, Condenser, Adsorber Bed, and Main Structure.

5.6 Research of Design Recommendations

5.6.1 Evaporator Tube and Condenser Tube

The evaporator and condenser are some of the most important subassemblies for the refrigeration unit. Both of the subassemblies must be leak-free while withstanding outside pressure caused by the vacuum inside the system. Not only does the material chosen to construct the evaporator and condenser have to be strong, it also has to have excellent heat transfer qualities. Ethanol phase changes occur in both of these subassemblies of the refrigerator. The ethanol is turned from a liquid to a vapor in the evaporator, while the ethanol is condensed from vapor to liquid inside the condenser. The evaporator must be capable of pulling as much heat out of the cooling box and putting it into the ethanol as fast as possible to keep the temperature down and keep the vaccines at the correct temperature. On the other hand, during the daytime the condenser must pull as much heat as possible from the ethanol vapor in order to cool it down and convert the ethanol back into its liquid form. Copper is a viable option because of its availability in remote regions, and material properties.

Table 5. Material Properties of Copper

Property	Value
Thermal conductivity	401 W/mK
Thermal expansion	16.5 μm/mK
Young's Modulus	110 - 128 GPa
Shear Modulus	48 GPa
Poisson Ratio	0.34
Brinell Hardness	874 MPa
Density	8.96 g/cm^3
Melting Point	1357.77 K

With a thermal conductivity of 401 W/m-K, copper has the second highest thermal conductivity of all pure metals at room temperature, after silver[5]. Having a high thermal conductivity allows the copper used inside the condenser and evaporator to gain or lose heat at a rapid pace. Copper is also resistant to corrosion when exposed to moisture[1]. Unlike other metals, copper does not react with water, but oxygen in air will react slowly at room temperature to form a layer of black-brown copper oxide on the surface. However this layer serves to protect the copper against any further corrosion[1]. Therefore utilizing copper as the material of choice for the evaporator and condenser will increase the longevity of the refrigeration unit.

Figure 13. Varieties of copper fittings

Figure 14. Black-brown oxidation

When a vacuum is pulled on any given system, the pressure is not pushing from the inside, instead the atmospheric pressure is pushing the body from the outside, increasing the stress on the system. Therefore it is very important to use an optimized shape capable of enduring a stress of 14 lb/in^2 in manufacturing the evaporator and condenser. Using geometry with multiple edges, such as a rectangle, will result in stress concentrations at those weak points. This is why the subsystem designs must incorporate a geometry which has the least amount of edges. Choosing a circular tube allows the system to have excellent stress enduring characteristics. Using circular copper tubes also allows more flexibility for manufacturing purposes[5]. This is because there are is a large variety of geometries available for copper piping such as T-fittings, 90° elbows, 45° elbows, and connector tubes of varying lengths.

5.6.2 Flat Plate Solar Collector

The adsorber bed is a very important structural component because of the stresses it will have to tolerate. It is the largest volume subassembly which will have to endure a load of 14 lb/in^2. Therefore it is crucial that the bed is made from relatively rigid materials. At a thermal conductivity of 54 W/m-K, steel does not possess good heat transfer properties when compared with copper, however if designed correctly its thermal conductivity is sufficient for the adsorber bed application. With a thermal conductivity of about 10 W/m-K, activated carbon possesses poor heat conducting properties. Therefore, the flat plate adsorber bed will incorporate steel fins inside the compartment which will hold the activated carbon to help spread heat. These steel fins will also act as structural supports for the flat plate adsorber bed. Steel sheets can be permanently joined with other steel sheets by welding. The bond which is created due to welding is very strong and can handle high stress applications. Inside the adsorber bed, an aluminum window screen mesh is used to contain the granular activated carbon fiber in place. The mesh is chosen not because it is strong enough to contain the activated carbon, but because it allows enough air flow through to the activated carbon. To hold the activated carbon's weight in place, perforated steel is used. The perforated steel is strong enough to support the weight but at the same time it also allows for enough air flow to reach the carbon.

5.6.3 Activated Carbon

The kind of activated carbon needed has to be able to adsorb the ethanol in its vapor form almost instantaneously. This kind of activated carbon requires a thoroughly developed structure of pores. In general, there are three kinds of pores which exist inside the microstructure of any form of activated carbon.

1. Macropores (> 500 Angstrom*)
2. Transitional Pores (20-500 Angstrom*)
3. Micropores (0-20 Angstrom*)

*Angstrom = 0.0000001 mm

Macropores are mostly used for water filtration systems along with treating solid waste found inside liquids[4]. The Transitional Pores are more suitable for adsorbing large molecules for the purpose of removing discoloration[4]. Micropores, however, are very useful for vapor applications[1]. This pore structure is vital for capturing and trapping vapors of any kind. When analyzing different kinds of activated carbon for this project, there are two main parameters which must be given great consideration. The porosity or the abundance of micropores, and the grain size of the carbon. Powder carbon is not very useful for our application due to its hard handling characteristics. Although more surface area can be achieved with powered carbon, it is difficult to package inside the adsorber bed. Therefore, activated carbon of granular form is preferred instead. The larger grain size makes it easier for packaging inside the adsorber bed and allows the design to be more flexible.

Figure 15. Granular activated carbon

Figure 11. Powder activated carbon

When considering the pore structure, activated carbon made from coconut shells has an abundant amount of micropores[4]. Coconut shells are also readily available in most rural areas around the world. According to the <u>Experimental Investigation of Activated Carbon Fibers/Ethanol Pairs for Adsorption Cooling System Application</u> research paper, Activated Carbon Fiber (ACF) A-20 is recommended for use in the adsorption refrigeration cycle. However ACF A-20 is not readily available in most rural areas and is very expensive. Using ACF A-20 would result in a better performing cycle however its lack of availability and cost make it an unfeasible option.

Therefore activated carbon made from coconut shells is a good choice for the refrigeration unit because more micropores equal more vapor adsorption.

5.6.4 Support Structure

Many options are available for making the support structure. For this project's scope, the support structure must be rigid enough to support at least 300 pounds of weight. Even though this is not the adsorber bed's actual weight, a safety factor was added such that the structure is able to hold more weight than what is necessary. Wood has excellent properties when it comes to being axially compressed. It is readily available in most rural regions of the world and most of the time is cheaper to buy when compared with steel. Wood is also easier to work with because instead of welding, screws can be used to connect the necessary joints of the structure.

5.6.5 Condenser Fins

The condenser requires multiple fins in order to transfer heat from the ethanol vapor to the ambient air in order to convert it in to liquid form. Therefore the material chosen for this purpose must have excellent heat transfer. Aluminum has a thermal conductivity of 235 W/m-K which is relatively high when compared with other metals. Aluminum is also very ductile and easy to work with for manufacturing purposes. Because of these properties, aluminum flashing is used to create fins. Aluminum is quite easy to cut and shape, if the correct thickness is chosen. Aluminum has very good heat transfer properties and is ductile enough to withstand any major stresses the fins might see such as strong winds.

6. Modeling of Design Recommendation

To ensure the design functions properly, it was necessary to model the various components according to the processes that drive the heat transfer and chemical reactions. These calculations and their resultant findings are explained in detail below.

6.1 Cooling Load Model

In order to determine the required amount of refrigerant, adsorbent and size of the solar collector, it is necessary to know the amount of energy required to maintain the refrigerator's temperature for one cycle. This model uses steady state heat transfer analysis, assuming the interior of the refrigerator is at a constant temperature. The surroundings of the refrigerator are also treated as a constant. To know the cumulative amount of power required for a 24-hour refrigeration cycle, one must multiply the results from this model by 24 hours. For a more accurate model, it may be best to assume that the day is actually two distinct periods with unique temperatures. For example, the model may be run for an ambient temperature of 27°C and then multiplied by 12 hours to simulate a hot day. The model would then be run again with 18°C for the surrounding temperature and multiplied by 12 hours to model the heat flux at night. The results for night and day would be summed to reflect the total cooling power required for the refrigerator. Using this example, one could easily adapt the process for a day divided into three or more distinct temperature-time periods.

The model considers the three modes of heat transfer: conduction, convection and radiation. The heat transfer is calculated using thermal resistivity, where the modes are modeled with a thermal resistance that is a property of area, material properties and dimensions. Using this method, the series resistances of convection, conduction and radiation can be summed and the heat transfer due to all modes can be calculated at once.

The thermal resistivity can be calculated by:

$$R_{conduction} = \frac{\ell}{kA} \tag{1}$$

$$R_{convection} = \frac{1}{hA} \tag{2}$$

$$R_{radiation} = \frac{1}{h_r A}\text{, where } h_r = \varepsilon\sigma(T_s + T_{sur})(T_s^2 + T_{sur}^2) \tag{3}$$

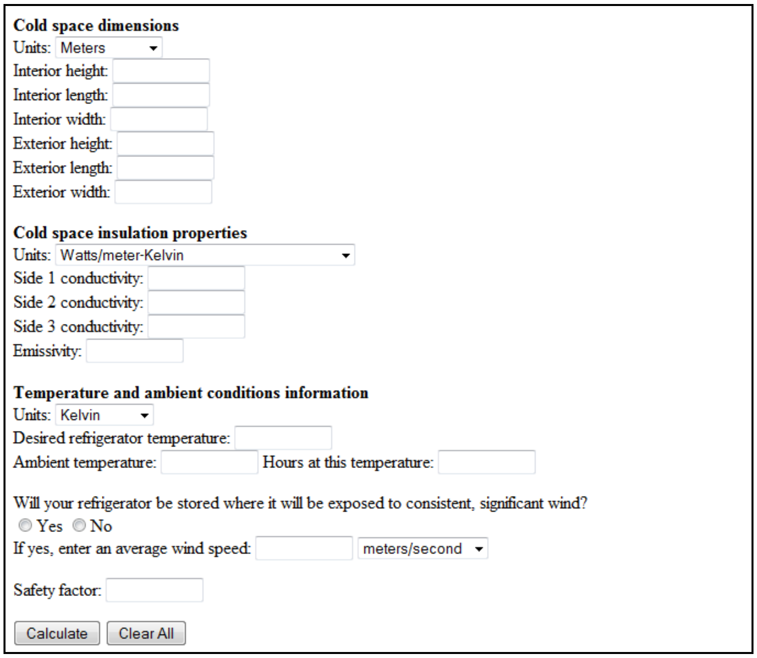
The convection coefficient, *h*, requires an involved calculation using a Nusselt number correlation. To perform these calculations, the team created a web-based PHP code that iterated to find the correct Nusselt numbers and convection coefficients. The inputs to the 500 line code are as follows:

Inputs

- Interior Cold Space Dimensions
- Cold Space Insulation Properties
- Ambient Temperature Conditions
- Average Wind Speed
- Safety Factor

Outputs

- Heat load per day



Cold space dimensions
Units: Meters
Interior height:
Interior length:
Interior width:
Exterior height:
Exterior length:
Exterior width:

Cold space insulation properties
Units: Watts/meter-Kelvin
Side 1 conductivity:
Side 2 conductivity:
Side 3 conductivity:
Emissivity:

Temperature and ambient conditions information
Units: Kelvin
Desired refrigerator temperature:
Ambient temperature: Hours at this temperature:

Will your refrigerator be stored where it will be exposed to consistent, significant wind?
○ Yes ○ No
If yes, enter an average wind speed: meters/second

Safety factor:

Figure 17. Heat load calculator screen shot

The results of the model estimated that 301.34 kJ of energy would be input to the system during a 24-hour cycle. To remove this energy from the system, 0.4 liters of ethanol must be evaporated. To ensure that there was enough refrigerant to keep the system cool, the team upsized the quantity to 1 liter. With this number, it was then possible to determine the amount activated carbon required and the amount of solar energy that was necessary to recharge the cycle.

6.2 Activated Carbon Model

Due to the efforts of last semester's team, the Dubinin-Radushkevich (D-R) equation was used to calculate the amount of adsorbent material needed to adsorb the ethanol. The D-R equation relates adsorption concentration X, to the temperature and the pressure with experimentally derived constants such as the maximum concentration X_0, and adsorption pair's characteristic energy D. For Granular Activated Carbon 48C and ethanol these parameters were determined to be $.135\,{}^{kg}\!/_{kg}$ and 1.716e-06 respectively.

$$X = X_0 \exp\left\{-D\left[T \ln\left(\frac{P_S}{P}\right)\right]^n\right\} \tag{4}$$

The saturation pressure P_s, refers to the vapor pressure of the ethanol at the given temperature T, of the system. During a regular cycle, the system experiences varying temperatures and pressures. The temperature can vary anywhere from 3° C to 100°C and the pressure can vary from 29 inches Hg vacuum to 21 inches Hg vacuum. Since the adsorption rate of the activated carbon is not constant, due to the changing temperature and pressure of the system, worst case scenario is chosen to determine the amount of activated carbon needed. Therefore temperature T, of 373 K and pressure P, of 21 inches Hg vacuum were used to determine the adsorption concentration X, which came out to be 16.9806 kg.

6.3 Solar Collector Model

Basic heat transfer fundamentals were used to roughly calculate the required solar collector surface area. Several inputs were required such as the average insolation available per year $\ddot{q}_{in}$, average cloudiness of the sky c, an estimate of the efficiency of the collector itself η, and the required input load $\dot{q}_{in}$.

$$\dot{q}_{in} = c\eta\ddot{q}_{in}A \tag{5}$$

Insolation is a measure of solar radiation energy received on a given surface area in a given time. Average insolation values were obtained from the internet using a website called Gaisma.com. This website contains the average monthly insolation, cloudiness, temperature, wind speed, and precipitation of most major cities around the world. For our project's requirements Quetzaltenango, Guatemala was chosen as the target city. On average, Quetzaltenango receives 429.65 Wh/m^2 of insolation and has a cloudiness factor of .54 per year. Heat losses due to conduction and convection were taken into account and the solar collector was estimated to be 37 percent efficient. The required input load was determined to be 83.61 Watt-hours by using the cooling load model. After solving for area *A*, it was determined that a solar collector with an area of 0.974 m^2 is necessary for this application.

6.4 Condenser Fins Model

To dissipate sufficient amount of heat from the ethanol vapor in order to convert it back into its liquid form, fins have to be added to the condenser. An excel spreadsheet provided by Dr. Craig Somerton was utilized to determine the number of fins needed. Since copper tubes are used for creating the condenser, annular fins will provide the greatest contact with the metal. Maximizing the contact area between the metal and the fins will result in more efficient cooling for the ethanol vapors. The following parameters were entered into the spreadsheet for annular fins.

Base Temperature: 80 °C
Thickness of Fin: 0.000234 m
Outer Radius of the Fin: 0.16 m
Bare Surface Area: 0.32856 m^2
Ambient Temperature: 21.11 °C

Required Heat Transfer: 83.611 W
Density of Fin Material: 2700 kg/m^3
Inner Radius of the Fin: 0.011113 m
Heat Transfer Coefficient: 2 W/m^{2}K
Thermal Conductivity of Fin: 237 W/m K

For annular fins, the outer radius must be optimized in order to prevent any loss of material. A larger fin does not necessarily translate into a larger heat transfer rate. To help with this optimization, the outer radius of the fin is varied in the spreadsheet until the heat transfer rate stops increasing. At a radius of 0.16 m the heat transfer rate of the fin peaked at 1.93 W. Since the total heat transfer required is 83.611 W, the spread sheet output a total of at least 44 fins required for the condenser.

7. Manufacturing

The prototype has three main manufactured components: evaporator, condenser, and adsorber bed. This section outlines the materials and fabrication of each component. Reference the appendix for detailed engineering drawings of each component. The following section on sealing joints is now presented due to the importance in every section of the manufacturing process.

7.1 Sealing Joints

One way of joining together two like metals is by introducing filler. For example, if a piece of copper needs to be attached to another piece of copper, then solder can be used as filler. This method of sealing requires the following steps to be carried out.

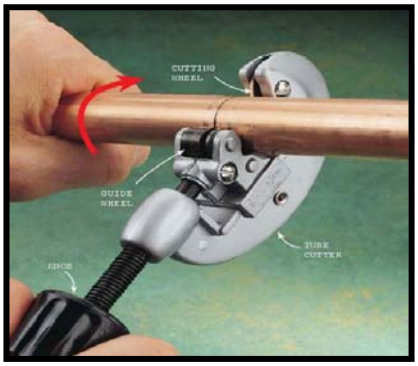


Figure 18. Cutting copper pipe

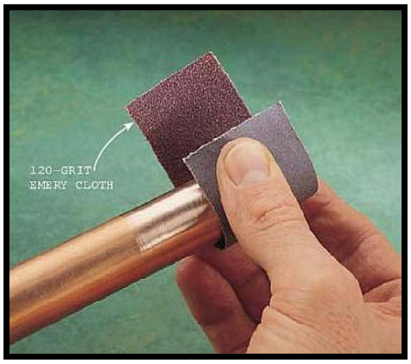


Figure 19. Cleaning/etching copper pipe

Figure 20. Applying flux to joint

Figure 21. Heating and applying solder

First, the joints must be cleaned off by using sandpaper until they become as shiny as a new penny to get rid of any dirt and oil. This step is called cleaning and etching the joints. Next, flux needs to be added to the joints. Flux helps the solder flow easier through the joints when heated. Next, the joints need to be pressed together and heated up to about 200° C, which is the melting point for solder. The solder must be applied thoroughly and all the way around the joint. After applying the solder, heat needs to be removed to allow the solder to cool down and harden. Any excess solder needs to be removed by using a clean piece of cloth. This method of joining two metals will create a very strong bond capable of standing up to 7130 lbs/in^2. Soldering method will be utilized in assembling the condenser and the evaporator. Another method of joining two like materials is called welding. There are many different kinds of welds which can be used for joining two metals together.

Figure 22. Metal stick welding

Figure 23. Thread sealing tape

Stick welding is one of the most effective forms of welding. A rod is used to weld together two like materials such as steel. The joints created through welding are just as strong as and sometimes even stronger than the steel itself. Welding will be used for assembling the flat plate adsorber bed. One of the most common forms of joining two parts together is through the use of threads. Threads are great for applications which do not require a tight seal. However if an air tight seal is required, then thread sealing tape must be used. The thread sealing tape is wrapped around the male thread multiple times. Then the male thread is screwed into the female thread creating an air tight seal. This form of sealing is effective but limited in its applications for complex manufacturing processes. This method of sealing will be used for joining the subassemblies with each other.

7.2 Manufacturing of the Evaporator

The evaporator structure consists of a bank of copper tubing and fittings sized to fit along the walls of the cold space. The dimensions of the evaporator will vary based on the size of the cold space used.

Figure 24. Completed evaporator in cold space to locate hole.

a.) Material List:

90 degree copper elbow 1” OD x ¼” wall x ¾” ID	8 units
Copper tee 1” OD x ¼” wall x ¾” ID	15 units
4.125 copper tube 1” OD x ¼” wall x ¾” ID	5 units
8.0 copper tube 1” OD x ¼” wall x ¾” ID	8 units
1.562 copper tube 1” OD x ¼” wall x ¾” ID	14 units
Lead free solder	1 roll
Solder flux	1 unit
Solder flux brushes	1 brush
Sand paper	small square
Wire brush	1 unit
Propane torch	1 – 2
Copper cutter	1 unit

b.) Fabrication

1. Utilize the methods described in Section 7.1 to cut 3/4” stock copper tubing to the lengths specified in the materials list above. .
2. Dry fit the cut to length copper tubing and fittings to create the structure shown in Figure 19 above. Due to copper fitting quality, it may be necessary to rotate fittings in order for the structure to come together. Place structure in cold space to ensure proper dimensions of the evaporator.
3. Thoroughly clean and flux each copper tube and fitting as described in Section 7.1. Reconstruct evaporator leaving a tee fitting as the only open hole. See Figure 24.
4. Solder each joint using methods described in Section 7.1.
5. Place soldered evaporator in cold space and mark the position of the hole to connect to condenser.
6. Drill a hole through cold space to fit a copper stub out.

7.3 Manufacturing of the Condenser

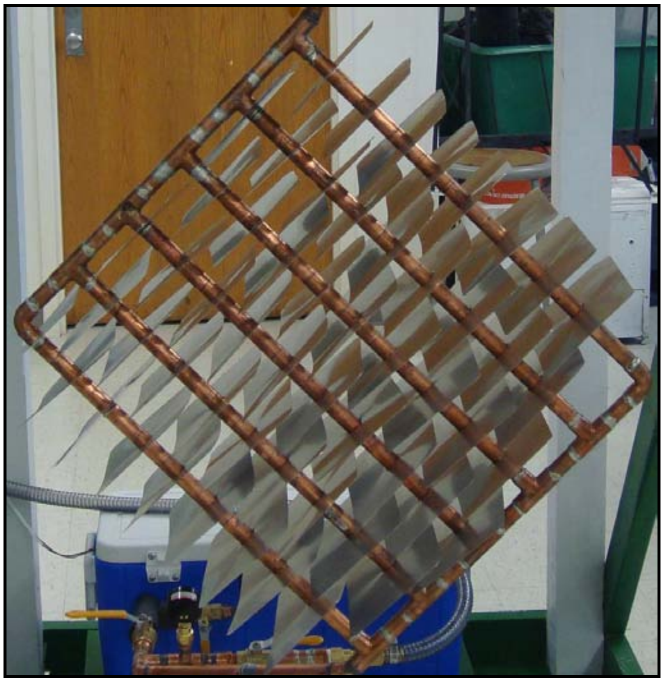


Figure 25. Completed condenser with fins attached.

a.) Material List:

45 degree copper elbow 1” OD x ¼” wall x ¾” ID	2 units
90 degree copper elbow 1” OD x ¼” wall x ¾” ID	2 units
Copper tee 1” OD x ¼” wall x ¾” ID	10 units
Aluminum flashing condenser fin 6” x 10”	51 units
24.0” copper tube 1” OD x ¼” wall x ¾” ID	6 units
2.0” copper tube 1” OD x ¼” wall x ¾” ID	12 units
3/4” Tap punch	1 unit
6” PVC Tube 1” ID	1 unit
Lead free solder	1 roll
Solder flux	1 unit
Solder flux brushes	1 brush
Sand paper	1 roll
Wire brush	1 unit
Propane torch	1 – 2
Copper cutter	1 unit
Tin snipes	1 unit

b.) Fabrication

1. Utilizing 3/4” copper tubing cut to the specifications shown in the material list above, dry fit the copper tubing and fittings to create the structure shown in Figure 25. Due to copper fitting quality, it may be necessary to rotate fittings in order for the structure to come together.
2. Cut aluminum flashing for condenser fins to the specifications shown in the materials list.
3. Locate the center of condenser fin, place ¾” punch at the center of the fin, and firmly hit the punch with mallet to remove hole for copper tube. Be sure to use the punch over a soft surface, such as wood. With a firm hit, this will flare the edges of the hole in the flashing. Repeat the process for each fin.
4. Thoroughly clean and flux each copper tube and fitting. Reconstruct half of the condenser design, leaving one end open to install fins.
5. Solder each joint.
6. Place condenser fin on end of ¾” copper tube of the half constructed condenser. With the flared end of the fin up, place 6” PVC tube with a 1” ID over the flared portion of the fin and press fit the fin onto the ¾” copper tube. The fin should have a tight fit to maintain contact with the copper. Repeat this process for each fin, and space them evenly along the length of the tube.
7. Thoroughly clean and flux each joint, and solder together the remainder of the condenser.

7.4 Manufacturing of the Adsorber Bed

Figure 26. Base of solar collector.

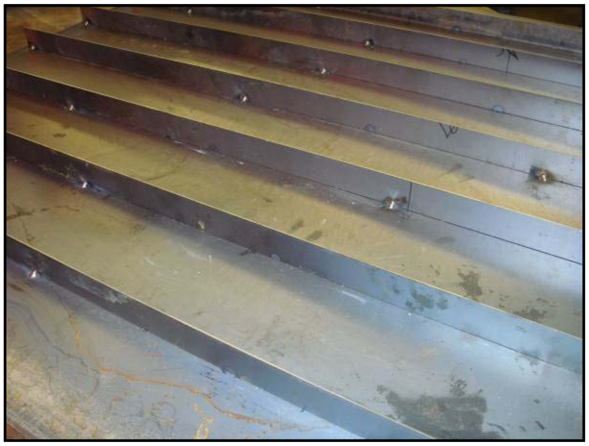


Figure 27. Top of solar collector with fins

a.) Material List:

Steel adsorber top 39.5” x 39.5” x .059”	1 unit
Steel adsorber side 39.5” x 2.625” x .059”	4 units
Steel adsorber fins 39.4” x 1.125” x .059”	7 units
Aluminum adsorber mesh 39.28” x 39.28” x .009”	1 unit
Adsorber perforated steel 39.28” x 39.28” x .125”	1 unit
Steel adsorber bed tube support 1” x 1” OD x .875” wall	9 units
Steel adsorber bottom 39.4” x 39.4” x .059”	1 unit
Steel tube 6” x 1” OD x .875” ID	1 unit
Copper tube 4” x .875” OD x .75” ID	1 unit
Welding equipment	1 unit
Activated Carbon	17 kg
Spray can of primer	1 can
Spray can of flat black paint	1 can
Brazing rod	2-3 sticks
Brazing flux	1 unit
Oxyacetylene torch	1 unit

b.) Fabrication

1. Utilizing the steel adsorber top and three adsorber sides cut to the specification shown in the material list above, weld the three sides to the bottom sheet.
2. Drill a 1.125” hole in the bottom of the adsorber, 36.5” from the open side.
3. Insert the 6” steel tube into the hole and weld into place.
4. Arrange the nine steel adsorber bed tube supports equidistant around the bottom of the adsorber bed, similar to that shown in Figure 26. Spot weld each of the supports.
5. Place the adsorber perforated steel that is cut to the dimensions shown in the materials list on top of the tube supports. Spot weld the perforated steel to the adsorber bed sides.
6. Place the aluminum adsorber mesh on top of the perforated steel in the base of the solar collector.
7. Using the steel adsorber top and seven steel adsorber fins described in the material list, weld the fins to the top, spacing them 4.9375” apart. See Figure 27 above for reference.
8. Place the adsorber top on the base and weld in place. The fins that are attached to the top should be perpendicular to the open side. This will allow this activated carbon to be poured into the adsorber.
9. Pour 17 kilograms of activated carbon into the adsorber.
10. Put the remaining steel adsorber side in place on the open end and weld adsorber shut.

11. Thoroughly clean and flux steel stub out from the adsorber and the 4” copper tube.
12. Insert the 7/8” OD copper tube into the steel tube approximately 1” along the clean portion of the tube. Braze the copper tube to the steel tube.

7.5 Assembly of Adsorption Refrigerator

Figure 28. Completed assembly of adsorption refrigerator.

a.) Material List

14” Copper tube 1” OD x ¼” wall x ¾” ID	1 unit
45 degree copper elbow 1” OD x ¼” wall x ¾” ID	1 units
Lead free solder	1 roll
Solder flux	1 unit
Solder flux brushes	1 brush
Sand paper	1 roll
Wire brush	1 unit
Propane torch	1 – 2
Copper cutter	1 unit

b.) Fabrication

1. Fixed the position of the adsorber.
2. Thoroughly clean and flux the fitting into the condenser and the copper stub out from the adsorber.
3. Vertically orient the condenser and solder in place.
4. Dry fit the copper tube and 45 degree fitting with the condenser and evaporator. Mark the angular position of the fittings by drawing a line at each fitting-tube intersection with a permanent marker.
5. Thoroughly clean and flux the copper tube and fittings.
6. Solder the copper tube and fittings into dry fit position.

8. Testing

8.1 Michigan Testing

Because the weather and average solar load in Michigan is not conducive to using the refrigerator, the team was unable to conduct testing outside. Instead, four 250-watt infrared bulbs were used to simulate a 1000-watt solar radiation load. Using these lights prevented the team from running and observing a 24-hour cycle. Instead, a shortened 9-hour test was run with three hours of cooling, three hours of solar heating and another three hours of cooling.

Figure 27 shows the results of that test, during which temperatures were measured for the surfaces of the evaporator, condenser, solar collector and a bottle of water in the cooler. Within the first 30 minutes of starting the ethanol evaporation, the temperature of the copper inside the cooler dropped to 4.3°C, a positive sign. However, after this time, the temperature steadily rose, settling about 10°C below ambient.

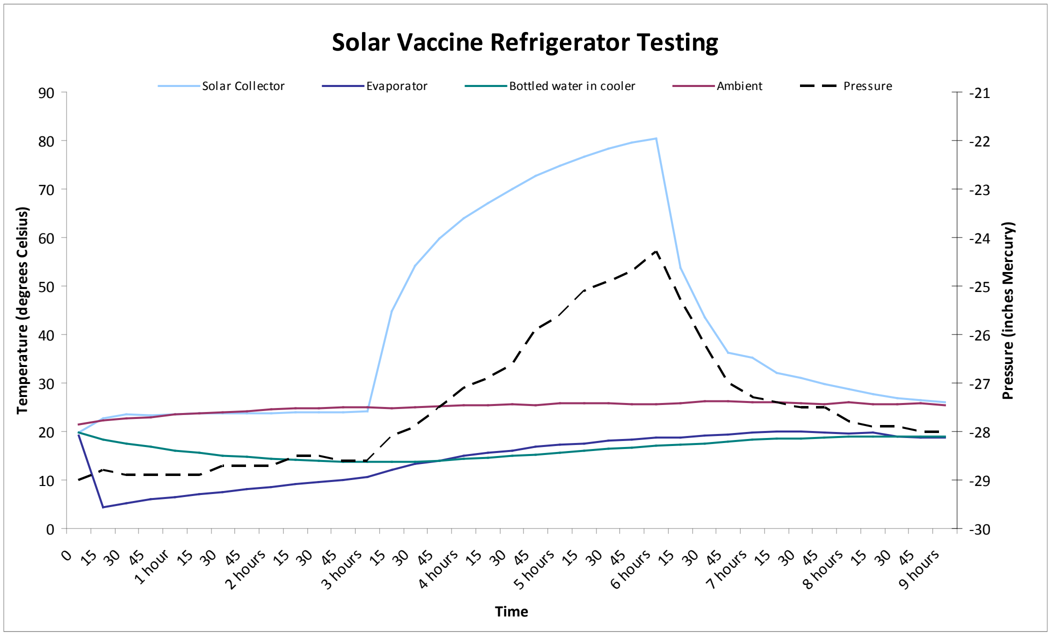


Figure 29. Nine hour refrigerator test temperatures.

The team has formulated a strong idea of what caused this phenomenon. Modeling of the system was based on a steady state performance, in which the amount of refrigerant was selected to maintain a temperature of about 4°C. This model did not account for the amount of cooling necessary to drop the temperature of the cooler and its contents to the desired temperature. It is predicted that if the team ran three to five cycles, there would be a larger and larger differential between the ambient and cooler temperatures until the desired 4°C was achieved. Additionally, with cooler temperatures near the saturation point, the evaporation of ethanol would slow down as the refrigerant repeatedly cooled and warmed fractions of a degree near the boiling point.

The refrigerator did show a small dip in temperature near the end of the cycle as condensed ethanol began to evaporate again. Due to the small amount of cooling that occurred, the team is confident that only a small portion of the ethanol condensed. This was likely caused by the shortened solar heating cycle. Furthermore, reducing the system volume with less condenser plumbing or a smaller solar collector volume might result in higher pressures and more condensation. Repeating several 24-hour test cycles back to back should be a high priority for future work.

The plots of the solar collector temperature and system pressure in Figure 29 illustrate how the condensation occurs. As the activated carbon is heated, the ethanol is desorbed and fills the entire system as a vapor. As more ethanol is desorbed, pressure continues to increase. This raised pressure increases the condensation temperature above ambient, returning the ethanol to a liquid.

Since large pieces of glass and Plexiglas aren't readily available in developing countries, the team questioned whether the solar collector should incorporate a greenhouse design. To understand the implication of such a design, a test was run to evaluate the temperature of the solar collector as it was heated with and without a greenhouse covering. The test measured the surface temperature of the collector while it was heated with the four infrared heat lamps. The data is shown below in Figure 30.

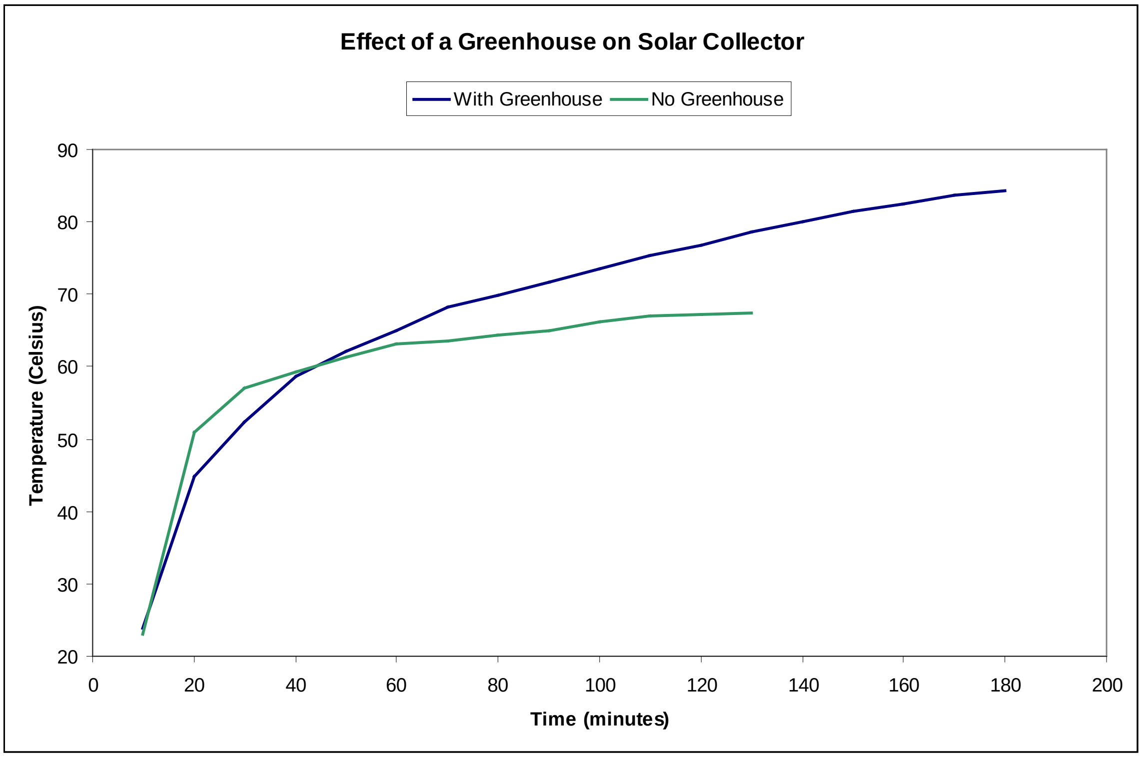


Figure 30. Greenhouse testing results.

As the plot shows, the greenhouse has a significant effect on the solar collector temperature, making it 15 degrees hotter than the collector without a greenhouse. Additionally, while the non-greenhouse temperature leveled around 120 minutes, the greenhouse temperature continued to climb even after 180 minutes. Based on these findings, the team recommends that a greenhouse design be used to ensure enough heat is captured for the desorption process. However, the team also believes that the system would still work without a greenhouse in sun-rich regions near the equator.

8.2 Guatemala Testing

The team's primary goal in Guatemala was to gain an understanding of material availability, fabrication capabilities and local culture. With just five days to source supplies and build the device, there was only time to take data on one day. Figure 31 shows the recorded temperatures of the cooler, solar collector and surroundings.

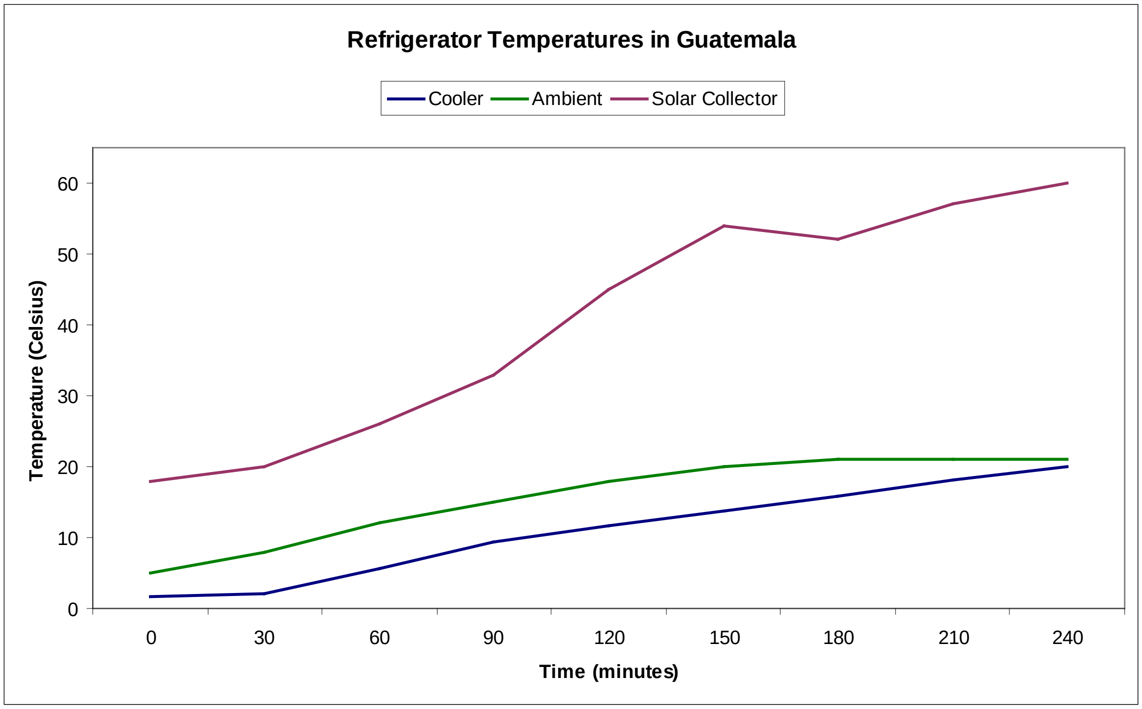


Figure 31. Guatemala testing data.

The temperature started at 1.3°C and steadily rose throughout the day. In Guatemala, the team did not have any thermal mass in the cooler, which allowed the interior air to warm quickly.

Additionally, the cooler was partially in the sun for a significant period of time as the sun rose. When implemented, it will be necessary to ensure the cooler is shielded from direct sunlight. One possible solution is to mount cloth shields to the structure.

In Guatemala, the team also used their time to collect solar radiation data. Using a handheld solar radiation meter, the team collected data one morning that showed the radiation steadily increasing as the sun moved overhead. The meter was always oriented in the same direction – pointed for maximum solar load at midday. As the team expected, the highest value was approximately 1000 W/m^2. Using Gaisma.com, the team also researched the average solar radiation in Guatemala over a 12-hour day. This amount should be sufficient for use of the refrigerator year round. The data is pictured in Figures 32 and 33.

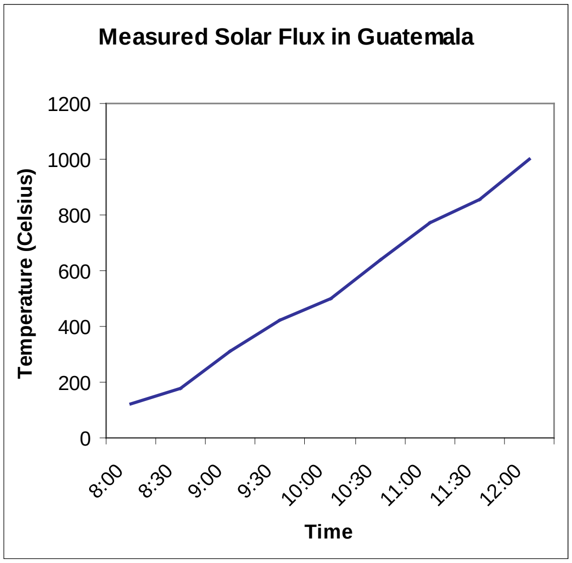


Figure 32. Measured solar flux

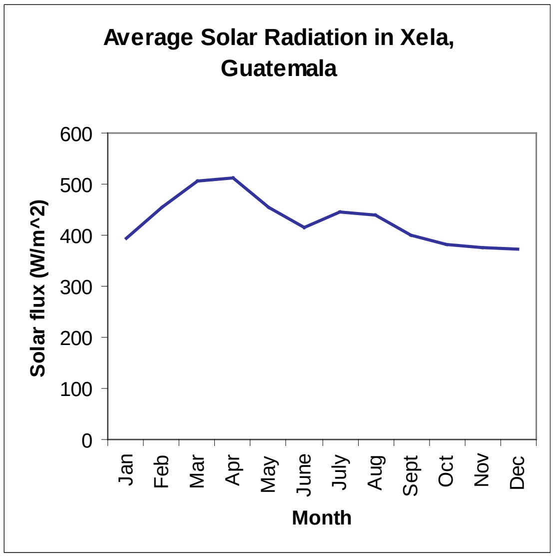


Figure 33. Average solar radiation

9. Economic Analysis

To calculate the sales price of a single activated carbon-ethanol refrigerator, a time value of money analysis was conducted. Since this product will not be sold for profit and the design will be released for public use, a non-profit approach was used. To calculate the unit sales price, the total product cost must first be calculated. The total product cost of the activated carbon-ethanol refrigerator can be divided into two sections:

1. Engineering cost
2. Development cost
    a. Material
    b. Fabrication

9.1 Engineering Cost

Five student engineers worked on this project over a time period of 15 weeks. Each student engineer contributed to the project an average of 10 hours per week with an estimated pay rate of \$100 per hour. Therefore, the total engineering cost was:

$$15\ weeks \times \frac{10\ hours}{week} \times \frac{\$100}{hour} \times 5\ student\ engineers = \$75{,}000$$

9.2 Development Cost

a. Material cost

The bill of materials used to fabricate the final prototype is included in the appendix. The total material cost for a single activated carbon-ethanol refrigerator was \$1,091.08.

b. Fabrication cost

The number of hours it would take for a pair of skilled worker to manufacture and assemble a single activated carbon-ethanol refrigerator was calculated using the numbers reflecting the actual construction experience in Guatemala. It took 2.5 days for 5 workers to build a single unit working 10 hours a day. This equals a construction time of 125 hours. A local welder was utilized in Guatemala and the paid wage was equivalent to \$1.13 per hour. Using this information the total fabrication cost is:

$$\left(125\ hours \times \frac{\$1.13}{hour}\right) = \$141.25$$

Summing the material cost and the fabrication cost, the total development cost is:

Development Cost *= \$1,091.08+ \$141.25 = \$1,232.33*

The total cost of the final prototype is the sum of the engineering cost and the development cost.

Total cost *= \$75,000 + \$1232.33= \$76,232.33*

The next step in determining the unit sales price was to calculate the annual cost. The *development cost* calculated above is a present value, and must be converted into an annual value using the $\left(\frac{A}{P}, i, N\right)$ factor. The interest rate and number of compound periods required to compute this factor were estimated as 4 percent and 5 years, respectively. The $\left(\frac{A}{P}, i, N\right)$ factor was then calculated using the following formula:

$$\left(\frac{A}{P}, i, N\right) = \left(\frac{i(1+i)^N}{(1+i)^N - 1}\right)$$

Where P is the present value, A is the annual value, i is the interest rate, and N is the number of compound periods. Substituting the values for i and N into the equation, the $\left(\frac{A}{P}, i, N\right)$ factor was found to equal *0.225*. Now the present value can be converted to the annual value:

Annual value *= 0.225 x \$1,232.33 = \$277.27*

To determine a justifiable estimation for the number of activated carbon-ethanol refrigerators expected to be manufactured in a year, a skilled labor crew of two men was used. In the interest of starting a cottage industry in a developing country, a crew of two men could be employed full time. To calculate the number of units produced in a year, the number of hours two men would work full time for a year was divided by the time taken to construct one unit. The calculation looks as follows:

$$Units = \left(\frac{2\ men * 40 \frac{hours}{Week} * 52 \frac{Weeks}{Year}}{125\ hours} \right) = 33$$

Multiplying this number by the annual value produces the annual cost:

Annual cost *= $277.27/refrigerator x 33 refrigerators/year = $13,647.81*

Finally, the unit sales price for a vaccine refrigerator was calculated using the following equation with an economic factor of 0.80.

Unit Sales Price = $277.27* + 0.80($1,091.08) + *$141.25 = $1291.38

The calculated unit sales price is higher than the initial project goal of $400; however, this is a preliminary prototype. In the future, many alternatives are predicted to reduce the cost of each unit. These proposed alternatives are:

1. Purchasing materials in bulk – This will reduce the price substantially
2. Working-unit only components – Some of the costly items on the prototype are for testing and concept proof. Production units would not need these parts; therefore, the cost would be greatly reduced.
3. Activated carbon is one of the larger expense items on the budget report. However, by locally producing your own activated carbon that will drastically reduce the unit sales price.
4. Revisions to the materials – Depending on the specifics of the build location and the materials available there, the specifics of the materials can be altered. Materials such as steel for use in the frame components and possibly the condenser and evaporator will reduce the cost. Alternate materials, such as flattened aluminum cans instead of the flashing used in the design, will reduce the cost.
5. Revisions to the design – As more research is done by others it is likely that design revisions will occur. One likely design change would be the elimination of the valves in the system; again, this would reduce cost.

10. Final Recommendation

The student design team has created a design suitable to be put into production. It is recommended that the original plan of publishing manufacturing instruction online be pursued through the industrial sponsor, the Appropriate Technology Design Collaborative. It is crucial that a community be fostered to promote and support the technology as groups utilize the technology and contribute their own research and results in return.

While the team has invested significant time in creating a functioning design, there are still areas for improvement. As the technology is used and tested by more people, there will likely be improvements to the design. The team has identified two areas where significant changes might be made: cost and material selection.

Currently, the team uses about $200 of purchased activated carbon in each refrigerator. Activated charcoal can be made from coconut shells or other organic substances by burning the material and treating it with superheated steam. Developing a method to produce it locally using scrap material would allow the price of the refrigerator to be cut. Additionally, cost reductions can be made using scrap materials or purchasing in bulk.

The prototypes built by the team were primarily made of copper, steel and wood. These materials were selected because of their availability, heat transfer properties, and ease of use in manufacturing. In Guatemala, purchasing these materials locally was not an issue. However, in parts of Africa, materials like copper tubing may be difficult to find and it may be necessary for the design to be adapted with aluminum or steel tubing.

With rigorous research, modeling and testing, the Appropriate Technology Design Collaborative student design team has created a vaccine refrigerator that can be built and used in developing countries. However, there are still improvements that can be made to the system. Just as the final prototypes have been an evolution over three semesters of work, it is expected that the vaccine refrigerator design will continue to evolve to improve on cost, efficiency and accessibility.

11. Acknowledgements

Our design team would like to thank the following individuals for their contributions to the team. Their guidance and assistance have made this project possible and successful.

- The Appropriate Technology Design Collaborative (ATDC) for their continual support in and out of the country
- Appropriate Infrastructure Development Group (AIDG) for providing tools and work space in Guatemala
- Mr. John Barrie for his support and vision
- Mr. Ben Barrie for guiding us through Guatemala
- Dr. Craig Somerton for expert knowledge and guidance
- Dr. Laura Genik for knowledge and guidance in heat transfer principles
- Mr. Roy Bailiff for his machine and material knowledge and building space

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13. Appendix

13.1 Complete Guatemala Materials List

Material	Quantity	Who’s Bringing?
Copper T’s ¾” I.D.	24	MSU
Copper T ¾” reduction to ½”	1	MSU
Copper 90^{o} ¾”	8	MSU
Copper 45^{o} ¾”	3	MSU
8’ Copper tube ¾” I.D.	3	Guatemala
Copper end cap ¾”	1	MSU
Aluminum Flashing 6” x 50’	1	MSU
Hole Punch ¾”	1	MSU
Tin Snips	1	Guatemala
Solder – Lead Free	1 Roll	Guatemala
Solder Flux	1	MSU
Flux Brushes	1-2	MSU
Sand Paper	1 Sheet	Guatemala
Wire Brush	1	Guatemala
Propane Torch	1-2	Guatemala
Pressure Gauge	1	MSU
4’ Steel Tube ¾” I.D.	1	Guatemala
Brazing Rod	2-3 Sticks	Guatemala
Oxyacetylene Torch	1	Guatemala
4’ x 8’ Plywood Sheet 5/8”	1	Guatemala
1” screws	1 box (50pc)	Guatemala
Wood glue	1 bottle	Guatemala
48” x 48” plastic or Plexiglas	1	Guatemala
4’ x 8’ steel 16 or 18 gauge	1	Guatemala
Primer Paint	1	Guatemala
Flat Black Spray Can	1	Guatemala
Welding Equipment	1	Guatemala
Screen door mesh, Smallest hole size	4’ x 4’	Guatemala
Cooler	1	Guatemala
Perforated Steel (make ourselves?)	4’ x 4’	Guatemala
Activated Carbon	17 kg	MSU
Highest proof Alcohol	1 liter	Guatemala
½” cut-off valve	1	MSU
Adapter	1	MSU
Vacuum pump & Power Cord	1	MSU
2” Insulation Pink	4” x 8”	Guatemala
Expanding foam can	1	Guatemala
English tape measure	1	MSU
3” Screws	3 boxes (50pc)	Guatemala

Large hinges	3	MSU
8’ Wood 4” x 4”	4	Guatemala
8” Wood 2” x 4”	8	Guatemala

13.2 Budget Report

Solar Vaccine Refrigerator Budget Report, MSU

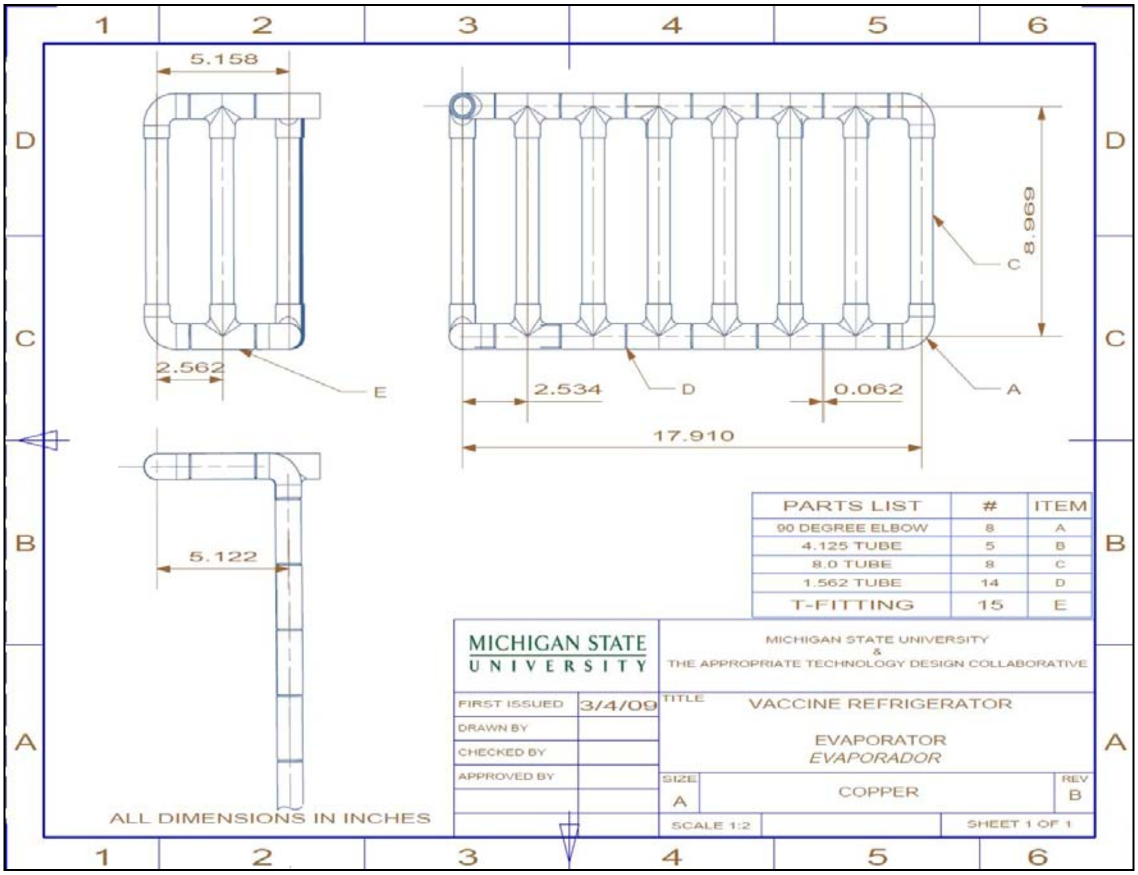
Item	**US Dollars ($)**
Activated Carbon	$ 186.33
Flashing, Plywood, Insulation Plexiglas	$ 74.22
Steel	$ 140.08
Cooler, Thermometers	$ 52.44
Copper pipe, flux, solder, tools fittings	$ 113.18
Lumber	$ 104.19
Pump Oil	$ 30.25
Pressure Gages, Loctite	$ 57.98
Ball Valves, Punch	$ 85.17
Fittings, Soldering supplies	$ 113.59
Spray Paint	$ 11.10
Wood, Copper Fittings	$ 65.49
Plexiglas, wood and framing	$ 45.06
Ethanol	$ 12.00
TOTAL	$ 1,091.08

Solar Vaccine Refrigerator Budget Report, Guatemala

Item	**Cost (Q)**	**US Dollars ($)**
Activated Carbon	-	$ 186.33
Copper Tube Fittings	-	$ 130.20
Electrical Connector	4.5	$ 0.56
Black Spray Paint	40	$ 4.98
Cooler	385	$ 47.89
Wood Glue	32.5	$ 4.04
Copper Tube	700	$ 87.07
Steel Sheet	800	$ 99.50
Plywood, etc	462.97	$ 57.58
Paint Primer	54.99	$ 6.84
Sheet Metal	893	$ 111.07
Tubo Tip	550	$ 68.41
Lamina	373	$ 46.39
Screws	45	$ 5.60
Fittings	44.95	$ 5.59
Central Minera	76	$ 9.45
plumbing fixtures	163.96	$ 20.39
welder	141	$ 17.54
Grinder Disks	64	$ 7.96
TOTAL		$ 917.39

13.3 Engineering Drawings

The following images show the assembly drawings with the list below showing the parts that make up the assembly. The part files are not shown to conserve space.



Evaporator Assembly

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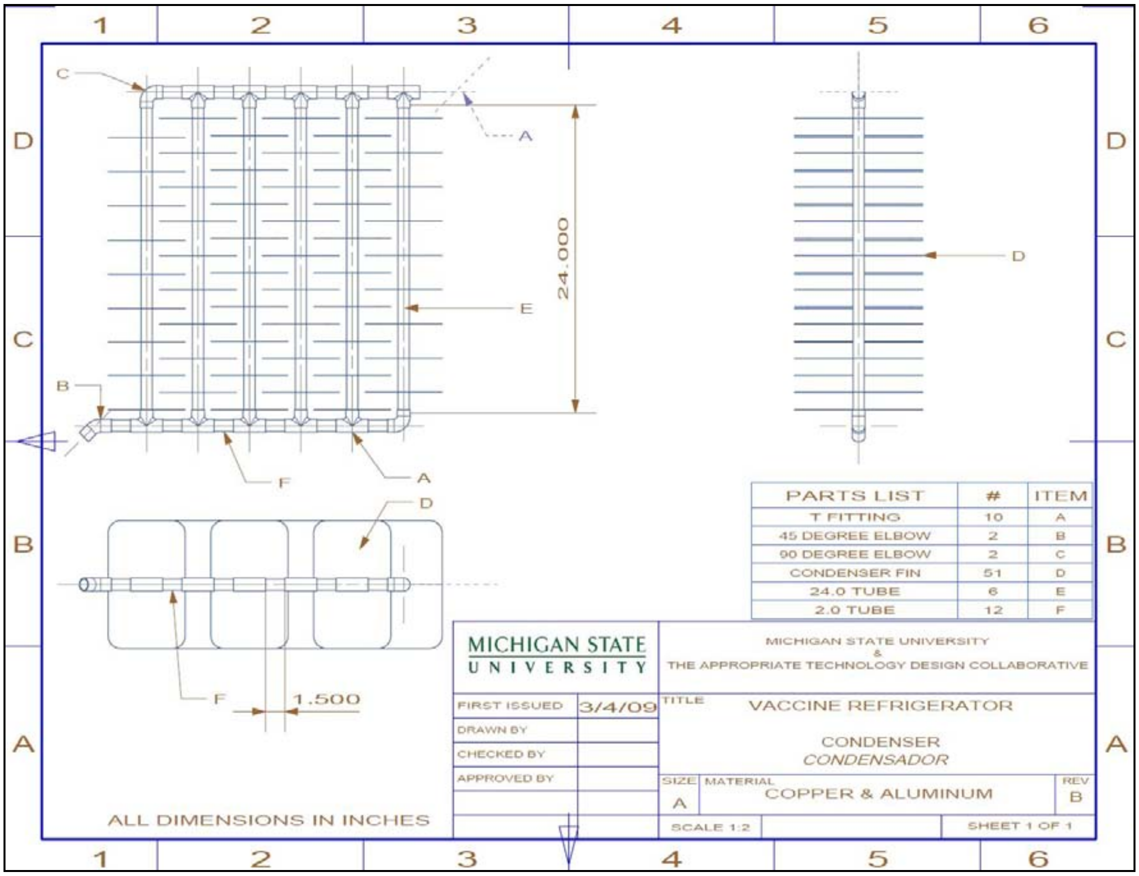
- 4.125_tube.prt
- 8.0_tube.prt
- 1.562_tube.prt
- T_fitting.prt



PARTS LIST	#	ITEM
T FITTING	10	A
45 DEGREE ELBOW	2	B
90 DEGREE ELBOW	2	C
CONDENSER FIN	51	D
24.0 TUBE	6	E
2.0 TUBE	12	F

MICHIGAN STATE UNIVERSITY & THE APPROPRIATE TECHNOLOGY DESIGN COLLABORATIVE

FIRST ISSUED	3/4/09
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CHECKED BY	
APPROVED BY	

TITLE VACCINE REFRIGERATOR

CONDENSER

CONDENSADOR

SIZE A

MATERIAL COPPER & ALUMINUM

REV B

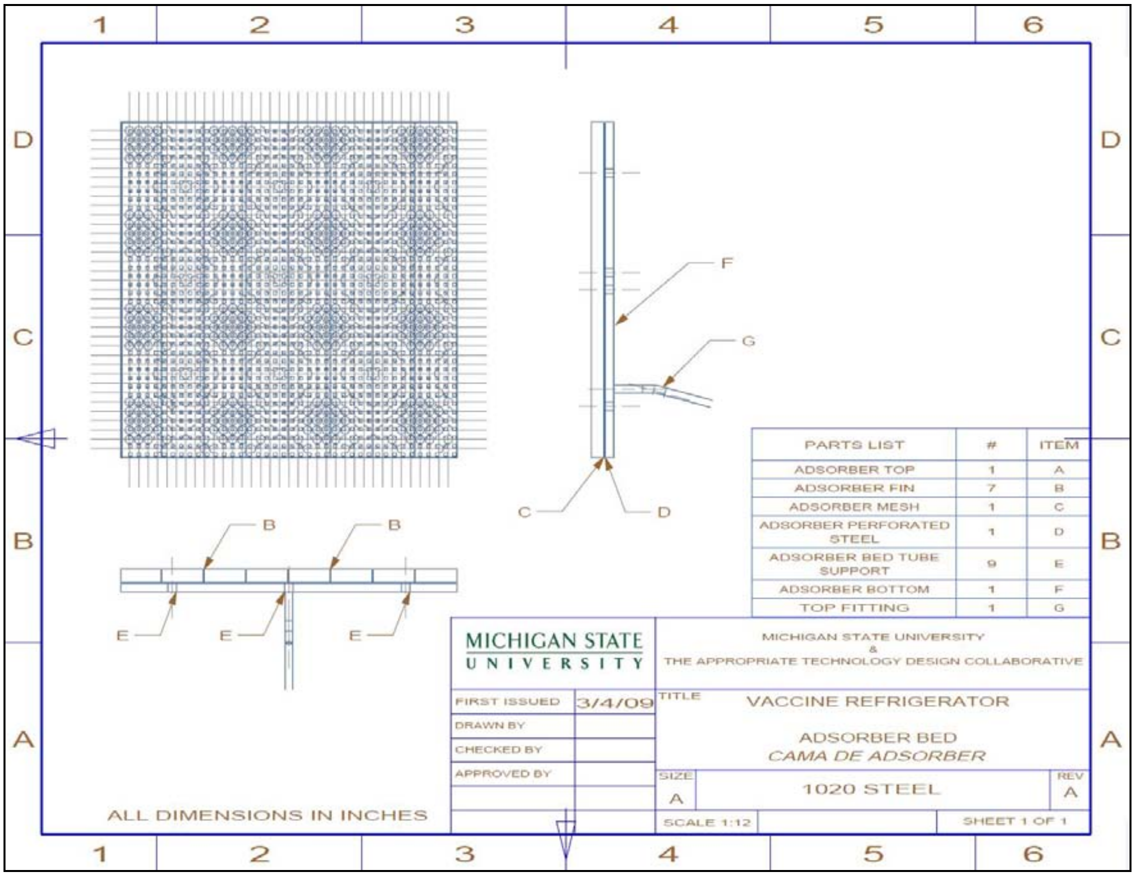
SCALE 1:2

SHEET 1 OF 1

ALL DIMENSIONS IN INCHES

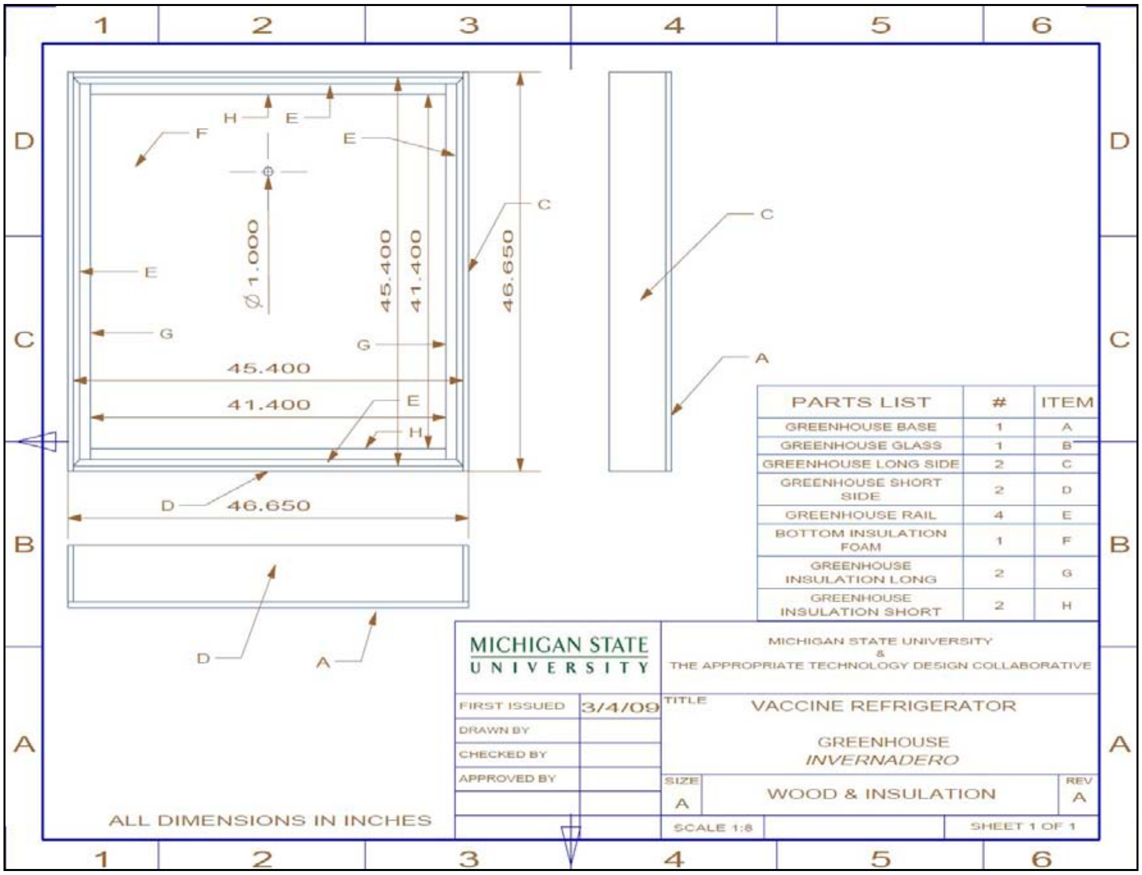
Condenser Assembly

- T_fitting.prt
- 45_degree_elbow.prt
- 90_degree_elbow.prt
- Condenser_fin.prt
- 24.0_tube.prt
- 2.0_tube.prt



Adsorber Bed Assembly

- Adsorber_top.prt
- Adsorber_fin.prt
- Adsorber_mesh.prt
- Adsorber_perforated_steel.prt
- Adsorber_bed_tube_support.prt
- Adsorber_bottom.prt
- Top_fitting.prt



PARTS LIST	#	ITEM
GREENHOUSE BASE	1	A
GREENHOUSE GLASS	1	B
GREENHOUSE LONG SIDE	2	C
GREENHOUSE SHORT SIDE	2	D
GREENHOUSE RAIL	4	E
BOTTOM INSULATION FOAM	1	F
GREENHOUSE INSULATION LONG	2	G
GREENHOUSE INSULATION SHORT	2	H

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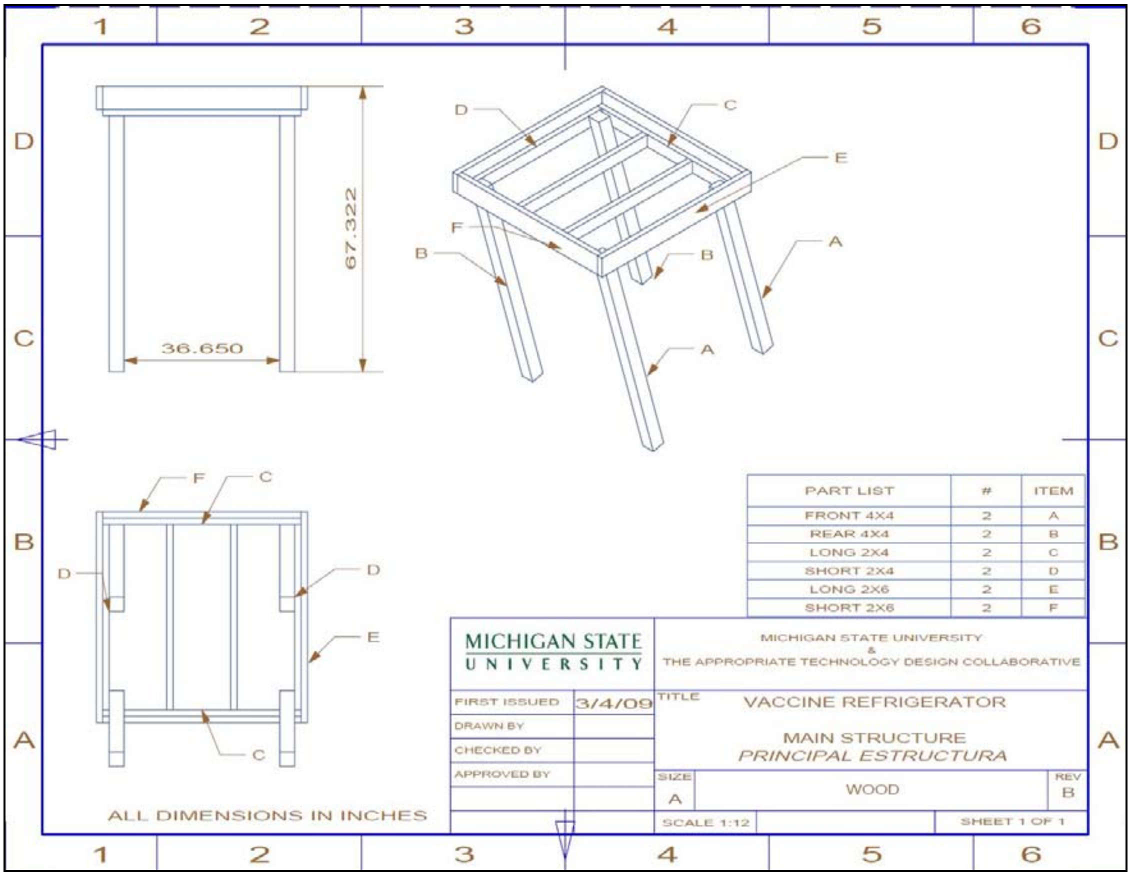
THE APPROPRIATE TECHNOLOGY DESIGN COLLABORATIVE

FIRST ISSUED	3/4/09	TITLE	VACCINE REFRIGERATOR GREENHOUSE *INVERNADERO*
DRAWN BY			
CHECKED BY			
APPROVED BY		SIZE A	WOOD & INSULATION
		SCALE 1:8	SHEET 1 OF 1

REV A

Greenhouse Assembly

- Greenhouse_base.prt
- Greenhouse_glass.prt
- Greenhouse_long_side.prt
- Greenhouse_short_side.prt
- Greenhouse_rail.prt
- Bottom_insulation_foam.prt
- Greenhouse_insulation_long.prt
- Greenhouse_insulation_short.prt



PART LIST	#	ITEM
FRONT 4X4	2	A
REAR 4X4	2	B
LONG 2X4	2	C
SHORT 2X4	2	D
LONG 2X6	2	E
SHORT 2X6	2	F

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TITLE VACCINE REFRIGERATOR
MAIN STRUCTURE
PRINCIPAL ESTRUCTURA
SIZE A
WOOD
REV B
SCALE 1:12
SHEET 1 OF 1

Main Structure Assembly

- Front_4x4.prt
- Rear_4x4.prt
- Long_2x4.prt
- Short_2x4.prt
- Long_2x6.prt
- Short_2x6.prt

Additional Drawings

- Pipe_connection 1.prt
- Pipe_connection 2.prt
- Pipe_connection 3.prt
- Structure_base_board.prt
- Structure_base_front_back.prt
- Structure_base_middle.prt
- Structure_base_middle_sides.prt
- Structure_base_sides.prt
- 10.0_tube.prt