APPARATUS FOR THE DEVELOPMENT OF HYDROGEL SCAFFOLDS THROUGH CONTROLLED COOLING RATES

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EXECUTIVE SUMMARY

Eleven thousand new spinal cord injury cases occur in the United States annually. Existing treatments such as physical therapy and surgery do not restore functional axons; therefore, tissue-engineering unidirectional porous scaffolds are a potential replacement to facilitate guided axon regeneration. However, current freeze-drying techniques to produce unidirectional pores lack the technology to manipulate the pore size and orientation through controlled movement. This team will build a mechanical apparatus that is capable of moving a hydrogel scaffold through a temperature gradient of 7.08°C/cm with a cooling rate of 1 to 50°C/minute to produce uniaxial freezing. However, our device will only be programmed to move at 3°C/minute due to time limitations and our client’s request. The cooling rate cannot exceed 10%, so that the pore size remains within experimental ranges per respective cooling rate. Therefore, a cooling rate that is 10% more or less will produce pores that are within the referenced standard deviation.

The scaffold will be contained in a moving, Teflon-insulated vessel that rests on top of a copper substrate to ensure uniaxial freezing. Since our client creates a 20mm by 15mm cylindrical hydrogel, the vessel must be the same diameter to provide stability to the scaffold. These dimensions are important because the scaffold must adhere to the well wall in order to maintain proper mechanical stability. Vapors from liquid nitrogen will produce the temperature difference in a Teflon shaft through which the vessel will move; thermocouples attached to the copper and scaffold will measure the temperature at each point. The thermocouple inputs will indicate temperature changes within the scaffold. Next, LabVIEW will integrate the input temperatures and then will output a rate of descent of the vessel to maintain a constant cooling rate. This rate of descent is controlled by the stepper motor, which moves via a guidance rod connected to the rigid arm that is attached to the vessel. The specific cooling rate and the relative position of the vessel within the temperature gradient will determine the speed at which the vessel will be lowered. Each step of the motor translates rotational movement to vertical movement of the rigid arm with $8 \times 10^4$ maximum steps per minute. Thus far, we have constructed the entire device. We also have begun programming in LabVIEW.

In the Spring term, we will complete and optimize the algorithm for LabVIEW to move the vessel at 3°C/minute. We will also test the device using a scaffold and liquid nitrogen. By May 2010, we will have a complete prototype ready to be used by our client for uniaxial pore formation. Therefore, for future spinal cord research, the controlled mechanical apparatus will be capable of producing uniaxial pores whose sizes can be manipulated based on the constant cooling rate used.
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ABBREVIATIONS AND DEFINITIONS

°C: degrees Celsius
cm: centimeter
LabVIEW: Laboratory Virtual Instrumentation Engineering Workbench
MATLAB: MATrixLABoratory software
mm: millimeter
mV: milliVolt
N-m: Newton-meter
PCL: polycaprolactone
ProE: Pro/Engineer software
RPM: revolutions per minute
USB-DAQ: Universal Serial Bus-Data Acquisition device
VDC: voltage direct current
INTRODUCTION

Problem Statement

Spinal cord injuries are a serious problem that can degrade motor neurons, debilitating motor functions. Eleven thousand new spinal cord injury cases occur in the United States annually (Macias et al., 2009). Currently, no treatment exists to reverse the effects of a spinal cord injury but surgery and rehabilitation are used to prevent further problems. Researchers are focusing on tissue-engineered scaffolds to allow for and guide axon growth that can integrate electrical impulse activity for neuron regeneration. Thus, in order for the axons to communicate effectively, they must move in a unidirectional orientation. Experimentation has shown that a successful method to create these oriented pores is by using a freezing technique to form ice crystals within the scaffold (Stoklosa and Tuszynski, 2006; Moore et al., 2006). The actual crystal formation is prompted by a temperature differential between the hydrogel scaffold and the relatively colder copper substrate at the bottom. This temperature difference generates ice formation upwards towards the warmer portion of the scaffold. The cross-linked hydrogel provides a honeycomb matrix that aids in directing ice formation upwards (Figure 1).

The ice crystals are sublimated when placed in a vacuum and freeze-dried. Then, unidirectional channels are left behind, which can then be used in future spinal cord research (Heschel and Rau, 2002). However, current freeze-drying techniques to produce unidirectional pores lack the technology to manipulate the pore size...
diameter and orientation through controlled movement. Therefore, a controlled technique to achieve unidirectional pores must exist to formulate the necessary electrical synapses.

For spinal cord research, our client needs a method to create axially oriented pores in hydrogel scaffolds, through which the cooling rates regulate the pore sizes. In order to allow for axons to communicate across the injury site, the pores must be uniform and uniaxial. Our client requests a design that implements a mechanical apparatus for controlled cooling by manipulating the velocity through a temperature gradient. In turn, controlled cooling will generate pores of varying sizes. Through these objectives, the problems in the current methods will be eliminated. Our team will design a mechanical apparatus capable of uniaxial freezing with a constant cooling rate between 1 and 50°C/minute through a temperature gradient of 7.08°C/centimeter, assuming

![Figure 2: Temperature Gradient Relationship](image)

The following calculations show the relationship between the temperature and position within the Teflon shaft. In order to calculate it, the general PDE heat equation was used assuming steady-state conditions and air throughout the shaft. The temperature difference from the liquid nitrogen to room was set as 216°C.
a linear temperature distribution (Figure 2). The goal of the project is to produce a mechanical apparatus that controls the constant cooling rate of the hydrogel scaffold. While there is a relationship between cooling rate and pore diameter, our goal is only to achieve a constant cooling rate of 3°C/minute.

**Design Specifications of Our Solution**

Since no current technique exists to control the cooling rate of the scaffold within a temperature gradient, our design must encompass the following four criteria regardless of the solution methods.

There are four specifications that are design must adhere to:

1. The vessel must not be smaller or larger than 15mm to securely fit the scaffold. Our client requests that our apparatus accommodate a hydrogel size that his lab intends to use. The hydrogel scaffolds are made in 24-well plates, which are 15mm in diameter and 20mm in length. Then, the cross-linking agent is added to the scaffold and quickly transferred to the cooling apparatus. These dimensions are important because the scaffold must adhere to the well wall in order to maintain proper mechanical stability. Therefore, the scaffold cannot be of any other size. Since the scaffold is removed from the 24-well plate and placed in a vessel, the vessel must not be smaller or larger than 15mm to securely fit the scaffold.

2. The apparatus will deliver a cooling rate between 1 and 50°C/minute. These rates have been proven and patented (Heschel and Rau, 2002) to be most effective for varying the size of the pores. The specific cooling rate and the relative position of the vessel within the temperature gradient will determine the speed at which the vessel will be lowered. Varying the cooling rates will in turn manipulate the pore size diameter. Therefore, specific cooling rates will result in controlling the pore size diameters.
3. The cooling rate cannot exceed 10%.

Based on the available results from O’Brien et al. as seen in Figure 3, the cooling rate cannot exceed 10%, so that the pore size remains within experimental ranges per respective cooling rate. For example, at a cooling rate of 0.9°C/min produces pore sizes of 95 ± 12.2um, which is a 20% pore size deviation. Thus, a 10% deviation in cooling rate will fall within the 20% deviation of the pore sizes. (Data obtained by O’Brien, FJ., et al. 2004).

4. The dimensions of the remaining materials are constrained by the available sizes and prices that meet our budget limitations.

For the thicknesses of the materials, Appendix B shows the complete calculations for two different Teflon thicknesses of the vessels. McMaster-Carr offers Teflon thicknesses for
reasonable prices as seen in the budget. Thus, we could only choose dimensions offered by the supplier; however, these dimensions do provide minimal heat loss as substantiated by the calculations in Appendix B. Furthermore, the copper disc size was limited due to its weight since the motor is not made to handle heavy objects. Therefore, we chose a thickness of 3.18mm for the copper substrate to minimize weight and maximize instantaneous heat transfer, as it also supported by our budget.

**PROTOTYPE**

**Intended Prototype**

Our design will primarily consist of a rigid arm that will act as a crane to lower a vessel containing the hydrogel scaffold towards a reservoir of liquid nitrogen in a Teflon shaft (Figure 4). In addition, there will be temperature sensors, an input controller for the temperature sensors, a stepper motor, a controller for the motor, and LabVIEW to control the velocity of the vessel.

The vessel will be lowered into shaft using a hollow, aluminum rigid arm with a length that exceeds that of the shaft (305 mm), an outer diameter (38.1mm) less than that of the outer diameter of the vessel (88.9mm), and a thickness of 6.35mm (Figure 5). Aluminum was selected due to its light and rigid properties, while fitting our budget constraints. It must be hollow to reduce weight and to bundle the thermocouple wires to prevent entanglement. The rigid arm length is dictated by the need to descend the entire length of the shaft so that the vessel can be exposed to the entire temperature gradient. Because the rigid arm is attached to the motor, the rigid arm will require additional length compared to the shaft. The outer diameter of the rigid arm must be counter sunk at least 35mm into the vessel to ensure a snug fit, which will be secured with setscrews. Therefore, the outer diameter is slightly smaller than that of the vessel.
The thickness was selected so that there was enough room to allow for threading to translate motor rotation to vertical movement down the shaft.

![Figure 4: Cross-section model of Apparatus](image)

This figure represents the entire apparatus, beginning with the dewar (green). The shaft consists of Teflon (white). Within the cross-sectioned shaft is the moving vessel. On the base of the vessel is the copper substrate (gold), followed by the insulating Teflon around the circumference (light gray). The motor is attached to the shaft, which is also attached to the vessel (red). In orange is the threaded rod that allows for the lowering of the vessel. Around the orange threaded rod is a rigid arm that holds the vessel to the threaded arm. Around the entire apparatus is a rigid structure that holds the motor in place.

![Figure 5: Apparatus Drawing (in mm)](image)

Aluminum rigid arm outer diameter: 33.98; outer diameter of vessel: 95.44mm; vessel height: 68.42; scaffold diameter: 15; copper thickness: 3.20mm; copper diameter: 69.82; inner diameter of Aluminum rod: 22.02mm; height of aluminum rod: 393.30; inner diameter of Teflon shaft: 97.16; outer diameter of Teflon shaft: 131.82; height of Teflon shaft: 307. See Table 1 for all of the apparatus dimensions.

Connected to the rigid arm, a threaded stainless steel acme rod will be secured using an acme nut. The threaded acme rod will guide the movement of the vessel through the shaft. Thus, a
diameter equal to that of the motor head will be made within the guidance rod to hold the motor head. This attachment will allow the threaded rod to move in accordance with the motor.

The vessel containing the hydrogel will be exposed to liquid nitrogen vapors in a 2L dewar. In accordance with studies demonstrating the causal relationship between thermal gradients and parallel pore formation in the direction of the gradient, we will utilize conduction to transfer thermal energy to the hydrogel scaffold. The unidirectional heat conduction will be generated within the vessel by attaching a copper substrate to the bottom of the vessel. Teflon will form the circumference of the descending vessel surrounding the hydrogel. Teflon functions as the thermal insulator to prevent heat transfer in the horizontal direction. These materials have been shown to provide uniaxial freezing for pore formation in stationary devices (Madaghiele et al., 2008; Fu et al., 2007; Schoof, et al., 2001). In order to prevent rotational movement of the vessel as it is lowered into the dewar, an aluminum stylus piece will be connected to the shaft. This aluminum piece will fit into a guided channel made in the aluminum rod.

Since the scaffold is constrained to 35mm (maximum height) by 15mm (diameter) dimensions, the inner diameter of the vessel, namely the surrounding Teflon, must also be 15mm in diameter. Since researchers need to be able to load a scaffold up to 35mm and the rigid arm is countersunk 35mm, the height of the vessel is 70mm. Thus, the size of the scaffold constrained the limits of our vessel size. The thickness of the Teflon surrounding the scaffold will be 36.95mm, making the outer diameter of the vessel 88.9mm (15mm diameter of scaffold + 36.95mm thickness of Teflon). The heat conducting material, the copper substrate, at the bottom of the vessel must also be 88.9mm to fit securely within the Teflon vessel. To ensure uniform heat transfer, the copper will have a thickness of 3.18mm (Figure 5).
Furthermore, to ensure minimal heat conduction, the vessel will travel down a minimum of 305 mm Teflon shaft surrounded by Styrofoam as used in previous studies to prevent heat conduction in the radial direction (Wu et al., 2009; Fu et al., 2007; Schoof, et al., 2001). The minimum length that the shaft must be is 305mm in order to provide enough room for the vessel to move within the range of cooling rates. There will be a 6.35mm gap between the vessel and the shaft to allow movement. Thus, Teflon, the inner material of the shaft, will have an inner diameter of 101.6mm, a thickness of 12.7mm and an outer diameter of 127mm. The Styrofoam surrounding the Teflon shaft will be 25.5mm in thickness to decrease heat loss. The chosen thicknesses for the Teflon materials were based off of heat-transfer equations. Since, the scaffold is confined by three layers of material (two layers of Teflon and one of Styrofoam), a known equation for cylinders was applied to determine the amount of heat loss using different combinations of dimensions. Please refer to Appendix B for the complete calculations and explanations. The shaft will be attached to the dewar with a stabilizing plexiglass ring. The shaft will allow liquid nitrogen vapors to travel from the bottom of the dewar to the top of the device in contact with air, creating a temperature range from -196°C to 20°C. Using LaPlace integration to determine the temperature gradient within the shaft, we assumed the system is steady-state with only air moving throughout the shaft. From these calculations, we found that the vessel will move within a linear temperature gradient of 7.08°C/cm. The complete calculations and explanations can be seen in Appendix C. The entire apparatus will be supported using aluminum structures to ensure stability. Refer to Appendix A for the detailed views of the apparatus.

Two Type T thermocouples will be placed on the bottom of the copper substrate and two at the top of the vessel. Type T thermocouples fall within our temperature range, allowing to
measure from -220°C to 120°C and small temperature changes of ±1°C to provide precise readings (Omega, 2009). The temperature change of the copper substrate will be assumed to be instantaneous between descent intervals. This, in turn, will measure temperature at which the copper is exposed to and the temperature at the top of the vessel to provide constant feedback based on the position (relative to the liquid nitrogen base).

The movement of the vessel will be controlled by the mechanism shown below:

**Thermocouple → USB-DAQ → LabVIEW (w/ motor drivers) → Motor Controller → Motor**

The thermocouple inputs will plug directly into the USB-9211A, a data acquisition (USB-DAQ) port for thermocouples, which then feeds into the LabVIEW virtual instrument (VI). The minimum temperature readings necessary to measure an accurate cooling rate is ±1°C (±80mV) for the thermocouples, which this device is capable of doing. The LabVIEW VI will then incorporate motor-specific drivers that can translate voltage pulses to rotational movement of the motor head. LabVIEW then interfaces with the power supply and motor controller, which then modulates how many pulses the motor will receive based on voltage output (Arcus Technology, 2007). Since we need the velocity of the vessel to change as precisely as possible based on the temperature readings, the motor must be capable of outputting a maximum of 0.5°C/step change to ensure precise movement. The NEMA 17 motor has a maximum of 200 steps per revolution and cannot exceed 400 RPM with a payload of 0.35 N-m, according to the manufacturer’s torque curve. Therefore, the NEMA 17 is capable of outputting a maximum of 8x10^4 steps per minute. In addition, because the gear head radius is 12.7mm and each step moves 1.8°, the maximum displacement per step is 0.4mm. Therefore the motor cannot exceed 763 steps to extend the rigid arm through the length of the insulated shaft. Since the total temperature differential within the shaft is 216° and there is a maximum of 763 steps, each step
can change the temperature by 0.28°C, so the motor meets the needs of the solution. Furthermore, the rotational movement will translate a gear head with a radius of 12.7mm and a circumference of 80mm per each revolution. Therefore, assuming each arc length translates to vertical displacement down the shaft, the gear head can rotate a maximum of 3.82 revolutions (305mm/(80mm/rev)) to descend the vessel completely down the 305mm shaft.

The stepper motor is able to output a velocity in step-wise increments. For example, since each step is 0.4mm and each pulse represents one step, then if (10) pulses are made within 5 seconds, the average velocity will be 0.8mm/sec. Therefore, the velocity will be determined by how many pulses are made within each time interval. By changing the step-wise velocity, the scaffold’s cooling rate can be kept constant. The feedback from the thermocouples will allow for the vessel’s descent rate to increase or decrease within the temperature gradient in order to maintain a constant cooling rate of the scaffold. The vessel can move at a velocity between 0.14cm/min to 7cm/min in order to produce a cooling rate between 1 and 50°C/minute. The MATLAB program that we wrote is a simulation program, designed with the
intent of simplifying the sensing element of our design (Figure 6). The program factors the known heat properties of copper, the hydrogel scaffold, and the temperatures expected from the liquid nitrogen vapors into its final calculations. Using these parameters, it simulates different motor outputs (2 simulations for constant speed and 1 simulation for varying speed) to approximate the cooling rate of our hydrogel sample. The program estimates a range of motor speeds (0.14cm/min to 7cm/min) that will be necessary to achieve a cooling rate between 1 and 50°C/minute. Refer to Appendix C for the MATLAB model of the velocity-cooling rate relationship.

Prototype-to-date

The construction of the prototype is completed. The driving acme rod has been bored out to a depth of 19.05 mm to fit the motor head. The aluminum rigid arm was cut down to 393.3mm. The threaded rod fits into the nut, which has been press fit into the aluminum arm. The shaft has been cut down to 307 mm. The shaft was fitted to securely fit in the dewar using a plexiglass ring. Furthermore, the vessel has been bored out to fit the scaffold and the aluminum rigid arm. The rigid arm has been secured to the vessel using two setscrews, 180° degrees apart, that sit flush against the vessel and threaded into the aluminum rod. The copper disc was attached to the bottom of the vessel with two screws on opposing ends to hold it in place. In order to prevent rotational movement of the vessel, the aluminum stylus piece has been attached to the shaft to move along a guided channel in the aluminum rod. The aluminum structures to support the entire apparatus have been constructed. We are no longer including the Styrofoam layer that was added as a security factor since the two Teflon layers are sufficient to prevent heat loss. Table 1 shows the actual dimensions of the prototype that have been constructed.
The programming portion of the solution is also underway. We have installed the LabView software onto a Drexel laptop. We then met with a technical support consultant from National Instruments who has given us a tutorial on how to use the functions and tools in LabView. After this meeting, we began preliminary programming to control the speed of the motor relative to the temperature of the scaffold. Therefore, we will be able to implement a constant cooling rate at which the vessel will move. Since time is limited, we can only test one cooling rate in our algorithm. Our client has asked us to use 3°C/min. The constant cooling rate algorithm is currently being programmed (Refer to Appendix D for the current algorithm).

<table>
<thead>
<tr>
<th>Aluminum Rod</th>
<th>Vessel-Teflon</th>
<th>Vessel-Copper</th>
<th>Teflon Shaft</th>
<th>Acme Rod</th>
<th>Motor Head</th>
<th>Dewar</th>
</tr>
</thead>
<tbody>
<tr>
<td>I/D: 25.43</td>
<td>O/D: 95.44</td>
<td>Thickness: 3.20</td>
<td>I/D: 97.16</td>
<td>I/D: 9.65</td>
<td>Diameter: 5.10</td>
<td>I/D(top): 156.80</td>
</tr>
<tr>
<td>Height: 393.30</td>
<td>Height: 68.42</td>
<td>O/D: 131.82</td>
<td>O/D: 131.82</td>
<td>Height: 307</td>
<td>Height: 512</td>
<td>I/D (bottom): 96.00</td>
</tr>
<tr>
<td>Scaffold Height: 26.52</td>
<td>Diameter: 69.82</td>
<td>Thickness: 3.20</td>
<td>I/D: 9.65</td>
<td>Diameter: 5.10</td>
<td>Motor head depth: 19.05</td>
<td>Inside Depth: 230.40</td>
</tr>
<tr>
<td>Scaffold diameter: 15.00</td>
<td>Diameter: 69.82</td>
<td>Diameter: 69.82</td>
<td>O/D: 131.82</td>
<td>Height: 307</td>
<td>Length: 17.59</td>
<td>Outside height – 275.20</td>
</tr>
</tbody>
</table>

**Table 1: Actual Dimensions of Apparatus**

This table gives the actual dimensions of the components of the apparatus. The construction of the components resulted in similar, but not exactly equal, dimensions as calculated theoretically. All of the measurements are in millimeters. I/D=inner diameter; O/D=outer diameter.
Figure 7: LabVIEW Algorithm
The current algorithm includes the input of the thermocouple readings, which are connected to the DAQ card. The DAQ card signals the output for the temperature reading using an average of sine waveforms. This average is calculated through a “while loop” so there is a continuous reading. This reading will then be called into the motor program code, which has yet to be completed.

In order to complete our design, we learned how to use the tools and machines available in the Drexel machine shop. We received support from the employees in the machine shop who guided us to use the instruments. Furthermore, we had to accustom ourselves with LabView and understand how the software works (Figure 7). These two skills have brought our apparatus together, nearing its completion (Figure 8; Appendix E).
Figure 8: Prototype-to-date
The mounted device without the vessel and rigid arm attached. The entire structure, with the aluminum tabletop structure included, will stand at approximately 4 feet tall.

**PLAN OF ACTION**

In the spring term, we will complete the final steps in our apparatus design. We will optimize the programming in the LabView software, so that the vessel will move at a constant cooling rate of 3°C/min. First, we will do some preliminary manual testing with our device using
liquid nitrogen and a scaffold to get an idea of how the apparatus works. Then, we will modify the algorithm to output our desired cooling rate. The algorithm will code for the movement such that the user can enter the cooling rate and the algorithm will control the motor. Furthermore, we will verify the temperature gradient within the shaft to determine if it fits the theoretical assumptions as being a linear gradient of 7.08°C/cm. Finally, we will test the device using liquid nitrogen and the scaffold. With these components, we will define a cooling rate of 3°C/min with the proper algorithm. By May 11, 2010, we will have completed our programming and testing to conclude the final steps of our device.

**SOCIETAL AND ENVIRONMENTAL IMPACTS**

As discussed before, several studies have been performed to create oriented pores using a stationary freezing technique to form ice crystals within the scaffold in order to guide axons in a uniaxial fashion. Our design of a mechanical apparatus resulting in oriented pores will be a positive impact on researchers. It will not only be a research tool for scientists attempting to create uniaxial pores, but it will also relieve researchers from their results of imprecise pore diameters in scaffolds for the spinal cord. As mentioned before, current stationary techniques pose limitations on pore orientation and size, which results in unnecessary expenditure and time that the researchers could be investing in other areas. Since the different cooling rates will result in different pore diameters, scientists will be able to use our apparatus to create a variety of pore diameters, depending on their need. Furthermore, on a broader scale, if our design is capable of producing precise pores in scaffolds, researchers will be able to implement their cell-signaling and spinal cord injury studies with the scaffolds to hopefully relieve patients from paralysis.

There is one negative impact of our design. Our design will require manufacturing of the parts (dewar for the liquid nitrogen, Teflon, Styrofoam, copper vessel and shaft, thermocouples
and a crane) resulting in minute pollutions in the air. Any production rate will cause pollution; however, if our design can relieve researchers from extra hours, wasted funding and imprecise pores in scaffolds but can achieve accurately oriented pores and use funding for further research, patients may start getting their lives back.

**COST BUDGET**

In order to complete the design, we are using materials purchased as well as supplied in house. The rigid arm, guidance rod, vessel, and shaft materials came from McMaster-Carr. For the shaft, larger Teflon thicknesses increased our budget. The dewar and thermocouples were bought from Nalgene and Omega, respectively. Under the allotted time given to the team from the machine shop, the crane, shaft, and vessel have been constructed. To meet our programming needs, an individual license of LabVIEW was acquired from the Drexel Engineering Department. Arcus Technology offers a bundle package for the stepper motor, controller, and driver for $195, which we have purchased. We are using a power supply from Dr. Lelkes’s lab. The total cost of our supplies is $1,548.08 as shown in Table 2. Funding was provided from the Senior Design Budget. Refer to Appendix F for the complete budget.
<table>
<thead>
<tr>
<th>Product</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum rod-38.1mm outer diameter, 6.35mm thickness</td>
<td>37.76</td>
</tr>
<tr>
<td>Teflon stock-88.9mm outer diameter</td>
<td>159.10</td>
</tr>
<tr>
<td>Teflon-127mm outer diameter, 12.7mm thickness</td>
<td>177.30</td>
</tr>
<tr>
<td>Copper Sheet-3.175mm thickness</td>
<td>82.28</td>
</tr>
<tr>
<td>Threaded Acme Rod</td>
<td>44.45</td>
</tr>
<tr>
<td>Acme Round Nut</td>
<td>37.41</td>
</tr>
<tr>
<td>Aluminum Sheets-1.5875mm thickness</td>
<td>70.08</td>
</tr>
<tr>
<td>Dewar- Polythene</td>
<td>184.26</td>
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<tr>
<td>Thermocouples-Type T</td>
<td>68.00</td>
</tr>
<tr>
<td>LabVIEW</td>
<td>0</td>
</tr>
<tr>
<td>Power Supply</td>
<td>0</td>
</tr>
<tr>
<td>USB-9211A</td>
<td>492.44</td>
</tr>
<tr>
<td>Stepper Motor, Controller, and Driver</td>
<td>195.00</td>
</tr>
<tr>
<td>Mini USB cable</td>
<td>0.98</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>1548.08</strong></td>
</tr>
</tbody>
</table>

**Table 2: Project Budget.** The budget gives a breakdown of the costs associated with the construction and testing of our apparatus. The total cost of manufacturing and testing our design is **$1548.08.**
SCHEDULE
Since we made changes to our design in order to make the components fit together, we had to make changes to our schedule, so that it reflects these additions. Highlighted in yellow, the constructional changes have already been completed and one task is currently underway. Furthermore, we had to push back our start date for LabVIEW programming until the beginning of February, whereas we had scheduled it to start at the beginning of January. Since our device had additional components to be constructed, this caused a change in our programming schedule. Therefore, our temperature gradient testing will not begin until March to ensure that our LabView algorithm will be complete. We will have our prototype complete by the end of the term and will complete testing by the beginning of May 2010. This is shown in Table 3 below and the 2009 schedule can be seen in Appendix G. The team’s credentials will lead to successfully carrying out the design (Refer to Appendix H for resumes). Therefore, the team can stay on track according to the proposed schedule and complete each of the milestones in a timely manner.
### Table 3: Project Schedule

This is the schedule for our senior design project for 2009-2010. We began our project in April 2009 and will be finished in May 2010. The legend is as follows: Green—Completed; Gray—In Progress; Red—Not Started

<table>
<thead>
<tr>
<th>Number</th>
<th>Task</th>
<th>Start</th>
<th>End</th>
<th>Duration</th>
<th>2010</th>
</tr>
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<tbody>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>January</td>
<td>February</td>
</tr>
<tr>
<td>3</td>
<td>Attach Motor to Threaded Rod</td>
<td>1/11/2010</td>
<td>1/20/2010</td>
<td>9</td>
<td>❓</td>
</tr>
<tr>
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<td>Attach Rigid Arm to Shaft and Vessel</td>
<td>1/20/2010</td>
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<td>2/4/2010</td>
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<td>6</td>
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<td>2/10/2010</td>
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<td>7</td>
<td>Mount Motor to Board</td>
<td>2/10/2010</td>
<td>2/28/2010</td>
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<tr>
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<td>3/16/2010</td>
<td>4/28/2010</td>
<td>44</td>
<td>❓</td>
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</table>
REFERENCES


The images below represent various views of the apparatus, including an overview image, longitudinal cross-section of the controlled cooling apparatus, and a expanded cross-section of the moving vessel. The below images are color coded for easier identification. The following is a list of parts with corresponding color representations: Dewar—green, Stepper motor—red, Teflon shaft—white, copper substrate—gold, Aluminum rigid arm—dark gray, Threaded rod, orange, Threaded nut—mustard yellow, Teflon vessel wall—light gray, Aluminum tabletop scaffold, light gray.

Engineering Designs

**Right- Freezing Apparatus**
This drawing shows an isolateral cross sectional view of the design, showing all components of the apparatus. Starting from the top you can see the motor (red), acme threaded rod (orange), aluminum rod (dark gray), vessel and copper substrate (gray and gold, respectively), Teflon shaft (white), and dewar (green).

**Left- Locking Mechanism**
This is a zoomed view showing the locking mechanism, which prevents the darkened aluminum shaft from rotating relative to the aluminum scaffold. This will ensure translational movement of vessel by the motor and the acme-threaded rod.
**Left-Freezing Apparatus**

This is the complete design from a frontal cross section. The bottom reservoir is the dewar intended to contain the liquid nitrogen. The shaft made of Teflon. Within the cross-sectioned shaft is the moving vessel. On the base of the vessel is the copper substrate, followed by the insulating Teflon around the circumference. The motor is attached to the shaft, which is also attached to the vessel via an acme threaded rod.

**Top-Motor Attached to Rigid Arm on Support**

This schematic shows the tabletop support of the scaffold structure and the attachment to the threaded arm which will allow for the descending movement of the attached vessel.
Engineering Drawings
The following drawings showcase our updated model with applicable dimensions called out. The first page contains a descriptive and number-labeled part list detailing the names of the components used in our design. The second page contains a detailed dimension call-out of the key dimensions of the design.

Cooling Apparatus Parts List
The schematic drawing to the top left shows the parts of our design. Each number correlates to a specific part outlined on the table to the top right. The drawings below specify the scale of the part as well as what the transverse section will look like. The schematic model on the bottom right corner is the vessel. The gold is the copper plate and the gray is the surrounding Teflon material. The hydrogel would be placed in the hollow space in the middle.
Apparatus Drawings and Dimensions

The drawing on the left is a cross-section of the schematic model. The top right is the overall design for our apparatus. The drawing on the bottom right is a cross-section taken of the vessel itself, detailed and zoomed from the shown area on the left-most drawing. The dimensions of the vessel and shaft are the following: outer diameter of vessel: 95.44mm; vessel height: 68.42; scaffold diameter: 15; copper thickness: 3.20mm; copper diameter: 69.82; inner diameter of Teflon shaft: 97.16; outer diameter of Teflon shaft: 131.82; height of Teflon shaft: 307.

See Table 1 for all of the apparatus dimensions.
APPENDIX B- HEAT TRANSFER CALCULATIONS

The following calculations substantiate the dimensions for the vessel and shaft Teflon as well as for the Styrofoam. The equation is based off the resistance that is created from each of the materials, preventing heat loss from the system; the equation takes into account both convection and conduction heat loss. Therefore, each material must be taken into account. The objective of these calculations is to show minimal heat loss from the Teflon vessel and shaft and the surrounding Styrofoam frame. The temperature difference is between the freezing temperature of the scaffold, 273K, and room temperature, 293K. Even if the scaffold reaches a lower temperature than 273K, it is of no importance since the scaffold, which is primarily water, freezes at this temperature. Since the radius of the scaffold must be 0.0075m, this number is \( r_1 \).

The inner radius of the Teflon vessel is determined from the available sizes within our budget from McMaster-Carr, using outer diameters of 63.5mm and 88.9mm as the two choices incorporated into \( r_2 \). The supplier also constrains \( r_3 \) with the thickness of the Teflon shaft to 0.0127m based on inventory and budget. There is a constant addition into \( r_3 \) from the empty space between the vessel and the shaft of 0.00635m to allow for movement of the vessel within the shaft. The Styrofoam thickness is set to 0.0254m in the calculations because even when it was calculated with larger sizes, the heat loss difference was negligible. From the calculations, we can prove that our choices of materials and their dimensions are sufficient to prevent heat loss in the lateral direction. It is important to note that the vertical heat loss will be far greater than the radial heat loss, which is the desired effect.
Radial Heat Loss

\[ \frac{B}{L} = \frac{T_{1,\infty} - T_{4,\infty}}{\frac{1}{2 \pi r_A} + \frac{\ln(r_2/r_1)}{2 \pi r_A k_A} + \frac{\ln(r_3/r_2)}{2 \pi r_B k_B} + \frac{\ln(r_4/r_3)}{2 \pi r_C k_C} + \frac{1}{2 \pi r_4 h_4}} \]

- \( h_1 = h_4 \): heat transfer coefficient for convection
- \( k_A = k_B \): thermal conductivity for Teflon
- \( k_C \): thermal conductivity for Styrofoam

Constants

\( h_1 = h_4 = 13.5 \text{ W/m}^2\text{K} \) (average for a gas)
\( k_A = k_B = 0.245 \text{ W/m}\text{K} \)
\( k_C = 0.033 \text{ W/m}\text{K} \)
\( T_1 = 0^\circ\text{C} = 273\text{K} \) (freezing temperature for hydrogel)
\( T_4 = 20^\circ\text{C} = 293\text{K} \) (Room temperature)

Thickness of Teflon shaft = 0.0127 m (supplier constraint)
Empty space between shaft and vessel = 0.00635 m
Thickness of Styrofoam = 0.0254 m
\( r_1 = 0.0075 \text{m} \)
For 43.5 mm outer diameter of Teflon vessel:

\[ r_1 = 0.0075 \text{m} \]
\[ r_2 = 0.0075 + \frac{0.035 - 0.015}{2} = 0.03175 \text{m} \]
\[ r_3 = 0.03175 + 0.0127 + 0.00635 = 0.0508 \text{m} \]
\[ r_4 = 0.0508 + 0.0254 = 0.0762 \text{m} \]

\[
\frac{Q}{L} = \frac{273 - 293}{1 + \frac{\ln(0.0515/0.0415)}{2\pi (0.035)} + \frac{\ln(0.0508/0.0315)}{2\pi (0.245)} + \frac{\ln(0.053/0.052)}{2\pi (0.033)} + \frac{1}{2\pi (0.025)}}
\]

\[
\frac{Q}{L} = \frac{-20}{1.372 + 0.937 + 0.305 + 1.956 + 0.155}
\]

\[
\frac{Q}{L} = -5.143 \text{ W/m} \quad \text{Negative sign indicates direction}
\]
For 88.9mm outer diameter of Teflon vessel:

\[ r_1 = 0.0075m \]
\[ r_2 = 0.0075 + \frac{0.0889 - 0.015}{2} = 0.0445m \]
\[ r_3 = 0.04445 + 0.0127 + 0.00635 = 0.0635m \]
\[ r_4 = 0.0635 + 0.0254 = 0.0889m \]

\[ \frac{\dot{Q}}{L} = \frac{273 - 293}{2\pi \ln \left( \frac{0.0889}{0.0145} \right) + \ln \left( \frac{0.0635}{0.0445} \right) + \ln \left( \frac{0.04445}{0.0245} \right) + \ln \left( \frac{0.0145}{0.0303} \right) + \frac{1}{2\pi \ln \left( \frac{0.0889}{0.0145} \right)} } \]

\[ \frac{\dot{Q}}{L} = -\frac{-20}{1.572 + 1.157 + 0.232 + 1.623 + 0.133} \]

\[ \frac{\dot{Q}}{L} = -4.234 \text{ W/m} \]

Negative sign indicates direction

This size Teflon results in less heat loss than 63.5mm outer diameter, so the 88.9mm outer diameter will be used for the vessel.
Vertical Heat Loss

Heat transfer in vertical direction through copper disc:

\[ q_x = kA \frac{\Delta T}{\Delta x} \]

\[ k_{\text{copper}} = 400 \text{ W/m} \cdot \text{K} \]

\[ A = 2\pi r^2 + 2\pi rh = 2\pi (0.0445 \text{ m})^2 + 2\pi (0.0445 \text{ m})(0.0318 \text{ m}) \]

\[ A = 0.0133 \text{ m}^2 \]

\[ \Delta T = 20^\circ \text{C} - (-196^\circ \text{C}) = 216^\circ \text{C} = 216 \text{ K} \]

\[ \Delta x = 0.00318 \text{ m} \text{ (thickness of copper)} \]

\[ q_x = 400 \ (0.0133) \frac{216}{0.00318} \]

\[ q_x = 361 \text{ kW} \]

This large heat transfer (in comparison to the very small in the radial direction) shows that heat transfer copper will allow the heat to move into the scaffold in the vertical direction to produce ice crystals and in turn, pores. These calculations prove that copper is a good choice for a heat conducting material.
APPENDIX C-TEMPERATURE GRADIENT AND COOLING RATE CALCULATIONS

The following calculations show the relationship between the temperature and position within the Teflon shaft. In order to calculate it, the general PDE heat equation was used assuming steady-state conditions and air throughout the shaft. The temperature difference from the liquid nitrogen to room was set as 216°C. Through integrating the equation twice, the resulting relationship is linear with a dependency on the initial conditions: \( T(0) = 20°C \) (top of shaft) and \( T(X_{\text{max}}) = -196°C \) (bottom of shaft). Using MATLAB to determine the best shaft size that accommodates the range of cooling rates and velocities, \( X_{\text{max}} \) is set as 30.5mm.

Temperature Gradient Calculation

Assumptions:
- Steady-state, closed system
- Air throughout shaft
- \( T(0) = 20°C = 293\,K \)
- \( T(X_{\text{max}}) = -196°C = 77\,K \)

La Place Integration:

\[
\frac{dT}{dt} = 0 = \frac{\partial^2 T}{\partial x^2} \quad \text{(steady state)}
\]

0 = \int \int \frac{\partial^2 T}{\partial x^2} \, dx

\( T(x) = Cx + D \)
For $X_{max} = 30.5 \text{ cm}$:

\[ 293 = C(c) = D \]
\[ D = 293 \text{ K} \]

\[ 77 = C(30.5) + 293 \]
\[ C = -7.08 \text{ K/cm} \]

\[ T(x) = -7.08x + 293 \]
MATLAB Program and Commentary:

Assumptions:
To simply the program and serve the purpose of a basic model, the program as designed relied on several assumptions that are important to take note of. These assumptions were made to simply and idealize the model so that we could obtain graphical and numerical relationships between the design parameters: velocity and temperature gradient.

The first assumptions we made were with respect to the temperature gradient in the shaft. The copper plate (the portion of the vessel of particular interest) is moving downward through a temperature gradient in the shaft. The temperature gradient is due to the differential temperatures at the top (20°C) and bottom (-196°C) of the shaft, and it is present along the entire length of the shaft. The true nature/behavior of the gradient is unknown in the absence of experimental data, so for the purposes of this model, we have assumed that the behavior is completely linear. We calculated that for a length, 30.5 cm, . This assumption played into our results substantially, as will be discussed below.

Another key assumption we made, for simplicity purposes, was with respect to the copper itself. In order to determine the temperature of the copper with respect to time, we had to make various assumptions about the heat carrying capacity of copper. In order to simplify calculations, we assumed that the temperature of the copper was uniform throughout the material and that it changed its temperature instantaneously with respect to the gradient that we have assumed. This also factored in significantly, as will be discussed below.

In actuality, the velocity and precision of our mechanism will be constrained by the precision capabilities of the motor; this program was designed to have infinite precision, so for our model, we need to be aware of this shortcoming.

Methods:
Taking these assumptions into account, the model was constructed to output 5-column matrices with each row corresponding to a data measurement. The quantity of most interest was the temperature of the scaffold with the passing of each second of time. The temperature of the scaffold was determined by using a derived form of the Heat Transfer equation, which simplified into:

Cooling rate was determined by drawing a secant line between the current point and the measurement taken 5 seconds previous. Cooling rate is simply , so computing the slope of this secant line will give us this quantity. Cooling rate was also plotted.

In the first part, the model determines cooling rate for 2 different constant velocities. Two graphs are plotted for each different velocity, a Temperature VS Time graph and a Cooling Rate VS Time graph.

In the second part of the model, cooling rate is determined for a non-constant velocity, given by the equation where c is an arbitrary time-constant that controls the rate of decay of the equation, and as a function of time Velocity decays to zero. Three graphs are plotted in this second part: Velocity VS Time, Temperature of Scaffold VS Time, and Cooling Rate VS Time.
Results:

These are the figures that we obtained as mentioned above:
Figures 1 and 2 show the temperature felt by the scaffold when the vessel has a constant velocity of 0.14 cm/s and 7 cm/s respectively. As could be expected from our assumptions about the gradient and the heat-carrying ability of copper, the temperature change in the scaffold is linear as well. Linear temperature VS Time plots signifies a constant cooling rate as the second subplot on each figure indicates.

Figure 3 contains three subplots: Velocity, Temperature, and Cooling Rate all plotted against time. The function of this decaying velocity was to show the theoretical cooling rate of a varied velocity as compared with figures 1 and 2 that both showed constant velocities. As can be seen from the non-linear Temperature VS Time plot, the cooling rate is not constant, and this is illustrated in the third subplot.

As evidenced by the plots, a Velocity of 0.014 cm/s corresponds to a -1°C/min cooling rate and a Velocity of 7 cm/s corresponded to a cooling rate of -50°C/min.

**Discussion/Conclusion:**

As mentioned above, the assumptions made were significant ones which simplified our results and gave us a good indication of what we could expect in relation to general behavior of the heat transfer. The assumptions are, as stated, completely ideal, and mostly unrealistic. We were, regardless, able to obtain a velocity range necessary for generating 1-50°C/min cooling rates.

The next steps with this model would be to make the assumptions less ideal and more realistic to obtain a better result for the impact of velocity. This would be done by calculating the heat-carrying capacity of copper and the time that it takes the top surface of the copper (touching the scaffold) to reach the temperature of the bottom (exposed to the gradient). Another necessary step is to determine the true nature/behavior of the thermal gradient in the shaft and incorporate that in the model.

Adding these quantities would strengthen the capability of the model as an accurate predictor of cooling rate for the purpose of our design.

**MATLAB Code is below:**

```matlab
function void = SDheatTransfer()
% HEAT TRANSFER MODEL
% Biomed Senior Design - Team 6
%%%%%%%%%%%%%%%%%%%%%   HEAT TRANSFER MODEL   %%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%  Biomed Senior Design - Team 6  %%%%%%%%%%%%%%%%%%%%%%%%%

Vcmm=0.14; %Defines the starting velocity (Vo) in cm/min
V=Vcmm/60; %Converts Vo to cm/sec
length=30.5; %Sets value for length of shaft in cm
tt=length/Vcmm; %Number of Minutes vessel spends in shaft
tf=tt*60; %Converts to Seconds spent in shaft
R=zeros(1,6); %Set up the R matrix which will contain all info
R(1,3)=V; %Set displacement @t= 1-second to Vo-cm
R(1,4)=293; %Sets initial Scaffold Temperature @t= 1 second
B = 1131; %B is 1131 while scaffold is in liquid form
R(1,4)=293; %Sets initial Scaffold Temperature @t= 1 second
R(1,4)=293; %Sets initial Scaffold Temperature @t= 1 second
%to RT=293K
for t=1:1:tf; %Run a loop which will take measurements in 1-second
```
% increments
R(t,1)=t; %Record running time, t in column 1 in seconds
R(t,2)=V; %Record instantaneous V in column 2
%(constant in cm/s in this part)
if t>1 %For all time greater than 1 second, record the following:
R(t,3) = R(t-1,3)+R(t,2); %Record total distance from starting
%point in column 3
end
Tcopper = 293-(216/length)*R(t,3); %Calculate instantaneous cu temp
%based assumption of constant
%gradient within the shaft
R(t,4)=Tcopper; %Record copper temp in column 4
if t>1 %For all time greater than 1 second, record the following:
%Compute the scaffold temperature using the derived heat
%equation: T=(Thot-Tcold)*exp(-t/B)+Tcold
Tscaffold=(R(t-1, 5)-R(t,4))*exp((-1)/B)+R(t,4);
R(t,5)=Tscaffold; %Store this temperature in column 5
if R(t-1,5)<273 %If scaffold temp dips below freezing...
B=554; %Then re-define B
end
end
if t>5 AVGmeasurements=5; %Computes cooling rate of these # of
%measurements
n=4;
R(t,6)=((R(t,4)-R(t-n,4))/(R(t,1)-R(t-n,1)))*60; %Find cooling
%rate of the scaffold as an average of the last
%5 measurements including the most current
%and place them in column 6
end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Vcmm=7; %Input Velocity in cm/min
V=Vcmm/60; %Converts Vo to cm/sec
tt=length/Vcmm; %Number of Minutes vessel spends in shaft
tf=tt*60; %Converts to Seconds spent in shaft
S=zeros(1,6); %Set up the S matrix which will contain all info
S(1,3)=V; %Set displacement @t= 1-second to Vo=cm
B = 1131; %B is 1131 while scaffold is in liquid form
S(1,4)=293; %Sets initial Scaffold Temperature @t= 1 second
%to RT=293K
for t=1:1:tf; %Run a loop which will take measurements in 1-second
%increments
S(t,1)=t; %Record running time, t in column 1 in seconds
S(t,2)=V; %Record instantaneous V in column 2
%(constant in cm/s in this part)
if t>1 %For all time greater than 1 second, record the following:
S(t,3) = S(t-1,3)+S(t,2); %Record total distance from starting
%point in column 3
end
Tcopper = 293-(216/length)*S(t,3); %Calculate instantaneous cu temp
%based assumption of constant
%gradient within the shaft
S(t,4)=Tcopper; %Record copper temp in column 4
if t>1 %For all time greater than 1 second, record the following:
%Compute the scaffold temperature using the derived heat
%equation: T=(Thot-Tcold)*exp(-t/B)+Tcold
Tscaffold=(S(t-1, 5)-S(t,4))*exp((-1)/B)+S(t,4);
S(t,5)=Tscaffold; %Store this temperature in column 5
if S(t-1,5)<273 %If scaffold temp dips below freezing...
B=554; %Then re-define B
end
end
if t>5
end
end
AVGmeasurements=5;  %Computes cooling rate of these # of measurements
n=4;
S(t,6)=((S(t,4)-S(t-n,4))/(S(t,1)-S(t-n,1)))*60;  %Find cooling rate of the scaffold as an average of the last 5 measurements including the most current and place them in column 6
end
end

hold on
subplot(2,1,1);
plot (R(:,4), 'r', 'Marker', '.');  %Plot the Scaffold Temp VS Time
xlabel('Time in Seconds');
ylabel('Temperature in K');
title('Temp vs Time for Constant Velocity 0.14 cm/min');
grid on

Dy= R(200,5) - R(190,5);
Dx=10;
CoolingRate=(Dy/Dx)*60;
Relation=[VcmmCoolingRate];
subplot(2,1,2);
plot (R(:,6), 'r', 'Marker', '.');
grid on

figure,subplot(2,1,1);
plot (S(:,4), 'r', 'Marker', '.');  %Plot the Scaffold Temp VS Time
xlabel('Time in Seconds');
ylabel('Temperature in K');
title('Temp vs Time for Constant Velocity 7 cm/min');
grid on

subplot(2,1,2);
plot (S(:,6), 'r', 'Marker', '.');
grid on

PART 2 - Decaying Velocity

%Part 2

Vocmm=5;  %Defines the starting velocity (Vo) in cm/min
Vo=Vocmm/60;  %Converts Vo to cm/sec
tt=15;  %Number of Minutes vessel spends in shaft
tf=tt*60;  %Converts to Seconds
R=zeros(1,5);  %Set up the R matrix by defining row 1
R(1,3)=Vo;  %Set initial total displacement to Vo*1 second
R(1,5)=293;  %Set initial Scaffold temp to 293K
B=1131;  %Set 1131 as initial B value

for t=1:1:tf;  %Run loop for all that takes time until t=tf
  %taking measurements at every 1-second interval
  R(t,1)=t;  %Record running time, t in column 1 in seconds

  R(t,2)=Vo*exp(-t/c);  %Stores instantaneous velocity (as governed by this equation) in column 2

  if t>1  %For all t>1-second...
    R(t,3)=R((t-1),3)+R(t,2);  %calculate total distance travelled from the starting point
  end

end
\[ T_{\text{copper}} = 293 - \frac{216}{\text{length}} \cdot R(t,3); \] % Determine Cu temp as function of
% distance, assuming a linear
% gradient in the shaft
R(t,4) = T_{\text{copper}}; % Store Cu Temperature in the 4th column

\textbf{if} t>1 % For all time greater than 1-second
% Calculate the temperature of the scaffold using the heat
% equation
Tscaffold = (R(t-1,5) - R(t,4)) \cdot \exp\left(-\frac{1}{B}\right) + R(t,4);
R(t,5) = Tscaffold; % Store the scaffold temperature in column 5
\textbf{if} R(t-1,5)<273 % If the scaffold freezes...
B = 554; % Redefine B
\textbf{end}
\textbf{end}

AVGmeasurements = 5; % Computes cooling rate of these # of
% measurements
n = 4;
R(t,6) = ((R(t,4) - R(t-n,4)) / (R(t,1) - R(t-n,1))) \cdot 60; % Find cooling
% rate of the scaffold as an average of the last
% 5 measurements including the most current
% and place them in column 6
\textbf{end}
\textbf{end}

D_{\text{total}} = R(tf,3); % Determine the distance travelled down shaft at t=tf
PercentDescent = D_{\text{total}} / \text{length} \cdot 100 % Display the percent
% of total length that
% was descended

\textbf{hold}
\textbf{on}
figure, subplot(3,1,1);
plot (R(:,2), 'r', 'Marker', '.');
title('Velocity vs time');
ylabel('Velocity in cm/s');
xlabel('Time in seconds');
gridded
subplot (3,1,2);
plot (R(:,5), 'b', 'Marker', '.');
ylabel('Temperature of Scaffold in K');
xlabel('Time in seconds');
title('Temperature of Scaffold vs time');
gridded
subplot (3,1,3);
plot (R(:,6), 'r', 'Marker', '.');
gridded
xlabel('Time in Seconds');
ylabel('Cooling Rate in K/min');
title('Cooling Rate Vs Time');
\textbf{holdoff}
\textbf{end}
APPENDIX D - LABVIEW ALGORITHM

The following figures show the front panel and block diagram, respectively, for the LabVIEW algorithm in progress. The front panel is the user interface, where the various inputs are stored. The block diagram is the actual code for the program. The current algorithm includes the input of the thermocouple readings, which are connected to the DAQ card. The DAQ card signals the output for the temperature reading using an average of sine waveforms. This average is calculated through a “while loop” so there is a continuous reading. This reading will then be called into the motor program code, which has yet to be completed.
APPENDIX E- PROTOTYPE-TO-DATE PICTURES

The following pictures were taken at the machine shop while working on the different parts of the apparatus: the locking mechanism, the vessel, the threaded rod and the complete prototype-to-date can be seen in Figure 8 (page 18).

Brian cutting aluminum sheets on the high-speedband saw for the locking mechanism.
Wyatt is configuring the automatic mill.

Above is a picture of the locking key mechanism, which will prevent rotation of the rigid arm, allowing for purely translational movement of the vessel through the Teflon shaft.
The two picture above are of the aluminum vessel with the copper plate attached. In the top photo, it is clear that the copper is attached via two Phillips-head screws. Therefore, in addition to making a tight seal with the Teflon, the copper itself is completely removable, allowing for easy removal of the frozen sample post-cooling.
Above is a photo of the aluminum rigid arm (without the slots for the locking mechanism shown earlier). The rod contains the threaded brass nut, which has been press-fit into the rod as shown.

Above is another view of the arm with the matching threaded rod shown next to it on the right side.
Above is a photo of the Nema-17 stepper motor we will using to control the lowering of the vessel into the Teflon shaft.
APPENDIX F - COST BUDGET

The cost budget chart below outlines the materials we have ordered including their quantity, price, source, and status. The rigid arm, threaded acme rod, vessel, and shaft materials came from McMaster-Carr. The dewar and thermocouples were bought from Nalgene and Omega, respectively. To meet our programming needs, an individual license of LabVIEW was acquired from the Drexel Engineering Department. We are using a power supply in Dr. Lelkes’s lab. The stepper motor, controller, and driver were purchased from Arcus Technology. The total cost of our supplies is $1,548.08. Funding was provided from the Senior Design Budget.

<table>
<thead>
<tr>
<th>Product</th>
<th>Quantity</th>
<th>Price ($)</th>
<th>Cost ($) (including shipping)</th>
<th>Source</th>
<th>Status</th>
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<td>Acquired</td>
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<td>159.10</td>
<td>McMaster-Carr</td>
<td>Acquired</td>
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<tr>
<td>Teflon-127mm outer diameter, 12.7mm thickness</td>
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<td>175.30</td>
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<td>Copper Sheet-3.175mm thickness</td>
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<td>Acquired</td>
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<td>Threaded Acme Rod</td>
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<td>40.45</td>
<td>44.45</td>
<td>McMaster-Carr</td>
<td>Acquired</td>
</tr>
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<td>Acme Round Nut</td>
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<td>32.41</td>
<td>37.41</td>
<td>McMaster-Carr</td>
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<td>Aluminum Sheets-1.5875mm thickness</td>
<td>4</td>
<td>15.02</td>
<td>70.08</td>
<td>McMaster-Carr</td>
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<tr>
<td>Dewar- Polyethylene</td>
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<td>172.00</td>
<td>184.26</td>
<td>Nalgene</td>
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<td>Thermocouples-Type T</td>
<td>2</td>
<td>34.00</td>
<td>68.00</td>
<td>Omega</td>
<td>Acquired</td>
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<tr>
<td>LabVIEW</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>Drexel Engineering Department</td>
<td>Acquired</td>
</tr>
<tr>
<td>Power Supply</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>Dr. Lelkes’s Lab</td>
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<tr>
<td>USB-9211A</td>
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<td>476.10</td>
<td>492.44</td>
<td>National Instruments</td>
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<td>Stepper Motor, Controller, and Driver</td>
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<td>195.00</td>
<td>195.00</td>
<td>Arcus Technology</td>
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<tr>
<td>Mini USB Cable</td>
<td>1</td>
<td>0.98</td>
<td>0.98</td>
<td></td>
<td>Acquired</td>
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<tr>
<td><strong>TOTAL</strong></td>
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<td></td>
<td><strong>1548.08</strong></td>
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</tr>
</tbody>
</table>
APPENDIX G - SCHEDULE

The team began research in the summer of 2009, and a finalized apparatus will be completed by 01May2010. From September to November, a final apparatus was detailed through designing a model in Pro/E and building a K’NEX prototype. Material choices and apparatus dimensions were calculated to order the necessary materials. Materials arrived in December and construction began soon after for the shaft, vessel, and rigid arm.

<table>
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<tr>
<th>Senior Design Project-2009</th>
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<tbody>
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<tr>
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</tbody>
</table>
APPENDIX H - RESUMES

Komal Ahuja
3013 Farmhouse Lane • Garnet Valley, PA 19061 • 610-453-3255 • komalahuja122@gmail.com

Education
Drexel University
Master of Science in Biomedical Engineering and Bachelor of Science in Biomedical Engineering
Expected Graduation Date of June 2010
Cumulative GPA: 3.98

Honors and Awards
- Drexel University College of Engineering, Dean’s Scholarship - 2005 to Present
- Drexel University Dean’s List – 2005 to Present
- Panmuni Honors College – 2005 to Present
- Drexel Theta Chi Chapter of Kappa Theta Epsilon: National Cooperative Education Honor Society – 2007 to Present
- Drexel Tau Beta Pi National Engineering Honor Society – 2008 to Present

Professional Experience

RN/Discovery Research Assistant
April-September 2009

- Mastered rat and mouse in-vivo studies for blood draws and tissue harvesting
- Performed tissue homogenization, RNA purification, and RNA normalization for toxicity testing
- Ran cytokine ELISA assays MCP-1, PAF-1, IL-6 for mouse, rat, and monkey samples
- Determined antibody cross-reactivity using Western blots
- Executed ScanLoop RT-PCR and Taq-man assays to test mir122 and mir126 plasma levels
- Performed RT-PCR testing for knock-down analysis
- Trained colleagues to use Complete Blood Count and automated purification instruments
- Analyzed data using GraphPad Prism, Sequence Detection System, and Excel to determine cytokine knock-down in the presence of different siRNA compounds
- Prepared electronic laboratory notebooks and documentation to present data

Centocor a Johnson & Johnson Company
Clinical Pharmacology Sciences Validation Co-op
April-September 2008

- Developed and validated pharmacokinetic assays to determine drug concentrations in clinical and non-clinical studies
- Developed a matrix to report the concentrations seen in human serum along with the effect of the drug
- Prepared samples used for assays including dilutions, controls, buffers, and coated plates
- Ran ELISA assays
- Measured target:drug binding on detection in developed assays
- Analyzed data using SoftMax and Excel to determine the recovery of each analyte in the presence of different molar ratios of drug and target
- Used results to make modifications to assay necessary to pass validation
- Presented findings to department senior management and directors
- Performed all tasks in accordance with the Standard of Procedures of the Clinical Pharmacology and Experimental Medicine department
- Learned and executed laboratory functions without supervision
- Prepared laboratory notebooks and documentation to present data

Children’s Hospital of Philadelphia: Center for Injury Research and Prevention
Research Assistant
April-September 2007

- Completed proper crash investigation protocol for various vehicle projects
- Compiled crash vehicle information and evidence with NASSMAIN (National Automotive Sampling System application), SLIDE, and Adobe Acrobat Reader
- Prepared biomechanical-related grants to assess pediatric development
- Assisted NHTSA to improve vehicle safety through HVE (Human-Vehicle-Environment) programming simulations
- Developed infant and toddler manikin stiffness database using Access
- Analyzed “Clinical Assessment of Thoracic Stiffness” study through Excel spreadsheets and frequency plots

Skills
- Computer Software - AutoCAD, Maple 10, LabVIEW, Adobe Acrobat Reader, Microsoft Word, Excel, PowerPoint, Access
- Laboratory Techniques - Micro pipetting, Sample Preparation, ELISA, Bradford Assay, Gel Electrophoresis, Fingerprinting, Affinity Chromatography, Western Blotting, Peptide Mapping, Cell Fractionation, SDH Assay, RT-PCR analysis, Taq-man assay, DNA Isolation and Purification, Shotgun Cloning, Patch Plating

Relevant Coursework
- Human Physiology
- Organic Chemistry
- Experimental Biomechanics
- Principles and Techniques in Cell Biology
- Principles and Techniques in Molecular Biology
- Engineering Principles of Living Systems
ATISHA PATEL
46 Brambling Lane, Voorhees, NJ 08043  856-425-1136  atisha223@gmail.com

Education
Drexel University
Bachelor of Science in Biomedical Engineering, Expected in June 2010

Professional Experience
Protez Pharmaceuticals, Subsidiary of Novartis Pharmaceuticals
Philadelphia, PA
Research Microbiologist
March 2008- July 2009
• Tested novel compounds that synergize with antibiotics to inhibit the growth of antibiotic resistant bacteria
• Performed daily assays testing minimum inhibitory concentration of novel compounds, as well as enzyme purification and DNA extraction, cloning, and transformation from drug resistant bacteria.
• Maintained cell cultures and performed cytotoxic analyses as well as hemolysis studies for novel compounds
• Researched methods of transferring characteristics, such as resistance to antibiotics over time.
• Devised a matrix to report the minimum inhibitory concentrations seen in bacteria with the effect of antibiotics
• Used results to modify assay protocols for future testing
• Prepared laboratory notebooks and documentation for weekly data presentation and submitted to FDA

Drexel University
Philadelphia, PA
Redesigning Levee System
November 2005-May 2006
• Designed an engineering design to improve the standard levee system in New Orleans, Louisiana
• Designed an architectural section with AutoCAD
• Analyzed mathematical equations to determine the proper dimensions and materials for the levee system

Research Experience
University of Pennsylvania School of Dental Medicine, Department of Orthodontics
Philadelphia, PA
May 2009-October 2009
• Studied deleterious effects of orthodontic appliances on MRI imaging
• Reviewed literary journals
• Analyzing MRI images of a plastic tyndodont with attached orthodontic appliances.
• Studied different forces applied with various Edgewise appliances

Leadership Experience:
President of American Red Cross Club at Drexel University
September 2007- Present
Provided students at the university with a community service outlet and resume builder. Organized first aid and CPR trainings on campus as well as HIV/AIDS peer counseling. Organized events to teach adults and children to read and educated young children about fire and water safety. Organized several blood drives throughout the year as well as events to clean up parks around the area and fundraisers.

President of Habitat for Humanity
Sept 2003-June 2005
Habitat for Humanity is a nonprofit organization that seeks to eliminate poverty housing and homelessness from the world. It invites people to build houses together for families in need. I initiated and organized a high school chapter, which helped raise money for the sites where Habitat built new homes.

Activities:
Big Brothers Big Sisters in Cherry Hill, NJ  June 2009 - Present
Shadowing Dr. Lenahan, DMD  April 2009 -Present
Variety of Indian Cultural Expressions  2006-2007

Skills
Hardware: IBM Compatibles, Apple Macintosh
Operating System: Windows 2000/XP, MacOs
Software: AutoCAD, Maple 10.0, LabVIEW, MatLab, Microsoft Word, Excel, PowerPoint
Laboratory Skills: Electrode; pH meter; Micropipetting; Determination of protein concentration using a Spectronic 20 spectrophotometer; Gel Electrophoreses; Affinity chromatography; Bradford Assay, Isolation, purification, digestion, ligation, transformation and screening of chromosomal DNA; Shotgun Cloning; Fingerprinting; Peptide Mapping; ELISA; SDH Assay; RT-PCR analysis; Taq-man assays; Western blotting; Enzyme Catalysis; Titration of Glycine; Data sheet analysis; Crystallization, sublimation, distillation of chemicals.

References
Available upon request
Brian Saunders  
414 N 33rd Street  
Philadelphia, PA 19104  
848-702-4827  
brian.saunders@drexel.edu

Education  
Drexel University  
Bachelors/Masters of Science in Biomedical Engineering  
Concentrations in Biomechanics and Mechanical Engineering  
Philadelphia, PA  
Anticipated Graduation: June, 2010  
Cumulative GPA: 3.55

Work Experience  
Globus Medical Inc.  
Project Engineer  
Audubon, PA  
March to September 2008  
• Worked in R&D to design, test, and maintain a multitude of interlaminar spinal cord implants and instrumentation.  
• Attended surgeries nationally and introduced products and designs to current and potential clients.  
• Met regularly with manufacturing engineers, product managers, and company executives to brainstorm new project ideas and to get current projects launched as soon as possible.

Synthes, USA  
Product Development Engineer  
West Chester, PA  
March to September 2007  
• Worked closely with engineers and surgeons on designing, developing, and testing a large variety of surgical devices.  
• Worked with engineers on a new generation of instrumentation, wherein surgeons will be able to percutaneously fixate fractures.  
• Collaborated with team members on a regular basis to meet project deadlines and to keep all company surgical devices originating from our group up-to-date with all new and evolving technology.

Relevant Coursework  
Material Engineering  
Human Physiology I, II  
Biomedical Statistics  
Biomedical Experimental Design  
Biomedical Ethics  
Biomechanics Laboratory  
Electric Circuits  
Biosensors  
Mechanics of Materials  
Engineering Principles of Living Systems I, II  
Engineering Law  
Biodynamics/Biomechanics

Engineering Skills  
Software includes: Pro Engineer, Maple, AutoCAD, Matlab, Labview

Other skills include: Good Knowledge of basic machining technique, use of basic mechanical testing equipment, good working knowledge of FDA process for new medical device approval, and good understanding of Intellectual property rights and patents.

Honors/Awards  
• Dean's List, 2005-Present  
• AJ Drexel Scholar, 2005-Present  
• Past-President and Past-Secretary of the Alpha Epsilon Pi Fraternity, 2006  
• Current Vice President and Past-Treasurer of the Drexel Interfraternity Council, 2008  
• Awarded “Leader of the Year” among all Drexel Greek men, 2009  
• Member of the Order of Omega, a prestigious honor given to the top 3% of Drexel Greek students, 2007  
• Past Secretary of Kappa Theta Epsilon National Cooperative Education Honor Society, 2007  
• Member of the Phi Eta Sigma National Honor Society, 2006  
• Member of the National Collegiate Honor Society, 2006
Wyatt Covington Strutz  
212 Redstone Ridge ◆ Cherry Hill, NJ 08034 ◆ (856)-906-2964 ◆ WCStrutz@gmail.com

Education

Drexel University  
Philadelphia, PA  
M.S. in Biomedical Engineering, expected in June 2010  
B.S. in Biomedical Engineering, expected in June 2010  
Cumulative GPA: 3.64

Experience

GlaxoSmithKline  
03/08-09/08. Co-op II: Cell Biology>>> Cell Technology Group  
Merion, PA  
- Designed and altered assays to gather data for macrophage influx studies  
- Tissue culture of human T-cells and monocytic leukemia cells  
- Performed multiple PCR experiments  
- Trained in flow cytometry using FACS and BD software  
- Trained in the use of Fluorescent Microscopy

Amicus Therapeutics  
03/07-09/07. Co-op I: Molecular Biology>>> Drug Discovery Group  
Cranbury, NJ  
- Tissue culture of human fibroblasts  
- Measured the enzyme kinetics to test the effects of compounds  
- Submitted several legal notebooks to FDA  
- Performed protein studies using the Western Blot technique

Banana Republic  
12/05-3/07. Sales Associate  
Cherry Hill, NJ  
- Achieved 3rd in sales out of roughly 40 employees during one season’s collection  
- Developed customer-unique selling techniques  
- Developed customer and peer etiquette

Drexel University  
06/06-09/06. Undergraduate Research  
Philadelphia, PA  
- Trained in proper tissue culture methods and protocols, including preparing various media  
- Tissue culture of endothelial bovine cells

Honors and Awards

- Zung Pah Woo End Scholarship, 2009  
- Phi Sigma Pi National Honors Fraternity, 2009-present  
- Tau Beta Pi Engineering Honor Society, 2008-present  
- Kappa Theta Epsilon National Co-op Honors Society, 2007-present  
- STAR Undergraduate Research Scholar, 2006  
- Drexel University Scholarship, 2005 - present  
- Drexel Pennoni Honors College, 2005 - present  
- International Baccalaureate Diploma, 2005  
- Comcast Scholar and Leadership Scholarship, 2005
Leadership Positions and Roles

President of Kappa Theta Epsilon National Co-op Honors Society: 06/08–06/09. (6 hrs/month) Provided many career and character development opportunities for members and alumni. For example, in 2008/2009, I helped manage roughly forty member volunteers for both the Fall and Spring career fairs Drexel hosts annually. These events provide students with direct contact to hiring managers of global companies, such as Johnson & Johnson and Microsoft.

Co-Chair of Student Advisory Committee: 08/08–06/09. (5 hrs/month) Worked along side the University's career development faculty to improve aspects of the cooperative education program based on student feedback. An example of one success was the ability for students on co-op to take up to one class per term for no additional costs.

Relevant Courses

- Calculus I, II, & III
- Biomedical Statistics
- Bioethics
- Economics I & II
- Physics I, II, and III
- Entrepreneurship
- Differential Equations I & II
- Cellular Biology
- Experimental Design
- Critical Reasoning
- Mechanics of Materials
- Business Law
- Organic Chemistry I, II, & III
- Molecular Biology
- Physiology I & II
- Applied Evolution
- Science Teaching Methods
- Corporate Governance

Community Service

Hospital of the University of Pennsylvania: Oncology Department, 09/07–01/08. (4 hrs/week) I provided hospice care patients with water and conversational support. To make better use of my time and have an impact on patients, I made an origami crane for each patient every week.

Lindy Scholars Mentorship, 04/09–present. (4 hrs/month) I, along with other volunteers, provided friendship and activities on Saturday mornings for middle school students from West Philadelphia. For one activity, we all watched ‘‘Stomp’’, which is an urban-style musical. Afterwards, we created music as a class.

Personal Interests and Hobbies

When not in class, doing homework, or participating in events hosted by an organization, I enjoy reading fantasy novels and watching the Science Channel. I have two golden retrievers, who I adore more than anything. During warmer seasons, I enjoy drinking iced coffee outside while reading a book and surfing at various southern New Jersey beaches. When I have available cash, I also like to invest in the stock market.