AC 2010-555: AN APPROPRIATE TECHNOLOGY PROJECT: A SOLAR POWERED VACCINE REFRIGERATOR

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Introduction

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° C for vaccine preservation, these regions need reliable long-term refrigeration where electricity is not available.

To address this problem, a capstone design team developed an affordable, robust refrigerator that operates with energy from 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 have been distributed for free on the Internet through the project's partner, the Appropriate Technology Design Collaborative (ATDC. 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.

This paper documents the design and development process, including a trip to Guatemala to build and test the refrigerator. Feedback from the student team on their learning experiences is also shared. A guide is provided for those faculty who would like to undertake the supervision of an appropriate technology design project.

Background

Recently the term Appropriate Technology has become prevalent in the efforts that the developed world is taking to assist developing countries. The term applies to technology for energy, water, and health that depart from the conventional western technology and is focused on the appropriate use of a developing country's resources, so as to not disrupt its culture and environment. Further, the technology should be simple and inexpensive to employ and could lead to the development of cottage industries. For most of us that have been involved in bringing alternative energy technologies to the developing world the concept of appropriate technology brings a paradigm shift. No longer should we think about coming into a village installing a $100,000 solar photovoltaic pumping system and then walk away very pleased with ourselves. In addition to maintenance and upkeep issues, for the one village that is helped there are millions of villages left to struggle with their water supply.

Three years ago the Appropriate Technology Design Collaborative (ATDC) approached the design program at Michigan State University for technical assistance in the development of appropriate technology products. ATDC 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 (NGO) 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.

With the emphasis of Michigan State University on study abroad and the need to address EAC/ABET outcome h (the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context), a partnership with ATDC seemed ideal.

Organization of the Design Project

As a project in the capstone design course, students would have just one semester to work on the project. This was a problem, since it was perceived that the magnitude of this project would not allow its completion in a semester. The decision was made to run the project over two semesters with two senior design teams being assigned, one for the fall semester and one for the spring semester. The fall semester team would focus on the conceptual design of the refrigerator, while the spring team would design the features of the refrigerator and construct operational prototypes. From the beginning, it was planned for the teams to travel to Tanzania during the spring semester to implement the design. Because of ATDC's contacts, the decision was later made to do the build and test in Guatemala. The team for the fall semester was selected via the standard procedure for the capstone course. Students in the class self-select to form teams and then submit a proposal indicating their project preferences. The author (who also serves as the Design Program coordinator) reviewed the proposals that had the vaccine refrigerator project highly rated and selected the team. For the spring semester team, a somewhat different process was used, in that the trip to Guatemala had become a certainty with students carrying little burden of the cost. Near the end of the fall semester, the spring semester class was emailed with information about the project and a request to submit an individual application. The application is shown in Appendix A. Only 9 of the 62 students in the class applied. A group of four faculty members, all significantly engaged in the undergraduate program, reviewed the applications and selected the five member team using the following criteria:

a. Student's reason for participating on this project.
b. Student's skills and talents that he/she brings to the project.
c. Student's academic standing.
d. Impact on student's career and life.

The two teams are given below:

Fall Semester Team
Brian Kunkel, William Hurles, and Bryce Thelen
Spring Semester Team
Nabeel Aslam, Kevin McPhail, Ryan McPhee, Brent Rowland, and Eric Tingwall

The author took on the role of faculty advisor for both teams.

<u>The Design</u>
Following the traditional design process, the first step was to develop a concise problem statement. After significant discussion with ATDC, the following statement was developed:

> The goal of this project is to design and manufacture a refrigeration system capable of maintaining the temperature range of 2-8˚C, ideal for vaccine storage, that can be built, maintained, and operated using locally available technology and resources in these locations that will extend the lifespan of life saving vaccines.

Design parameters were identified and some of the more important ones are given below.

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.

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.

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.

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.

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.

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

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.

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.

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.

In the evaluation of the design parameters, the teams identified function and performance, delivery date, operating costs, and reliability as having the greatest importance.

Using the techniques of brainstorming, product research, and analogy many conceptual designs were developed. The team recognized that there were three main aspects to any refrigeration system: refrigeration process, refrigerant, energy source. The team developed design concepts for each aspect and then mixed and matched to determine a refrigeration system. These conceptual designs are given below.

<u>Refrigeration Process</u>
Vapor Compression
Absorption
Adsorption

Refrigerant
R-134a
Zeolite and Water
Silica Gel and Water
Activated Carbon and Methanol
Activated Carbon and Ammonia
Activated Carbon and Ethanol

Energy Source
Human or Livestock
Solar Photoelectric
Solar Thermal
Wind Turbine
Diesel of Fuel Oil Generator
Biomass Combustion

After a standard decision evaluation, the team selected a refrigeration system that consisted of an adsorption process using activated carbon and ethanol powered by a thermal solar collector.

As with most refrigeration cycles, the adsorption cycle operates between a high temperature heat reservoir and a low temperature heat reservoir and requires an energy input. The low temperature heat reservoir is the cold apace that will contain the vaccines. Interacting with the cold space will be the evaporator, in which the working fluid of the system will boil at a low temperature. The boiling temperature is controlled by the system pressure. The high temperature heat reservoir is the ambient environment and a condenser interacts with the ambient, in which the working fluid of the system condenses and thus rejects the heat absorbed in the cold space. The energy input in a refrigeration system typically maintains the pressure difference between the evaporator and the condenser, so that the working fluid can boil at a low temperature in the cold space, but condenses at a high temperature in its interaction with the high temperature heat reservoir. For a vapor compression refrigeration system, the energy input is typically electricity that powers a compressor, which maintains the pressure difference. For the adsorption system of the current project, the energy input is solar energy, which is used to drive working fluid from the activated carbon to raise the system pressure. The capacity of the activated carbon to adsorb the working fluid is directly dependent on the temperature of the activated carbon. The higher the temperature the less working fluid it can hold.

It may be useful to walk through a typical cycle for the ethanol - activated carbon adsorption refrigeration cycle. This is a 24 hour cycle. The evaporator operates during the night time hours, while the condenser operates during the daytime hours. Beginning sometime after sunset, the ethanol liquid in the evaporator boils and the ethanol vapor begins to rise up through the system. It passes through the condenser, but with no condensation since the ethanol phase change temperature is still well below the ambient temperature. The vapor continues to rise to the top of the system where it begins to flow through the activated carbon particle bed. The bed's temperature is fairly low so that it begins to adsorb the ethanol vapor. If designed correctly, the adsorption rate is equal to the evaporation rate in the cold space, so that the system pressure remains constant. As we approach sunrise, most of the ethanol liquid in the evaporator has boiled off. Once the sun rises and solar energy begins to enter the carbon bed, its temperature rises, its capacity to hold ethanol decreases, and ethan0l vapor begins to desorb from the carbon bed. As desorption continues, the pressure in the system rises, until the phase change temperature reaches above the ambient temperature, at which time the condenser begins to operate. Liquid ethanol then runs to the evaporator at the bottom of the system. This desorption continues through out the day, until sunset, at which time the carbon bed begins to cool. At this point ethanol vapor will once again be adsorbed into the carbon bed and the pressure will fall to the level needed for evaporator operation. Boiling will begin again in the evaporator and the cycle repeats.

The refrigeration system identified by the team was recognized to have six components: cold space, evaporator, condenser, activated carbon bed, solar collector, and supporting structure. The spring semester team carried out the design of these components that included computational modeling associated with ethanol properties, solar collector operation, heat exchanger performance, and cooling load determination. The team decided to build a system that uses a standard plastic ice chest for the cold space, a tubular copper evaporator, tubular copper condenser with fins, a steel container for the activated carbon bed, a steel flat plate solar collector, and a wood frame. These elements provide excellent heat transfer and structural 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.

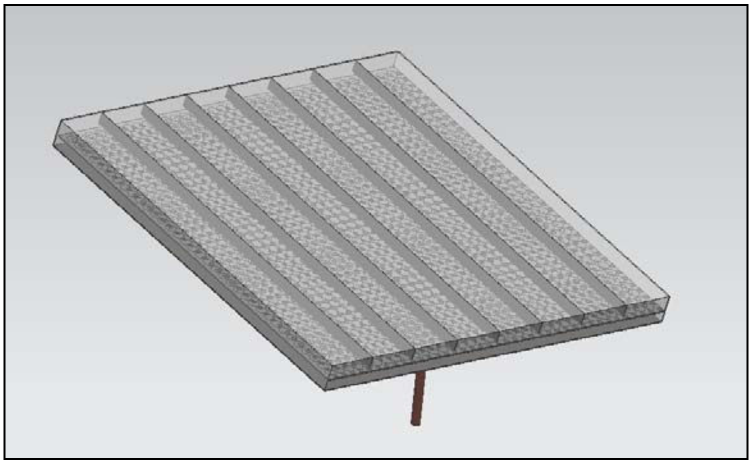


Figure 1. Solar collector design

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.

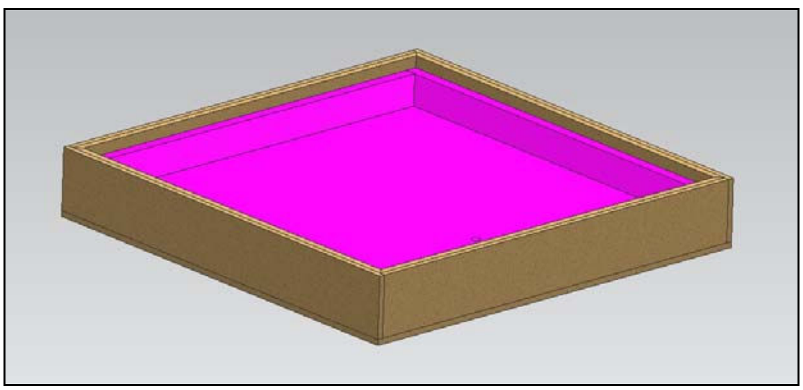


Figure 2. Greenhouse design

The structure for the entire refrigerator is shown in Figure 3. 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 3. 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.

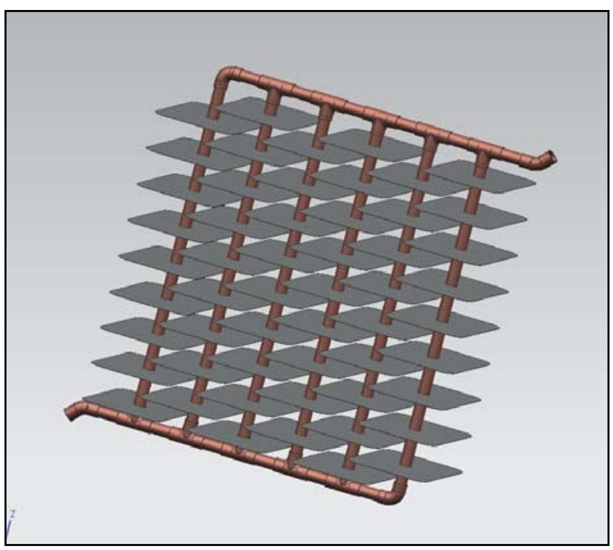


Figure 4. Condenser design

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 condenses.

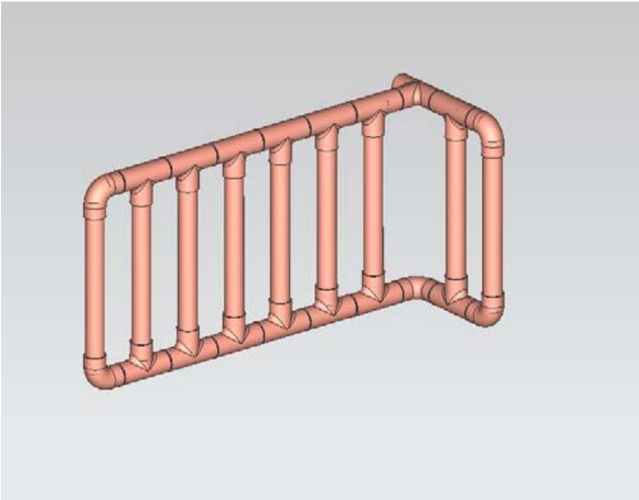


Figure 5. Evaporator design

The complete design of the system is shown in Figure 6. 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.

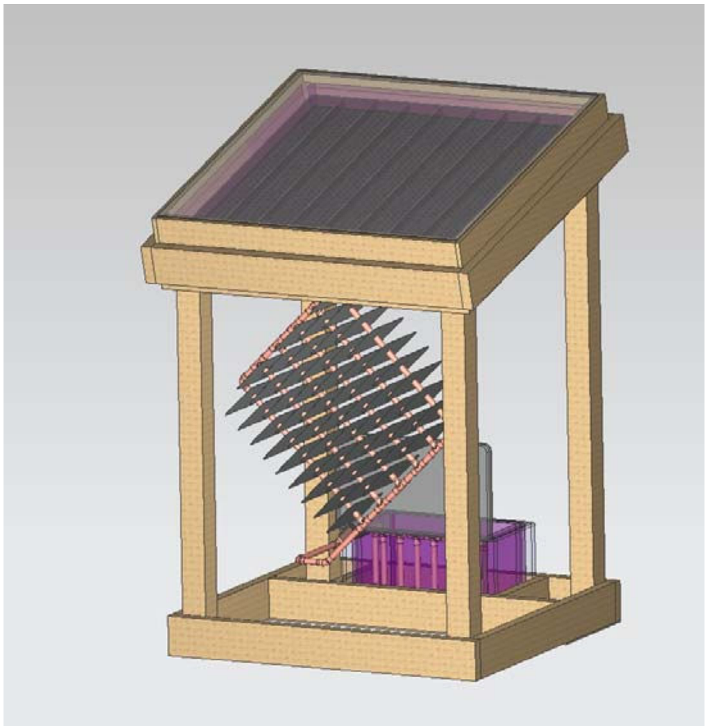


Figure 6. Complete refrigerator design

The team built two refrigerators, one in Guatemala and one on campus following the Guatemala trip and a picture of the final refrigeration is shown in Fig. 7.

Figure 7. Completed assembly of adsorption refrigerator.

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 8 shows the recorded temperatures of the cooler, solar collector and surroundings.

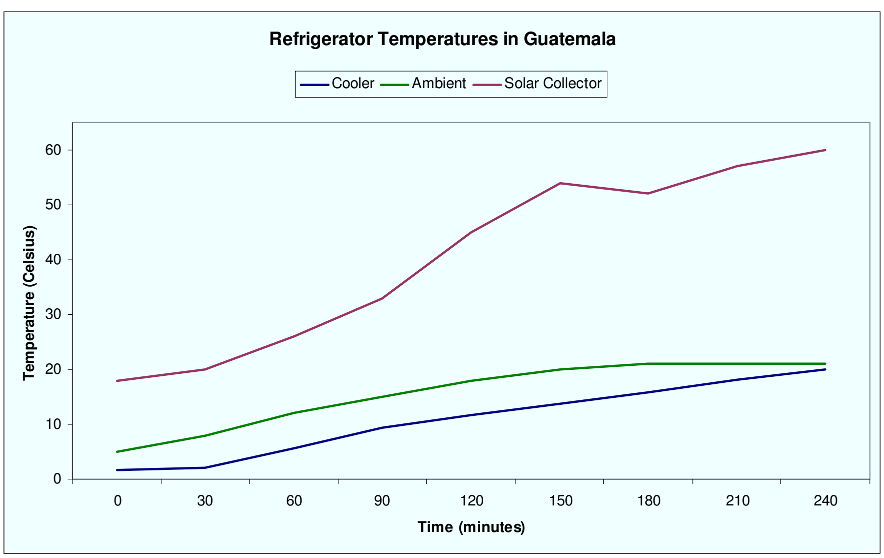
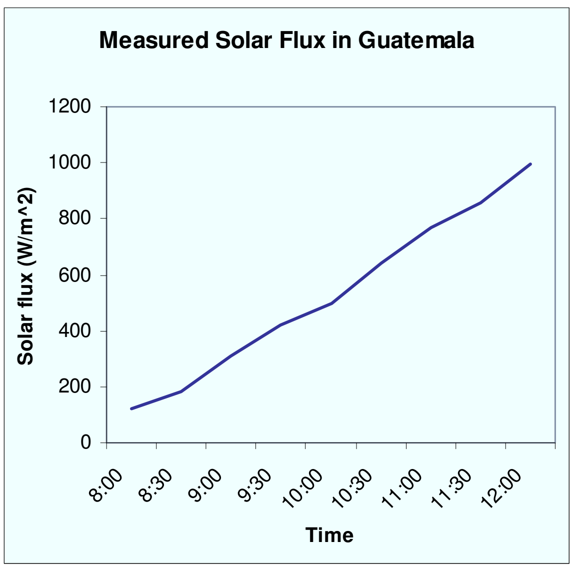


Figure 8. Guatemala testing data.

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 9 and 10.



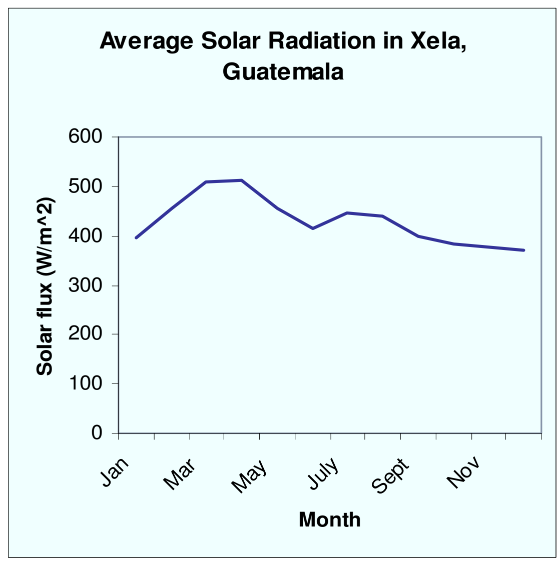


Figure 9. Measured solar flux Figure 10. Average solar radiation

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 indoor testing was conducted. 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 (lights turned off), three hours of solar heating (lights turned on), and another three hours of cooling (lights turned off).

Figure 11 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.

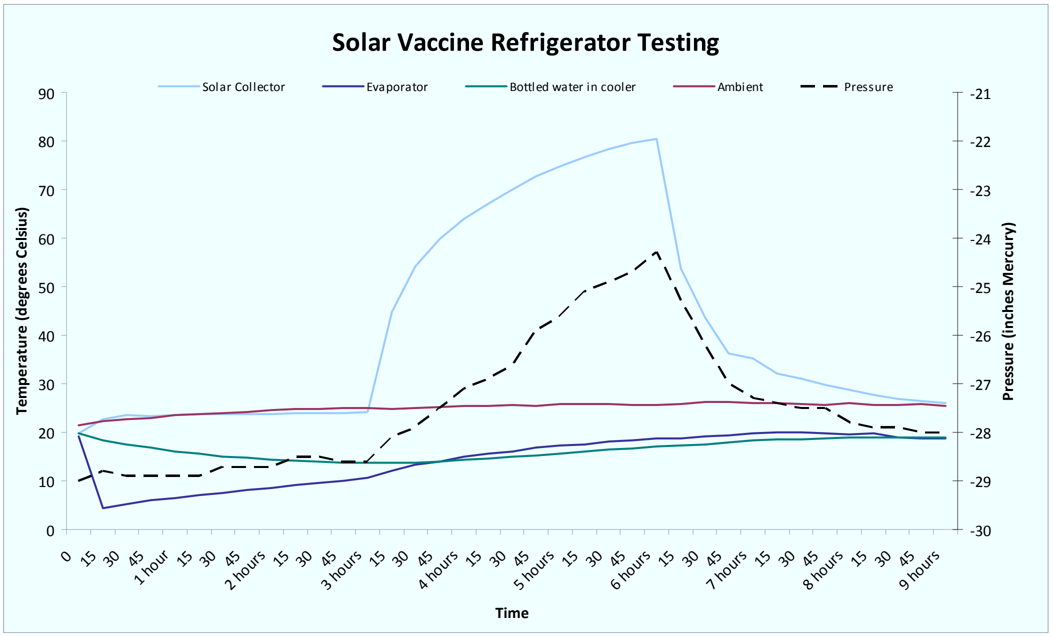


Figure 11. Nine hour refrigerator test temperatures.

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 11 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 12.

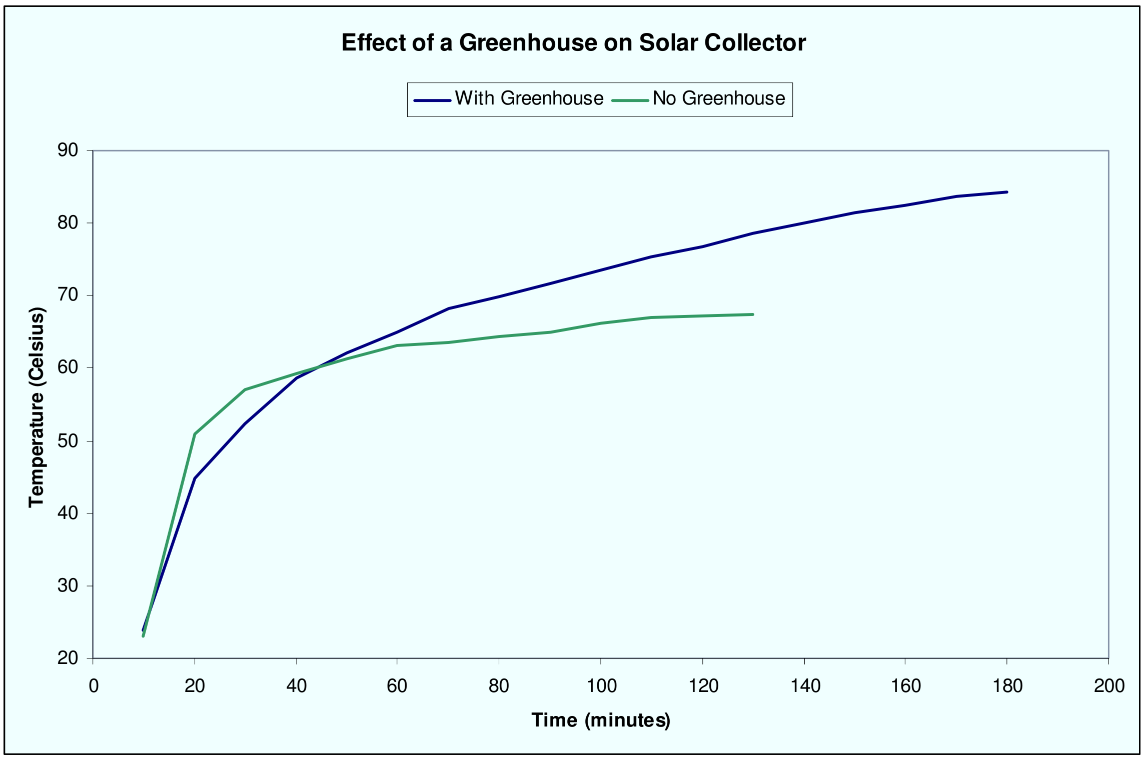


Figure 12. Greenhouse testing results.

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.

<u>Travel to Guatemala</u>

An important part of this project was a trip to Guatemala where the team built and tested a prototype refrigerator. This was an essential experience for such a project whose machine is intended for use in the developing world. The design team must understand the culture of the end user, as well as materials and manufacturing methods available in the country where the machine will be used.

With design drawings and manufacturing directions in hand, the trip began with a flight from Detroit to Guatemala City. After arriving in Guatemala City, the team traveled to Quetzaltenango (known commonly as Xela). It had been arranged that the team would use the workshop of the Appropriate Infrastructure Development Group (AIDG). The workshop was not what the team had expected. The team had expected something like the Engineering Building machine shop, but instead found something more like a home garage shop. That is, no machine tools, just hand tools. A welding system had to be borrowed from a local trade school and had to be transported via taxi, since the AIDG truck was out of service.

Figure 13 Appropriate Infrastructure Development Group Workshop

The first task of the team was to buy the materials required for the build. These included sheet metal, copper tubing and fittings, paint, various screws, bolts and nuts, and an ice chest to be used for the cold space of the refrigerator. The purchasing was quite an experience as the team went from shop to shop buying materials and supplies, with Ben Barrie of ATC translating for the team and the author making the payments. To transport some materials a local driver would be hired.

With materials in hand, the team began making their refrigerator. With limited machine tools available, the team had to modify its manufacturing process. For example, to cut the sheet metal the team had to use a circular saw. What took an hour in the Engineering Building machine shop, took 16 hours at the AIDG workshop. Since the AIDG workshop was only available during the day, the team even resorted to cutting and assembling copper tubing for the condenser and evaporator of the refrigerator on the front steps of its hostel in the evening.

Figure 14 Using a Circular Saw to Cut Sheet Metal

At the end of four days, the team had completed the refrigerator, charged it with the ethanol, and left it over night to complete its cooling process. Early the next morning, about 6 am, two team members could wait no longer and took the 2 mile walk to the workshop to find that the refrigerator had cooled the ice chest down to 1.3°C. The team was elated with its success.

With its time at the ADIG workshop completed, the team had the extraordinary opportunity to visit the Mayan ruins at Tikal. For those of you who have seen Star Wars, this was the locale used for the rebel basis in Episode IV. It was truly spectacular to see the ruins of an enormous city that existed from 200 to 900 AD. It covers about 6 square miles, with over 3000 structures, and was estimated to be the home to 90,000 people. This experience gave the team unique insight into Guatemalan history and culture.

Acknowledgements
The author would like to thank John and Ben Barrie of the Appropriate Technology Design Collaborative for her contributions to this endeavor. Most of the technical aspects of this paper were drawn from the final reports of the two

student teams. Finally, the financial assistance of the Somerton Family Trust was essential to the success of the trip to Guatemala.

Appendix A. Application Form

Guatemalan Vaccine Refrigerator Application

Student Name: ____ PID: ________________

Email: ____ Phone: _____________

Why do you want to participate on this project?

What talents and experiences would you bring to the project?

How do you see this project affecting your life and career?

What experiences have you had “roughing it”, that is, encountering difficult living conditions?

Please list the names of other students you would like to work with.