

# Wheelchair Seat Cushion to Mitigate Bed Sores Cooled via Heat Pipes

A Major Qualifying Project Report  
submitted to the Faculty of  
WORCESTER POLYTECHNIC INSTITUTE  
in partial fulfillment of the requirements for the  
Degree of Bachelor of Science

by

Yusuf H. Rashid

Cing Lun Thang

Bin Zou

Advisor: John M. Sullivan, Jr

Project Number: JMS-1302

Date: April 25, 2013

## Abstract

People restricted to wheelchairs for extended periods of time are at a high risk for developing bedsores or pressure ulcers. Pressure ulcers result in approximately 60,000 deaths each year. The frequency of pressure ulcers is correlated with stagnant activity, elevated body temperatures and humidity. Wheelchair bound people frequently exhibit these conditions. Along with the pressure applied to the skin due to prolonged immobility, heat and moisture significantly accelerate tissue deterioration by increasing the effects of friction. To address the thermally related problems involved with pressure ulcers, we designed and fabricated a self-regulating cooling pad that utilizes heat-pipe technology to cool wheelchair-confined patients. Heat pipes are inexpensive sealed pipes that frequently make use of the evaporation and condensation of a fluid known as the working fluid to transfer heat from one location to the other. Our design uses a pad filled with an ammonia mixture, which will change phase from liquid to vapor at approximately 28°C (82°F). The energy required to vaporize the ammonia comes from the seated person. The vapor rises naturally to the back of the wheelchair where it releases its energy to the ambient temperature environment, circa 22°C (71°F) and then condenses back to the pad. Our cooling device requires no external energy and can potentially reduce the frequency of pressure ulcers by reducing the effects of heat and moisture accumulation.

## **Acknowledgements**

We would like to sincerely thank Professor Allen Hoffman and Professor Stephen Nestinger for their support and use of the Assistive Technology Resource Center and the Robotics, Mechatronics and Automation Lab. In particular, we would like to give special thanks to Kevin Arruda and Greg Overton, who guided us every step of the way in the manufacturing and machining aspects of our project. We would also like to thank Peter Hefti, Paula Moravek and Barbara Furhman for guiding us in obtaining the correct materials and equipment for completing this MQP project. In addition, we would like to express our gratitude to the professors from various departments on their input to make our project a possibility, particularly Professor James Dittami from the Chemistry and Biochemistry department and Professor Jill Rulfs from Biology & Biotechnology department. Finally, we would like to extend a special thanks to our advisor, John M. Sullivan for his wealth of understanding, support, and advice.

## Executive Summary

Wheelchair users are prone to developing pressure ulcers. A pressure ulcer is a painful medical condition that is a result of prolonged immobility. As the name suggests, pressure ulcers are a result of extended periods of pressure and stress in locations of bony prominences, and lead to significant tissue deterioration. The stress and pressure caused by remaining in the seat leads to the development of pressure ulcers for wheelchair users.

Even though stress and pressure are the biggest contributors to the development of pressure ulcers, heat and moisture play a significant role in the process. Heat and moisture accumulation between the skin surface and the seat intensify the deterioration by increasing the stress between the body and seat. Commercially available pressure ulcer mitigation products cater to the pressure related issues of pressure ulcers and do not account for the thermal related problems. The objective of this project was to design, develop, and test a wheelchair cooling system utilizing heat pipe technology.

Heat pipes were first introduced in the market as heat transfer mechanisms in the 1960s. Most commonly used for spacecraft and satellite applications, heat pipes use phase change mechanisms to transfer heat. Enclosed systems, heat pipes have working fluids within them that change phase when near a heat source and then evaporate to another region where heat dissipation takes place to condense the working fluid.

For the wheelchair cooling heat pipe, the wheelchair user was intended to be the constant heat source that would provide heat input to vaporize the working fluid. Surface body temperature was measured to be approximately 32°C and therefore a working fluid with a boiling point lower than that temperature was needed so that phase change heat transfer could take place. With the help of a partial vacuum, ammonium hydroxide was chosen as the working fluid for the system. By creating a partial vacuum, the boiling point was brought down to approximately 28°C. Heat dissipation would take place once the gas would come into contact with room temperature at approximately 22 °C and working fluid would condense back to complete the cycle. To provide effective heat transfer and corrosion resistance to the chosen working fluid, carbon steel was chosen as the system material.

Due to the high toxicity of the working fluid, sealing the system was of utmost priority. With the use of silicone O-rings and Teflon tape, the group was able to seal the system. Before actual testing of the cooling device could take place, leak tests were performed. The system was pressurized twice and left to rest for 12 hours to determine any leaks, which would result in a pressure drop. The pressure remained constant over the course of both tests, after which working-fluid tests were initiated.

Using temperature indicator labels to measure temperature changes and a pressure gauge to measure pressure, the heat transfer process was verified through measured temperature and pressure changes. A hot plate was used as a constant heat source. Once the working fluid vaporized, natural buoyancy carried the gas through to the top of the pipe. The increasing temperature measured with the temperature strips verified the functionality of the heat pipe. As the pressure of the cooling pad rises, the boiling point of the working fluid also rises. An elevated body temperature of 37.7 °C (100°F) would not be a risk factor because it would result in a maximum pressure of approximately 2 atm. Any further increase in the pressure would lead to a boiling point that is greater than human body temperature and consequently stop the cycle. This pressure and temperature rise ensures the safety of the cooling system. Due to pressure build up being potentially dangerous, the cooling device's self-regulatory pressure check system served as a good safety measure because the increase in pressure also caused a simultaneous increase in the boiling point of the working fluid. The test showed that the pressure increase had caused the boiling point to increase beyond the current temperature of the working fluid and as a result the vapor condensed while simultaneously decreasing the pressure.

The project was able to verify that heat pipes could be used as an effective heat transfer mechanism for stationary seated people. Research has indicated that reducing the temperature will help mitigate pressure ulcers. Further research to identify other working fluid and material combinations that could serve the system requirements and conditions is warranted.

## **Authorship**

Every member of the group contributed equally in this project effort. The writing and editing was divided such that each member did one third of the writing and editing. Content development was shared such that each member determined, developed and manufactured the final model prototype.

## Table of Contents

Abstract .....	i
Acknowledgements .....	ii
Executive Summary .....	iii
Authorship.....	v
Table of Contents .....	vi
List of Tables .....	viii
List of Figures .....	viii
1. Introduction.....	1
2. Literature Review.....	2
2.1. History of heat pipes .....	2
2.2. Heat pipe structure and design .....	5
2.2.1. Condenser .....	6
2.2.2. Evaporator .....	7
2.2.3. Heat transfer parameters .....	7
2.3. Current applications .....	7
2.3.1. Solar energy.....	8
2.3.2. Spacecraft .....	8
2.3.3. Permafrost.....	9
2.3.4. Heat pipes heat exchangers.....	10
2.3.5. Medical applications.....	10
2.4. Pressure ulcer .....	11
2.4.1. Pressure.....	12
2.4.2. Friction and shear .....	12
2.4.3. Microclimate.....	13
3. Preliminary Designs.....	14
3.1. Preliminary design 1.....	14
3.1.1. The wedge.....	15
3.1.2. Material.....	17
3.1.3. Working fluids.....	18
3.1.4. Gap pad.....	18

3.2. Preliminary design 2.....	20
4. Final Design .....	21
4.1. Fluid selection .....	21
4.2. Construction material selection.....	25
4.3. Seal.....	26
4.4. Shape and dimensions .....	28
4.4.1. Bottom plate .....	29
4.4.2. Top plate .....	30
4.4.3. Flange .....	31
4.5. Pipe design .....	31
4.6. Heat cycle.....	32
5. Testing & Results.....	34
5.1. Test tube verification test.....	34
5.2. Testing with actual model .....	34
6. Conclusions & Recommendations.....	38
References.....	40
Appendix A: Heat Transfer Calculation MatLab Codes.....	43
Appendix B: Wheelchair Measurement Collection .....	44
Appendix C: Wheelchair Measurement Data Analysis .....	48
Appendix D: Heat Pipe in Test Tube Experiment .....	49
Appendix E: Transportation Limitations .....	50
Capillary Limit .....	50
Boiling Limit.....	50
Entrainment Limit .....	50
Sonic Limit.....	50
Viscous Limit .....	50
Condenser Limit.....	51
Appendix F: Material Compatibility Chart.....	52
Appendix G: Meeting with Paula Moravek .....	54
Appendix H: Actual Model Photographs.....	55



## List of Tables

Table 1 - Working fluid comparison.....	18
Table 2 – Pressure Calculations .....	22
Table 3 - Wheelchair Data Measurements .....	48
Table 4 - Wheelchair Data Analysis .....	48

## List of Figures

Figure 1 - Heat pipe mechanism (ForSteel, 2008) .....	5
Figure 2 - Heat pipe mechanism with wick structure (Acrolab, 2008) .....	6
Figure 3 - Condenser and evaporator section of heat pipe (Nikolayev, 2012).....	6
Figure 4 - Four stages of pressure ulcers (Lippincott Williams & Wilkins, 2006).....	11
Figure 5 - Isometric and front view of entire wheelchair assembly.....	14
Figure 6 - Piping of the heat pipes .....	15
Figure 7 - Diagram of air pocket issue (left) & Diagram of resolution of issue (right).....	16
Figure 8 - Side view of inclined heat pipe casing .....	17
Figure 9 - Inclined gap pad and cooling pad.....	17
Figure 10 - U-Shaped Design .....	20
Figure 11 - Enthalpy mass fraction chart .....	23
Figure 12 - General properties of steels .....	25
Figure 13 - Isometric view of final design.....	28
Figure 14 - Cross-sectional view of final design .....	29
Figure 15 - Isometric view of bottom plate.....	29
Figure 16 - Isometric view of top plate.....	30
Figure 17 - Close up of hole sets.....	30
Figure 18 - Isometric view of flange (left) & bottom view of flange (right) .....	31
Figure 19 - Heat cycle temperature difference.....	32
Figure 20 - Wheelchair heat cycle diagram .....	33
Figure 21 - Experiment set up.....	34
Figure 22 - Proposed locations of thermal couples.....	34
Figure 23 - Temperature vs. Time (top of pipe).....	36
Figure 24 - Pressure vs. Time .....	37

## 1. Introduction

Each year, approximately 60,000 patients die as a result of pressure ulcers. In the United States alone, pressure ulcers cost \$9.1 billion to \$11.6 billion per year and according to a Medicare report from 2007, each pressure ulcer added \$43,180 in hospital stay costs per patient (Berlowitz et al., 2008). Pressure ulcers, also known as pressure sores, are areas of damaged skin that develop as a result of prolonged periods of immobility. These ulcers develop in soft tissues around areas of bony prominences. Wheelchair users, especially those with lost sensation in their lower limbs, are high in risk for developing pressure ulcers. Apart from pressure peaks, pressure ulcers also develop as a result of the magnitude of shear and friction forces between the skin surface and seat cushion as well as due to the additional effects of temperature and moisture (Cooper, Ohnabe & Hobson, 2006).

Although pressure sores result due to prolonged exposure to pressure near bony prominences, heat and moisture have been known to be significant accelerators in the development of the ulcers. Currently available products for pressure ulcer mitigation are focused heavily on the pressure management of pressure sores and do not delve into the thermal aspect involved with pressure sores. Primarily cushions, these products incorporate gel filled, fluid-filled, air-fluidized, and viscoelastic systems to reduce the amount of stress on the user by increasing the area of contact. Each of these products has its own advantages and disadvantages but none of these products are able to efficiently manage or reduce the effects heat and moisture accumulation.

Heat pipes have been used for thermal management since the mid-1900s. Heat pipes are relatively inexpensive closed heat transfer devices that frequently incorporate the processes of condensation and evaporation to transfer heat from one location to the other. Heat pipes are economically advantageous because they do not require electrical power. Heat pipes are versatile and can be employed in small scale and large scale applications. Applications can range from transportation, gas pipelines, and energy to the food industry. The first applications of heat pipes within space during the 1960s proved so successful that ever since then heat pipes have become a regular feature in satellites as an inexpensive method to reduce the large temperature gradient between opposite satellite faces. Heat pipes in the medical industry are most commonly used during procedures that have high temperature sensitive environments (Reay, McGlen & Kew,

2006). The purpose of this project is to investigate the use of heat pipes in the alleviation of pressure ulcers.

## 2. Literature Review

### 2.1. History of heat pipes

The first heat transfer devices to use phase change mechanisms were called Perkins tubes and date back to the early-1800s. The Perkins Tube used a two-phase system and was a predecessor to the heat pipe. The first heat pipe was patented in 1944 (Reay, McGlen & Kew, 2006).

R.S Gaugler of the General Motors Corporation introduced the idea of a heat pipe for use in refrigeration applications. Gaugler described a capillary structure to move liquid from the condenser section to the evaporator section. Cross sections of Gaugler's heat pipe designs showed that there was very limited area for vapor movement. To improve heat transfer from the heat pipe to the ice, Gaugler employed heat pipes fitted into a tubular vapor chamber within his refrigeration system. Unfortunately, due to the availability of other heat transfer devices, Gaugler's heat pipes were not pursued beyond the patent stage (Reay, McGlen & Kew, 2006).

George Grover officially coined the name 'heat pipes' for his patent. He incorporated a wire mesh wick design and sampled different working fluids such as sodium, Lithium, and silver. Grover conducted testing of heat pipes at Los Alamos Laboratory, New Mexico, and later published his results (Reay, McGlen & Kew, 2006).

The UK Atomic Energy Laboratory and Joint Research Centre, in Ispra, Italy conducted extensive research outside of the US for the application of heat pipes in nuclear thermionic diode convertors (Reay, McGlen & Kew, 2006). At the Ispra Laboratory, heat pipes were implemented in disintegrating waste heat from the collectors and for transporting heat to the emitters. The heat pipes were expected to operate in temperature ranges of about 1600 to 1800 °C for emitters and about 1000 °C for collectors. Extensive research surrounded the reliability of the emitter heat pipes over long periods of operation (Reay, McGlen & Kew, 2006).

Contracted by the US Government, RCA was the first commercial organization to work on heat pipes. During a two-year stretch from 1964 to 1966, RCA developed heat pipes made

of different wall materials and working fluids. They were successful in operating the heat pipes in temperature regions of 1650 °C. Deverall and Kemme first developed heat pipes for satellite applications incorporating water as the working fluid (Reay, McGlen & Kew, 2006). Several articles were published between 1967 and 1968 regarding the use of heat pipes for applications such as, air conditioning, engine cooling, and electronics cooling. The first satellites that incorporated heat pipes for added heat transfer capability took flight in 1967 (Reay, McGlen & Kew, 2006).

To test the functionality of heat pipes in space, stainless steel heat pipes with water as the working fluid were heated at one end and then sent into space on an Atlas-Agena vehicle. Using a remote data-tracking device, data was recorded once the heat pipe began operating while in orbit. Once on orbit, the heat pipe automatically turned on and data was recorded using a remote data tracking device. The performance reports were successfully sent to five tracking stations (Reay, McGlen & Kew, 2006).

Heat pipes continued to become more and more popular, so much so that in his paper on heat pipe theory, H.A. Cheung was able to cite over 80 technical papers on heat pipes (Reay, McGlen & Kew, 2006). In his report, Cheung highlighted the thermal capabilities of heat pipes, stating how heat pipes were capable of transferring heat fluxes of 7 kW/cm<sup>2</sup> and was able to operate at elevated temperatures (1500 °C) for long periods of time. Cheung also described different wick structures, including a wick structure that incorporated the use of an artery. The artery was constructed to provide a low-pressure drop path for transporting liquid from the condenser to the evaporator. In the evaporator section, a fine pore wick would then redistribute the liquid around the heat pipe circumference (Reay, McGlen, & Kew, 2006).

To minimize temperature differences between transponders in the GEOS-B satellite, two T-6 aluminum alloy heat pipes with Freon 11 as the working fluid were used for satellite thermal control in 1968 (Reay, McGlen & Kew, 2006). The use of heat pipes significantly lowered the temperature gradient within the GEOS-B compared to the previous GEOS-A satellite which did not utilize heat pipes for thermal management. In the year following the deployment of the GEOS-B satellite, published literature on heat pipes highlighted how corporations within the United Kingdom such as the Royal Aircraft Establishment (RAE) and the British Aircraft Corporation (BAC) were also investigating the utilization of heat pipes for the thermal control of satellites (Reay, McGlen & Kew, 2006).

Research at various laboratories around the world continued at that time, specifically catered to the development of heat pipes incorporating liquid metals as working fluids. Busse described heat pipe development that was taking place in Europe during 1968 (Reay, McGlen & Kew, 2006). By that time, emphasis was also beginning to be put on the various wick structures, the influence of non-condensable gases on performance and the factors affecting the evaporator that limited heat flux. In 1969 David Reay began work on tubular and flat plate heat pipes while at IRD. Research on variable conductance heat pipes (VCHP's) began at RCA and Dynatherm Corporation during that same year (Reay, McGlen & Kew, 2006). Research was focused on reservoir construction, susceptibility to thermal effects and reservoir size.

Wickless heat pipes were first introduced by NASA during this time. Motor rotors and turbine blade rotors can be cooled using rotating heat pipes. Rotating heat pipes transfer liquid from condenser to evaporator using centrifugal acceleration. Rotating heat pipes are particularly advantageous because their transport capability is much greater than wicked pipes and because they do not suffer from capillary pumping limitations seen within conventional heat pipes. Cryogenic heat pipes began to gain significant notice due to the rising need for cooling detectors. Nitrogen was the primary working fluid in these heat pipes but occasionally liquid oxygen was also used. The working fluids were acceptable for temperature ranges between 77 and 100 K (Reay, McGlen & Kew, 2006)

Research into space applications of heat pipes continued into the early 1970s. Universities in Britain and Continental Europe were being funded by the European Space Agency (ESA) to develop heat pipes for ESA satellites. Other companies also continued to develop heat pipes for spacecraft thermal control to keep up with the rapid development. During the 1990s, European companies continued providing space ready heat pipes to pan-European space programs ((Reay, McGlen & Kew, 2006).

The trans-Alaskan oil pipeline incorporated the use of heat pipes into its design during the 1970s. McDonnell Douglas Astronautics Company produced 12,000 heat pipes per month ranging in length between 9 and 23 m to be used as pipeline supports. These support restricted the melting of the permafrost. During that same time period, Sony delivered approximately 1 million unites of tuner-amplifier products that included heat pipes integrated

into the design (Reay, McGlen & Kew, 2006). Compared with conventional extruded aluminum units, these heat pipes were 30 percent more efficient and 50 percent lighter. In recent years, primary focus has circled around gravity-assisted heat pipes, especially for terrestrial applications. Long heat pipes ranging in length from 70 to 110 m are being tested at the Kyushu Institute of Technology in Japan for use in de-icing of roads and floor heating/cooling. Majority use of heat pipes has continued to revolve around the cooling of computer chips. Computer manufacturers require cooling systems that are small in size and are inexpensive. Heat pipes used in computers range in diameter from 2 to 3 mm and cost about US \$1 each. This allows mass production to take place at very low costs (Reay, McGlen & Kew, 2006).

## 2.2. Heat pipe structure and design

The simplest way to describe a heat pipe is that a heat pipe, as we can see in

Figure 1 below, is a mechanism that transports heat from the heat source and emits the energy in another place. The material for the tubing is required to be of high thermal conductivity in order for the heat pipe to operate and as a result conventional heat pipes utilize copper or copper alloys (Yang, Yan, & Mullen, 2011). The wall of the tube is usually lined with a wick structure that affects the capillary pressure as we can see in the alternative heat pipe structure in Figure 2. A working fluid is the medium in which heat is absorbed and emitted from the evaporator to the condenser. Transportation limitations are involved with the working fluid transfer; additional details of transportation limitation can be found in Appendix E: Transportation Limitations.

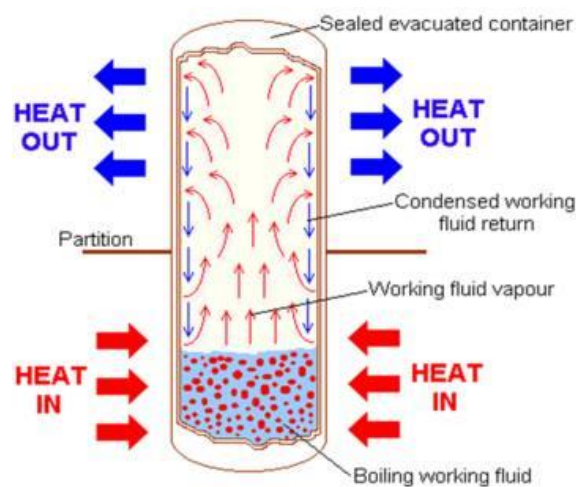


Figure 1 - Heat pipe mechanism (ForSteel, 2008)

The axial structure is divided into the condenser, evaporator and adiabatic sections. The radial structure is comprised of vapor and liquid sections.

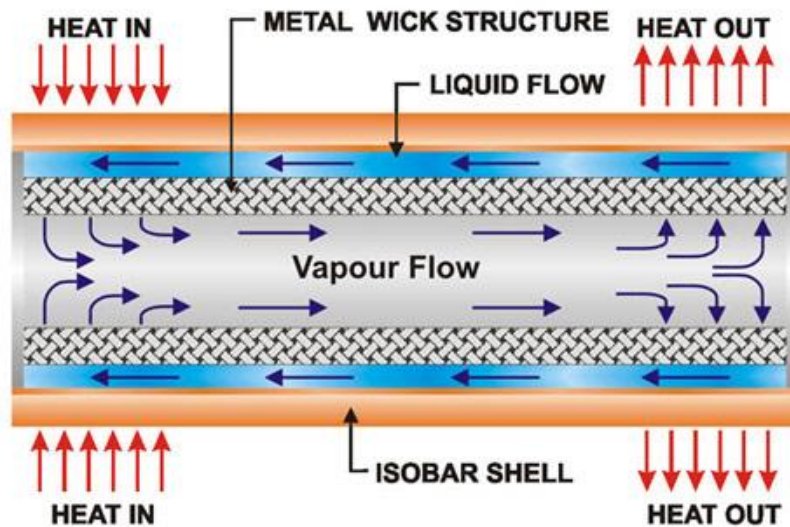


Figure 2 - Heat pipe mechanism with wick structure (Acrolab, 2008)

### 2.2.1. Condenser

As we can see in Figure 3, in the condenser section, the vaporized working fluid condenses to maintain continuous heat transfer. The fluid flow path into the condenser is modeled as that of vapor flowing axially into a long cavity with porous walls. The condenser is divided into regions where the (1) vapor is flowing, and the (2) vapor is static.

The length of the condenser depends on the axial inertia at the entrance of the cavity. For small axial inertias, there is the possibility of the vapor ceasing to flow axially before reaching the end of the designed length.

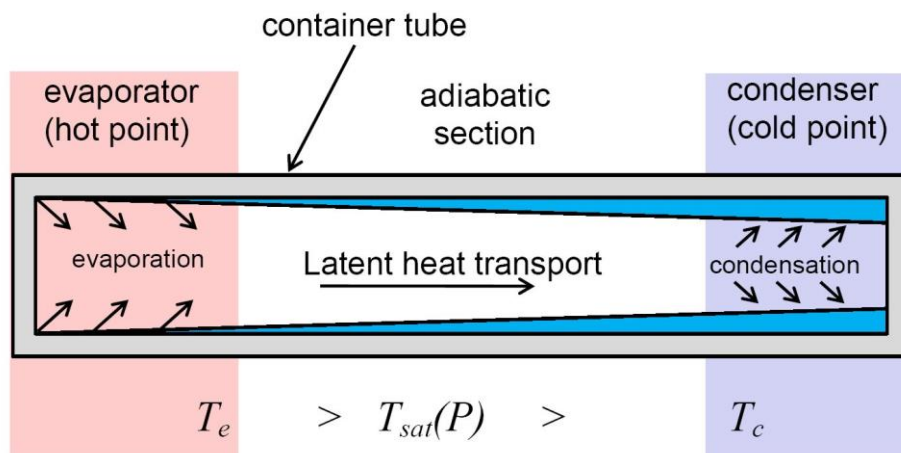


Figure 3 - Condenser and evaporator section of heat pipe (Nikolayev, 2012)

### **2.2.2. Evaporator**

The evaporator is the section, as shown in the figure above, in which heat enters and vaporizes the working fluid. The length of the wick is divided into two sections: one with liquid flowing in the wick and another with the wick filled with static vapor. The length of the evaporator depends on the wick structure and an operating meniscus radius (Colquitt, 1973).

### **2.2.3. Heat transfer parameters**

The most important and heavily researched parameter that affects heat transfer in heat pipes is the property of the working fluid. It is the property of the fluid that determines the temperature range for heat pipe operation.

In addition to this, metal properties affect surface tension, heat of vaporization and relative pressure drop for liquid and vapor flow (Colquitt, 1973). Research today is focused on how to increase the thermal conductivity of these working fluids which has led to the development of the concept of “Nano fluids”, first introduced by Choi in 1995. A Nano fluid is a fluid with nanometer-sized particles suspended into base liquid. (Liu & Li, 2011)

The transportation of the working fluid from the condenser back to the evaporator in a flat heat pipe is a result of a wick structure incorporated in the heat pipe. The radius of this wick structure at the heat pipe’s top and bottom layer should be small as this will result in a high capillary pressure across the heat pipe. However, a small radius causes a low permeability of the wick due to frictional effects. Forces acting on the body should also be taken into consideration, consequently resulting in the significance of orientation. Gravity assisted orientation maximizes heat pipe potential. There are different cases of wick structures that affect the capillary pressure such as the rectangular microgrooves, supported foil channel, wire screen, sintered metal and screen covered artery (Wits, Legtenberg, & Mannak, 2008).

## **2.3. Current applications**

Applications of heat pipes can vary from a wide spectrum, starting as small as in the Nano-scale to a macro level. The sections below will discuss the current applications of heat pipes within renewable energy, permafrost, heat pipe heat exchangers and medical applications.



### 2.3.1. Solar energy

Heat-pipe-based solar water heaters that incorporate heat pipes to transfer heat from the collector to the water store are widely prevalent in the market. Loop heat pipes for use in solar collectors have also been investigated recently. Research in Brazil has shown that the use of flat plate solar collectors with loop heat pipes can effectively overcome the restrictions associated with conventional solar collector systems such as the need to have an electric pump circulate the fluid (Reay, McGlen & Kew, 2006). This concept would be very useful in rural areas where grid connections for electricity do not exist (Reay, Kew 2006).

It is well-known that heat pumps can be inefficient energy transporters when utilizing ambient energy sources such as air. This is true because if air temperature were to drop, the compressor of the heat pump would have to do more work thereby lowering the coefficient of performance - the ratio of useful energy output to the energy needed to power the system. Research in Taiwan has shown that the coefficient of performance of the heat pipe heat pump system can be increased by almost 30 percent by using a heat pipe water heater (Reay, McGlen & Kew, 2006).

### 2.3.2. Spacecraft

Focus on heat pipe technology for spacecraft systems has transitioned to a global stage, with Japan, India, Brazil and China devoting research and capital to rocket and satellite technologies (Reay, McGlen & Kew, 2006). Heat pipes in satellites are primarily used to achieve temperature equality between the solar cell array facing the sun and the cold satellite surface. C.J. Savage, in a paper on the applications of a heat pipe, mentions how thermal gradients within a spacecraft due to internal heat generation by electronics components, and external heat sources such as solar radiation can be minimized through the utilization of heat pipes (Reay, McGlen & Kew, 2006).

The size of the AO-40 spacecraft prevented temperature equality to be achieved on all sides. One side would continuously face the sun, while the other would be completely isolated from the sun and inevitably get very cold. Along with the significant temperature gradient, semiconductors within the MOSFET devices were to be kept at temperatures below 125 °C for reliability purposes. Incorporation of heat pipes into the design mitigated these issues. The heat pipes would recover or reuse waste heat from a heated

location within the spacecraft to help warm other components of the system. To allow for effective heat transfer within the AO-40 satellite, equipment panels that had been fixed with electronic modules were bonded to four heat pipes. The design provided thermal exchange between the low temperature side panels and equipment panels (Jansson, 2010).

The need for such heat transfer mechanisms is due to the lack convection in space. Effective heat transfer can be very challenging in space because of the vacuum. Heat pipes in space application are also beneficial because they do not feel the effects of gravity. Gravity restricts the design of the heat pipe by only allowing the heat pipe to work at an optimal level if the evaporator section is below the condenser section so that the condensate can flow easily. In the presence of gravity, a 0.1 inch increase in the height of the evaporator section to the condenser section can significantly reduce the amount of liquid that can be drawn. In space these limitations are reduced due to the absence of gravity but working heat pipes might still feel the effects of localized acceleration due spacecraft movement (Jansson, 2010).

### **2.3.3. Permafrost**

Pipelines that use permafrost for structural stability can be severely damaged if the permafrost were to melt. During summer months, the foundations of structures maybe destabilized due to the thawing of permafrost. The incorporation of heat pipes into pipeline design has helped mitigate this issue. The Alyeska Pipeline Service Company contracted McDonnell Douglas Corporation to produce nearly 100,000 heat pipes for the Trans-Alaska Pipeline. The contract was valued at approximately \$13,000,000. Heat pipes of lengths between 9 and 18 m were used to prevent the melting permafrost around the pipe supports. McDonnell Douglas (Reay, McGlen & Kew, 2006) developed heat pipes that used ammonia as the working fluid to extract heat from the ground to be released to a radiator located above ground level. This extraction of heat allowed for rapid soil cooling in the autumn after installation. Permafrost was maintained at a temperature of almost 0.5 °C below its normal temperature at the end of the thawing season. Interest in heat pipe technology for permafrost application will continue to grow because permafrost preservation will become more difficult as global warming increases (Reay, McGlen & Kew, 2006).

#### **2.3.4. Heat pipes heat exchangers**

Heat pipe heat exchangers (HPHE) are primarily used to control humidity. HPHE are extensively used within air conditioning systems. The HPHE minimizes heating costs by extracting heat from warm ambient air to reheat the dew point airstream. The HPHE also precools ambient air before it reaches the air conditioner to increase the efficiency of the cooling coil. As a reheat system, the HPHE can effectively reduce the relative humidity below 70% by heating the airstream coming from the cooling coil. HPHEs are used in many industries such as, power plants, oil refining, and metallurgy and in the services industry such as restaurants. HPHEs are also used to recover thermal energy lost through the exhausts of ground vehicles such as in buses, vans, and trucks. Recovered heat can be used reused in other heating applications (Duffy, Jiajitsawat & Wang, 2007).

#### **2.3.5. Medical applications**

Heat pipes within the medical industry are commonly used for the noninvasive treatment of pelvic, gynecological and rectal conditions. Heat pipes are used to provide cooling to the mucous membranes of the organs. Other organs also benefit from the cooling of reflex ganglions in conditions such as chronic gastritis, ulcerative colitis, and acute gastritis (Duffy, Jiajitsawat & Wang, 2007).

During some forms of surgery such as electro surgery, the tissue being treated might stick to an electrode that is used to apply electrical energy. This can lead to various complications such as restricting the delivery of power to the tissue, and forcing the surgeon to periodically remove the device from the patient and clean it before continuing. The sticking of the electrode to the tissue might also cause a portion of the tissue to be torn away resulting in bleeding. Heat pipes are introduced to maintain a temperature of 80 °C at the surgical site and provide cooling at the electrode-tissue interface (Duffy, Jiajitsawat & Wang, 2007).

## 2.4. Pressure ulcer

Pressure ulcers are usually found in aging people and people with mobile disabilities. These ulcers are extremely painful, slow to heal and can be fatal. Pressure sores can occur at

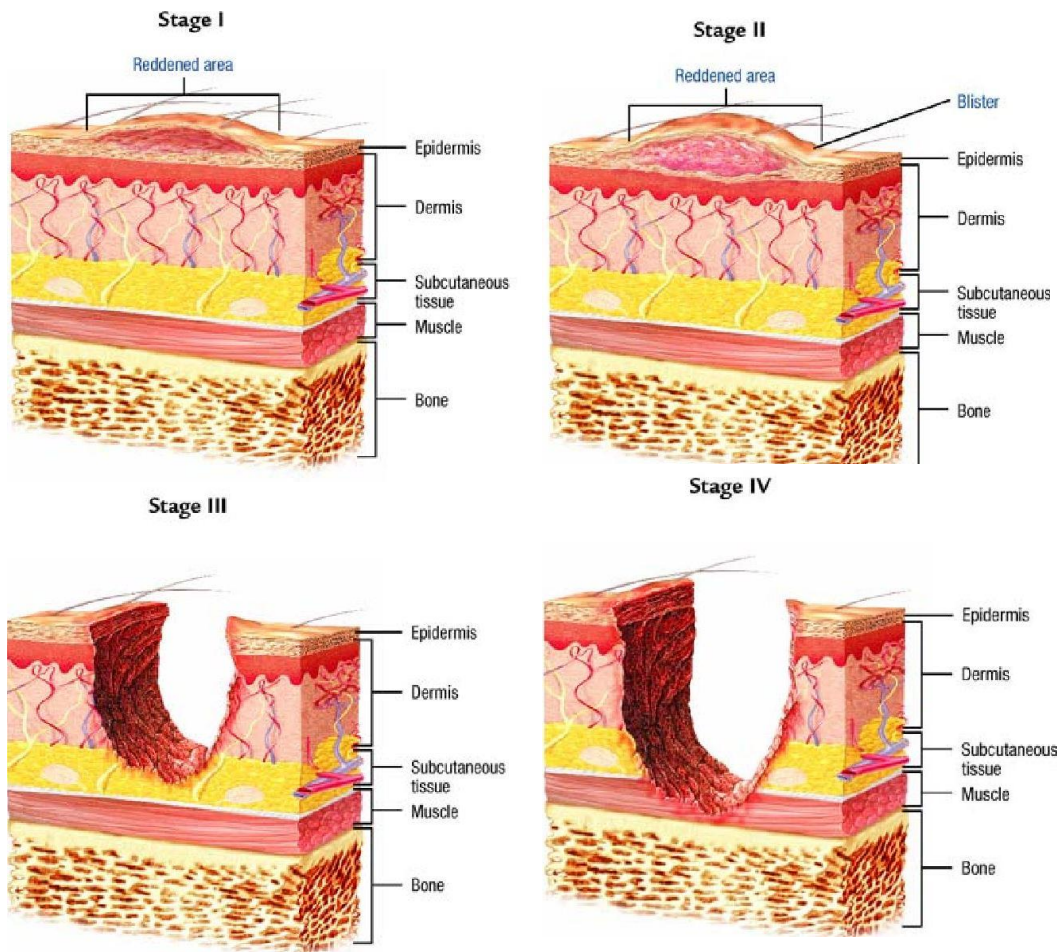


Figure 4 - Four stages of pressure ulcers (Lippincott Williams & Wilkins, 2006)

four separate stages as we can see in Figure 4. According to recent estimates, 1.3 million to 3 million adults have developed pressure ulcers with estimated healing costs of \$500 to \$40,000 for each ulcer depending on the stage of the pressure ulcer (Premier Inc., 2013). A report analyzing the cost of pressure ulcer in the UK in the year 1999-2000 was in the range of £1.4-£2.1 billion, roughly \$2.23-\$3.39 billion (Bennett, Dealey, & Posnett, 2004).

Pressure applied on the surface of contact was thought to be the primary cause of pressure ulcers. However, recent and ongoing research is revealing that there are other important factors to consider. Shear, friction and microclimate are believed to have important roles in the development of pressure sores. It is important to note how these factors are

related to one another. For instance, pressure and shear are closely linked due to the perpendicular and tangential component of the reacting force. Friction is also responsible for the development of the shear while the microclimate influences the skin tissues to determine the effects of pressure, shear and friction (Pressure ulcer prevention: pressure, shear, friction and microclimate in context. A consensus document, 2010).

#### **2.4.1. Pressure**

When pressure is applied to the skin over a bony prominence, the tissues immediately horizontal to the bony prominence are compressed. Shear and tensile stresses can be found along the surface of contact between the seat and buttocks.

Duration and magnitude of pressure were confirmed to be factors of pressure ulcer development in a 1959 publication by Kosiak. Kosiak applied known pressure loads and histologically examined tissue viability. It was found in the study that “microscopic pathologic changes were noted in tissues subjected to as little as 60mmHg for only an hour” (Kosiak, 1959).

However, in the 1970s, Reswick and Rogers published pressure curves that gave information on the non-injurious and injurious levels according to length of exposure. Although consistent with Kosiak’s findings, the study showed that pressures near a bony prominence are three to five times higher internally. Recently, it has been proposed that these curves can be modified to reflect that low pressures can be applied without damage occurring (Gefen, van Neirp, DL, & Oomens, 2008 ).

It is shown that skin temperature can modulate the effects of the pressure effects. Studies show that skin and soft tissue damage is reduced by localized cooling of the skin.

#### **2.4.2. Friction and shear**

Friction contributes to the development of shear stresses that ultimately result in pressure sores. The coefficient of friction is mainly influenced by the materials of both the clothing of the patient and the seat. Another factor is the surface wetness of the skin. When the skin is wet due to perspiration or ambient humidity, the moisture increases the coefficient of friction as well.

When a person is seated, pressure is applied to the skin surface causing the compression of body tissues. The resulting shear force distorts the adjacent tissue. Shear can reduce or prevent blood flow by direct compression of the blood vessels, bending of

the blood vessels perpendicular to the skin, and by stretching and narrowing the dermal capillary bed. Pressure and shear are closely related. Biomechanical modeling shows that at high levels of shear stress, only half as much pressure is required to produce blood vessel occlusion as when little shear is present (Bennett, Kavner, Lee, & Trainor, 1979). Conversely, when shear is absent, tissues can tolerate high pressures without blood flow occlusion (Linder-Ganz & Gefen, 2007).

### 2.4.3. Microclimate

The term microclimate in relation to pressure ulcers usually refer to the skin surface or tissue temperature and the humidity or skin surface moisture at the contact interface. As previously discussed, moisture increases the coefficient of friction and as a result, the shear stress. The temperature of the tissue is thought to have an effect on the development of pressure ulcers as well.

Pyrexia (raised body temperature) is a recognized risk factor for pressure ulcers (Bergstrom & Braden, 1992), (Nixon, Brown, & McElvenny, 2000) it is well known that an increase in body temperature by 1° C raises the need for oxygen and energy by about 10% (Fisher, Szymke, Apte, & Kosiak, 1978). This results in tissue perfusion being unable to meet the needs of the tissue. This suggests that a patient with an elevated body temperature exposed to pressure and shear may develop tissue damage more quickly, at lower levels and/or shorter durations of pressure/shear at normal body temperature (Brienza & MJ, 2005). This leads to the suggestion that increased skin temperature may cause the development of pressure ulcers.

In addition, temperature affects the strength of the stratum corneum: at 35° C the mechanical strength of the stratum corneum is 25% of that at 30° C (Flam & Raab, 2005).

There are some investigations relating the changes of local skin temperature with the impact of pressures on tissues. In an animal study, a known pressure (100 mmHg) was applied for specified hours along with heat indentors to 25, 35, 40 or 45° C. Moderate tissue damage was observed at 35° C and deep tissue damage at 40 and 45° C. However, there was no cutaneous or muscle damage where load was applied when the temperature was kept at 25° C (Kokate, Leland, & Held, 1995).



### 3. Preliminary Designs

#### 3.1. Preliminary design 1

Through the process of doing background research in existing designs, brainstorming, and discussions in feasibility of initial idea, the team created a preliminary design with the use of Computer Aided Design (CAD) programs, in this case Solidworks. In the following section, design set up, material selection and applicability of system is explained in order to describe the design process used to create this preliminary design.

The principle components of the initial preliminary design are broken down to the following parts: the wheelchair, gap pad, heat pipe, cooling fins and pipes that connect the heat pipe and cooling fin. Except for the wheelchair, each component was created in Solidworks and assembled together in order to create a three-dimensional sketch of the initial design. Snapshots of the entire wheelchair assembly can be seen in Figure 5 below.

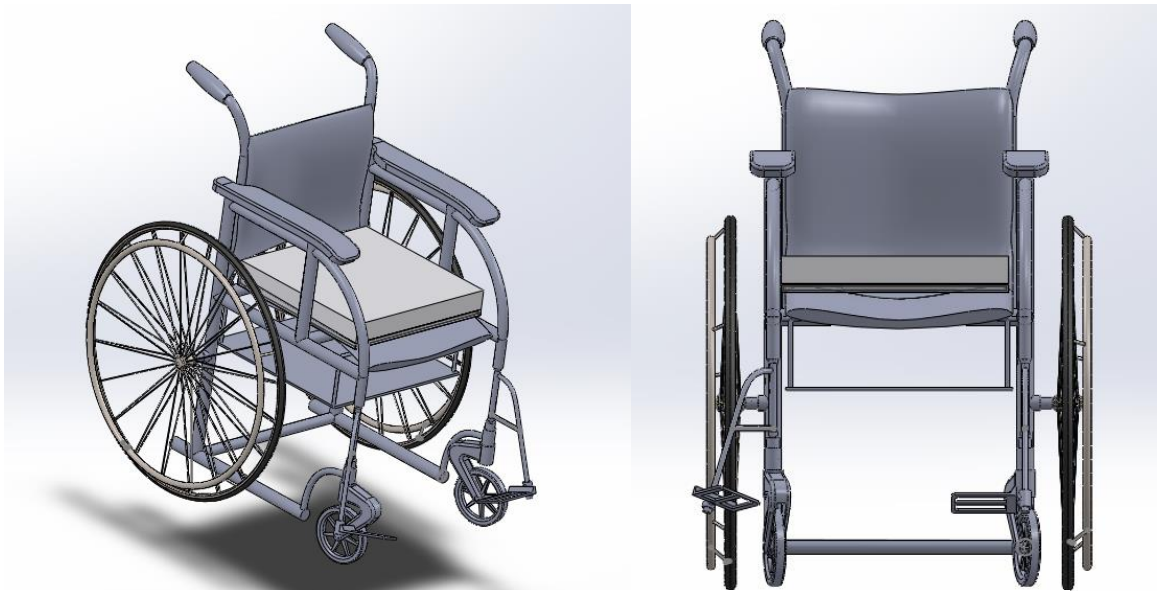


Figure 5 - Isometric and front view of entire wheelchair assembly

In the assembly above, the thick white sheet at the top of the wheelchair seat is the gap pad with a uniform thickness of 4 cm and rectangular dimensions of 41 cm by 41 cm. Located directly below the white gap pad is the heat pipe casing. In the figure below, the pipes that connect the heat pipe to the cooling fins can be seen more clearly. As we can see,

the pipes are wrapped tightly around the seat so that the pipe doesn't interfere with the wheels of the wheelchair. (The model of the cooling fin is clearly still missing in the design below and more work will be put into this section about the cooling fins in B-term) In addition, it can be seen that the pipes are connected into the heat pipe at different altitudes, this is to differentiate the inlet and outlet portion of the heat pipe.

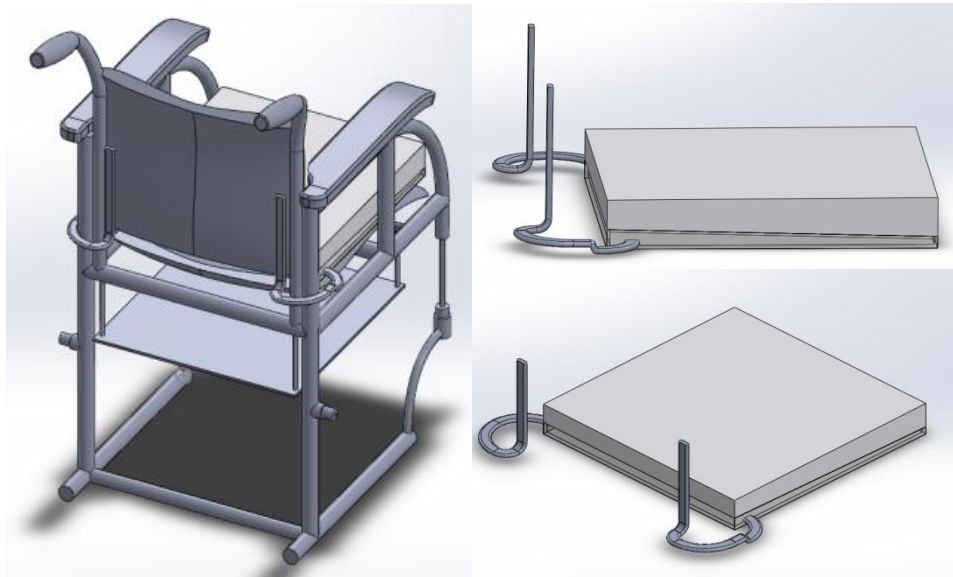


Figure 6 - Piping of the heat pipes

### 3.1.1. The wedge

As soon as initial Computer Aided Design (CAD) drawings were created, one of the most apparent issues with the heat pipe casing was originally designed with a uniform thickness for the sake of simplicity of manufacturing. The underlying issue with this however, was that potential air pockets could form in the front end of the heat pipe casing. Through the formation of gas bubbles by evaporation in the working fluid, the gas bubbles would naturally travel upward due to buoyancy forces. Assuming that the top layer of the heat pipe casing was parallel to the ground, gas bubbles would be trapped at the top layer and there would be no existing force that pushes the air bubbles toward one end of the casing. An illustration of such an issue is shown in the left side of the figure



below. If the bubbles were not pushed to one end of the casing, then only a limited amount of gas bubbles would be able to travel to the condensation chambers.

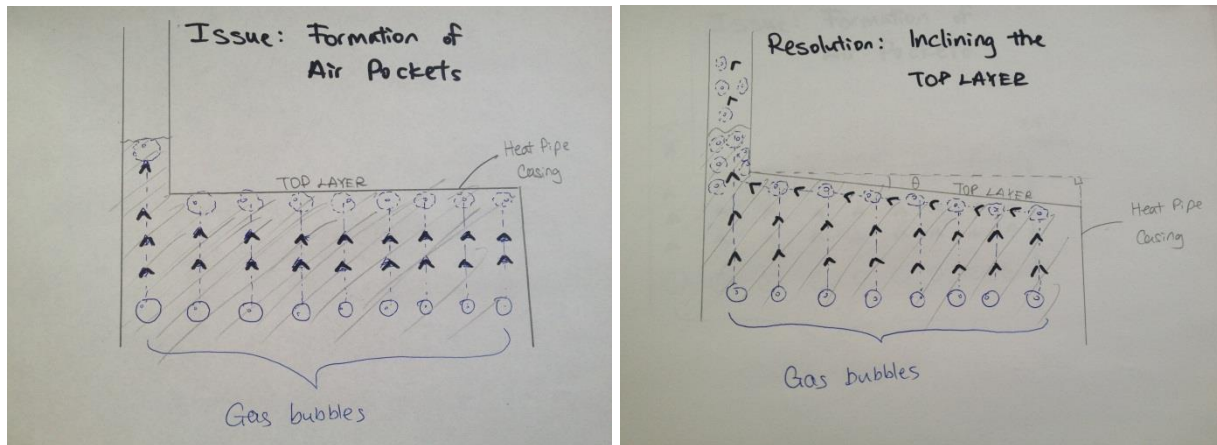


Figure 7 - Diagram of air pocket issue (left) & Diagram of resolution of issue (right)

In order to resolve this issue, the idea of simply inclining the top layer of the heat pipe was implemented into our design. A diagram of this resolution can be seen on the right side of the figure above with a CAD drawing below. With just a slight incline, we can see in the figure below that due to natural buoyancy, air bubbles will travel to a higher ground which is up and towards the new incline top layer. The pipe connected to the condensation chamber is linked at the end of this inclined top layer, to ensure that all of our formed gas bubbles travel up the pipe and resolve the issue of air pockets. In the design below, the slope of the incline of the top layer is approximately  $2.4^\circ$ , which is sufficient to allow gas bubbles to travel up the incline. In addition, the slope is small enough as well so that the inclined seat doesn't become a discomfort for wheelchair users. However, even if the slope were too steep, a simple solution to resolve this issue is to shape the gap pad so that when the gap pad is placed on top of the cooling pad, the two would form a flat rectangular box. A sketch of this solution theory can be found in Figure 9.

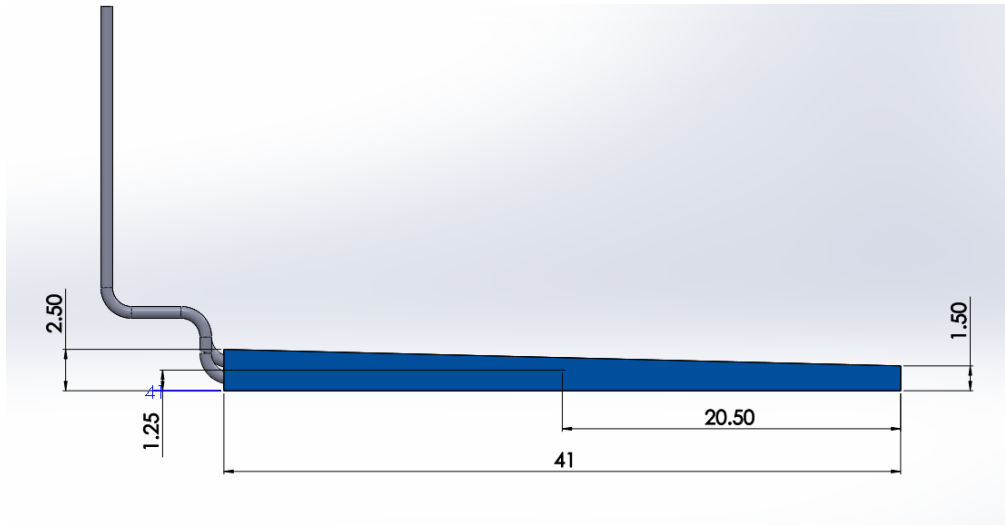


Figure 8 - Side view of inclined heat pipe casing

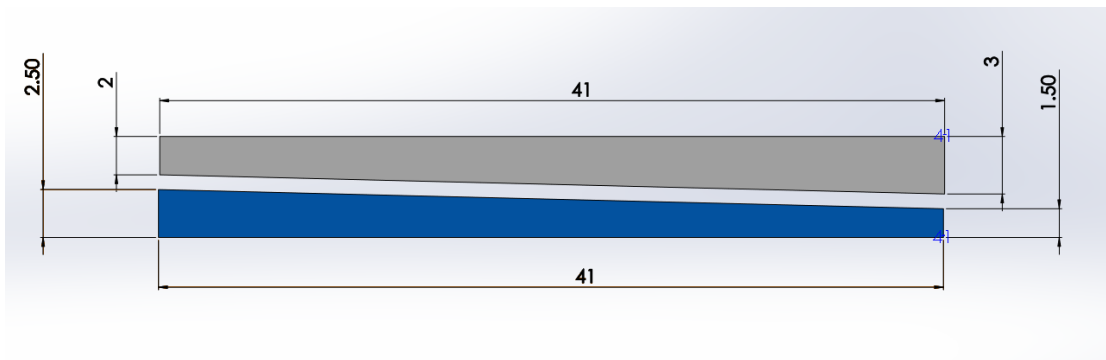


Figure 9 - Inclined gap pad and cooling pad

### 3.1.2. Material

The main function of the heat pipe is to transport the heat that changed the phase of the ammonia-water solution from inside the wedge to fins that will be attached to the wheelchair to dissipate the heat.

Factors of consideration for the material to use are that the material should be thermally conductive in order to adequately transport the heat from the ammonia water mixture to the fins. In addition to this, it would advantageous for the design to choose a heat pipe that is light-weight in order to minimize the additional force needed for wheelchair motion. Because the pipes will carry this ammonia-water solution that can be harmful on contact, it is vital to make sure that these pipes are robust with no chance of leakage or breakage. Because of all these considerations, copper was chosen to be the material of the heat pipe.

### 3.1.3. Working fluids

The working fluid for our system will be chosen based on the following considerations:

- Applicability to our system
- Availability of working fluid
- Environmental and health effects of the working fluid

The normal seat temperature range for someone sitting in a wheelchair for prolonged lengths of time is about 28-32 °C. Our system requires liquid to vapor phase change to occur below this temperature range. Phase change will provide effective heat dissipation from the body. The table below summarizes the investigation into the liquids that fit these criteria.

Table 1 - Working fluid comparison

Liquid	Boiling Point	Safety Hazard
Ammonium Hydroxide	32 °C	<ul style="list-style-type: none"><li>• Inhalation can cause severe burning of throat, nose and respiratory tract</li><li>• Skin exposure can lead to severe irritation and burns</li><li>• Ingestion will cause corrosive damage to mouth, throat, and stomach</li></ul>
3M Fluorinert™ FC-87	30 °C	<ul style="list-style-type: none"><li>• Low-toxicity levels</li><li>• Non-irritating to eyes and skin</li></ul>

### 3.1.4. Gap pad

In order for the body to be a working heat source, one of the most significant factors is that the material must be thermally conductive in order to transmit the heat to the working fluid.

$$Q_{Generated} = A * K_{Gel} \frac{(T_{Body} - T_{Heat Pipes})}{x_{Gel}}$$

In order to calculate the rate of heat transfer that takes place because of conduction, factors such as the cross-sectional area, the thermal conductivity of the gap pad, the temperature difference between the heat emission and heat absorption bodies and the thickness of the gap pad have to be taken into consideration. Using an energy balance between the two bodies, use the equation editor,

$$Q_{Req Phase Change} = Q_{Generated}$$

This heat generated is the amount of heat needed for phase change.

In order for the system to work and dissipate heat, there must be mass flow of the working fluid in the system according to the equation below.

$$m = \frac{Q_{Req Phase Change}}{(h_{Gas} - h_{Liquid})}$$

The thermal conductivity of the gap pad is one of the parameters that depend on the design that dictate the success of the project.

As previously stated, due to the fact that pressure is one of the most important factors to consider for pressure ulcers; one of the most effective means is to distribute the pressure to other parts of the contact interface to minimize concentrated pressure areas. Immersion and enveloping are two ways to distribute the pressure.

The surface area the patient covers while sitting dictates the effect pressure will have on the body where the larger the surface area covered, the smaller the effects of pressure on the body. As a result, it is ideal for the person to be slightly immersed in the seat to increase the surface area for pressure distribution. However, if the material is too soft, there is a possibility that the material would compress and the patient will be seated on the support surface of the seat. Related to this material property is enveloping. This is when the material contours according to the body and areas where pressure is applied to maximize comfort and minimize pressure. Degree of immersion and envelopment can be impaired by increased tension at the surface of the support especially when combined with the sagging of the support surface itself. This can be seen for instance in a hammock which prevents support surface molding into contours and produces high pressures over small areas.

As a result, the two most important factors to consider when choosing a gap pad is the thermal conductivity as well as the “hardness” and thickness of the gap pad.

Calculations for varying thermal conductivity as well as varying gap pad thickness can be seen in the Appendix A: Heat Transfer Calculation MatLab Codes.

### 3.2. Preliminary design 2

Some liquids considered as working fluid options were very corrosive. Stainless steel was found to be compatible with most of these working fluids and therefore been had selected as a preliminary material. Material compatibility sheets are given in Appendix F: Material Compatibility Chart.

Unfortunately, stainless steel for this design would have been very costly and therefore other material options were examined. Even though the wall-shaped replacements to the pipes allowed more heat to be exchanged, the increase in metal required for the entire system exceeded our budgetary constraints. As a possible solution to the excessive cost, a suggestion was made to use a combination of plastic and sheet metal. The sheet metal would then be used in only three locations: top/lid surface, and both outside walled surfaces. This design did decrease the cost significantly but because sealing the entire system with adhesive was very difficult without increasing the probability for leakages, the design was not implemented.

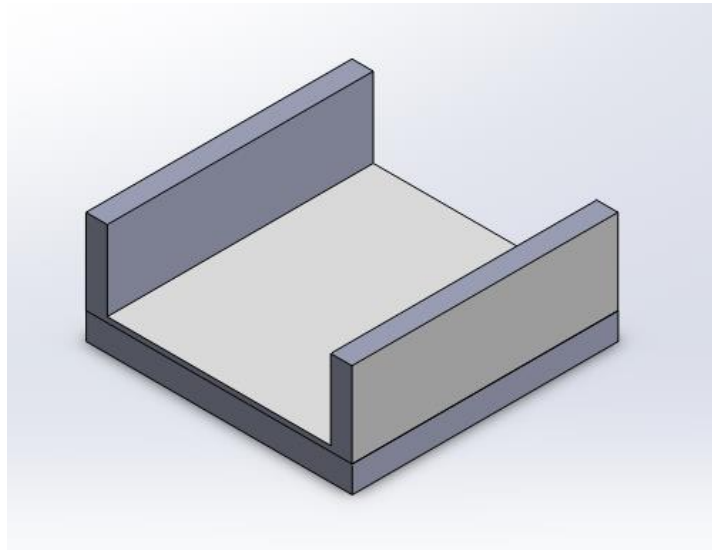


Figure 10 - U-Shaped Design

## 4. Final Design

### 4.1. Fluid selection

The fluid selection was based on the following criteria:

- Compatible Temperature range
- Budgetary Constraints
- Environmental and Hazard Identification

The temperature range for the system will be from 22°C to 27°C. Initially Ammonium Hydroxide had been investigated as an adequate working fluid for the given temperature range but the commercially available solutions were not concentrated enough. Commercially available ammonium hydroxide solutions consisted of approximately 30% ammonia. With this concentration the solution would have vaporized at 31-32°C (dependent on exact concentration), which is greater than the required temperature range. A 33-34% concentrated solution of ammonium hydroxide would have provided the appropriate temperature range. Through the team's consultation with Professor Dittami from WPI, the Chemistry Department of WPI confirmed that although it is possible to increase the concentration of ammonia in ammonium hydroxide, it is difficult to monitor or evaluate the specific concentrations of ammonia without sophisticated instruments and processes. Following this consultation, other solutions that would give the appropriate temperature range for possible working fluids were investigated and finally determined that lowering the boiling point by depressurization would be the most suitable option. The Clausius-Clapeyron equation was used to determine the amount of vacuum that was to be created within the system.

$$\ln\left(\frac{P1}{P2}\right) = \frac{\Delta H_{vap}}{R} \left(\frac{1}{T1} - \frac{1}{T2}\right)$$

Liquids with boiling points below 50°C were considered. The following table presents calculations<sup>1</sup>:

Table 2 – Pressure Calculations

Liquid	R J/mol-K	$\Delta H$ J/mol	T1 °C	T1 (K)	T2 (27°C)	P1 (atm)	$\Delta H/R(1/T1-1/T2)$	P2 (atm)
Ether	8.314	29000	35	308	300	1	0.30199934	0.739339
Pentane	8.314	26700	36	309	300	1	0.311791317	0.732134
Methylene Chloride	8.314	28600	39.8	312.8	300	1	0.469221586	0.625489
Methyl Iodide	8.314	28410	42.6	315.6	300	1	0.563024849	0.569484

Out of the aforementioned liquids the options were narrowed to Methylene Chloride and Ammonium Hydroxide based on their handling and storage specifications.

With the help of a vacuum, the desired boiling point temperature could be reached within both liquids. Using the Clausius-Clapeyron equation, the pressure required to boil methylene chloride at 27 °C was calculated to be 0.625 atmospheric pressure (atm). To boil ammonium hydroxide at 27 °C, the desired vacuum was found to be approximately 0.8 atm.

Another very important impact to consider was the availability of the liquid. Ammonium Hydroxide was readily available at many chemical companies and more importantly was stored in plastic and glass containers. Since storage and safety are two very important factors in the fluid selection process, having a liquid that was stored household containers was a key component of the final decision.

The enthalpy-mass fraction chart below was used to determine the appropriate vacuum level for the ammonium hydroxide:

<sup>1</sup> Liquid properties obtained from <http://www.thermo.com/research/kdb/hcprop/showprop.php?cmpid=818>

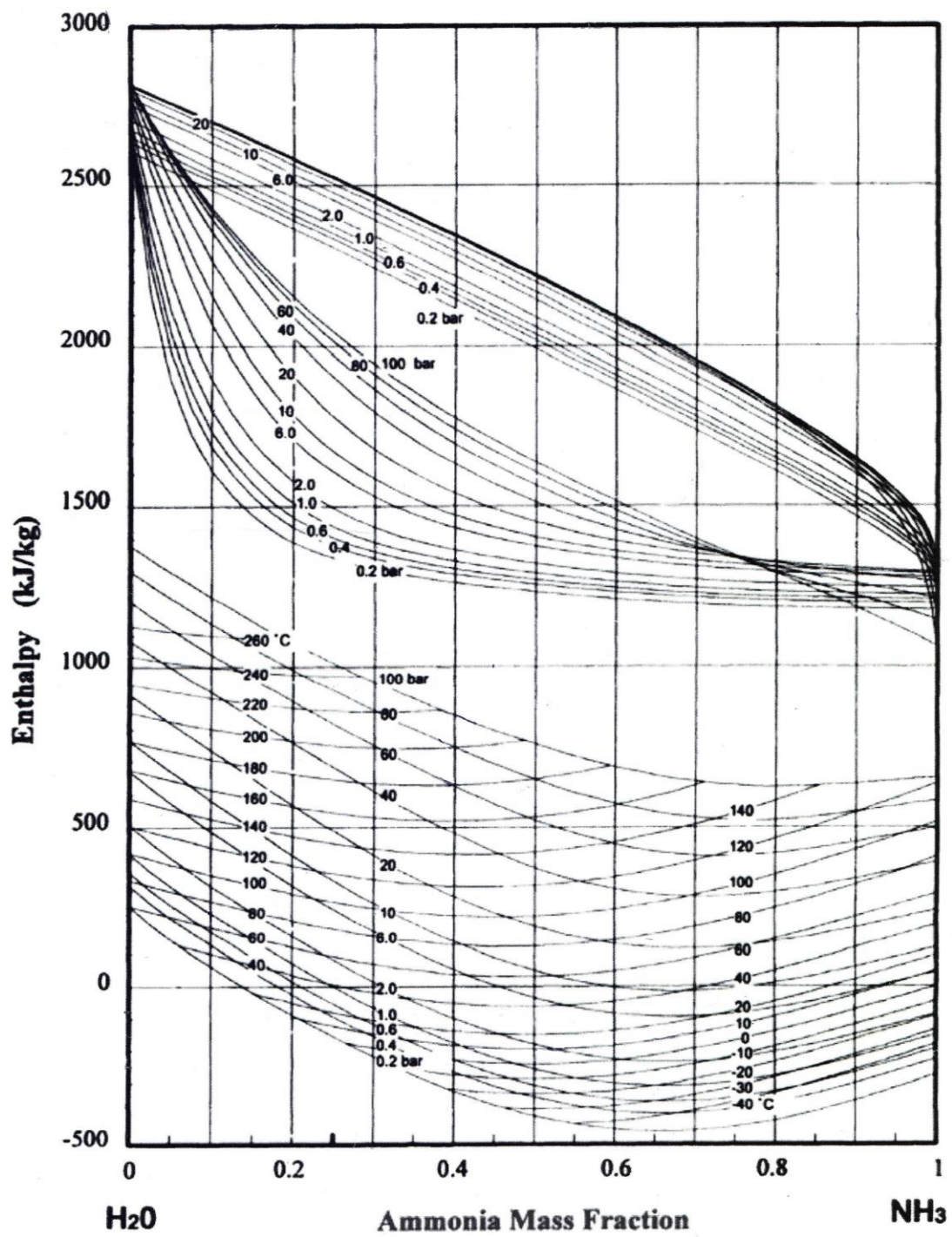


Figure 11 - Enthalpy mass fraction chart



Environmental and safety hazards were a major concern for the project and therefore safety was a crucial deciding factor for the working fluid selection. Hazards identification summary for each liquid using MSDS provided by VWR are given below:

Ammonium Hydroxide:

- Corrosive to eyes and skin
- Ingestion may cause burns to mouth, throat, and stomach
- Very toxic if inhaled
- Severe organ damage may occur due to prolonged exposure

Methylene Chloride/Dichloromethane

- Corrosive to skin and eyes
- Harmful if ingested with possible severe irritation of the gastrointestinal tract
- Inhalation causes respiratory tract irritation, headaches, and drowsiness.  
Prolonged exposure to high concentration of vapors may result in unconsciousness and central nervous depression
- Carcinogenic effects seen within animals
- Possible cancerous effects

Taking into account all the criteria mentioned above we decided to choose Ammonium Hydroxide as the working fluid for our system. Ammonium Hydroxide was better suited for the system because:

- I. Ammonium Hydroxide would not have needed to be depressurized as much as methylene chloride
- II. Remaining within our budget for the entire system was very important to us and therefore the price difference was vital to the group's decision
- III. Even though both liquids were equally toxic, the possible carcinogenic effects of methylene chloride prompted us to favor ammonium hydroxide
- IV. Ammonium hydroxide is stored in glass bottles. In case there is a need of pouring the working fluid into other containers, finding glass containers would be convenient.
- V. Ammonium Hydroxide is readily available compared to the methylene chloride.

## 4.2. Construction material selection

Material Selection was dictated by the following:

- Working Fluid Compatibility
- Thermal Properties
- Budgetary Considerations
- Machinability

Because ammonium hydroxide had been chosen as our working fluid we were limited to very few compatible materials. Plastic materials were available such as PVC were compatible with ammonium hydroxide but did not provide good thermal properties. Carbon steel and stainless steel provided good thermal properties and were chemically compatible with the chosen working fluid. After comparing the properties of both stainless steel and carbon steel it was determined that carbon steel would be the better material choice for the cooling system. Carbon steel proved to be more cost effective than stainless steel because it provided a better thermal conductivity while being corrosion resistant to ammonium hydroxide.

Properties of carbon steel and stainless steel are given below:

Properties	Carbon Steels	Alloy Steels	Stainless Steels	Tool Steels
Density (1000 kg/m <sup>3</sup> )	7.85	7.85	7.75-8.1	7.72-8.0
Elastic Modulus (GPa)	190-210	190-210	190-210	190-210
Poisson's Ratio	0.27-0.3	0.27-0.3	0.27-0.3	0.27-0.3
Thermal Expansion (10 <sup>-6</sup> /K)	11-16.6	9.0-15	9.0-20.7	9.4-15.1
Melting Point (°C)			1371-1454	
Thermal Conductivity (W/m-K)	24.3-65.2	26-48.6	11.2-36.7	19.9-48.3
Specific Heat (J/kg-K)	450-2081	452-1499	420-500	
Electrical Resistivity (10 <sup>-8</sup> Ω-m)	130-1250	210-1251	75.7-1020	
Tensile Strength (MPa)	276-1882	758-1882	515-827	640-2000
Yield Strength (MPa)	186-758	366-1793	207-552	380-440
Percent Elongation (%)	10-32	4-31	12-40	5-25
Hardness (Brinell 3000kg)	86-388	149-627	137-595	210-620

Figure 12 - General properties of steels<sup>2</sup>

<sup>2</sup> Table Extracted from

[http://metals.about.com/gi/o.htm?zi=1/XJ&zTi=1&sdn=metals&cdn=b2b&tm=16&gps=119\\_13\\_824\\_896&f=00&tt=2&bt=1&bt\\_s=1&zu=http%3A/www.efunda.com/materials/alloys/alloy\\_home/steels\\_properties.cfm](http://metals.about.com/gi/o.htm?zi=1/XJ&zTi=1&sdn=metals&cdn=b2b&tm=16&gps=119_13_824_896&f=00&tt=2&bt=1&bt_s=1&zu=http%3A/www.efunda.com/materials/alloys/alloy_home/steels_properties.cfm)

### 4.3. Seal

As previously discussed, the solution to obtain the desired temperature for phase change is to depressurize the container to 0.8atm. Sealing the container is extremely important first and foremost, due to safety reasons. Inhalation of ammonium hydroxide gas at such high concentrations is hazardous to health. In addition to the safety concerns, in order for the phase change to occur at the desired temperature, the pressure needs to be at a constant 0.8atm.

An O-ring, which is usually installed in a machined groove between two surfaces, seals these two surfaces by blocking the fluid flow. As compression force brings the two surfaces together, the O-ring is squeezed to fill in the space between the two surfaces. The elastomer, the O-ring material, is responsible for the making the O-ring a good seal. It is capable of remembering its original shape for a long time despite the squeeze due to its highly viscous, incompressible fluid properties with high surface tension (NewDealSeals).

The choice of using an O-ring was made due to the advantages O-ring sealing had over other methods such as welding or adhesion. Although the system does not operate in extreme temperatures, O-rings are able to seal over a wide range of pressure and temperature including the desired temperatures. O-ring failure is very gradual and can easily be identified. Because the O-ring is subject to compression in the system, the O-ring will fail when it no longer retains its original shape. In addition to this, O-rings are cost effective, require very little room and are light weight. There are basically two types of sealing: static sealing where there is no moving part such as the system and dynamic sealing that involves reciprocating, rotating and oscillating motion (NewDealSeals).

There are several factors to consider when choosing an O-ring such as the following:

- Size
- Durometer
- Chemical compatibility

The system requires a static sealing that experiences external pressure as the pressure externally is greater than the internal pressure. As a result, the inside diameter of the O-ring

should correspond to the inside diameter of the groove or be slightly smaller (1-3%) (NewDealSeals).

The cross-section of the O-ring also determines the characteristic of the seal. A large cross-section area was chosen because of its superior reaction to compression forces compared to an O-ring with a small cross-section. However, there are also disadvantages that result from choosing a large cross section such as its poor physical properties in terms tensile strength and elongation. Because the O-ring is under compression forces rather than tension forces, a larger cross-section was deemed to be the appropriate choice (NewDealSeals).

With respect to the system, the variation in the outside diameter of the O-ring was a significant factor in the weight increase. The size was determined based on the amount of area required to seat an individual within the seat without going past an overall system weight of 30 pounds. The 30 pound mark was set so that there was enough depth of cut within the bottom plate to support the appropriate amount of liquid required to support the heat transfer cycle. Also, size and cost increased proportionately and therefore remaining under budget was an essential consideration. After considering many different diameters, the group determined that a 15.25" diameter was the ideal size for the system. When choosing the cross section, Kevin Arruda had advised the group to select the maximum cross-section available for ease of machining as well. A larger cross-section would reduce the possibility of error when creating the O-ring groove. O-ring cross-sections were standard across many commercial websites An O-ring with a cross section of 0.275" was selected

The material of the O-ring is determined to be silicone based on a number of factors such as the durometer and chemical compatibility. Because the range of the temperature is very small, the effects of temperature such as thermal expansion were not taken into account.

At very low pressures, O-rings with lower hardness such as 50-60 Shore A would properly seal the system. However, determining the proper seal for a system with high pressure requires consideration of the pressure applied as well as the shore hardness. For the system of interest that does not fall into either ends of the spectrum, a hardness of 70 Shore A is an appropriate choice (NewDealSeals)

The chemical compatibility of the O-ring was of great importance as the ammonium hydroxide is known to corrode certain elastomers. A careful examination of the O-ring handbook ensured that O-rings made of silicone would be compatible with ammonium hydroxide (NewDealSeals).

All manufacturers of O-rings with a durometer of 70 such as silicone-based O-rings advised that the O-rings should not be compressed passed 30% of their original height. The possibility of O-ring fracture would increase if the compression force on the O-ring cross section exceeded the 30%

As a result of the compression force for a the silicone O-ring, manufacturers such as Apple Rubber compute tables in order to determine the dimensions of the groove in order to ensure that the O-ring will not be compressed to more than it should. As a result, a groove width of 0.3 and a gland depth of 0.169 inches are chosen.

#### 4.4. Shape and dimensions

With the support from John Sullivan, Kevin Arruda and Peter Hefti, contributing advice from a thermal, manufacturing and application stand points, the team was able to finalize the design of the prototype as seen in Figure 13. To begin, it was determined that the shape of the entire design consist of a circular shape in order first allow optimal sealing ability by using an O-ring seal; and secondly, according to Peter Hefti and Kevin Arruda, a circular shape will ease the process of depressurization. The detailed description of the shape and dimensions of this prototype will be portrayed through two different sections: the top plate and bottom plate.

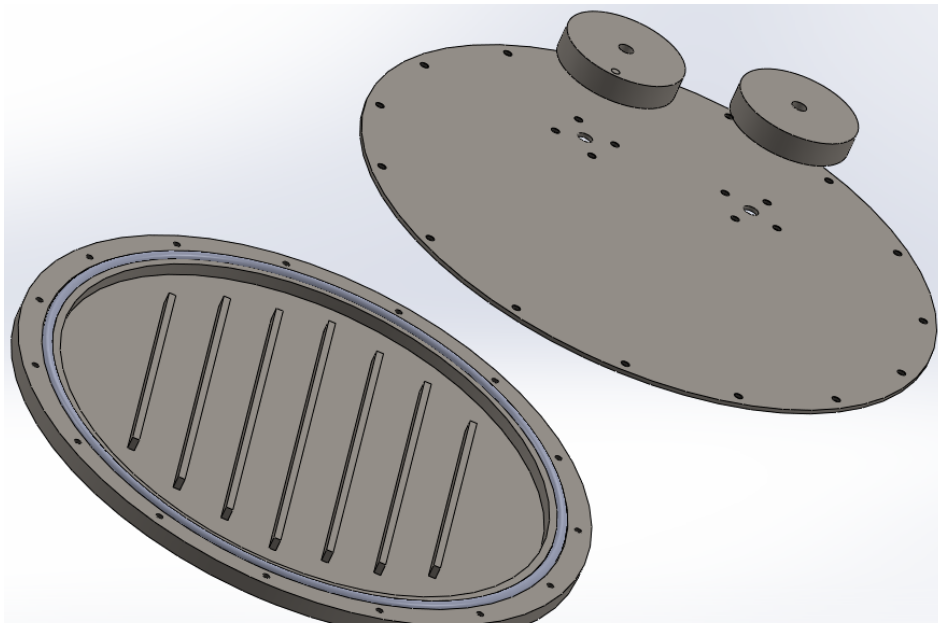


Figure 13 - Isometric view of final design

#### 4.4.1. Bottom plate

The bottom plate consists of three main features. In order to seal the top and bottom plates, first an O-ring groove will be utilized in this model in order to seal the top and bottom plates. A cross-sectional view of this O-ring groove is shown in Figure 14.

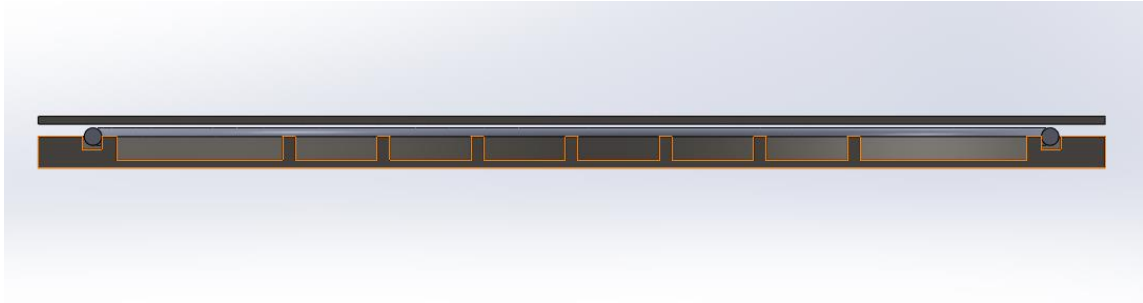


Figure 14 - Cross-sectional view of final design

Secondly, within the O-ring groove of the bottom plate, the team will use Computer Numerical Controlled (CNC) machines to create a cylindrical pocket inside the O-ring groove in order to fill the prototype with ammonia hydroxide. In order to aid the direction of evaporation of gas bubbles and also for structural integrity purposes, thin rectangular grooves will be left in the pocket as shown in Figure 15.

Finally, in order to bind the top and bottom plate together, 15 size #7 threaded screw holes were placed in equal distance around the edges of the bottom plate. Each screw is blind tapped through the bottom plate 0.4 inches deep.

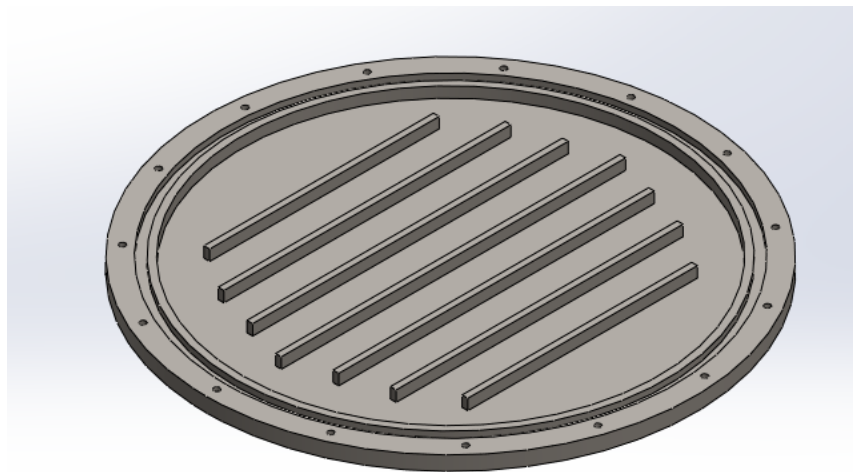


Figure 15 - Isometric view of bottom plate

#### 4.4.2. Top plate

The top plate consists of two main features: fifteen #7 screw holes (unthreaded) that line up with the holes in the bottom plate in order to bind the top and bottom plates. From figure below, we can also see two sets of holes located near the center to the plate which will be used to bind the flanges to top plate. All of the holes on the top plate are non-threaded.

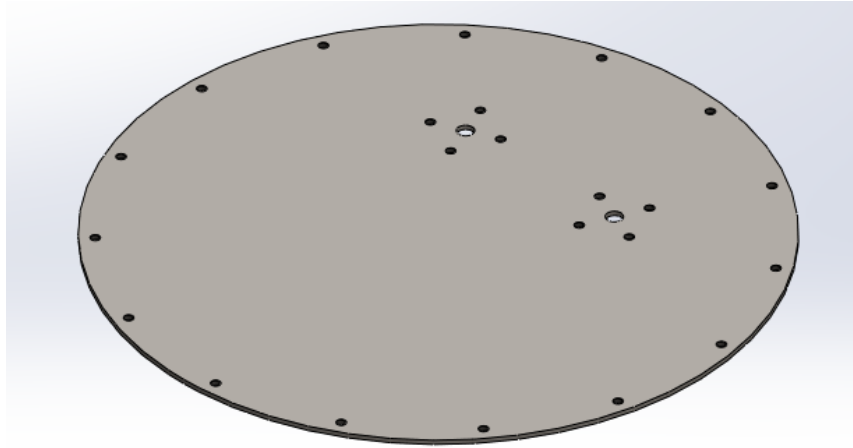


Figure 16 - Isometric view of top plate

The center hole located in the middle of one set of holes is surrounded by four smaller ones. The four holes surrounding the center hole will be used for the binding screws to bind the flange and top plate; these four holes will be the same screw size as the screws that connect the top and bottom plates. The center hole will be used to connect a 0.5 inch pipe from both ends.

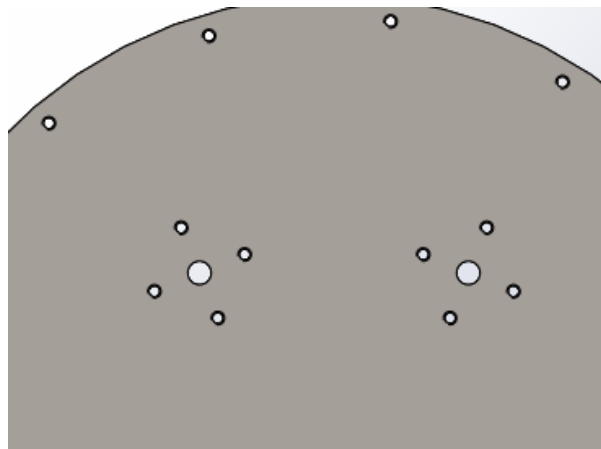


Figure 17 - Close up of hole sets

#### 4.4.3. Flange

As shown in the two views in figure below, we can see that in this 3.5 inch diameter flange, there is one threaded through hole for the pipe located on the center of the flange. On one side of the flange, just as the pattern on the top plate, four smaller holes surround the center hole. In order to fully seal the flange to the top plate, an O-ring groove will be cut outside the 5 holes in order to enclose them.

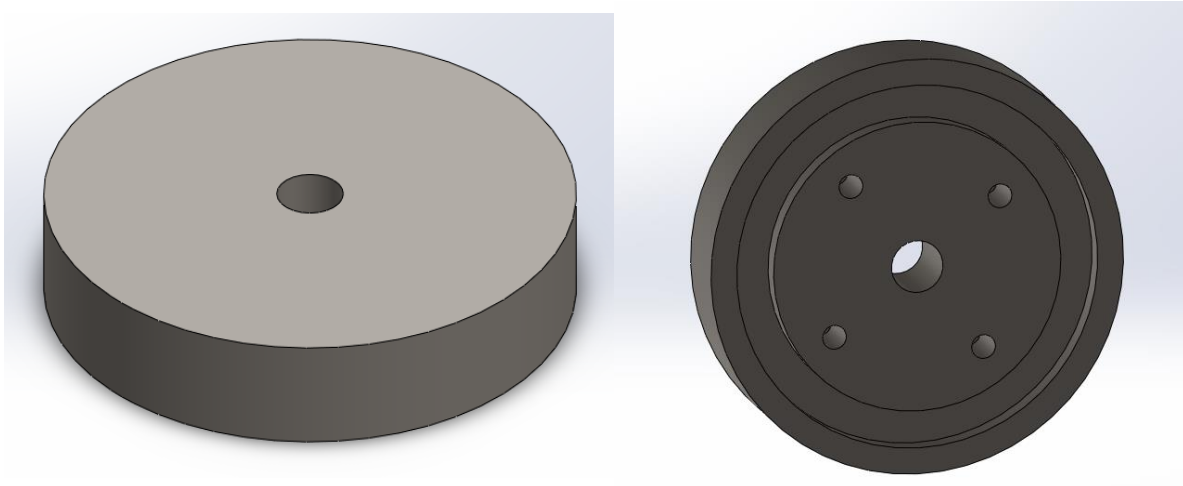


Figure 18 - Isometric view of flange (left) & bottom view of flange (right)

#### 4.5. Pipe design

An Important parameter to consider when designing the pipe system is first and foremost, the chemical compatibility with the two phases of both vapor and liquid ammonium hydroxide. Because of the presence of water in the solution, rust becomes a matter of concern as well.

The first pipe is designed to have a cross fitting (four openings) attached to the threaded pipe. Two of these holes will have be the entry and exit openings for the pipes while the remaining two holes will have a pressure gage attached as well as a valve used to empty the contents of the system.

On the other pipe, a tee shaped fitting will be placed and similar to the first pipe, two of these holes will have the entry and exit openings of the pipes. However, the remaining opening will serve the purpose of fitting in the vacuum pump in order to bring the pressure of the system down to 0.8 atm.



#### 4.6. Heat cycle

After careful consideration of possible methods of manufacturing the heat pipe design model, it was determined that depressurizing the system would be the most feasible in all the design due to the main fact that concentrating ammonium hydroxide to our targeted concentration would be too difficult. From our calculations, if the pressure were to be lowered to approximately 0.8 atm, then the temperature of evaporation would only be

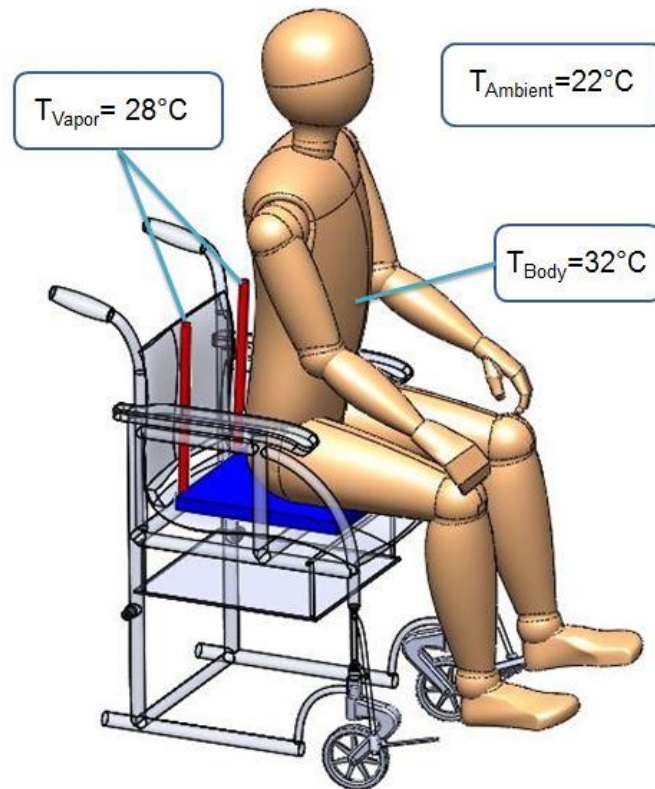


Figure 19 - Heat cycle temperature difference

approximately  $28^{\circ}\text{C}$ . As we can see in Figure 19, this temperature of evaporation would be sufficient enough for surface body temperature ( $\sim 32^{\circ}\text{C}$ ) at the hands and butt to evaporate the working fluid. Once the working fluid evaporates into vapor, the vapor will travel up into the second vertical compartment where heat will be dissipated into the environment and finally condensate and flow back into the system.

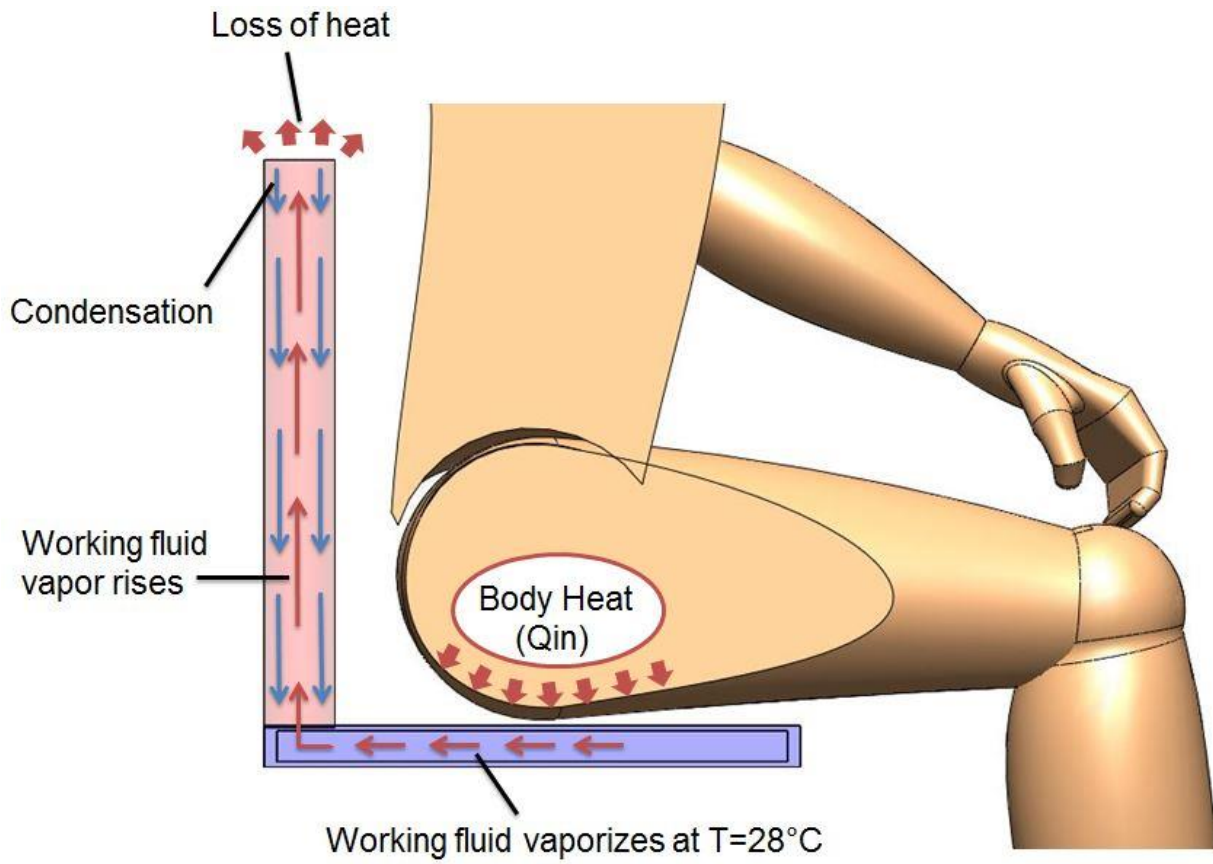


Figure 20 - Wheelchair heat cycle diagram

## 5. Testing & Results

### 5.1. Test tube verification test

In order to examine and explore the efficiency of heat transfer in the project's design, an experiment was designed to model our heat pipe's heat transfer mechanism and system. As shown in Figure 21, a proposed image can be seen of how the experiment was set up. In the experiment, a single test tube with a fixed concentration of ammonium hydroxide was partially submerged into different temperatures of water. The temperature change over different locations on the test tube was collected and examined. The different temperatures that our test tube will be submerged into were the following four: 4°C, 23°C, 28°C, and 40°C. These four are chosen to represent a cold, ambient, body and hot temperature. In Figure 22, we can see the proposed locations where the change of temperature was collected over time. (A more specific report on procedure and details of this experiment can be found in Appendix D: Heat Pipe in Test Tube Experiment)

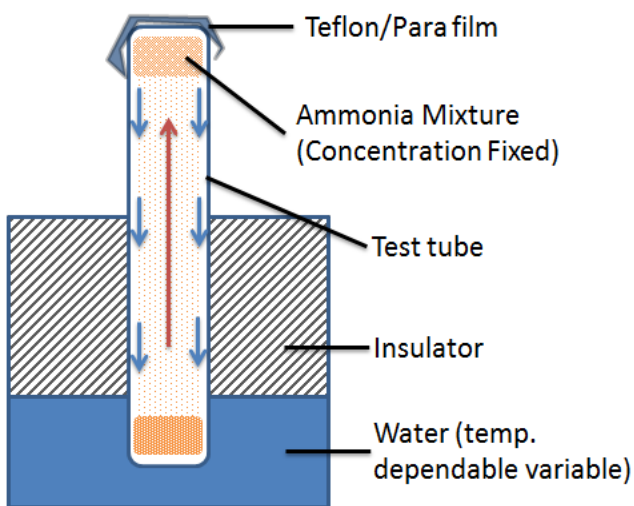


Figure 21 - Experiment set up

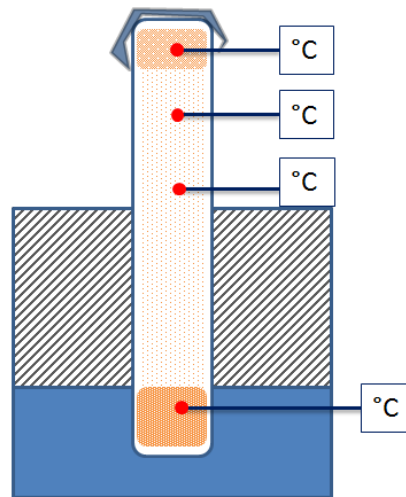


Figure 22 - Proposed locations of thermal couples

### 5.2. Testing with actual model

The objective of the following tests was to prove two concepts previously explored. The first concept to prove was that by bringing the ammonium hydroxide to boiling point, the vapor of this working fluid was able to transfer heat as per definition of a heat pipe. This was shown by monitoring the temperature change at the top of the steel pipe which was determined to be the location where vapor would rise to. A sixteen-point vertical

thermometer with adhesive backing was used to measure the temperature change. These temperature-indicating strips had a range of 14°C to 31°C fitting well into the temperature range that the heat cycle would perform. With an accuracy of  $\pm 1^\circ\text{C}$ , the temperature indicator made use of liquid crystal technology. The green shade displayed the actual temperature, the brown shade displayed the temperature above the actual temperature and the blue showed the temperature below the actual temperature. The reason why these temperature indicators were used instead of thermocouples which would capture more accurate temperature changes over time was due to the manner in which the tests were conducted.

Making safety a top priority during the testing phase, all necessary precautions were taken. In addition to working under a fume hood at all times in case of a leak, protective gloves, masks and goggles were worn during the testing period. Additional safety tests were performed to ensure that the cooling system would not leak toxic ammonium hydroxide fumes. These tests were performed in three phases. Firstly, after all the parts of the cooling system were assembled, the cooling system was pressurized to 20 psi and a leak detector was applied to all the connection joints of system as these are the parts most vulnerable to leakages. Small bubbles will appear in areas where there are leakages. When the cooling system has passed the first leak test, the system which is already pressurized to 20 psi is left at the lab for 12 hours in order to monitor leakages. If there is a change in pressure, the leak detector is once again applied in order to locate the leakage. The cooling system is then reassembled and the process repeated. When the system passes the 20 psi test, it is then pressurized to 40 psi and left for another 12 hours to monitor any change in pressure. It is only when the system passes this 40 psi test that the air is evacuated, the ammonium hydroxide solution is poured into the system and the chamber is depressurized. Despite these safety tests, all tests done on the system that contains ammonium hydroxide is carried out in the hood. As a result of working under a hood, it was more convenient to use temperature indicators as there was spatial constraint in the lab for a temperature reading set up using thermocouples.

Placing the cooling system on a hot plate which was kept at a steady 85°C, the ammonium hydroxide was brought to a boil. The time taken to reach the boiling point was monitored through the pressure gage which started displayed an increase in pressure. Initially

the cooling system was depressurized using a vacuum pump to a pressure of -7.5inHg and after 2 minutes of heating. The objective to show the working process of the heat pipe is realized by the increase in temperature at the top of the steel pipes attached to the cooling system. As the heat from the hot plate boils the ammonium hydroxide, the rising gas carries the heat to the top of the pipe, heating up the area up as well. As a result, a change in temperature can be recorded at this location which is measured by the temperature indicator. The graph below shows the change in temperature at the top of the pipe with respect to time.

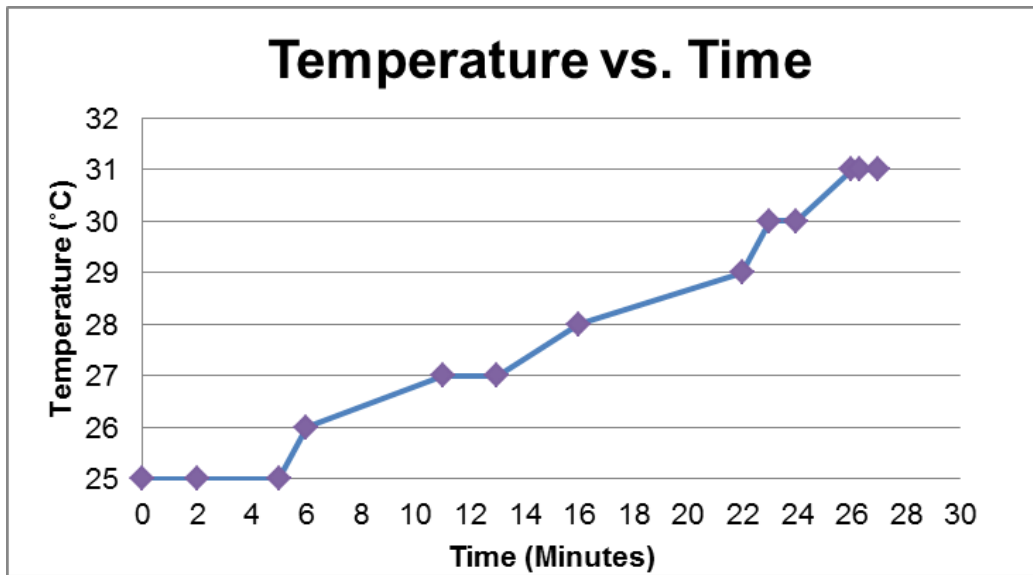


Figure 23 - Temperature vs. Time (top of pipe)

The second objective is show the safety model of the design. As proposed, the pressure build up from evaporation could be a safety hazard. However, the nature of the fluid shows that an increase in pressure results in an increase in the boiling point of the fluid. As the cooling pad is heated and the pressure builds up in the chamber, the boiling point rises to a higher point than the current temperature of the working fluid. As a result, the vapor condenses resulting in a decrease in pressure. The graph below shows the change in pressure with respect to time.

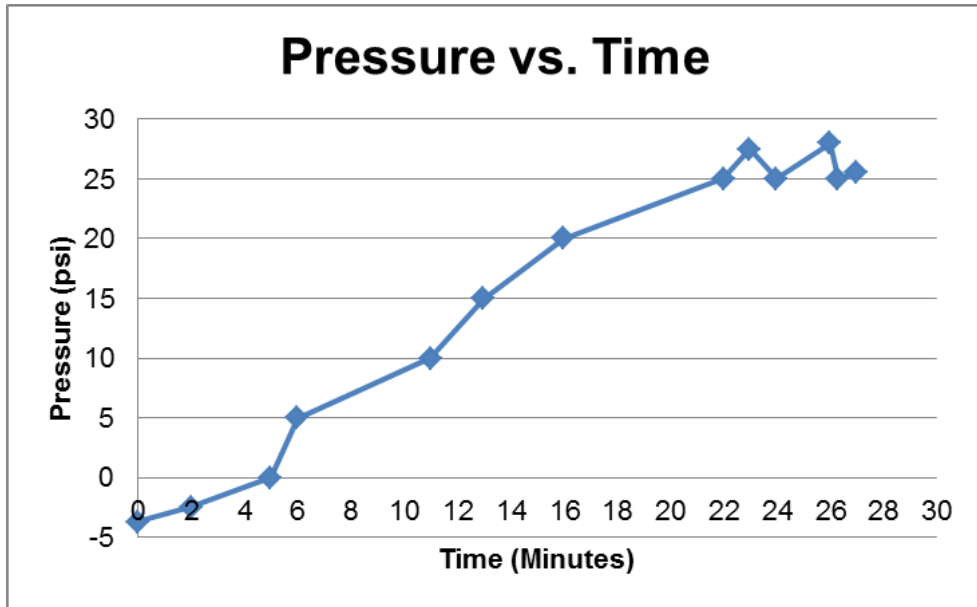


Figure 24 - Pressure vs. Time

It is to be noted that after 23 minutes of heating, the increase in pressure suddenly drops from 27.5 psi to 25 psi. It then increases to 28 psi and then drops back down to 25 psi again. As this fluctuation is occurring, there is audible confirmation of the vapor phasing back to liquid state.

## 6. Conclusions & Recommendations

The results confirmed that the cooling system verified the concept of a functional heat pipe. As the system was heated, heat was transferred to the pipes and dissipated to the surroundings as demonstrated by the increasing temperature at the top of the pipe. In addition, the pressure recordings confirmed effects of pressure on the phase change temperature of our working fluid. When the increase in pressure resulted in an increase in the boiling point of the working fluid, the phase change from gas to liquid was verified by the decrease in pressure. Although this model successfully proved the concept of heat transfer of heat pipes, it is important to explore the limitations of this prototype.

It is important to explore other working fluids with low boiling points. Reasons to do so is because although the system passed all the tests to ensure that it was leak proof, it is very hard for a system to be completely sealed for long. As a result, the potential risks of ammonium hydroxide fumes should be considered especially if the user is confined to inhaling the fumes. When choosing this working fluid, material compatibility is an important factor to take note of.

Because ammonium hydroxide has selective compatibility with metals, a working fluid that is compatible with metals with high thermal conductivity such as copper or aluminum is preferred. A high thermal conductivity will ensure that the time taken to initiate the cycle will be reduced which starts the cooling process faster. Another factor that will initiate the cooling cycle quicker is to insulate the bottom plate as well. Learning from previous failed tests, a thermally conductive bottom plate aids in dissipating the heat input, which does not start the cooling cycle. The new design proposed is an integration of different materials such as a thermally conductive top plate joined to a bottom plate made of an insulating material. It is highly recommended that polymers should be explored for material substitution.

A higher thermal conductivity for the top plate will also decrease the effect of introducing a gel pad that is thermally conductive yet soft and can distribute pressure evenly as well. While the cooling system solves the problems that come with effects of heat, an additional gel pad which distributes the pressure load will successfully promote the cooling pad to be a system that mitigates bed sores providing a solution to both the pressure aspect as well as the heat aspect of the development of pressure sores.

The final assembly weighed in approximately 30 lbs. which is not ideal for a wheel chair confined user. However, if the bottom plate is made of a polymer, this will significantly reduce the weight of the cooling system. It is also recommended to reduce the thickness of the top plate which will not only cut the total weight of the system but will also cause conduction to take place quicker and the cooling cycle to start in a shorter time.



## References

- Acrolab. (2008). *Isobar Heat Pipe*. [Web Photo]. Retrieved from <http://www.acrolab.com/products/isobars-heat-pipes.php>
- Ahmad, H. H., & Rajab, R. H. (2010). *An Experimental Study of Parameters Affecting a Heat Pipe Performance*. College of Engineering Univeristy of Mosul.
- Bennett, G., Dealey, C., & Posnett, J. (2004). *The cost of pressure ulcers in the UK*. London: Barts and the London, Queen Mary's School of Medicine and Dentistry.
- Bennett, L., Kavner, D., Lee, B., & Trainor, F. (1979). Shear vs pressure ascausative factors in skin blood flow occlusion. *Arch Phys Med Rehabil*, 60(7): 309-14.
- Bergstrom, N., & Braden, B. (1992). A prospective study of pressure sore risk among institutionalized elderly. *J Am Geriatr Soc*, 40(8):747-758.
- Berlowitz, D., et al. (2008). *Preventing Pressure Ulcers in Hospitals*. Retrieved from <http://www.ahrq.gov/professionals/systems/long-term-care/resources/pressure-ulcers/pressureulcertoolkit/putoolkit.pdf>
- Brienza, D., & MJ, G. (2005). Using support surfaces to manage tissue integrity. *Adv Skin Wound Care*, 18:151-57.
- Colquitt, L. W. (1973). *Correlation of Heat Pipe Parameters*. Georgia Institute of Technology.
- Cooper, R., Ohnabe, H., & Hobson, D. (2007). *An Introduction to Rehabilitation Engineering*. [eBook]. Retrieved from [http://books.google.com/books?id=K\\_R2ceF1W6oC&printsec=frontcover&source=gbs\\_ge\\_summary\\_r&cad=0#v=onepage&q&f=false](http://books.google.com/books?id=K_R2ceF1W6oC&printsec=frontcover&source=gbs_ge_summary_r&cad=0#v=onepage&q&f=false)
- Drienza, D., & Geyer, M. (2005). Using support surfaces to manage tissue integrity. *Adv Skin Wound Care*, 18:151-57.
- Duffy, J., Jiajitsawat, S. & Wang, J. (2007). *Heat Pipe Application*.
- Fisher, S., Szymke, T., Apte, S., & Kosiak, M. (1978). Wheelchair cushion effect on skin temperature. *Arch Phys Med Rehabil*, 59(2):68-72.
- Flam, E., & Raab, L. (2005). What is low air loss therapy? *European Pressure Advisory Panel, 8th EPUAP Open Meeting*.
- ForSteel. (2008). *Heat Pipe Technology*. [Web Photo]. Retrieved from <http://www.forsteel.cz/heat-pipes.html>
- Gefen, A., van Neiroop, B., DL, B., & Oomens, C. (2008 ). Strain time cell-death threshold for skeletal muscle in a tissue engineered model system for deep tissue injury. *J Biomech*, 41(9): 2003-12.
- Jansson, D. (2010). *Heat Pipes*. Retreived from [http://www.arrl.org/files/file/QEX\\_Next\\_Issue/Jul-Aug\\_2010/Jansson.pdf](http://www.arrl.org/files/file/QEX_Next_Issue/Jul-Aug_2010/Jansson.pdf)

- Kokate, J., Leland, K., & Held, A. e. (1995). Temperature-modulated pressure ulcers: a porcupine model. *Arch Phys Med Rehabil*, 76(7):666-73.
- Kosiak, M. (1959). Etiology and pathology of ischemic ulcers. *ArchPhys Med Rehabil* , 40(2): 62-69.
- Linder-Ganz, E., & Gefen, A. (2007). The effects of pressure and shear on capillary closure in the microstructure of skeletal muscles. *Ann Biomed Eng*, 35(12): 2095-107.
- Lippincott Williams & Wilkins. (2006). *ACC Atlas of Pathophysiology*. [Web Photo]. Retrieved from [http://www.liyamus.com/Part%20II\\_Disorders/11\\_Skin%20Disorder/Pressure%20ulcers.htm](http://www.liyamus.com/Part%20II_Disorders/11_Skin%20Disorder/Pressure%20ulcers.htm)
- Liu, Z.-H., & Li, Y.-Y. (2011). A new frontier of nanofluid research-Application of nanofluids in heat pipes. *International Journal of Heat and Mass Transfer*, 6896-6797.
- NewDealSeals. (n.d.). Advantages of O-Rings. In *O-Ring Technical Handbook* (pp. 25-26). Warmenhuizen: NewDealSeals.
- NewDealSeals. (n.d.). Chemical Compatibility Guide. In NewDealSeals, *O-Ring Technical Handbook* (p. 55). Warmenhuizen: NewDealSeals.
- NewDealSeals. (n.d.). How do O-Rings Seal. In NewDealSeals, *O-Ring Technical Handbook* (pp. 16-17). Warmenhuizen: NewDealSeals.
- NewDealSeals. (n.d.). Select the cross-section. In NewDealSeals, *O-Ring Technical Handbook* (pp. 124-125). Warmenhuizen: NewDealSeals.
- NewDealSeals. (n.d.). Select the hardness/radial clearance. In NewDealSeals, *O-Ring Technical Handbook* (pp. 125-126). Warmenhuizen: NewDealSeals.
- NewDealSeals. (n.d.). Select the O-Ring Size. In NewDealSeals, *O-Ring Technical Handbook* (pp. 120-121). Warmenhuizen: NewDealSeals.
- Nikolayev, V.S. (2012). *Modeling of pulsating heat pipe (PHP)*. [Web Photo]. Retrieved from <http://www.pmmh.espci.fr/~vnikol/PHP.html>
- Nixon, J., Brown, J., & McElvenny, D. e. (2000). Prognostic factors associated with pressure sore development in the immediate post-operative period. *Int J Nurs Stud* , 37(4): 279-84.
- Premier Inc. (2013, February 18). *Pressure ulcer prevention*. Retrieved February 18, 2013, from Premier Inc : <https://www.premierinc.com/safety/topics/pressure-ulcer/Pressure-Ulcer-Prevention.jsp>
- Pressure ulcer prevention: pressure, chear, friction and microclimate in context. A consensus document. (2010). *Wounds International*.
- Reay, D., & Kew, P. (2006). *Heat Pipes Theory and Application and Design*.
- Scott, E., Leaper, D., Clark, M., & Kelly, P. (2001). Effects of warming therapy on pressure ulcers-a ranhdomized trial. *AORN J* , 73(5):921-38.

Wits, W., Legtenberg, R., & Mannak, J. (2008). Selecting Capillary Structures for Heat Pipes in Multilayer Printed Circuit Boards. *5th European Thermal-Sciences Conference*.

Yang, X., Yan, Y., & Mullen, D. (2011). Recent developments of lightweight, high performance heat pipes. *Applied Thermal Engineering*, 33-34.

## Appendix A: Heat Transfer Calculation MatLab Codes

The MatLab code was written in order to give an estimation of rate of heat absorption compared to the rate of heat dissipated from the pipes. First, the rate of heat input was calculated using Fourier's Law of conduction. The time component was for phase change from liquid to gas was calculated as the mass flow rate which gives way to the velocity at which the fluid will flow.

The kinematic viscosity, thermal diffusivity was calculated to obtain the Prandtl number. With the Prandtl number and the Nusselt number, the coefficient of heat transfer for the pipe was calculated. Finally, rate of heat convected out could be computed and the heat rate in and heat rate out could be compared.

```
%-----All units SI-----
clc;clear;
cp_nh3=2.19;
%specific heat capacity of ammonium
cp_h2o=4.186/273;
%specific heat capacity of water
cp_sol=(0.3*cp_nh3)+(0.7*cp_h2o)
%specific heat capacity of solution
rho= 890;
%density of ammonium hydroxide
ky=16.3;
%thermal conductivity of steel
length=((90/360)*2*pi*0.04)+0.22+0.41;
%total length of pipe
dinnerpipe=0.04;
%diamter of inner pipe
Asurface=0.28;
%surface area of seat
x=0.38/100;
%thickness of top lid
delT=3;
%temperature difference from (30-27) to (27-24)
delh=1600;
%total enthalpy of working fluid
Apipe=(pi*dinnerpipe^2)/4;
%Area of pipe
Asurfacepipe=0.11;
%surface area of pipe
viscosity=1.3*0.001;

qin=(ky*Asurface*delT)/x
mdot=qin/delh
velocity=mdot/(rho*Apipe)

kinematicviscosity=cp_sol/rho;
thermaldiffusivity=ky/(rho*cp_sol);
Pr=kinematicviscosity/thermaldiffusivity;
Re=velocity*rho*dinnerpipe/viscosity;
Nusselt= .023*(Re^.8)*(Pr^.4);
heattransfercoefficient= Nusselt*ky/length;

qout=heattransfercoefficient*Asurfacepipe*delT
```

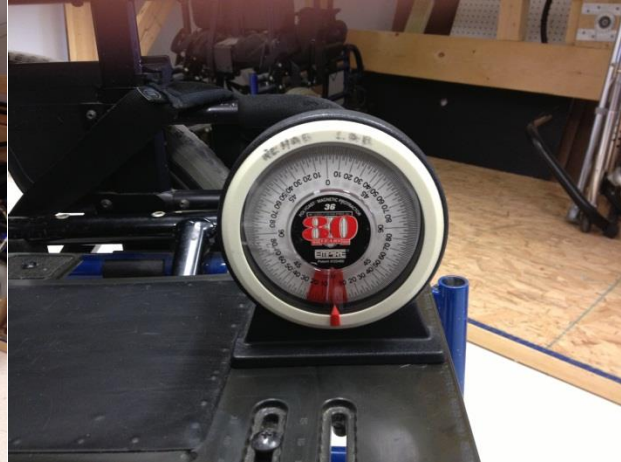
## Appendix B: Wheelchair Measurement Collection

### Wheelchair A

Picture of wheelchair



Slope measurement: 7°



Width Measurement: 14'' + 1/4



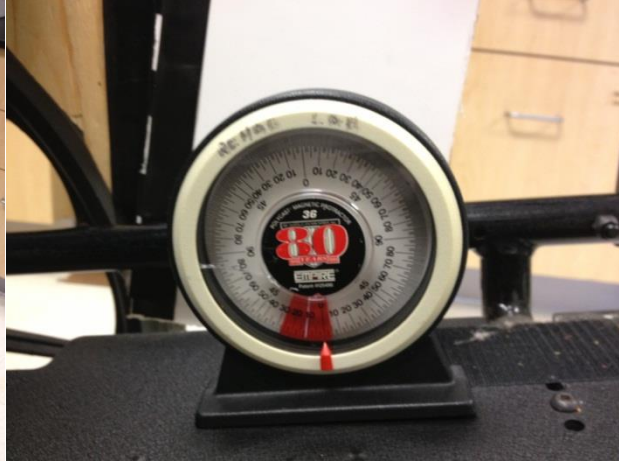
Length measurement: 16'' + 7/8



## Wheelchair B

Picture of wheelchair

Slope measurement: 12°



Width Measurement: 15" + 7/8

Length measurement: 19"



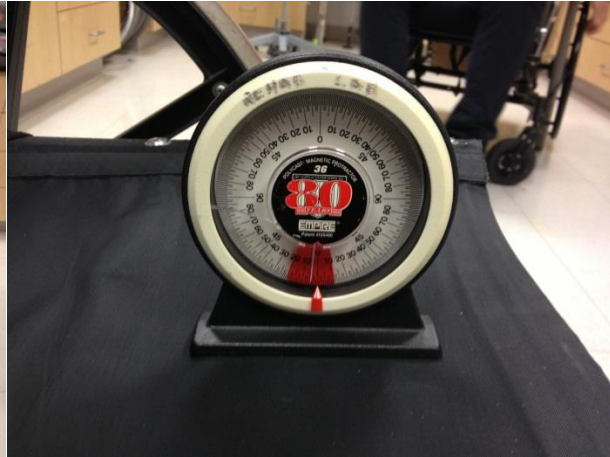


## Wheelchair C

Picture of wheelchair



Slope measurement: 5°



Width Measurement: 17'' + 3/4



Length measurement: 15'' + 5/8



## Wheelchair D

Picture of wheelchair

Slope measurement:  $10^\circ$



Width Measurement:  $18'' + 1/8$

Length measurement:  $16'' + 3/8$





## Appendix C: Wheelchair Measurement Data Analysis

Table 3 - Wheelchair Data Measurements

Wheelchairs	Slope (°)	Width		Length	
		INCH	CM	INCH	CM
A	7	14.25	36.20	16.88	42.86
B	12	15.88	40.32	19.00	48.26
C	5	17.75	45.09	15.63	39.69
D	10	18.13	46.04	16.38	41.59

From the table, above we can see the dimension measurements from four sample wheelchairs. The collected data was measured in inches and converted into centimeters in the column next to it. In addition, we can see the values for Minimum value, Maximum value, Range and Average for these measurements in Table 4.

Table 4 - Wheelchair Data Analysis

	Slope (°)	Width		Length	
		INCH	CM	INCH	CM
<b>Min. Value</b>	5	14.25	36.20	15.63	39.69
<b>Max. Value</b>	12	18.13	46.04	19.00	48.26
<b>Range</b>	7	3.88	9.84	3.38	8.57
<b>Average</b>	8.5	16.50	41.91	16.97	43.10

## Appendix D: Heat Pipe in Test Tube Experiment

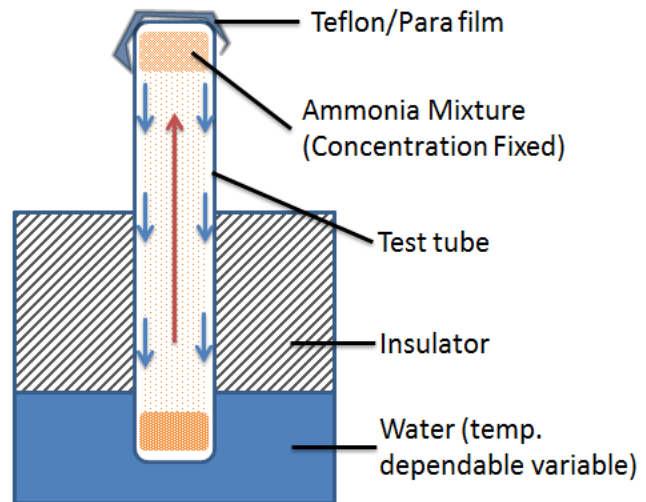
**Objective:** Analyze the different temperature changes over time at different points on a vial/test tube that is immersed at different temperatures with a fixed ammonium concentration.

**Apparatus:**

- Test tubes/vials
- Ammonium Hydroxide
- Beakers
- Water bath/hot plate
- Stopper
- Teflon or Parafilm
- Insulator
- Thermal couples
- Ice

**Control variables:**

- Ammonium Concentration
- Insulator
- Test tube sizes
- Water volume
- Beaker

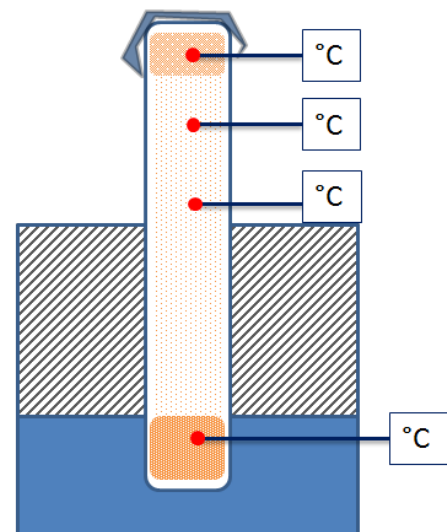


**Independent Variable:** Water temperatures:

1. Cold ( $\sim 4^{\circ}\text{C}$  using ice and water)
2. Ambient ( $\sim 23^{\circ}\text{C}$  using room temperature)
3. Body ( $\sim 28^{\circ}\text{C}$  using hands)
4. Hot ( $\sim 40^{\circ}\text{C}$  using hotplate/ water bath)

**Dependent Variable:** Temperature changes at different points over time

- Thermal couples will be attached at the positions shown in the diagram on the right
- One position is below insulation, and the other 3 positions will be distributed equally on the length on top of insulation
- Thermal couples will be attached using adhesive
- Will use Lab View to record data of temperatures over time



## Appendix E: Transportation Limitations

### Capillary Limit

The capillary limit or hydrodynamic limit determines the ability of the capillary structure to pump the working fluid for circulation. The heat pipe fails to perform heat transfer if this pumping rate does not provide a sufficient amount of liquid to the evaporator section.

### Boiling Limit

When the radial heat flux in the evaporator section becomes excessively large, two processes occur: the working fluid boils and the temperature of the metal walls become exceptionally high. Consequently, vapor bubbles form in the wick that prevent the liquid from wetting the pipe walls. This causes hot spots and ultimately, the dehydration of the evaporator.

### Entrainment Limit

As the vapor and liquid move in opposite directions, a shear force exists between the interfaces of these two phases. When the high velocity vapor carries away some droplets of liquid with the vapor back to the condenser, this stops the return of the liquid to the evaporator which may disrupt the cycle.

### Sonic Limit

Analogous to a converging-diverging nozzle with a constant mass flow rate, as the area converges the velocity increases with the mass flow rate until there can be no further augmentation in mass flow rate. Similarly, the velocity of the vapor increases along the evaporator and reaches a maximum at the end of the evaporator section.

### Viscous Limit

When operating at low temperature, the vapor pressure difference between the evaporator and condenser regions of the pipe may be too small. This may cause viscous forces within the vapor region to be dominant over the pressure gradient. Because flow is generated as a result of this pressure gradient, the difference may cause the flow to stagnate.

## Condenser Limit

The heat transfer rate in the condenser section is governed by the condenser and heat sink (i.e system heat is being displaced to). At steady state, the heat rejection rate in the condenser must equal the heat injection rate in the evaporator. Heat transfer in the condenser usually occurs through convection or radiation. Low convective heat transfer coefficients and low surface emissive or limited surface area can cause the heat pipe to reach its condenser limits. (Ahmad & Rajab, 2010)

## Appendix F: Material Compatibility Chart<sup>3</sup>

Chemical Corrosion and Material Choice Guidance Chart		SchuFF FETTEROLF	
Chemical Medium	1) Carbon Steel	2) Stainless Steel	3) Duplex, Hastelloy, Alloy 20, Inconel, Nickel, Monel, Titanium etc.
Acetic acid, crude			316 stainless steel
Acetic acid, pure			Monel
Acetic anhydrate		Yes	
Acetone	Yes		
Aluminum chloride			High Density PE
Aluminum sulfate		Yes	
Alums		Yes	
Ammonia(gas)	Yes		
Ammonium chloride			High Density PE
Ammonium hydroxide	Yes		
Ammonium phosphate (monobasic)		Yes	
Ammonium phosphate (dibasic)		Yes	
Ammonium phosphate (tribasic)	Yes		
Ammonium sulfate		Yes	
Aniline	Yes		
Benzene, benzol	Yes		
Boric acid		Yes	
Bromine			Stainless steel lined with Monel, Kynar or Teflon
Calcium chloride			Nickel or Monel
Calcium hydroxide	Yes		
Calcium hypochlorite		Yes	
Caron tetrachloride		Yes	
Carbonic acid		Yes	
Chloroacetic acid			Stainless steel with PE lining
Chlorine, dry		Yes	
Chlorine, wet			Tantalum or Hastelloy
Chlorinc, acid			Hastelloy
Critic acid		Yes	
Cooper sulfate		Yes	
Ethanol	Yes		
Ethylene glycol	Yes		
Fatty acid		Yes	
Ferric chloride			Stainless steel with epoxy coating
Ferric sulfate			Stainless Steel with PP Coating
Ferrous sulfate		Yes	
Formaldehyde		Yes	
Formic acid		Yes	316 Stainless steel
Glycerol	Yes		
Hydrocarbon (aliphatic)	Yes		
Hydrochloric acid			Stainless steel with epoxy coating
Hydrogen peroxide			Low carbon stainless steel with PE coating
Lactic acid		Yes	
Magnesium chloride			Nickel or Monel
Magnesium sulfate	Yes		
Metanol	Yes		
Nitric acid			Stainless steel with PP coating
Oleic acid		Yes	
Oxalic acid			Monel
Phenol (carbolic acid)		Yes	
Phosphoric acid		Yes	

<sup>3</sup> Chart taken from <http://www.schuf.com/products/line-blind-valves/Chemical-Corrosion---Material-Choice-Guide.pdf>

# SchuF FETTEROLF

Chemical Medium	1) Carbon Steel	2) Stainless Steel	3) Duplex, Hastelloy, Alloy 20, Inconel, Nickel, Monel, Titanium etc.
Potassium hydroxide		Yes	
Sodium bisulfate		Yes	
Sodium carbonate	Yes		
Sodium chloride	Yes		
Sodium hydroxide	Yes		
Sodium hypochlorite		Yes	
Sodium nitrate	Yes		
Sodium sulfate	Yes		
Sodium sulfide	Yes		
Sodium sulfite	Yes		
Sodium thiosulfate		Yes	
Stearic acid		Yes	
Sulfur			
Sulfur dioxide			Steel with Teflon coating Hastelloy
Sulfuric acid (95% + )			Hastelloy
Sulfuric acid (75%~95%)	Yes		
Sulfuric acid (10%~75%)			Hastelloy
Sulfuric acid (<10%)			Hastelloy
Sulfurous acid		Yes	
Trichloroethylene		Yes	
Zinc chloride			Nickel or Monel
Zinc sulfate	Yes		

#### Notes:

1) This table is presented to give an indication of what materials might be suitable for a specific chemical compounds. It is not a definitive or exhaustive list.

2) As other factors such as **medium concentration, atmospheric conditions, temperature or pressure** can have an effect on the correct choice of material, please always check with SchuF Fetterolf or your in-house safety expert for final confirmation.

3) If yes is found in the first column "Carbon Steel", this indicates that carbon steel can be used but does not exclude the use of other materials listed in columns 2 and 3.

4) Please note that this chart does not indicate the specific category of a particular material. For stainless steel for example this can range from 304 to 316 as standard and to 414 for special applications.

5) This chart is intended for use by SchuF Fetterolf staff and representatives only. SchuF Fetterolf will bear no responsibility to 3rd parties who use the chart.

#### For your notes and comments:

#### Contact information:

SchuF Fetterolf  
Tel.: +49 6198 571115  
Fax.: +49 6198 571200

#### Address:

An der Guldenmühle 8-10  
65817 Eppstein / Frankfurt  
Germany

#### E-mail and Web:

[sales@schuf.com](mailto:sales@schuf.com)  
[sales@schuf.de](mailto:sales@schuf.de)  
[www.schuf.com](http://www.schuf.com)

## Appendix G: Meeting with Paula Moravek

November 16th

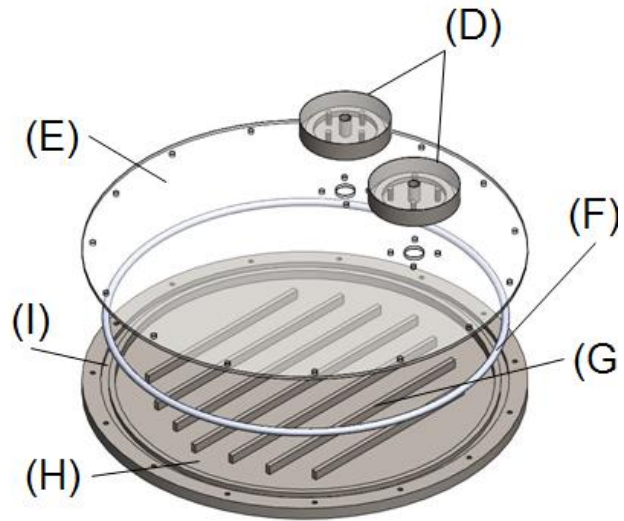
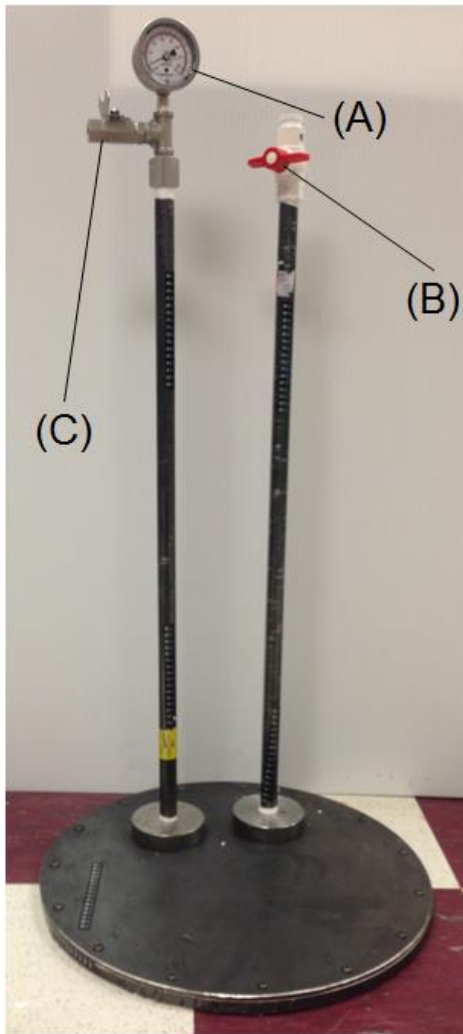
- Vial
  - Teflon lining - pure liquid ammonium won't react
  - Borosilicate glass – safe since to use with glass
  - Dimensions are not long enough
  - Cap is custom sized
- Test tube
  - Glass
  - Dimensions is suitable
  - Use Teflon or Para Film
    - Teflon can buy in Wal-Mart but very easily breakable
    - Para Film is one use only but easy to use but be careful of high temperatures because it's made out of wax
- Ammonium
  - Stockroom has supplies of ammonium hydroxide
  - Professor has to sign it off
- Water bath vs. Hot Plate
  - Chemistry stock room does not lend hot plates out
  - Look for options of available hot plates on campus to lend
  - Buy a water bath? (Very expensive, at least \$500-\$2000)
  - Issue- using ice to keep water in a constant cold temp

November 19th

- Ammonium availability
  - Stock room has 28% ammonium hydroxide
  - 50% is available online
- Safety measures with Ammonium
  - Gas will mostly likely leak
  - Dumping it out
    - It should fine to dump in sink but above 10% need to keep in Hazardous waste bottle
    - Check with David Messier about this
  - Need to be fully protected when doing this
  - Must have an advisor with us first couple of times since we are new to this
    - Either professor Sullivan or someone else who is an expert in this field
  - Pour small amounts of strong acid/base into the weak base/acid or chemicals will jump into your face
  - Best to keep in hood for storage but if not possible, then keep alone in a cabinet for example
  - Keep ammonium away from acid or else chemical reaction will lead to production of heat
  - When in doubt, check online and the MSDS site for safety procedures



## Appendix H: Actual Model Photographs



- (A) Pressure/Vacuum Gage
- (B) Valve (Fluid Input)
- (C) Valve (Depressurization)
- (D) Flanges
- (E) Top Steel Plate
- (F) O-Ring
- (G) Ribs
- (H) Bottom Steel Plate
- (I) O-Ring Groove (lower plate)

