Design and Manufacture of Low Cost Vaccine Cooler

by

Cynthia D Walker

Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of
Bachelor of Science in Mechanical Engineering

at the
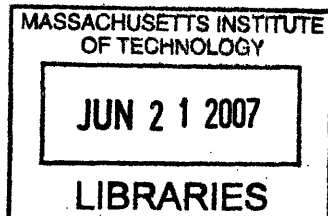
Massachusetts Institute of Technology

June 2007

Signature of Author..
Department of Mechanical Engineering
May 11, 2007

Certified by...
John G Brisson II
Associate Professor of Mechanical Engineering
Thesis Supervisor

Accepted by..
John H. Lienhard V
Professor of Mechanical Engineering
Chairman, Undergraduate Thesis Committee

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ABSTRACT

Vaccines are very sensitive to temperature, needing to be held between 2 and 8°C to maintain potency. In developing countries where electricity and fuel supplies are unreliable, many vaccines are ruined due to thermal exposure. These are also the locations where vaccines are needed the most, yet often many of the vaccines given are ineffectve. Long holdover vaccine coolers are designed to maintain a proper internal temperature during long periods of power loss. The most prevalent technology is the ice-lined cooler, but in the field these often have problem with freezing the vaccines. A vaccine cooler was designed that modifies the ice-jacket idea by separating the ice compartment and the vaccine chamber, connecting them through a heat transfer regulating device. The objective of this research is to design and prototype the heat transfer regulating device. After several design iterations a cooling loop filled with R-134a made of 1/8 piping, a 0.055 in ID capillary, and a Clippard normally-closed valve was combined with a modified car thermostat, using peanut oil as its working fluid, to create a thermosyphon type heat transfer device with a safety shutoff to prevent freezing. The prototype was manufactured and tested. It was found that with the proper amount of working fluid, it is possible to run the cooling loop at 4°C and pull heat from the vaccine chamber side to the ice. The peanut oil thermostat was tested and was found to open at a slightly lower temperature than expected, 2.5°C, but still within range. These results indicate that the concept is viable and should be tested in the vaccine cooler.

Thesis Supervisor: John G Brisson II
Title: Associate Professor of Mechanical Engineering

ACKNOWLEDGEMENTS

I would like to thank my advisor John Brisson II for his advice and support throughout the project. Without all the long meetings that helped me along the design process, the loop never would have been made.

I also need to thank Mr. Michael Demaree for all his help in fabricating the prototype and putting up with me during the two weeks I spend everyday in the basement.

I also thank my family and fiancé for all of their encouragement over the last four years. Without their unwavering emotional support I would not have been able to make it through my undergraduate career, nor complete this thesis.

Finally, I must thank the Edgerton center for their financial assistance, without which none of the materials could have been purchased.

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Chapter 1

Introduction

According to the World Health Organization, in 2002 an estimated 2.1 million people died of diseases that could be prevented by immunization [1]. The majority of these individuals live in developing countries where the procurement of effective vaccines is difficult due to problems within the system of transportation and storage. As a MIT 2.006 Thermal-Fluids Engineering class design project, four students developed a novel vaccine cooler design to keep vaccines within the necessary 2-8°C in regions where the power supply is intermittent. This paper describes the initial project design, the refinements made to the design of the most critical module and the results of prototyping.

While all vaccines slowly lose their potency, exposure to temperatures outside of 2-8°C causes irreversible damage and a dramatic drop in effectiveness [2]. This specific condition makes the transportation and storage of vaccines difficult, especially in developing countries where electricity is irregular and travel is hard. Both the warming and freezing of vaccines cause damage, yet most coolers focus on keeping the vaccines cold and so have problems with freezing.

In order to be a viable solution to the problems plaguing vaccine storage in developing nations, vaccine coolers must always maintain an internal temperature of 2-8°C. Power is often intermittent, so coolers must have a long holdover time. The goal for the design of the new cooler was that the internal temperature would stay within the proper range for over 24 hours without power in an environment where the temperature ranges from 10 to 45°C. The cooler also needs to be comparatively priced or cheaper than existing coolers as well as easily maintained.

1.1 The Cold Chain

BioFarma Transport Province Transport District Transport Health Center Midwife / Clinician / Doctor

Figure 1.1: Cartoon depicting the different stages of the cold chain for developing countries.[1]
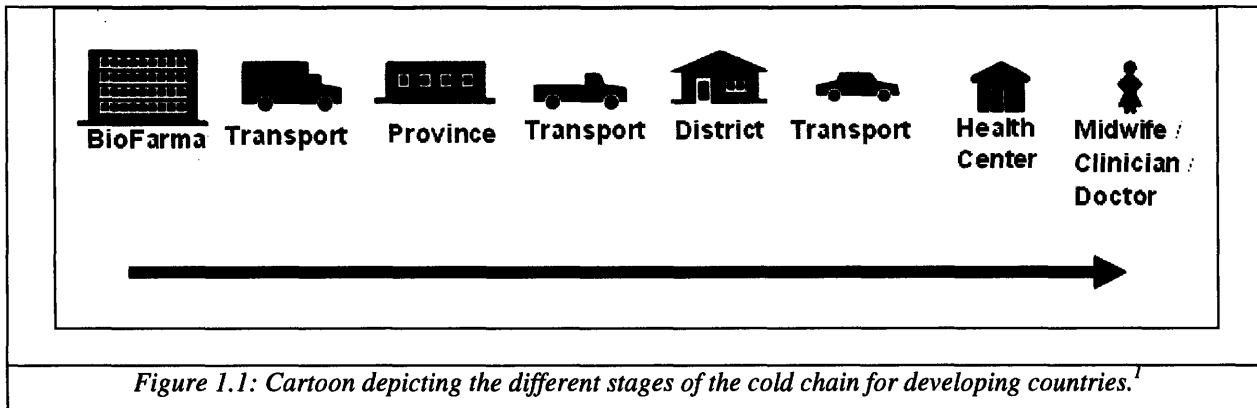
The system of transportation and storage of vaccines from manufacturing to end user is called the cold chain. In developing countries, the cold chain usually has many stages as shown in Figure 1.1. The last few stages of the cold chain often lack reliable power and so holdover technology is used. The holdover methods used to keep vaccines from warming often cause them to freeze. For this reason many vaccines arrive at their final destination in poor condition.
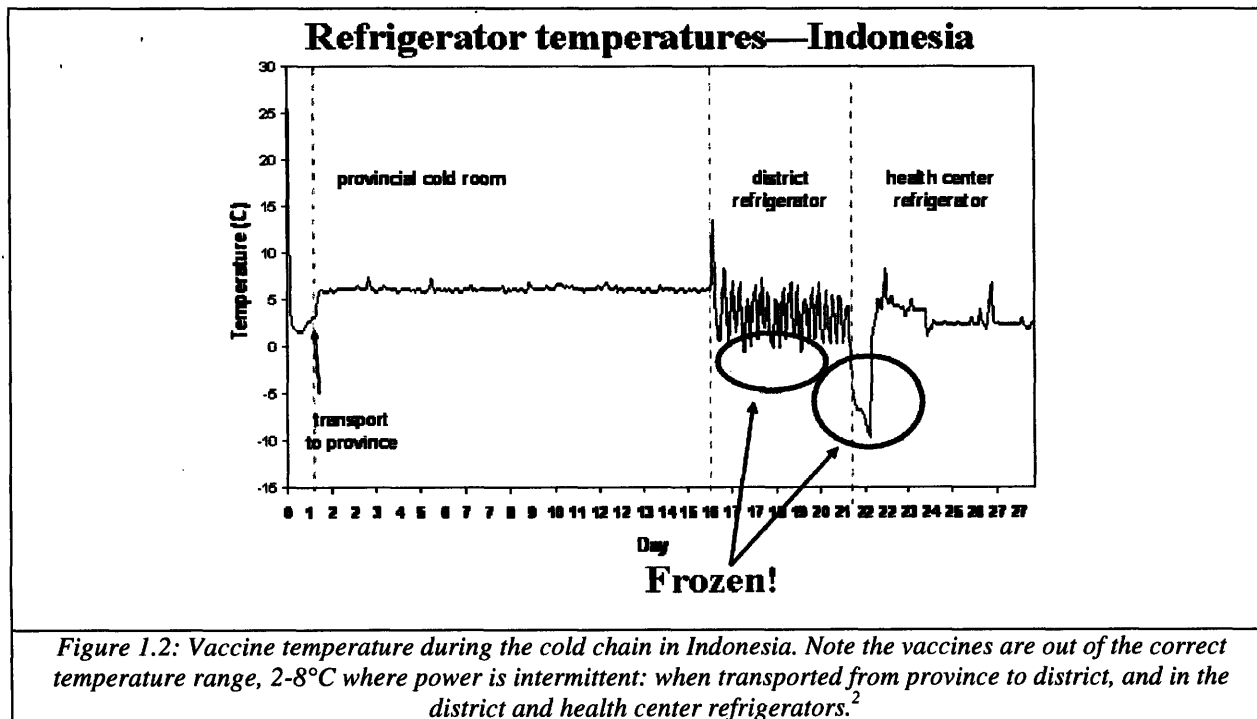
Refrigerator temperatures—Indonesia

provincial cold room   district refrigerator   health center refrigerator

transport to province

Frozen!

Figure 1.2: Vaccine temperature during the cold chain in Indonesia. Note the vaccines are out of the correct temperature range, 2-8°C where power is intermittent: when transported from province to district, and in the district and health center refrigerators.[2]

As shown in Figure 1.2, the cold chain problem areas occur in locations where conditions are far from ideal: transportation in the province, the district refrigerator and the health center refrigerator. These places often have intermittent electricity, thus keeping the vaccines cool is done using ice packs. There is no control on how much heat is lost to the ice packs, so the temperature may easily drop below the vaccine freezing point. Another factor that causes the refrigerators to run at inaccurate temperatures is equipment damage or failure due to the dirty environments in which they are located. There are also a limited number of qualified technicians so repairing coolers is most often left to self-taught individuals with limited resources. Repairs are often haphazard and imperfect so coolers run poorly. All these factors are rough on vaccine coolers so there is a need for a reliable, easily maintained vaccine cooler that can withstand long periods without electricity while still maintaining a reasonable internal temperature.

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[2] Figure 1.2 reproduced with permission from PATH. Authored by: Carib Nelson. Source: Preventing-Freezing-in-Cold-Chain-Apr2003.ppt - <http://www.path.org/files/TS_cc_preventing.pdf>

Chapter 2

Background

2.1 Existing Technology

When designing a vaccine refrigeration system there are five large design criteria that dictate how the cooler works. These include the refrigeration type and power supply which are often dependent on each other. The other three main considerations are the temperature control device, insulation type and holdover capacity method.

2.1.1 Refrigeration Type

The refrigeration type refers to the process by which cooling is achieved. The three main types of refrigeration in vaccine coolers are compression, absorption, and Stirling.

Compression refrigeration is the process used by normal American home refrigerators. It consists of a compressor and two heat exchangers, one in the environment and one in the cooler area. By evaporating a working fluid in the cooler area and condensing the fluid in the atmospheric exchanger, heat is transferred from the cooler box to the environment. Compression refrigeration is relatively inexpensive compared to other refrigeration techniques and whenever there is more than 8 hours of electricity a day, compression refrigerators are preferred because the thermostats used with them ensure correct temperatures [3].

Absorption refrigeration still uses two heat exchangers, but instead of a compressor, heat is used to run a generator [4]. Absorption refrigerators do not perform as well as compression refrigerators and although they have no moving parts, they require constant maintenance to ensure successful operation [3]. The need for maintenance, the lower efficiency, and the added cost of the fuel are all disadvantages of absorption refrigeration. Despite the disadvantages,

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absorption refrigeration is often needed in locations where there is no connection to the electrical grid or the fuel supply is more reliable than the electricity supply.

The third refrigeration technique is Stirling. The application of the Stirling cooling system as a vaccine cooler is relatively new so there are only a few out in production. One of these is the Twinbird "Free Piston Stirling Cooler FPSC-TB40." The cooler uses environmentally friendly helium as its working fluid and can cool down to -23.3°C [5]. The problem with current Stirling coolers is that their cost is prohibitively high for the developing countries where vaccine coolers are needed the most.

2.1.2 Power Supply

The power supply is often related to the type of refrigeration used. Compression refrigeration and current Stirling technology requires electricity to run the compressor while absorption requires fuel, often kerosene. The advantages of using electricity are that there are reliable electrically powered coolers already designed for developed nations and electricity is a relatively cheap power. The advantage of using kerosene is that it is a fuel that is already used in most developing countries for other things that require power, such as lighting and cooking. The downsides of kerosene are that there are major health issues caused by inhaling the fumes and the fuel is more expensive than electricity. Simple grid electricity and kerosene are the most common methods of powering vaccine coolers; however the areas where vaccines are needed most are those that have the least stable electrical and fuel supply. One power source that is not in limited is the sun.

Solar power systems are becoming more prevalent in developing countries for both refrigeration systems and as an alternative power supply to kerosene [3].

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Vaccine Refrigerator Powered by a Photovoltaic System

Figure 2.1: Solar refrigeration system components.[3]
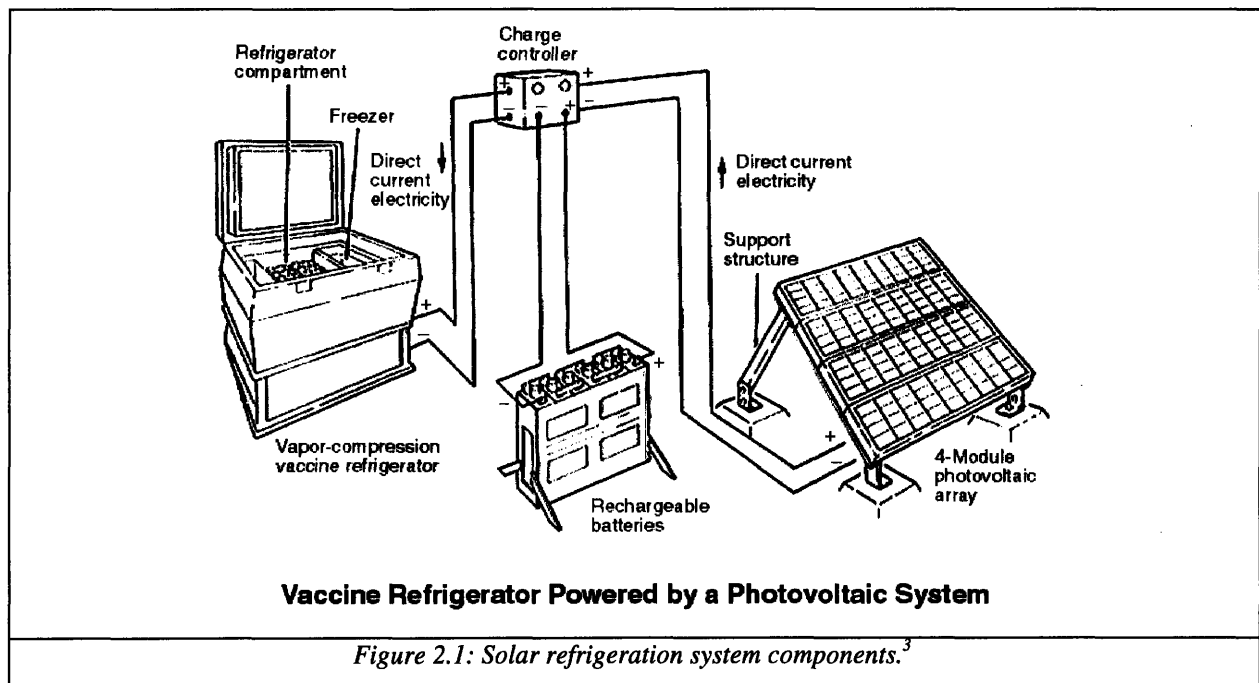
As shown in Figure 2.1, the main components of a solar powered vaccine refrigeration system are the photovoltaic array, rechargeable batteries, charge controller and vaccine refrigerator. The advantages of this system are that it is not dependent on unstable grids or fuel supply and that many of the locations which do not have access to power are locations that get large amounts of sunlight. This system can also be used to power any type of refrigeration system that runs off electricity, so it can be used as a backup when the electrical grid fails. Despite these advantages, there are quite a few disadvantages. The system requires expensive solar panels that need a knowledgeable setup, alignment and maintenance. It also requires batteries which need to be regularly maintained and replaced every five years. This is a significant problem with using solar power because the locations are often remote, isolated small communities that do not have the funds to replace the batteries [3]. The life cycle cost of the system over 10 years is relatively high as compared to other refrigeration systems, so until solar panel and battery technology advance, this system is most often not the best choice as a vaccine cooler power supply [3].

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[3] Figure 2.1 reproduced with permission from PATH. Original source:
<http://www.polarpowerinc.com/products/refrigerator/ref_images/reliable_draw05.gif >

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2.1.3 Temperature Control System

A third major design decision is the temperature control system. These devices are used to determine when the refrigeration system should be turned on and off. Some common devices are thermocouples, bimetallic strips, bimetallic mercury switches and freeze detection switches. Thermocouples are metallic connections that change resistance as they change temperature. Bimetallic strips are composed of two strips of material connected together along their flat sides. When the temperature rises, the two materials expand different amounts causing the entire strip to bend. This movement can either close or open a circuit. Bimetallic mercury switches use the same principle as the bimetallic strips, but the material is formed into a shape, usually a spiral with a vial of mercury on top. As the length of the material changes, the movement of the coil shifts the mercury container causing the mercury to slide into place, completing a circuit. As with the power supply they are signaling, these temperature control systems do not function without power because they are used in the completion of electric circuits.

2.1.4 Holdover System

When the electricity fails or the kerosene doesn't get delivered, the refrigeration and temperature control systems stop working. For this reason, coolers need to have a system in place to maintain the correct temperature during power loss. Current technology for long holdover coolers is limited to conventional ice-lined or phase change material (PCM) lined technology or maintaining a battery backup/generator.

Figure 2.2: Ice Lined Coolers. The ideal (left) versus the reality (right) Note the ice trays on the left wall indicating the temperature in the cooler is below freezing.[4]

The conventional ice-lined refrigerator usually consists of a top opening cooler that has an internal lining filled with ice tubes or packs. A large amount of energy is required to melt the ice and until all the ice has changed phase, the temperature remains relatively constant. This means ice-lined coolers can maintain an internal temperature below 8°C with only 8 hours of electricity every 24 hours [3]. The long holdover time is a significant advantage in those locations that do not have consistent electricity. The problem with this cooler is that occasionally the bottom of the cooler drops below 0°C putting the vaccines at risk of freezing [3]. Figure 2.2 displays both the ideal and actual usage of an ice-lined refrigerator. As shown in the actual usage picture, ice is forming along the wall and the users are freezing ice packs as well as storing vaccines. This shows that the cooler is below the recommended temperature and will cause damage to the vaccines. This is one technology where the first concern was keeping the vaccines from warming during periods of electrical failure, but the unintended consequence was the freezing of the vaccines.

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[4] Figure 2.2 reproduced with permission from PATH. Author of left picture: unknown. Author of right picture: Carib Nelson.

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In order to overcome the freezing problem, other phase change materials (PCMs) are used instead of water. PCMs are often chemicals such as Polyethylene Glycol (PEG) 400, a non-toxic food additive with a melting point around 6°C [6]. The advantage of using PCM is that the temperature at which it melts, and thus the temperature that vaccine chamber will be held at, may be higher than ice, such as the 6°C of PEG 400. The disadvantages of using PCMs are that they generally have a lower heat of fusion so less energy is needed to melt them and they increase the cost of the cooler. In the case of PEG 400 the heat of fusion is 140 kJ/kg, less than half that of water (334 kJ/kg), thus the PCM will have less than half the holdover time for the same amount of fluid [6]. PEG 400 costs about $17 USD per liter, while water is effectively free and PEG would have to be included with the cooler upon purchase while water is available anywhere [6]. This is also a problem for the long term maintenance because if there are any leaks, the PCM is not easily replaced by the local users, while water can be replaced constantly.

The final alternative holdover technology is maintaining a set of backup batteries or a generator. The advantage of this system is that any refrigerator running off of electricity and electronic temperature control systems can be used. The disadvantage of maintaining backup batteries is that they require regular maintenance and replacement, just as in a solar powered system. Running a generator is problematic because it needs to be maintained, and also requires fuel so is only effective as a backup for electricity powered coolers. Since both the electrical and fuel supplies are often irregular, the generator may not be as reliable as necessary.

2.1.5 Insulation

The last large decision when designing a cooler is the type of insulation to use. Expanded polystyrene, ceramic wool batting, vacuum panels and fiberglass are all common types of insulation. Expanded polystyrene is foam that expands into a mold. Ceramic wool batting and fiberglass insulation are both man-made fibrous insulation. Vacuum panels are sections devoid of all air. The gap is very effective at limiting heat transfer because there is nothing to convect or conduct across the gap, so the only source of heat exchange is radiation. The choice of insulation is usually based on a tradeoff of cost and how effective the insulation needs to be; for example, vacuum panels are one of the most expensive types of insulation, but provide the best insulation for the thickness.

2.2 Background Cooler Design

CONDENSOR   THROTTLE   ICE   EVAPORATOR   FOAM CONTAINER

COMPRESSOR   HEAT TRANSFER LIMITING DEVICE LOCATION   EVAPORATOR FIN   METAL BOX
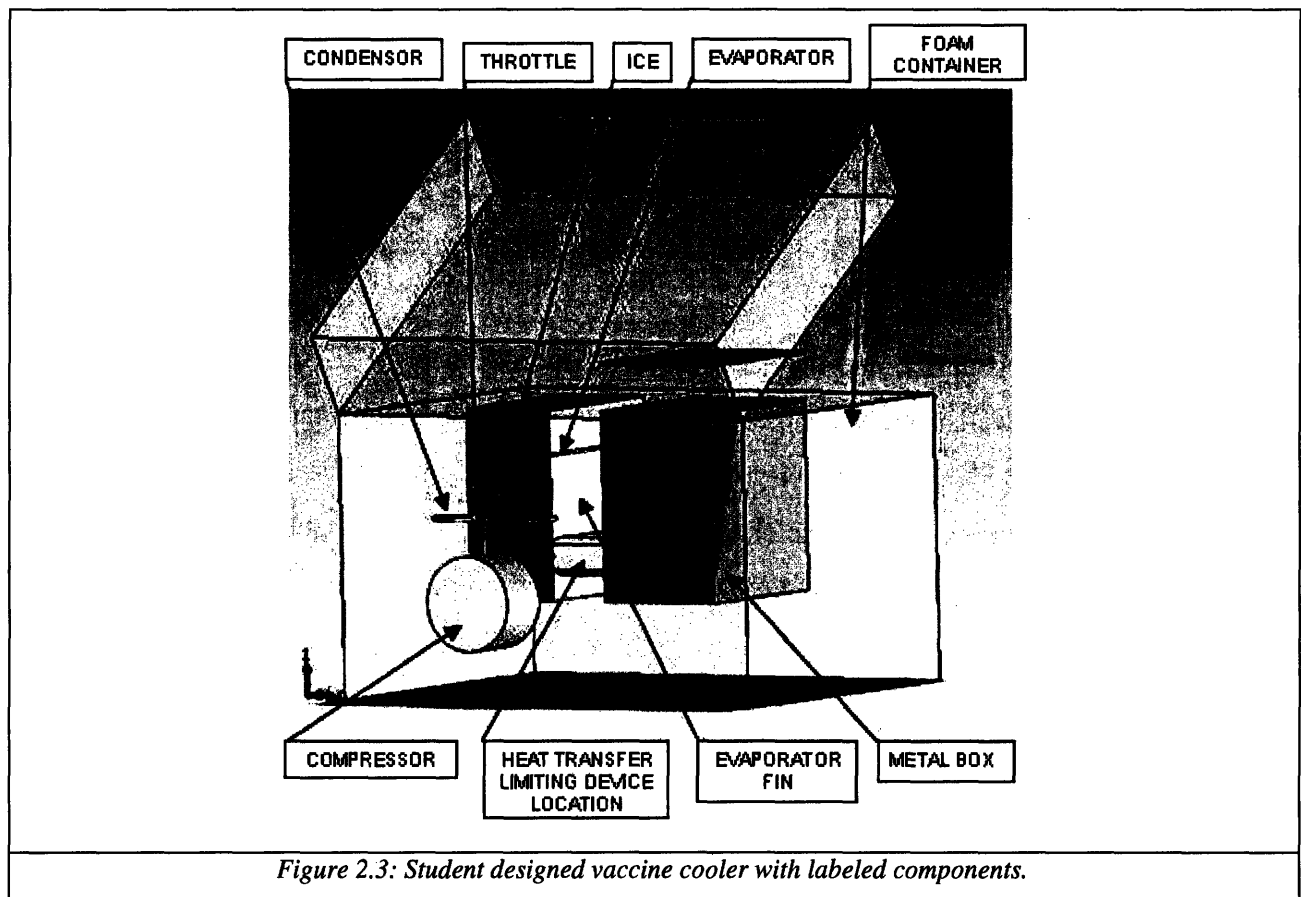
Figure 2.3: Student designed vaccine cooler with labeled components.

As a class project for MIT's 2.006 Thermal-Fluids Engineering II course, a group of four students, Robert Panas, Dave Lopez, Martin Segado and Cynthia Walker, designed a vaccine cooler that incorporates the theory behind the traditional ice-lined cooler with a heat transfer limiting device. In a traditional ice-lined cooler, the ice surrounds the vaccine chamber and is only separated by insulation. In the student design, as shown in Figure 2.3, the ice is in a separate chamber which is thermally connected to the vaccine chamber through a heat transfer regulating device similar to a thermosyphon. By not surrounding the vaccines with the ice, some heat from the environment can enter the vaccine chamber, thus keeping the temperature above the ice melting temperature. This should help solve the problem traditional ice-lined coolers have with freezing vaccines while eliminating the extra cost of using a PCM. The heat transfer regulating device controls the heat lost to the ice thereby regulating the internal temperature of the vaccine chamber. When the cooler changes temperature, the heat loss increases or decreased to compensate.

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2.2.1 Cooler Box Structure

The main purposes of the cooler box structure are to provide insulation between the different components and the environment and to be a rigid framework in which the components are held. In designing a vaccine cooler for developing countries, it is also necessary to have the cooler box be easily manufactured and made with inexpensive materials to keep costs down. The students decided to construct the box out of rigid polyurethane 2 lb density foam, a pourable expanding foam which can be easily formed into the rectangular shape needed for the vaccine cooler [7].

When the ice is at 0°C and the vaccines are at approximately 4°C (steady state) the heat transfer through the walls ranges from 1.6 W to 7 W as the environmental temperature varies from 10°C to 45°C. Due to the symmetry of the box, half the heat transfer is absorbed by the ice, while the other half enters the vaccine chamber [6]. With 0.1m of foam between the ice and the vaccine chamber, there was a 0.14 W heat flux to the ice through the insulation [6]. Using these heat loss numbers, the two chambers and the heat transfer control device were designed.

2.2.2 Vaccine Chamber Design

The vaccine chamber consists of a thin walled aluminum box. When the top of the cooler box is opened the aluminum box remains closed until its top is removed. This helps keep the vaccines cool when the top is opened for maintenance and when accessing the ice chamber; however, the main purpose of the aluminum box is to more evenly distribute the temperature within. Because conduction through aluminum is much more effective than convection through air, heat travels through the aluminum, shunting most of the heat flux coming through the cooler box foam directly to the heat transfer device without effecting the vaccines within. If the aluminum box were not in place then a large temperature difference within the chamber would occur. The aluminum box significantly decreases the temperature gradient to a max temperature difference of 2.7°C on the warmest day [6].

The heat regulating device is designed such that it starts pulling heat out of the chamber when the thermostat reaches 4°C so the warmest part of the cooler should be at 6.7°C on the warmest day. Vaccines will be placed touching the aluminum box or metal racks to facilitate heat exchange with the aluminum, thus their temperature should never be higher than the max wall temperature.

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2.2.3 Ice Chamber Design

Ice was chosen as the hold over material because it has a high thermal capacity and water can be found anywhere. The ice chamber is a box with a thin aluminum sheet connected to the evaporator of the cooling system. This aluminum sheet also functions as a fin between the heat transfer device and the ice.

2.2.4 Refrigeration System Design

In traditional coolers the refrigeration system cools the chamber in which the vaccines reside and is regulated by a temperature control device inside the same chamber. In this design the cooling system is used to freeze the ice and is not directly in contact with the vaccine chamber. The ice acts as a buffer so the varying temperatures created by the refrigeration system and any power outages do not cause the temperature in the vaccine chamber to fluctuate.

The design completed for the class project used a compression refrigeration system as the cooling mechanism. As mentioned in the discussion of refrigeration technology, the compression refrigeration system is the least expensive system and the cost of electricity is low compared to the cost of fuel. Compression refrigeration also does not cause health problems like those caused by the burning of kerosene. These are the reasons compression refrigeration was chosen, but any of the previously mentioned refrigeration systems could theoretically be used.

2.2.5 Heat Transfer Regulating Device Design

The novel component of this cooler design is the heat transfer regulating device that controls the heat flow from the vaccine chamber to the ice. The device functions much like a thermosyphon which transfers heat by evaporating a working fluid in one location and condensing it at another. The evaporation pulls energy out of the surrounding material and condensing rejects energy to its contact. The work completed for this thesis was to design and prototype this device as it is the most critical module of the cooler.

Chapter 3

Qualitative Designs

3.1 Scope

When approaching the design of the heat transfer regulating device it was found to be best to break the system into components. The two components are the cooling loop and the flow control device. Transferring heat to the ice from the vaccines is accomplished by evaporating a working fluid next to the vaccine chamber aluminum box and condensing it next to the ice chamber fin. The cooling loop is the piping that allows this movement to occur. The flow control device consists of the mechanism that closes off the flow and the component that determines when to shut off the flow.

3.2 Cooling Loop and Flow Control Designs

As shown in Figure 3.1 above, there are two sides to the cooling loop; the vaccine chamber side and the ice chamber side. Both sides are attached to the aluminum sheeting that compose the walls of the two chambers. The vaccine chamber touches the warm side of the loop and this is where the evaporation of the working fluid occurs. The gaseous working fluid then flows upward due to the pressure increase caused by the change in phase from liquid to gas. Once the gas reaches the ice chamber side of the cooling loop it condenses and the liquid that forms runs down the condensing pipe under the pull of gravity. The liquid enters the vaccine chamber side of the loop and the cycle repeats.
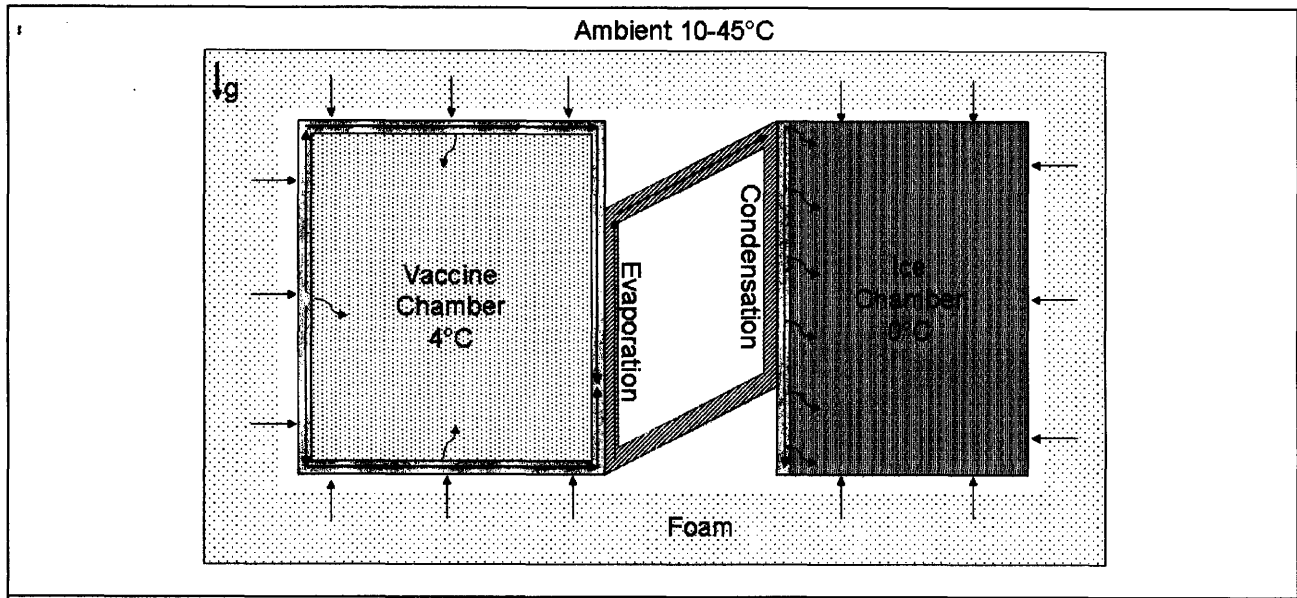
Figure 3.1: Vaccine cooler schematic with arrows depicting the direction of heat flow.

3.2.1 Design 1: Liquid Flow Control with Bulb and Needle Valve Regulator

The initial design focused on restricting the flow of the fluid in the condensing pipe using the fluid control device. As shown in Figure 3.2, there is a large evaporation chamber with a reservoir of working fluid next to the vaccine chamber connected to a large condensing chamber next to the ice.
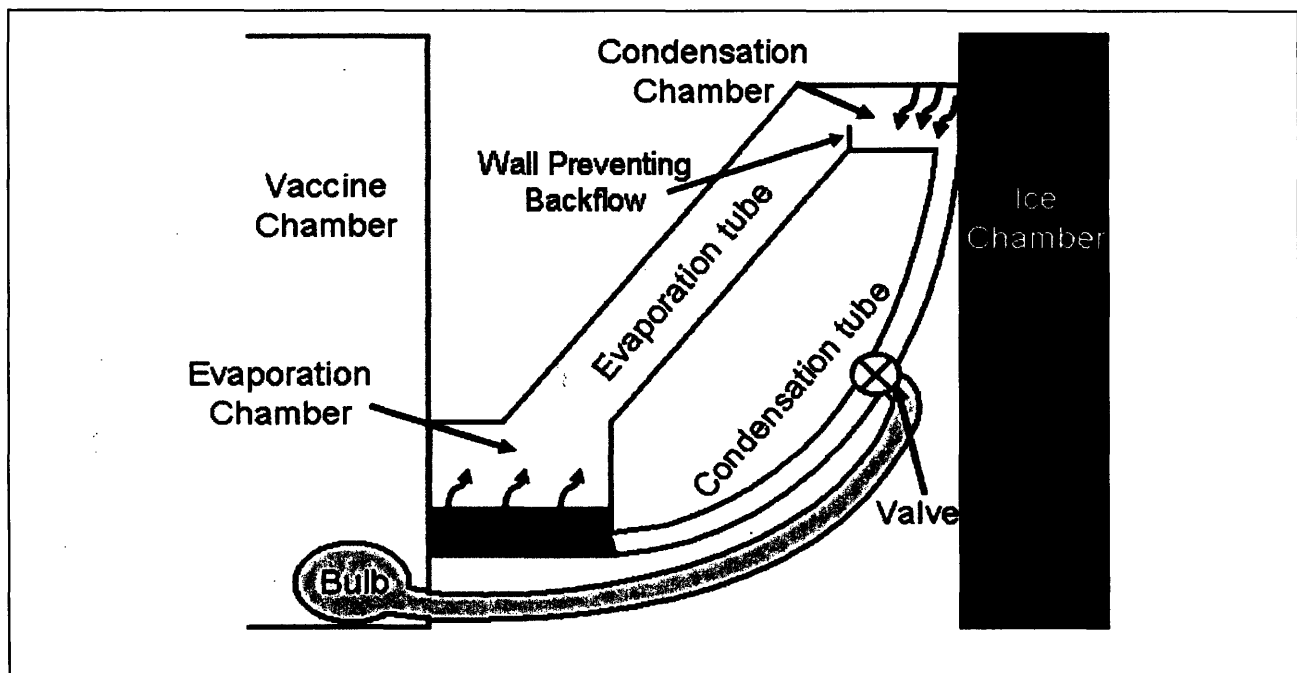
Figure 3.2 : Heat transfer regulating device idea 1.

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In this design, there is a small wall blocking the condensing chamber from the lower portion of the evaporation tube so that after the liquid has condensed it cannot flow back down the evaporation tube. In the middle of the condensing tube is the flow control device. When the valve is closed there is no flow from the condenser to the evaporator so the heat flux can be controlled by limiting the working fluid flow.

The flow control device is a modified needle valve connected to a bulb that is placed in the vaccine chamber as shown in Figure 3.3. As the working fluid in the bulb warms, the pressure increases. When the force caused by the pressure in the bulb overcomes the force of the return spring the valve opens. As the temperature in the vaccine chamber cools the bulb cools and the return spring pushes the valve closed.

This design has several weaknesses that make it impractical, the largest of which involves the flow control device. Placing a closed system, the bulb/valve connection, within another closed system, the cooling loop, is very difficult due to the limited accessibility through the outer system. Another difficulty is sealing the necessary sliding joints. These two requirements make this design extremely difficult to manufacture and thus expensive.
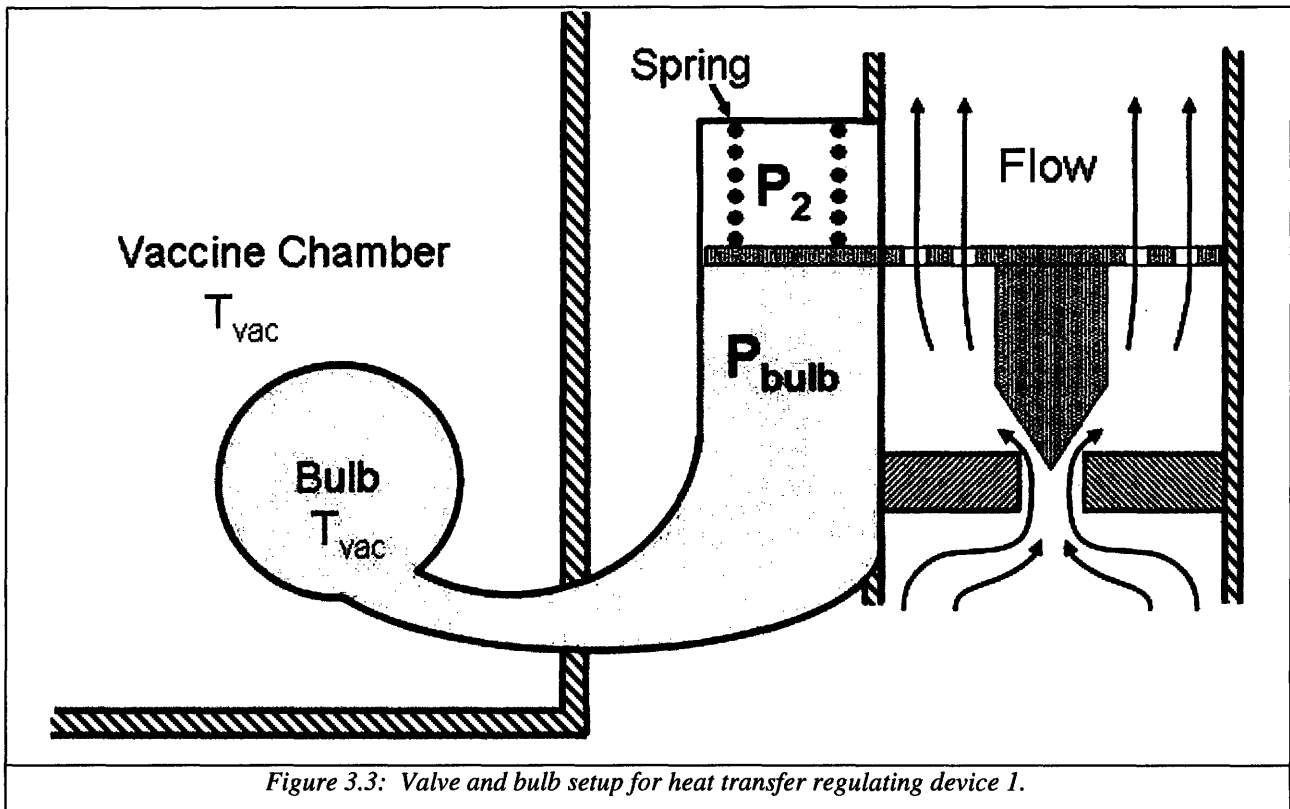
Figure 3.3: Valve and bulb setup for heat transfer regulating device 1.

Attaching the bulb to the valve requires modification to the valve which causes sealing problems and so removing the bulb would greatly simplify the design. To get rid of the bulb, the valve would need to be placed in contact with the vaccine chamber, so restricting the flow through the evaporation pipe would be the best option. Another advantage of restricting the flow in evaporation pipe is that the volumetric flow rate of the gas is larger than the volumetric flow rate of the liquid so a less precise valve could be used.

3.2.2 Design 2: Gas Flow Control with Modified Needle Valve Regulator

The second design attempted to resolve the problems that occurred when placing the valve on the liquid side of the cooling loop by placing the valve on the gaseous side. The cooling loop setup is the same as the first design except the valve is now placed in the evaporation tube.

The flow regulating device is still expected to be a needle valve, but modified as shown in Figure 3.4. The needle valve is now its own separate container, referred to in this paper as a thermostat. The thermostat is attached to the aluminum box of the vaccine chamber. When the vaccine chamber warms the aluminum and thus the end of the valve warms as well. The increased temperature causes the pressure to increase and pushes the rod of the valve out of its container. The rod is connected to an aluminum disk surrounded by a seal. This disk moves out opening a gap in the pipe.

Figure 3.4: Modified needle valve for heat transfer regulating device 2.

Moving the valve next to the vaccine chamber is an improvement since, but there are still problems with the valve design. Manufacturing and sealing the evaporation tube and valve connection area would be difficult due to the tight tolerances needed to create a refrigerant tight seal. The moving parts associated with sliding the disk i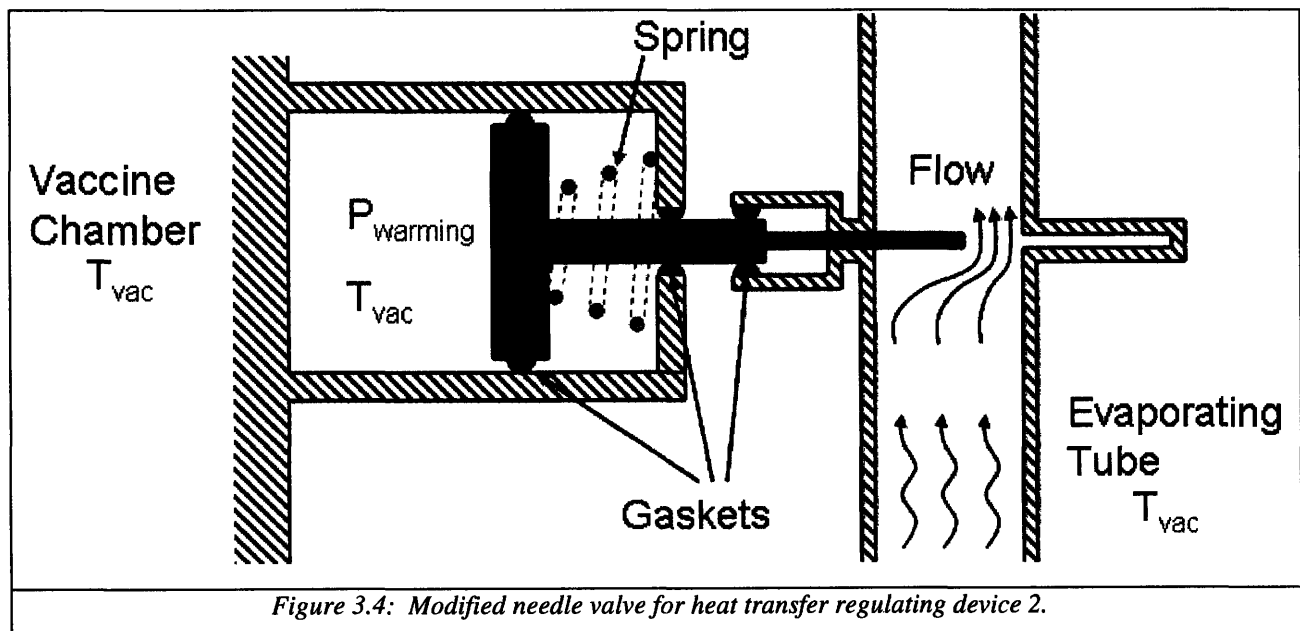n and out of the pipe also add to the complexity. The predicted high cost and low reliability of designing and manufacturing a new valve of this sort precluded this design.

3.2.3 Design 3: Gas Flow Control with Modified Car Thermostat

The first two design iterations involved modifying a needle valve. The sealing of the connections between the valve and piping is very complex so finding a standard valve and designing an actuation method was evaluated next. A car cooling system thermostat was examined as a possible solution. In car thermostats, depicted in Figure 3.5, a wax pellet is placed within a sealed chamber. A rod projects into the wax compartment but is separated from the wax by a flexible rubber seal. At ambient temperature the wax is a solid. When the coolant around the wax chamber warms up the wax begins to melt. Most liquids, have a higher specific volume then their solid states. What this means is that the liquid version of the material takes up more space than the same amount of solid. When the solid wax melts it pushes against the rubber seal forcing the rod up. In car thermostats the rod is held in place through its connection to the top of the thermostat, the "hat," so the chamber is forced to move down, away from the rod. The inner part of the thermostat seal is connected to the chamber, thus when the chamber moves down a gap is created in which the fluid flows through.

The wax chosen for these thermostats has a melting point around 180°F which is too high for the cooling loop. In order to use this design the wax must be replaced by a different working material that has a melting point around 4°C. Research found that peanut oil has a melting point of 3°C [8].
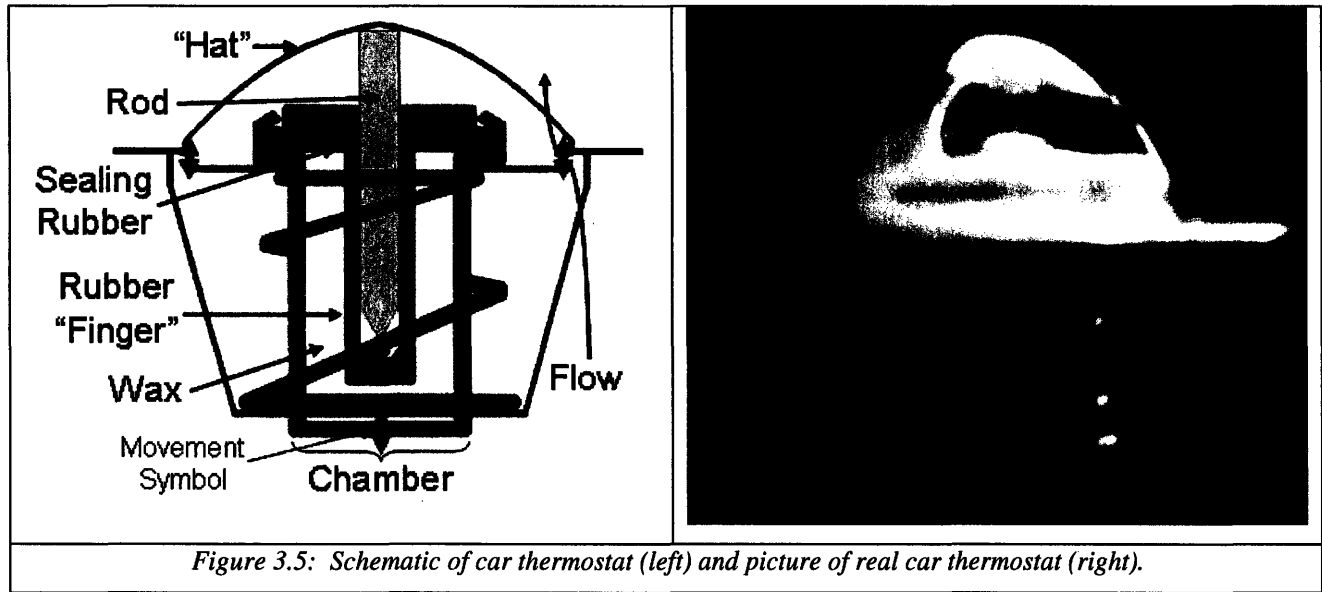
Figure 3.5: Schematic of car thermostat (left) and picture of real car thermostat (right).

Peanut oil is an optimal choice because it not only has the correct melting point, but is non-toxic and readily available in developing countries. This means manufacturing in the future may be possible in countries closer to the end destination of the cooler and repairs could be completed on location. Car thermostats are located inside the refrigerant pipe so the original idea was to include the peanut oil version inside the gas flow pipe.

This design greatly improves the thermostat design by building off of technology that is already implemented and inexpensive. Car thermostats are already available at auto-parts stores for under $6 USD. Altering the manufacturing process of car thermostats to peanut oil thermostats would not be difficult and in the prototyping stage, using the parts of a car thermostat and exchanging the wax is not as difficult as creating a new valve mechanism. The reliability of this design has already been tested in the design of car thermostats and there are no precision fits to align and calibrate.

3.2.4 Design 4: Gas Flow Control with External Peanut Oil Thermostat

After calculating the gas flow rate, it became obvious that a pipe with an inner diameter large enough to accommodate a thermostat was simply too large and that an internal thermostat would not create a tight enough seal to keep the small flow rate from flowing through the valve. The design was altered to use a valve that could be actuated external of the cooling loop, such as a push button valve. The basic idea of the car thermostat was altered such that the oil

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Figure 3.6: Schematic (left) and picture (right) of thermostat/valve mechanism used in heat transfer regulating device design 4.
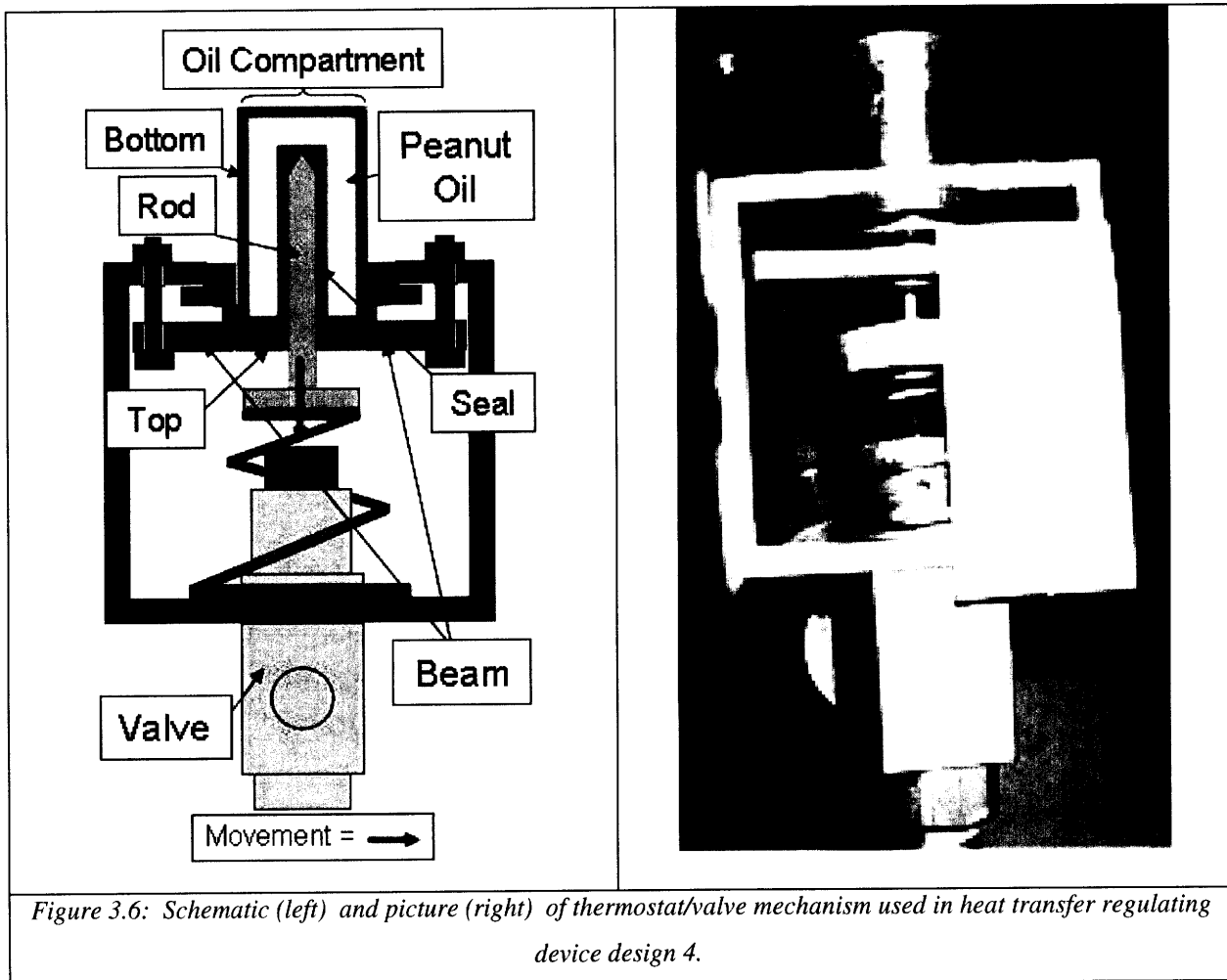
compartment is held stationary and when the solid melts, the rod moves out pushing against the button on the push button valve, as shown in Figure 3.6.

Much of the cooling loop tubing was sized to fit with the push button valve. The pipes are shaped into a parallelogram, pictured in Figure 3.7 below, so the fluids flow to the desired location easily. The slant in the evaporation pipe is necessary so that the gas that is being pushed up by the increasing pressure also moves in the horizontal plane toward the ice. The condensation tube slants down so the fluid runs to the bottom of the evaporation pipe under gravity. There are no evaporating or condensing chambers because there is not enough fluid to need them. The condensation tube is significantly smaller than the evaporation pipe because very small flow rates travel through the condensation tube and the small cross sectional area decreases the heat leak through the pipe.

The external peanut oil thermostat and cooling loop designed with it is the final design iteration before prototyping.

Figure 3.7: Picture of completed prototype of cooling loop and heat transfer regulating device design 4.
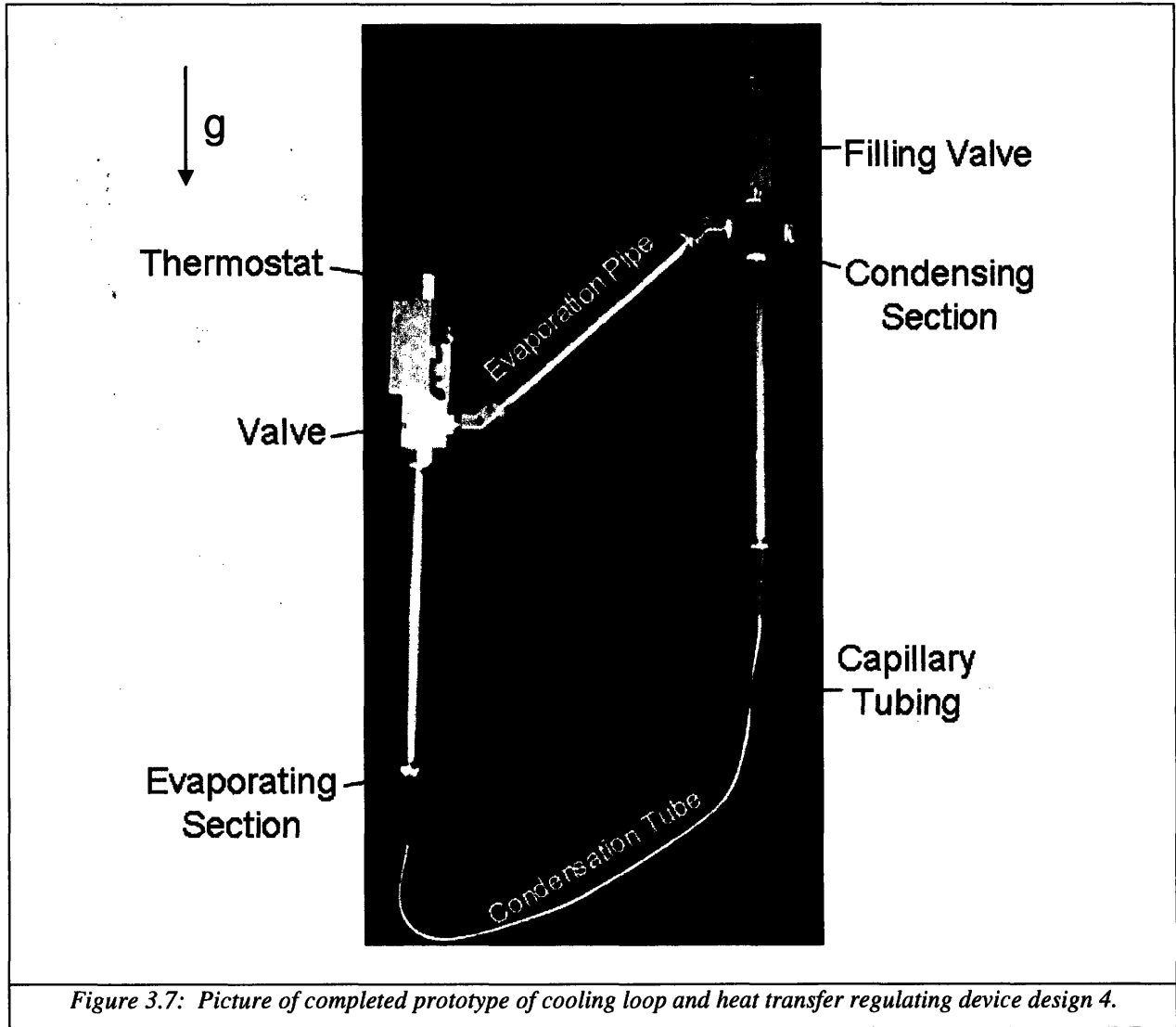
Chapter 4

Analytical Design

This chapter discusses the analytical design completed to determine dimensions for the cooling loop and thermostat. It also discusses the modeling completed to predict how the loop will function.

4.1 Thermostat Analytical Design

The intention in basing the thermostat design off of a car thermostat is that most of the components of a car thermostat can be reused in the prototype and that in final manufacturing the same techniques and possibly some of the same machines can be used. The most important part to reuse is the sealing rubber and corresponding rod because they are well formed and function well together. The peanut oil thermostat designed is shown in Figure 4.1 below.

Figure 4.1: Part drawing of the peanut oil thermostat oil chamber. All dimensions are in inches.
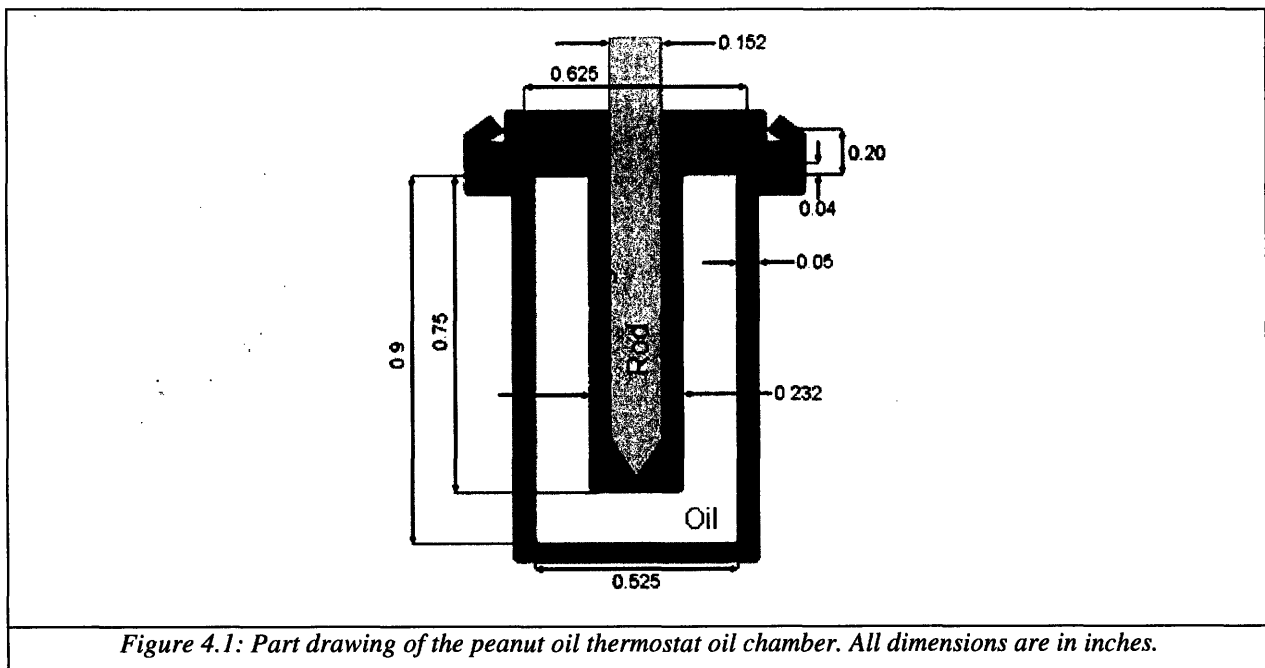
The seal top has an outer diameter of 0.625 inches and the finger in which the rod resigns is 0.232 inches in diameter. Ideally the oil container would be an internal cavity where the inner diameter is unrestricted because there would be a top which closes onto the seal finger, but for ease of manufacturing the prototype a simple cylinder with a separate a top was designed. A wall thickness of 0.05 inches was chosen such that the seal fits on the top of the chamber without falling in, but the internal volume is as large as possible. The walls of the thermostat are pressed over the seal's edge to seal the container. This sealing process is the same process that is used on the car thermostat wax containers.

The length of the container and how far the rod extends are dependent upon the oil volume. The change in volume, ΔV, that is needed to push the rod out to some length, Δl_{rod}, is

$$\Delta V = \frac{\pi d_{rod}^2}{4} \Delta l_{rod} \tag{4.1}$$

where d_{rod} is the diameter of the rod. The maximum change in volume can be found by inputting the maximum change in distance that the rod reaches, Δl_{rodm}. The maximum change in volume can also be calculated from the multiplication of the initial volume, V_o, and the fractional change in volume caused by melting, f:

$$\Delta V = V_o f \tag{4.2}$$

The dependence between h and Δl_{rodm} can be found by combining equations 4.1 and 4.2, giving:

$$\Delta l_{rodm} = \frac{\left(d_i^2 h - d_{rub}^2 h_{rub} \right) f}{d_{rod}^2} \tag{4.3}$$

where d_i is the inner diameter of the container, d_{rub} is the diameter of the rubber "finger", h is the length of the container, and h_{rub} is the length the rubber projects into the container. All the dimensions are shown in Figure 4.1. To use this equation, the fractional change in volume due to the phase change, f, needs to be found.

Finding the physical properties of peanut oil proved difficult so the fractional change in volume was determined from experimentation. A measured amount of peanut oil was frozen and the new height of the column was measured. It was found that peanut oil decreases 2.67% by volume when frozen going from ambient temperature, around 30°C, to frozen, around -2°C. To accommodate for the slight decrease in volume that occurs between 30°C and 3°C and from 3°C to -2°C a volume change of 2% was used in calculations instead of 2.67%.

When designing the thermostat the limitations placed upon the height of the container due to available prototype manufacturing processes turned out to be more confining then the length restriction upon the distance the rod projects from the container. Due to the constraints the maximum height attempted was 0.9 in. From equation 4.3, it was predicted that the maximum change in rod projection length would be 0.18 inches.

4.2 Cooling Loop Analytical Design

The thermostat interacts with the cooling loop when the thermostat rod presses the button of the push button valve. The push button valve chosen is a Clippard 2-way normally closed valve with 1/8 in NPT connections located in the design as shown in Figure 4.2. A normally closed valve is necessary because the thermostat rod moves outward when the vaccine chamber and thermostat are warm. The Clippard valve was chosen because the seal is compatible with R-134a, it uses 1/8 in pipe, which is the smallest pipe size with screw on connections, and the button is easily pressed.
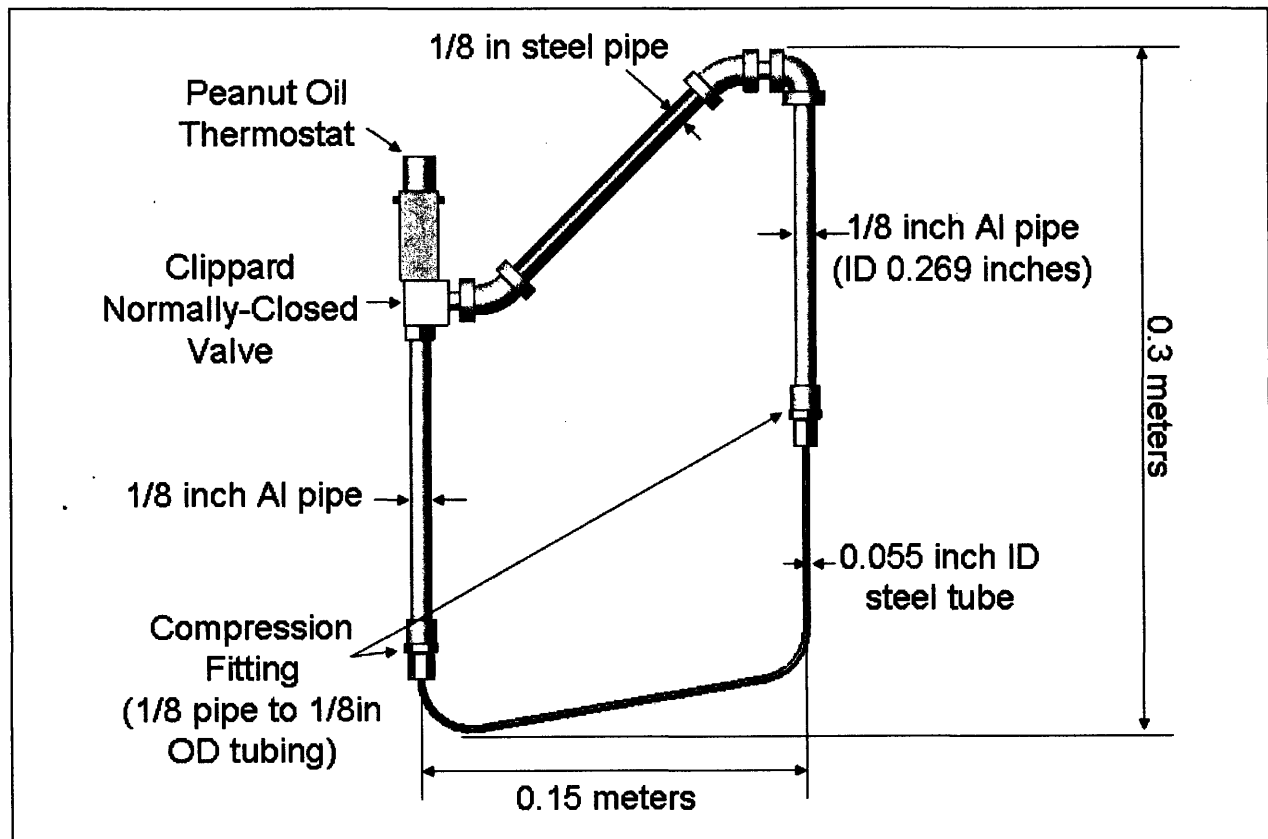

Figure 4.2: Dimensioned drawing of the cooling loop.

The evaporation piping as well as the upper condensing pipe are made of 1/8 in pipe. 1/8 in pipe was chosen because it is the smallest piping that is available with threaded connections and is compatible with the Clippard valve. Threaded connections were desirable for ease of assembly and so pieces can be easily exchanged if something needs to be redesigned after testing. The pipes attached to the vaccine aluminum box and aluminum cooling fin are made of aluminum so that they may be welded onto the aluminum sheets, guaranteeing a good thermal connection. The upper pipe and capillary tubing are made of stainless steel to avoid rusting as well as limit the heat transfer through the piping itself. The overall heat transfer through the piping when the valve is closed is 0.021 Watts for a vaccine chamber temperature of 4°C and an ice temperature of 0°C. This heat loss is around two orders of magnitude smaller than the minimum heat flux in, 1.6 W, so the heat leak is acceptable.

R-134a was chosen as the cooling loop working fluid because it is a common refrigerant and therefore, readily available. The system is pressurized at 3.5 atm so the R-134a will boil at 4°C. The peanut oil valve will begin to open around its melting point temperature of 3°C so it should be open before the boiling of the R-134a, and thus the heat transfer, begins.

In this design, there are no evaporation or condensation chambers. This is because there is no need for large reservoirs of fluid because it was estimated that only 7.5 grams of R-134a is needed to reach the correct charge with the given volume. This can be held within the pipes without extra storage space. If extra storage space were to be added, then the correct charging amount would simply increase.

4.3 System Response Predictions

Several models were completed to ensure the design would function within specification before the prototype was manufactured. In all the models lump parameter assumptions were made about the vaccine chamber, ice chamber and thermostat; meaning the air within the vaccine chamber, the ice in the ice chamber and the thermostat peanut oil are each assumed to be at uniform temperatures. This was done to simplify the models and was determined to be acceptable because each was found to have relatively little temperature variation.

Six models were completed: two undisturbed models, one at the maximum and one at the minimum ambient environmental temperatures, a model of the system response when vaccines are removed from the system, models of the system response when warm vaccines are placed in
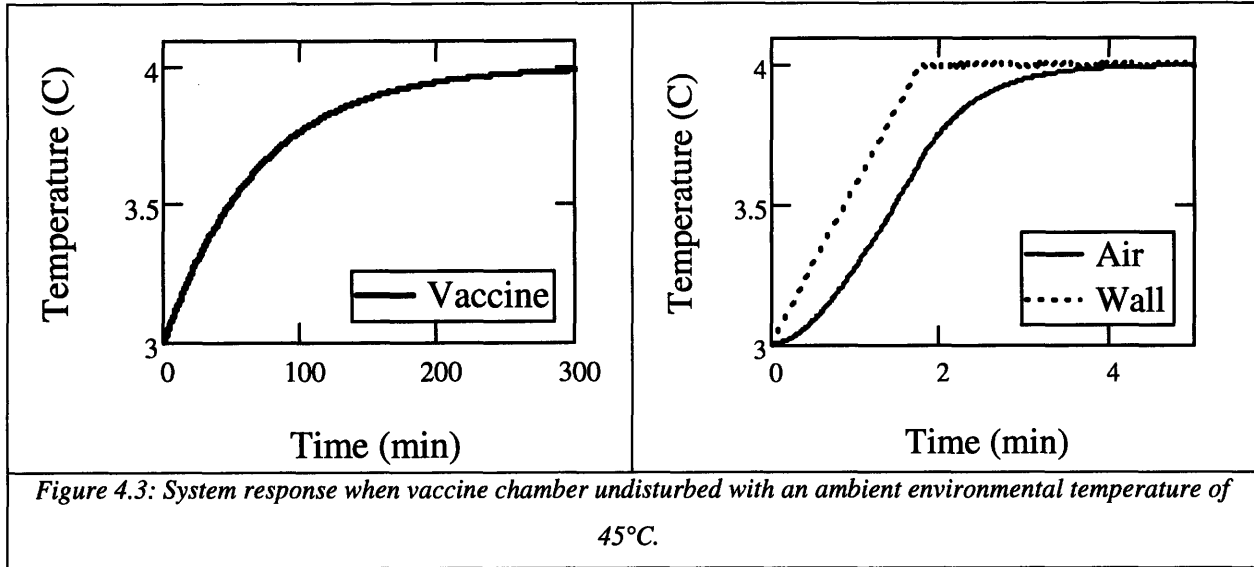
the cooler both at the warmest and coolest environmental temperature, and a model of the system response when cold vaccines are placed in the cooler. The important temperatures and times for each model are recorded in Table 4.1 below.

For all models, the maximum heat loss by conduction through the foam to the ice was calculated to be at 0.079 Watts and heat loss through the pipes was calculated to be 0.021 Watts. This heat loss was calculated with a 4°C difference in temperature between the ice and vaccine chamber. The cooling system was designed to function where the cooling loop is capable of pulling 12 Watts from the vaccine chamber, so when the cooling loop is activated in the models, it is assumed to be pulling 12 watts from the cooler. It is also assumed that the thermostat opens the valve and the cooling loop begins to run at full capacity when the system reaches 4°C.

The models also assume that the vaccines are only losing heat to the air. In the design of the vaccine chamber the vaccines are meant to be placed touching the wall of the vaccine cooler or on metal racks which connect to the wall. This would pull heat out of the vaccine with more efficiency than convection through the air so the vaccines will have smaller increases in temperature if any, the time for the vaccines to cool to equilibrium will be significantly less than shown and that the wall temperature will be slightly higher. It will not be significantly higher because the cooling loop is designed to pull out twice the maximum heat flux into the system so that it can quickly cool the vaccines. By modeling the vaccine heat loss as simply being through the air the worst case scenarios are examined and the results will clearly indicate whether the system will function within specification.

Table 4.1: Model results for six operating scenarios.

Model #	Ambient Temp (°C)	Initial Air Temp (°C)	Initial Wall Temp (°C)	Initial Vaccine Temp (°C)	Max Vaccine Temp (°C)	Min Vaccine Temp (°C)	Vaccine Steady Time (min)	Air Steady Time (min)	Wall Steady Time (min)
1	45	3	3	3	4	3	312.1	4.2	1.8
2	10	3	3	3	4	3	419.85	15.5	13.9
3	45	45	4	4	4.39	4	253.3	4.5	2.5
4	45	45	4	8	8.27	4	259.3	4.6	2.5
5	10	10	4	8	8.004	4	375.3	3.8	0.05
6	10	10	4	2	4	2	457.8	3.8	0.05

Figure 4.3: System response when vaccine chamber undisturbed with an ambient environmental temperature of 45°C.

The first model, model 1 in Table 4.1, was designed to predict how the system functions when undisturbed. This model was completed with the maximum environmental temperature, and thus the maximum heat flux through the insulation of around 6.3 W. The initial conditions were set at the ideal which is a vaccine temperature of 3°C and an infinite ice supply at 0°C.
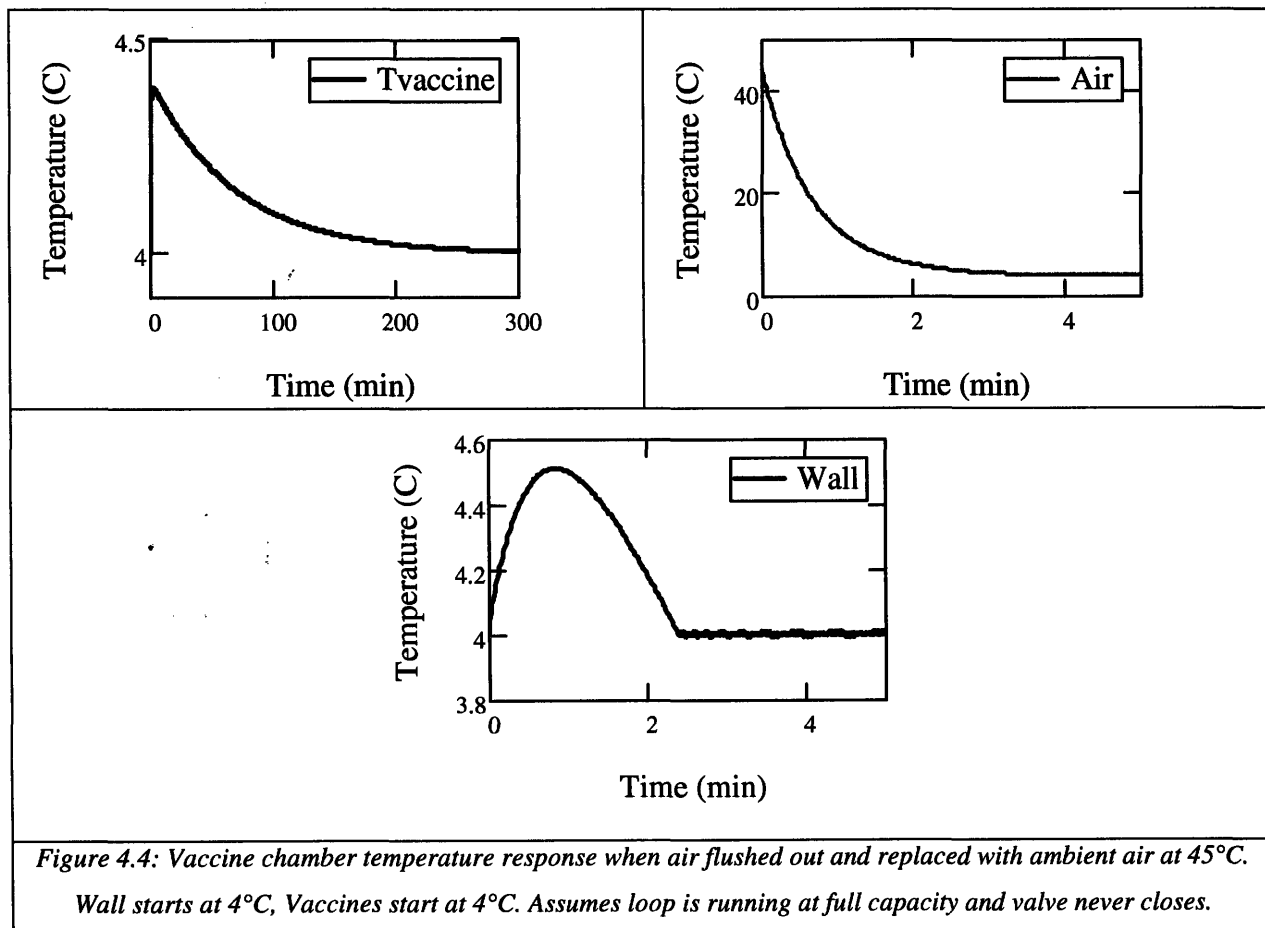
As shown in Figure 4.3, the wall and air temperatures rise to 4°C and remain there. What these graphs do not make apparent is that the wall and air temperature are undergoing a slight oscillation around 4°C as the incoming heat flux warms the chamber, the cooling loop turns on to remove the heat, the temperature drops and the loops turns off. The heat flux warms the chamber again so the cycle continues. The vaccine also rises to 4°C, but much more slowly because it has a smaller surface area to mass ratio and a large thermal capacitance. The vaccine temperature does not oscillate because its thermal capacitance is too large for the high frequency oscillations of the air and wall to pull it with them.

Another model, test 2 in Table 4.1, was completed in which the environmental temperature was assumed to be constant at the minimum 10°C. The heat flux into the system is 0.892 W instead of 6.26 watts so everything warms more slowly. The same general response is observed as in Figure 4.3, but at a slower rate as expressed in Table 4.1.

In both the 45°C and 10°C environment situations the system steadies out to run around the temperature of the boiling working fluid, 4°C. There is a sharp stop in the wall temperature for both models. This is due to the fact that the cooling loop is modeled as a fully on/off system. In reality the valve begins to open around 3°C and the boiling in the cooling loop should be at full capacity at 4°C. Within that 1°C change there is some heat pulled out of the wall by the

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cooling loop from initial boiling which will cause a more gradual rise in wall and air temperature than is depicted in Figure 4.3. Due to this discrepancy, the models are useful in understanding the long term effects, but not short term response.

There are no significant drops in temperature below 3°C for either test so the thermostat never closes. In these ideal situations the thermostat would never need to be used, but it is included in the loop as a safety precaution against disturbances. One common disturbance is the opening of the vaccine chamber to remove vaccines. It is necessary to know how long it takes for the system to recover and return to steady state, the undisturbed equilibrium, in order to guarantee the vaccines will not warm too much in that time. To model this, a worst case scenario was used where it is assumed that the entire vaccine chamber is flushed with air at the warmest environmental temperature, 45°C and only one vaccine is present. Important temperatures and times are available in Table 4.1 under test 3. Figure 4.4 shows the response of each of the components of the vaccine chamber as a function of time.

Figure 4.4: Vaccine chamber temperature response when air flushed out and replaced with ambient air at 45°C. Wall starts at 4°C, Vaccines start at 4°C. Assumes loop is running at full capacity and valve never closes.

It takes about 4.5 minutes for the air temperature to drop down to the steady state equilibrium temperature of 4°C. In this time the wall temperature rises past equilibrium and then drops back down. This is because both the heat from the warm air in the chamber and the normal heat transfer from the environment are entering the wall, causing it to rise far past equilibrium and turn the cooling loop on. The cooling loop then pulls out the excess heat from the wall until it reaches equilibrium. The vaccine also reacts to the initial warming of the air by spiking in temperature to 4.4°C and then slowly cooling down to equilibrium.

The worst case scenario in which only one vaccine is left in the cooler after the air is flushed was originally modeled. As the number of vaccines is increased, the heat from the air is distributed so the temperature rise in each vaccine is smaller as shown in Figure 4.5. This means that flushing the system with air will not cause the vaccines any damage no matter how many vaccines are present.
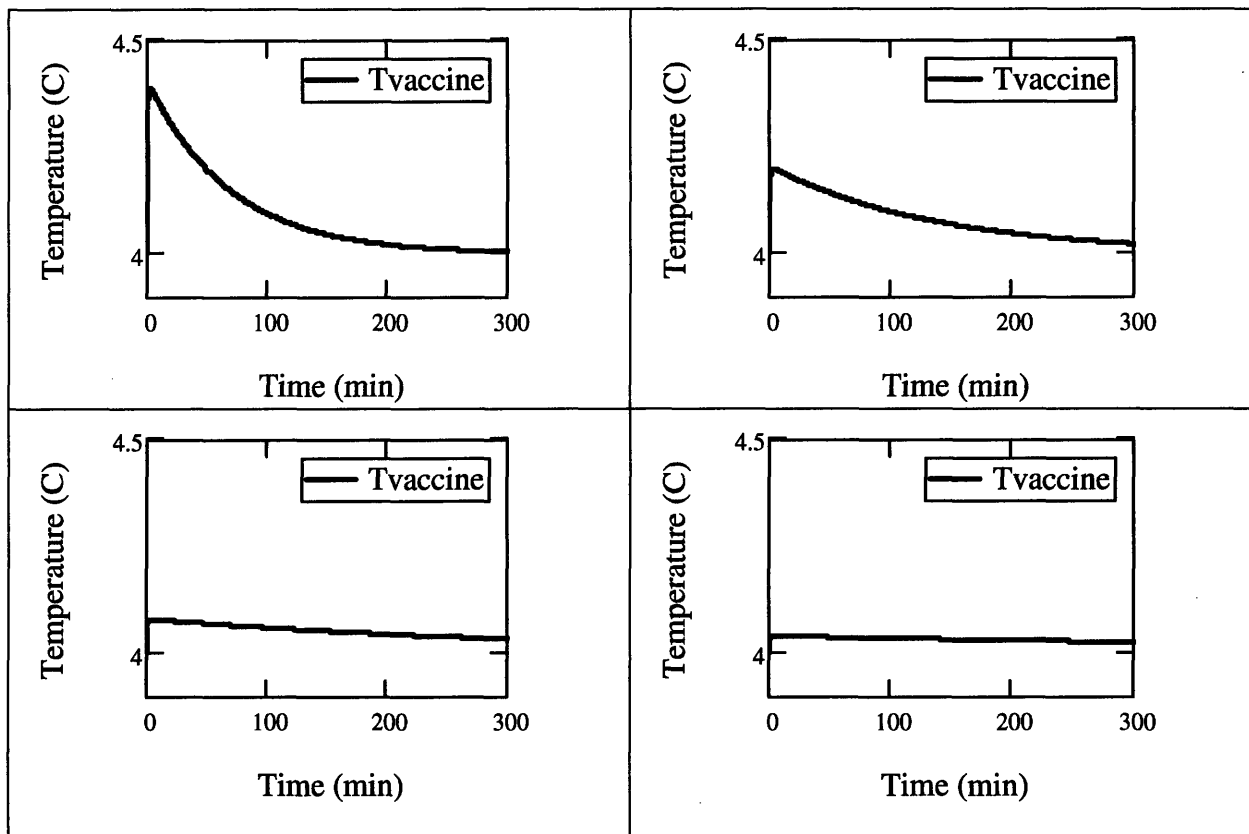

Figure 4.5: Vaccine chamber temperature response when air flushed and replaced with ambient air at 45°C with varying numbers of vaccines. Wall starts at 4°C, Vaccines start at 4°C. Assumes loop running at full capacity and valve never closes. Starting top left and working clockwise are tests run with 1, 2, 5, and 10 vaccines.

In this model the environmental temperature was assumed to be the maximum, 45°C. No model was completed for any lower temperatures because the response would be the same only faster because less energy will enter the system when lower temperature air is flushed through.

The second most common disturbance is the placing of vaccines into the chamber after being transported to the cooler's location. In this situation, test 4 in Table 4.1, the air is flushed and vaccines at 8°C are placed into the cooler. The response is very similar to when vaccines are removed. There is still the overshoot of the wall and the air takes about the same amount of time to decrease back to equilibrium. The vaccine also warms, this time past the 8°C entrance temperature and then begins to cool. This increase is less than 0.3°C; nonetheless, being over 8°C causes the vaccines to start to become less effective. This is the worst case scenario, and if the vaccines are this high, it is most likely that they have been oscillating around being too warm before entering the cooler anyway. Also, the mass of the vaccines in this model is approximately one vaccine. As shown in the previous model, as the mass increases, the spike in temperature decreases to an almost negligible amount. When vaccines are placed into the cooler it will most likely be after transportation, so it is safe to assume that there will be more than one vaccine placed in the cooler so the increase would be negligible. As mentioned in the beginning of this section, the vaccines are being modeled as only losing heat through the air. In reality, their contact with the aluminum wall will dramatically decrease their temperature because the conduction will very quickly pull the excess heat out of them, thus in reality the vaccines may never actually increase in temperature.

With only one vaccine in the cooler it takes about 4 hours to cool to equilibrium, with more vaccines the time increases. Again this time is based on the assumption that the vaccines only lose heat to the air. In reality they would lose heat to the wall and the cooling loop would pull out 12 Watts. This 12 Watts is double the amount of heat entering the system so 6 Watts of heat would solely be pulling from the vaccine, significantly decreasing the cooling time. This model shows that even in the worst case the vaccine chamber will function, but in reality it will function even better.

The opposite of this situation is when vaccines that are at the minimum temperature, 2°C, are placed in the vaccine chamber. In this situation, test 6 in Table 4.1, the vaccines will drag the air and the wall temperatures down such that the thermostat/valve system closes and does not open. The system will then warm up to equilibrium, with responses like those in test 1 and 2.

This is the situation in which the physical shutoff is needed because when the outside temperature is at its minimum and the vaccines enter the cooler cold, there is very little heat entering the system and all of it needs to be used to warm the vaccines.

The models completed for this project indicate that the cooler system will maintain the proper temperatures under all the expected operating conditions; thus the vaccines will not be damaged in the cooler.

Chapter 5

Physical Implementation

The objective of this research was to design and show proof of concept for a cooling loop that would be useful in a vaccine cooler. Modeling indicated the loop would satisfy the cooler needs, so a prototype was manufactured. Design decisions were made while prototyping the device which would be different for the mass manufactured system. These differences do not effect the functioning of the device so the prototype will still prove whether the concept is viable or not. After manufacturing, tests were completed on the cooling loop and thermostat and data on the performance of both components was collected.

5.1 Prototype Deviations from Mass Manufactured System

In manufacturing the prototype some components were made differently than would be expected for the mass manufactured version. These changes were made to help facilitate the prototyping process given the limited resources available. The alterations do not affect the overall functioning of the cooling loop or thermostat, so the prototype is still able to prove that the concept is viable.

As mentioned in Chapter 4, the piping in the prototype is 1/8 in NPT pipe with threaded connections. The threaded connections make assembly easy and also allow the system to be taken apart if something needs to be redesigned or should there be a failure during testing. The problems with using threaded connections for the mass manufactured system are that the pieces are more expensive than unthreaded components and the threads are often prone to leak. In the final system, the connections would be welded so they are strong and less likely to leak. The manner in which the pipes are connected do not affect the flow of the working fluid, so there is no change in the functioning of the cooling loop.

The prototyped thermostat, shown in Figure 3.6 is not a self contained component. The top of the container is held to the bottom by a beam of aluminum attached to the rectangular outer structure by screws. In the final manufactured system the thermostat would be a self contained component and the rectangular outer structure would be made of a formed sheet metal piece much like the regular car thermostat pictured in figure 3.5. These changes are external, so as long as there is no leakage from the oil compartment, there is no change to the functioning of the thermostat.

The spring used in the thermostat was originally the same spring used in car thermostats, but upon testing it was found to be too stiff. A different conical spring with a lower spring constant was chosen. Conical springs are used because they can have wider diameters and compress farther than straight springs with the same spring constant, thus the spring can fit in the small space available.

In the final cooler design the cooling loop is attached to aluminum fins that encircle the vaccine chamber and compose one wall of the ice chamber. The actual cooler was not manufactured so there were no aluminum fins to transfer heat to or from. To accommodate for the lack of a cooler, two L-shaped aluminum fins were made to attach to the side pipes. These fins were bolted around the pipe and put into separate temperature containers which heat could be pulled from and dumped to as shown in Figure 5.1.
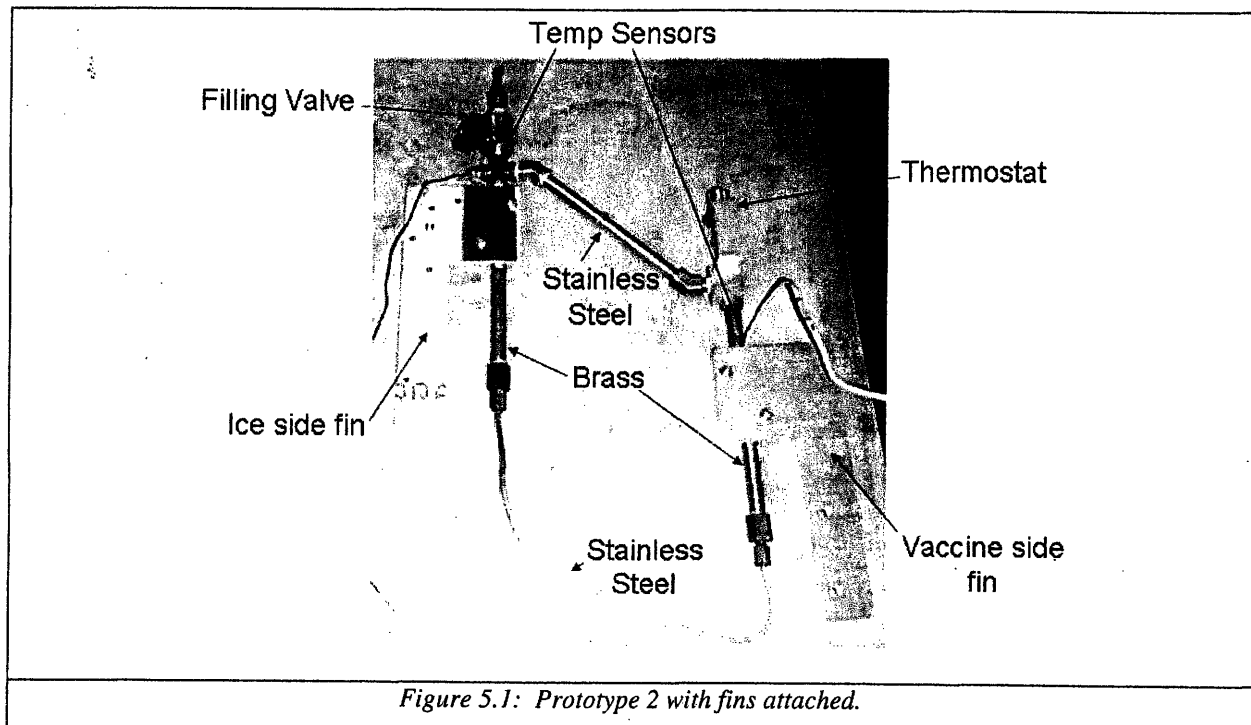

Figure 5.1: Prototype 2 with fins attached.

Two cooling loop prototypes were manufactured. The first had aluminum side pipes as designed, but during pressure testing several leaks were found around the threads. Threaded aluminum pipe is difficult to use because aluminum threads are not as well formed as threads of other materials. While it is possible to use threaded aluminum piping, it was decided that for the proof of concept prototype it was not critical which material was used so long as it was more thermally conductive than the steel pipes crossing from one side of the loop to the other. Brass was chosen for its ease of procurement and assembly as well as decent thermal conductivity. Another reason it was deemed allowable to use brass in place of aluminum was because this prototype would not be welded to the vaccine chamber box or the ice fin, instead fins would be bolted to it as mentioned above. By changing the piping material to brass, it was easier to achieve refrigerant tightness and still prove the concept works.

5.2 Testing Setup

To test the cooling loop without the cooler box, two styrofoam ice chests were used to isolate the cooling loop sides as shown in Figure 5.2.
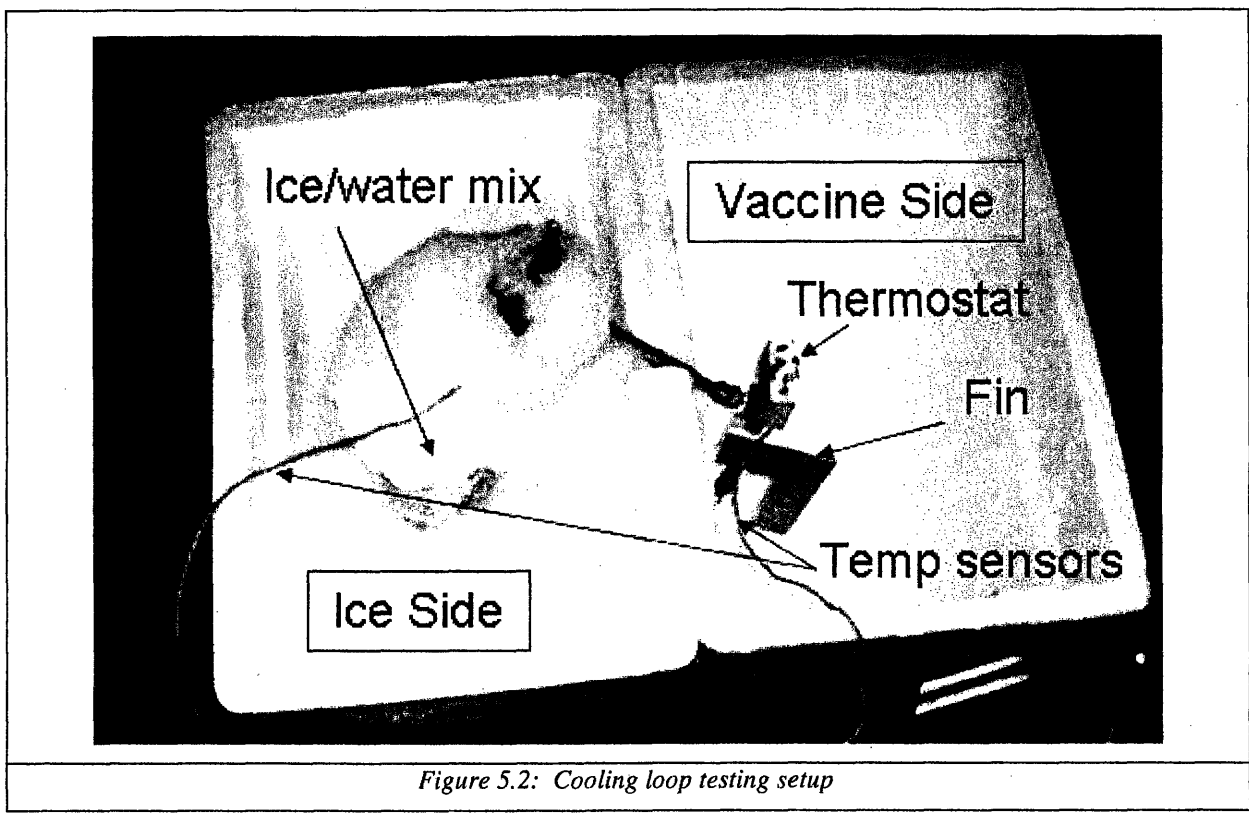

Figure 5.2: Cooling loop testing setup

The cooler boxes were placed next to each other and slices were made in the sides for the cooling loop to slide into. As mentioned in section 5.1, two fins were attached to the cooling loop. The ice side fin was placed in a cup filled with a mixture of ice and water which was then placed in one ice cooler and surrounded by ice. The water was used to increase thermal conductivity of the ice because crushed ice is not very conductive by itself. The extra ice in the cooler was to help reduce the effects of the heat entering the cooler from the environment because the syrofoam chests are thin walled and the slice in the side allows warm air to enter the cooler. The fin on the vaccine chamber side was placed in the air of the other chest. The temperature of the "warm" side was measured at the interface of the fin and the pipe.

The cooling loop was evacuated and charged with R-134a. There was not an accurate way to measure the mass of R-134a being added into the system while charging so the loop was overfilled and then vented. The gram scale available was only accurate to half a gram and the exact amount of fluid needed in the loop was unknown so tests were completed at multiple charges.

5.3 Results

Figure 5.3: Vaccine chamber pipe temperature versus time at different R-134a masses when cooling loop running.
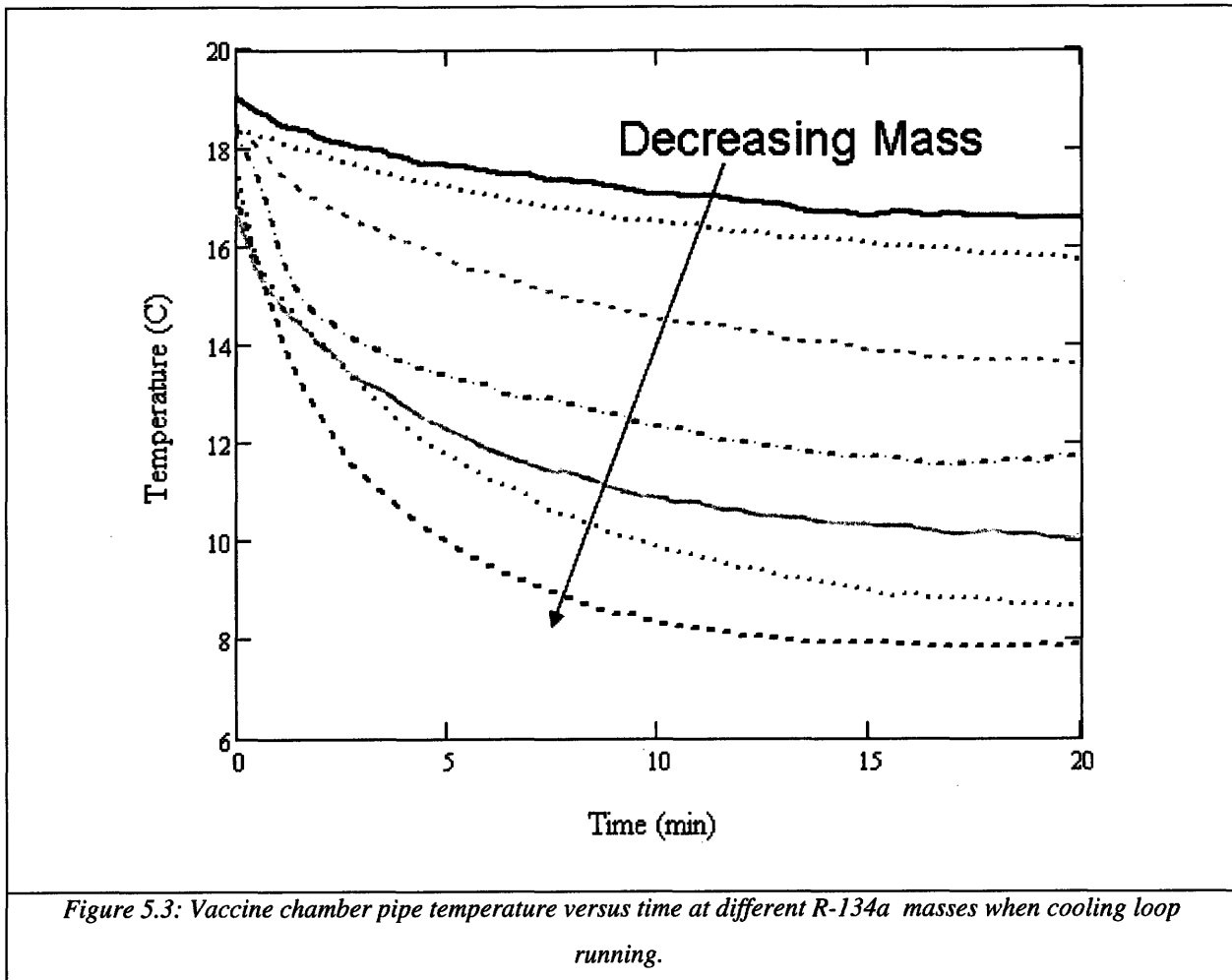
Figure 5.3 shows the temperature of the vaccine side pipe versus time. For each test there is an initial rapid decrease in temperature that levels out to a steady value. As more fluid is vented from the cooling loop the steady state working temperature lowers, due to changes in the relative condensing and evaporating surface areas. The condensing chamber is placed higher than the evaporating chamber so that the working fluid fills more of the evaporator than the condenser. When the system is overfilled, both the condensing and evaporating pipes are filled, so condensation is limited, but evaporation rate is high. As the amount of R-134a is decreased, the liquid recedes, freeing more condenser area while decreasing the evaporating area. At some point there will be too little fluid in the system for the evaporator to function. Between being overfilled and under filled, the cooling loop working temperature varies with respect to the relative surface areas.

The desired working temperature of 4°C was not reached during the tests. Reducing the amount of working fluid even more should bring the temperature to the desired level. It is possible that reducing the level of fluid below what was tested could under fill the system before the desired working temperature is reached. Should this occur, the solution would be to change the geometry of the loop by raising the condenser pipe relative to the evaporator pipe. This extra height difference would allow more of the evaporator to be filled with working fluid before the height of the fluid starts to block the condenser. Another option would be to add in a second set of pipes to increase the surface area of both the condenser and evaporator.

Testing of the thermostat was completed separately from the cooling loop. The temperature that the valve opens and closes at was determined by placing the thermostat is a cup of 0°C water. The water was allowed to warm and the displacement of the tip of the rod was measured at different temperatures. As shown in Figure 5.4, the thermostat begins to open around 2.5°C. This is lower than predicted, but is still acceptable because it is within the required 2-8°C temperature range.

Figure 5.4: Thermostat rod displacement versus temperature. Peanut oil begins to melt around 2.5°C where the rod begins to move out.
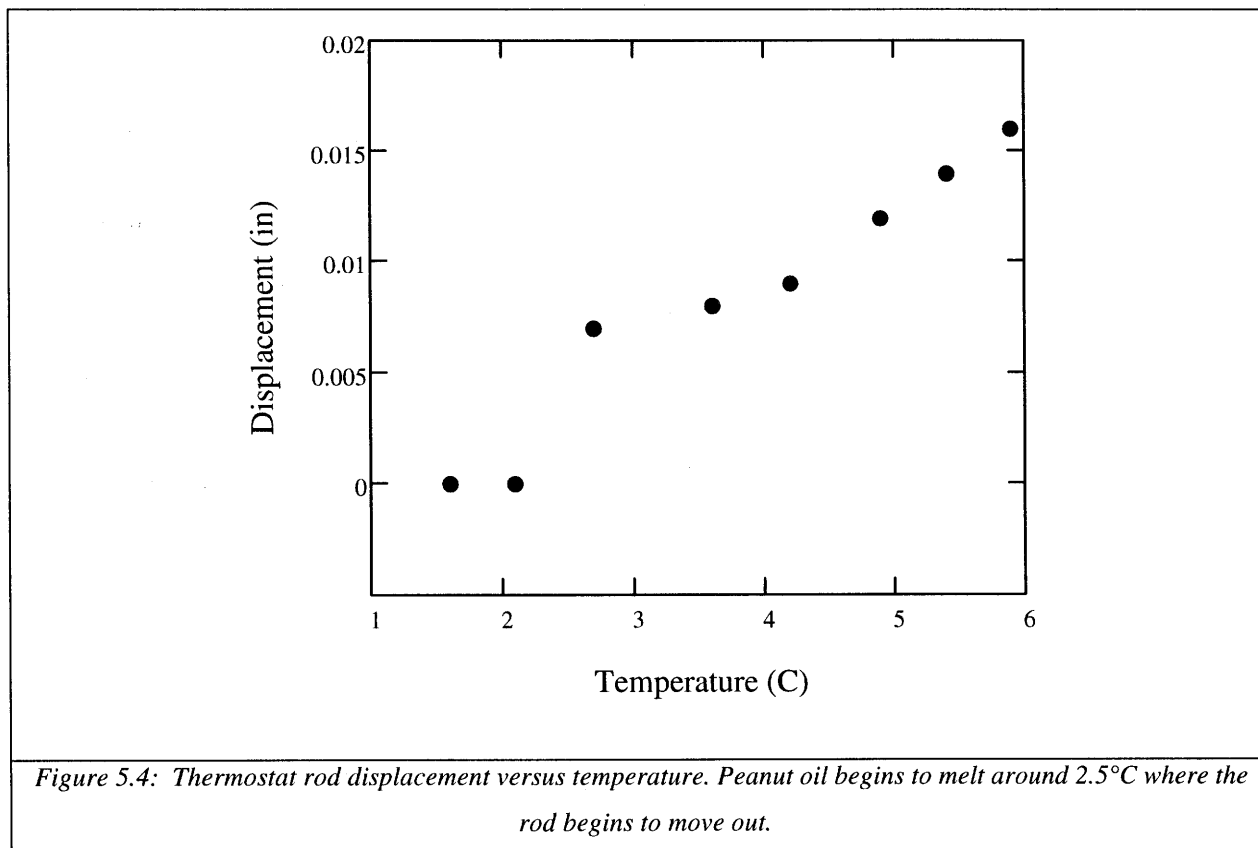
Figure 5.4 displays the desired information about what temperature the peanut oil begins to melt, but nothing more. Once the melting temperature is reached, the displacement is dependent on the length of time the thermostat is held at that temperature. The only difference a warmer temperature makes is that the melting will occur faster. Because the test was not completed with each temperature being held for the same length of time, the relative displacements are not related and thus do not supply any further information.

The thermostat was allowed to warm completely and the maximum displacement was measured at 0.175 inches. As found from equation 4.3, the theoretical maximum displacement was calculated to be 0.18 inches. The measured value is slightly lower than the predicted; however, there is a significant level of variability in the measurement because when a force is applied to the rod, it moves slightly. Given the error inherent in the measurement, the similarity between these two values indicates that the theory describing the thermostat is accurate.

Testing of the cooling loop shows that with proper charging and condenser and evaporator heights, the heat regulating device will cool the vaccine chamber as desired. The thermostat test reveals that the safety shutoff would also function properly and prevent vaccines from freezing.

Chapter 6

Conclusion

The objective of this research is to prototype the heat transfer regulating device of a long-holdover vaccine cooler design. Long holdover vaccine coolers are necessary in developing countries where the power supply is unreliable and intermittent. Current vaccine cooler technology is problematic with regard to the holdover method in that many of the systems freeze vaccines or are expensive and require regular maintenance. A design was proposed where an ice chamber pulls heat from a vaccine chamber through a thermosyphon type heat regulating device. The work completed in this thesis was to design the heat regulating device and fabricate a prototype to prove the concept works in instantiation and not just on paper.

6.1 Summary

The work in this thesis is the second step in the process of developing a new vaccine cooler. The design and fabrication of the most critical module is paramount to determining the feasibility of the overall product. The results of the work are as follows:

- The iterative design of the heat regulating device resulted in the choice of an R-134a cooling loop with a safety valve controlled by a peanut oil thermostat.

- Characterization of the systems response to varying environmental conditions and disturbances through analytical modeling of the system showed the systems theoretical viability.

- Fabrication of the cooling loop and thermostat resulted in a proof of concept prototype.

- Testing of the device found that with the proper amount of working fluid the cooling loop can maintain a temperature of 4°C and the thermostat will close around 2.5°C

Four design iterations were completed before one was selected to be manufactured. Each design built off the previous, fixing problems found in the previous designs. The final design was a cooling loop made from 1/8 aluminum and steel pipes and a 0.055in diameter steel capillary filled with R-134a at 3.5atm. The thermostat system is composed of a Clippard normally closed push button valve and peanut oil filled thermostat whose design is characteristic of car refrigeration system thermostats.

Multiple models were created to test the system's normal response and its response to disturbances that are common in the operation of a vaccine cooler. The system's normal operating response is to run at the temperature at which the R-134a boils, 4°C, which means the thermostat valve is normally open and only closes when disturbances are introduced. Worst case disturbances were modeled and in each situation the vaccines remain within the desired temperature range.

The cooling loop was prototyped twice. The first prototype was made with aluminum threaded pipe and had problems sealing around the threads. The second prototype was manufactured with brass threaded pipe because the threading on brass pipe is better. In the actual manufacturing of the vaccine cooler the pipe would be welded aluminum piping. The use of brass in the prototype is acceptable because the prototype is meant to prove that the concept works not that the specific materials are the best solution. Tests revealed that the concept will work for the vaccine cooler when properly charged. The thermostat will close within the desired temperature range so, should the cooler drop to the lower end of the temperature range, the cooling loop will be shut off.

6.2 Future Work

This work focused on the heat transfer limiting device of the vaccine cooler designed in the MIT 2.006 class. The prototyping proved that the concept works, so future work needs to be completed to prove the entire cooler functions as designed. A second prototype should be completed for the heat transfer device, the refrigeration system design needs to be refined and the entire vaccine cooler should be prototyped to prove the feasibility of the design.

6.2.1 Alterations to Heat Transfer Regulating Device

The heat transfer regulating device should be manufactured in the same manner as originally designed. What this means is using welded connections between aluminum pipes instead of threading and brass pipes. The second prototype cooling loop also needs to be attached to the vaccine chamber box and ice chamber fin so more accurate data can be collected about the system time constants and cooling ability.

The thermostat should be manufactured from new parts and be made into a sealed container instead of the two piece container that was used in this first prototype. Alternative oils should also be studied because the actual melting point of the thermostat was found to be slightly lower than desired. Cottonseed oil was also found to have around a 2% volume change when frozen as well as a declared melting point around 3°C [9]. At the very least, a thermostat using cottonseed oil instead of peanut oil should also be evaluated to determine which oil works best.

6.2.2 Refining the Refrigeration System Design

The vaccine cooler was originally designed to work with a compression refrigeration system, but the other refrigeration systems mentioned in the background section should be investigated as possible options for cooling the ice. Since the refrigeration system is not directly cooling the vaccines, the type of system is not critical to the design so long as it fulfills the requirement of freezing the ice in the ice chamber. Perhaps different refrigeration systems can be designed to work with the cooler so it can be used in locations that are on as well as off the power grid

6.2.3 Vaccine Cooler Prototyping

Once the heat transfer regulating device is prototyped a second time and the refinements are completed for the refrigeration system an entire cooler should be prototyped. Prototyping the entire cooler will show any errors in calculations and whether the chosen materials are best for the design. After prototyping, if the system functions properly the prototype should be given to an organization, such as PATH, to be developed into a mass manufactured product and used in developing countries.

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