A Miniature Cascade Impactor to Capture Bacteria from the Air

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6 May 2011

Date
Miniature Cascade Impactor to Capture Bacteria from the Air

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Jessica Hastings
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DATE: May 4, 2011
TO: Professor Mark Riley
FROM: Group Three: Samanta Dadayeva, Jessica Hastings, Kevin Korf, Meredith Roberts
SUBJECT: Miniature Cascade Impactor to Capture Bacteria

Attached is the design report for a device that will capture bacteria from the air presented in the spring semester of 2011.

Bacterial contamination is often a health issue in workplaces, particularly in agricultural, mining, pharmaceutical, and construction environments. In these industries, workers are frequently exposed to harmful and infectious bacteria. Since government regulations require that these companies uphold health standards, it would be useful to know how much biological contaminant workers are exposed to (16). In pharmaceutical labs, a clean environment is essential to the production of safe, quality drugs. It is important for pharmaceutical facilities to have methods of detecting various modes of contamination within the lab (31). Although many devices are able to capture bacteria from the air, none are able to allow quick and efficient quantification of the bacteria captured and are often large and costly. Since ultrafine, metallic particles in the air are known to kill bacteria, these must be separated from the bacteria in order to grow bacterial colonies that will accurately represent the amount of bacteria in the air. These concerns have necessitated the development of a portable device that can sort bacteria from particulate matter in the air based on particle size and can subsequently be analyzed to quantify the amount of bacteria within a designated environment.

The design created is a miniature cascade impactor that is able to separate particles based on size. This new cascade impactor is cost effective, runs for eight hours, uses a minimal power source, and is small enough to be clipped on. The device consists of five shelves, each of which will capture a different particle size. Larger particles will be captured initially while smaller particles will flow through the device to be captured or expelled subsequently. This collecting process is governed by the Stokes number. The device is connected to a micropump that achieves a flow rate of approximately 144 ml/min when powered by a 4.5 V battery to guarantee a proper air velocity through the device. There are several future improvements to be made to the device before entering the market.
Statement of Roles and Responsibilities

The work presented here was a collaborative effort for ABE498a and ABE498b, Senior Capstone in Biosystems Engineering. A team of four students worked together to identify an engineering problem and design a fully developed solution to address this problem. Most responsibilities were shared in order to promote multiple perspectives to generate the best possible design. However, responsibilities were generally split up as follows:

Meredith Roberts – Design Theory Research, Design Selection, SolidWorks 3D Model, Computational Fluid Dynamics, Mechanical Analysis, Experimental Design

Kevin Korf – Design Theory Research, Design Selection, Rapid Prototyping, Machining

Samanta Dadayeva – Design Theory Research, Design Selection, SolidWorks 3D model

Jessica Hastings – Experimental Design, Background Research
**Executive Summary**

The objective of designing a miniature cascade impactor was to enable employers to determine the level of biological containments employees have come in contact with during an average work day. This technology would be useful for employers where there are hazardous risks for the employees. Current sampling devices are expensive, and portable, and do not provide accurate/easy methods of analysis. The final design was based on the following criteria:

**Constraints:**
- Separate bacteria from particulate matter by particle size
- The device must be small enough to later be incorporated into a portable device that could be clipped on near the nose and mouth of the user
- Total budget of the project must be less than $500
- Minimal power should be used, while at the same time providing enough power for the device to run for an eight hour time span.

**Summary of Design:**
- A Cascade impactor design with five stages was chosen to separate and collect bacteria
- A collection time of eight hours determined the area of the collection shelves
- Particle capture was determined using Cunningham-stokes diffusion
- Computational fluent dynamics displayed the air flow of the channel. This was used to verify the velocities and pressures in the channel.
- TCS micropump D210 was chosen based on its price, size and flow rate
- Manufacturing of the device was done by Solid Concepts, a rapid prototyping company

**Testing and Results**
- Testing was performed by putting the new miniature cascade impactor in a chamber with the instantaneous microbial detection device produced by BioVigilant Systems Inc.
- After multiple trials of comparing the amount of bacteria collected to the BioVigilant data, a collection efficiency of 13% was achieved.

**Recommendations**
- Scale up channel dimensions and incorporate a more powerful pump
- Increase size of removable slide
- Add removable shelves to each stage
- Choose smoother material
- Increased number of stages to increase collection efficiency
Abstract

This design separates bacteria from particulate matter and ultrafine particles so that the amount of bacterial contamination in the air can be determined. The final design consists of a micropump to facilitate air flow through a five stage cascade impactor. The impactor is based on Cunningham-stokes diffusion to collect bacteria on a removable shelf for ease of analysis. Experimental results demonstrate that the impactor attained a collection efficiency of 13%. There are a variety of improvements that could be made to increase this collection efficiency, the most important of which are scaling up the channel inlets and increasing the pump flow rate.
Acknowledgments

We would like to acknowledge the following people for contributing to this project by guiding us throughout the design process:

Dr. Mark Riley – Project Advisor

Dr. Donald Slack – Faculty Support

Dr. Christopher Choi – Provided CFD software

Mario Mondaca – CFD assistance

Felipe Montiel – Experimental setups

Charlie De Fer – ABE shop – machining assistance
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Introduction

Statement of the Problem

Bacterial contamination is often a health issue in workplaces, particularly in agricultural, mining, pharmaceutical, and construction environments. In these industries, workers are frequently exposed to harmful and infectious bacteria. Since government regulations require that these companies uphold health standards, it would be useful to know how much biological contaminant workers are exposed to (16). In pharmaceutical labs, a clean environment is essential to the production of safe, quality drugs. It is important for pharmaceutical facilities to have methods of detecting various modes of contamination within the lab (31). Although many devices are able to capture bacteria from the air, none are able to allow quick and efficient quantification of the bacteria captured and are often large and costly. Since ultrafine, metallic particles in the air are known to kill bacteria, these must be separated from the bacteria in order to grow bacterial colonies that will accurately represent the amount of bacteria in the air. These concerns have necessitated the development of a portable device that can sort bacteria from particulate matter in the air based on particle size and can subsequently be analyzed to quantify the amount of bacteria within a designated environment.

Background

The average human inhales approximately 10 m³ of air per day while the concentration of bioaerosol particles in both outdoor and indoor areas is typically 1,000 particles per cubic meter (17, 30). This effectively shows that a person could potentially breathe in up to 10,000 bioaerosol particles per day. If the bioaerosol particles inhaled are infectious, this large amount of inhaled bacteria could lead to severe health complications.

The EPA’s “The Clean Air Act” sets the air quality standards in an attempt to protect the public’s health and welfare. The EPA (Environmental Protection Agency) erects regulations on the safety of particulate airborne particles. EPA qualities of regulation address toxic and carcinogenic components such as asbestos, urethane fumes, and lead paint. However, there is comparatively less attention and regulatory controls in relation to biological agents (40). There
are jobs that require more exposure to biological contaminates than others. For example, high concentrations \((10^4 - 10^{10} \text{ cfu/m}^3)\) can be found in sawmill and agriculture industries (30).

Another organization that works to protect people in hazardous jobs is International Labour Organization. This organization is an agency of the United Nations that works with employers to minimize risks to employees in occupations where there is a risk to exposure of hazardous agents. Their goal is to incorporate “prevention strategies to anticipate, identify, evaluate, and control hazards arising from the constantly evolving world of work” (16). They work with the Department of Labor’s Occupational Safety and Health Administration to ensure a safe work environment.

Corresponding with the interest in the health of the public, there are currently devices that specifically measure and analyze clean rooms to verify their pure state. One of these machines, created by BioVigilant called IMD-A 200-1, is a real time analyzer of the contents of biological particles in the air (5). This machine, however, is big and bulky, and is not intended to be moved. Cascade impactors are commonly multi-stage sampling devices for determining the size distribution of a particulate aerosol. The aerosol flows into the impactor’s disk surface where it can be “captured”. Larger particles impact on the first disc, becoming captured, while smaller particles continue in the air stream to become captured later. The velocities in the chamber increase for each sequential disk to successfully capture smaller particles (7). Analysis of the disks allows for the determination of what is present in the sampling environment. A unique aspect of the new design that would be beneficial to users is its portability, which would serve to detect what biological contaminants the user encounters.

Aerosolized pathogenic bacteria are found in several day-to-day environments such as the workplace. For example, Streptococcus pneumonia is a bacterium that is exclusively a human pathogen and is spread through the population by coughing and sneezing in close vicinity (\textit{Streptococcus pneumonia}). Indication of a contaminated environment could help a person of risk avoid certain scenarios where this type of bacteria is prevalent. As another example, Bioagents are bacterium that can be used as a weapon of biological warfare whose early detection would be extremely beneficial for the infected parties and the prevention of further transition. Bacteria anthrax (\textit{Bacillus anthracis}) is an example in which most forms of
the disease are lethal and transfer is caused by spores being inhaled. The most publicly acknowledged outbreak of anthrax was the biological attacks that killed five people, and infected seventeen.

The bacterium used for the testing of this device is *Escherichia coli*, commonly known as *E. coli*. This gram-negative, rod shaped bacteria is about 1 micrometer, and may be pathogenic or nonpathogenic (14). This bacteria is the best-studied prokaryote and is a common model organism for biotechnology research. This organism will be the most appropriate to test the device with because of the readability and ease of sampling (14).

**Purpose of Project and Overview of Project Report**

The purpose of this project is to solve the high cost, large size, and inefficient quantification issues of conventional cascade impactors with the design of a miniature cascade impactor that will collect bacteria on a custom made glass slide while separating the bactericidal metallic microparticles from the collection plate. The following report will explain the methods used to research and develop this device, the construction methods, the usefulness and limitations of the device, an overall analysis of the resulting product, and finally recommendations for further product development.

**Methods and Design Approach**

**Design Theory**

The design for this project is a miniaturized cascade impactor that would separate particulate matter based on particle size. The design was dictated by a number of constraints that were necessary to solve the above stated problems. First, the device must be portable. The portability implied the design of a small, lightweight device that would not be cumbersome for the customer. As air naturally enters the body through the mouth or nose, the closer the device is to that area of the body, the more realistically representative its detection will be. Thus, the design was created small enough so that a clip could be mounted to it and then clipped onto the collar of a shirt when in use. Second, the device must be cost efficient. The massive sizes of conventional cascade impactors make them efficient, since they are able to achieve much
higher air velocities due to more powerful pumps but also make them extremely expensive (on the scale of $5,000 - $10,000 plus miscellaneous parts (32) and immovable. Even portable cascade impactors that currently exist cost anywhere from $800 - $2,400, depending on the efficiency of particle separation (21).

Finally, the device must separate particles from the air based on size, giving our device the cascade impactor design. Ultrafine, metallic microparticles created from combustion processes, typically smaller than 0.1 μm, are known to be toxic to bacteria (6). Contact between bacteria and these particles will result in bacteria death, which prevents some bacterial growth into colonies for counting and ultimately gives an inaccurate representation of the quantity of bacteria in the air. Since bacterial colony counting is the easiest and most efficient live bacteria quantification method, the metallic particles are separated to ensure proper bacterial growth. All particulate matter present in ambient air may contain ultrafine, metallic particles and therefore must be separated from the collected bacteria in this design.

Cascade impactors utilize particle inertia to separate particles based on size. Larger particles will generally have a larger inertia than smaller particles at the same velocities. The impactor uses “shelves” to separate different particulate matter sizes, the physics of which is governed by the Stokes number. The Stokes number is a dimensionless parameter that dictates what particle size will be collected on each shelf. It is a ratio of a particle’s velocity and relaxation time to its characteristic dimension, which is the width of the air stream in this case. The relaxation time is the time it takes for a particle to adjust to changing applied forces. A Stokes number much greater than 1 represents the high probability that the inertia of a particle will overpower the force of the turning airstream and continue its trajectory and impact the collection surface. Conversely, a particle with a Stokes number much lower than 1 represents a high probability of that particle’s trajectory continuing along the path of the airstream (11). It was found in the literature that a Stokes number of 0.5 corresponds to a collection efficiency of approximately 50%, but the correlation is not linear (30). The following equations were used to calculate the Stokes number for different sized particles on each shelf:

\[
\text{Stokes Number} = \frac{r_p U_0}{d_c};
\]
The Stoke's number assumes a no-slip boundary condition that does not necessarily hold true for smaller particles. The Cunningham correction factor is used to adjust for this with the following equations (29, 33):

\[ C_c = 1 + A(k_n) \]
\[ A = \alpha + \beta + \exp\left(\frac{-\gamma}{K_n}\right) \]
\[ K_n = \frac{\lambda}{1} \]
\[ \lambda = \frac{K_B T}{\sqrt{2\pi} d_p^3 \rho_p} \]

The constants \( \alpha, \beta, \) and \( \gamma \) used to calculate \( A \) are usually determined experimentally. However, as the proper facilities to perform these tests to determine the constants were not available, they were taken from take from the literature to be 1.155, 0.471, and 0.596, respectively (29).

Fortunately, after several calculations were performed, checked, and rechecked, it appeared that the particles collected by this device were not small enough to break down the no-slip condition. The Cunningham correction factor was calculated to be 1.00002 for ultrafine particles, which is negligibly larger than 1 and did not change the calculations for the Stokes number.

The relaxation time calculated into the Stokes number assumes a spherically shaped particle. However, there are very few particles that are even close to being perfectly spherical.
Therefore, the aerodynamic diameter is used to represent small, irregularly shaped particles as perfectly spherical.

Each of these representative spheres has unit density (1 g/cc) and has the same gravitational settling velocity as the particle represented. Thus, it maintains the inertia and settling velocity of the original particle while also allowing proper calculations of Stokes number. The aerodynamic diameter of *E.coli* was found in the literature to be 0.89μm (1).

The number of shelves on the cascade impactor design was determined by the degree of separation efficiency that was desired. The shelves are the surfaces that collect the impacted microparticles after they exit the airstream, the final of which will collect bacteria and will be referred to as the “collection shelf”. Since the EPA categorizes microparticles into 4 categories, 10 μm, 5 μm, 2.5 μm, and 1 μm particles, the cascade impactor was also given these cut off points for each shelf, with an extra shelf collecting 2.5 μm particles to account for bouncing effects, and to better separate inert microparticles from bacteria on the collection shelf.

Bouncing effects are detrimental to the success of the cascade impactor separation and were thus appropriately accounted for and remedied. Bouncing effects are when the particles exit the airstream and impact the surface but subsequently bounce off the intended shelf and either get re-incorporated into the airstream flow or roll onto a different shelf (13). In this miniaturized cascade impactor, the most important shelf was the collection shelf. The goal was to separate as many microparticles and ultrafine particles as possible from the collection shelf. Thus an extra shelf that captured 2.5 μm was incorporated into the design to catch any spillover that the previous shelves failed to secure. This allowed minimal spillover onto the collection shelf. Ultrafine particles were not captured and were allowed to go straight through the device untouched. Bouncing effects were also accounted for by designing the removable shelf to be a poly-l-lysine coated glass slide. Bacteria contain peptides in their cell walls which will adhere to the poly-l-lysine and help anchor them to the collection shelf after impaction.

A micropump was purchased from Thermal Cooling Systems that was able to achieve a maximum theoretical flow rate of 380 ml/min at 4.5 volts, corresponding to an initial inlet airflow velocity of 5.28 m/s when accounting for the dimensions of the impactor. The pump flow rate along with the Stokes number decided the dimensions of the cascade impactor. Inlet
sizes were manipulated to achieve appropriate velocities for collection. The relatively small flow rate of the micropump meant the dimensions of the impactor had to be scaled down, synergistically allowing a properly sized, portable device. In order to attain a capture efficiency of 100% for bacteria on the collection plate, the velocities were not only unreasonably large (causing bacterial cell burst upon impact and presenting an unachievable velocity) but that shelf would also capture a considerable amount of ultrafine particles. Thus, a collection efficiency of 50% for bacteria (Stokes number of 0.5) was the main goal that determined the impactor dimensions. The design was optimized by trying to reach as high a Stokes number as possible for bacterial collection while maintaining a reasonable velocity in the channel. A reasonable maximum channel velocity was assumed to be between 20-25 m/s.

**Computational Fluid Dynamics: ANSYS Fluent**

An important component of this design was to model the airflow through the channel using CFD such that the velocity profile could be visualized. It was also important to determine the pressure drop across the channel in order to guarantee that the pump will still function at the required flow rate. Fluent was also used to determine that the airflow is laminar and that there are no eddies formed directly above the shelves as this would result in loss of collected particles.

The geometry for the model was set up based on initial approximate values for the dimensions. As described above, the Stokes number must be at least 0.5 in order to obtain 50% capture efficiency. The maximum velocity that should be reached in the channel is between 20-30 m/s. Velocities greater than this may lead to bacterial death due to impact velocities. As shown in the figure below, at a velocity of 20 m/s there was 2% cell breakage (9). More than 2% cell death was considered to be significant since the final goal of the device is to quantify the amount of bacteria in the air. Therefore the shelf #5 inlet velocity was set to be 20 m/s and using the equation Q=vA, the inlet width, 158 μm, was determined. The remaining 4 inlet widths were chosen such that the Stokes number for bacteria collection on the previous shelves would be less than 0.1. Although this will result in some bacterial collection on the first four shelves, it is not feasible to completely eliminate collection on these shelves without
compromising collection of PM2.5 and PM10. This geometry was used for the initial Fluent simulation. The finest possible mesh was created in order to minimize the error in the calculations; the residuals were calculated to be on the order of $10^{-9}$. A steady state pressure driven flow was used during the simulation. The channel inlet was defined as the “velocity inlet” and set to 5.28 m/s based on the pump flow rate and the inlet area. The outlet was originally defined as “Outflow.” The wall material was set to Aluminum during the simulation since Fluent does not have any plastics programmed into it. This might result in a slight discrepancy between the model and the actual airflow due to frictional losses in the channel caused by roughness of the material. The velocities calculated by Fluent were slightly less than predicted by the equation $Q = vA$, most likely due to frictional losses and pressure buildup in the channel. The dimensions to each inlet were adjusted until the velocity at the shelf #5 inlet was approximately 20-25 m/s. The following data was obtained with the final dimensions of the channel:

![Figure 1](image-url)
**Figure 2** – Velocity at inlet of each stage/shelf. Sharp increase in velocity at shelf #5 inlet in order to capture bacteria. Red line shows velocity of bacteria right before impaction.

**Figure 3** – Pressure drop through channel. Each stage corresponds to an additional pressure drop eventually feeding into atmospheric pressure at the outlet.
A graph was obtained from Thermal Cooling System (TCS) showing how the pump flow rate varies with changes in pressure relative to atmospheric pressure (Appendix A1 table A1-2). The maximum pressure buildup in the channel as shown above is 901.8 Pa (~8mbar), which corresponds to little to no change in the flow rate of the pump.

The maximum Reynolds number calculated in the channel is 192.6 demonstrating that the flow is laminar as expected and required. The original design was to include bore tubing connected at the inlet and the outlet of the channel. However, the final design only included bore tubing at the inlet; the outlet was exposed to the atmosphere. This new schematic was run through Fluent by changing the outlet definition to “Pressure Outlet” and setting the gage pressure to 0 Pa since the outlet is open to the atmosphere. The results were very similar to the previous run:

![Fluent model with “Pressure Outlet”](image)

**Figure 4** - Fluent model with “Pressure Outlet”

The main difference between the two runs is a slight increase in pressure from 901.8 Pa to 930.5 Pa. This difference in pressure, however, will still not affect the flow rate of the pump. The velocity profiles, Reynolds number, and residuals are identical between the two runs.
**Alternative Designs**

The above CFD data is for alternative #1. Alternative design #2 differs in that its shelves are at a 5 degree incline. This modification to the design is meant to decrease the bouncing effects described earlier. The rationale behind this being that once a particle impacts the surface the angle of the shelves will project the particle towards the wall and the particle will eventually settle in the groove between the wall and the shelf. The CFD results on this geometry were not significantly different. The velocity profile and pressure drop were not statistically different between the two designs.

Although alternative #2 would decrease bouncing effects more so that alternative #1, alternative #2 was rejected due to manufacturability. Incorporation of the removable glass shelf would not be possible in alternative #2, and this feature was deemed more important than the slight improvement that angled shelves would have on bouncing effects.

**Stress Analysis**

A stress analysis was performed to ensure the device could withstand the compressive loads applied while bolting the multiple pieces together. In order to perform this analysis the required force needed to compress the o-rings was determined. The o-ring grooves were designed to undergo 20% compression and the purchased o-rings have a cross sectional area of 0.07”. Table A1-1 in Appendix A1 from the Parker O-Ring handbook published by the Parker Hannifin Corporation was used to determine the necessary compression load.

Since the hardness of the o-ring is not known there is range of compression loads that the part must withstand. The following stress analysis was performed assuming 90 shore hardness corresponding to a compression load of 27 lb/in. The total compression load on each o-ring (O.D.=0.5”) is therefore 42.4 lbs. This load will be applied with screws that are located at a radius of 0.4” from the center. Therefore the load distribution is 16.87 lb/in.

The governing equations for the stress analysis were taken from Roark and Young (41). The equations used are valid for flat circular plates of constant thickness, outer edge guided, and inner edge simply supported (Figure 5). The inner support represents the force exerted by the o-rings in response to compression of the device. The load (w) is the compressive force...
exerted by the bolts. The dimensions of the device that correspond to this schematic are \( a=0.591" \), \( b=0.341" \), \( r_0= 0.4" \), \( t= 0.0787" \). The applied load calculated above from o-ring compression is \( w= 16.87 \text{ lb/in} \).

![Diagram](image)

**Figure 5 – From Young and Roark “Formulas for Stress and Strain” (41)**

The following equations were used to analyze this schematic (41):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Equation</th>
<th>Calculated Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_{ax} M_{rz} )</td>
<td>( \frac{w^2}{b} \left( c_9 - \frac{c_6}{c_4} \right) )</td>
<td>4.21 lbs</td>
</tr>
<tr>
<td>( c_4 )</td>
<td>( \frac{3}{2} \left[ (1 + v) \frac{a^3}{E} + (1 - v) \frac{b^3}{E} \right] )</td>
<td>0.953&quot;</td>
</tr>
<tr>
<td>( c_6 )</td>
<td>( \frac{4}{a^3} \left[ (\frac{b}{a})^2 - 1 + 2 \ln(\frac{a}{r_0}) \right] )</td>
<td>0.062&quot;</td>
</tr>
<tr>
<td>( c_7 )</td>
<td>( \frac{1}{2} \left[ 1 - v^2 \right] \left( \frac{a}{E} - \frac{b}{E} \right) )</td>
<td>0.507&quot;</td>
</tr>
<tr>
<td>( c_9 )</td>
<td>( \frac{1}{2} \left[ (1 + v) \ln \left( \frac{a}{b} \right) + \frac{1}{2} \left( 1 - v \right) \ln \left( 1 - \left( \frac{b}{a} \right)^2 \right) \right] )</td>
<td>0.2767&quot;</td>
</tr>
<tr>
<td>( G_{max} )</td>
<td>( \frac{6M_{ax}}{t^2} )</td>
<td>4078 psi</td>
</tr>
<tr>
<td>Factor of Safety</td>
<td>( \frac{\text{Strength of Material}}{\text{Applied Load}} )</td>
<td>3.4</td>
</tr>
</tbody>
</table>

The flexural strength of the VeroGray FullCure©850 was given in the material datasheet (Appendix A7). A factor of safety was calculated to be 3.4. The chosen material was therefore considered to be strong enough to withstand the compressive load.

**Results**

**Technical Description**

We produced a Miniature Cascade Impactor based on our design approach and methods described in the previous section. The actual device consists of a system of five shelves that constitutes a channel for the flow of the air with the particulate matter (see Figure 6). The airstream enters through the initial inlet with a velocity of 5.28 m/s, and goes through the
serpentine channel with varying velocities (Figure 7). Each subsequent shelf separates particulate matter by their sizes. Shelf 1 collects 10 μm particles, shelf 2 – 5 μm, shelf 2.5 μm, shelf 4 - 2.5 μm, and shelf 5 collects 1 μm particles. Shelf 5 is the collection site of the bacteria, and contains a slot for the poly-l-lysine glass slide which helps to retain bacteria and reduce bouncing effects (Figure 8). The extra material around the channel allows ease of handling. This device can be assembled and disassembled with minimal effort, as shown in an exploded view in Figure 6.

Figure 6: Overview of the device

Figure 7 shows a cross section of the device with dimensions derived from our computational fluid dynamics analysis. The airstream enters from the top of the channel through the inlet, passing each shelf and separating particles based on size. We used female and male notches on the tops and bottoms of each shelf for proper orientation of the channel. Shelves were held firmly together with four radially positioned screws that went through the free material around the channel and ensured an airtight seal. O-ring grooves were designed to protect the material during compression and also to assist in providing an air tight seal. Grooves were designed as outlined in the Parker O-Ring Handbook published by Parker Hannifin Corp.
Ultrafine particles, such as metal ions, will not be collected on the shelves and will pass through the channel. This condition is desirable to prevent any interactions of the bacteria with ultrafine particle since they lead to bacterial death. Velocity of the air in the channel increases to approximately 23 m/s at the inlet of the fifth shelf, but decreases to approximately 9 m/s.
before the bacteria hits the actual shelf, facilitating adhesion of the bacteria to the slide. The following Figure #9 shows the velocity distribution from the Fluent model of the particles at the inlet for each individual shelf.

![Figure 9](image)

**Figure 9**

![Figure 10: Overall operating schematic of device](image)
Specifications

Our device is a system of five shelves, as shown in Figure 6, and collects bacteria on the fifth shelf. The bacteria collection shelf is the last stage of the system with a poly-l-lysine slide slot. In our experiments with the channel we used paper slides and obtained about 13 % efficiency when compared to results from BioVigilant machine. The experiments were conducted simultaneously with a BioVigilant system in a sealed acrylic chamber without running air purifier. Bacteria were periodically injected into the chamber with a nebulizer that aerosolizes a 1:100 concentrated solution of E. coli. Pump forces air through the inlet of the channel at the rate of 380 ml/min. As air passes through the channel, particles are separated by their size and bacteria are collected on the last shelf.

Figure # 11: A simplified version of our design concept. As air enters at the inlet with different sized particles, larger particles cannot make the turn and remain on the shelf, and the rest of the particles proceed to the next stage of the impactor. The process repeats itself until particles reach shelf 5 where bacteria is collected (green particles in F#10). It is important that ultrafine particles pass the bacterial collection shelf because they interfere with bacterial growth.
**Particle Capture at Each Stage**

Using the final channel dimensions and the velocities obtained from Fluent analysis the following values for the Stokes number was obtained (Table 1). The Stokes number for the target particle size at each shelf is bolded. There will be some bacterial collection on the second, third, and fourth shelf but this is unavoidable without compromising efficient separation of particulate matter greater than 2.5 um. There will be negligible collection of ultrafine particles on all the shelves. The device will run for just under 8 hours to obtain an optimal surface density for bacterial colony counting. Under normal air quality conditions established by the EPA (28) the particulate matter collection shelves will not become saturated until after the bacterial collection has saturated ensuring the device should not become clogged (Appendix A3).

<table>
<thead>
<tr>
<th>Stokes #</th>
<th>shelf #1</th>
<th>shelf #2</th>
<th>shelf #3</th>
<th>shelf #4</th>
<th>shelf #5</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;10um</td>
<td>9.043</td>
<td>20.324</td>
<td>23.635</td>
<td>23.635</td>
<td>136.233</td>
</tr>
<tr>
<td>&gt;5um</td>
<td>2.261</td>
<td>5.081</td>
<td>5.909</td>
<td>5.909</td>
<td>34.058</td>
</tr>
<tr>
<td>&gt;2.5um</td>
<td>0.565</td>
<td>1.270</td>
<td>1.477</td>
<td>1.477</td>
<td>8.515</td>
</tr>
<tr>
<td>&gt;0.89um</td>
<td>0.048</td>
<td>0.108</td>
<td>0.126</td>
<td>0.126</td>
<td>0.725</td>
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<tr>
<td>&lt;0.1um</td>
<td>0.001</td>
<td>0.001</td>
<td>0.002</td>
<td>0.002</td>
<td>0.009</td>
</tr>
</tbody>
</table>

Table 1

**Construction Methods**

The micro scale dimensions inside the channel of the device required a manufacturing technique that had the capability of producing micro scale features as well as the capability of achieving small tolerances. The two main manufacturing techniques that were explored were rapid prototyping and standard machining. Standard machining would be more economical if we could manufacture it at the Fabrication Shop and Laboratory (ABE Shop) sponsored by the College of Agriculture and the Department of Agriculture and Biosystems Engineering. However, we spoke with Charlie De Fer, head machinist, and determined that we could not achieve small enough tolerances. Therefore we decided to get the channel rapid prototyped. Solid Concepts Inc. is a company based here in Tucson that is capable of rapid prototyping. Although Solid Concepts Inc. has many processes to offer, after consultation with Joe Hevesh,
project engineer, we decided on using the PolyJet HD process since this process has the smallest achievable tolerances (0.001”). This process works by tracing cross sections of a 3D CAD drawing of 0.0006” thick on a liquid photopolymer resin with an ultraviolet laser. The resin is hardened when it contacts the laser and then the process is repeated with a new cross section. Specifically we chose the PolyJet Gray material, formally known as VeroGray FullCure® 850, due to its material properties. The main material property that was considered in the design was its flexural strength of 13,700 psi. The main concern with regard to the structural integrity of the device was the bending stress that would be applied when the bolts were tightened down, especially since the top and bottom piece are quite thin (2 mm). We were concerned the material would snap when the bolts were tightened all the way to compress the o-rings. However, as described above in the methods section, a factor of safety of 3.4 was calculated for the applied load and the given material properties. The total price of the channel came to $294 (see Appendix 6 for price quote).

After receiving the prototype, however, it became clear that a tolerance of 0.001” was not possible. The smallest and most important dimension of our device is the 175um gap that precedes the bacterial collection shelf (shelf #5). This gap was completely filled in during manufacturing obstructing airflow through the device. To remedy this situation we ordered 0.0079” (200um) diameter drill bits from Harvey Tools (harveytool.com) and proceeded to fix the device in the ABE shop. Although 200um is greater than the design called for, this is the smallest drill bit that could be obtained while staying under budget of $500. Unfortunately these drill bits are extremely fragile and during drilling all three of them broke. At this point the only option was to use a number 80 drill bit that the ABE shop already had in possession. This bit has a diameter of 0.013” (330um). To compensate for the much larger diameter, we drilled a series of 4 holes evenly spaced where the 175um slot should have been. These 4 holes of diameter 330um create a total cross sectional area equal to the cross sectional area of the 175 um slot of depth 2mm.

The 6 parts of the channel were put together using 1” 4-40 screws, nuts and rubber washers. 2.5mm bore tubing was used to connect the channel to the pump, and 0.25” 4-40 screws were used to bolt the pump to the base. This hardware was purchased at Ace Hardware.
The base used to anchor the channel and the pump down was constructed in the ABE shop using PVC as the material. The material used was scrap material and therefore did not cost anything.

**Operation**

The miniature cascade impactor is meant to test the level of exposure to biological contaminants that employees are exposed to throughout the course of a workday. The device should be cleaned thoroughly before use to minimized contamination. The device will operate in a normal work environment and is made to optimally run for 8 hours. The device will be assembled by lining the female and male notches together and having the screws properly placed and tightened. The tubing will be hooked up to the inlet of the device. The design will then be clipped to the collar of the workman’s shirt to sample the air around the worker’s mouth and nose. The workman will then tend to his usual duties for the length of the workday and turn in the device to his/her company at the end of the day. The company (or the worker) shall then disassemble the device and take great precautions to not contaminate the bacterial shelf, preferably by wearing sterile gloves. The bacterial shelf will then be removed, placed inside a small, clean container containing a solution of nutrient medium that will be included in the purchase of the device, and then sealed so that no bacteria will escape or enter the sample. The company will then send the bacterial shelf to a lab to be analyzed for levels and strains of bacteria. The level of bacterial exposure will then be compared with governmental standards.

**Testing and Calibration**

The first test run was for the micropump. Although the Thermal Cooling Systems website stated that the pump had a flow rate of approximately 380 ml/min with a power source of 4.5 V, the pump was tested to guarantee a flow rate for the pump. The pump was attached to rubber tubing, the opposite end of which was submerged under water so that air bubbles formed. The air bubbles were then collected by a 50 ml conical tube and timed to obtain the flow rate of the device. The resultant flow rate was 368 ml/min, not far off from the described flow rate. However, when the pump was hooked up to the device, the flow rate
dropped significantly from 368 ml/min to 144 ml/min (see Appendix 4), which might be attributed to unforeseen pressure buildup in the rubber tubing. Pressure buildup in the channel was accounted for during CFD simulation. However, 6 in of tubing was not included in the Fluent analysis and may account for the discrepancy between flow rates.

Testing of the device involved the use of an approved BioVigilant machine that does real time detection of bacteria. The collection shelf was prepared using a small piece of polished cardboard, but ideally should use a poly-L-lysine. Unfortunately local glasscutters were not able to cut such a small piece of glass, so paper was used as a substitute merely for ease of experimentation. The miniature cascade impactor was placed in a chamber as close to the BioVigilant detection probe as possible so that the air entering the device could be monitored for bioaerosol concentration. The chamber was then evacuated from as much particulate matter as possible using a small air purifier. A 1:50 concentration of bacteria (gram negative *E. coli* for safety) was then aerosolized into the chamber to verify collection efficiency of the impactor. The device was connected to the power source and started sampling air at the same time that the BioVigilant machine began sampling. The impactor was allowed to collect airborne bacteria over the course of an hour during which two small fans constantly circulated the air to ensure good bacterial mixing within the chamber. Following the experiment, the device and BioVigilant machine were turned off at the same time. This guaranteed that the running time of the device and the results of the BioVigilant machine matched. The impactor was then disassembled, and the piece of paper was submerged in a 500 μL solution of LB (10g Tryptone, 5g Yeast Extract, 10g NaCl, 1L ddH₂O, sterilized by autoclave) which would dissolve any deposited bacteria or particulate matter and would also serve as a nutrient solution to grow the bacteria. The bacteria containing LB solution was then spread onto an agar plate, incubated, and let grow over night. Four tests were run for the first day and three the second day.

The following day, the bacterial colonies were counted using a consistent counting method where individual dots were considered one colony, streaks ten, large spots 50, and the largest spots 100. Colonies oftentimes grow into each other and is difficult to count individually. Therefore, a colony counting method was necessary to achieve consistent, but inaccurate,
results. Colony counting machines that are extremely accurate are available commercially but are very expensive and were not available for the testing of this project. However, a consistent counting method allows for accurate comparison between test runs. Precision results of multiple test runs, regardless of the percent of bacteria actually collected, can be extrapolated to determine the amount of bacteria in the air sampled. Thus, the inaccuracy of the counting method does not invalidate the results of the test run. The results will simply prove whether or not the device works as intended, but will not tell the true percentage of bacteria collected.

The results showed that the first runs of each day collected a good amount of bacteria, 11% and 14%, whereas all of the subsequent runs collected a very small amount of bacteria, less than 1% (see raw data in Appendix 5). This could be attributed to two different problems. First the device may have a clogging problem due to the roughness of material, the amount of particulate matter that bombarded the device during testing, or incomplete cleaning between tests. The small, rough channels may have inadvertently caught the excess particulate matter that built up after the first run, clogging the inlets. Incomplete cleaning may cause a quicker buildup on shelves, leading to spillover, and ultimately cause the same problem. A second problem could be attributed to contamination of the device over the course of the day. The first run would collect all the built up bacteria over the course of the day and test positive whereas the subsequent runs wouldn’t collect nearly as much. Further testing needs to be done to find the true problem.

**External Constraints**

The only political constraint would be associated with the patent and verification of testing results. The average time that it takes to process a patent is 22 months, which could affect the implementation and funding of the device (Patent). The environmental and sustainability impact our device would have would determine how to recycle and reuse the components of the device. A 4.5 volt alkaline battery was used as the power source in the prototype. This battery would have to be properly recycled in order to have a minimal impact on the environment (4). The device was created with VeroGray FullCure® 850, which offers great dimensional stability important for reusing the device. Efficient cleaning and proper care
would be important with reusing the device and achieving correct results. After the pump fails, proper disposal or recycling would be important.

Health and safety is something that this device hopes to promote, allowing individuals a way to determine if they have been exposed to hazardous biological aerosol. There would be no health and safety concern with properly handling the device. The only risk would be accidental contamination of the user with the bacteria collected on the last shelf that may or may not be pathogenic.

Manufacturing of the device channel was hard to manufacture due to the unachievable tolerances for the manufacturing machines. The device required the lowest tolerance available, which was .001 in (25.4 μm) with Solid Concepts. This limitation comprises of approximately 15% of the smallest stage inlet and was a serious constraint. Unfortunately, it turned out that this limitation left the device with no 5th stage inlet at all.

**Conclusions**

The final design is a 5 stage cascade impactor which captures particles of varying sizes on each shelf. The top shelf captures particles greater than 10um, the second captures particles greater than 5um, the third and fourth shelves capture particles greater than 2.5um, and finally the fifth shelf captures bacteria with an aerodynamic diameter of 0.89um and is removable for ease of analysis. Overall the device works well to separate particulate matter and collect airborne bacteria and it was produced within the required budget (Appendix 8). Initial testing results show 13% capture efficiency relative to the amount of Bioaerosol particles detected by BioVigilant instantaneous microbial detection (product #IMD-A 200-1) machine. Most of our tests indicated that the requirements assigned to the project, including portability, capture of bacteria, and low cost, were met. Unfortunately, although it is assumed true, the separation of particulate matter was not tested for. A flaw in the design is the inaccessibility to the shelves other than the bacterial collection plate. This flaw prevented analysis of particle collection on these shelves. The difficulties encountered opened up many possible improvements for the device due to the inaccuracies unavoidably imposed by inaccessibility to precision machinery
and equipments. Even though Solid Concepts was unable to provide a working prototype, our device could have been repaired if precision drilling instruments were available.

The device needs much reworking before it is able to transform into a truly marketable product, but the design has great potential to do so. If the design were to be continued by another engineering group, the most challenging portion of the project, the theory and the calculations, have already been worked out. Focus of the project could be directed to making the improvements suggested in the recommendations sections and incorporating the channel into a portable clip-on device.

**Recommendations**

First, testing of the device could have been improved if the colonies were spread out more and each individual colony could be seen. An improvement to the growing method that was used would be to use several agar plates to grow the bacteria off a single run. For instance, dissolve the bacteria from the shelf in a milliliter of LB solution and spread that out between 5 agar plates, each receiving 200 μl. This way the colonies will have more room to grow and fewer colonies will grow into each other, forming macro-colonies. This will greatly improve the accuracy of the colony counting.

There are several components of the physical device and design process that could have been improved. The entire device could have been scaled up slightly to facilitate the manufacturing. Rapid prototyping was a clear choice to manufacture this device due to the extremely small openings and the precision that was required. Although they claimed they were able to achieve the accuracy needed for the manufacturing, when the device arrived it was apparent that they could not. Scaling up would allow manufacturing to be much easier and problems such as these could be avoided. It is important to understand that overly enlarging the device will eliminate its ability to be clipped on, so only small scale-ups are viable.

It would be beneficial if the bacterial collection shelf slot on the fifth shelf were larger in comparison to the rest of the device as well. The device was originally designed so that the slot for the glass slide would be just as wide as the channel so that only the tip would collect bacteria. However, in retrospect, air would only be exposed to the portion of the glass slide
that was in the channel. Since the different pieces of the device are tightly compressed, the sides of the channel would seal off air to the rest of the slide anyways if the slide was wider. The glass slide could have then been cut or even inserted as a whole slide for testing. In future improvements, when the device is larger, the slot could be made so that an entire poly-l-lysine slide can fit.

Shelves 1 through 4 should also be removable so that testing of separation efficiency is possible. Unfortunately, testing of this device did not involve testing if separation of particulate matter had actually occurred because the shelves preceding the collection shelf were not removable. If they had been removable, measurements could have been taken to see if each intended size of particulate matter was in fact collected on each shelf. Currently, inaccessibility to the small openings of the channel prevented this measurement. Having removable shelves throughout the device would facilitate cleaning of the device as well. Clogging of the device was a problem due to a combination of several possible factors, with incomplete cleaning as one possibility. Cleaning will be much simpler, efficient, and thorough if the removable shelves could be handled individually.

A smoother material for the device may also help to solve the clogging issue. It is hypothesized that the rough material that Solid Concepts had created the prototype with is another contributor to the clogging problem. The rough material may catch particulate matter in each stage inlet, which may build up over time. A smooth material will remedy this issue.

Finally, although not a vital component to the function of our device, additional shelves will allow for manipulation of separation efficiency. Although the device was tested with *E. coli*, other airborne bacterium is able to be collected as well but may not have the same aerodynamic diameter as *E. coli*. Therefore, creating additional shelves with different impact velocities can separate bacteria based on known sizes or even just increase efficiency of particulate matter separation.
References


[40] “Typical testing techniques used on most air quality and environmental surveys”, *Envirotest Lab: Air Quality testing methods and techniques*, May 04, 2011 http://www.envirotestlab.com/air_testing_inspection.html

Appendix A1

Table A1-1: O-Ring Compression Load Chart

Table A1-2: Pump Flow Rate Dependence on Pressure
### Appendix A2

#### Table A2-1: Cunningham Correction Factor Calculations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Unit</th>
<th>Value 2</th>
<th>Unit</th>
</tr>
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<td>1.38E-23</td>
<td>kg m^2/K s^2</td>
<td></td>
<td></td>
</tr>
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<td>air viscosity</td>
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<td></td>
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<td>density particulate matter</td>
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<td>kg/m^3</td>
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<td>density of E.Coli</td>
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<td>Pressure</td>
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<td>Velocity inlet</td>
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<td></td>
</tr>
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<td>m/s</td>
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<td>inlet width</td>
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<td>length of shelf</td>
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<tr>
<th>Particle Diameter (m)</th>
<th>Mean Free Path (λ)</th>
<th>Kn</th>
<th>A</th>
<th>Cc</th>
<th>t</th>
<th>Stokes #</th>
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<td>9.1E-17</td>
<td>1.8E-11</td>
<td>1.16</td>
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</table>
Appendix A3

Table A3-1: Inlet velocities at varying inlet widths for TCS D210 pump

<table>
<thead>
<tr>
<th>Inlet W (m)</th>
<th>Cross Sec Area (m^2)</th>
<th>Max Inlet V (m/s)</th>
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</thead>
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<tr>
<td>1.00E-04</td>
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<td>1.50E-04</td>
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<td>5.00E-04</td>
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<td>7.00E-04</td>
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<td>1.60E-06</td>
<td>3.96</td>
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<td>9.00E-04</td>
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<tr>
<td>1.00E-03</td>
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<td>3.17</td>
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Flow Rate @ max voltage (m^3/s)

Cost of Pump - TCS D210 (pump) $63

Table A3-2: Saturation time for Bioaerosols, PM10, and PM2.5

<table>
<thead>
<tr>
<th>Bioaerosol Saturation</th>
<th>PM10 Saturation</th>
<th>PM2.5 Saturation</th>
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<tr>
<td>Shelf Density</td>
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<td>Bioaerosol conc.</td>
<td>1000</td>
<td>PM10 conc.</td>
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<tr>
<td>Shelf depth</td>
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<td>Shelf length</td>
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<td>Flow Rate</td>
<td>6.3E-06</td>
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<tr>
<td>Collection Time (s)</td>
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<td>Collection Time (Hr)</td>
<td>7.89</td>
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### Appendix A4

#### Table A4-1: Flow Rate Raw Data

<table>
<thead>
<tr>
<th>Volume (L)</th>
<th>Volume (m³)</th>
<th>Time (s)</th>
<th>Flow Rate (m³/s)</th>
<th>Normalized Flow Rate</th>
<th>Flow Rate (ml/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.04</td>
<td>0.000004</td>
<td>6.1</td>
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<td>0.041</td>
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<td>0.0305</td>
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<td>6.08E-06</td>
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<td>364.54</td>
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</table>

Averages:
- **Average Flow Rate**: 368.37
- **Deviation**: 3%

### Pump + Channel

<table>
<thead>
<tr>
<th>Volume (L)</th>
<th>Volume (m³)</th>
<th>Time (s)</th>
<th>Flow Rate (m³/s)</th>
<th>Normalized Flow Rate</th>
<th>Flow Rate (ml/min)</th>
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<tr>
<td>0.035</td>
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<td>2.06E-06</td>
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<td>0.025</td>
<td>0.000025</td>
<td>10.73</td>
<td>2.33E-06</td>
<td>0.97</td>
<td>139.79</td>
</tr>
<tr>
<td>0.036</td>
<td>0.000036</td>
<td>16.14</td>
<td>2.23E-06</td>
<td>0.93</td>
<td>133.83</td>
</tr>
<tr>
<td>0.026</td>
<td>0.000026</td>
<td>11.41</td>
<td>2.28E-06</td>
<td>0.95</td>
<td>136.72</td>
</tr>
<tr>
<td>0.042</td>
<td>0.000042</td>
<td>15.71</td>
<td>2.67E-06</td>
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<td>160.41</td>
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<tr>
<td>0.035</td>
<td>0.000035</td>
<td>13.4</td>
<td>2.61E-06</td>
<td>1.08</td>
<td>156.72</td>
</tr>
<tr>
<td>0.032</td>
<td>0.000032</td>
<td>12.63</td>
<td>2.53E-06</td>
<td>1.05</td>
<td>152.02</td>
</tr>
<tr>
<td>0.025</td>
<td>0.000025</td>
<td>10.92</td>
<td>2.29E-06</td>
<td>0.95</td>
<td>137.36</td>
</tr>
</tbody>
</table>

Averages:
- **Average Flow Rate**: 144.60
- **Deviation**: 7%
Appendix A5

Table A5-1: Raw Data of Bacterial Collection Efficiency Experiments

<table>
<thead>
<tr>
<th>Sample Time (s)</th>
<th>BV Sample Vol. (ft^3)</th>
<th>BV Sample Vol. (m^3)</th>
<th>BV Total Biologics</th>
<th>BV Biol. Conc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run1</td>
<td>3720</td>
<td>2.506</td>
<td>0.071</td>
<td>59369</td>
</tr>
<tr>
<td>Run2</td>
<td>4320</td>
<td>2.905</td>
<td>0.082</td>
<td>53606</td>
</tr>
<tr>
<td>Run3</td>
<td>3660</td>
<td>2.455</td>
<td>0.070</td>
<td>179780</td>
</tr>
<tr>
<td>Run4</td>
<td>3660</td>
<td>2.450</td>
<td>0.069</td>
<td>231160</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample Vol. (m^3)</th>
<th>Colony Count</th>
<th>Impactor Biol. Conc.</th>
<th>Percent Captured</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-Apr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Run1</td>
<td>0.0090</td>
<td>1083</td>
<td>120798.25</td>
</tr>
<tr>
<td>Run2</td>
<td>0.0104</td>
<td>14</td>
<td>1344.68</td>
</tr>
<tr>
<td>Run3</td>
<td>0.0088</td>
<td>6</td>
<td>680.21</td>
</tr>
<tr>
<td>Run4</td>
<td>0.0088</td>
<td>2</td>
<td>226.74</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample Vol. (m^3)</th>
<th>Colony Count</th>
<th>Impactor Biol. Conc.</th>
<th>Percent Captured</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-May</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Run1</td>
<td>0.0087</td>
<td>5520</td>
<td>636226.43</td>
</tr>
<tr>
<td>Run2</td>
<td>0.0088</td>
<td>345</td>
<td>39112.28</td>
</tr>
<tr>
<td>Run3</td>
<td>0.0090</td>
<td>391</td>
<td>43612.30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>AVERAGE</th>
<th>STD DEV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>13.02</td>
<td>1.41</td>
</tr>
</tbody>
</table>
## Appendix A6

![Solid Concepts Logo]

### Solid Concepts Quote for Production Parts

**ISO 9001 Certified (Valencia CA, Poway CA); AS9100 Certified (Austin TX, Valencia CA 8.1.B)**

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Quantity</th>
<th>Unit</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Polyjet HD: Material=VeroGray, Finish= None (Unfinished), Surface Treatment=Wet/Dry Blast</td>
<td>1</td>
<td>$49.00</td>
<td>$49.00</td>
</tr>
<tr>
<td>2</td>
<td>Polyjet HD: Material=VeroGray, Finish= None (Unfinished), Surface Treatment=Wet/Dry Blast</td>
<td>1</td>
<td>$49.00</td>
<td>$49.00</td>
</tr>
<tr>
<td>3</td>
<td>Polyjet HD: Material=VeroGray, Finish= None (Unfinished), Surface Treatment=Wet/Dry Blast</td>
<td>1</td>
<td>$49.00</td>
<td>$49.00</td>
</tr>
<tr>
<td>4</td>
<td>Polyjet HD: Material=VeroGray, Finish= None (Unfinished), Surface Treatment=Wet/Dry Blast</td>
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<td>$51.00</td>
<td>$51.00</td>
</tr>
<tr>
<td>5</td>
<td>Polyjet HD: Material=VeroGray, Finish= None (Unfinished), Surface Treatment=Wet/Dry Blast</td>
<td>1</td>
<td>$48.00</td>
<td>$48.00</td>
</tr>
</tbody>
</table>

**Quote Number:** 20201226

**Quote Date:** 4/12/2011 8:32:08 AM

**Reference:**

- **Project Eng.:** Joe Hennessy  | (858) 748-2374
- **Sales Rep.:** Tom Logston  | (622) 234-2860

---

**Solid Concepts**

Rapid Prototyping
Short Run Production Parts
Tooling and Production Parts
3D Viewing & Markup Software

---

**Prepared For**

*Ken Hefley*

**University of Arizona**

1130 North Mountain Avenue

Tucson, AZ 85721-0119

**Phone:** (520) 123-0000

**Fax:**

**Email:** khefley@email.arizona.edu

---

**Rapid Prototyping**

**Short Run Production Parts**

**Tooling and Production Parts**

**3D Viewing & Markup Software**

---

**www.solidconcepts.com** | **quotes@solidconcepts.com**
### Solid Concepts Quote for Production Parts

ISO-9001 Certified (Valencia CA, Poway CA) | AS9100 Certified (Austin TX, Valencia CA, SL5)

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Quantity</th>
<th>Unit</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>chan2</td>
<td>x</td>
<td>y</td>
<td>z extents: 1.16</td>
<td>0.33</td>
</tr>
</tbody>
</table>

**Quote Total**: $294.00

**Standard Delivery**: Estimated shipment in 4 working days A.R.O. Actual schedule to be determined after receipt of order.

**Need it sooner?** A Rapid Delivery option is available at a slightly higher price. Please contact your PE for more information.

**Terms**: F.O.B. Origin, Net 30, On approved Credit. 1.5% per month late charge.

**Notes**: Solid Concepts' standard terms and conditions apply. Applicable tolerances: 
Projet HD +/- 0.035 in. or +/- 0.001 in. ft., whichever is greater.
Items quoted will be manufactured using Solid Concepts (SCI) standard processes using materials listed above and inspected per SCI standard acceptance criteria.

**Authorization to Proceed**

- **Name**: Meredith Roberts
- **Signature**: [Signature]
- **Date**: 4/13/11
- **F.O.D.**: 

**Offered by Solid Concepts Inc.**

- **Per**: Joe Hevesh, Project Engineering

*Have you tried Solid Concepts' new Rapid Quotes? Try it today at www.solidconcepts.com*

---

**Quote No**: 2012129-6  
**Page**: 2 of 2  
**Date**: 04/12/2011  
**Contact**: 2809 Avenue Creece • Valencia, CA 91355 • Phone (661) 285.4400 • Fax (661) 287.9311  
**Website**: www.solidconcepts.com | quotes@solidconcepts.com
### Appendix A7

#### VeroGray FullCure®850 Data Sheet

<table>
<thead>
<tr>
<th>Property</th>
<th>ASTM</th>
<th>Metric</th>
<th>Imperial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength</td>
<td>D-638-03</td>
<td>MPa</td>
<td>60</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>D-638-04</td>
<td>MPa</td>
<td>3000</td>
</tr>
<tr>
<td>Elongation at Break</td>
<td>D-638-05</td>
<td>%</td>
<td>15</td>
</tr>
<tr>
<td>Flexural Strength</td>
<td>D-790-03</td>
<td>MPa</td>
<td>95</td>
</tr>
<tr>
<td>Flexural Modulus</td>
<td>D-790-04</td>
<td>MPa</td>
<td>3000</td>
</tr>
<tr>
<td>Compressive Strength</td>
<td>D-695-02</td>
<td>MPa</td>
<td>85.5</td>
</tr>
<tr>
<td>Izod Notched Impact</td>
<td>D-256-06</td>
<td>J/m</td>
<td>25</td>
</tr>
<tr>
<td>Shore Hardness</td>
<td>Scale D</td>
<td>Scale D</td>
<td>86</td>
</tr>
<tr>
<td>Rockwell Hardness</td>
<td>Scale M</td>
<td>Scale M</td>
<td>49</td>
</tr>
<tr>
<td>HDT at 0.45 MPa</td>
<td>D-648-06</td>
<td>°C</td>
<td>49</td>
</tr>
<tr>
<td>HDT at 1.82 MPa</td>
<td>D-648-07</td>
<td>°C</td>
<td>47</td>
</tr>
<tr>
<td>Tg</td>
<td>DMA, E’</td>
<td>°C</td>
<td>56.5</td>
</tr>
<tr>
<td>Ash Content</td>
<td>NA</td>
<td>%</td>
<td>0.26</td>
</tr>
<tr>
<td>Water Absorption</td>
<td>D570-98 24 Hr</td>
<td>%</td>
<td>1.12</td>
</tr>
</tbody>
</table>
## Appendix A8

### Table A8-1: Budget

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit Price ($)</th>
<th>Quantity</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel</td>
<td>333.13</td>
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<td>333.13</td>
</tr>
<tr>
<td>nuts</td>
<td>0.25</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>bolts</td>
<td>0.30</td>
<td>4</td>
<td>1.2</td>
</tr>
<tr>
<td>4.5V battery</td>
<td>9.78</td>
<td>1</td>
<td>9.78</td>
</tr>
<tr>
<td>electric fasteners</td>
<td>2.98</td>
<td>1</td>
<td>2.98</td>
</tr>
<tr>
<td>o-rings</td>
<td>0.20</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>washers</td>
<td>0.15</td>
<td>4</td>
<td>0.6</td>
</tr>
<tr>
<td>2.5mm bore tubing</td>
<td>0.12</td>
<td>1.5</td>
<td>0.18</td>
</tr>
<tr>
<td>D210 micropump</td>
<td>72.09</td>
<td>1</td>
<td>72.09</td>
</tr>
<tr>
<td>Carbide miniature Drills</td>
<td>10.50</td>
<td>3</td>
<td>31.5</td>
</tr>
<tr>
<td>filter paper</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>poly-L-lysine slides</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td><strong>453.46</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix B – Student Resumes

Jessica Lauren Hastings  
jhasting@email.arizona.edu  
(520) 204-5399  
8105 E Moonstone Dr, Tucson, AZ 85750

EDUCATION:  
University of Arizona  
Bachelor of Engineering, May 2011  
Major: Bio-systems engineering  
GPA: 3.28

EXPERIENCE:  
12/09-Present  
Zelen Incorporated/Grecycle  
Office Manager/assistant  
Tucson, AZ

- Duties include clerical, marketing and financial management of both Grecycle and its parent company Zelen  
- Oversee companies financial records and manage customer payments  
- Responsible for the negotiation new customer agreements and maintenance of existing accounts

09/09 – 09-10  
Controlled Environment Agriculture Center  
Student Volunteer/Student worker  
Tucson, AZ

- Duties included growing year-round crops, crop management, pest management and plant nutrition  
- Responsible for understanding the physics and engineering behind greenhouse production and ensuring that the greenhouse was maintained within certain limits

08/08 - 05/09  
Human Origins Genotyping Laboratory  
Student researcher  
Tucson, AZ

- Responsible for research relating to DNA test kits for canine use  
- Required skills included dilutions, pipeting, PCR, gel electrophoresis and DNA sequencing

ACTIVITIES:  
Casa de los Ninos Volunteer, 2007  
Pima Hall Representative, 2008  
Biotechnology club, 2008  
Theta Tau Fraternity, 2009-present

AWARDS:  
Student Leadership award, 2007  
First place in the Introduction to Engineering Fair, 2008

ADDITIONAL SKILLS:  
C++ programming, MATLAB, Solidworks, HTML, Quickbooks
Kevin S. Korf
5702 East Monte Cristo Avenue
Scottsdale, AZ 85254 USA
Tel: (602) 571-1945
E-mail: kskorf@email.arizona.edu

---

**Education**

University of Arizona, Tucson, Arizona  
*B.S. in Biosystems Engineering* (May 2010)  
Senior Standing  
Minor: Mathematics  
Mechanical Engineering

**Work Experience**

C&D Zodiac Aerospace  
*Flammability Engineer Intern*  
May 2010 – August 2010

- Tested material cross sections of aircraft parts to meet the FAA standards.  
- Created material test plans according to FAA requirements.  
  - Guarantees all necessary parts are tested appropriately.  
- Organized and input data into the company database.  
- Sought out and corrected erroneous data in the database.

Pizza Hut  
*Delivery Driver*  
January 2010 – May 2010

- Checked for accuracy and quality of products before delivery.  
  - Ensured customer satisfaction.  
- Answered calls courteously and provided customers with product information.  
- Ensured cleanliness of restaurants in between deliveries.  
- Prepared products for next day usage to maximize product sales.

Gruber Industries  
*Accounting Assistant*  
May 2008 – August 2008

- Balanced bank statements and ledgers.  
- Organized and stored company records.  
- Accrued and recorded payables for each month.

Bonsai Nursery  
*Retail Clerk*  
August 2005 – December 2005

- Managed evening operations, and managed weekly inventory  
- Serviced customers with sales advice and product information.  
- Watered and cared for plants.  
- Counted and reconciled cash drawers daily.

**Skills**

- Bilingual - English and Mandarin Chinese  
- Proficient in Solidworks, AutoCAD, Microsoft Excel, Word, and Powerpoint.
Samanta Dadayeva
1125 N Wildcat Diers Rd
Tucson, AZ 85745
(520) 331-2649
87samant@email.arizona.edu

Objective
To obtain a permanent and secure position that will utilize my knowledge and skills

Education
University of Arizona, B.S. in Biosystems Engineering
Fall 2011 (expected graduation date)

Works Experience
University of Arizona, Tucson, AZ, 2010-present
Undergraduate TA/Grader

Cosmetic Dentistry, Tucson, AZ, 2006-2008
Dental Assistant
- Chair side Assistance
- Dental Charting
- Dental Radiographs
- Patient Education

Activities
St. Elizabeth Health Center, Tucson AZ, 2008
Volunteer Dental Assistant
- Chair side assisting in dental clinic
- Patient Education

Reference
Professor Chris Choi
Department of Agricultural and Biosystems Engineering
University of Arizona
P.O. Box 00000
(520) 000-0000
MEREDITH ANN ROBERTS
PHONE (CELL): 520-203-2389
EMAIL: MROBERTS@EMAIL.ARIZONA.EDU
14092 E. ANACAPA DR., VAIL, AZ 85641

EDUCATION
Bachelor of Science, Biosystems Engineering Anticipated 05/11
University of Arizona, Tucson, AZ – GPA: 3.96
Emphasis: Biomedical Engineering
Minor: Mathematics

RELEVANT COURSEWORK
Strengths of Materials, Sensors and Controls, Bioprocess Engineering, Engineering Analytical
Computer Skills (Excel VBA and MATLAB), Heat and Mass Transfer, Bio Micro/Nanotechnology
Applications, Numerical Methods in Biomedical Engineering, Computer Aided Design (CAD and
Solidworks)

RESEARCH EXPERIENCES
Undergraduate Biology Research Program (UBRP) 05/08 – present
Job Title: Student Researcher
▪ Work in collaboration with graduate students and undergraduates on multiple projects researching
chromosome maintenance/stability, nuclear architecture in relation to gene expression, and genetic
interactions
▪ Plan and perform experiments, analyze data, and present research results to lab group
▪ Practice laboratory techniques such as PCR, cloning, gel electrophoresis, fluorescent in situ
hybridization, and fluorescent confocal microscopy

Integrated Graduate Education and Research Traineeship (IGERT) 09/07 – 12/07
Job Title: Research Intern
▪ Researched seventeenth century metallurgy of pueblos on Spanish colonial frontier
▪ Prepared metal samples for analysis, documented data and sample information
▪ Performed chemical analysis of metal samples

PUBLICATIONS
Smith, H., Roberts, M., Hartl, T., Wang, X., Bosco, G. Chromo-barrel protein Mrg15 and
methyltransferase Set2 regulate condensin II dependent chromosome pairing and structure. (In
preparation)