MECH 4860

Final Design Report

[redacted]

Design of a

Breathing Thermal Mannequin

Prepared for

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Submitted On: Monday, December 2, 2013

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December 2nd, 2013

Dr. Paul Labossiere

University of Manitoba

Winnipeg, MB

EITC E1 - 546

Dear Dr. Labossiere,

On behalf of Team 7 of the 2013 class of MECH 4860, I am submitting to you our report entitled "Final Design Report – Design of a Breathing Thermal Mannequin". This report summarizes the work completed that will allow Price Industries Ltd to build a device which replicates the breathing functions of a human being. The concepts were evaluated on the basis of fulfilling the customer needs as outlined in our first report, Project Definition Report – Design of a Breathing Thermal Mannequin, and our second report, the Concept Definition Report – Design of a Breathing Thermal Mannequin.

If there are any questions concerning the content or the recommendation presented in this report, please contact me at any time.

Sincerely,

Jordan Hanaway

Project Manager

Team 7

Phone:

Email:

Executive Summary

The members of Team 7 were tasked by Price Industries to design an apparatus that would accurately replicate the characteristics of a human breathing. These characteristics include, flow rate, temperature, carbon dioxide composition and exit velocity.

Over the course of the Fall 2013 term the team went through the full design process, beginning with outlining the project scope and determining the objectives and target specifications. The main objectives that the team and client settled on were to accurately replicate human breathing as far as flow rate, temperature, carbon dioxide composition and exit velocity were concerned; to limit the size and weight to that which would fit inside an average human torso and be transported by two people; and to use off-the-shelf components wherever possible.

Upon completion of the project definition report and presentation the team brainstormed as many ways to achieve the project objectives as possible; these potential solutions were then weighted, ranked and discussed with the client to produce a complete solution that met as many objectives as possible.

The final design uses a custom, single-acting, piston pump to provide the correct flow rate. The pump will be manufactured using off-the-shelf parts with some machining required to reach its final form. The CO_2 will be injected after the pump and will be measured using a simple flow meter. Based on this measurement the CO_2 composition can be regulated by the laboratory supply line. Heating of the air mixture is done via a copper tube wrapped in heat tape; the length of tube was calculated to be 1.304m with an outer diameter of 0.0254m to reach the target air temperature of 33˚C. Finally, the correct exit velocity is achieved by using a nozzle consisting of a step down connector, wye joint and flexible PVC tubing. This nozzle design allows the air mixture to be ejected at the correct angle of 60˚ and 69˚ below horizontal when viewed from the side and front respectively as well as at the correct speed of 2.56 m/s.

With the exception of the pump, all the parts are available off-the-shelf, ready to assemble. The total cost of supplies including control systems for a single apparatus is $2018.17. Cost becomes $1502.72 per unit when mass-producing a quantity of 30. The unit is compact enough to fit inside a mannequin; however the client has expressed intent to package the apparatus in a backpack initially to give easy access to the parts.

Overall, the team was able to create a design that meets the client's desire to replicate human breathing, and when fabricated as outlined in the report will function as intended.

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1. Introduction

Price Industries (Price) is a worldwide provider of air distribution products and services. The company has a reputation for providing quality products that perform to their rated specifications. This reputation is mainly due to the thorough product testing that occurs at the Winnipeg facility, Price Research Center North (PRCN).

The research center features numerous specialised test chambers that can be used to test a variety of products including, but not limited, to diffusers, blower coils, and radiant products. The research center also includes simulation rooms that are used for testing product set ups and demonstrating product performance to customers under a variety of environmental conditions. These rooms can be used to analyze flow patterns through smoke tests and create detailed velocity and temperature plots for any configuration of products.

In order to achieve more accurate test results and create more accurate demonstrations, Price Industries would like to simulate the effect of people within the test space. This simulation feature will create a more accurate representation of the internal and external loads that their products will be exposed to. To simulate the effect of people within the test space, Price Industries would like to introduce mannequins into the lab that replicate the breathing output and thermal plume of a human being.

The goal of the project with Price Industries is to design a system that can be built into a mannequin that accurately simulates the breathing output and thermal plume of a human being, including the following features:

1. Exhale temperature
2. Exhale velocity
3. Exhale flow rate
4. Exhale carbon dioxide (CO_2) content
5. Thermal plume

In addition to accurately simulating the above human qualities, the system should be able to fit within a standard sized, adult male mannequin and maintain a weight less than 50lbs in order to ensure easy transportation of the mannequin between lab rooms. For ease of maintenance and manufacturing, the design should use only standard parts and tools. Finally, the cost of the breathing system materials should be kept under $2000 so that multiple breathing systems can be manufactured by the client while maintaining a relatively low total cost.

1.1. Project Objectives

There are numerous project objectives that must be met in order to ensure customer satisfaction with the design of the breathing simulator. The various project objectives are grouped into four main categories: function, environment, lifespan, and cost. In addition to the project objectives discussed below, a table including the list of prioritized customer needs, from which the project objectives were derived, and the target specifications for those needs is shown so that it can be determined whether or not an objective was met.

1.1.1. Function

The main function of the breathing simulator design is to be able to inhale ambient air and exhale that air with the appropriate human characteristics. These characteristics include exhale flow rate, exhale angle of discharge, exhale CO_2 content, and exhale temperature. One characteristic that the design is not required to produce is the 100% humidity found within human breath as this is outside of the scope of this project.

In addition to the breathing characteristics that must be simulated by the design, the thermal plume of a human being is also required. Price Industries already has a simulation procedure in effect for thermal plume, thus the design of the breathing simulator must work with those existing methods.

1.1.2. Environment

The breathing simulator is intended for use in an indoor test environment at PRCN. The proposed design must be compatible with any existing infrastructure at Price Industries and follow the necessary codes and standards for use of CO_2 in an indoor environment.

In addition to the external environment restrictions imposed on the design, the breathing simulator should maintain a low weight and small size so that it can be easily fit within a standard sized male mannequin, or backpack, and can be transported easily between lab rooms by 1-2 people.

1.1.3. Lifespan

The breathing simulator will be used once a week to conduct tests ranging from 24-36 hours in duration. The ideal design will be able to meet these demands and have an expected lifespan of 7 to 10 years.

1.1.4. Cost and Manufacturing

For ease of manufacturing and to reduce costs associated with manufacturing and maintenance, the client would like the design to be comprised entirely of readily available parts. Additionally, the cost of parts for the breathing simulator should be less than \$2000, the cost of machining and assembly should be less than \$6000 (40 hours at \$150 /hour), and control and data acquisition systems should be less than \$5000.

1.1.5. Customer Needs and Specifications

TABLE I below lists the customer needs and the priority of each need as determined in the initial meeting with the client. Additionally, the metric associated with each need and the target values of the design are outlined so that the ability of the design to meet customer needs can be evaluated.

TABLE I: PRIORITIZED CUSTOMER NEEDS Error! Reference source not found.

Need [1]	Importance	Metric	Units	Marginal Value	Ideal Value
Inhale and exhale at a temperature representative of a human	5	Temperature	kJ/min	31-35	33 [3]
Inhale and exhale at a flow rate representative of a human	5	Flow rate	L/min	5.4-6.6	6 [4]
Exhale with gas composition representative of a human	5	CO_2 gas composition	% mass	3.1-4.1%	3.6% [4]
Exhale breath from nose at angle representative of a human	5	Angle	° below horizontal from side, ° from centerline from front	55-65, 64-74	60, 69 [3]
Thermal plume produced	5	Energy	kJ/min	4-6	0, 5[5]
Safe incorporation of CO_2 in exhaled breath	5	Conforms to codes and standards	Binary	pass	pass
System is compatible with existing gas supply lines	5	Uses existing equipment	subj.	most	all
Minimal heat production by breathing apparatus	4	Energy	kJ/min	<0.5	0

Need [1]	Importance	Metric	Units	Marginal Value	Ideal Value
System fits into human mannequin	4	Size	cm	45 X 30 X 15	30 X 20 X 15
Readily available parts for purchase	4	Parts available to buy	binary	pass	pass
Readily available tools can be used for assembly	4	Tools required for maintenance/assembly	list	metric	metric
System can be assembled in-house	4	Tools required for maintenance/assembly	hours	<40	20
System can be easily transported	4	Size, Total mass	binary	pass	pass
System parts are affordable in cost	3	Cost	$/unit	<2000	500
Maintenance of system is easy	3	Time to disassemble	hrs	<4	2
Worn parts easily replaced	3	Time to disassemble	hrs	<4	2
System is comprised of long lasting components	3	Time until failure	years	7+	10
Overall system is light in weight	2	Total mass	kg	0-27	23
Identify humidity of human breath	1	Moisture percentage	% RH	75-100%	100%[6]

With these prioritized needs in mind, the team strived to design a product that would address the customer's needs and meet the target specifications outlined in TABLE I.

2. Design Details

A conceptual design that meets the client's needs was developed by the team and discussed in the conceptual design report. The analysis and method associated with the design selection can be found in Appendix A. After completing said analysis, the team made the following conclusions [7].

A single acting piston pump was chosen to supply the flow rate based on its ability to produce discrete breaths with the appropriate volume per breath.

It was decided that the in-house carbon CO_2 supply at PRCN was the ideal CO_2 source, as it does not require the constant refilling that a compressed gas canister would require, and the amount of CO_2 available at Price is much greater than would be available in a canister.

The CO_2 will be injected on the inhale to allow a longer period of time for the CO_2 to mix thoroughly with the rest of the inhaled air and reach a uniform gas composition and temperature.

The exhale mixture is to be heated using heat tape. This method of heating provides high reliability and temperature control.

Finally, the thermal plume will be controlled using the existing method at Price (heat tape). The heat energy from the heat tape can be adjusted to account for any heat generated by the breathing system. However, the heat produced by the breathing system should be kept as low as possible so that few changes need to be made to the existing system. The overall conceptual design schematic is shown in Figure 1.

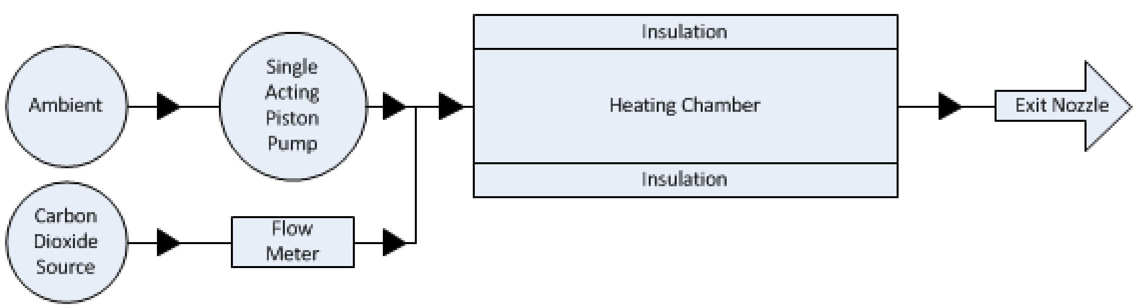

Figure 1: Thermal breathing mannequin conceptual design schematic

Using the conceptual design outlined above, the team created a detailed design and manufacturing process that would meet the client's needs. For simplicity, the design has been broken down into four categories: flow rate generation, CO_2 source and injection, exhale temperature, and exhale velocity.

2.1. Flow Rate Generation

Since the breathing system design is required to accurately simulate the breathing of a human being it is essential that the design be able to generate a breathing flow rate representative of an average person. An average person breathes 12 times per minute, with a volume of 500 mL per breath equating to a total flow rate of 6 L/min [4]. The flow of the inhale and exhale breaths follows a roughly sinusoidal pattern.

From the weighted scoring concept selection that was carried out by the team it was decided that a single acting piston pump was the ideal way to achieve the required flow rate and simulate the sinusoidal flow of breath [7]. A single acting piston pump is able to create discrete breaths that follow a sinusoidal pattern while obtaining the correct volume per breath. In order to achieve the correct number of breaths per minute, the speed of the piston can simply be adjusted.

One of the main objectives of this project was to create a system comprised entirely of off-the-shelf parts; however this objective could not be met while achieving the technical qualities of human breath required. An off-the-shelf pump with a 500 mL displacement that was able to produce a 6 L/min flow rate could not be found. As an alternative to purchasing an existing pump which would not meet all design requirements, the team decided to design a pump using off-the-shelf parts so that the manufacturing of the pump would be as simple, and require as little time, as possible.

The pump design is broken down into the design and/or selection of, the piston and cylinder, the inlet and outlet valves, the crankshaft and connecting rod, the motor, and the housing.

The piston and cylinder, shown in Figure 2, will be made of oil-filled nylon bar and tube stock. 3.5” (88.9 mm) inner diameter, 4.5” (114.3 mm) outer diameter tube stock will be used as the cylinder, and 4” (101.6 mm) bar stock will be used for construction of the piston and the cylinder base plate. Oil-filled nylon is a self-lubricating material that will keep maintenance requirements low and prevent the piston from sticking within the cylinder. Additionally, this material is easy to machine which will keep manufacturing time and cost low. A sealing ring will not be required to prevent air from flowing over and around the piston due to the low pressure differential on each side of the piston. A close fit between the piston and cylinder will keep the amount of blow by to a minimum and facilitate piston motion.

Figure 2: Piston and cylinder assembly

Purchased check valves, shown in Figure 3, will be used as the inlet and outlet valves of the pump. Check valves only allow flow in one direction making them ideal for use at the inlet and the outlet of the pump. On the suction stroke of the pump air will be drawn in through the inlet valve, and on the discharge stroke of the pump air will force the outlet valve open and flow through to the rest of the breathing simulation system.

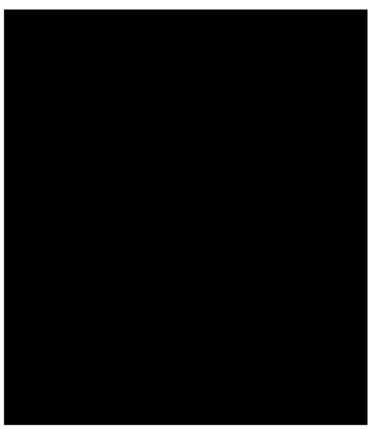

Figure 3: Inlet and outlet valves [9]

The cracking pressure is the required pressure on the valve for it to open and allow flow. For the chosen check valves the cracking pressure is 0.33 psi or 2275.27 Pa. A low pressure check valve was chosen specifically so that the pump outlet pressure would be nearly ambient and leakage within the pump is minimized.

The crankshaft and connecting rod, shown in Figure 4, used to drive the piston will be made of Kevlar-filled nylon. This material is lightweight with a high tensile strength (118.6 MPa [9]). The high strength to weight ratio of this material is ideal for this application because weight can be minimized in the crankshaft and connecting rod while supporting the load applied to the piston. Other benefits of using nylon are its resistance to wear and corrosion which will keep maintenance requirements low compared to other materials such as aluminum or steel.

Figure 4: Crank assembly

Assuming that the maximum pressure on the piston is equal to the cracking pressure of the check valves and the piston diameter is 88.9 mm, the maximum force on the piston is 14.1 N. The 14.1 N of force applied to the piston must also be supported by the crank shaft and connecting rod. The cross section of both pieces is 6.35 mm by 19.1 mm which results in a stress of 232.8 kPa. The yield strength of Kevlar-filled nylon is 118.6 MPa; therefore the crankshaft and connecting rod are able to support the piston force easily.

The lengths of the crankshaft and connecting rod are used to define the stroke length of the piston. The stroke length in conjunction with the area of the cylinder determines the total displacement of the pump. With a cylinder diameter of 88.9 mm, and therefore an area of 6207.2 mm^2, the required stroke length to produce a 500 mL displacement is 80.6 mm. In addition to the stroke length, the length of the crankshaft also affects the amount of torque required to drive the piston. The crank length (40.3 mm) is directly proportional to the required torque; therefore maintaining a short crank length is beneficial as it reduces the required torque.

Based on the maximum pressure within the cylinder (2275.27 Pa) and the crank length of 40.3 mm, the minimum required torque to drive the piston is 0.57 Nm or 5.05 in-lbs. Therefore, a motor that is capable of producing a minimum of 5.05 in-lbs of torque is required for the pump to be functional.

An electric motor was chosen to drive the piston pump. A 24 V, compact DC motor from McMaster Carr, shown in Figure 5, was selected for a number of reasons. A DC motor was chosen as opposed to an AC motor for the improved adjustability. The speed of DC motors can be controlled easily by varying the voltage applied to the motor and the torque can be controlled by varying the amount of current applied to the motor [8]. A 24 V motor was selected over a 12 V motor capable of producing the same amount of power because the former will produce less heat. The increased heat generation associated with 12 V motors is a result of the additional amperage required to create the same amount of power. As stated in the project objectives, heat generation is a concern in the breathing system design to minimize interference with the existing thermal plume equipment at Price.

The DC motor chosen by the team is capable of producing up to 50 in-lbs of torque while the minimum required torque for operation of the pump is 5.05in-lbs. Since required torque is about one tenth of the available torque of the motor, this motor will be able to drive the piston without problem.

The chosen motor can be run at speeds up to 25 RPM; this is slightly more than double the average number of breaths per minute of a human being. A motor controller was selected for use with the chosen motor so that the speed of the breathing simulator can be adjusted to accommodate a wider range of breath speeds to simulate varying activity levels.

Figure 5: 24 VDC McMaster-Carr electric motor [9]

Finally, the pump housing will be made of cast nylon. Once again this material was chosen for its strength, light weight, resistance to corrosion, and machinability. The pump housing uses as little material as possible leaving most of the pump area open for easy maintenance access as well as weight and cost reduction. The housing consists of a back plate, two support rings and a motor support as shown in Figure 6.

Figure 6: Pump housing

The complete pump assembly is shown in Figure 7. The manufacturing procedure for the pump and how it connects to the rest of the breathing simulation system is discussed in Section 3.0. Additionally, technical drawings of pump components are located in Appendix B.

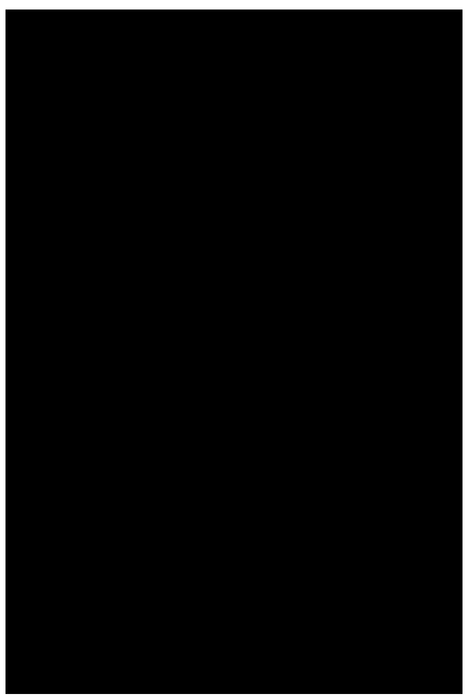

Figure 7: Pump assembly

The proposed pump design meets the client needs by producing the appropriate flow rate and maintaining a low weight and cost. The pump is able to produce the required 6 L/min flow rate with 12 discrete breaths in a sinusoidal flow pattern through the use of a single acting piston with 500 mL displacement and a motor speed of 12 RPM. The cost and weight of the pump was kept low by using mainly off-the-shelf parts and plastic instead of metal material. Although a pump was not able to be purchased as a single component, the custom pump design meets the client's need for off-the-shelf parts by incorporating purchased materials which require minimal machining.

2.2. Carbon Dioxide Incorporation

An important element and key objective of the breathing mannequin project is the incorporation of carbon dioxide into the exhaled airflow from the simulator. Atmospheric air at sea level contains 0.3% CO_2 by partial pressure and human respiration causes a concentration increase to 3.6% (36,000 parts per million). In order to achieve this 3.3% concentration increase in the exhaled airflow, a controlled amount of CO_2 will be injected into the inhaled air as it travels through the breathing simulator.

The concept generation and selection phase of the project determined that utilizing the existing pressurized CO_2 system at Price would be the most economical of the possible supply methods. The pressure in the existing system is able to be regulated, and as such, no further regulation equipment was deemed necessary for the project.

The breathing simulator must have the ability to precisely control the flow of CO_2 so as to make sure the desired concentrations are achieved. Since the breathing simulator is designed to have a flow rate of 6 L/min in 500 mL increments, the volumetric rate of CO_2 injection can be accomplished through examining the law of partial pressure shown in Equation (1), where *V* represents a volume value, and *p* is a pressure value.

$$\frac{V_{CO_2}}{V_{Total}} = \frac{p_{CO_2}}{p_{Total}} \tag{1}$$

The total amount of CO_2 and thus, the rate at which it needs to be steadily injected, can be determined as per the Equation (2).

$$V_{CO_2} = \left(\frac{p_{CO_2}}{P_{Total}}\right)(V_{Total}) = 0.198\ L/min \tag{2}$$

It was determined through client consultation that a continuous injection of CO_2 in to the system would be ideal, as there were many complications that arose from timing the injection with either the inhalation or exhalation cycles of the pump. The incorporation of further control systems would be required to properly time the injection of CO_2 with the pump, thus increasing complexity and cost. Additionally, due to the short injector pulse width required, it would not be possible to obtain an accurate flow measurement considering the settling time of the meter reading. Digital flow meters could be a viable solution as they have a faster response and settling time, however the cost of a digital flow meter would exceed the entire budget for the project.

Using a constant flow approach to injection, an inline CO_2 flow meter, model FLDC3502ST, was sourced from Omega and is shown in Figure 8. This flow meter is capable of controlling, measuring and displaying the flow rate within the desired accuracy. The flow meter has an accuracy of 5% of the full scale meter reading. Utilizing a meter with a maximum flow rate of 0.3 L/min meter results in enriched carbon dioxide content between 3.2 and 4.0%, which is on par with the marginal value range for this specification.

Figure 8: Carbon dioxide flow meter FLDC3502ST [12]

The next phase in the design of the CO_2 injection system involved connecting the existing gas supply at Price, through the flow meter, to the appropriate injection point on the breathing simulator. The CO_2 system at Price utilizes 1/4” outside diameter (OD) flexible tubing. Quick connect male and female compression style tube couplings, depicted in Figure 9, can easily connect the system to the existing gas supply line. The attachment couplings have internal valves that stop gas flow when the couplings are disconnected, thus assuring that no CO_2 is able to leak into the testing environment. The tube fittings are for 1/4” OD tubing and feature a 1/8” coupling size. It should also be noted that all fittings and tubing for the assembly were sourced from McMaster-Carr, and more detailed part information is included in the Section 4.0, the cost analysis, Section 4.0 of this report.

[redacted]

Figure 9: Male and female quick disconnect compression style fittings [9]

Flexible tubing will connect the CO_2 delivery components in the simulator to the supply line. The tubing selected consists is a chemical-resistant clear fluorinated ethylene propanol (FEP) tubing having a 1/4" OD and 1/8" inner diameter (ID). This material will not allow CO_2 permeation through the tubing walls as will some other tubing materials. This tubing also allows the use of compression style fittings which will ensure that no CO_2 leaks from the fittings into the testing environment. The gas supply tubing can then be attached to the female flow meter fittings by using a 1/8" brass NPT male compression tube fitting shown in Figure 10. Attachment to the breathing system occurs at the exit side of the flow meter, using the same fitting previously mentioned for use at the flow meter inlet.

[redacted]

Figure 10: Brass compression tube fitting [9]

The final connection of the CO_2 injection system is to the breathing simulator itself. The concept development phase analyzed the best point in the breathing system to introduce CO_2, assuming the team was able to source a piston pump from an external supplier. The outcome of the analysis dictated the CO_2 was to be injected into the inhalation tube prior to reaching the pump, allowing for optimum uniformity in gas composition and temperature. As the team has instead designed a custom pump, it was decided the appropriate injection point should instead occur after the pump stage. This precaution takes into account the possibility of residual air left in the pump after the exhalation cycle, which cannot be ruled out as the pump has not been built and tested, producing varying CO_2 levels in each exhale.

Final attachment of the injection system is then accomplished by attaching the FEP tubing originating at the flow meter outlet to a 5/8" barbed T-fitting located just after the pump outlet. This is accomplished by pressing one side of a small length of 3/4" FEP tubing onto the T-fitting and attaching a 3/4" brass female compression fitting to the other end. The 1/4” tubing from the exit of the flow meter can then be appropriately cut, whereby a 1/4” brass female compression fitting can be fastened. The two female fittings can then be mated using a 3/4” to 1/4” brass female-to female adapter. An assembly schematic for the two female fittings and adapter can be seen in Figure 11.

Figure 11: Female-to-female adapter schematic

2.3. Exhale Temperature and Thermal Plume Generation

The selected method of heat production for the air mixture to be exhaled is the heat tape design, Concept 4B (Appendix A). This design will feature the wrapping of heat tape around a tube in which the air is heated to obtain the required exhale temperature of 33 °C [3]. The main customer needs pertaining to this portion of the design are the temperature requirement and requirement concerning heat energy released by the mannequin. Like other systems, the items that will be taken into account during design include cost, availability of parts for purchase, component size, weight, maintenance requirements and expected component life.

At the conceptual design stage, several methods of achieving these requirements were proposed, including designs involving a heat exchanger, heat tape, heat wire, an oven, or utilizing excess heat from the pumping system (Appendix A). The prevailing design concept which was favoured by our selection criteria and, importantly, the client, was the heat tape design. This design was preferable due to its ability for high accuracy and precision, small size and low cost compared to other design options. The heat tape design features a tube or pipe which is wrapped in the tape to transfer heat to the internal air before it is pumped out through the exhale nozzle. The design can be broken down into four major subsections: that of the heat chamber design, heat source, temperature regulation and insulation.

2.3.1. Heat Chamber Design

The heating chamber will consist of a pipe around which the heat tape will be wrapped to transfer heat through the pipe walls to the air inside, effectively raising the temperature to the desired value. There are some important design factors to consider for sourcing the heat chamber pipe, including volume, size, availability of parts and heat transfer characteristics of the material.

The movement of the air into and out of the chamber is driven by the single-acting, fixed volume pump which first inhales one breath on the intake stroke and successively exhales this air into the heating chamber on its exhaust stroke. The next motion is another inhale, in which the air within the heating chamber is stagnant. It is during this time that the air is able to absorb heat energy, until the pump is again on its exhaust stroke and the air is exhaled back into the room via the exhale nozzle. It should be noted that some air will still remain in the lines between the heating chamber and exhale point, and this volume should be minimized as the temperature of this residual air will decline. Therefore, the volume of the heat chamber should be exactly equal to the volume of one breath to ensure no air is passed straight through without undergoing adequate heating, and that no air remains in the pipe for longer than the designed time frame and exceeds the design temperature.

Another factor to consider is the shape of the chamber. The longer and narrower the tube, the more even the heat distribution will be within the tube. However, extremely long tubing will not be practical due to increased size, weight, and assembly time of the system. For the best packaging and minimal size, the tube should be somewhat flexible to allow for bends and angles to be implemented if desired. For the tubing material, a metallic material is preferable to plastic, as metals have a higher rate of thermal conductivity and allow for faster heat transfer to the air. For the heating chamber pipe, the Multipurpose Copper Tubing from McMaster-Carr is selected as the chamber structure as shown in Figure 12.

Figure 12: Bendable copper tubing from McMaster-Carr [9]

This copper tubing consists of Alloy 122 and has excellent heat transfer qualities. The tubing is rated to temperatures up to 200°C so it is well suited for this application. It has a soft temper which makes it able to be easily bent by hand, allowing for assembly with minimal tools and easy packaging within the mannequin. The ability to bend the tubing will make routing the lines to the proper exit nozzle angles easier than having to piece together straight sections of tubing. In order to minimize flow restrictions within the tubing, the tubing should be wrapped in such a way to achieve consistent internal geometry along the length. The cost of the tubing is inexpensive, priced up to $11 for a 10 ft length in diameters ranging from 0.152” to 0.87” [9].

As mentioned, the tubing is available with a variety of inner diameters up to 0.87 inches. To achieve a volume of 500 mL, one breath, within the tubing, TABLE II displays the required tube length corresponding to each available diameter from McMaster-Carr.

TABLE II: AVAILABLE TUBING DIAMETERS AND CORRESPONDING LENGTHS

Inner Diameter (mm)	Required Length (m)
3.86	42.710
3.05	68.525
5.46	21.347
4.65	29.465
7.04	12.860
6.22	16.439
10.21	6.106
9.40	7.208
12.57	4.027
15.75	2.567
22.10	1.304

TABLE II shows that the largest available internal diameter, 22.1mm, corresponds to the only reasonable tubing length required to achieve the desired internal volume. The minimum length of this tubing offered for sale by McMaster-Carr is 3048 mm, which will be sufficient to supply tubing for up to two breathing systems [9].

2.3.2. Heat Source

In order to increase the air temperature, the device determined to be most practical is a heating tape or cord which will be wrapped around the piping. The geometry of the heat chamber is critical to determining the required heat flux for the heating tape.

Copper Alloy 122, the chosen tubing material, has a thermal conductivity, k, of 401 W/m·K [10]. The wall thickness, L, of the copper tubing is only 1.65 mm and due to the material’s high rate of thermal conductivity, the heat will transfer extremely quickly through the chamber walls. The ratio between internal thermal resistance to boundary layer thermal resistance, known as the Biot number, is shown in Equation (3) [11].

$$Bi = \frac{hL}{k} \tag{3}$$

The velocity of the air through the piping will be approximately 0.5 m/s before the tube fills. At this speed, the thermal convection coefficient, h, of the air is assumed to be 17.15 W/m^2·K [10]. Once the air is stagnant, the thermal convection coefficient will drop to approximately 10.45 W/m^2·K and so an average value of 13.8 W/m^2·K will be assumed. Therefore, the resultant Biot number is 5.68 x 10^{-5}. A low Biot number such as this confirms that the limiting factor in determining the required heat flux is the ability of the air to absorb the heat energy. As determined in the target specifications, the average breathing flow rate is 6 L/min, allowing 5 seconds per breath. Taking into account the piping dimensions, the mean velocity of the air as it enters the chamber will be 0.52 m/s. Equation (4) relates heat energy by convection, q_{conv}, to mass flow rate of a fluid, $\dot{m}$, specific heat of a fluid, C_p, mean inlet fluid temperature, $T_{m,i}$, and mean outlet fluid temperature, $T_{m,o}$, for internal flow within a pipe assuming a constant surface heat flux [11].

$$q_{conv} = \dot{m}C_p(T_{m,i} - T_{m,o}) \tag{4}$$

The inlet temperature of the air is assumed to be room temperature, equal to 22°C and the small amount of carbon dioxide injected into the system is considered to have a negligible effect on the overall air temperature. At 22 °C, the specific heat of the air is 1.007 kJ/kg·K and the density is 1.185 kg/m^3 [10]. Therefore, the mass flow rate is calculated as a function of cross sectional area of the tubing, air velocity and density, equal to 2.37 x 10^{-4} kg/s. To achieve an outlet temperature of 33°C, the required heat energy is calculated from Equation (4) as 2.63 W. In terms of heat flux, this is equivalent to 2.90 x 10^{-5} W/m^2.

Several heat tape products from various manufacturers were considered for the heat source, however, the Wraparound Heating Cord by Omega shown in Figure 13 was determined to be the best design option due to manufacturer reputation, accuracy and cost. The heating cord is suitable for heating fluids within electrically conductive piping as small as 3.2 mm in diameter. The maximum exposure temperature is 482 °C with a power density of 3 x 10^{-3} W/mm^2, which exceeds the heat flux requirement of 2.90 x 10^{-5} W/m^2. This product is preferable considering its compact size and ease in packaging within the system by simply wrapping it around the copper piping [12].

Figure 13: HTC Series Heating Cord by Omega [12]

Omega offers this heating cord in lengths of 0.9 m, 1.8 m and 3.6 m. Any combination of these cord lengths can be used to wrap around the copper piping in a helical pattern. Using Equation (5), the pitch, p, associated with each available cord length, L, can be calculated according to overall height or pipe length, h and pipe diameter, d.

$$p = \frac{\pi d h}{\sqrt{L^2 - h^2}} \tag{5}$$

With a pipe length of 1.304 m and outer diameter of 0.0254 m, the possible heat cord lengths and corresponding pitches are shown in TABLE III. The lowest cost associated with combining available lengths in order to achieve each cord length is also shown.

TABLE III: HEAT CORD LENGTHS AND CORRESPONDING WRAP PITCH [12]

Heat Cord Length (m)	Pitch (mm)	Cost
0.9	n/a	$26.00
1.8	83.9	$30.00
2.7	44.0	$56.00
3.6	31.0	$38.00
4.5	24.2	$64.00
5.4	19.9	$68.00
6.3	16.9	$94.00
7.2	14.7	$76.00

In order to achieve uniform heating along the tube length, a small pitch and increased number of revolutions of the heating cord is desired. However, cost must also be taken into account. Considering the values of cost and pitch in Table TABLE III, a reasonable cord length of 3.6 m is chosen.

2.3.3. Temperature Regulation

In order to control the heat output from the heating cord, the CSi32 Series Miniature Benchtop Controller by Omega will be used. This device features a PID controller to regulate power supply to a heating device in order to maintain a specific temperature of an object or medium as measured by a thermocouple [12]. A thermocouple reading is input to the controller which processes the difference between the measured temperature and desired temperature, which is set by the user. The device then uses a fully auto-tuned PID controller to adjust the power input to the heat source in order to stabilize the temperature at the desired value. The operation range is within 0 °C to 50 °C, which encompasses the required temperature of 33 °C. The unit is compatible with many types of thermocouples and RTDs, but provides the best accuracy of ± 0.4 °C when used with a J type thermocouple. The PID controller is fully adjustable and enables the user to define the parameters which control temperature deviation from the set point. Therefore, this product will meet the acceptable limits for exhale temperature deviation of ± 2 °C as defined in the project target specifications if properly tuned by the operator. The unit weighs only two pounds and will be a necessary component to ensure accuracy in the heating system [12].

A J type thermocouple will be used to measure the air temperature within the heating chamber. It will be mounted as close to the exhale nozzle as possible by drilling a small hole through the wall of the copper tubing and inserting the thermocouple probe into the chamber. The probe should not contact the copper piping but only the internal air. The 5TC Series thermocouple from Omega has been selected for the air temperature measurement [12]. This thermocouple is recommended for gas and surface measurements in which an exposed thermocouple is required. It features an insulated, exposed junction configuration and is offered in J, K, T and E types. Sheathing is available in PFA, glass braid or KAPTON options. PFA sheathing is suitable for temperatures up to 260 °C with excellent abrasion resistance and good flexibility, whereas glass braid sheathing is normally recommended for high-temperature applications up to 482 °C and has poor abrasion resistance but good flexibility. KAPTON sheathing is rated up to 316 °C with excellent abrasion resistance and good flexibility [12]. For the purposes of the breathing apparatus, PFA sheathing is selected, as high temperature resistance is not required. The thermocouple wire lengths are available in 1 m and 2 m denominations. The 1 m length will be selected to minimize the effect of noise on the measurement, assuming that the temperature controller can be located within 1 m of the thermocouple placement. The AWG of the thermocouple wire is available in 20, 24, 30 and 36 gauges, any of which will be suitable for the measurement requirements. An AWG of 24 is chosen since it is available at the lowest cost for a package of 5 thermocouples.

2.3.4. Insulation

Thermal insulation of the heating components is required to ensure that no heat energy from the system is released in addition to what is already produced for the mannequin’s thermal plume system. Any other components in the breathing apparatus which may generate heat will also require insulation.

The Thermo-Tec Thermo Guard FR Heat and Sound Insulation by Thermo Tec has been selected from Jegs to provide adequate thermal insulation of the necessary components. The thermal guard is available in a sheet of dimensions 48” by 72” with a two-sided foil face as shown in Figure 14 [13].

Figure 14: Thermo-Tec thermo guard FR heat and sound insulation [13]

The product features high quality heat insulation and is able to block 90% of radiant heat at temperatures up to 815°C. The Thermo Guard insulation is made up of light weight, flame retardant, 3/8” thick sheet which can be easily installed by simply wrapping it around items which require thermal insulation. The product can be trimmed to any shape for easy assembly and flexibility in customization. Due to the strict specifications of thermal insulation for this breathing system, no more than 0.5 kJ/min of heat released, it is recommended that two layers of Thermo Guard be used to ensure no heat from the heating chamber is transmitted into the surroundings [13]. In doing this, Price can continue to use their existing thermal plume system on the mannequin without having their heat values affected by additional heat generation from the breathing simulator.

Based on heat chamber and insulation sheet dimensions, it is estimated that for each heating chamber, 0.364 m^2 of Thermo Guard will be required. Therefore, each purchase of one sheet will supply insulation for up to six heating chamber assemblies.

2.4. Velocity

Once the air has been heated to the appropriate temperature, it must be directed out of the mannequin at an angle and speed simulating the average nasal exhale of a human male. The following design takes into consideration variables such as cost, availability of parts for off-the-shelf purchase, size, weight, and importantly, accuracy.

The average human breathing cycle is approximately 5 seconds long, 2.5 seconds for inhaling and 2.5 seconds for exhaling. In this exhale period the amount of air exhaled is 500 mL. The average cross-sectional area of a single nostril is 0.71 ± 0.23 cm^2 for males and 0.56 ± 0.1 cm^2 for females. For consistency, since we have derived our size constraints based on a male mannequin, 0.71 cm^2 is the value selected for the design. It will be assumed that the nostrils are located 1.87 cm apart with the same area and are free of obstructions, resulting in an exhale velocity of 2.56 m/s.

The jet of exhaled air is directed at an angle of 69 degrees below horizontal as viewed from the front and 60 degrees below horizontal as viewed from the side. The client considered these angles and the speed of the air to be important characteristics of the breathing cycle and specifically requested that they be replicated as closely as possible.

The optimal design that would meet the required target specifications is a simple rapid prototyped nozzle that combines the reducing couplers and wye joints into one entity as shown in Figure 15. However, the client expressed concern over the access to a rapid prototyping machine and requested a solution made from off-the-shelf parts. Thus numerous step downs and connecting tubes are required.

Figure 15: Optimal nozzle design

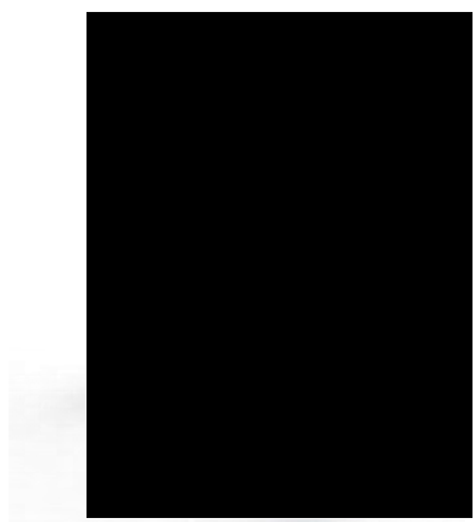

Figure 16: Nozzle assembly of purchased components

The off-the-shelf nozzle will use a pipe to hose fitting specified for use with the copper heating pipe. This fitting will then be stepped down to a 3/8" ID for a flexible tube to connect to it. The flexible tube will then make a u-bend to orient the nozzles in the correct direction. After the u-bend the tube will be connected to a 3/8' wye joint with two 3/8" tubes exiting from it. These two flexible tubes can then be located into the mannequin and oriented in the directions specified. The final assembly resemble Figure 16.

2.5. Design Summary

In the design of each aspect of the breathing system, the team kept in mind the predefined customer needs and worked closely with Price Industries. The team included the customer in all major design decisions to ensure client satisfaction with the final product. The final design consists of a single acting piston pump which draws in air at a fixed flow rate through an inhale nozzle located at the mannequin's mouth. The pump expels this air into a chamber where a fixed amount of carbon dioxide is added to the air before it is heated to a desired temperature. On the subsequent piston stroke, the air is pumped out of the mannequin through a nozzle at a precise angle and velocity to replicate the conditions of a human being's exhaled breath.

For the flow rate design, the team initially intended to purchase a pump from an external supplier at the customer's request. However, after consulting numerous pump manufacturers, the team was unable to find a pump which met all the flow rate design requirements. Upon reviewing this information with the customer, the team and customer reached an agreement that the most effective option would be to design a custom pump to ensure that all design requirements could be satisfied. In keeping with the original design intention, the final pump design is comprised entirely from off-the-shelf components from McMaster-Carr. The piston and cylinder material is oil-filled nylon bar and tube stock which is self-lubricating to keep maintenance requirements low and improve pump life. One-way check valves with a 2275.27 Pa cracking pressure control flow in and out of the pump at nearly ambient pressure. The crankshaft design is constructed of Kevlar-filled nylon which is strong but lightweight in order to support loads associated with driving the piston. The pump is able to achieve a flow rate of 6 L/min in 12 discrete 500 mL intervals and is driven by a 24 V, compact DC motor from McMaster-Carr. The motor has variable speed and torque capabilities which can be regulated by a motor controller device. A pump housing was designed from cast nylon in order to support the various pump components.

It was discovered that a discrete injection system for the CO_2 injection design would entail a timing system and very precise components to handle the small 0.198 L/min flow rate. This would increase cost and decrease accuracy. Therefore, it was determined that a continuous CO_2 injection into the air stream would be preferable in order to keep the design simple. The FLDC3502ST Carbon Dioxide Flow Meter from Omega was selected to control the CO_2 flow rate into the system. The meter is capable of flow rates up to 300 mL/min with a 5% full scale accuracy which meets design requirements. The system can be easily integrated into Price's existing infrastructure with quick disconnect fittings from McMaster-Carr which can hook up to existing CO_2 airlines in the facility. The airlines of the assembly are constructed of 1/4" OD flexible, clear, FEP tubing which will not allow CO_2 to permeate through the walls and prohibits leakage when used with compression style fittings. The optimal injection point for the CO_2 was determined to be after the piston pump outlet before the heating chamber. A number of fittings have been sourced to incorporate this design into the system.

The exhale temperature design features a heating chamber consisting of a copper tube structure made up of Multipurpose Copper Tubing from McMaster-Carr. The copper tubing was deemed preferable due to its excellent heat transfer characteristics and the fact that it can be easily bent by hand to facilitate implementation into the mannequin. The internal volume of the tubing has been designed to hold exactly 500 mL or one breath of air. The heat source for the heating chamber is the HTC Series Heating Cord from Omega, which provides a heating power density of 3×10^{-3} W/mm^2 [12]. The heating cord will be purchased in a 36" length and wrapped around the copper tubing in a helical pattern with a 31.0 mm wrap pitch to provide even heat distribution along the tubing. The temperature of the air will be regulated with the CSi32 Series Miniature Benchtop Controller from Omega. This will allow operators to regulate power to the heating cord by inputting a desired temperature which the controller will compare with feedback from a RTC Series J type thermocouple measuring actual air stream temperature. The temperature controller has an accuracy of ± 0.4 °C when used with a J type thermocouple and a range of 0 °C to 50 °C [12]. It is noted that there may be a small amount of heat lost from the air within the exit nozzle before it is exhaled, as there is no heating in this section of the airline. However this is considered to have a negligible impact on the mean air temperature. The heating system will be insulated by two layers of Jegs' Thermo-Tec Thermo Guard FR Heat and Sound insulation, which consists of a two sided foil 48" X 72" sheet that can be trimmed to any desired size. Each layer of the Thermo Guard is capable of blocking 90% of heat energy produced, hence the reason for the second layer to further improve insulation of the heat chamber.

The final stage in the breathing system is the exhalation of the heated air mixture. The nozzle design is a Y shape to replicate the geometry of a male nose. The two outlets are 1.87 cm apart and direct the air at an angle of 69 degrees below the horizontal aw viewed from the front and 60 degrees below the horizontal as viewed from the side. The cross-sectional area of each outlet is designed to achieve an airspeed of 2.56 m/s. Two options for producing the nostril design were suggested to the customer, one featuring a simple, lightweight, rapid-prototyped part and a second comprising of off-the-shelf hoses and fittings. The resulting, overall design is depicted in Figure 17.

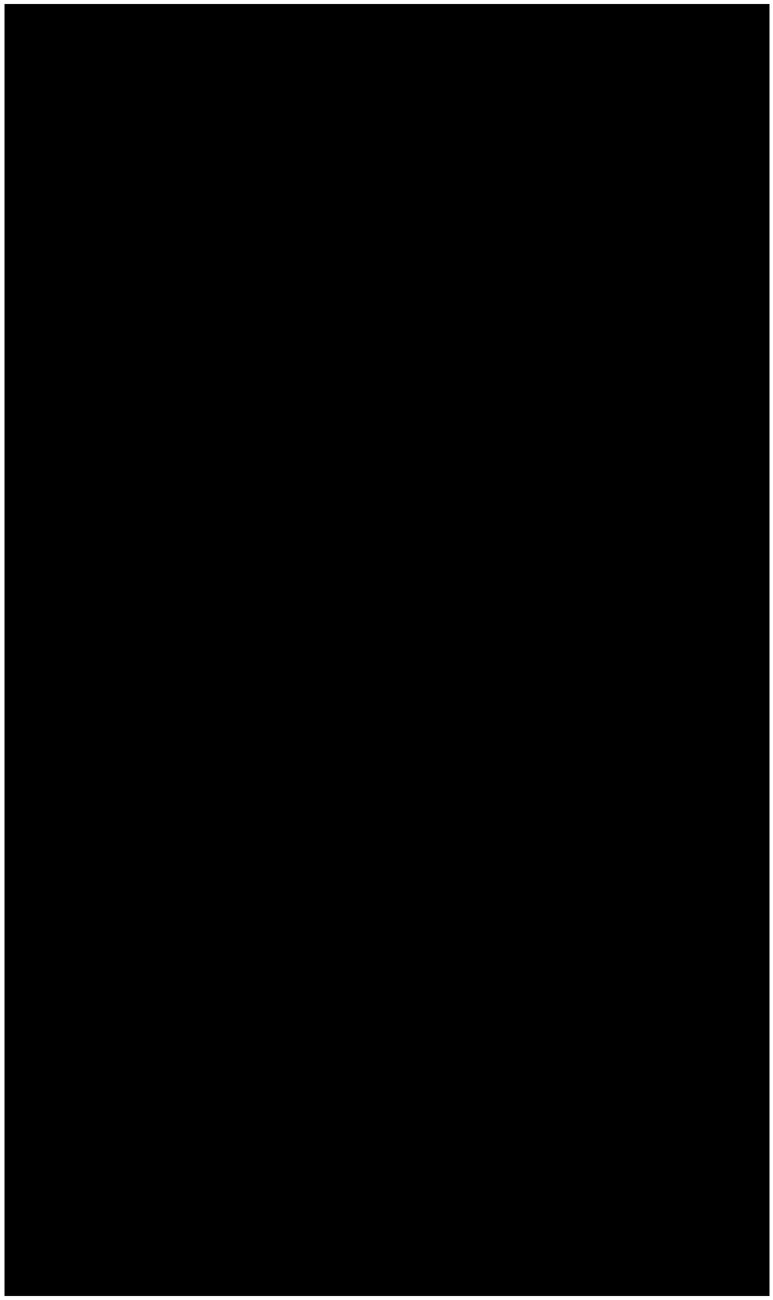

Figure 17: Full breathing system assembly

The overall system is approximately 45 cm X 20 cm X 15 cm in size and weighs approximately 5.6 kg. As many components as possible were sourced from external suppliers, and where it was necessary to design custom parts, the design was kept simple with readily available materials and basic machining processes. All components were selected from known suppliers with good reputations for quality parts to ensure durability and long life of the system.

3. Manufacturing

As determined through client interviews, one of the major requirements of the breathing system design is that it be comprised entirely of off-the-shelf parts [2]. Because the system is comprised of off-the-shelf parts, manufacturing of the breathing system is quick and easy compared to a completely custom design.

The manufacturing requirements and assembly instructions for all elements of the design, as well as how all sections tie into the overall design, has been laid out in each of the four design sections: flow rate generation, CO_2 source and injection, exhale temperature and thermal plume, and exhale velocity.

3.1. Flow Rate Generation

The custom pump will be manufactured entirely using parts from McMaster-Carr. There are five main components of the piston pump design that must be purchased or manufactured and then assembled, including the piston and cylinder, the inlet and outlet valves, the crankshaft and connecting rod, the motor, and the housing.

The piston and cylinder are to be manufactured using oil-filled nylon bar and tube stock. Oil-filled nylon was chosen as it is a self-lubricating material that will not bind and will be very low maintenance. The piston will be manufactured from 4" bar stock (McMaster Carr part 8664K72) and turned down to fit within the 3.5" ID tube stock (McMaster Carr part 84755K644) that will serve as the cylinder. It is very important that the piston is turned down to a sliding fit within the cylinder. Too tight a fit will cause the piston to bind within the cylinder, and too loose a fit will allow air to leak between the piston and the cylinder instead of being forced out through the outlet valve. A connection block must also be machined atop the piston to provide a point of attachment for the connecting rod.

The 4" bar stock will also be used to create the base plate of the cylinder in which the inlet and outlet valves will be installed. This will involve turning the stock down to size to fit within the cylinder and machining appropriately sized and shaped holes for installation of the valves. An epoxy for plastics, specifically nylon (McMaster-Carr part 7513A1), should be used as a method of securing the cylinder base plate within the cylinder.

The inlet and outlet valves on the pump are simple polypropylene 3/4" NPT female check valves purchased from McMaster Carr (McMaster-Carr part 5492K14). The same epoxy that should be used on the cylinder and base plate (McMaster-Carr part 7513A1) should also be used to secure the valves within the base plate. The 3/4” female threading on the valves allows for attachment of various fittings as needed. A barbed 5/8” fitting will be installed on the inlet valve (McMaster Carr part 5463K476). This fitting will allow the inhale tubing that runs between the nozzle and the pump to fit securely onto the inlet valve.

The crankshaft and connecting rod are to be machined from 1/4” Kevlar-filled nylon (McMaster-Carr part 8501K92). A 1/2” internally threaded shoulder 1/2” in length (McMaster Carr part 96655A131) with a 1/4” long #10-32 pan head screw (McMaster Carr part 91792A825) will be used to create the pivot attachment between the crankshaft and the connecting rod, while a 1” long shoulder (McMaster Carr part 96655A133) also with a 1/4” long pan head screw will be used to create the pivot between the piston and the connecting rod. The CAD model files required for machining the crankshaft and connecting rod will be made available for the client in a Step file format to increase the speed of machine programming, and the technical drawings for these parts are available in Appendix B.

The electric motor required for operating the pump will be purchased from McMaster-Carr (McMaster-Carr part 6409K26). The speed of the 24 VDC motor can be controlled using a speed controller which can also be purchased from McMaster-Carr (McMaster-Carr part 7729K13).

Finally, the pump housing consists of four pieces: a base plate, two supporting rings, and a motor support. Components of the pump housing will be machined from cast nylon (McMaster-Carr part 8687K57 and 85055K12). After machining, the components of the housing can be assembled according to the drawings in Appendix B using 1/4”-20 bolts and nuts (McMaster-Carr parts 92865A544 and 95505A601, respectively). The motor can be attached to the motor support using the mounting hardware that is supplied with the motor. The CAD files for the parts of the pump housing will be made available for the client in a Step file format to increase the speed of machine programming.

With regards to manufacturing, the client requested a design made entirely of off-the-shelf parts. Unfortunately, that need was not able to be met completely as some machining is required for the pump housing and the piston.

3.2. Carbon Dioxide Incorporation

The most important step of the manufacturing process of the CO_2 system is to ensure that the Omega FLDC3502ST flow meter is positioned in the proper upright manner as per the manufacturer’s operational manual. As the packaging of the system has not been defined within the scope of this report, the mounting of the flow meter is an important consideration. The flow meter is capable of a panel mount so it may be possible to directly fasten the meter to the piston pump housing, thus reducing the length of tubing between the flow meter and injection point to minimize any flow losses.

The first step is to attach the quick connect socket the existing CO_2 system at Price, and the quick connect plug to a cut end of the of FEP tubing. An appropriate amount of tubing should then be laid out and cut so as to connect the fittings to the inlet coupling of the flow meter. A 1/8" brass male compression fitting is then to be appropriately attached to this end of tubing and threaded into the female flow meter fitting.

A piece of 3/4" FEP tubing roughly 2.5" in length should then be cut and correctly attached to the barbed T-fitting at the outlet side of the pump. A standard hose clamp should be tightened over at the barbed fitting joint to ensure no leaks occur. The 3/4" brass female compression fitting can then be attached to the open end of the 3/4" FEP tubing piece.

The following process then describes attaching the exit fitting of the flow meter to the 3/4" female tube fitting. The piece of 1/4" FEP tubing from the flow meter outlet should be cut to an appropriate length as to attach to the 3/4" female fitting. A 1/4" female brass compression fitting can then be appropriately attached the cut end of tubing. The 3/4" and 1/4" female compression fittings can be connected by means of the 3/4" to 1/4" male-to-male adapter, thus completing the connection of the CO_2 injection system to the rest of the breathing system. An assembly drawing for the CO_2 injection system is available in Appendix B. It should be noted that although unlikely, all fittings and couplings should be checked for leaks to ensure proper operation of the system.

3.3. Exhale Temperature and Thermal Plume Generation

In order to assemble the heating chamber, the copper tubing (McMaster-Carr part 8955K291), is to be cut at a length of 1304 mm and wound into a helical formation in order to minimize sizing and keep internal flow geometry consistent along the length. A small hole is to be drilled at the exhale end of the tubing to allow for the mounting of a thermocouple into the airstream. The heating cord (Omega part HTC-120) can then be wrapped around the outer diameter of the tubing at a pitch of 31.0 mm. The cord is to be plugged in to the temperature controller (Omega part CSi32J) to allow for energy regulation to the cord in order to achieve the desired heating. Also input to the controller is the thermocouple reading, which is mounted in the heat chamber airstream to provide feedback to the controller. The controller itself will not be packaged with the breathing system components, but placed near the mannequin in an easily accessible area for operators. The entire heat chamber must be insulated in order to prevent excess heat given off by the components. The insulation sheet (Thermo-Tec part 893-14125) is to be cut into 1304 mm lengths and wrapped around the heating cord to provide two layers of thermal insulation. The inner layer material will be approximately 110 mm wide and the outer layer material will be approximately 170 mm wide. It may be secured in place with any generic tape or adhesive product.

3.4. Exhale Velocity

The rapid prototyped version of the exhale nozzle does not require any significant assembly instructions beyond attachment to the heat chamber using a 1” ID flexible PVC tube and hose clamps to ensure the tube does not detach from the nozzle or heating chamber.

The off-the-shelf nozzle version consists of a number of tube lengths and fittings. Like the rapid prototyped nozzle the off-the-shelf nozzle connects to the heating chamber using a 1” ID flexible PVC tube and hose clamps. This is then stepped down to a 3/8” ID barbed tube adapter. 3/8” ID flexible PVC tube is then used to connect a wye joint to split the airflow. Finally 3/8” flexible PVC tubes are used to direct the flow to the correct position and angles. It is important to note that since mounting inside the mannequin was outside the scope of this project, the final mounting of the nozzles is left up to the client to determine.

3.5. Manufacturing Time

As requested by the customer, the breathing simulation system design uses primarily off-the-shelf parts. In situations where custom parts were not readily available, raw materials were used to design parts with relatively simple machining processes.

Using recommended feed rates and tool speeds for cast, oil-filled, and reinforced nylon (shown in TABLE IV), the approximate machining time for the various pump components could be calculated.

TABLE IV: RECOMMENDED MACHINING SPEEDS FOR OIL FILLED, CAST, AND REINFORCED NYLON [14]

	Operation	Tool Material	Depth of cut	Speed (sfpm)	Feed (in/rev)
Tuning	Rough Cut	Carbide	0.150”	500-800	0.005-0.020
	Finish cut	HSS/Carbide	0.025”	800-1000	0.002-0.005
End Milling	Rough	HSS/Carbide	0.250”	250-450	0.002-0.010
	Finish	HSS/Carbide	0.050”	350-550	0.001-0.005
Drilling	Drilling	< 1” diameter		150-450 (150-300 for reinforced nylon)	0.004-0.015

Taking into account the dimensions of the material and tooling being used as well as the speed of the tooling and the feed of the material, the machining time required for each component could be calculated. A set up time of 15 minutes was applied to all machining operations. Equation ((6)(8), in which D_o is the work diameter (in), L is the length of the work part (in), v is the cutting speed (in/min), and f is the feed (in/rev), was used to determine that amount of time, T_m, required for lathing operations [15].

$$T_m = \frac{\pi * D_o * L}{v * f} \tag{6}$$

TABLE V shows the machining times for the required lathing operations and the values of the variables required in calculations.

TABLE V: LATHE TIME CALCULATION

Lathe Operations						
Part	**D (in)**	**L (in)**	**v (in/min)**	**f (in/rev)**	**T_m (min)**	**Set Up (min)**
Piston	4	1	500	0.005	5.03	15
Cylinder Base	4	1	500	0.005	5.03	15
					Total (min):	**40.06**

Equation (7) was used to determine the machining time required for milling operations, where L is the length of the work (in), D is the diameter of the milling cutter (in), w is the width of the cut (in), f is the feed (in/rev), and v is the cutting speed (in/min) [15].

$$T_m = \frac{L * \sqrt{w(D - w)}}{f * v} \tag{7}$$

The machining times required for milling operations and the variables used in calculating those machining times are displayed in TABLE VI.

TABLE VI: MILL TIME CALCULATION

Mill Operations							
Part	**L (in)**	**D (in)**	**w (in)**	**f (in/rev)**	**v (in/min)**	**T_m (min)**	**Set Up (min)**
Piston	4	0.15	0.1	0.002	250	0.57	15
Crankshaft	3	0.15	0.1	0.002	250	0.42	15
Connecting rod	4	0.15	0.1	0.002	250	0.57	15
Base	12	0.25	0.15	0.002	250	2.94	15
Cylinder Support 1	7	0.25	0.15	0.002	250	1.71	15
Cylinder Support 2	7	0.25	0.15	0.002	250	1.71	15
Motor Support	3.5	0.15	0.1	0.002	250	0.49	15
						Total (min):	**113.41**

Finally, Equation (8) was used to calculate the time required for drilling operations [15];

$$T_m = \frac{\pi * D * (t + A)}{f * v} \tag{8}$$

where D is the drill diameter (in), v is the cutting speed (in/min), t is the thickness (in), A is an approach allowance (in), and f is the feed rate (in/rev). The machining time required for drilling operations are displayed in TABLE VII along with the variables used in calculating those machining times.

TABLE VII: DRILL TIME CALCULATION

Drill Operations								
Part	QTY	D (in)	t (in)	A (in)	F (in/rev)	V (in/min)	Tm (min)	Set Up (min)
Base	9	0.25	0.5	0.1	0.004	150	0.59	15
Cylinder Support 1	2	0.25	0.5	0.1	0.004	150	0.13	15
Cylinder Support 2	2	0.25	0.5	0.1	0.004	150	0.13	15
Motor Support	4	0.25	1	0.1	0.004	150	0.52	15
							Total (min):	**61.37**

From the above calculations, the total estimated machining time associated with manufacturing the pump is 215 minutes (3.58 hours).

The assembly time of the breathing simulation system was also estimated by the team. The assembly time values indicated in TABLE VIII are simply estimates. To determine actual assembly time, it is recommended that a time study be conducted.

TABLE VIII: TIME ESTIMATES OF ASSEMBLY OPERATIONS

Assembly Component	Operation	Time (min)	QTY	Total Time (min)
Pump	Install screws/bolts (hand turned)	0.75	8	6
	Install internally threaded shoulders	0.5	2	1
	Install cylinder base plate and valves using epoxy	20	3	60
CO2 Injection System	Attach tubing to barbed fittings	0.25	5	1.25
	Mount flow meter	5	1	5
	Attach threaded fittings	0.5	2	1
	Install hose clamps	2	1	2
Exhale Temperature Generation	Cut pipe to desired length	7	1	7
	Drill hole in pipe for thermocouple	5	1	5
	Mount thermocouple	15	1	15
	Wrap heating cord around pipe	10	1	10
	Cut insulation to size	10	1	10
	Install insulation	10	1	10
Nozzle Assembly	Cut tubing to desired length	2	1	2
	Install tubing on barbed wye fitting	1	1	1
	Install hose clamp to copper tube	2	1	2
	Adjust nozzle angle	10	1	10
	Total Assembly Time (min):			**148.25**

Because the manufacturing of the breathing system is mainly assembly of off-the-shelf parts and little machining, the manufacturing time per system was kept low at approximately 363 minutes (6.05 hours) per system. This low manufacturing time meets the client's needs as it falls within the client's maximum manufacturing time of 40 hours. A bill of materials for the design is shown as part of the cost analysis in Section 4.0.

3.6. Maintenance

Throughout the project careful consideration was taken to reduce the amount of regular maintenance needed to maintain the operational capabilities of the breathing simulator. There are a number of maintenance practices recommended by the design team to ensure proper continued performance of the simulator. These maintenance practices include:

- Ensuring the electric motor is kept clear of dust and debris.
- Regular inspection of the pump components (specifically the crank arm, the piston and the cylinder) for wear. Any worn parts should be replaced.
- Regular inspection of the system fittings to ensure leak-free operation.
- Yearly calibration of the carbon dioxide flow meter is recommended to ensure continued accurate operation.
- Yearly calibration of the thermocouple and control device to ensure continued accurate operation.

Following the aforementioned maintenance practices is recommended and will promote longevity and accurate operation of the breathing simulator.

4. Cost

The cost of the breathing system is divided into three main categories: parts, labour, and control components. The budget for each of these three categories was determined during interviews with the client. The standard system components were allocated a budget of $2000 and the control systems required to operate and monitor the breathing system were allocated a budget of $5000. Labour was allocated a maximum of 40 hours for the assembly of one unit.

TABLE IX shows the bill of materials for the construction of one breathing system as well as the cost associated with each part. The cost section of the bill of materials is divided into two totals, one displaying the cost associated with a one-off production and a second total displaying the unit cost associated with mass producing thirty units, in which bulk order purchasing can be taken advantage of. The one-off cost to build only one breath system is $925.45 while the mass produced cost per unit is $438.10. Thirty units was chosen as the quantity for mass production based on the clients' desire to eventually build thirty breathing thermal mannequins.

As mentioned previously, the control systems required for the breathing simulator were given a budget of $5000. The resulting cost totals consumed only a fraction of the budget, with the cost for a one-off production equal to $1092.62 and a unit cost of $1064.62 for the production of thirty units. TABLE V shows a breakdown of the required control components and the cost associated with each.

In both TABLE IX and TABLE X, the required quantity of some items is zero. This is because some items are available in larger stock sizes or larger quantity packages at decreased prices that can be used when manufacturing 30 units, but are not practical when manufacturing a single unit.

The final cost element is labour. As discussed in Section 3.5, the number of labour hours required for manufacturing a single breathing system is expected to be approximately 6.05 hours. Using a labour cost of $150 per hour [2] the approximate cost of labour is $907.50 to assemble one unit.

Given that cost of components is $925.45, the cost of control systems is $1092.62, and the cost of labour is $907.50, the total cost of one breathing system is $2925.57 if only one system is made. If thirty breathing systems are made the cost of components is $438.10, the cost of control systems is $1064.62, and the cost of labour is still $907.50, so the total cost per unit is $2410.22. From these numbers we can see that the proposed breathing system design meets the client's needs with respect to budget.

TABLE IX: STANDARD COMPONENT COST SUMMARY

COST SUMMARY OF STANDARD COMPONENTS

				ONE-OFF COST			MASS-PRODUCED UNIT COST (30 UNITS)			
System	**Component**	**Manufacturer**	**Part Number**	**Unit Cost**	**Quantity**	**Total**	**Unit Cost**	**Quantity**	**Total**	**Comments**
Exhale Temperature Generation	Heating Cord	Omega	HTC-120	$38.00	1	$38.00	$38.00	30	$1,140.00	
	7/8" ID Coiled Copper Tubing (10 ft)	McMaster-Carr	8955K291	$112.78	1	$112.78	$112.78	3	$338.34	Smallest qty supplies tubing for 2 breathing systems
	7/8" ID Coiled Copper Tubing (50 ft)	McMaster-Carr	8955K291	$451.13	0	$0.00	$451.13	2	$902.26	
	15/16"-20 Female Brass Yor-Lok Tube Fitting	McMaster-Carr	5272K516	$35.74	2	$71.48	$35.74	60	$2,144.40	
	24" x 48" Thermo Guard	Thermo Tec	893-14125	$57.99	1	$57.99	$57.99	5	$289.95	Is good for two layers of insulation for 6 heating chambers
					Subtotal:	$280.25	Subtotal per unit:		$160.50	
Flow Rate Generation	4" Bar Oil-Filled Cast Nylon (1ft)	McMaster-Carr	8664K72	$101.40	1	$101.40	$101.40	1	$101.40	Minimum qty can produce for 3 pistons and 4 base plates
	4" Bar Oil-Filled Cast Nylon (2ft)	McMaster-Carr	8664K82	$171.94	0	$0.00	$171.94	4	$687.76	
	3.5"ID Tube Oil-Filled Cast Nylon (1ft)	McMaster-Carr	84755K644	$48.66	1	$48.66	$48.66	15	$729.90	Minimum qty supplies material for 2 cylinders
	3/4" NPT Female Check Valve	McMaster-Carr	5492K14	$13.54	2	$27.08	$13.54	60	$812.40	
	Epoxy For Plastics (1.7 oz Cartridge)	McMaster-Carr	7513A1	$86.00	1	$86.00	$86.00	2	$172.00	
	Compact DC Gearmotor	McMaster-Carr	6409K26	$44.30	1	$44.30	$44.30	30	$1,329.00	
	1/4" Kevlar Filled Nylon Sheet (6" x 6")	McMaster-Carr	8501K92	$49.24	1	$49.24	$49.24	0	$0.00	Minimum qty can produce 4 crankshafts and connecting rods
	1/4" Kevlar Filled Nylon Sheet (12" x 12")	McMaster-Carr	8501K22	$152.91	0	$0.00	$152.91	2	$305.82	
	0.5" Internally Threaded Shoulder (0.5" Length)	McMaster-Carr	96655A131	$7.00	1	$7.00	$5.96	30	$178.80	
	0.5" Internally Threaded Shoulder (1" Length)	McMaster-Carr	96655A133	$11.00	1	$11.00	$9.44	30	$283.20	
	1/4" 10-32 Pan Head Slotted Machine Screw (Qty 100)	McMaster-Carr	91792A825	$7.17	1	$7.17	$7.17	1	$7.17	
	1/4"-20 Grade 5 Bolt (1-1/4" Length)	McMaster-Carr	92865A544	$7.54	1	$7.54	$7.54	3	$22.62	
	1/4"-20 Grade 5 Nut	McMaster-Carr	95505A601	$3.26	1	$3.26	$3.26	2	$6.52	
	1/2" Cast Nylon Sheet (12" x 12")	McMaster-Carr	85055K11	$54.96	0	$0.00	$54.96	1	$54.96	
	1/2" Cast Nylon Sheet (12" x 24")	McMaster-Carr	85055K12	$100.57	1	$100.57	$100.57	0	$0.00	
	1/2" Cast Nylon Sheet (24" x 48")	McMaster-Carr	85055K14	$315.87	0	$0.00	$315.87	2	$631.74	
	1" Nylon Bar (3" x 12")	McMaster-Carr	8687K57	$31.58	1	$31.58	$31.58	8	$252.64	Minimum quanitity supplies material for 4 motor supports
					Subtotal:	$524.80	Subtotal per unit:		$185.86	
Carbon Dioxide Injection	3/4" Female Compression Fitting (Brass)	McMaster-Carr	50915K233	$28.73	1	$28.73	$28.73	30	$861.90	
	5/8" T-fitting	McMaster-Carr	5463K613	$7.12	1	$7.12	$7.12	30	$213.60	
	1/4" Clear FEP Tubing	McMaster-Carr	2129T11	$2.45	5	$12.25	$2.45	150	$367.50	
	3/4" Clear FEP Tubing	McMaster-Carr	2129T21	$7.27	1	$7.27	$7.27	10	$72.70	
	1/4" Compression Socket	McMaster-Carr	5012K662	$14.43	1	$14.43	$14.43	30	$432.90	
	1/4" Compression Coupling	McMaster-Carr	5012K692	$10.70	1	$10.70	$10.70	30	$321.00	
	1/8" NPT Male Compression Fitting (Brass)	McMaster-Carr	50915K315	$2.15	2	$4.30	$2.15	60	$129.00	
	1/4" NPT Female Compression Fitting (Brass)	McMaster-Carr	50915K215	$3.37	1	$3.37	$3.37	30	$101.10	
	1/2" to 1/4" Male-Male Adapter (Brass)	McMaster-Carr	5485K36	$5.23	1	$5.23	$5.23	30	$156.90	
					Subtotal:	$93.40	Subtotal per unit:		$88.55	
Exhale Nozzles	Nylon Wye for 3/8" Tube ID	McMaster-Carr	5463K725	$13.16	1	$13.16	$13.16	3	$39.48	Wyes supplied in packages of 10
	Nylon 3/8" ID Tube to 3/4" Pipe Adapter	McMaster-Carr	5463K229	$6.54	1	$6.54	$6.54	3	$19.62	Adapters supplied in packages of 10
	3/8" PVC Tubing	McMaster-Carr	5233K65	$0.73	10	$7.30	$0.73	50	$36.50	Minimum length is 10 ft.
					Subtotal:	$27.00	Subtotal per unit:		$3.19	
				ONE-OFF TOTAL*	**$925.45**		MASS PRODUCTION TOTAL PER UNIT*	**$438.10**		

*Before tax

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TABLE X: COST SUMMARY OF MEASUREMENT SYSTEM COMPONENTS

COST SUMMARY OF MEASUREMENT SYSTEM COMPONENTS				ONE-OFF COST			MASS-PRODUCED COST (30 UNITS)			
System	**Component**	**Manufacturer**	**Part Number**	**Unit Cost**	**Quantity**	**Total**	**Unit Cost**	**Quantity**	**Total**	**Comments**
Exhale Temperature Generation	Temperature controller	Omega	CSi32J	$445.00	1	$445.00	$445.00	30	$13,350.00	
	J-type thermocouple	Omega	5TC-GG-J-24-36	$35.00	1	$35.00	$35.00	6	$210.00	Smallest available package includes 5 thermocouples
					Subtotal:	$480.00	Subtotal per unit:		$452.00	
Flow Rate Generation	Low-Voltage DC Motor Speed Controls	McMaster-Carr	7729K13	$329.62	1	$329.62	$329.62	30	$9,888.60	
					Subtotal:	$329.62		Subtotal:	$329.62	
Carbon Dioxide Injection	Flow Meter	Omega	FLDC3502ST	$283	1	$283	$283	30	$8490.00	
						$0.00			$0.00	
					Subtotal:	$283		Subtotal:	$283	
				ONE-OFF TOTAL*	**$1092.62**		MASS PRODUCTION TOTAL PER UNIT*	**$1064.62**		

*Before tax

5. Recommendations

There are a number of features related to the project which the team felt could be addressed in the future given additional time and funding. Recommendations for enhancing product capabilities include:

1. Design and build a mounting system used to support the individual simulator components within the mannequin.
2. Have a custom piston pump professionally built to ensure lifespan and functionality.
3. Utilize 3D printing to fabricate the exit nozzle to reduce the number of step down valves required and achieve a more accurate exhale velocity.
4. Employ a more accurate control system to regulate the carbon dioxide flow.
5. Incorporate carbon dioxide sensors to ensure accurate CO_2 incorporation.

Testing of the custom piston pump is also highly recommended, as the actual performance of the pump is a theoretical projection and the lifespan is yet to be determined. Construction of a prototype will allow proper testing and fine-tuning of the design to ensure the device fully meets the project specifications.

6. Conclusion

The breathing simulator design project resulted in a specialized system to ensure Price remains at the forefront of the HVAC industry through commitment to research and development. The breathing simulator will allow Price to study the effects of people within a test space by accurately replicating the breathing output and thermal plume of a human being. The breathing simulator design is able to simulate a number of important characteristics of human respiration including flow rate, temperature, CO_2 content and air exit velocity. The breathing simulator project encompasses the following three main features and target specifications related to the physiological criteria in TABLE XI.

TABLE XI: KEY TARGET SPECIFICATIONS OF THE BREATHING MANNEQUIN PROJECT

	Feature	Units	Marginal Value	Ideal Value
1	Exhale Temperature	°C	31-35	33
2	Exhale Velocity	m/s	5-8	6
3	Exhale Carbon Dioxide Content	% PP	3.1-4.1%	3.6%

In addition to accurately simulating human breathing, the system has a weight of less than 27 kg and can be incorporated into a standard sized adult male mannequin or backpack allowing ease of transport between lab rooms. The system is comprised almost entirely of off-the-shelf parts, allowing easy procurement of parts for subsequent systems and maintenance. However, a commercially available pump that could meet the unique specifications needed to ensure proper operation of the simulator was not available, and as a result the team successfully designed a custom piston pump that was able to meet the project specifications. The materials required for manufacturing the breathing simulator system, including control components, cost a total of $2925.57 for a single unit and $2410.22 per unit if 30 units are manufactured. This cost is well under the combined control and materials budget of $7000.

The main function of the breathing simulator is to inhale ambient air and exhale that air with the appropriate physiological characteristics. The ability to inhale and exhale air at the appropriate volume and flow rates characteristic of an average human being, as shown in TABLE I, was accomplished through the careful design of a custom piston pump controlled by an electric motor.

One of the project objectives required the exhaled air temperature to be characteristic of a human. The breathing simulator accomplishes this objective through a heating system consisting of a heating cord wrapped around copper piping, thus transferring heat to the air as it travels towards the exit nozzle. The air temperature is monitored and controlled by means of a temperature regulating system. The piping is insulated to ensure that little heat is lost to the environment and interferes with Price's existing thermal plume simulation.

Another project objective required the breathing system to add the appropriate volume of carbon dioxide to the exhaled air, so that it would be representative of human respiration. The incorporation of carbon dioxide into the exhaled air of the system is accomplished by using a flow meter to control the volumetric flow rate of carbon dioxide into the air. The existing carbon dioxide lines at the test facility will be utilized for the gas supply.

The final functional objective of the simulator involves the discharge of the exhaled air into the test environment at the correct velocity. This objective is accomplished by means of a nozzle which replicating the internal geometry of a human nose. The nozzle directs air out of the system at discharge angles that simulate flow from a nose, allowing effective simulation conditions.

The breathing simulator was required to have a lifespan of 7 to 10 years with minor maintenance. This specification was met for the majority of off-the-shelf parts sourced in the project. However, there was insufficient time in the project to fully construct and test the custom pump; therefore the lifespan and specific maintenance requirements for the pump could not be determined.

TABLE XII below summarizes the nineteen customer needs that were addressed in the breathing simulator project. Included in the table are the details on the target value specifications for the metrics of the project and the actual value achieved in the proposed design. Additional comments describing relevant information pertaining to a particular need are also included.

TABLE XII: HOW CUSTOMER NEEDS WERE MET

Customer Need	Target Value	Marginal Value	Design Value	
			Value	Note
Inhale and exhale at a temperature representative of a human	33 °C	31-35 °C	33 °C	Allowable temperature drift is set by programming of temperature controller.
Inhale and exhale at a flow rate representative of a human	6 L/min, 0.5 L/breath	5-8 L/min, 0.4-0.6 L/breath	6 L/min, 0.5 L/breath	Flow rate may be adjusted up to and 12.5 L/min.

Customer Need	Target Value	Marginal Value	Design Value	
			Value	Note
Exhale with gas composition representative of a human	3.6% Partial Pressure	3.1-4.1%	3.2-4.0%	Injection rate of carbon dioxide is within specification
Humidity of human breath identified	100%	75-100%	n/a	Customer did not want humidity included in project scope.
Overall heat generation of breathing system lower than human body heat production	0 kJ/min	< 0.5 kJ/min	Testing required	Thermo Guard by Thermo-Tec thermal insulation product blocks 90% of radiant heat. Two layers are recommended but exact heat transfer cannot be determined in design phase. More layers of insulation may be added at the customer's discretion if required.
System is able to fit into human mannequin	30 X 20 X 15 cm	45 X 30 X 15 cm	45 X 20 X 15 cm	This size excludes tubing to the nose.
System is affordable in cost	$500*, $5000**	< $2000*, $5000**	$925.45*, $1092.62**	*for standard components. If 30 units are built the unit cost is $430.98 **for measurement devices. If 30 units are built the cost per unit is $870.62
System is compatible with existing gas supply lines	all	most	all	System is compatible with existing ¼" supply lines.
Maintenance of system is easy	2 hours	< 4 hours	N/A	Required maintenance is based on inspection.
Overall system is light weight	23 kg	< 27 kg	5.6 kg	Includes all standard components but not measurement devices.
Easy replacement of worn parts	2 hours	< 4 hours	< 2.5 hours	Expected full assembly time is less than 2.5 hours.
Parts are readily available for purchase	pass	pass	Pass	
System can be assembled with readily available tools	pass	pass	pass	System is able to be assembled utilizing simple hand tools.
System is comprised of long lasting components	10 years	> 7 years	Testing required	Pump life is unknown without physical testing. Purchased components do not specify life expectancy however all suppliers are well-known for quality products.
System can be assembled in-house	20 hours	< 40 hours	2.5 hours	This assembly time does not include any necessary machining time
System can be easily transported	pass	pass	pass	System is lightweight and able to be easily transported by 2 people.
Safe incorporation of CO_2	pass	pass	pass	Incorporation of carbon dioxide in compliance with

Customer Need	Target Value	Marginal Value	Design Value	
			Value	Note
				related codes and standards.
Exhale breath at angle representative of a human	60 ° below horizontal from side, 69 ° from centerline from front	54-66 ° below horizontal from side, 61-77 ° from centerline from front	60 ° below horizontal from side, 69 ° from centerline from front	Rapid prototyped nozzle has exact required angle. Outsourced nozzle angle will depend on mounting within the mannequin. Tubing is flexible to allow for bends.
Thermal plume produced	5 kJ/min	4-6 kJ/min	n/a	Will continue to use existing thermal plume system at Price.

The breathing simulator project resulted in a design for Price Industries capable of meeting the project objectives and fulfilling eighteen of nineteen customer needs that have been established for the project. The completed breathing simulator will provide Price with further understanding as to the effect of human respiration on an indoor environment. As Price Industries continues to be an innovative leader in the HVAC industry, the breathing simulator design will contribute to the ongoing research and development for the creation of industry leading products.

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Appendix A

Concept Generation, Analysis, and Selection

Table of Contents

1. Introduction

The design of the breathing simulation system began with brainstorming and concept generation. In order to select the most appropriate design for the breathing simulation system, Team 7 conducted thorough analysis of the generated concepts using a weighted scoring system. This design process was documented in the Conceptual Design Report, an excerpt from which is included in Section 2 and Section 3.

2. Concept Generation

With the project problem and client needs thoroughly understood and defined, the team was able to come up with some preliminary design concepts. A very open ended brainstorming session produced numerous design ideas from each team member which were reviewed and discussed. There was limited research into external sources for ideas, as there are no known competitor products which relate to the desired product design of a breathing, thermal mannequin. Additionally, patents were reviewed for concepts similar to those in our project, but no patents were found that were directly applicable to our project. The patents that were found relate to either individual system components, or to very complex and detailed cardio-pulmonary systems for use in the medical industry.

Codes and standards were also reviewed by the team, to ensure that designs would be evaluated with those standards in mind. One specific standard that needs to be followed is ASHRAE 62_1_2004, which provides guidelines governing indoor air quality. This standard will be followed to ensure safe levels of carbon dioxide within the test simulation room are maintained. The Handbook of Compressed Gases published by the Compressed Gas Association contains standard and code information pertaining to compressed carbon dioxide gas. This handbook will give insight to the regulation regarding standards and codes as they apply directly to the physical incorporation of compressed carbon dioxide into the design.

In order to develop design concepts, the product design was broken down into five major sections, with the means of air movement simulating the 'breathing' being the first sectional division. The source of and the point of injection of carbon dioxide into the system were determined to be the second and third sections respectively. The means of elevating and moderating the temperature of the 'exhaled' air was identified as a fourth section and, finally, the production of heat from the mannequin itself to simulate human body heat categorized the final section of the product design. The team's design ideas were grouped into these five categories and the key features of all ideas were discussed. From this stage, analysis techniques based on criteria generated by the team and client were used to select the 'best' design concept to pursue for the final product design.

2.1. Flow Rate Generation

In order to create the inhaling and exhaling phenomenon associated with breathing, the team narrowed down brainstorming results to six of the top design ideas which would have the potential to move air as desired. As a result of the customer requesting that readily available parts be utilized in the design, the team explored five different common types of pumps as methods of creating the flow rate. Customer needs that apply to this design component include accurate breathing flow rate and discrete inhale and exhale breaths. The six designs include a single acting piston pump, a double action piston pump, a 'bellows' design, an electronically controlled pressurized air system, a lobe or screw pump and lastly, a fan.

(1A) Single Acting Piston Pump

The initial design considered is a single-acting piston pump, in which a reciprocating piston is used to draw a fluid through a one way valve and force the fluid out through an outlet pipe [1]. As the piston draws back and increases the available volume of the cylinder, suction is created, and as the piston pushes forward, decreasing the available volume of the cylinder, delivery is created. A single acting piston pump has fluid in contact with only one side of the piston and as such there is one suction and one delivery stroke per cycle of the piston. Because there is only one suction and delivery stroke per cycle, the flow is discontinuous with discrete suction and delivery. The volume of each stroke is determined by the volume of the cylinder cavity and the total volume flow rate can be adjusted by increasing or decreasing the speed of the piston.

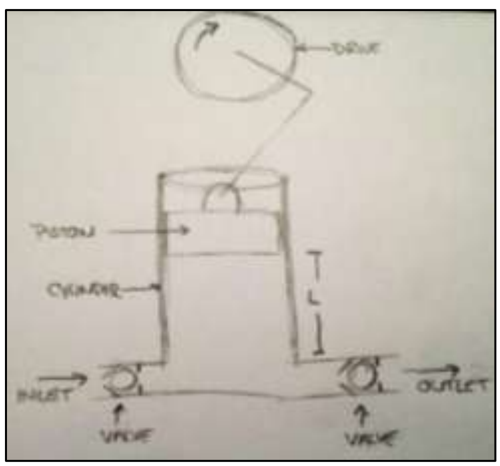

Figure 1: Single acting piston pump [2]

(1B) Double Acting Piston Pump

The double acting piston pump is very similar to the single acting; however, in this design, there is fluid in contact with both sides of the piston. Because there is fluid in contact with both sides of the piston there are two suction and two delivery strokes per cycle of the piston [1]. As fluid is drawn into the cylinder on one side of the piston, it is forced out on the other side, resulting in continuous flow. Like the single acting piston pump, the volume of each stroke is determined by the volume of the cylinder, and the total flow rate can be adjusted by adjusting the speed of the piston.

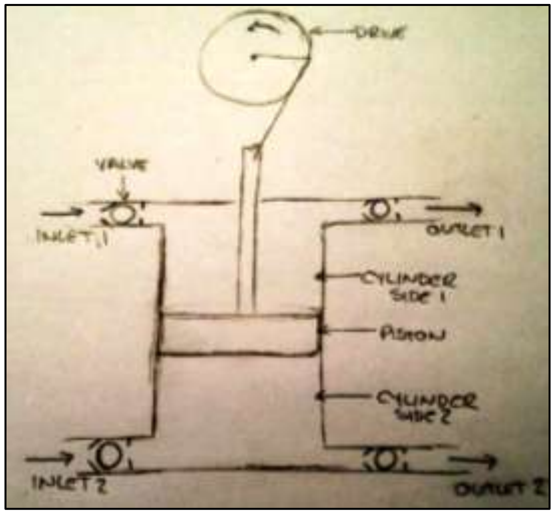

Figure 2: Double acting piston pump [3]

<u>(1C) Bellows Pump</u>

A bellows pump functions on the same principle as a single acting piston pump. A driving rod, used to create a reciprocating motion, is coupled to a bellows cavity that moves fluid through the expansion and collapse of the bellows cavity [4]. As the cavity expands, fluid is drawn in through the inlet valve, and as the cavity is collapsed the fluid is forced out through the outlet valve. Like the single acting piston pump, there is only one suction stroke and one delivery stroke per cycle of the driving rod, thus flow is discontinuous. Also, the volume of each stroke is determined by the volume of the bellows cavity, and the total volume flow rate can be adjusted by adjusting the speed of the driving rod.

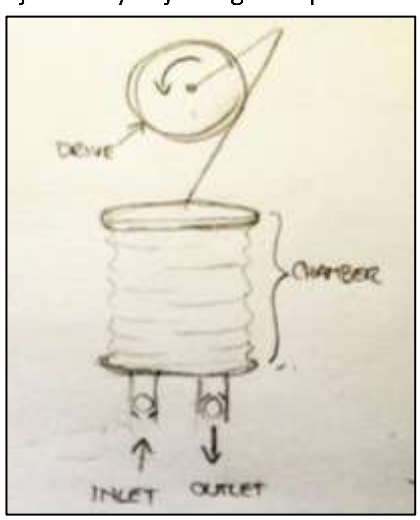

Figure 3: Bellows pump

[5]

(1D) Electronic Pump System

The electronic pump system, illustrated in Figure 4 features a standard air pump which constantly produces air pressure. The inlet to the pump pulls ambient air in from the room through the 'inhale' air nozzle, while the outlet of the pump is connected to a series of airlines eventually leading to the 'exhale' air nozzle. The air pressure out of the pump is regulated to the appropriate exhale conditions via a pressure regulator. The key design feature in this option is electronically controlled solenoid valves which actuate at specific intervals to allow a certain amount of air to pass through, dependent upon desired flow rate. A solenoid valve would be located before the pump inlet to control inhale characteristics, and another at the exhale point to control exhale characteristics. Advantages of this system include a high level of control in the system, potentially great accuracy, and a range of adjustability; however, it is likely that cost and complexity will be high. In the event of a system failure, this design could be more difficult to troubleshoot than other proposed ideas.

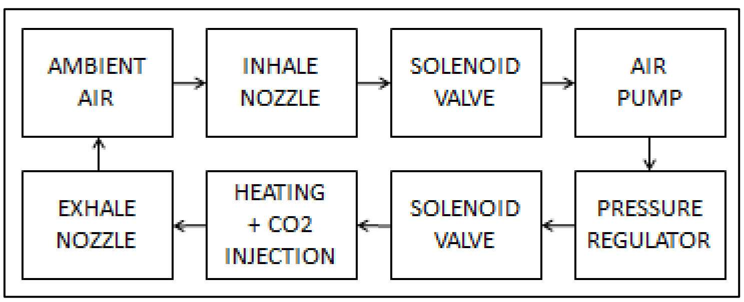

Figure 4: Electronically controlled flow rate design schematic [6]

(1E) Lobe Pump

Lobe pumps or gear pumps consist of two lobes enclosed within a tightly fitted housing. As the lobes rotate, a gap between the lobes forms creating a vacuum at the entrance to the pump that draws fluid in. The fluid is transported to the exhaust port between the lobes and the housing wall. As the lobes mesh together again, the fluid is forced out through the outlet port [7]. Due to the continual movement of the lobes, this type of pump creates continuous flow that can be adjusted by increasing or decreasing the speed of rotation of the lobes.

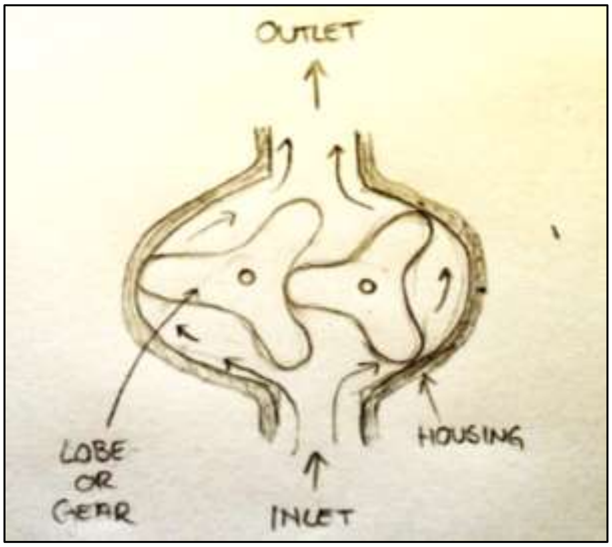

Figure 5: Lobe pump [8]

(1F) Fan

Axial flow fans or axial flow pumps consist of a propeller and a rotor. The rotation of the propeller draws in fluid on one side of the propeller, parallel to the driving shaft, and throws the air on the other side of the propeller, also parallel to the shaft [9]. This type of pump or fan creates continuous flow due to the continuous rotation of the propeller, and the volume flow rate can be adjusted by adjusting the speed and size of the propeller.

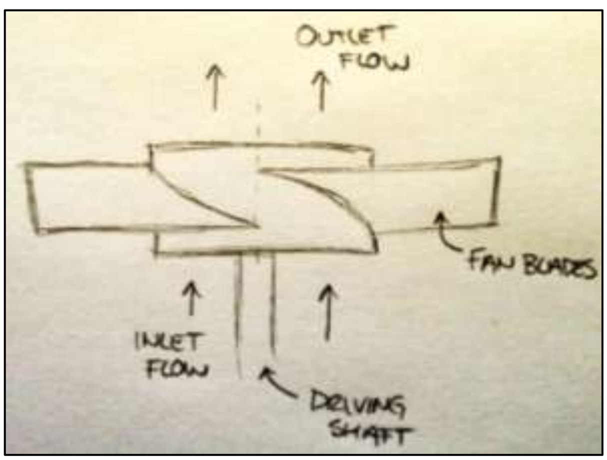

Figure 6: Axial flow fan [10]

Summary of Flow Rate Design Concepts

In summary, all design options proposed by team members in order to achieve the required breathing flow rate are summarized in TABLE I. Key features of each of these design options are also identified.

TABLE I: FLOW RATE DESIGN CONCEPTS

Number	Concept	Key Features
1A	Single Acting Piston Pump	-Piston pump powered by electric motor -adjustable speed -fixed volume -discrete inhale and exhale -Large size
1B	Double Acting Piston Pump	-Piston pump powered by electric motor -adjustable speed -fixed volume -Continuous inhale and exhale -Large size
1C	Bellows	-Discrete inhale and exhale -Able to seal -Powered by electric motor -Large size -One way valves for inhale and exhale
1D	Electronic pump system	-Suction for inhale -regulated pressure for exhale -electronically controlled timing of inhale and exhale -Discrete inhale and exhale
1E	Lobe pump or screw pump	-Powered by electric motor -adjustable speed and volume -continuous inhale and exhale
1F	Fan	-Powered by electric motor -continuous inhale and exhale -adjustable speed and flow rate -small size

As functionality and accuracy, are the most important customer needs for the design, some of these concepts will prove to be more promising than others if they are able to achieve all functional requirements in terms of breathing flow rate. However, the team will need to conduct more in-depth analysis and consider additional criteria such as cost and weight in order to select the best design concept for achieving the breathing flow rate.

2.2. CO_2 Source

As the product must incorporate carbon dioxide in the exhaled breath, the source of the carbon dioxide was considered as another section of the design. The source of the CO_2 is an important part of the final design as it will affect the size, weight and portability of the finalized design. The team agreed on two main sources that were most practical for meeting our customer's needs: carbon dioxide canisters or hooking up to the existing carbon dioxide airlines at Price. These design options are described in more depth in order to fully evaluate each option.

(2A) Carbon Dioxide Canisters

Canisters were suggested due to their ease of access and portability. When one canister runs out, it would simply be replaced and refilled. This leads to very short set up times as well as very easy maintenance. However, the canisters would have to be contained within the breathing apparatus itself, which would add considerable weight and, given that the tests are expected to run as long as 36 hours, finding a canister that would have enough CO_2 capacity may prove difficult.

(2B) Hook Up to Existing Airlines

The Northern Research Center at Price Industries has CO_2 supply lines built into the facilities' infrastructure. This provides a near unlimited supply of CO_2 at regulated pressure levels for an unlimited period of time. Unlike the canister concept, the CO_2 is generated outside of the breathing apparatus and piped in. This piping brings up additional design challenges, as the supply piping must be insulated to prevent it from affecting ongoing tests, and the breathing apparatus must use appropriate connectors to interface with the CO_2 supply lines.

Carbon Dioxide Source Summary

A summary of each design concept for sourcing carbon dioxide is shown in TABLE II along with the key design features of each.

TABLE II: DESIGN OPTIONS FOR CARBON DIOXIDE SOURCE

Number	Concept	Key Features
2A	Canisters	-Must be refilled -Large size -Increased safety concerns -More portable -Heavier
2B	Existing Airline at Price	-Inexpensive -Unlimited supply -Suggest by the client

It can be seen that concept 2B, using the existing airlines at Price to supply carbon dioxide to the design, has the most advantages associated with it. Further analysis using various criteria will be performed to confirm this is the top design selection.

2.3. CO_2 Injection Point

In addition to sourcing the carbon dioxide, the point of injection into the system was another element to consider in the product design. The team determined there were three possibilities for when to introduce the carbon dioxide into the system, as shown in TABLE III, including injection into the inhaled air, or into the exhaled air before or after heating. Features of each of these options were discussed by the team.

(3A) Injection on Inhale

This design concept involves CO_2 injected into the airstream on the inhale portion of the breath. This CO_2-Air mixture would then be transported through a tubing system into the heating apparatus where the mixture would be heated to the appropriate temperature for an average human exhalation. The mixture would then be pumped out, simulating a human exhale. The injection point is shown in Figure 7.

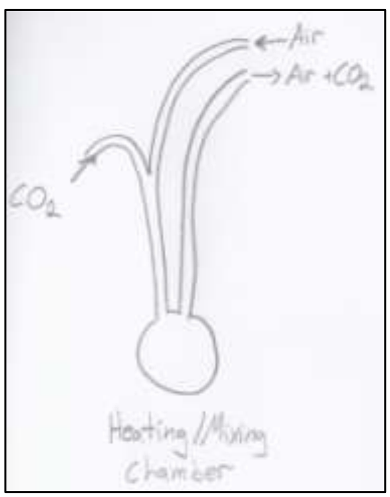

Figure 7: CO2 injection on inhale [12]

(3B) Injection on Exhale Prior to Heating

This design concept involves CO_2 injected into the airstream after the inhale had taken place, yet prior to heating. This concept is very similar to the first in terms of how the CO_2 mixes with the air inhaled, however, there is less time for the mixture to reach a steady temperature which would make heating the mixture a more difficult task. Injection point is shown in Figure 8.

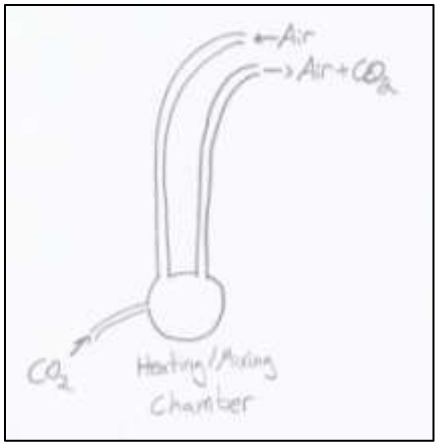

Figure 8: CO_2 injection on exhale, prior to heating [13]

(3C) Injection on Exhale Post Heating

This concept involves the CO_2 injected into a pre heated airstream. This method would require that the air be heated beyond the average exhale temperature, as the CO_2 would most likely be cooler than the average exhale temperature, and mixing the two would result in a temperature drop. Injection Point is shown in Figure 9.

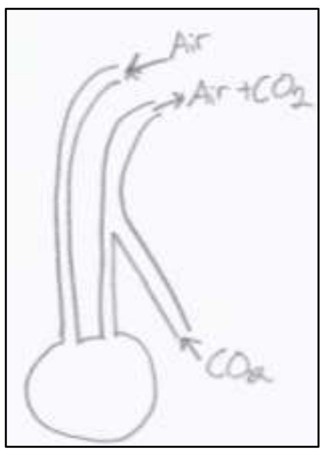

Figure 9: CO2 injection on exhale, after heating [14]

Summary of Carbon Dioxide Injection Point Options

Shown in TABLE III are the possible options of when to introduce carbon dioxide into the design to achieve appropriate exhale conditions.

TABLE III: DESIGN OPTIONS FOR CARBON DIOXIDE INJECTION POINT

Number	Concept	Key Features
3A	On inhale	-Better mixing -Heated
3B	On exhale prior to heating	-Heated
3C	On exhale after heating	-Not heated, may effect exhale temperature

At this stage of the design process, it remains unclear which of the three suggested design concepts will best suit our product design. More in-depth analysis will be used to rank concepts 3A, 3B and 3C and determine which will best meet our design requirements.

2.4. Exhale Temperature

In order to meet the requirement to have the exhaled air at a temperature representative of a human breath, the team needed to come up with a method of heating and/or regulating the temperature of the exhaled air. Five ideas were evaluated, including using a heat exchanger, heat tape, heat wire, an oven or using the by-product heat produced by the pump if the team were to select a pump to achieve the flow rate requirement. A more detailed explanation of each of the temperature simulation concepts will be presented below. It should also be noted that currently it is assumed that the ambient air temperature of the inhaled air will be less than the accepted T value of human exhale, generally found to be 33^{o}C [11].

(4A) Heat Exchanger

The heat exchanger concept involves having the inhaled air pass over a radiator type heat exchanger in which a warm working fluid is traveling through a system of tubes or fins. This warmer fluid is then able to transfer heat energy to the colder inhaled air as it contacts the surface of the heat exchanger. The heat exchanger concept is depicted in Figure 10 below. This concept is similar to what one would expect to employ for an automobile radiator or a household refrigerator.

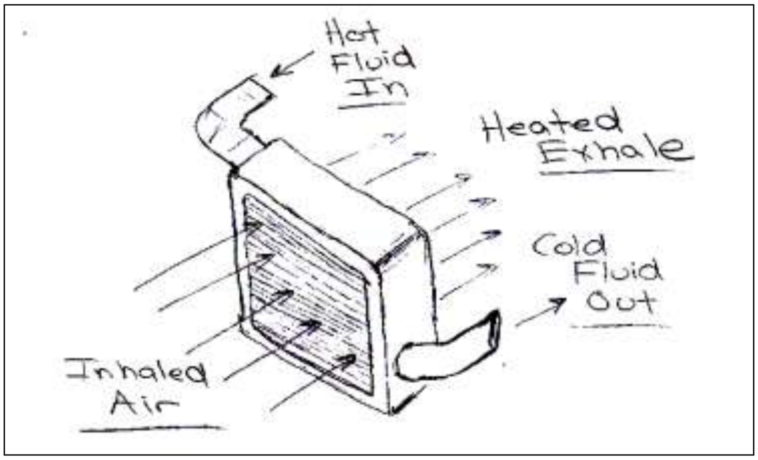

Figure 10: Heat Exchanger Concept [15]

(4B) Heat Tape

This concept involves having the inhaled air pass through a section of piping that is wrapped in a heated tape. The heat tape is to be wrapped around the piping/hose, allowing thermal energy to be transferred to the inhaled air before it is exhaled out of the simulator. The heat tape concept to raise the temperature of the exhaled air is shown in Figure 11 below. It will likely also be necessary to insulate the piping in order to reduce any heating losses, as well as ensure no heat is escaping into the surrounding environment, which could negatively impact the simulation.

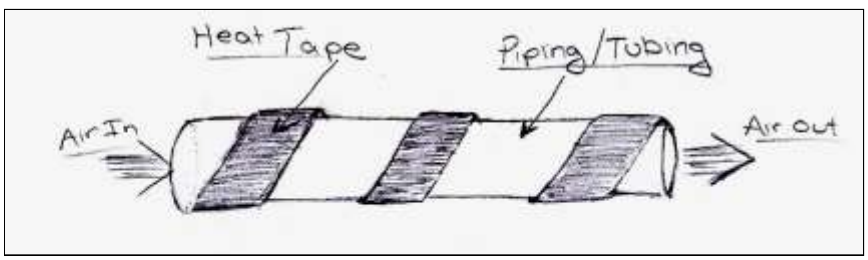

Figure 11: Heat Tape Concept [16]

(4C) Heat Wire

The heated wire concept involves a method of heating the inhaled air similar to utilizing the heated tape concept. The wire must have an internal resistance, and if the wire is allowed to carry electrical current, the internal resistance within the wire will produce heat. The strand of heated wire will be placed within the piping used for the inhaled air as shown in Figure 12. As the inhaled air travels through the breathing system it will be heated through the thermal energy transferred to it by the heated wire.

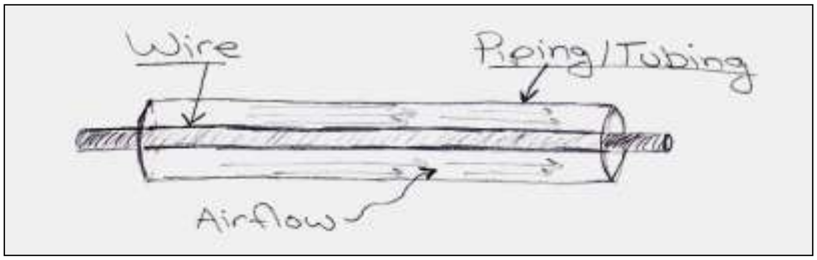

Figure 12: Heated Wire Concept [17]

(4D) Oven

The heating element concept is another way the breathing simulator could achieve the desired exhale temperature. This concept involves having a heating element placed within an insulated space. The inhaled air will travel into the device containing the heating element whereby the heating element will transfer thermal energy to the air, and the heated air is then able to be exhaled by the simulator. There will likely also be some type of mixing device needed to keep the air in the oven at a uniform temperature, as it is not known whether free convection alone will accomplish this even distribution. This concept is similar to what one would find in a household convection oven, and is depicted in Figure 13: Heating Coil (Oven) Concept.

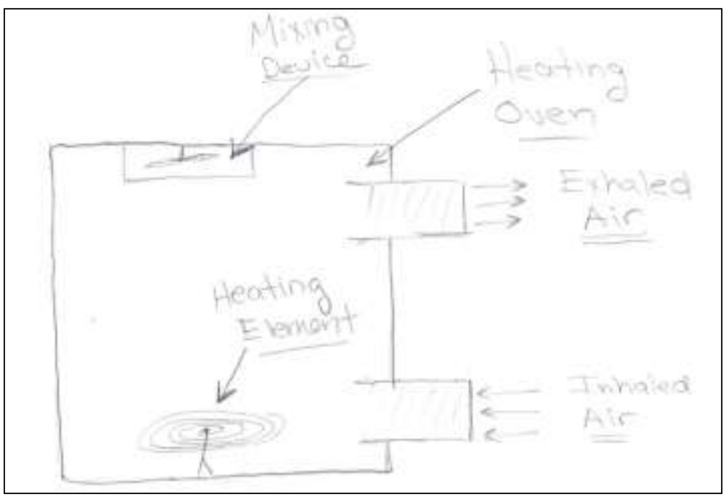

Figure 13: Heating Coil (Oven) Concept [18]

(4E) Capture Waste Heat from Pumping Device

The final concept for producing the desired exhaled air temperature from the breathing simulator involves utilizing any heat generated by the breathing simulator system and transferring this energy to the inhaled air. The simulator components would have to be encased by an insulating material(s), and the inhaled air would be passed through the encased area. The air would either be circulated in direct contact with the simulator components or circulated through the insulated space through a network of pipes or hoses.

Summary of Exhale Air Heating Design Concepts

The design concepts associated with producing a desired exhale air temperature are summarized in TABLE IV along with the key features of each.

TABLE IV: EXHALED AIR HEATING DESIGN CONCEPTS

Number	Concept	Key Features
4A	Heat exchanger (water)	-Large size -Heavy -Easy to control temperature
4B	Heat Tape	-Small size -inexpensive -decreased reliability -consistency may vary based on set up
4C	Heat Wire	-Small size -inexpensive -decreased reliability -consistency may vary based on set up
4D	Oven	-Heating element -fan to circulate air -easy to control temperature -difficult to source
4E	Heat from pump	-may not be enough heat -not adjustable -inexpensive -simplifies system

The most expensive design concepts appear to be the heat exchanger and potentially the oven; however, these ideas may offer a greater degree of accuracy and control. A negative aspect of the heat exchanger is the need for a second 'heating' fluid, which adds more complexity to the design. Going forward, more in-depth analysis using specific criteria must be performed to isolate the most promising design concept from this selection in order to achieve exhale air temperature.

2.5. Body Temperature

The last section of the design concept relates to the thermal plume requirement for the design. The mannequins must have the ability to replicate body heat production similar to a human being. The team decided the options were to use the by-product heat produced by the components in the breathing system, add a heat-releasing tape purchased as an off-the-shelf component or use a combination of each to generate the thermal plume.

(5A) Capture Heat from Breathing System

An option discussed by the team was to take advantage of the heat waste generated from the mechanical components used in the breathing system and consider this the thermal plume. Advantages of this idea include weight and costs are kept to an absolute minimum in that no additional parts are needed. Disadvantages include the fact that the heat plume would not only be difficult to control but would most likely change intensity as running time or component life increased. This would make the system unreliable and inconsistent. The system may not even be capable to produce the heat requirements and therefore it is given a poor outlook as a design option.

(5B) Capture Heat from Breathing System in Addition to Heat Tape

In the event that the breathing apparatus is able to produce some heat but needs an additional source to meet the customer requirements, heat tape combined with this waste heat from the breathing system is an option for the thermal plume of the mannequin. Advantages to this design are again lower cost and weight since potentially a lesser amount of heat tape would be used than the final design option. However, although it is theoretically possible to achieve the appropriate heat plume values with this design method, the consistency is again in question as this option is subject to the changing heat energy produced by the breathing system components which cannot be guaranteed to remain constant.

(5C) Heat Tape Only

The third concept considered by the team was to use heat tape as the only method of heat generation for the thermal plume. Disadvantages to this option in comparison to the previous two are additional weight and cost due to more tape being used. There is also the possibility of needing to purchase insulating materials for the breathing system to ensure any heat produced from the components do not offset the desired heat energy values produced by the tape. The customer is already using a similar design in their testing laboratories to generate body heat from mannequins and is satisfied with the performance so this was seen as a positive design consideration. The heat tape is regarded as a highly accurate and controllable method of generating the thermal plume.

Summary of Thermal Plume Design Concepts

Each idea for producing the mannequin thermal plume is described in TABLE V along with a summary of the key features of each suggestion.

TABLE V: BODY HEAT DESIGN CONCEPTS

Number	Concept	Key Features
5A	Use heat from breathing system	-Efficient -inexpensive -may not be the right temperature
5B	Use heat from breathing system with additional heat tape	-Efficient -inexpensive -adjustable?
5C	Insulate breathing system and use heat tape	-Requires insulation (increased weight and cost) -Highly controllable

It is apparent that design suggestions 5A and 5B could be too difficult to regulate and may not satisfy customer requirements. Option 5C, heat tape only and insulation of the breathing system components, will offer the most benefits in terms of accuracy of heat production, however it could be heavier and more costly. Additionally, insulation of the breathing system could prove to be tricky and add complexity to setup and maintenance requirements.

3. Concept Selection and Analysis

After generating numerous design concepts for each of the five design components discussed in the previous section, the team was able to move on to concept analysis and selection. In order to select the best concept for each design component, selection criteria were set out for evaluating the design concepts.

Using the selection criteria set out by the team and the client, the concepts generated in section two were compared to each other in a concept screening matrix. The concept screening matrix was used to eliminate some less promising designs before conducting more extensive analysis. The designs that were not eliminated in the concept screening matrix were then analysed using a weighted scoring table to choose the final design that would be pursued by the team. The concept screening matrixes and concept weighted scoring tables are discussed in section 3.1 and 3.3 respectively, and are followed by a final design summary in section 3.4.

The selection criteria that the team generated for evaluation of design components are set out in TABLE VI below. The selection criteria are based on customer needs and qualities that are necessary for optimal performance of the final design.

TABLE VI: DESIGN COMPONENTS AND APPLICABLE SELECTION CRITERIA

Design Component	Selection Criteria
Flow Rate	• Accuracy (of flow rate) • Ability to produce discrete breaths • Adjustability (speed and volume) • Size • Weight • Cost • Manufacturability • Availability of parts
CO_2 Source	• Safety • Cost • Weight • Size • Convenience • Maintenance Level • Temperature of gas
CO_2 Injection Point	• Accuracy (of exhale temperature) • Packaging • Mixing (of CO_2 with exhale)

Design Component	Selection Criteria
Exhale Temperature	• Accuracy (of temperature) • Reliability • Availability of parts • Packaging • Manufacturability • Consistency • Adjustability • Cost • Weight • Size
Body Temperature	• Accuracy (of body temperature) • Cost • Size • Weight • Adjustability

The selection criteria mentioned in TABLE VI in some cases apply to more than one design component. TABLE VII shows the customer needs that each selection criterion applies to and the justification for those criteria.

TABLE VII: SELECTION CRITIERIA JUSTIFICATION

Selection Criteria	Relevant Need	Justification
Accuracy	• Inhale and exhale at temperature representative of human breath • Inhale and exhale flow rate representative of human breath • Exhale gas composition representative of human breath • Thermal plume representative of a human being	Accuracy is very important to the design as it is necessary that the mannequin be able to produce accurate human breathing and thermal qualities and will be able to produce correct test results
Ability to produce discrete breaths	• Inhale and exhale at a flow rate representative of human breath	The ability to produce discrete breaths will help create a more accurate representation of actual human breath
Adjustability	• N/A	An adjustable design will be able to produce a greater range of simulation conditions, and will allow the system to be adjusted to achieve accurate human breathing and thermal qualities
Availability of parts	• Worn parts can be replaced easily • Readily available parts can be used for assembly	Incorporating readily available parts in the design will ensure that parts can be replaced easily and will eliminate any machining costs associated with

Selection Criteria	Relevant Need	Justification
		custom parts
Cost	• System is affordable in cost	The client proposed a $2000 budget, thus low cost is considered an asset
Manufacturability	• System can be assembled in house • Readily available tools can be used for assembly	The breathing thermal mannequin will be produced in small numbers; therefore easy assembly that does not require any custom tooling is beneficial
Size	• System can be easily transported • System fits into a human mannequin	The breathing system must fit within a standard size mannequin, thus smaller designs are preferred
Weight	• System is light in weight • System can be easily transported	To increase the ease of transporting mannequins between lab rooms lightweight designs are preferred
Safety	• Safe incorporation of CO_2 in exhaled breath	CO_2 use must comply with relevant codes and standards
Compliance with existing infrastructure	• Should work with existing infrastructure	The client requested that the breathing system be compatible with the existing CO_2 infrastructure in the lab
Maintenance Level	• Maintenance of system is easy • Worn parts are easily replaced • System is comprised of long lasting components • System can be assembled in house • Readily available tools can be used for assembly	Low levels of maintenance, and easy to perform maintenance (easy access to, removal of, and installation of components) are ideal as it will keep cost low and decrease downtime of the machine.
Temperature of Gas	• Inhale and exhale temperature representative of a human	Warm or neutral temperatures of CO_2 gas prior to injection into the system are preferred as the gas will not require as much heating
Packaging	• System fits into a human mannequin • Maintenance of system is easy • Safe incorporation of CO_2 in exhaled breath	Packaging that promotes easy installation and serviceability within the mannequin is preferred, especially the CO_2 injection point
Mixing	• Exhale gas composition representative of a human	Increased mixing of CO_2 gas with the rest of the exhale breath will increase the accuracy of the CO_2 content
Reliability	• System is comprised of long lasting components	High reliability will decrease downtime of the breathing system and decrease the amount of maintenance required
Consistency	• N/A	Consistency is an important quality so that all mannequins produce similar results and test results are consistent with each other

3.1. Preliminary Concept Screening

In the preliminary concept screening phase, concept screening matricies were used to determine which design concepts deserved further investigation and eliminate design concepts that did not.

The screening matricies compare design concepts based on the selection criteria to one reference concept which is assigned a score of zero for all selection criteria. The most intuitive designs are chosen as the reference concepts and the remaining design concepts are given a score of 1, 0, or -1 for each selection criteria based on whether it is meets that criteria better, the same, or worse than the reference concept. Concepts are then ranked based on the scores that they were given; more positive scores receive a higher rank. Designs that were ranked 1, 2, or 3 in the concept screening moved on to detailed design analysis.

The following five tables, TABLE VIII through TABLE XII, are the concept screening matricies for the five design components. Concepts marked with a "yes" in the "Continue?" row of each matrix are further analysed in section 3.3 of the report with a weighted scoring matrix.

TABLE VIII: FLOW RATE GENERATION CONCEPT SCREENING

		CONCEPT VARIANTS						
SELECTION CRITERIA		1A	1B	1C	1D	1E	1F	REF. (1A)
Accuracy		0	0	1	1	-1	-1	0
Ability to Produce Discrete Breaths		0	-1	0	0	-1	-1	0
Adjustability		0	0	0	1	0	1	0
Size		0	0	0	-1	0	1	0
Weight		0	0	1	-1	0	1	0
Cost		0	-1	0	-1	0	1	0
Manufacturability		0	0	0	0	0	-1	0
Availability of Parts		0	0	-1	1	0	1	0
TOTAL	1	0	0	2	3	0	5	
TOTAL	0	8	6	5	2	6	0	
TOTAL	-1	0	2	1	3	2	3	
NET		0	-2	1	0	-2	2	
RANK		3	5	2	3	5	1	
CONTINUE?		YES	NO	YES	YES	NO	YES	

Based on the concept screening shown in TABLE VIII, concepts 1B, the double acting piston pump, and 1E, the lobe pump, were eliminated.

TABLE IX: CO_2 SOURCE CONCEPT SCREENING

		CONCEPT VARIANTS		
SELECTION CRITERIA		2A	2B	REF. (2A)
Safety		0	1	0
Cost		0	1	0
Weight		0	1	0
Size		0	1	0
Compliance with existing Infrastructure		0	1	0
Maintenance		0	1	0
Temperature of Gas		0	1	0
TOTAL	1	0	7	
TOTAL	0	7	0	
TOTAL	-1	0	0	
NET		0	7	
RANK		2	1	
CONTINUE?		YES	YES	

Because there are only two concepts to consider for the CO_2 source, both concepts were passed through the concept screening stage and on to the detailed analysis.

TABLE X: CO_2 INJECTION POINT CONCEPT SCREENING

		CONCEPT VARIANTS			
SELECTION CRITERIA		3A	3B	3C	REF. (3A)
Accuracy of exhale temperature		0	0	-1	0
Packaging		0	0	0	0
Manufacturing		0	0	0	0
Mixing		0	-1	-1	0
TOTAL	1	0	0	0	
TOTAL	0	4	3	2	
TOTAL	-1	0	1	2	
NET		0	-1	-2	
RANK		1	2	3	
CONTINUE?		YES	YES	YES	

Because there are only three options to consider for the CO_2 injection point, all three concepts passed through the screening and onto the detailed analysis.

TABLE XI: TEMPERATURE OF BREATH CONCEPT SCREENING

SELECTION CRITERIA	CONCEPT VARIANTS 4A	4B	4C	4D	4E	REF. (4A)
Accuracy	0	-1	-1	0	-1	0
Reliability	0	-1	-1	0	-1	0
Availability of parts	0	1	1	0	0	0
packaging	0	1	1	0	-1	0
Manufacturability	0	0	0	1	-1	0
Adjustability	0	-1	-1	0	-1	0
Cost	0	1	1	1	1	0
Weight	0	1	1	0	1	0
Consistency	0	-1	-1	0	-1	0
Size	0	1	1	0	1	0
TOTAL 1	0	5	5	2	3	
TOTAL 0	10	1	1	8	1	
TOTAL -1	0	4	4	0	6	
NET	0	1	1	2	-3	
RANK	4	2	2	1	5	
CONTINUE?	NO	YES	YES	YES	NO	

As shown in TABLE XI, two concepts were eliminated from the temperature of breath design component. The eliminated concepts are 4A, heat exchanger and 4E, residual heat from pump.

TABLE XII: BODY TEMPERATURE CONCEPT SCREENING

SELECTION CRITERIA	CONCEPT VARIANTS 5A	5B	5C	REF. (5B)
Accuracy	-1	0	1	0
Cost	1	0	-1	0
Size	1	0	-1	0
Weight	1	0	-1	0
Adjustability	-1	0	1	0
TOTAL 1	3	0	2	
TOTAL 0	0	5	0	
TOTAL -1	2	0	3	
NET	1	0	-1	
RANK	1	2	3	
CONTINUE?	YES	YES	YES	

Finally, within the body temperature design component no concepts were eliminated during concept screening.

3.2. Weighted Criteria

After the preliminary concept screening had taken place, it was necessary to conduct more thorough analysis of the remaining designs. This analysis was conducted through weighted scoring of design concepts. Before designs were given scores for each selection criteria, criteria weighting was performed by the team in conjunction with the client to ensure that their needs would be fully met. Criteria weighting is important as it gives insight into which criteria are more important to meet and allows that to be taken into account while scoring design concepts. To determine the weight that each selection criteria should carry, a 1-to-1 comparison of importance between each criterion was carried out in a criteria weighting matrix. The number of appearances of each criterion within the matrix, or number of hits, was added up and used to determine the weight for that criterion. A summary of the number of hits and the calculated weight for each selection criteria is located at the bottom of each criteria matrix. Additionally, sensitivity analysis was carried out by the team to ensure that small changes in the criteria weighting matricies would not drastically affect the results of the weighted scores.

TABLE XIII, TABLE XIV, TABLE XV, TABLE XVI, and TABLE XVII below show the criteria weighting for flow rate generation, CO_2 source, CO_2 injection point, exhale temperature, and body temperature respectively.

TABLE XIII: FLOW RATE GENERATION CRITERIA WEIGHTING

FLOW RATE GENERATION Criteria	Accuracy A	Ability to produce discrete breaths B	Adjustability C	Size D	Weight E	Cost F	Manufacturability G	Availability of Parts H
A Accuracy		A	A	A	A	A	G	A
B Ability to produce discrete breaths			B	B	B	B	G	B
C Adjustability				D	E	F	G	H
D Size					D	D	G	H
E Weight						E	G	H
F Cost							G	H
G Manufacturability								G
H Availability of Parts								

Total Hits	6	5	0	3	2	1	7	4
Weightings	0.21	0.18	0.00	0.11	0.07	0.04	0.25	0.14

TABLE XIV: CO_2 SOURCE CRITERIA WEIGHTING

CO_2 SOURCE	Safety	Cost	Weight	Size	Compliance with Existing Infrastructure	Temperature of Gas	Maintenance Level
Criteria	A	B	C	D	E	F	G
A Safety		A	A	A	A	A	A
B Cost			C	D	B	F	G
C Weight				D	C	F	G
D Size					D	F	G
E Compliance with Existing Infrastructure						F	G
F Temperature of Gas							F
G Maintenance Level							

Total Hits	6	1	2	3	0	5	4
Weightings	0.29	0.05	0.10	0.14	0.00	0.24	0.19

TABLE XV: CO_2 INJECTION POINT CRITERIA WEIGHTING

CO_2 INJECTION POINT		Accuracy of Temperature	Packaging	Manufacturability	Risk of Leakage	Mixing Of Additional Gasses
Criteria		A	B	C	D	E
A	Accuracy of Temperature		A	C	D	A
B	Packaging			C	D	E
C	Manufacturability				C	C
D	Risk of Leakage					D
E	Mixing Of Additional Gasses					

Total Hits	2	0	4	3	1
Weightings	0.20	0.00	0.40	0.30	0.10

TABLE XVI: EXHALE TEMPERATURE CRITERIA WEIGHTING

EXHALE TEMPERATURE	Accuracy of Temperature	Reliability	Availability of Parts	Packaging	Manufacturability	Consistency	Adjustability	Cost	Weight	Size
Criteria	A	B	C	D	E	F	G	H	I	J
A Accuracy of Temperature		A	A	A	E	A	A	A	A	A
B Reliability			B	B	E	F	B	B	B	B
C Availability of Parts				C	E	F	F	C	C	C
D Packaging					E	F	D	H	D	D
E Manufacturability						E	E	E	E	E
F Consistency							F	F	F	F
G Adjustability								H	I	J
H Cost									I	J
I Weight										J
J Size										

Total Hits	8	6	4	3	9	8	0	2	2	3
Weightings	0.18	0.13	0.09	0.07	0.20	0.18	0.00	0.04	0.04	0.07

TABLE XVII: BODY TEMPERATURE CRITERIA WEIGHTING

BODY TEMPERATURE	Accuracy	Cost	Size	Weight	Adjustability
Criteria	A	B	C	D	E
A Accuracy		A	A	A	A
B Cost			C	D	B
C Size				C	C
D Weight					D
E Adjustability					

Total Hits	4	1	3	2	0
Weightings	0.40	0.10	0.30	0.20	0.00

In summary, for the flow rate generation component manufacturability and accuracy are the most heavily weighted criteria. With respect to the CO_2 source, safety and the temperature of the gas entering the system are the main concerns. The most heavily weighted criteria for CO_2 injection point are manufacturability and risk of CO_2 leaks. The main concerns for exhale temperature are manufactuability, accuracy of temperature, and consistency. Finally, the most prevalent selection criteria for body temperature are accuracy and size.

3.3. Weighted Concept Scores

To determine the best design, scores on a scale of one to five were assigned to each design for each selection criterion. These scores were then multiplied by the criteria weight, determined in the previous section, to obtain a weighted score that represents the score and the importance of that score. Each design component was then assigned a rank based on the sum of its weighted scores. Higher scores are preferred, thus concepts with the highest total score were chosen to be pursued in the final design.

TABLE XVIII shows the weighted scores for the flow rate generation design concepts. The single-acting piston pump was chosen as the final design with a total score of 4.14, compared to the second place design which received a weighted score of 3.64.

TABLE XVIII: FLOW RATE GENERATION WEIGHTED SCORES

FLOW RATE GENERATION									
		Single Acting Piston Pump (1A)		Bellows (1C)		2 Pump (1D)		Fan (1F)	
Criteria	**Weight**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**
Accuracy	0.21	4	0.86	4	0.86	5	1.07	1	0.21
Ability to produce discrete breaths	0.18	5	0.89	5	0.89	5	0.89	1	0.18
Adjustability	0.00	1	0.00	1	0.00	5	0.00	5	0.00
Size	0.11	3	0.32	3	0.32	2	0.21	4	0.43
Weight	0.07	3	0.21	3	0.21	2	0.14	4	0.29
Cost	0.04	4	0.14	2	0.07	1	0.04	5	0.18
Manufacturability	0.25	4	1.00	4	1.00	2	0.50	4	1.00
Availability of Parts	0.14	5	0.71	2	0.29	4	0.57	5	0.71
	Total	4.14		3.64		3.43		3.00	
	Rank	1		2		3		4	
	Continue?	YES		NO		NO		NO	

As shown in TABLE XIX, use of the existing airlines is the ideal design choice for the CO_2 source. It is clearly the best design with a score of 4.29 compared to 2.67 for CO_2 canisters.

TABLE XIX: CO_2 SOURCE WEIGHTED SCORES

CO_2 SOURCE					
		Canister (2A)		Existing Airlines (2B)	
Criteria	**Weight**	**Score**	**Weighted**	**Score**	**Weighted**
Safety	0.29	5	1.43	5	1.43
Cost	0.05	2	0.10	4	0.19
Weight	0.10	2	0.19	4	0.38
Size	0.14	2	0.29	4	0.57
Compliance with Existing Infrastructure	0.00	5	0.00	5	0.00
Temperature of Gas	0.24	2	0.48	4	0.95
Maintenance Level	0.19	1	0.19	4	0.76
	Total	2.67		4.29	
	Rank	2		1	
	Continue?	NO		YES	

As shown in TABLE XX, the CO_2 injection point on the inhale was chosen. This design was only slightly better than the other two alternatives; however it will provide a more accurate exhale temperature and better mixing of the CO_2 with the inhaled air due to the increased amount of time that the CO_2 will be in the system.

TABLE XX: CO_2 INJECTION POINT WEIGHTED SCORES

CO_2 INJECTION POINT							
		On Inhale (3A)		On Exhale Prior to Heating (3B)		On Exhale After Heating (3C)	
Criteria	**Weight**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**
Accuracy of Temperature	0.20	5	1.00	4	0.80	3	0.60
Packaging	0.00	3	0.00	3	0.00	3	0.00
Manufacturability	0.40	3	1.20	3	1.20	3	1.20
Risk of Leakage	0.30	2	0.60	3	0.90	4	1.20
Mixing Of Additional Gasses	0.10	5	0.50	3	0.30	1	0.10
	Total	3.30		3.20		3.10	
	Rank	1		2		3	
	Continue?	YES		NO		NO	

Through the analysis conducted in TABLE XXI, it was decided that heat tape is the best way to achieve the desired exhale temperature. The scores for the heat tape and heat wire are fairly close; however, the availability and manufacturability of the heat tape set it apart from the alternative.

TABLE XXI: EXHALE TEMPERATURE WEIGHTED SCORING

EXHALE TEMPERATURE							
		Heat Tape (4B)		Heat Wire (4C)		Oven (1D)	
Criteria	**Weight**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**
Accuracy of Temperature	0.18	5	0.89	5	0.89	5	0.89
Reliability	0.13	3	0.40	3	0.40	5	0.67
Availability of Parts	0.09	5	0.44	5	0.44	3	0.27
Packaging	0.07	4	0.27	5	0.33	2	0.13
Manufacturability	0.20	4	0.80	3	0.60	2	0.40
Consistency	0.18	5	0.89	5	0.89	5	0.89
Adjustability	0.00	3	0.00	3	0.00	4	0.00
Cost	0.04	5	0.22	5	0.22	2	0.09
Weight	0.04	4	0.18	4	0.18	2	0.09
Size	0.07	4	0.27	4	0.27	2	0.13
	Total	4.36		4.22		3.56	
	Rank	1		2		3	
	Continue?	YES		NO		NO	

Shown in TABLE XXII, heat tape only with no residual heat from the breathing system is the ideal way to create the desired thermal plume.

TABLE XXII: BODY TEMPERATURE WEIGHTED SCORING

BODY TEMPERATURE							
		Heat From Breathing System (5A)		Heat From System + Heat Tape (5B)		Heat Tape Only (5C)	
Criteria	**Weight**	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**
Accuracy	0.40	1	0.40	3	1.20	5	2.00
Cost	0.10	5	0.50	4	0.40	4	0.40
Size	0.30	5	1.50	5	1.50	4	1.20
Weight	0.20	5	1.00	5	1.00	3	0.60
Adjustability	0.00	1	0.00	3	0.00	4	0.00
Total		3.40		4.10		4.20	
Rank		3		2		1	
Continue?		NO		NO		YES	

3.4. Final Design Summary

After going through the needs weighting and concept selection, the team was able to select the most advantageous designs for each of the five different sub categories, and putting them together, a final design.

The flow rate supply device will be a single acting piston pump. The rationale for this design decision was based on the fact that it would be able to accurately produce the required flow rate and produce discrete breaths, both needs being very high priority for the client. Additionally, these types of pumps are very common and, therefore, the sourcing of one that meets the flow rate requirements should be easier.

The CO_2 source will be the in-house supply lines at the Price research lab. While this will restrict us to only using the breathing apparatus where these lines exist, the fact that the CO_2 supply is limitless and does not require additional safety measures be taken with CO_2 canisters, is a major advantage.

The design that netted out being the most beneficial for the CO_2 injection point was to inject the CO2 on the inhale portion of the breath. While all three options were very close, the amount of control over the temperature and longer length of time for the CO2 to mix with the air made it the best option.

The way that the exhale mixture will be heated is by using a heat tape based device. This was chosen as it provided the greatest control over the temperature with the highest reliability, two of the more heavily weighted needs categories.

Finally, the overall body temperature will be produced using heat tape while insulating the breathing apparatus. This method, while heavier, allows for greater consistency of the overall body temperature and can be fine-tuned to ensure accuracy. This method is also familiar to the engineers at Price as it is currently in use on some of their thermal mannequins.

Combining all five elements, the team will be able to produce a breathing thermal mannequin that uses parts readily available for purchase and maintain the budget of $2000 per unit.

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Appendix B

Technical Drawings

Table of Contents

List of Figures

1. Introduction

An important aspect in product design is the ability to accurately construct and assembly the required parts and components. Included in this appendix are the technical drawings required for manufacturing and assembly of the breathing pump and the carbon dioxide injection system. The pump component drawings are shown in Section 1 of this appendix, and the pump assembly drawings in Section 2. The Carbon Dioxide injection system assembly drawing is played in Section 3.

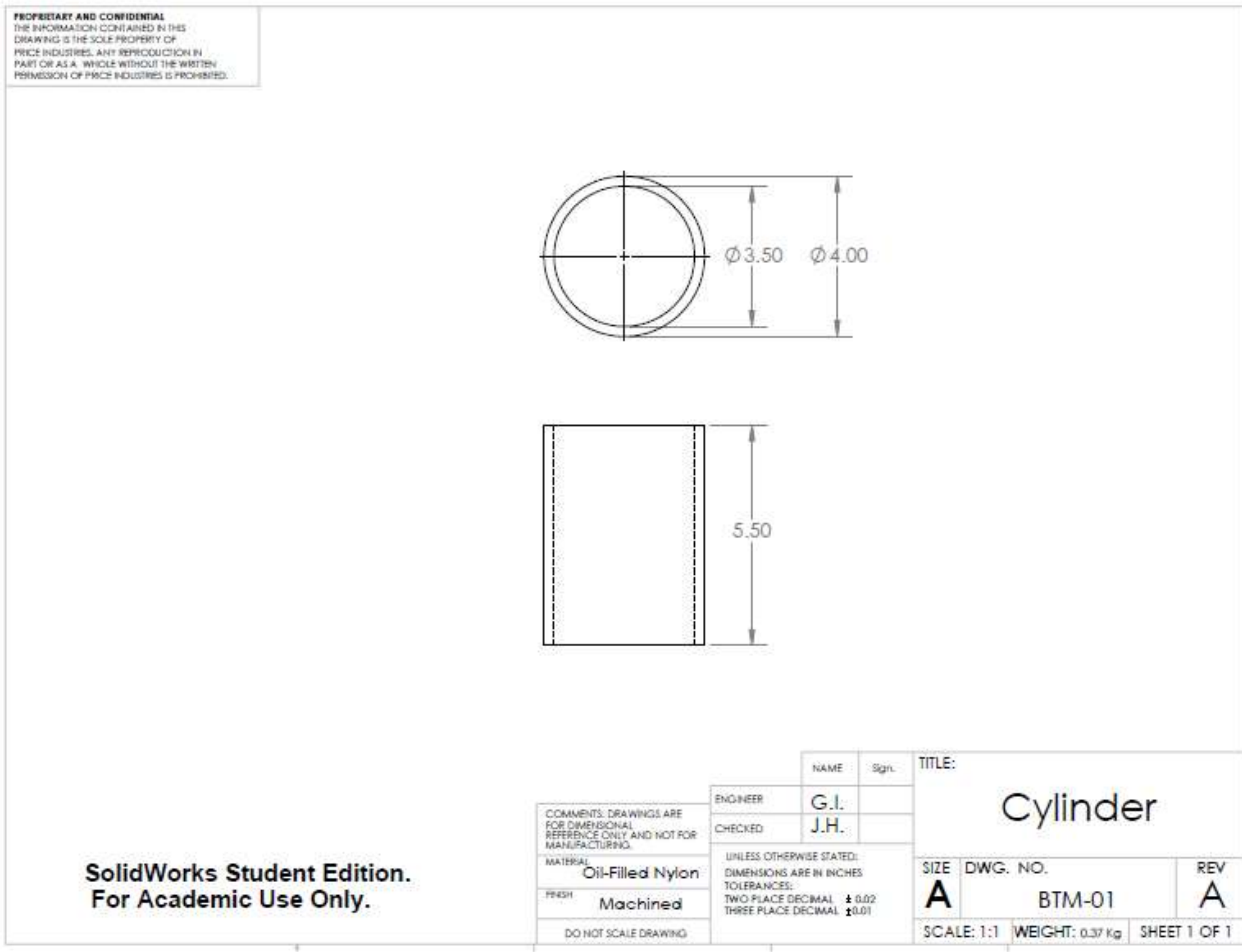

Figure 2: Drawing BTM-01, cylinder

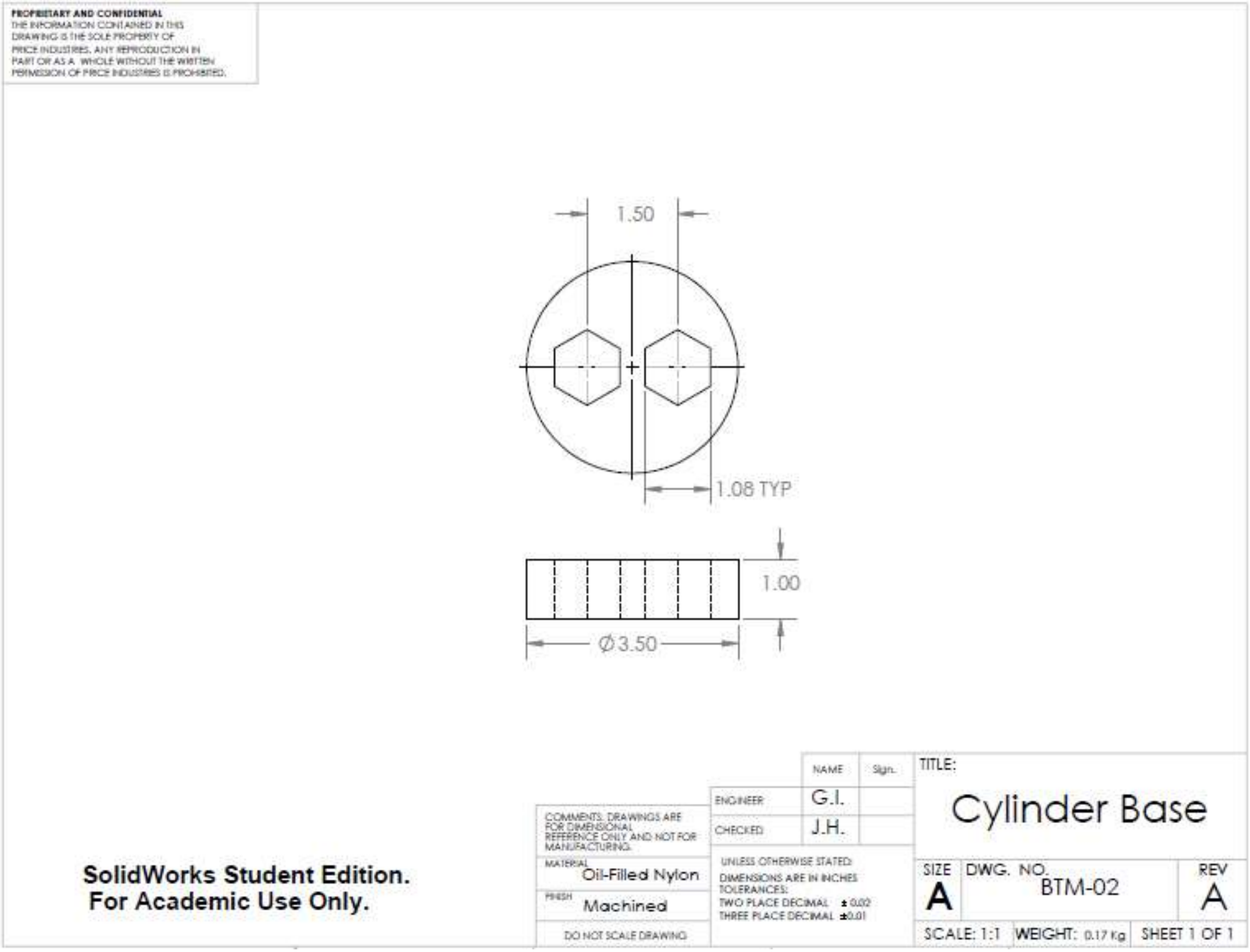

Figure 3: Drawing BTM-02, cylinder base

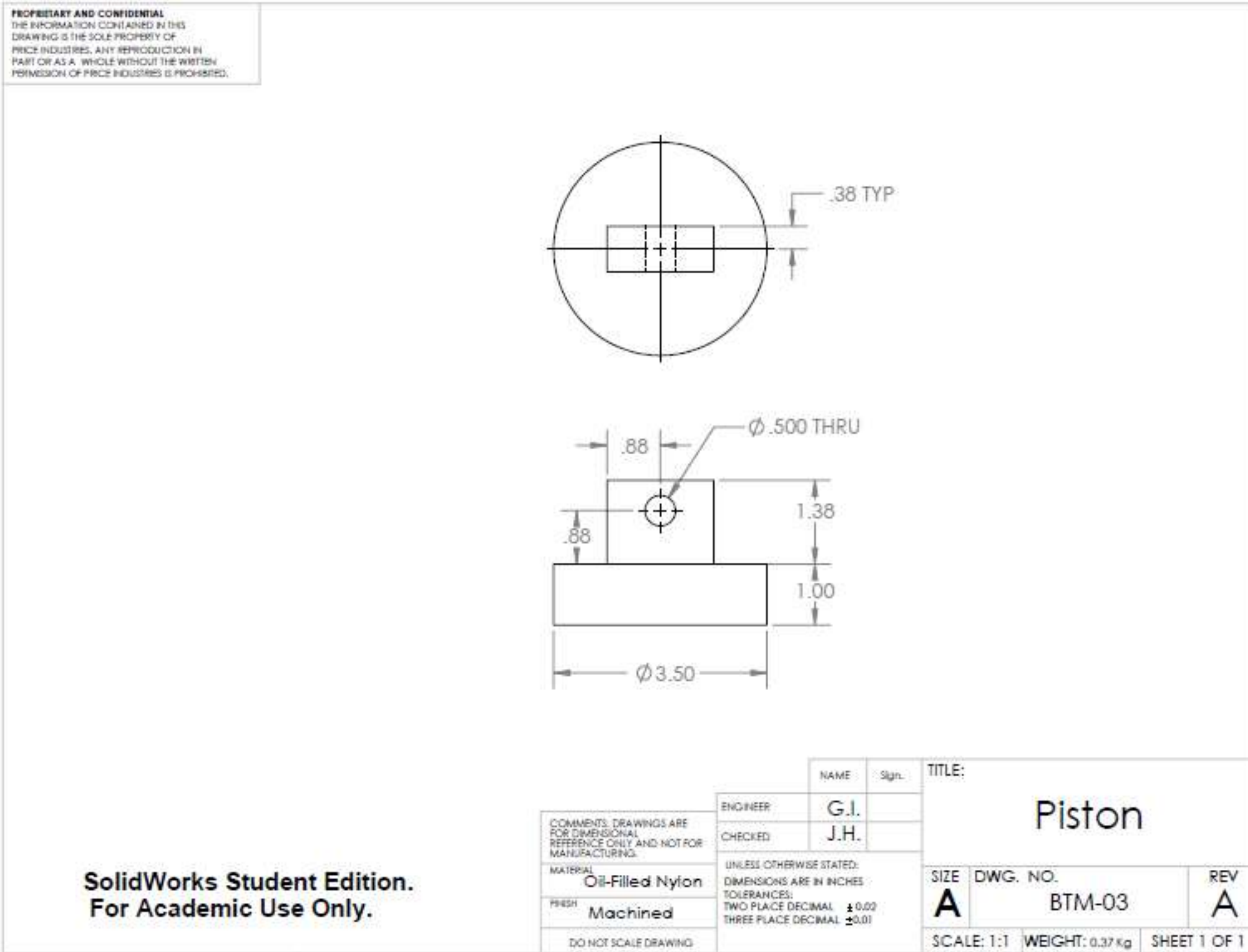

Figure 4: Drawing BTM-03, piston

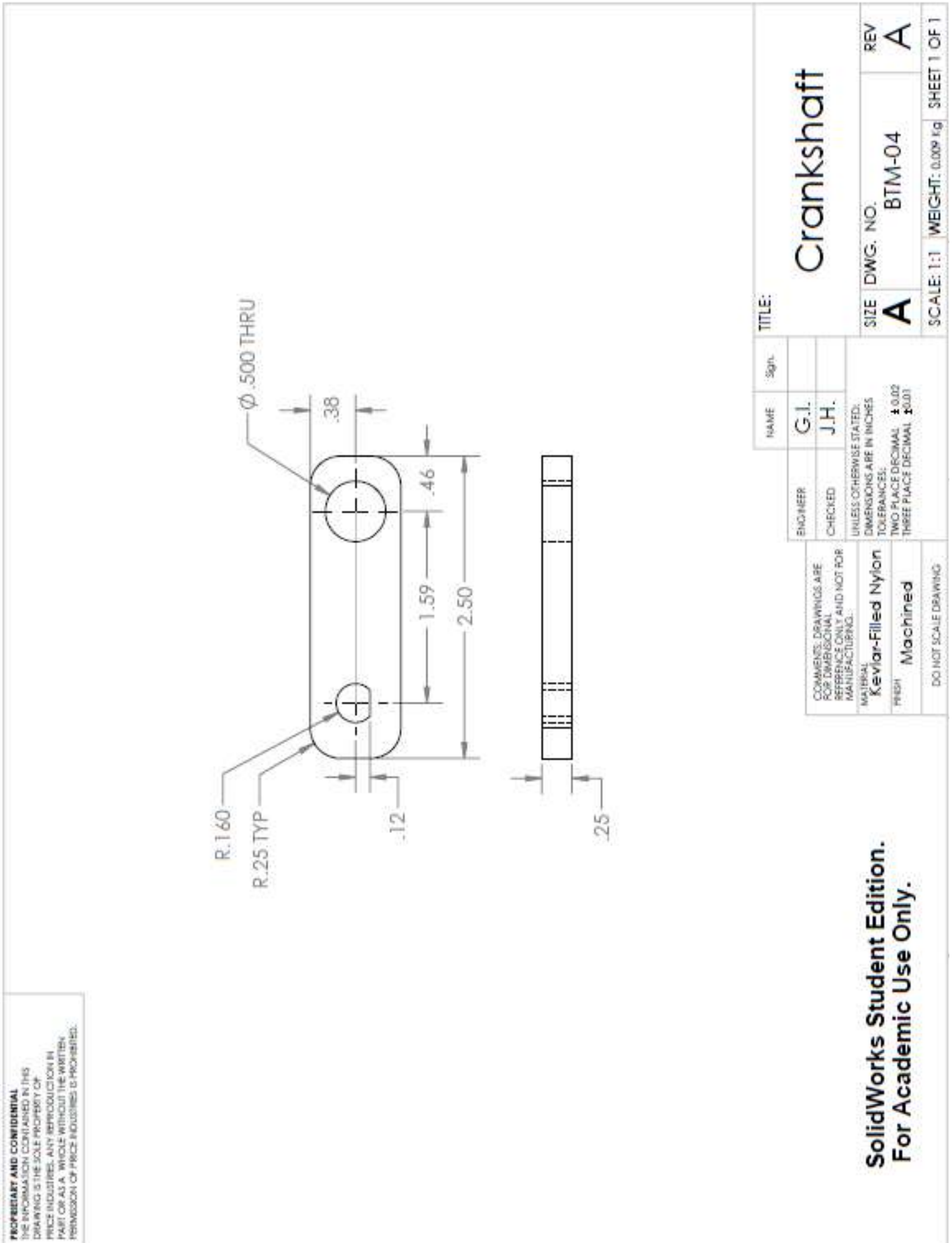

Figure 5: Drawing BTM-04, crankshaft

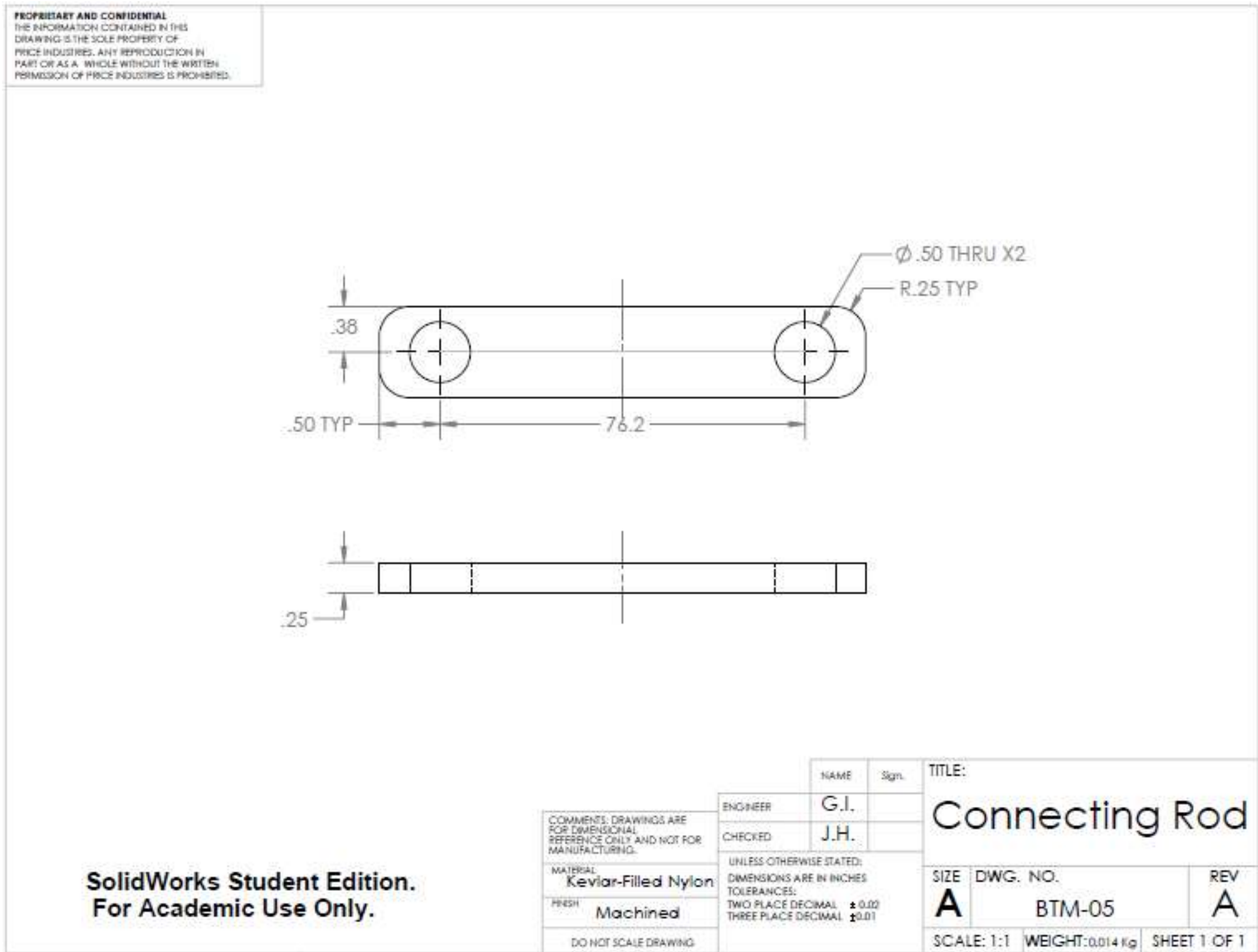

Figure 6: Drawing BTM-05, connecting rod

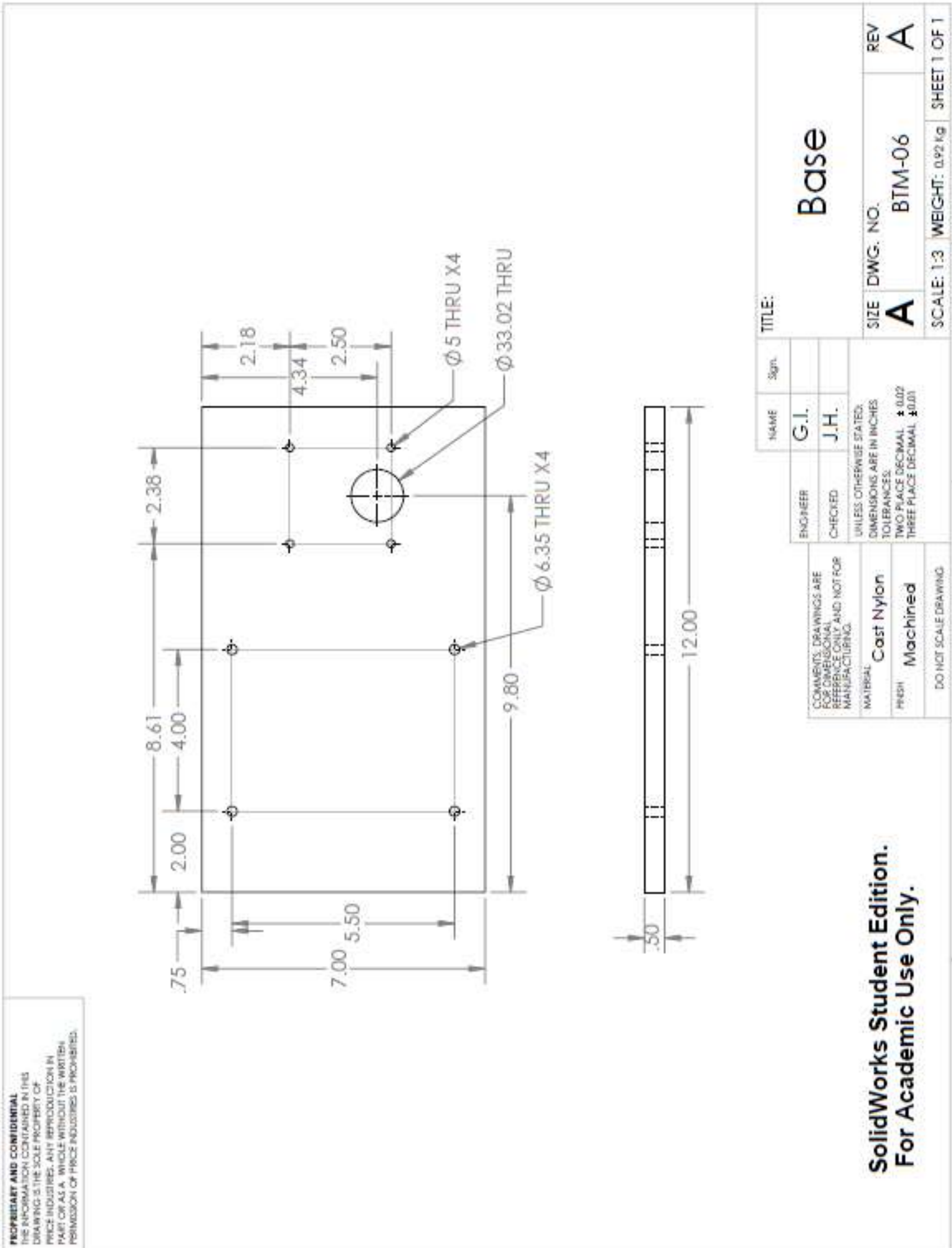

Figure 7: Drawing BTM-06, base

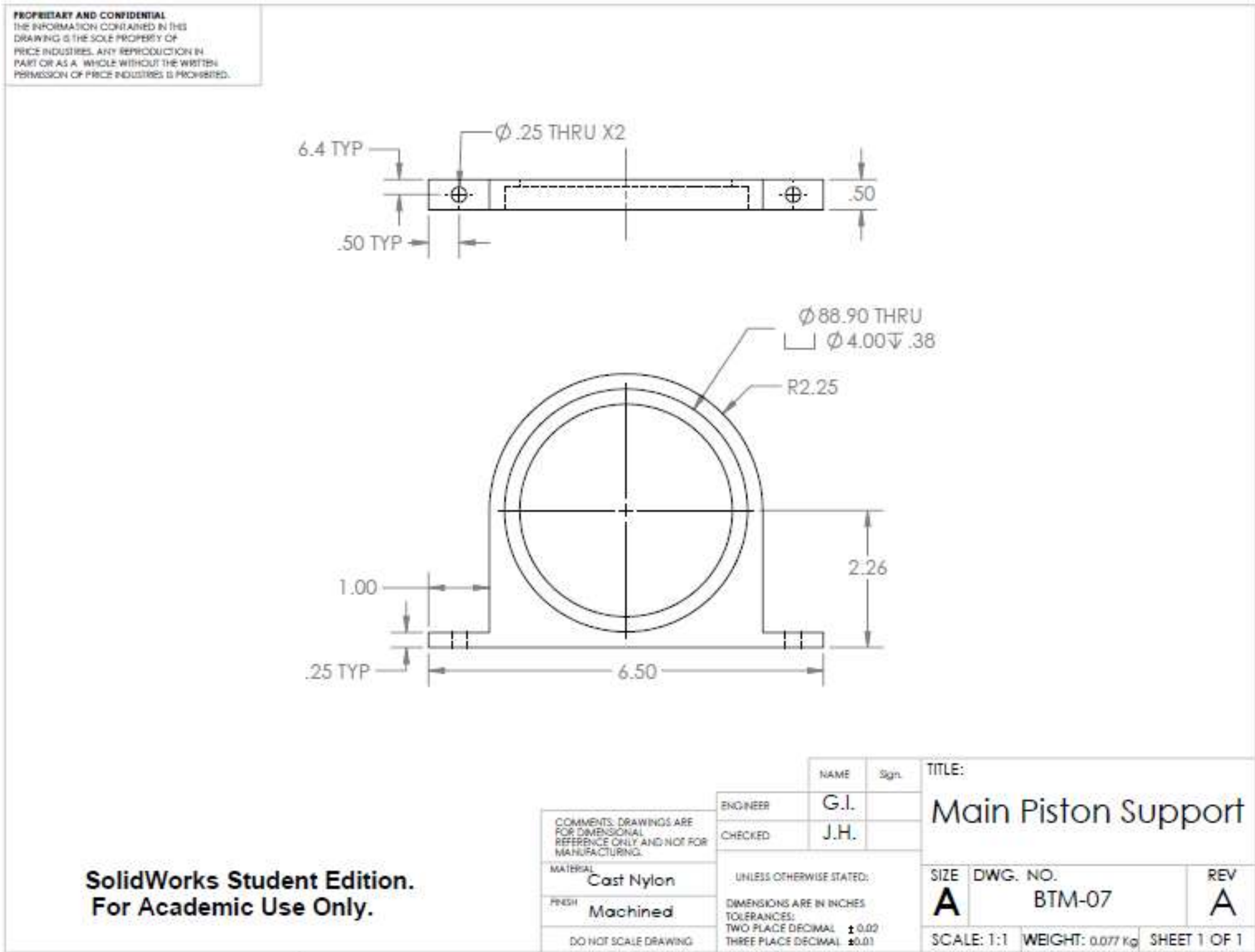

Figure 8: Drawing BTM-07, main piston support

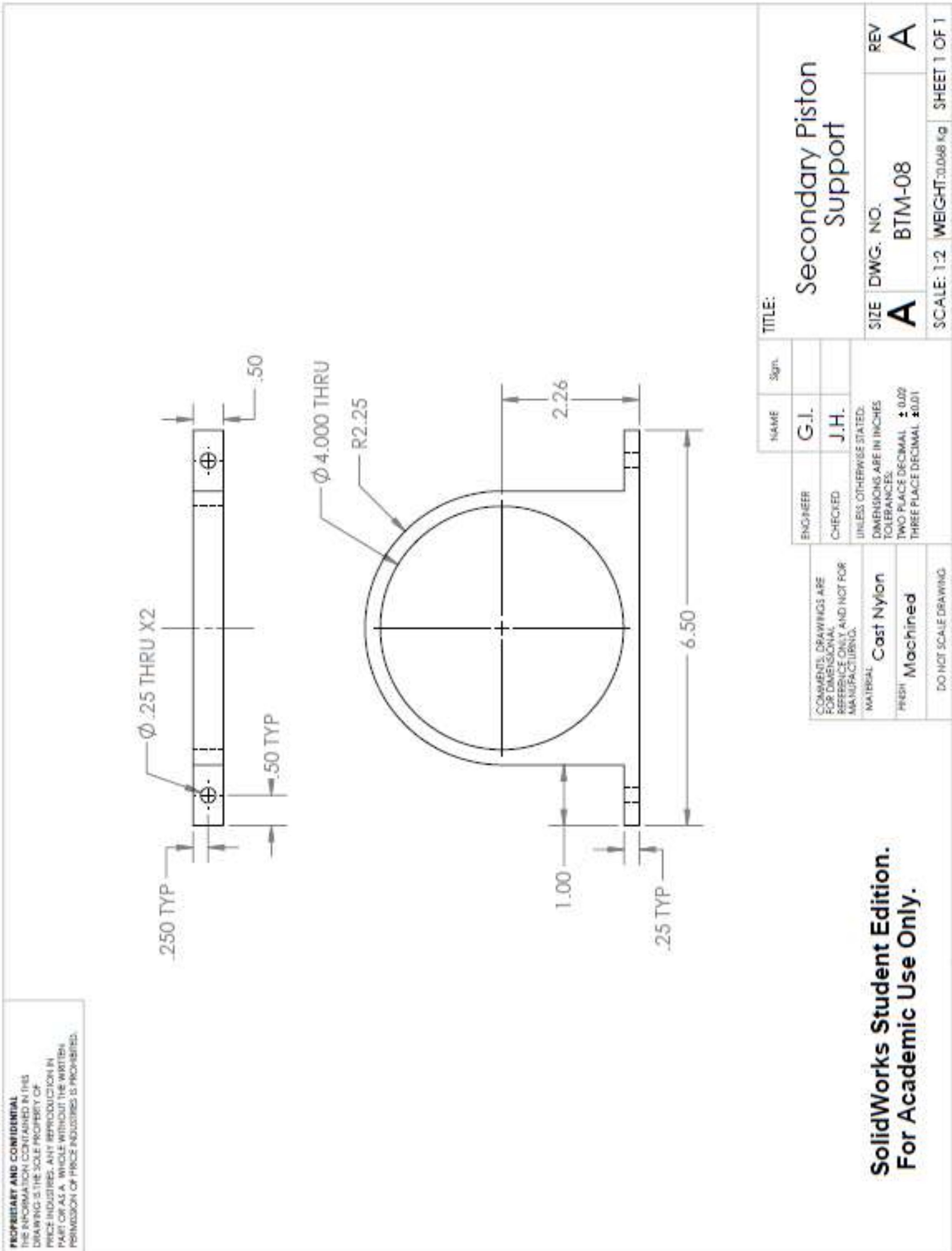

Figure 9: Drawing BTM-08, secondary piston support

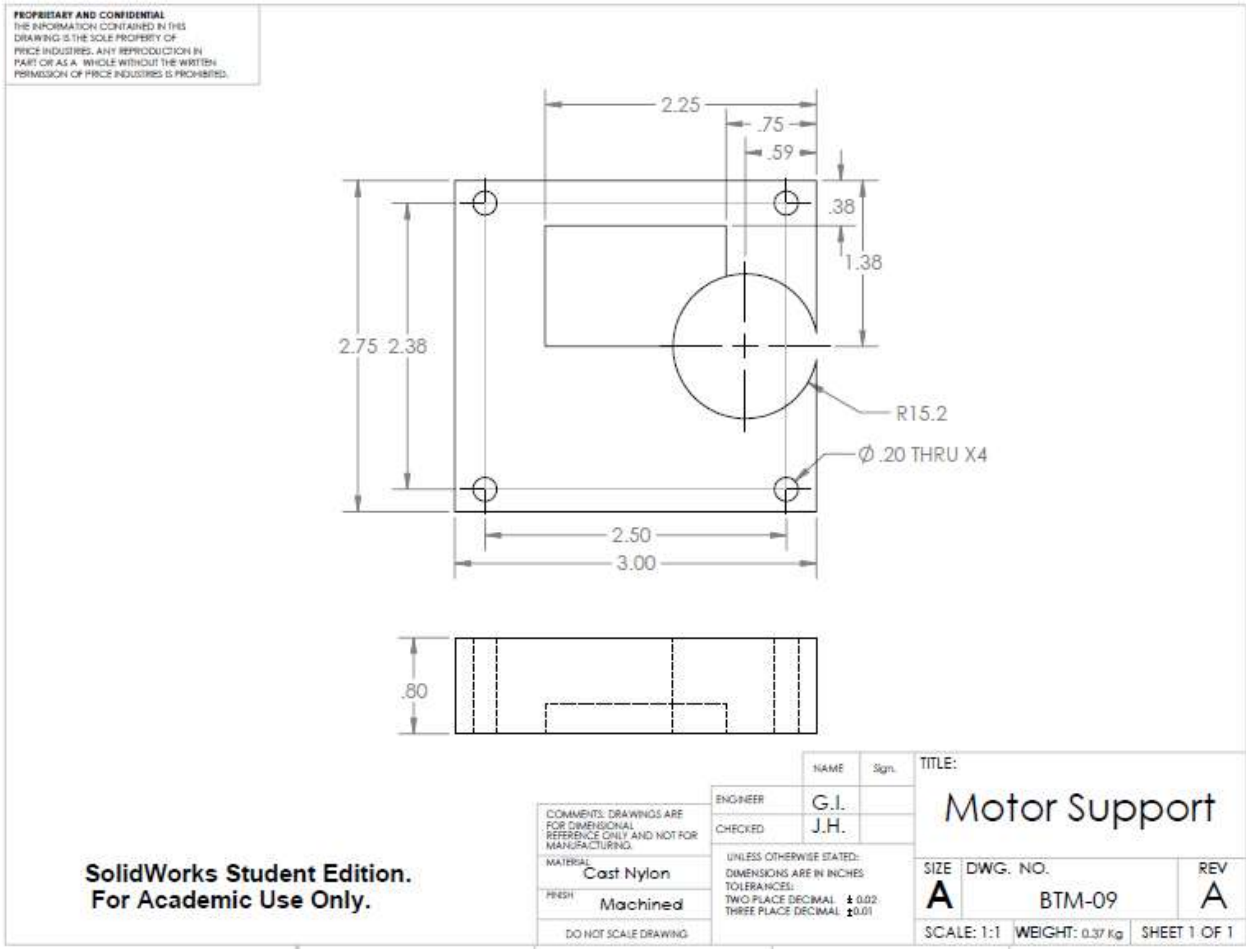

Figure 10: Drawing BTM-09, motor support