Concept Design Proposal Final Draft

AME 470 Team Unum:

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1 Executive Summary

1.1 Product Description

The **AuRA Valve** is the **Au**tomatic **R**egulating **A**ir **Valve** named after Aura, the goddess of the morning wind. This product will simplify and increase the accuracy of inflation for use with athletic balls, car and bike tires. The proposed design will be connected to an existing pump or air compressor on one end, and the inflatable vessel on the other end. Within the product itself, a microprocessor will control the flow of air to the inflatable in order to achieve the desired pressure. A simple user interface will allow the user to enter a target pressure and watch the status of their inflatable as the air flows from the source to the vessel. When the target pressure is reached, the microprocessor, which receives pressure readings from a pressure sensor, will control a valve to divert the airflow away from the inflatable vessel. At this time the user will be alerted that the vessel is full and airflow from the source should be stopped.

Some key characteristics of the Aura Valve System are its universality and portability. Team Unum immediately identified universality as a key feature of the system if it was to succeed. Making the system truly universal requires the use of connectors which will work with all existing compressors and air pumps at one end and all

athletic balls, car and bike tires on the other end. Meeting this requirement would then allow users to easily integrate the Aura Valve into their inflation routine without replacing their existing air source. Portability is also a key feature of the Aura Valve system. The vision of Team Unum is that the user can simply throw the small device in a gym bag or back pack, allowing them quick access to accurate inflation regardless of time, place or circumstance. With this in mind, size requirements were set to define a "handheld" device and weight requirements were set to be under three pounds. Additionally, while the Proof-of-Concept model uses an AC/DC Adaptor as a power source, the final product will run on conventional battery power, eliminating the need for an external power source.

1.2 Concept Strengths and Weaknesses

Concept Strengths	
AuRA VALVE	Alternate Methods
• *Ease of use:* The all-in-one concept requires the user to operate only one device, and there is no interruption during the inflation process to check pressure.	• Traditional methods of inflating, then measuring, then inflating again require switching between two tools, which slows the inflation process and is more difficult for the user to do.
• *Improved Accuracy:* The transducer, which measures the vessel pressure, is accurate within 0.5% of the target pressure.	• Some of the best pocket pressure gauges can perform only within 1% or greater of the target pressure.
• *Universality:* There is no need to buy several air pumps or needles in order to fill up bike and car tires, and all athletic balls. The universal connectors eliminate the need for different tools, and the operating pressure range encompasses all pressure needs.	• Some pressure gauges are designed for bike owners, others for use with athletic balls. Keeping track of more than one pressure gauge for a range of applications causes clutter and increased expense.
• *Built-in Safety:* The Aura Valve is designed to divert airflow away from the vessel, rather than simply stopping the airflow stream. This prevents a build-up of pressure within the tool. Additionally, the off-design operating condition of the Aura Valve diverts air to the atmosphere, which ensures the user that if power is lost to the tool, airflow will not continue in the direction of the vessel. This way, potentially dangerous situations are avoided by allowing air to enter the vessel only when the microprocessor is on and operating.	• Uncontrolled inflation can lead to situations where vessels become over-inflated and may eventually explode. Designing a system that simply stops the airflow to the valve ignores the activity of the air source, which may continue to pump air in the direction of the vessel. A loss in power supply to the tool causes the intelligent aspect of the tool to be disabled, and the lack of a mechanical backup could prove disastrous.

Concept Weaknesses	
AuRA VALVE	Alternate Methods
• *Power Supply:* The intelligent system requires a 12 volt supply of power for the microprocessor and user interface as well as the solenoid valve and transducer. Without power the Aura Valve cannot fill a pressure vessel.	• Simple pressure gauges require no power supply, because they are simply a mechanical reaction to the pressure level in the vessel.
• *Weight:* Due mostly to the weight of the solenoid valve, the Aura Valve will weigh approximately 3 pounds.	• Simple pressure gauges are extremely lightweight, usually weighing much less than 1 pound.
• *Size:* While still handheld and portable, the user will not be able to simply put this device anywhere. It will be approximately the size of a handheld voltmeter, with proposed final packaging dimensions less than 7”x4”x5”.	• Simple pressure gauges are small enough to fit in the pocket of the user.
• *Entire system performance:* Each component has been selected because Team Unum believes it can fulfill the needs of the product. However, it is also important that the individual components work well together without increasing the uncertainty in measurements.	• Simple pressure gauges rely on very few components to mechanically measure the pressure of a vessel. Propagation of error is not an issue, in most cases.

1.3 Key Technical Factors of Design

Choosing the appropriate valve with which to control the direction of airflow was a very important part of the design process. The results of the Trade Study Section 3.2 performed caught the attention of Team Unum, as it was clear that the valve would

be the most costly and complicated component of the product. It was discovered that the airflow configuration desired for this application required a less-common valve configuration, which would ultimately add more cost to the development of a Proof-of-Concept prototype. While the cost significantly increases the cost of the overall prototype, confidence that it would meet all project specifications drove Team Unum to accept the part for integration into the system. Packaging of the entire Aura Valve system is another important issue. The housing design will have to consider the size of all internal components, as well as the flow configuration. The prototype will aim to hold all components in place, whereas the final product will add value to the product by making the system easy to hold, as small as possible and attractive.

1.4 Product Assembly Drawings

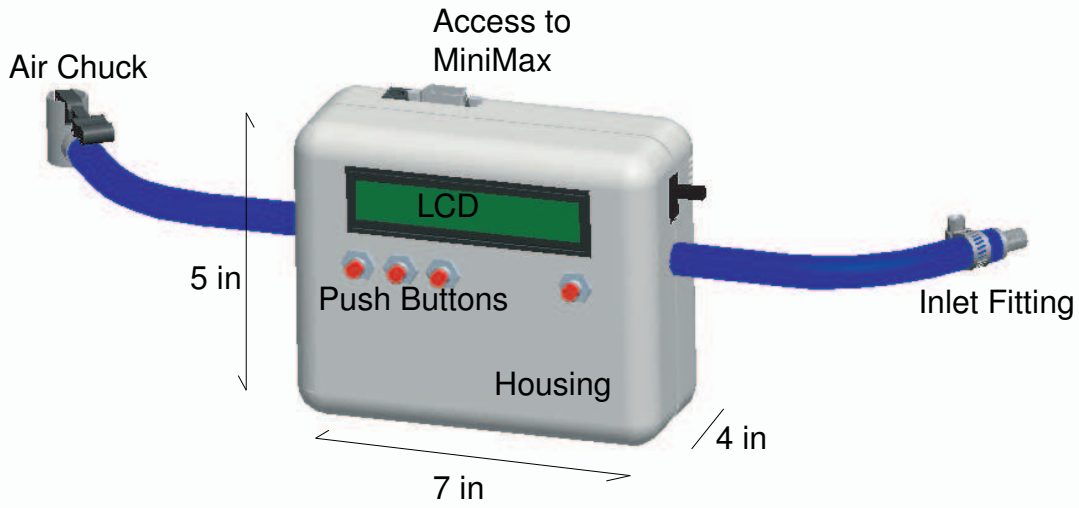


Figure 1: Aura Valve Final Concept Package

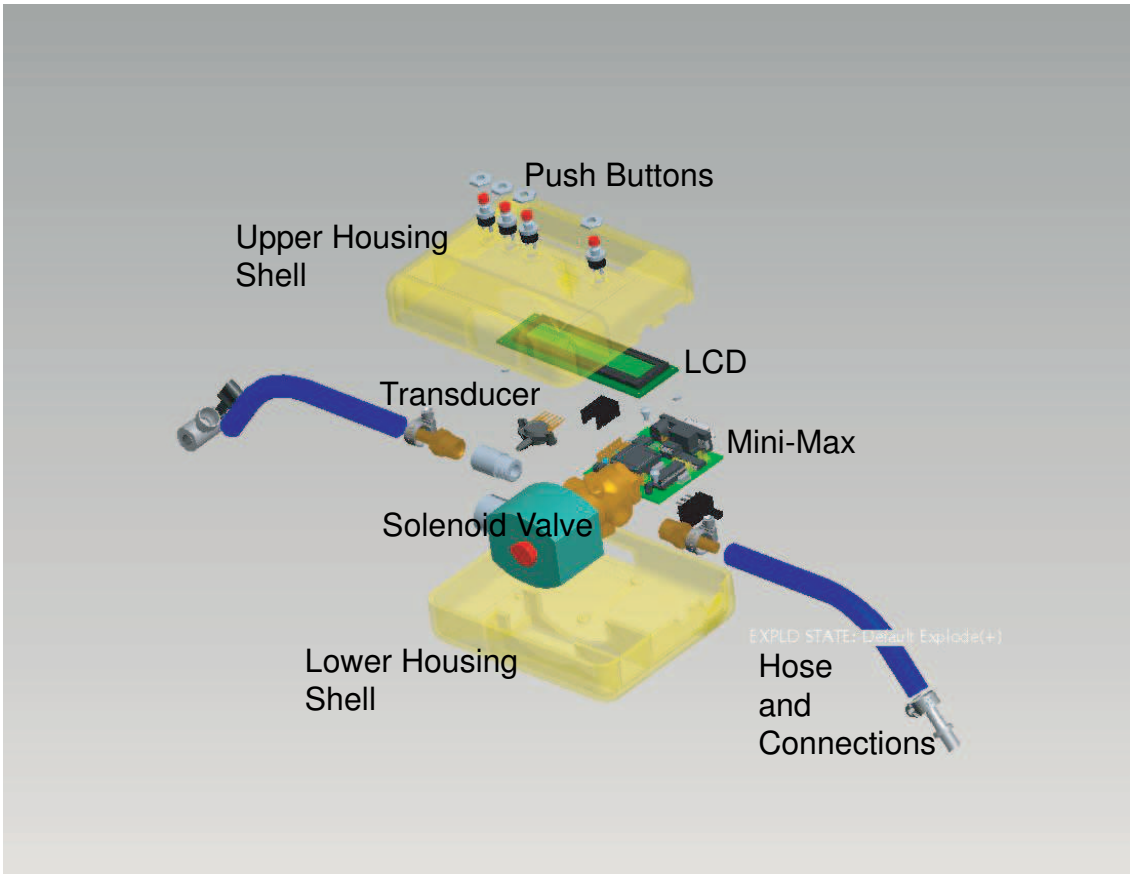


Figure 2: Aura Valve Exploded View

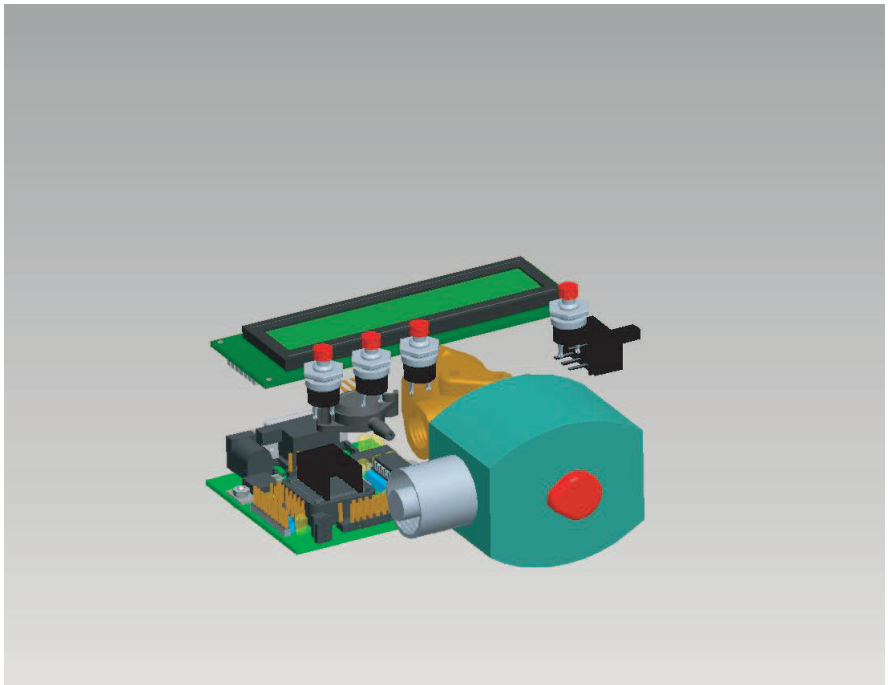


Figure 3: Concept Electrical Component Assembly

Figure 4: Aura Valve Housing

2 Proposed Concept Engineering Validation

2.1 Design Requirements and Target Specifications

Once the concept of an automatic air regulating valve was finalized, the design of the device had to be limited by imposing a series of design requirements to the original idea. There are 4 general design factors that greatly influenced the choices of quantitative design requirements: the target market, available capabilities and resources to design and manufacture, time and cost. The target market was a key issue since the design of an air valve for personal use differs greatly from the design of a valve for commercial use. The decision was made to focus only on residential applications mainly because the output pressure range could be limited to 0-65 psi. As will be explained later, the pressure of most vessels that a customer encounters on his everyday life does not exceed 60 psi. Commercial applications were broader and a larger output pressure range was required in order to be competitive in the market.

Team Unum is part of AME 470, Ltd. As engineers working in the design of a smart tool, the team had to analyze all the resources available within the company in order to set design requirements for the AuRA valve. Some of these resources are the tools and equipment available, the support for electronic applications and

the experience that each member of the team has had in certain areas related to the design. Time and cost were two especially important resources that had to be considered when setting design requirements for the prototype. Time is limited since the goal of team Unum is to have a working prototype in 4 months. Reasonable requirements had to be chosen in order to achieve this goal. The budget provided by AME 470, Ltd. to Team Unum was a total of $500. This also had a significant impact on the design requirements. As will be explained in the explanation of each design requirement, there is a difference between the requirements set for a working prototype and the requirements set for the final product at later stages of the design.

Pressure range: Input 0-80psi, Output 0-65psi

The desired output pressure range was selected first because of its direct interface with the vessel that the user wants to inflate. In order to select an appropriate range that will make the product competitive and meet the needs of the customer, some research was done about the pressure requirements of the most common vessels for residential use. The results were the following:

- Athletic balls: 6-15psi.
- Automobile tire: 32-36psi.
- Off-road bike: 45-65psi.

- On-road bike: 65psi.

Considering these numbers, a reasonable output pressure range of 0-65psi was selected. Considering a perfect situation with 100% efficiency and no pressure losses whatsoever, the input pressure range should be the same. However, since this is not true, an input pressure range of 0-80 psi was set. Possible sources of pressure loss are connections between the air source and the valve and other multiple connections within the valve.

Pressure diversion method: one input, two outputs

One of the main controlling functions within the valve takes place when the flow of air coming from the input is either directed to or away from the vessel. As a safety feature, team Unum decided that the valve was required to divert the flow when the vessel target pressure was reached. Merely stopping the airflow coming from the air supply could cause the pressure to build up within the AuRA valve if the source is not powered off on time. Since user safety is a main concern of team Unum, the Aura valve is required to have a pressure diversion device which is able to exhaust the airflow when the target is reached. This function was analyzed in a Trade Study included in the Appendix, Section 3.2.

Pressure measurement method: Analog signal

Since the AuRa valve is an intelligent tool, its pressure measurement device should be able to send an analog signal to the microprocessor to identify the current vessel pressure. This signal must be compatible with a microprocessor so that it can be useful in transmitting the status of the inflation process. The Trade Study in Section 3.3 provides a complete explanation of the selection process.

Microprocessing unit

Due to the functions that the AuRA valve is expected to perform, it is required to have some kind of microprocessor that can control the flow of information within the device. It should be able to set the target pressure as the user desires and open the valve to begin the inflation process. It must also receive a signal from the pressure measurement device and constantly compare it to this target pressure. When the target pressure has been reached it must send a current to the valve to close it and terminate the process.

Connections: 1/4" threaded fasteners, compatible with Presta and Schrader valves

There are essentially 4 main connections within the valve. One between the pressure

source and the valve, one at each side of the valve, one for the pressure transducer and one with the vessel. The source is connected to the valve through a machined connection that is compatible with the tip of the air source on one side and connects to a hose on the other side. The connections at each side of the solenoid were made using standard 1/4" NPT threads (male and female) with hose barbs. The pressure transducer was attached by means of a small tube machined from solid aluminum. Finally, the connection to the inflating vessel was done through a universal connecting head. This tip fits both Presta and Schrader standard connections available in the market.

Physical dimensions: weight less than 3 pounds, volume 7"x5"x4.5"

The potential use for this product was an important factor in deciding its physical dimensions. This is a product that needs to be portable. In most cases, the user might want to carry it inside a bad or keep it in the glove compartment of a car for rapid accessibility. For this reason, the lighter and smaller it is, the better. However, the specifications of certain components inside the device also have to be considered in order to determine reasonable design requirements in this category. The valve is without a doubt the heaviest component of the Aura Valve System. All the other main components such as the pressure transducer, hoses, connectors and housing are

not likely to weigh more than another 1.5 lbs. The volume is also limited by the dimensions of the valve, which is the largest component as well. It is reasonable to say that the final product should have a volume of 7" x 4" x 4.5".

Power supply:

The power supply requirement was also set by the operation of the solenoid valve, which is controlled by energizing its 12 Volt coil to divert the air flow. This is the highest power requirement from the different components of the valve. Even though for the sake of testing a prototype in this project an AC/DC converter will be used, this is not a convenient nor attractive feature for the final product. The user needs this product to be portable and should not have to plug it in every time he desires to use it. Therefore, a battery pack should be considered for the next phase of design.

User interface: 20x4 LCD screen, 4 individual buttons

A 20x2 LCD screen (Figure 10) provides enough space to display the necessary information that the user needs to know during the inflation process. A big display will allow for user friendliness. The 20x2 size allows for a number of features that inform the user about the current status of the inflation process. One of the features is to have one of the 2 lines in the LCD fill up as the vessel is being filled up. The concept

of individual buttons were chosen over a keypad for simplicity and user friendliness as well. All the user needs is an up key and a down key to set the pressure and an enter and cancel key to operate the device.

Cost: under $30

In order for potential customers to buy this product it needs to be affordable. Even though the automatically regulated air valve does indeed provide a number of benefits, users will only be willing to pay a certain amount of money for them. After assessing the potential customer base, and asking Notre Dame students what they would be willing to pay, a cost of $30 seems like a reasonable price for the final product on the shelves. The prototype developed by Team Unum will certainly be more expensive because all of the components are being purchased individually and in accordance with the allotted resources from AME 470, Ltd.

Packaging hardness: safe to drop from five feet

This product is likely to be used in a variety of settings that may require it to withstand impact. A device that costs $30 and breaks when it is accidentally dropped is not likely to satisfy the user needs. Five feet is a reasonable height for the average accidental drop (about shoulder height of a person). TThis is a feature that will be

added at later stages of the design process. The housing for the initial prototype will be rapid-prototyped out of stereolithograhy material which is not likely to withstand a drop. However, this is only a Proof-of-Concept prototype which will not be dropped. Once the prototype is working then some additional features, like increased housing hardness can be added.

Inflation: fills up a basketball in 4 seconds with 5% accuracy

According to the specifications of the selected solenoid valve, this is one of the capabilities of the device. After doing some calculations involving the flow coefficient of the solenoid and the air pressure on a regular basketball the result was an inflation time of approximately 4 seconds. The basketball was chosen randomly as a reference. All calculations can be seen in the solenoid valve trade study included in the appendix.

Tube to attach pressure transducer: 0.625"diameter, 1.125"long, 0.3" diameter

These dimensions will maintain smooth flow from the solenoid into the vessel without any disruption of flow caused by the pressure sensor. The tube will have a very small opening to fit the pressure transducer.

Other considerations: Waterproof

Again, this is another requirement which will make the final product more attractive for the customer. Sometimes, the user will need to inflate his tires under the rain and the product should be able to respond under this situation. Even though this is not an important issue at the prototype level it is definitely an important feature to incorporate later on.

Hose length: 1-ft inlet and outlet hoses

The AuRA valve will have 2 hoses attached to its housing. One is the inlet hose and will be connected to the air supply, and the other will be the outlet hose and will be connected to the pressure vessel. Both of these hoses should be 1 foot in length. This is enough to allow for flexibility and easy connections to the air supply and vessel.

2.2 Concept Selection

The most important concept decision during the early stages of the AuRA Valve was the method of air flow diversion. All the other decisions such as the type of connections to use, pressure measurement device, electronic components and packaging were made as a consequence of the air diversion method that was selected. As part

of AME 470 Ltd., Team Unum is committed to ensure the safety of the customers. Therefore, safety was an important issue that limited the suggested concepts. Since the device would operate with air pressures of up to 80 psi at the inlet, an exhaust vent has to exist in order to release the air flow to the atmosphere when the target pressure is reached. The idea of simply constraining the air flow when the vessel was filled up does not seem very attractive because pressure could build up within the AuRA valve if the air source is not powered off and continues to supply a flow of air. For this reason, the air control system was required to have three connections: one inlet from the air supply, one outlet to the inflatable vessel, and another outlet to the exhaust. The suggested concepts were the following:

- **Metal tube in a "Y shape" with mechanically actuated flap**

  A schematic of this concept is shown in Figure 5. As the Figure reveals, a metal

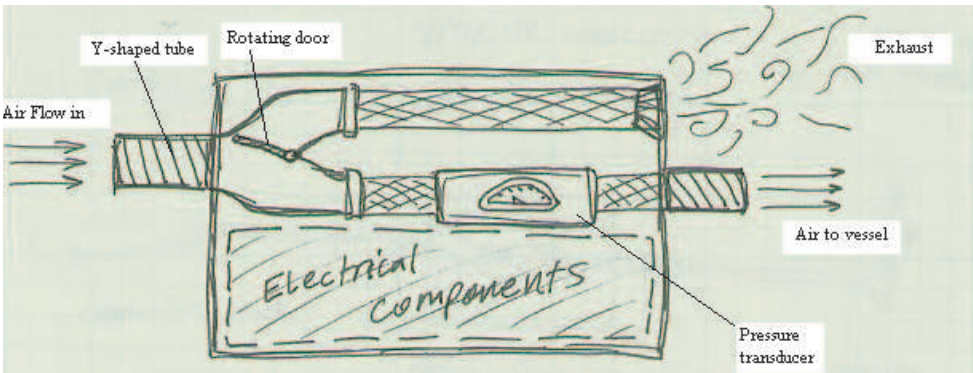


Figure 5: Concept 1 Sketch

Y-shaped tube would be used in order to have the 3 required connections. At the exact spot were the inlet is divided into two outlets, a rotating flap would be machined having the same area as the cross section of the tube. While the inflation process is going on, the door would block the outlet vent and direct all the flow into the vessel. Once the target pressure is reached, the microprocessor would activate a motor that would rotate the door to block the other vent and all the air would be diverted towards the exhaust.

*S*trengths

- Cost is low because only a motor has to be purchased from an external supplier, all other components can be machined or obtained within the resources of AME 470 Ltd.
- Part count is minimized since the output shaft of the motor can be directly attached to the rotating flap.
- Voltage requirements are low since a motor with low voltage requirements is enough to drive the rotating door.
- Dimension of the Y-shaped tube are fairly small.
- Weight is low since the motor and the tube are not very heavy.

*W*eaknesses

- Precise and detailed machining is required to fit the flap inside the Y-shaped tube with accuracy. The Y-shaped tube has to have an opening to fit the input of the motor and attach it to the metal door. Also, the door has to be precisely built so that it completely seals the vents.
- In case of failure, it is very difficult to replace the metal door without having to replace the Y-shaped tube as well.
- Accuracy is reduced because the rotating flap will not close the desired vent instantaneously. Even though it might take only a couple of seconds to rotate the flap air is still flowing through to the vessel during this time and the actual final pressure will de different from the actual pressure.

- **Rotating barrel**

As Figure 6 shows, a barrel would be machined and placed on top of the casing that carries the air flow. There would be a hole machined into the casing and a similar opening on the barrel. In the inflating mode, the two holes would be misaligned and the flow would go from the inlet through the casing and into the vessel. When the target pressure is reached, the barrel would be rotated using a motor and gears like the figure shows in order to align the two openings and divert the flow of air. An anti backflow valve would be needed so that the air does not flow out of the vessel in the exhaust mode.

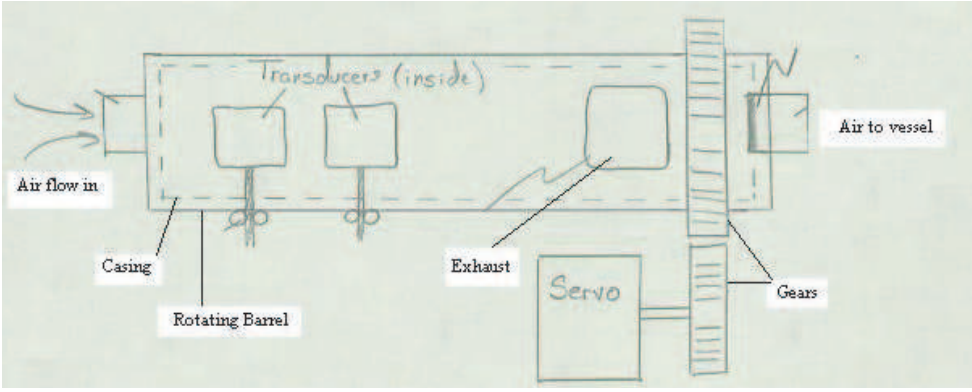


Figure 6: Concept 2 Sketch

*S*trengths

- Cost is reduced since the components that would have to be obtained from an external supplier are a DC motor and an anti backflow valve. All other components could be obtained within AME 470 Ltd.
- The machining is easier than the first concept; a barrel with holes and some gears are enough to control the airflow.
- The dimensions of this concept are smaller as compared to the other concepts because only one direction of airflow is needed. Even though airflow would be exhausted when the target pressure is reached, there is no need to have a Y-shaped tube.

*W*eaknesses

- There are two additional parts that have to be included if this concept were to be selected: the anti backflow valve and the rotating barrel.
- The durability of these gears is questionable because the valve is expected to withstand a drop from 5 feet.
- Accuracy is an issue because it takes time to align the two holes. Like in the first concept, this might only be a couple of seconds but the actual vessel pressure would be affected.

- **Lowering plate**

A Y-shaped tube would also be needed in this case located as shown in Figure

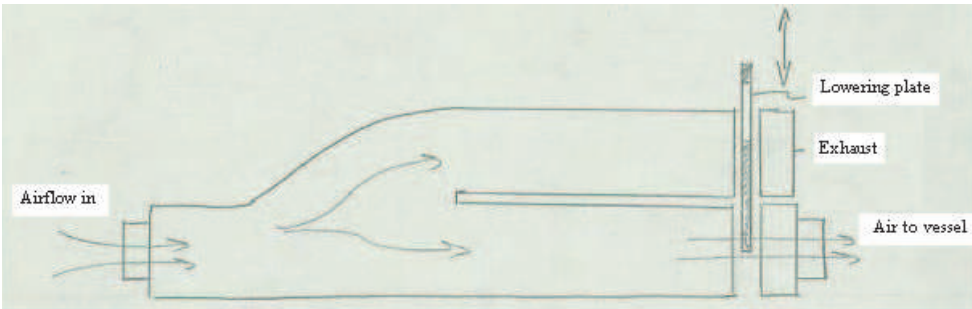


Figure 7: Concept 3 Sketch

7. A plate with a hole of similar dimensions to the pipe outlets would be machined having teeth on one side. These teeth would mesh with an outer

gear connected to a motor that would lower and raise the gate. In the inflating mode, the gate would be completely raised and air would flow into the vessel. When the target pressure is reached, the gate is lowered, blocking the lower opening and diverting the flow towards the exhaust.

*S*trengths

- Cost is reduced because, like the first concept, only a motor has to be purchased from an external supplier.
- The geometry of the gate is simple, therefore its machining would not be complicated.
- Power requirements are low because a low-voltage (3 Volt) motor can be used.

*W*eaknesses

- Accuracy is very low in this design since the plate is constantly moving up and down and would be difficult to seal. A considerable amount of pressure would be lost when the air passes through the gate and into the vessel. Even though there would be some pressure loss in every single one of the proposed concepts, in this case the pressure loss will be significantly higher because the moving gate would not be sealed to the tube. In this

geometry it is much easier for the airflow to deviate.

- Durability of the components is also questionable since the gears used to lower and raise the plate would have to withstand a drop.
- The dimensions of this concept are bigger than the other concepts because the gate needs space to open and close.

- **Solenoid valve**

In this concept (Figure 8), a three way solenoid valve is introduced in order

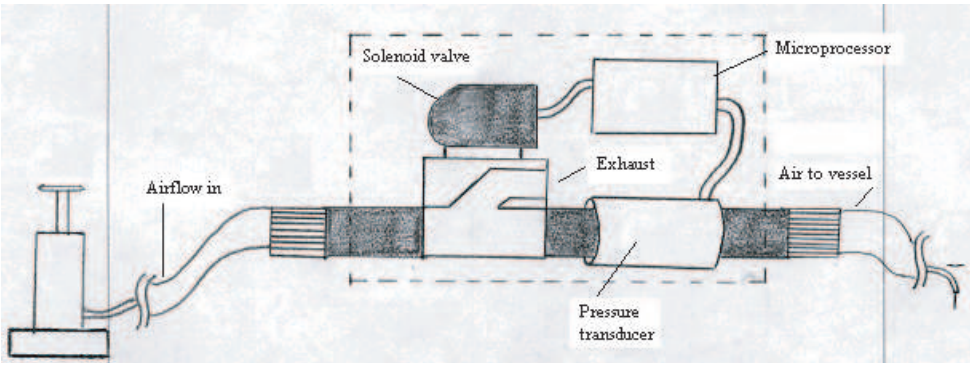


Figure 8: Concept 4 Sketch

to control the flow of air. In the universal mode, a solenoid valve can have the air flow directions needed in this case. In the inflating mode, air will go from the inlet to the vessel. In the exhaust mode the air is diverted to flow out of the third connection.

*S*trengths

- Since the solenoid valve would be purchased from an external supplier, no major machining would be necessary.
- The dimensions are reduced to the dimensions of the solenoid.
- In case of malfunction the solenoid could be changed with ease.
- The solenoid is a durable and precise component because the diversion of the airflow is done almost instantaneously. The inflation process would be favored.
- The part count would be reduced since the solenoid can perform this function by itself.
- The part count would be reduced since the solenoid can perform the flow controlling functions.

*W*eaknesses

- Cost is the main drawback of the solenoid since the price range of this device is $70-$100.
- The solenoid is a fairly heavy component (1.5-2.0 lbs) that could affect the weight requirements.

- Power requirements are high since the solenoid must be energized with 12 volts.

The selected concept was the fourth option, which employs a solenoid valve to direct the airflow. Even though at first glance all four concepts might seem to have a similar number of strength and weaknesses, there are some particular details of concepts 1-3 that led team unum to discard them and pursue concept 4. In Concept 1, for example, the machining was extremely hard to perform. A high level of detail was needed to fit the shape of the rotating door inside the tube. Furthermore, once the flap was machined, another issue was fitting it into the Y-shaped tube without leaving any holes opened through which the air could escape. Concept 2 is an interesting option but accuracy is a decisive factor. Once the target pressure is reached it will take time to align the two openings to divert the air flow. Even then, some air might tend to continue to flow towards the vessel. Even though machining was not as difficult as with Concept 1, it still required some time and money to machine these parts. Concept 3 had even greater issues with accuracy. It was complicated to seal the air path through the plate since the plate was constantly moving up and down. Some air flow could have escaped in this section since it would have been difficult to seal the metal plate in place. Finally, the solenoid option had a series of attractive attributes that outnumbered its weaknesses. With a $500 budget, money was not a driving

force for our decisions. The solenoid presented a trade off between the convenience of not having to machine vs. paying more money and having a heavier component. Since the drawbacks were affordable, the decision was made to pursue Concept 4: the solenoid valve.

2.3 Proposed Concept Technical Description

2.3.1 Operation of the Aura Valve

The AuRA Valve is intended to be used as an airflow control device, accepting pressurized air from an air compressor, hand pump, or foot pump, directing this airflow through the device, measuring the current air pressure within the system, delivering this pressurized air into an inflatable, and redirecting the airflow away from the inflatable when its pressure reaches the target pressure specified by the user. Key goals in the design of this product include ease of operation, versatility, compactness, and robustness. The following description of intended operating procedures will provide an overview of the construction with which the user will interface.

The user will initially connect the AuRA Valve to an AC wall outlet with the product resting on a surface or ground between an inflatable and an air source. Future developments of this product will incorporate on-board rechargeable battery

packs. The user will depress a power button, powering on the system. He will then connect the *Smarthead*^{TM} valve head to the inflatable stem, securely locking the valve head to either a Presta or Schrader valve on either a bicycle or car tire. If a sports ball is to be inflated, a standard 5/16-32 UNEF inflation needle will be inserted into the valve chuck, locked into place, and inserted into the ball valve. Using the increment and decrement buttons on the product face (Figure 9), he will input the target pressure of the inflatable, selecting "enter" when the desired target pressure is displayed on the LCD (Figure 10) and beginning the pressure control process. The

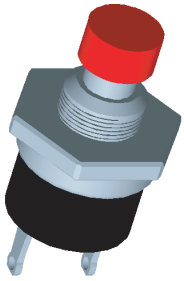


Figure 9: User Interface Pushbutton

selectable pressure range will be between 0 psi and 65 psi, in increments of 1 psi. At this point, the solenoid valve will cease exhausting inlet air and begin responding to the internal system pressure. Using the chuck from the existing air supply, the

Figure 10: User Interface LCD

user will lock the pump onto the inlet chuck adapter of the AuRA Valve and begin pumping, forcing air through the system and into the inflatable. If an industrial or large-scale pump is used as an air supply, he will simply switch the compressor on. The target pressure will continue to be displayed on the LCD, as will the current system pressure. Upon reaching a pressure within 5% of the target, the system will divert the airflow away from the vessel, exhausting the excess air out of the system while allowing no backflow from the inflatable. At this point, the user will switch off the air source and disconnect both the source and the inflatable. The power button will again be depressed to turn off the system, which may now be stored.

During operation, air will flow from the air supply, through the chuck adapter and hosing, into a solenoid valve (Figure 11) which directs the flow either into the vessel or exhausts it into the atmosphere. If the air is directed into the vessel, it flows through a transducer adapter, where a pressure transducer (Figure 12)measures its current pressure. The air will continue onward into the $Smarthead^{TM}$ assembly and

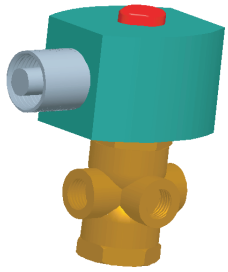


Figure 11: Solenoid Valve

into the inflatable. The pressure transducer will relay pressure information to the MiniMax microcontroller (Figure 13) which will actuate the solenoid valve based on these pressure readings. When the pressure of the inflatable rises to within 5% of the target pressure, the microcontroller will actuate the solenoid valve to exhaust the air into the atmosphere and prevent backflow from the inflatable.

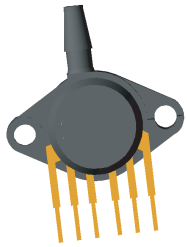


Figure 12: Pressure Transducer

Aesthetic considerations have been partially explored above. It is desired that the system remain as compact as possible, preferably arriving at a volume no greater than 7" × 4" × 4.5" and with a weight less than 3 lbs. An aesthetic housing design, aimed at minimizing the system volume and providing durability against lifetime abuse, will be designed and manufactured from stereolithography material. The LCD will provide two lines of text with 20 characters apiece, allowing the user to see both the target pressure, as well as the system's progress towards that target. For the current prototype, standard surface-mount buttons will be used, though future design iterations may incorporate flat or waterproof keypad-type buttons.

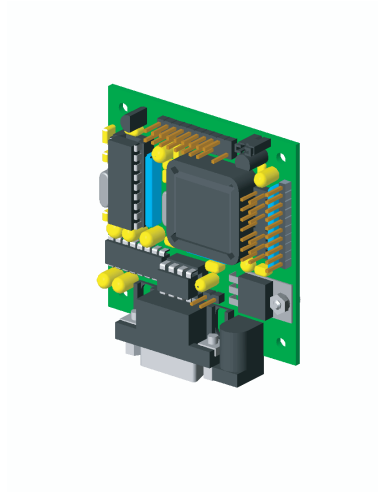


Figure 13: Minimax Microcontroller

Safety is a primary concern for this product. Poorly chosen pneumatic components, if over-pressured, can fail, causing serious injury to the user. Addressing these safety concerns, components have been chosen with pressure ratings beyond the required maximum pressure by at least 100 psi. The solenoid valve was selected so that, should the user begin the inflation process on an unpowered system, the valve will simply exhaust all incoming air, rather than begin an uncontrolled inflation process. In addition, during powered operation, should the pressure ever rise above the maximum capacity of 80 psi, a safety feature incorporated in the programming of the microprocessor will ensure that it automatically begins exhausting the air. With these safety measures in mind, the airflow, power, and control subsystems were de-

signed to provide this described functionality.

2.3.2 Technical Issue - Airflow Control

Component Definition

The functional core of the AuRA Valve lies in the mechanical control of the pressurized airflow through the system. It is the successful direction of this airflow, as well as the prompt and accurate airflow cutoff that the user expects from the product, and the electrical and logical subsystems exist solely to govern the successful actuation of this mechanical subsystem. In the broadest scope, the mechanical airflow subsystem consists of the mechanical hardware necessary to accept airflow from an outside source, to mate with several types of pressure vessels to deliver this air, to measure the internal system pressure, to divert the airflow upon reaching a critical air pressure, and to conduct airflow between these various devices with minimal pressure loss.

The generality of these functional requirements leaves much freedom in designing the subsystem. However, apart from its independent success, the airflow subsystem must interact with other subsystems, as well as conform to the overall product specifications itemized above. Interactions between the power supply and logical control

subsystem are detailed below. A balance between weight, size, cost, and functionality must also be achieved, as a functional yet compact and cost-effective final product is the goal.

In fulfilling the functional subsystem requirements outlined above, overall mechanical components were selected. The primary piece of hardware is a valve, capable of diverting a pressurized airflow. This device must be controllable by integrated intelligence, be able to divert the airflow quickly so as to avoid over-inflation, and minimize airflow constriction. Ultimately, a 3-way universal solenoid valve was selected as this device.

An electromechanical device was required to interface between the air pressure in the inflatable and the logical control of the system. The purpose of this device is to measure the pressure of the inflatable and relay that information to a microprocessor for system control. This device must be able to read pressures between 0 and 65 psi in order to sense all potential system pressures. It must then convert that pressure into a signal readable by a microcontroller. Finally, it must be able to connect to the system's airways and electrical circuits, causing minimal airflow constriction and pressure losses. A standard pressure transducer was selected as this device.

Finally, various static mechanical components were needed to connect the major valve and pressure-measuring devices. Though far less complex than their larger

counterparts, these components provide critical system interfaces to existing consumer products. These components were required to withstand pressures up to 80 psi without failure, as well as to securely mate with the valve and pressure transducer and to connect to a variety of existing air sources and common inflatables, including sports balls, bicycle tires, and car tires. Several components, including PVC hosing, pipe fittings, commercial bike valves, inflation needles, and prototyped components were incorporated into the subsystem.

Valve Evaluation

Due to constraints on the scope of this project and on the capabilities of AME 470 Ltd, it was decided that any complex valve device utilized would be purchased, rather than manufactured in-house. For this reason, individual characteristics of a valve will depend solely on the individual valve model; characteristics cannot be independently varied. Solenoid valves were selected based on their functional capabilities as well as existing solenoid experience within Team Unum. Once the overall valve type was selected, individual valve models were compared with the intent of selecting the one with the optimum set of characteristics.

Direct-acting solenoid valves, ie valves actuated electronically, were selected for their ability to operate at pressures of 0 psi, which would correspond to inflating

empty vessels. It was also decided that, for safety reasons, it is preferable to divert an airflow than to simply block the airline and allow pressure to backup and grow in the system. For this reason, a three-way solenoid valve was selected. This type of valve has an inlet opening and two outlets, one leading to the pressure vessel and another to be exhausted to the atmosphere. Of the array of three-way valves, a universal valve configuration was required. In this configuration, de-energizing the valve would divert the inlet valve to the exhaust valve. Any other configuration would divert the pressure vessel to the exhaust, thereby deflating the inflatable. Based on these configuration requirements, four solenoid valves were selected for evaluation.

Of the models considered, the power requirements were first examined. Solenoid valves typically operate at between 6 and 240V, as well as function with reduced performance at 85% power. The intended system power supply (standard batteries or a converted DC source derived from an outlet) place overall limits on the power available for a valve. In addition, increasing the power requirement also increases the required size and weight of the valve. Based on the 3 lb system weight limit and the 7" $\times$ 4" $\times$ 4.5" system volume limit, the solenoid valve power requirement is constrained to less than 24V.

The pressure range of the valve must meet specified product requirements. The valve must be able to operate between 0 psi (a completely deflated system) and 65

psi (an inflated mountain bike tire), though a valve capable of safely handling higher pressure differences is desirable. All valves have a specified maximum operating differential, governing the maximum pressure at which they can safely function. A tradeoff between pressure range and valve robustness (accompanied by increase size and weight) exists.

The flow rate through a valve is significant in the quick operation of the product. The flow rate is calculated in the Trade Study on the solenoid valve (Section 3.2). Analysis of this relationship revealed that insignificant variation existed between the valves in their flow rates.

Examining these valve characteristics and weighing their individual importance, it was decided that factors such as size, weight, and pressure range would have greater weight in valve selection than power requirements, cost, and flow rate. The relative performances of each valve with respect to these weighting factors were given numeric values as seen in the Trade Study. The model with the highest measure of merit (MOM) was deemed optimal and selected. From this process, the ASCO P/N 8320G184 solenoid valve was chosen.

This valve will fulfill all functional requirements expected of it. In relation to the system as a whole, its size and weight (3.75" $\times$ 1.95" $\times$ 1.19" and 1.5 lbs, respectively) are larger than expected and impose a further need for efficient design in the rest

of the system. A replacement 12V solenoid will allow this valve to operate within the power scheme of the rest of the AuRA Valve without imposing unreasonable performance loss. The $89 cost is par with similar valves and manageable with a $500 budget. However, in future product developments, alternative valve options will need to be examined with cost in mind.

Pipe Fitting Analysis

The static components of the airflow subsystem are far less complex than the valve or transducer devices, yet provide critical functionality and, if overlooked, can become critical failures of the system. As with the solenoid valve, due to the fabrication capability limitations of Team Unum as well as the widespread availability of inexpensive standardized pipe fittings, it was decided that standard fittings and hosing should be purchased wherever possible.

The majority of the pipe fittings were selected to mate with the solenoid valve. All valve configurations utilized a standard 1/4" NPT (National Pipe Taper) thread size. Standard barbed fittings with this thread were available with connections for either 1/4" or 3/8" inner diameter hosing, of which the 1/4" diameter was selected for increased airflow capacity. All fittings were rated at 200 psi, far exceeding the requirements posed by the AuRA Valve. In order to reduce the overall part count,

brass couplings were utilized wherever possible.

Connections to the inflatable, as well as to existing air supplies, required adapting to unusual or non-standard connection types. In order to adapt to all bicycle and car tires, the valve must be compatible with both Presta and Schrader type stem valves. In addition, inflation of sports balls requires the use of inflation needles with a 5/16-32 UNEF thread. The Smarthead by Topeak, a valve head adapting to Presta valves, Schrader valves, and inflatable needles, provides all these functions in one piece of hardware and was purchased commercially for $18.00. The 5/16-32 UNEF thread, standard throughout the inflatable industry, is not available in standard pipe fittings. Consequently, a custom fitting combining this thread and a 1/4" hose barb must be fabricated to provide interface between the AuRA Valve and existing foot and hand pumps.

The selection of the solenoid fittings constrained the selection of the pneumatic tubing. To mate with the pipe fittings, tubing of 1/4" inner diameter was required. In addition, as the tubing would be used both inside and outside of the system housing, the material must be durable, as well as safely withstand the maximum pressure capacity of the system, with a significant safety margin. Options considered included braided hosing, PVC hosing, and rubber hosing. The three options cost $1.00/ft, $2.50/ft, and $3.30/ft, respectively and have pressure ratings of 100 psi, 300 psi, and

300 psi, respectively. These two major factors, as well as material durability, weight, and weather resistance, were incorporated into a trade study which concluded that PVC tubing was the optimum choice for both external and internal hosing.

Selection of these mechanical components will provide a system capable of safely withstanding pressures exceeding the maximum required pressures of the AuRA Valve by as much as 100 psi. The incorporation of the Topeak *Smarthead*^{TM} and custom-fabricated chuck adapter will provide product versatility and marketability. The size of the fitting components must be considered in the final housing design, but are dwarfed in weight by the solenoid valve. Negative effects of the fitting system will occur only on the aesthetic level.

Pressure Transducer Analysis

The system's pressure sensor serves to measure the air pressure within the airway and, using a provided voltage, transmit a signal to the microprocessor relaying this pressure information. A simple pressure transducer can be made through cheap materials such as strain gauges and soda cans, so several sources for this component, including in-house production, were examined in a Trade Study (Section 3.3). Ultimately, three types of pressure transducers were considered: homemade transducers, traditional transducers, and in-line transducers.

A homemade pressure transducer, comprised of strain gauge rosettes and a pressure-sensitive housing, was considered initially. This method provided unlimited customization, allowing a transducer to be tailored to the application. The low cost was also a selling point of this method, as thin metal sheets and strain gauges are both quite inexpensive. The selection of an appropriate metal housing posed a problem, however, as it was required to be both sensitive to pressure changes, yet must not plastically deform or fatigue. In addition, the size of such a system limits the output signal voltage (generally in the mV range), requiring additional circuitry to amplify this signal for microprocessor use. System robustness also posed a problem with this method. Such a component would require 1.5-5V for operation, costing between $10 and $30, and producing outputs with 0.5% accuracy.

The traditional pressure transducer is available in a wide variety of configurations and, due to its established use, offers confidence in its accuracy (0.25-1.5%) and reliability. The average component cost (between $18 and $30), was somewhat higher than for a homemade transducer, but not unreasonable for the current budget. The compact and robust housing design made this selection more appealing for a durable system. However, this type of transducer is typically not configured for attachment to our existing piping system, requiring a custom-fabricated adapter to link it to the pathways. This imposes additional costs, as well as potential for further pressure

loss.

The flow-through pressure transducer can be linked directly to standard piping, removing the need for custom-fabricated adapters. The accuracy (0.2%) is also excellent. However, this type of transducer, apart from being rare, is intended for precise laboratory settings. As such, it requires a high air purity which cannot be guaranteed in commercial use. The power requirement (11-30V) is significantly higher than its counterparts, as is its cost ($60-$100).

As with the solenoid valve, the best transducer option was selected by evaluating each option's measures of merit. The desired system accuracy is desired to be 5% of the target pressure. All of the transducers provide far more accuracy than is expected of them, making accuracy a relatively unimportant means of comparison and was assigned a weighting factor of 0.1. Being one of the most expensive system components, it is desirable that the transducer cost as little as possible. Thus, it was assigned the largest weighting factor, 0.6. Finally, the transducer contributes to overall system power requirements which will in turn affect system life, size, and weight. Consequently, a transducer with small voltage needs is desirable, giving power requirements a weighting factor of 0.3.

Each transducer variable (cost, accuracy, and power requirement) was assigned a numeric value relative to the other configurations . From this, the measure of

merit of each transducer was calculated. Based on this calculation, the flow-through transducer produced the highest merit measure, though all three options produced extremely close measures.

Application of system constraints and examination of the effects of pressure losses refined this transducer selection. It was determined that, due to the transducer geometry, losses at the transducer connection would be minimal. Furthermore, the minimum cost of the flow-through transducer is almost double the target cost of the entire system. Taking both the results of the measure of merit analysis and these further considerations into account, it was determined that a traditional pressure transducer should be used for this system. Specifically, the Motorola MPX5700-GP-ND was selected (see Figure 12).

Selection of the traditional transducer provides a reasonable degree of accuracy (0.25%) as well as a power requirement (5V) consistent with other electromechanical devices in the system. Pressure losses due to transducer connection will remain a concern and will have to be minimized through the use of airtight sealant or tubing methods. Its connection method does not meet the standards utilized in the rest of the product's tubing, requiring a custom adapter to be fabricated to connect the transducer to the airway. The small size (approximately $.31in\times$ $.71in\times$ 1.18 in) will have minimal effects of product size and the transducers weight is negligible com-

pared to the rest of the system. Its signal output is great enough to be read by a microprocessor without the need for an amplification board.

Conclusion

Guided by three trade studies, a mechanical airflow subsystem has been developed for the AuRA Valve. This subsystem will be capable of mating with existing pumps and inflatables, of conducting pressurized air through the system safely beyond the required pressure capacity of 80 psi, of quickly diverting the flow of air, and of measuring the internal air pressure within an accuracy of 5% of the target pressure. A three-way universal solenoid valve was selected to control air direction, a standard pressure transducer utilized to measure internal pressure, standard pipe fittings used to link these major components, and the Topeak $Smarthead^{TM}$ incorporated to connect to common inflatables. Weight and size of these components must be taken into account in the layout design of this system, in an effort to keep the final product compact yet robust. Incorporation of the electrical and logical control systems was a major consideration in the selection of these components, and both electromechanical devices will interface easily with common electrical components.

2.3.3 Technical Issue - Power Supply

Component Definition:

One of the most important design issues of the AuRA Valve is the power supply. There are many electrical components that have a variety of different power needs. The power supply must be able to provide adequate power to all components so they can function properly. Failure to do so could cause the valve to be inaccurate or not even work at all. As a result, it is imperative for the power supply to fulfill the needs of the individual components.

The power supply must also meet the criteria set forth in the design requirements. Technically, nothing is explicitly stated about the power supply. Thus, there is much freedom with its design. However, it should be designed with consideration of the final design requirements. When combined with the other subsystems, the valve as a whole must still meet the final design requirements. Making the power supply too large or too expensive could adversely affect other components.

Before any type of power supply can be evaluated, the power requirements of the system must be defined. The solenoid requires the highest voltage out of any component. It needs 12 volts to energize the coil that changes the direction of air flow. The power supply must be able to provide that voltage, otherwise the solenoid will not function correctly.

Many of the components have current needs in addition to their voltage needs. As a result, the power supply must be able to deliver a certain amount of current with the 12 volts. The average monthly current consumption is calculated in the Power Supply Trade Study included in the Appendix. The analysis was based on the estimated average use of the valve during a one-month time period. The final result was obtained by summing the current consumption of the individual components. The Appendix contains all of the details on how the result was computed. Ultimately, it was determined that the AuRA Valve will use approximately less than 400 mA-hr per month. There are no specific requirements pertaining to the current consumption, but it is considered in the later design stages. The current usage plays a large role in selecting a power supply because it has a significant effect on valve portability.

Power Supply Evaluation:

Three different methods of supplying power were examined: an AC to DC converter, standard alkaline batteries, and a rechargeable battery pack. Those categories are further subdivided into more specific groups (such as dividing up standard batteries by battery size, for example).

The first method involves the use of a simple AC to DC converter. It would tap into a standard 120 volt AC outlet and convert the output to 12 volts DC. Then,

the 12 volt source could power all of the AuRA Valve's components. A huge benefit to this method is that the source could supply power for as long as needed. The outlet would essentially act as a continual source of voltage and current. A user would never have to worry about replacing batteries. However, the major downside is that the portability of the valve would be greatly reduced. It would only be able to operate in the vicinity of a standard outlet.

Standard alkaline batteries provide a different alternative for the power supply. Unlike the AC to DC converter, they would facilitate portability. However, that is the only area where they are better than the converter. They would not be a source of constant voltage and current for the valve's components. Over time, their voltage and current would slowly decrease. Eventually, the batteries would reach a point where they could not supply the power necessary for the valve to operate. The user would have to replace those batteries with newer batteries. Although that is required for many electronic devices, it would be more frequent with the AuRA Valve because it draws a high amount of current. It is determined later on whether or not the portability benefits outweigh all of the negatives.

The last option for a power supply would use rechargeable batteries. The batteries would provide the portability of standard alkaline batteries, but with longer life. The battery pack would be custom-designed to get a good balance between size and life.

When drained, it would be recharged by an AC to DC converter that hooked up directly to the valve. Also, it could be powered directly by the converter if it were plugged in during use. Its operation would be very similar to that of a standard cell phone battery. This design would combine the benefits of the AC to DC converter with those of the standard batteries.

Clearly, the best option would be to use a rechargeable battery pack. It basically combines the first two methods into one power supply. It has the ability to go with the user and operate anywhere. It achieves that task better than the standard batteries because the battery pack is rechargeable. It is not necessary to purchase new batteries once the pack is drained. It can be recharged simply be attaching the valve to an AC to DC converter. Furthermore, that same AC to DC converter can be used to supply the valve's power. If an outlet is nearby, the valve can be plugged in so the battery pack is not used. Overall, the best method of supplying power to the AuRA Valve is through a rechargeable battery pack.

Alkaline Battery Analysis:

The Power Supply Trade Study only examined standard alkaline batteries as a power source. Its purpose was to find the best battery size for the valve. It did not analyze AC to DC converters because it was focused on portable power. The converters are

not viewed as a portable power source so they were omitted.

Rechargeable battery packs, on the other hand, were omitted for different reasons. They were left out of the trade study because the study focused on power for the valve prototype, not the final product. Although the rechargeable battery packs would be the best option for the final product, they are not a good idea for a prototype. It is extremely difficult to design a recharging system for batteries. No one in Team Unum possesses the necessary skills to carry out that task. Moreover, a poorly designed charger can be a safety hazard. If done incorrectly, the battery pack can heat up and explode. Due to that fact, rechargeable battery packs were not considered for the prototype. After the prototyping stage is completed, that power supply method will be re-evaluated. If it is selected as the power supply for the final design, the design work will be outsourced to engineers that specialize in that particular area.

The Power Supply Trade Study focused on one main design variable: battery size. The quantity and the arrangement of batteries were also considered. The state variables included battery life, volume, weight, and cost. These four factors were regarded as the most important characteristics of the batteries.

There were not many constraints for the state variables. As stated previously, the original design requirements did not address the power supply at all. Consequently, the trade study simply used the final product's requirements as rough guidelines.

The volume of the batteries had to be less than 7”x4”x2” and the weight had to be less than 3 lbs. Cost had to be less than $30 for the entire valve, but not the batteries. They did not have any cost constraints since they would be supplied by the user. Also, there were no requirements for battery life. The lack of constraints caused the measure of merit to be the deciding factor on which battery size would work best.

The measure of merit compared the benefits of different battery sizes against one another. The performance of each battery size with respect to each state variable was normalized in a table. Then, each normalized value was scaled by a weighting factor and summed. The resulting value was that size’s measure of merit. Since the final value relied heavily on the weighting factor, four different weighting schemes were used. Each scheme represented the features that a potential user might be looking for. The process of calculating the measure of merit is explained more in depth in the Appendix.

The overall evaluation of the batteries has beneficial results. The same batteries consistently appeared on top even when the weighting factors were altered. This means that those batteries can work well for many different users.

Based on the measure of merit, the final design should use the 9 volt battery size. The AAA battery size would also be acceptable. In fact, it is slightly better than the

9 volt in terms of battery life, weight, and volume. However, due to their difference in cost, the 9 volt size was consistently superior in measure of merit.

Although battery quantity was not considered in the measure of merit, it would be simpler for the user to keep track of fewer batteries. For a 12 volt configuration, 8 AAA batteries would be needed as opposed to just two 9 volt batteries. Many users may see that as another advantage for the 9 volt size.

The battery comparison yielded results that will be good for the prototype. At most, the batteries will only add a few fractions of a lb to the valve. The weight falls well within the requirement of 3 lbs. Also, its volume is nowhere near the size constraint. The 9 volt battery configuration will meet all of the power needs of the AuRA Valve's electrical components. It has enough capacity to power the valve for at least 1.75 months (based on the average current consumption calculation and the capacity of a 9 volt battery). In reality, that is a very conservative estimate so the actual time period is probably longer. Compared to other alkaline batteries, the 9 volt battery configuration is the design choice with the best measure of merit.

Conclusion:

Despite the results of the Power Supply Trade Study, the AuRA Valve prototype will use an AC to DC converter. The main goal of fabricating a prototype is to

demonstrate the feasibility of the concept. The design process is going to involve a great deal of testing and hands-on analysis. If batteries were to be used, they would need to be replaced frequently due to their low capacity. A great deal of money would be wasted buying new batteries. Also, decreasing voltage and current could cause undesirable effects on the system. The AC to DC converter would work best because it is inexpensive and it provides a constant output. The converter's lack of portability is not an issue because the prototype will be tested primarily indoors. For those reasons, the prototype will use an AC to DC converter rather than batteries.

2.3.4 Technical Issue - Microprocessor Control Logic

Component Definition:

The microprocessor control is an important feature of the AuRA Valve. Several different components must work together in unison. The control process involves user input, sensors, electromechanical components, and a microprocessor. The main challenge is coordinating the activity of those components so the valve performs its function correctly. Proper arrangement of the components and reliable programming are critical.

The control process begins with user input. The method of input needs to be simple, yet adequate for the system's needs. The user should be able to easily

understand how to enter information. Additionally, there should be something that provides updates on the state of the system. Then, the user can make changes if needed. The microprocessor will receive the information from the user and adjust its control routine accordingly.

The next aspect of control involves sensing. The valve must have a sensor that is robust and accurate. The microprocessor needs to check pressure measurements on a frequent basis to see if the target pressure has been reached. If the sensor fails, the whole system will fail. The control procedure is dependent on knowing the system pressure at any given time.

Although the electromechanical components are controlled by the microprocessor, they are the components that physically control the air flow. One of their most important characteristics is speed. They must be able to change the air flow's direction in very little time. If the microprocessor determines that the pressure of the system is equal to the desired pressure, then the air flow into the vessel must terminate immediately. Otherwise, the vessel could become over-inflated.

The last element, the microprocessor, links everything together. It reads input from both the user and the sensor. Then, it controls the electromechanical components based on those readings. The main requirement is that the microprocessor must be able to handle all of the inputs and outputs. If it does not have enough

capacity for the other control elements, then it never has a chance of success. Also, it needs to be programmed so the valve behaves as intended. The programming should be effective and dependable. It should produce repeatable results every time the valve is put into operation.

Control System Setup:

The microprocessor is the most important control element. In order for the valve to function properly, the microprocessor must fulfill the criteria listed previously. The MiniMAX controller (Figure 13) will be used for the AuRA Valve. It is a good microprocessor because it has a sufficient amount of I/O pins and it can be programmed easily. Essentially, it fulfills the needs of the valve because it can adequately control the other components.

The user will interact with the MiniMAX through an LCD and four pushbuttons (Figure 9). The LCD's main purpose is to make the valve more user-friendly. It will display messages instructing what the user needs to do. Then, after the user has entered a pressure value, it will display the state of the system. It will show the target pressure (the value entered by the user) as well as the current pressure. Basically, it will keep the user informed about the pressure status and provide instructions when needed.

The pushbuttons provide a way for the user to change the target pressure. When prompted, two pushbuttons will be used to increase and decrease the target pressure. Then, the value will be saved by pressing a third pushbutton. After that, the MiniMAX will go to the next step in the control routine. If the user wants to change the target value later, a button can be pressed and the routine will start over.

The setup for the LCD is fairly simple. It is fitted with a cable that fits into the LCD socket on the MiniMAX board. The pins from the LCD already match up correctly with the corresponding pins on the microprocessor. The pushbuttons, however, involve more effort.

There are several different ways that the pushbuttons can be attached to the MiniMAX. Each method involves a ground source and one I/O pin. The first approach sends a high signal (+5 volts) to an I/O pin when a button is pressed. Normally, the I/O pin is connected to ground through a resistor. When the button is pressed, the pin becomes connected to the microprocessor's internal 5 volt source. As a result, the I/O pin reads 5 volts as opposed to the regular 0 volts. The microprocessor recognizes the voltage change as the pressing of a button.

The second technique is similar to the first, except the high and low signals are reversed. The I/O pin reads 5 volts initially, but then reads 0 volts once a button is pressed. It works in that manner because the I/O pin is normally connected to

the internal 5 volt source through a resistor. When the button is pressed, the pin is grounded causing the signal to drop to 0 volts. Just as before, the microprocessor knows that the signal change corresponds to a button being pressed. These two methods describe the most common ways of using pushbuttons. However, the second approach is more widely used because it is more reliable. It has a higher rate of dependability compared to the first method. Consequently, it is the method that will be used with the AuRA Valve.

A linear pressure transducer (Figure 12) will be used for the valve's sensor. It will send an analog signal to the microprocessor based on the pressure of the system. Then, the MiniMAX will convert the signal to a pressure value using a calibration factor. The setup for the transducer is fairly simple. Although there are six pins on the component, only three are needed for this application. One pin is connected to the microprocessor's 5 volt source and one pin is connected to ground. Those two pins provide the necessary power for the sensor to operate. The last pin is linked to an I/O pin. It is the pin that sends the MiniMAX the analog pressure signal. The air flow is physically controlled by the electromechanical components. They need to redirect the flow into and out of the vessel very quickly. Based on the requirements, a solenoid valve (Figure 11)is best suited for the main electromechanical component. It is a reliable device that is controlled simply by turning it ON or OFF. However,

due to its voltage and current requirements, the integration of this component is slightly complicated. Unlike the other control elements, the solenoid does not have any pins. The direction of air flow is changed by energizing or de-energizing the solenoid's coil. This makes the setup more difficult because a relay needs to be used (another electromechanical component). The relay acts as a switch that is controlled by the microprocessor. It starts out normally open, but the switch closes when its magnetic coil is energized. The coil is energized by the microprocessor sending a high signal through one of its I/O pins. However, the I/O pins typically do not supply enough current for that type of a component. As a result, it must be arranged in a complex manner.

First, one pin on the relay must be connected to the MiniMAX through an I/O pin and a transistor (the other lead on the transistor is connected to ground). The relay's other pin is connected to the internal 5 volt source in parallel with a diode. The arrangement of the transistor and the diode boost the I/O pin's output current so it is high enough to operate the relay switch. Then, when the MiniMAX sends a high signal, the relay's switch will close. That will cause the solenoid to become energized, allowing air to flow into the vessel.

Microprocessor Programming:

The microprocessor is the intelligence of the AuRA Valve. It is constantly receiving information and telling the other components how to act. If it fails, the valve cannot function properly. It is essential that the microprocessor knows how to interpret information and control the other components. The MiniMAX will be able to carry out those two functions only if it is programmed correctly.

The AuRA Valve has simple control logic. The user enters a target pressure using the pushbuttons. Then, the MiniMAX looks at the current pressure of the system based on transducer readings. If the current pressure is less than the target pressure, then the air flow is directed into the vessel by activating the relay (which activates the solenoid). During inflation, the MiniMAX compares the current pressure with the target pressure until they are equal (or as soon as the current pressure is greater than the target pressure). Then, the MiniMAX stops the flow into the vessel by de-energizing the relay's coil (which de-energizes the solenoid's coil). At that point, the vessel's pressure equals the target pressure (within some margin of error).

Although the main goal of the program is functionality, it should also be user-friendly. It should be written so the user can operate the valve without consulting an instruction manual. All of the necessary instructions should be displayed on the LCD screen.

The MiniMAX requires the program to be written in the C language. The pro-

gram will make use of several functions for the different control components. The resulting code will be more readable and easier to test. After each section of coding is complete, it will be compiled and downloaded to the microprocessor. Next, it will be thoroughly tested to ensure that it behaves in the intended manner. Currently, the pseudo code consists of the following:

- Turn ON Routine MiniMAX starts in sleep mode *(power connected, but not ON)*
  - Do nothing until the interrupt is activated *(User pushes ON button which activates the interrupt)*
  - Turn ON the microprocessor
  - Go to User Input Routine
- User Input Routine
  - Print instructions for the user on the LCD
  - Wait for user to input a new target pressure with the pushbuttons *User adjusts target pressure with pushbuttons, then hits the ENTER button*
  - Store the target pressure
  - Go to Pressure Measurement Routine

- Pressure Measurement Routine
  - Begin reading pressure data from transducer
  - Display current pressure and target pressure
  - If current pressure is less than target pressure, go to Relay Routine
- Relay Routine
  - Activate relay *(Relay turns on solenoid and the vessel begins inflating)*
  - Continue comparing the current pressure to the target pressure
  - If user presses a button, turn off relay and go to User Input Routine
  - If current pressure is greater than or equal to target pressure, turn off relay *(Relay turns off solenoid, vessel stops inflating)*
  - Go to Termination Routine
- Termination Routine
  - Print message on LCD that notifies user that inflation is complete
  - Continue to display pressure of system
  - Print message telling user to detach vessel and turn off AuRA Valve
  - If OFF button has not been pushed after 5 minutes, go to sleep mode

Conclusion:

The control elements of the AuRA Valve are vital to the product's success. Together, they determine how the valve behaves. If any one of those components does not perform its task correctly, the system will fail. In addition to being arranged properly, they must be commanded accurately. The MiniMAX is in charge of controlling the individual components, but the MiniMAX itself is controlled by a program. Therefore, the microprocessor programming is the most important element of the control structure. It has to be written so it can simultaneously interpret data and control the solenoid. Although each control component is significant, the programming is undoubtedly the most influential aspect.

3 Appendix

The following Trade Studies were performed in order to select the best components and/or configurations for the proposed Aura Valve. The detailed analysis of these individual design issues played an integral part in the overall design of the product. The following issues were studied in depth as Trade Studies:

- Power Supply
- Air Valve
- Pressure Sensor
- Connectors and Hosing
- Product Housing

3.1 Trade Study: Power Supply

5 October 2004

- Project Description:

  The goal of this project is to create a smart tool that regulates air inflation. The tool will include several important components that are critical to its success. These components need to be studied in depth so that the best design

decisions are made. Please note that throughout this study the smart tool will be referred to as the AuRA Valve. The acronym stands for Automatically Regulated Air Valve.

- Purpose:

  The purpose of this trade study is to evaluate the power supply options for the AuRA Valve. The valve will derive its power from a standard AC outlet as well as batteries. It would be ideal to use AC power at all times, but that is not realistic. The valve is intended to be used on bicycle tires, automobile tires, and athletic balls. Often, these items are inflated in locations that do not contain AC outlets. As a result, it is imperative that the AuRA Valve be able to run off of batteries.

  This trade study will focus on battery power. More specifically, it will focus on the benefits and disadvantages of using different alkaline batteries (such as the 9 volt, AAA, AA, C, and D sizes). The batteries will be evaluated according to their state variables. Then, the best battery arrangement will be determined from the measure of merit.

  Three different voltage scenarios will be investigated (6, 12, and 24 volt). This will be done because the other electrical components have not been selected yet.

Consequently, the power consumption for the valve is unknown. The batteries will be analyzed for three different output voltages and the power consumption will be estimated.

- Variables:

Design Variables: The main design variable for this study is battery size. The battery sizes in consideration are 9 volt, AAA, AA, C, and D. The secondary design variables are the quantity of batteries and the arrangement of the batteries. There is no limit on how many batteries can be used or how they can be arranged. There is no need for those constraints because the state variables will dictate what is reasonable.

It was decided a priori to use one size of standard alkaline batteries for the battery power. That decision was made for a few reasons. The first reason deals with convenience. While it is possible to create a customized battery pack for the AuRA Valve, most users would prefer regular batteries. Then, it is much easier to replace the batteries. Battery replacement is further simplified if only one particular battery size is used (as opposed to mixing sizes; for example, using one 9 volt battery along with two AA batteries).

Also, it would have been possible to use rechargeable batteries (or a rechargeable battery pack) and have a built in charger. However, designing a battery charger is an extremely complicated task. If done incorrectly, the batteries could heat up and explode. For reasons of safety, the charger will not be included in the design. If the user wants to use rechargeable batteries, it is still an option. Standard rechargeable batteries could be used in place of the alkaline batteries. Though when drained, they would have to be charged in an external charger not connected to the AuRA Valve.

State Variables: The trades study will consider four state variables. Those four state variables include cost, battery life, volume, and weight.

There are no constraints for cost or battery life, because nothing was said about them in the original design requirements. There was a cost requirement for the AuRA Valve as a whole (under $30), but that did not mention the batteries. It will be up to the user to provide batteries, so their cost is not factored into the total valve cost.

The maximum volume and weight of the AuRA Valve were specified in the design requirements to be less than 7" x 4" x 2" and 3 lbs (1361 grams) respectively. The requirements did not provide specifications for individual components, but everything together cannot exceed the dimensions above. As

a result, the size constraints for the batteries are not obvious. Since the size and weight of the other components are unknown, the volume and weight constraints for the entire valve will be used for the batteries. That assumes the other components take up no space and weigh nothing, which is clearly not true, but those constraints will be adequate for this study. The size of the other components will be taken into account when it is time for the final battery selection.

- Measure of Merit:

The final design variables will be chosen by their measures of merit. The measure of merit is a numerical value based on the state variables for the different options. In order to compare variables with different units, everything must be normalized according to the best option. For example, if the cheapest configuration to supply 12 volts costs $5, all of the cost variables have to be divided by $5. Then, the cost values will be greater than or equal to 1 (with 1 being the best). The same technique will be used for volume, and weight. Battery life, however, will be scaled by the middle value because there is such a large range. It is treated differently and that is explained later on.

Once normalized, the values will be scaled by a weighting factor. It is a neces-

sary action because there are different priorities for the design. Although the volume of the batteries is significant, the cost may be deemed more important. This difference must be reflected so the best option is selected.

The optimal design will have the lowest value for the measure of merit. That can be achieved by minimizing cost, volume, and weight while maximizing life. Equation 1 illustrates this relationship. It can be seen that the values for cost, volume, and weight are added to the measure of merit. As they become larger, the design worsens (as does the measure of merit). Conversely, the value for battery life improves as it gets larger so it is subtracted from the measure of merit.

$$M_n = w_{cost}v_{cost} + w_{volume}v_{volume} + w_{weight}v_{weight} - w_{life}v_{life} \tag{1}$$

The final measure of merit (M) depends greatly on the weightings (w) assigned to each variable (v). The determination of the weightings is explained later on.

- Analysis:

Power Consumption Estimate: The first part of the analysis deals with the

power consumption of the entire valve. As stated above, most of the electrical components have not been selected yet, so the exact power usage is unknown. It is possible to determine a reasonable estimate of its monthly power needs.

The AuRA Valve will probably not be used on a daily basis. Since most people do not need to inflate objects frequently, the estimate will be based on a monthly time period. The first step is to figure out the average time each of the components will be running. For the purpose of analysis, it will be assumed that in one month the user will inflate a set of car tires, two athletic balls, and a pair of bicycle tires.

The ON time for components depends on how quickly items can be inflated. That time further depends on the flow rate of the valve and the volume of the vessel. The solenoid is the limiting factor for the flow rate. The solenoids under consideration for the AuRA Valve have flow rates between 1 and $7ft^3$ per min. The lower flow rate, $1ft^3$ per min, will be used to keep the estimate conservative. By multiplying the flow rate by air's density and dividing by its molecular weight, the flow of moles per minute can be calculated (shown by Equation 2). For air, it was found to be 1.2 moles per min.

$$\frac{moles_{air}}{minute} = \frac{\rho_{air}(flowrate)}{molecularweight} \tag{2}$$

The Ideal Gas Law (Equation 9) is needed to figure out how many moles of air fill up a volume of $1ft^3$ at 1 psi. For air, that value was 0.078 moles.

$$n = \frac{Pv}{RT} \tag{3}$$

Those two values can be used to calculate the time to fill a certain volume to a specified pressure. A constant can be computed by dividing the moles of air by the molar flow rate (results in 0.065 min or 3.9 sec). Then, multiplying that constant by the desired pressure (in psi) and volume (in ft^3) will yield the inflation time (although the units are not actually entered into the Equation 4, it is necessary to use psi and ft^3 so that the answer is scaled appropriately from 1 psi and $1ft^3$).

$$inflationtime = (3.9sec)(Pressure)(Volume) \tag{4}$$

Using Equation 4, estimates can be made for the inflation times for the different vessels. For each of the estimates, the vessels are assumed to start out completely deflated. Consider an automobile tire with a volume of $3ft^3$ and a 34 psi requirement. Then, the inflation time would be 6 minutes and 38 seconds (398 seconds). For a regular set of four tires, the total time would be

approximately 26 minutes and 32 seconds (1560 seconds). Similarly, for a $2ft^3$ athletic ball that requires 8 psi, the inflation time would be 63 seconds. Two of those balls would take about 2 minutes and 6 seconds (126 seconds) to inflate. Lastly, a pair of bicycle tires needing 65 psi with a volume $0.2ft^3$ would each require 51 seconds to inflate (a total time of 1 minute and 42 seconds).

Other factors also need to be considered, most importantly time when the valve is ON, but nothing is being inflated. The expected order of operations is as follows:

1. AuRA Valve is turned ON
2. Valve is connected to the vessel
3. Desired pressure is entered
4. Compressor is turned ON
5. Solenoid is activated and vessel inflates
6. Specified pressure is achieved and solenoid is turned OFF
7. Compressor is turned OFF
8. Valve is disconnected
9. Valve is turned OFF

The action of the solenoid only needs power when a vessel is inflating. The solenoids being investigated use about 400 mA in operation. The microprocessor, on the other hand, draws power as soon as it is turned ON. The selected microprocessor, the Mini-Max, uses about 100 mA on average. The pressure transducer only uses about 20 mA and the LCD's current usage is negligible.

When a vessel is being inflated, the maximum of 520 mA is needed. Maintaining the assumptions above, the maximum current is used for 29 minutes and 48 seconds each month. That results in a current drain of 258 mA-hr.

If only the Mini-Max is ON, 100 mA is needed. It is assumed that it takes an extra 4 minutes to complete the setup and tear down while the AuRA Valve is ON, but not inflating. That adds 32 minutes to bring the total ON time to 1 hour and 2 minutes. That causes 103 mA-hr to be used.

The total current drain per month is equal to 361 mA-hr. That is a conservative estimate for a number of reasons. It assumes the flow rate of the solenoid is low and also that the vessels are initially deflated. In reality, the flow rate will probably be higher and the vessels will be partially inflated. The overly conservative estimate will help determine a reasonable battery life for the valve.

Battery Comparison: The standard alkaline battery sizes are 9 volt, AAA, AA, C, and D. Selection is difficult because the different sizes vary greatly in their

characteristics. As a result, there is a wide range for each of the state variables. A table of battery properties and the resulting state variables are shown in Table 1. The properties are listed for each of the possible output voltage values (6, 12, or 24 volts). The volume was calculated under the assumption that all of the batteries would take up a rectangular space. Even though most of them have a cylindrical shape, the space they will occupy in the valve housing will be rectangular. Also, note that D batteries could not be used for a 24 volt configuration because they exceed the weight constraint.

6 volts	Voltage (V)	# Batt. Needed	Final V	Capacity (mA-hr)	Weight of 1 Batt. (g)	Total Weight (g)	Volume of 1 Batt. (in^3)	Total Volume (in^3)	Cost of 1 Batt.	Total Cost
9 volt	9	1	9	625	46	46	1.37	1.37	$3.30	$3.30
AAA	1.5	4	6	1200	11	44	0.30	1.20	$1.25	$5.00
AA	1.5	4	6	2600	23	92	0.65	2.59	$1.00	$4.00
C	1.5	4	6	7800	61	244	2.09	8.38	$1.65	$6.60
D	1.5	4	6	18000	134	536	4.39	17.56	$1.65	$6.60
12 volts	Voltage (V)	# Batt. Needed	Final V	Capacity (mA-hr)	Weight of 1 Batt. (g)	Total Weight (g)	Volume of 1 Batt. (in^3)	Total Volume (in^3)	Cost of 1 Batt.	Total Cost
9 volt	9	2	18	625	46	92	1.37	2.74	$3.30	$6.60
AAA	1.5	8	12	1200	11	88	0.30	2.39	$1.25	$10.00
AA	1.5	8	12	2600	23	184	0.65	5.18	$1.00	$8.00
C	1.5	8	12	7800	61	488	2.09	16.75	$1.65	$13.20
D	1.5	8	12	18000	134	1072	4.39	35.12	$1.65	$13.20
24 volts	Voltage (V)	# Batt. Needed	Final V	Capacity (mA-hr)	Weight of 1 Batt. (g)	Total Weight (g)	Volume of 1 Batt. (in^3)	Total Volume (in^3)	Cost of 1 Batt.	Total Cost
9 volt	9	3	27	625	46	138	1.37	4.12	$3.30	$9.90
AAA	1.5	16	24	1200	11	176	0.30	4.79	$1.25	$20.00
AA	1.5	16	24	2600	23	368	0.65	10.37	$1.00	$16.00
C	1.5	16	24	7800	61	976	2.09	33.50	$1.65	$26.40
D	1.5	16	24	18000	134	2144	4.39	70.23	$1.65	$26.40

Table 1: Table of battery properties and state variables for the 3 voltage requirements

The values above were normalized using the methods listed previously. The best value was used as the normalizing factor for each of the state variables (except for life, where the middle value was used). The lower two voltage options all have the same normalized state variables (because they all increase by the same factor from 6 volts to 12 volts). Thus, the measures of merit are independent of the desired output voltage. The measures of merit do not need to be calculated for 24 volts, which will be explained later on.

Before any measure of merit can be calculated, the weighting factors must be set. These factors are very important because they determine the relative importance of the state variables compared to one another. One customer might place cost as the most important factor. Another customer might think that battery life should have the highest priority. The differing interests can cause the process to be very difficult. Consequently, it makes sense to use several different weighting schemes and see if one battery size is consistently near the top. The resulting measures of merit are shown in Tables 2 through 5.

6,12 volts	Battery Life	Total Weight	Total Volume	Total Cost	M.O.M.
9 volt	0.21	1.05	1.41	1.00	***3.67***
AAA	0.50	1.00	1.00	1.51	***4.01***
AA	1.00	2.10	2.20	1.21	***6.51***
C	3.10	5.55	6.98	2.00	***17.63***
D	7.14	12.18	14.63	2.00	***35.95***
weight	*1*	*1*	*1*	*1*	

Table 2: Table of normalized state variables for 2 voltage requirements (scheme 1)

Scheme 1 shows the measures of merit when all of the weighting factors are set to 1. The best options are the 9 volt, AAA, and AA batteries. The C and D sizes do not appear to be smart design choices. Their weight and volume are much greater than the others, causing their measures of merit to be higher (which is undesirable).

6,12 volts	Battery Life	Total Weight	Total Volume	Total Cost	M.O.M.
9 volt	0.21	1.05	1.41	1.00	***7.14***
AAA	0.50	1.00	1.00	1.51	***10.53***
AA	1.00	2.10	2.20	1.21	***15.93***
C	3.10	5.55	6.98	2.00	***43.33***
D	7.14	12.18	14.63	2.00	***89.93***
weight	*8*	*1*	*1*	*3*	

Table 3: Table of normalized state variables for 2 voltage requirements (scheme 2)

Scheme 2 assumes the user of the AuRA Valve cares more about battery life than anything else. Some users may dislike replacing batteries on a frequent basis. They are concerned somewhat about the other variables, but the biggest factor is battery life. In that case, the same 3 batteries provide the best options. The 9 volt is again the best, with AAA and AA not too far behind.

6,12 volts	Battery Life	Total Weight	Total Volume	Total Cost	M.O.M.
9 volt	0.21	1.05	1.41	1.00	***16.82***
AAA	0.50	1.00	1.00	1.51	***16.02***
AA	1.00	2.10	2.20	1.21	***30.12***
C	3.10	5.55	6.98	2.00	***83.95***
D	7.14	12.18	14.63	2.00	***176.69***
weight	*2*	*7*	*5*	*2*	

Table 4: Table of normalized state variables for 2 voltage requirements (scheme 3)

Scheme 3 represents a user that is more concerned about weight and volume than life and cost. Perhaps the valve is to be attached to someone's bike in which case it should be small and light. The 9 volt and AAA batteries are again the best options, but this time the AAA is slightly better than the 9 volt. The AA, C, and D batteries performed poorly because of their large size.

6,12 volts	Battery Life	Total Weight	Total Volume	Total Cost	M.O.M.
9 volt	0.21	1.05	1.41	1.00	***13.82***
AAA	0.50	1.00	1.00	1.51	***17.58***
AA	1.00	2.10	2.20	1.21	***21.28***
C	3.10	5.55	6.98	2.00	***48.28***
D	7.14	12.18	14.63	2.00	***86.49***
weight	*1*	*4*	*1*	*8*	

Table 5: Table of normalized state variables for 2 voltage requirements (scheme 4)

The last weighting scheme evaluates the batteries based on a user who wants an inexpensive and light battery. The 9 volt battery has the lowest measure of

merit, followed by the AAA battery, and then the AA battery. Similar to the other schemes, the C and D batteries have poor measures of merit.

- Results:

Battery Comparison: The overall evaluation of the batteries has beneficial results. The same batteries consistently appeared on top even when the weighting factors were altered. That is good because it means that the batteries can work well for many different users.

The final design should use the 9 volt battery size. The AAA battery size would also be acceptable. In fact, it is slightly better than the 9 volt in terms of battery life, weight, and volume. However, due to their difference in cost, the 9 volt size was consistently superior in measure of merit. Also, it is likely that 24 volts will be needed for the output voltage. If that is the case, then the normalized values would all change. The AAA size would only be better than the 9 volt in terms of battery life. At that output voltage, the 9 volt configuration weighs less, takes up less space, and costs less. Furthermore, 16 AAA batteries would be needed as opposed to just three 9 volt batteries. It would be simpler for the user to keep track of fewer batteries, creating another

advantage for the 9 volt size.

The other three battery sizes should not be considered at all. The AA size performed average in some of the schemes, but terrible in others. The C and D sizes had excellent battery life, but their measures of merit were hurt too much by their large size. None of those batteries would be suitable for the AuRA Valve.

- Implications for the Final Design:

  The battery comparison yielded results that will be good for the final design. At most, the batteries will only add 5 ounces of weight to the valve (for a 24 volt output). That value is well within the requirement of 48 ounces. Also, its volume is nowhere near the size constraint. Also, the 9 volt battery configuration will meet all of the power needs of the AuRA Valve's electrical components. It has enough capacity to power the valve for at least 1.75 months. In reality, that is a very conservative estimate so the actual time period is probably longer. All in all, compared to other alkaline batteries, the 9 volt battery configuration is the design choice with the best measure of merit.

3.2 Trade Study: Air Valve

- Introduction:

  Team Unum's project consists in the design of an automatic air pressure regulator. The final product will be a device which is connected to an external air pressure source and inflates some kind of vessel, which is also connected to the device. The user will be able to input a desired target pressure to inflate the vessel and start the inflation process. Once the target pressure is reached, the automatic air pressure regulator will sense this and will stop the flow of air into the vessel. The design of such a device requires the use of some kind of valve to regulate the air flow that goes from the pressure inlet source to the vessel being inflated. As a matter of fact, one of the main controlling operations of an "intelligent" air pressure regulator takes place at the location of the valve. This device must be able to receive a signal from a microprocessor and based on this instruction it must either let air go through (from the inlet to the vessel during inflation) or stop the air flow into the vessel (when the desired pressure has been reached). The purpose of this trade study is to investigate what kind and specific model of solenoid valve is the best to perform this function. This investigation will include a quantification of the various specifications of each valve design offered in the market. Once these specifications are laid out and

compared to the design requirements and limitations, each valve will have positive and negative attributes to contribute to our design. The objective is to use engineering knowledge and skills to select the most convenient valve for the design. It is important to understand that the valve will be purchased from an existing market and will not be directly designed. For this reason the actual engineering modeling and analysis in this study will not have a very marked technical level. However, the selection of a solenoid valve is such a key issue for the design of an air pressure regulator that it is worth investigating in order to make the most educated choice out of a very extensive list of solenoid valves available in the market.

- Design Variables:

  Because of the nature of this specific trade study, there is only one design variable at stake: which valve to choose. This design variable can be regarded as a batch variable because there is no direct correlation between each different valve. Selecting the best design variable involves selection from a finite set of choices. This is the only choice that the group can have direct control over because the valve will be purchased from an existing market. If the group were building the valve, then direct choices on the length, width, thickness, material properties, etc could be made and these would also be design variables. In

the selection of a valve, these are only states or specifications associated with each kind of valve that is considered. The limitations or constraints on the sole design variable are directly related to the constraints of these states associated with the chosen valve. These will be discussed later in the report. There are two main criteria that must be considered in the solenoid valve selection process: the principle of operation and the mode of operation. In order to make the best choice, it is helpful to understand exactly what these two criteria are and how they describe the functions of the valve. Once the functions are clearly laid out, some specific models can be analyzed in order to select the best one.

- Principle of Operation:

  A solenoid valve involves two main functional units: a solenoid (electromagnet) with its core and a valve body containing the fluid inlet(s) and outlet(s). When the solenoid is energized, the orifice controlling the airflow is either opened or closed. In most valves, the solenoid is mounted on top of the valve body allowing for a compact configuration. There are 3 main principles of operation for solenoid valves: Direct Acting Valves: the actuation is controlled electrically. When the solenoid is energized the orifice on the valve body will either open or close. These valves will operate at pressures from 0 psi up to each different valve's rated maximum. Internally Pilot Operated Valves: these valves use

inner line pressure for operation. In addition to the opening and closing procedure from the Direct Acting Valve, they use inner line pressure to improve the tightness of the closed position Manual Reset Valves: these must be manually latched into position.

- Type of Solenoid Valve and modes of operation:

  This is perhaps the most important specification, as will be discussed later. There are 3 main modes of operation for solenoid valves depending on the desired inlet-outlet configuration. 2-way solenoid valves: these are the simplest mode with only one inlet and one outlet pipe connection. They either allow fluid to flow from inlet to outlet or they do not. They are available in either: -normally closed: the orifice is closed when the valve is de-energized and opens when the valve is energized. -normally open: the orifice is open when the valve is de-energized and closes when the valve is energized. 3-way solenoid valves: these have an additional pipe connection. The first connection is the fluid inlet (from the pressure source), the second one is the outlet to the vessel and the third connection is an exhaust to the atmosphere. They are commonly used when flow needs to be regulated in more than one direction, for example, to apply and exhaust pressure from a vessel using a single valve. They are available in three kinds of modes of operation:

- normally closed: When the valve is de-energized, the pressure (inlet) port connection is closed and the vessel port is connected to the exhaust port. When the valve is energized, the pressure (inlet) port is connected to the vessel port and the exhaust port is closed.
- normally open: When the valve is de-energized, the pressure (inlet) port is connected to the vessel port and the exhaust port is closed. When the valve is energized, the pressure (inlet) port is closed and the vessel port is connected to the exhaust port.
- universal: the flow can be diverted in any way and the direction of the flow can be reversed. 4-way solenoid valves: They are generally used to operate double-acting cylinders or actuators. They have 4 or 5 pipe connections including one pressure inlet, two vessels and one or two exhaust ports.

- State Variables:

  As mentioned above, team Unum will not be manufacturing a solenoid valve. For this reason all valve specifications become states associated with the selection of our design variable. The following is an explanation of most of these specifications and the constraints imposed by the design requirements of an air pressure regulator. This will help understand the function of a solenoid valve (which might not be obvious) and it will simplify the decision process.

- Coil Operating Voltage Ranges: Nominal values of coil operating voltages for direct current (DC) range between 6-240 Volts. Normally, most valves are able to operate at 15
- Solenoid Constructions: This variable involves the material of the internal parts of the solenoid. The area of the valve that is in contact with the fluid is normally made of 300 and 400 series magnetic stainless steel. In AC-operated valves, the shading coil can be made out of copper or silver. In DC constructions, no shading coil is required and the core tubes are usually 300 series stainless steel. Since the DC-operated valve in the air pressure regulator will control air flow, the material inside the valve is not of great concern. The most affordable material should impose the limit on this state.
- Operating Pressures: The pressure differences between the outlet and inlet allows the valve to work properly. Even though not all valves have specific requirements for pressure differences, there are two kinds of variables which could appear: Maximum Operating Pressure Differential: refers to the maximum difference in pressure between the inlet and the outlet against which the solenoid can safely operate the valve. Minimum Operating Pressure Differential: is the pressure required to open the valve

and keep it open. The limits on these values are imposed by the input and output pressure ranges that the air pressure regulator will be able to handle. These requirements are 0-80 psi for input and 0-65 psi for output.

- Ambient Temperatures: Even though this is not a big concern in our specific design, it is worth mentioning that most solenoids have an operating range between the 32F (0C) to whichever maximum value each different valve specifies. The maximum temperature values are obtained from testing under continuously energized conditions. The temperature range on which the valve will operate is not likely to exceed the extreme temperatures listed for solenoid valves. The device will need to operate at an approximate range of 15C from room room temperature.

- Response Times: The time required to go from a fully closed to a fully open orifice position directly depends on the valve size and operating mode, electrical service, fluid, temperature, inlet pressure and pressure drop. Under regular conditions, small direct acting valves take between 5 to 10 milliseconds, while larger valves take between 20 to 40 milliseconds. It must also be pointed out that DC valves have 50% slower response times than equivalent AC valves. Response time will have a direct effect on accuracy. The time it takes to close the orifice when the valve is

energized will determine how much unwanted air goes into the vessel once the closing command is given to the valve from the microprocessor. The target accuracy is within 5% of the specified desired pressure.

- Geometry: There are 3 basic geometrical values which are of interest in this case. The valve's overall length, width and height must be compatible with the intended constraints for housing dimensions. The final project is required to measure 7" x 4" x 2".

- Type of connections: The standard connection type for a solenoid valve is National Pipe Thread (NPT). Depending on the mode of operation selected (2, 3 or 4-way) the number of pipe connectors will vary. Another thing that can vary is the connection size, although most threads are either 1/4" NPT or 1/8" NPT. The only requirement in this field is that it must be compatible with standard connections currently available in the market. The NPT thread is a convenient standard which will make internal connections within the device easy to do.

- Flow rate: Flow rate values reveal the volume of air that can go through the orifice of the solenoid at a given period of time. This value is related to the amount of time that it will take to inflate a given vessel depending on the desired pressure. The constraints on this state variable will be

considered further on the analysis.

- Analysis:

  Now that all design and state variables have been laid out with corresponding constraints and limitations, it is proper to consider and analyze several models of solenoid valves out in the market. Before mentioning the models explicitly, there are some requirements that must be considered in order to start narrowing down the valve choices. The first is a safety requirement. Team Unum is concerned with the safety of the consumer overall. As a safety feature of the air pressure regulator, there must be an escape path for the air inside the solenoid. In case the pressure builds up, or any component is malfunctioning there must be a path for the air to escape and reduce the pressure. This requirement narrows down the mode of operation to only 3-way solenoid valves which are the only ones that can have three connections: one inlet, one outlet and an exhaust to the atmosphere. In order to keep narrowing down the choices of valves, a closer look must be taken at the modes of operation of Normally Closed, Normally Open and Universal solenoid valves. As explained before, the normally closed and normally opened valves include 2 positions. In one of these positions the output (to vessel) port is connected to the exhaust port. This will not be convenient for the design of an air pressure regulator because

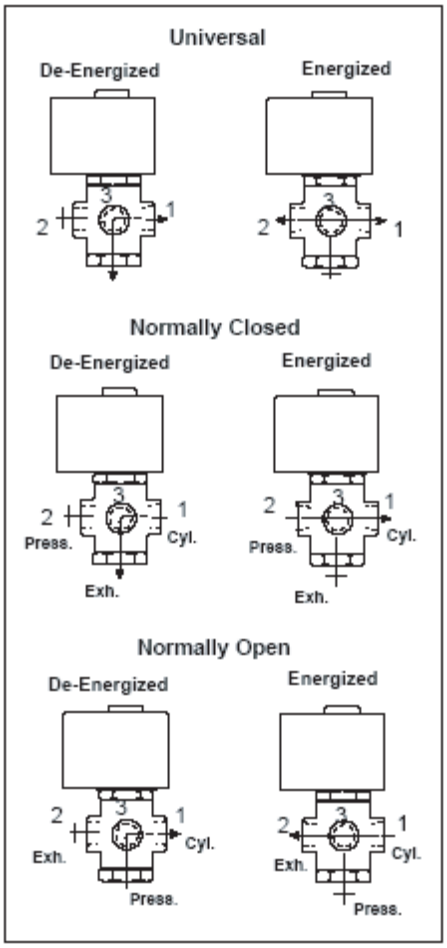
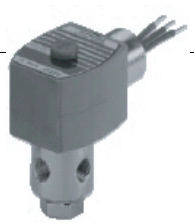


Figure 14: Modes of Operation

the air would be able to flow back out from the vessel to the exhaust port. A schematic of these 3 different modes of operation is provided in Figure 3. As the figure reveals, the universal valve is the only one that permits the 2 positions required by the device. On the first position when the valve is de-

energized (upper left in figure 14) the inlet (port 1 in the figure) is connected to the exhaust port (2 in the figure). In the second position (upper right in figure 14) the inlet is connected to the vessel (port 3 in the figure). As a result, the choice for solenoid valves is narrowed down to 3-way universal solenoid valves.

After this initial filtering of options, there are four models that comply with the requirements and that should be considered and analyzed. They are presented in Figures 3.2 to 17 with all their specifications.

Brand: ASCO Valve		
Model: P/N 8320G182		
Variable	**Value**	**Picture**
Principle of Operation	Direct Acting	
Type of Valve	3-way Solenoid	
Mode of Operation	Universal	
Voltage Range	24 Volts DC	
Solenoid Construction	Copper, Silver and Steel	
Pressure Range	0-160 psi	
Ambient Temperature	0-120°F	
Response Times	N/A	
Geometry	3.75" X 1.95" X 1.19"	
Weight	.6lb	
Pipe Connections	1/4" NPT	
Orifice Size	11/64"	
Flow Coefficient (Cv)	0.35	
Price	$109.00	

The next step is to understand the order of importance of each state in order to determine a correct measure of merit to select the best valve. From a first look at the list, flow-related variables such as orifice size, flow coefficient, and pipe connections seem to be the most important. Some numerical analysis will prove that from the variation in flow coefficient (Cv) among the 4 suggested

Brand: ASCO Valve		
Model:P/N 8320G184		
Variable	**Value**	**Picture**
Principle of Operation	Direct Acting	
Type of Valve	3-way Solenoid	
Mode of Operation	Universal	
Voltage Range	24 Volts DC	
Solenoid Construction	Copper, Silver and Steel	
Pressure Range	0-115 psi	
Ambient Temperature	0-120°F	
Response Times	N/A	
Geometry	3.75" X 1.95" X 1.19"	
Weight	.6lb	
Pipe Connections	1/4" NPT	
Orifice Size	11/64"	
Flow Coefficient (Cv)	0.35	
Price	$89	

Figure 15: Asco Valves

Brand: Parker		
Model:04F3OU2104A3F4C80		
Variable	**Value**	**Picture**
Principle of Operation	Direct Acting	
Type of Valve	3-way Solenoid	
Mode of Operation	Universal	
Voltage Range	available in 6,12 or 24 Volts DC	
Solenoid Construction	Copper, Silver and Steel	
Pressure Range	0-80 psi	
Ambient Temperature	0-120°F	
Response Times	N/A	
Geometry	4.15" X 1.6" X 1.3"	
Weight	.85lb	
Pipe Connections	1/8" NPT	
Orifice Size	3/64"	
Flow Coefficient (Cv)	0.16	
Price	$80	

Figure 16: Parker Valve

valves, the flow rate does not change very much. The flow rate (Q) is related to the flow coefficient (Cv) by the following equation:

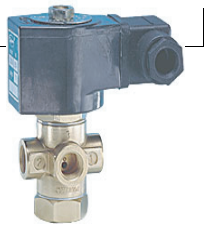
Brand: Clark Solutions		
Model: 1365		
Variable	Value	Picture
Principle of Operation	Direct Acting	
Type of Valve	3-way Solenoid	
Mode of Operation	Universal	
Voltage Range	available in 12 and 24 Volts DC	
Solenoid Construction	brass and stainless steel	
Pressure Range	0-100	
Ambient Temperature	0-120° F	
Response Times	N/A	
Geometry	3.9" X 3.5" X 2.3"	
Weight	.85lb	
Pipe Connections	1/4" NPT	
Orifice Size	3/64"	
Flow Coefficient Cv	0.348	
Price	$90	

Figure 17: Clark Valve

$$Q = (K_v \times F_{gm} \times F_{sg}) \tag{5}$$

where, is the flow factor = (.863)(Cv) F_{gm} and F_{sg} are graph factors

The design requirements for the automatic air pressure regulator, state that the maximum inlet pressure to the valve will have a maximum of 80 psi (5.5 bar). The pressure drop within the valve (from inlet to outlet) can be estimated to be 7.5 psi (.517 bar). This is a reasonable estimate because the maximum output pressure is only required to be 65 psi. From Figure 18, for an inlet pressure of 5.5 bar and a pressure drop of .5bar, the factor is approximately $50m^3$ per hour. So equation takes the following values for the suggested valve designs:

$$Q_{ASCO} = (8.63) \times (.35) \times (50\frac{m^3}{h}) = .25\frac{m^3}{min} \tag{6}$$

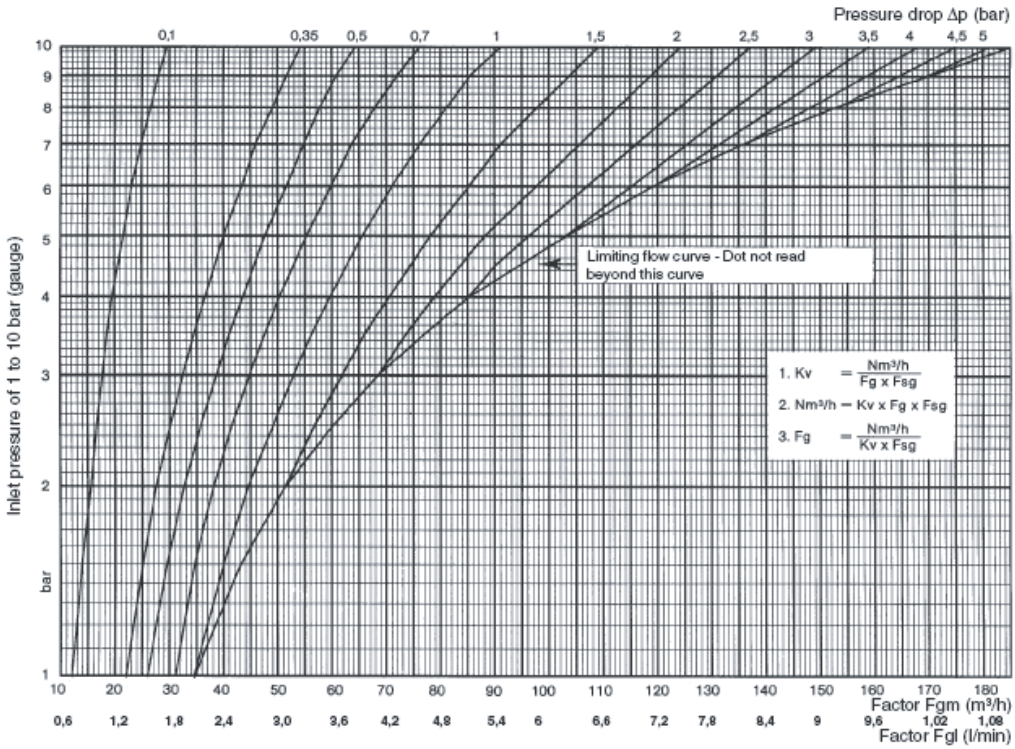


Figure 18: Pressure Drop

$$Q_{Parker} = (.863) \times (.16) \times (50\frac{m^3}{h}) = .11\frac{m^3}{min} \tag{7}$$

$$Q_{Clark} = (.863) \times (.348) \times (50\frac{m^3}{h}) = .25\frac{m^3}{min} \tag{8}$$

An example will clarify further why these differences in flow rates will not be very significant. From the ideal gas law, we can relate the pressure of a vessel to the number of moles of air that fill it up.

$$pV = nRT \tag{9}$$

where, = pressure (psi) = volume (in3) = number of moles of air (moles) = universal gas constant=73.5893(lb-in) / (K-mol) = temperature (K)

If a basketball in a room is taken as an example, the pressure is 8 psi, the volume is approximately $1ft^3$, and the temperature is 298K. Equation 9 can be solved to get the grams of air inside a basketball in the following way:

$$n = \frac{8\frac{lb}{in^2} \times 1728in^2}{73.5893\frac{lb-in}{K-mol} \times (298K)} = 0.63moles \times 28.97\frac{g}{mol} = 18.25gramsair \tag{10}$$

For the different valve models, the time to fill up a basketball can be calculated then:

$$Q_{ASCO} = (0.25\frac{m^3}{min}) \times (1.229\frac{kg}{m^3}) \times (1000\frac{g}{kg}) = 307.25\frac{gair}{min} \tag{11}$$

$$t_{ASCO} = (18.25gair) \times (\frac{1min}{307.25gair}) \times (\frac{60sec}{min}) = 3.56sec \tag{12}$$

$$Q_{Parker} = (0.11\frac{m^3}{min}) \times (1.229\frac{kg}{m^3}) \times (1000\frac{g}{kg}) = 135.19\frac{gair}{min} \tag{13}$$

$$t_{Parker} = (18.25gair) \times (\frac{1min}{135.19gair}) \times (\frac{60sec}{min}) = 8.1sec \tag{14}$$

$$Q_{Clark} = (0.25\frac{m^3}{min}) \times (1.229\frac{kg}{m^3}) \times (1000\frac{g}{kg}) = 307.25\frac{gair}{min} \tag{15}$$

$$t_{Clark} = (18.25gair) \times (\frac{1min}{307.25gair}) \times (\frac{60sec}{min}) = 3.56sec \tag{16}$$

So the difference is only a couple of seconds which might not make a big difference to the user. When filling up a bike tire to 65 psi then this time difference might be slightly larger, but still in the seconds range. Even though it is desirable to reduce the inflation time, all of the selected valves give a reasonable rate. Considering the preceding example, it is reasonable to give a higher merit to other states such as size, weight and pressure range. Size and weight should be the highest weighted states due to the packaging and housing requirements that must be met. Following these in order of importance are pressure range (in psi), voltage (volts DC), cost (USD) and flow rate (m^3/min). Even though price should be of great importance, the prices of all 4 designs considered is fairly close, therefore it does not make a big difference in the study considering the $500 budget.

- Measure of Merit and Results:

  The table below provides the points of each design on each state variable con-

sidered. A model can have 9, 3, or 1 point depending on how well it satisfies the design requirements in each state category.

	ASCO P/N 8320G182	ASCO P/N 8320G184	Parker	Clark
Size (S1)	9	9	3	1
Weight (S2)	9	9	1	1
Pressure Range (S3)	1	3	3	3
Voltage (S4)	3	3	9	9
Cost (S5)	1	3	3	3
Flow Rate (S6)	3	3	3	1

According to the importance of each state variable determined on the analysis, an equation of merit was developed in order to obtain which is the best valve design. The measure of Merit (MOM) equation is:

$$MOM = 2S_1 + 1.8S_2 + 1.7S_3 + 1.2S_4 + S_5 + 0.9S_6 \tag{17}$$

The final results are the following:

$$MOM_{ASCO/N8320G182} = 2(9) + 1.8(9) + 1.7(1) + 1.2(3) + 1 + 0.9(3) = 43.2 \tag{18}$$

$$MOM_{ASCO/N8320G184} = 2(9) + 1.8(9) + 1.7(3) + 1.2(3) + 3 + 0.9(3) = 48.6 \tag{19}$$

$$MOM_{Parker} = 2(3) + 1.8(1) + 1.7(3) + 1.2(9) + 3 + 0.9(3) = 29.4 \tag{20}$$

$$MOM_{Clark} = 2(1) + 1.8(1) + 1.7(3) + 1.2(9) + 3 + 0.9(1) = 23.6 \tag{21}$$

Therefore, the chosen valve is the ASCO P/N 8320G184.

- Discussion and Influence of the Results:

  The results yielded by this trade study are very useful and will have a direct impact on the success of the automatic air pressure regulator. As mentioned in the introduction, this is where one of the main controlling functions of the device will take place, so the careful selection of an appropriate valve is a very important study. There are several results that are worth discussing further. Since the valve will not be manufactured by Team Unum, the availability of these valves in the market is key for the success of this trade study. Even though research has been done in several webpages and catalogues, there might be some other difficulties when trying to purchase one of these valves. However, the final selection of a specific model was not the only satisfactory result obtained. All kinds of solenoid valves were considered and only Universal 3-way solenoids fulfil the flow handling requirements. This result should be considered in the future. Another important result obtained from the analysis was the relationships between all the flow coefficients and the actual flow rate of the valve. As it turns out, a doubled flow coefficient (Cv) only increases about 4 seconds on the inflation time of a basketball. This is a result that was not expected before this trade study was done. Some valves could have been turned down because their flow coefficient was too low without realizing the consequences on the

actual inflation process. Another result that will have a direct impact on the manufacturing process is the cost of this type of valves. When first looking at some catalogues as a group, team UNUM considered Normally Opened and Normally Closed Solenoid Valves which are in the $30 to $40 range. As the study reveals, these valves will not permit the desired direction of air flow. A universal solenoid valve must be purchased instead and this will have a direct impact on the budget. The selected valve has a price of $89 which is more than double than the price considered at first instance. Since our budget is $500 in total, this device is still reasonable to purchase. In the future, however, and if this prototype of an automatic air pressure regulator proves to be a feasible design, other flow directing options could be considered in order to cut production costs.

3.3 Trade Study: Pressure Sensor

5 October 2004

- Objective and Introduction

The purpose of this trade study is to determine the best choice for a pressure gauge to be used in our system. According to Omega Engineering, "A

pressure transmitter is a standard pressure measurement package consisting of three basic components: a pressure transducer, its power supply, and a signal conditioner/retransmitter than converts the transducer signal into a standardized output"[2]. The pressure transducer itself will be studied here. Both the power supply and signal output will be incorporated into the entire system design. Because there are many pressure sensors available, this study will help to narrow down and define the most important criteria for our selection of this component. Along with defining the critical criteria to be considered, it is hoped that this trade study will provide solid recommendations based upon a well-educated study of the field. The following is the result of internet and product searches performed over a period of time following the general approval of the Trade Study Proposal submitted on September 21st, 2004. It should be noted that deviations from the original Trade Study Proposal are readily present in this trade study. The reason for such deviations is, for the most part, in response to questions and comments received from the management in regard to the original proposal.

- Summary of Design Variables

Many options exist for use in sensing pressure. While the field of study is very

broad, our specific application finds use for only a fraction of the possibilities. There are three feasible options for pressure sensors in our application:

- "Homemade" transducers using strain gauges mounted on a deformable material
- Typical pressure transducers, previously designed, tested and manufactured
- Flow-through pressure transducers, previously designed, tested and manufactured

Within each category there exists a wide range of options. Our design variables are then to determine which of the above three categories our needs full under, then to select the appropriate sensor from that best category.

- Summary of State Variables

The state variables of interest are accuracy, cost, and power requirement. These state variables will be analyzed for all pressure sensors under consideration.

- Summary of Measure of Merit

The Measure of Merit equation was developed to weigh the state variables

with regard to their relative importance in our application. "Relative importance" is hard to define. It takes into account our constraints (see section below for more information on constraints), as well as the impact of this decision on the other trade studies being performed. The specific values in the Measure of Merit equation, Equation 22, will be defined later in this Trade Study.

$$M.O.M. = \frac{a}{S_1} + \frac{b}{S_2} + \frac{c}{S_3} \tag{22}$$

- Summary of Constraints

The constraints of this trade study are microprocessor compatibility, orientation relative to flow and housing configuration and consideration of reasonable cost and weight in regard to our entire system. While the specific price of the pressure sensor has not been limited, our target price for the consumer is less than $30 for the complete system. Additionally, the entire system is not to weigh more than three pounds. After preliminary research, we determined that weight would not become much of an issue in the selection process. The findings of this trade study which follow agree with this hypothesis.

- Summary of Modeling and Analysis Methods

The three pressure sensor types under consideration were analyzed based on their compatibility with the valve system. The most important aspect of the pressure sensor's interaction with the rest of the system is disruption of airflow through the path at the point it must measure the pressure. It is desired to get the most accurate reading of the gauge pressure within the inflatable vessel without slowing or blocking the airflow. The results of this analysis show positive and negative aspects of each type of pressure sensor in this respect.

- Analysis of Design Variables

As indicated in the summary section above, the initial choice to be made is between the "homemade" type pressure sensor, the typical pressure transducer, and the flow-through transducer. These three types of pressure sensors are described more completely below.

  - "Homemade" Pressure Sensors:

    These basic pressure sensing devices make use of a strain gauge as shown in Figure 19 and a deformable material, which are commonly housed in some sort of protective case. The deformable material is a very important choice in the design of this component, because it must be sensitive enough to move with changing pressure, yet not permanently deform. A

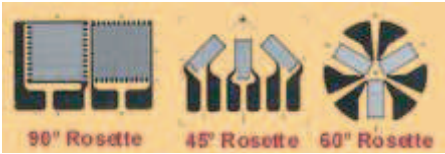


Figure 19: Types of Strain Gauges[6]

material which permanently deforms will greatly reduce the life and accuracy of the pressure sensor, because the more use it receives the less accurate the sensor will be. The benefits of this type of pressure sensor are customizability and cost. First, customizability is a benefit of this type of sensor because it can be built to perfectly interface with the entire smart-valve system. It can simply be placed wherever it is needed to sense the pressure in the air supply line. Because both the sensor and the diaphragm material can be chosen to fit the specific application, the options for construction are essentially endless. From a cost perspective, the diaphragm could be made from a material as inexpensive as a soda can, and strain gauges can be found for relatively low prices. More details on these state variables will be discussed later in this Trade Study.

– Typical Pressure Transducers:

  When one wishes to find a pressure transducer (Figure 20), a 30 second search will yield more than enough possibilities. The problem, then, is to

find which one of the numerous types are right for the specific application.

Figure 20: Common Pressure Transducer from Omega Engineering[5]

The benefits of the traditional pressure transducer are the wide range of specifications available, the ability to customize the sensor for our application, and the accuracy and reliability of this previously designed, tested and manufactured component. The main drawback of this type of pressure sensor is the fact that it would have to be integrated into our system, because it is not configured to simply attach to the path of airflow. In this case, a special piece of tubing would have to be fabricated to integrate the transducer into the smart valve system. Figure 21 illustrates a potential design for this system integration. The importance of tight seals to prevent pressure loss cannot be stressed enough in this potential de-

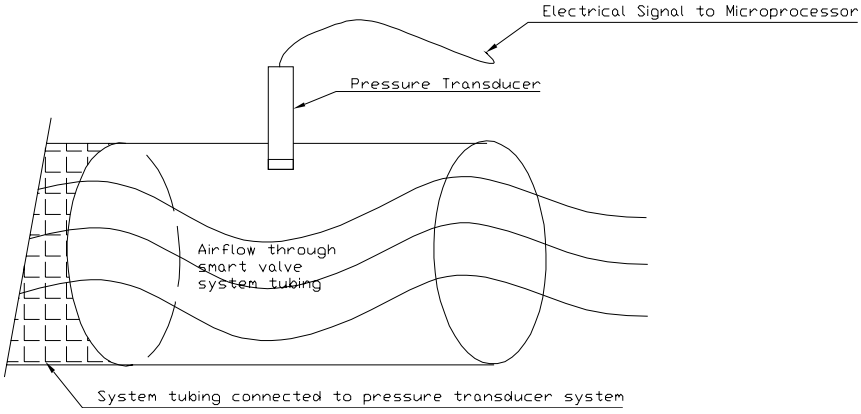


Figure 21: Proposed Design for Integrating Transducer into System

sign. Great care must be taken to ensure that pressure loss does not occur at either the connection between the system tubing and the transducer tubing or at the hole into which the transducer will be placed at the top of the tubing. The tubing itself could be fabricated from a wide variety of materials, from the same material as the rest of the system tubing, to perhaps something less flexible and more durable. Because it is located within the system housing and will not need to be easily accessible by the user, it can be of a more permanent arrangement than the outer tubing.

– Flow-through Pressure Transducer:

The flow-through type transducer (Figure 22) measures the pressure of a fluid which is flowing through it. This component requires no additional

Figure 22: Setra Ultra High Purity Flow-through Transducers[3]

construction before it can be integrated into our system, as it is designed to fit into our flow-path. However, unlike the traditional pressure transducer, this component is not as widely available. Research indicates that this type of pressure transducer is used in applications where high purity is very important. The result is a very limited variety of transducers with specifications not necessarily suited to our application, potentially with costs out of a price-range reasonable for this application. The state variables will be discussed later in this Trade Study.

- Comparison of State Variables

The state variables (accuracy, cost and power requirement) for a range of choices in each of the three design variable categories are compared in the

table below. The following data ranges have been compiled from a variety of sources in an attempt to show the available options as closely as possible. Although there are more expensive options than those listed, the pressure sensors which are clearly more complex than our established needs were not considered.

Table 1: Summary of State Variables

Strain Gauge Option		
Accuracy [%]	Cost [$]	Power Req't [V]
0.5	10-30.00	1.5-5.0
Traditional Transducers		
Accuracy [%]	Cost [$]	Power Req't [V]
0.25-1.5	18-30.00	5.0
Flow-through Transducers		
Accuracy [%]	Cost [$]	Power Req't [V]
0.2	60-100.00	11-30

- Calculation of Measure of Merit

The objective of this trade study is to find an optimal choice for selection of a pressure sensor. The state variables can be weighted to determine an optimal solution among the design variables. Choosing the weighting of the state variables requires consideration of the relative importance of the state variables to the design overall. First, the accuracy of the pressure sensor is important because improved inflation accuracy is one of the overall objectives of the smart valve inflation system. Without accuracy in the individual components, the overall system will fail. On the other hand, our specification for overall system accuracy is within 5% of desired pressure. It can be seen from the Table 1 that all of the pressure sensor options fall well within the range of acceptable accuracy. For this reason, the weighting of the state variable accuracy is relatively low in our M.O.M. equation. It has been given a weighting of 0.1. The power requirement is important to the overall power requirement of the system. It is relatively less important than the cost requirement, however it is more important than the accuracy requirement. For this reason, it has been given a weighting of 0.3. The cost of the pressure sensor is important to the overall system, because it will be a significant factor in the cost of the system.

It is one of the most expensive parts of the system, therefore reduction of its cost will have a great impact on the total cost. For this reason, it has been given a high weighting of 0.6. Equations 23, 24 and 25 define these weightings, which represent accuracy, power requirement and cost, respectively.

$$a = 0.1 \tag{23}$$

$$b = 0.3 \tag{24}$$

$$c = 0.6 \tag{25}$$

Next, the M.O.M. equation will be analyzed for each of the three design variables using the defined state variables. For sake of comparison, the bottom value of the range will be used where applicable. Equations 26-34 define the values of the state variables accuracy in % (S1), power requirement in volts (S2) and cost in $ (S3), respectively for each of the design variables.

$$S1_{straingauge} = 0.5 \tag{26}$$

$$S2_{straingauge} = 1.5 \tag{27}$$

$$S3_{straingauge} = 10.00 \tag{28}$$

$$S1_{transducer} = 0.25 \tag{29}$$

$$S2_{transducer} = 5.0 \tag{30}$$

$$S3_{transducer} = 18.00 \tag{31}$$

$$S1_{flow-through} = 0.2 \tag{32}$$

$$S2_{flow-through} = 11.0 \tag{33}$$

$$S3_{flow-through} = 60.00 \tag{34}$$

The above values were used to calculate the M.O.M. for each of the design variables. Equation 35 is the final form of the weighted equation used to calculate these values, shown in Table 2.

$$M.O.M. = \frac{0.1}{S_1} + \frac{0.3}{S_2} + \frac{0.6}{S_3} \tag{35}$$

Table 2: Measure of Merit Values

Option	M.O.M.
Strain Gauge	0.46
Traditional Transducer	0.49
Flow-through Transducer	0.54

Based on results obtained from the Measure of Merit equation, the best choice is the Flow-through Pressure Transducer. Although the voltage requirement and cost are quite high, the accuracy drives the M.O.M., despite its relative unimportance. To carry this decision further, the constraints must be considered.

- Application of Constraints

  The design variables will now be considered in regard to the constraints of our system.

  - Microprocessor Compatibility:

    First, we have the microprocessor compatibility. All three of the transducer types are compatible with the PIC877 Microprocessor which has been chosen. However, the output voltage is desired to be in the range which will not require an amplifier. The majority of low-cost strain gauges have output voltages in the mV range, which requires an amplifier. While this is not a deciding factor, it adds complexity to our design which could be avoided by using a pressure sensor which has output voltage in the readable range. Both the traditional and the flow-through transducer are available in the readable range.

  - Orientation Relative to Airflow and Housing Configuration:

    While it is feasible for all three options to be incorporated into the path of airflow, they will all be configured in different ways. As mentioned earlier, the "homemade" pressure sensor can be made to adapt to the system environment, as it is essentially being created from the materials needed.

On the other hand, because it could never be a refined component like the others, its incorporation into the product could be less than elegant. It would have to be well-protected from the environment and strategically placed within the system to ensure the most accurate pressure reading. The clear choice in regard to path of airflow is the flow-through type transducers, as they are specifically designed to measure the pressure of fluids flowing through them. There seems to be no disadvantage of this type of component when airflow is concerned. Likewise, the traditional transducer adapted to the flow pipe could also prove very adaptable to the application, with the requirement of a small hole in the system tubing to be incorporated into the system.

– Reasonable Cost:

  After a discussion of the range of costs expected for each sensor type, it is clear that the flow-through transducers are the most expensive. In fact, because the minimum price falls considerably above the target overall price of the entire system, it is recommended that this option be considered seriously disadvantageous to the design of the entire system. Because the M.O.M. function of all three components were not considerably different (although it is noted that the flow-through system scored the highest),

the high-cost issue of the flow-through type sensor severely decreases the benefit of such a device. Both the strain gauge and traditional transducers lie in a reasonable range for the application.

- Reasonable Size and Weight:

  It should be noted that, after considerable research, it has been determined that neither size not weight should have a considerable impact on the selection of the pressure sensing component. Of the sensors researched, the typical mass was found to be less than 7 ounces. Size is also not considered a critical issue.

- Conclusions from Airflow Analysis

It is clearly desirable to reduce frictional effects within the pressure sensing component of the system. With this in mind, the three design variables must be compared in order to predict possible causes of frictional losses within the components. Equation 36 describes the friction coefficient (a dimensionless parameter for surface frictional drag) for internal, (assumed) fully developed flow [8].

$$C_f = \frac{\tau_s}{\rho u_m^2/2} \tag{36}$$

However, since τ is the surface shear stress based on dynamic fluid viscosity, the surface and the geometry of the component are no considered here. Furthermore, because the pressure sensing component of the system will be a very small part of the entire length of the system, it can be safely assumed that there will be no significant pressure drop due to losses within the pipe. The most important precaution to keep losses at a minimum will be tight connections between the different components.

- Conclusion and Final Recommendations

This Trade Study was performed in order to reduce the myriad of pressure sensor choices by means of a reasonable, informed decision making process. While all three types of pressure sensors have their own advantages, it is when these advantages align with the needs of the system that a choice can be made. The Measure of Merit Equation helps to prioritize and assign value to the importance of state variable values, whereas the constraints gave guidelines into which final decisions should fit. Because this Trade Study involved the selection of previously designed, tested and fabricated components, there was relatively little analysis to be done. However, it is important to consider what effect the component will have on the overall system. The conclusion was made that the

losses experienced in the pressure sensor will not have a great impact on the overall system, because the "pipe" length of the pressure sensor is relatively short.

It is recommended that the pressure sensor component be assembled with the traditional pressure transducer fitted to the airflow tubing of the rest of the system, as in Figure 21. The best specific transducer which has been found to date is from Motorola (see Figure 23). It costs $18.19, uses a 5.0V supply and is well within the accuracy range required. Although this choice was not the

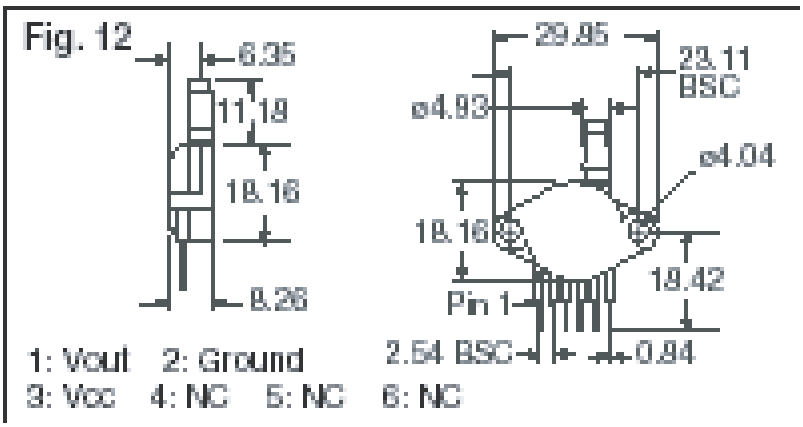


Figure 23: Motorola MPX5700GP-ND from Digi-Key Corporation[4]

clear-cut winner in terms of measure of merit, it fit well with the constraints of the system. Its low cost, high adaptability shows promise for this application. The main concern with this choice is sealing off the interfaces to reduce pres-

sure losses. With careful consideration of this factor, it is believed that this will perform well in the smart valve system.

3.4 Trade Study: Connectors and Hosing

October 5, 2004

1. Purpose

The specific purpose of this Engineering Trade Study is to analyze the different connections and hoses available for use in the smart air valve being developed by our team and decide which connections are the most appropriate for our purpose. The device being designed needs to be able to connect to a variety of different input sources (i.e. air compressors, bicycle pumps) and also to an even wider variety of outputs (namely, for our device, athletic balls, car tires, and bike tires). The main issues involved with this are compatibility with the vast number of inflatable interfaces and the required pressures for the different inflatables. The connections and tubing chosen for our design need to be highly adaptable to a variety of connections and need to be able to withstand pressures of around 100 psi.

2. Connections

2.1 In-housing Air Connections

Connections required between the actual components of our product, concealed

within the casing of the device, are somewhat different in nature than those that attach to the air sources and the inflatables. These threaded connections come under the NPT (National Pipe Taper) standard, so it will not be difficult to find fittings that will attach properly to each other since all come under this standard. Sizes of fittings, however, come in a variety of sizes depending on the use. Typical sizes are 1/8", 1/4", 3/8", and 5/8". For our purposes, it is the standard that 1/8" is too small and will not provide the appropriate flow rates for our devices, as well as making it difficult to make the proper connections. 5/8" is more often used for high-end pneumatic systems and would be far too large for use in our device. Therefore, the decision comes down to 1/4" and 3/8" connectors. Attachments are available to make both connectors adaptable to each other, but it would be altogether easier to not require two standards. In this case, we've decided to go with whatever standard we can find to connect to our solenoid valve which will actually control our airflow. The following table shows the current possibilities of solenoid valves for out design.

Table 1: Solenoid Selections The important fact to note is that the solenoid valve sizes only range from 1/8" to 1/4", therefore we will use 1/4" NPT connectors. Connectors come as both male (external threads) and female (internal threads) which couple to each other. Female will most likely be used on the tubing ends and male couplings will be used on the actual casing, however, for the most part this distinction

is trivial and dependent on what is easiest to manufacture. Female couplings cost $4.99 each and male couplings cost $3.99 each.

Figure 24: Male Coupling and Female Coupling

These connectors are made of brass and rated at around 200 psi so pressure restrictions should not be an issue for these connections. Our valve will only operate at a maximum pressure of 80-100 psi. Still, safety is a concern when operating with such high pressures and all of the connections will be tested under controlled conditions in the lab. It is important to make sure that what is being manufactured is not going to be some sort of projectile "weapon" if the correct precautions are not taken. Another reason for testing is to check pressure losses from leaks in the threads. If there is a significant pressure loss the threads can be lined with Teflon tape to completely seal them. This precaution is usually only required in more industrial type pneumatic devices, but the option may arise. Another type of connector that was being investigated was the quick-connect coupling. These are spring-loaded

couplings that enable the user to quickly attach and disconnect the tubing from the casing. This sort of coupling would be useful if there were several different connecting tubes required for full adaptability of our product, but they are typically too expensive. However, the group can test these connections versus the standard threaded connections to see if there is a significant time difference in connecting the two to where it would merit the extra cost. More than likely, there is not a worthwhile difference, but it should still be tested.

2.2 Connections to Inflatables

Of a more important consideration than the internal connections in the product are the external connections to the inflatables (tires and athletic balls). One of the vital facets of the design of the smart air valve and the eventual marketability of the product is its compatibility with existing standard air valves. Bike tires, which are one of the primary outputs for the product, have two different standards for air valves: the Presta and Schrader Valves. Presta valves are more common in high-end bicycles used for road racing that operate at a higher psi than off-road bikes (100 versus 60 psi). They are thinner and more elongated and fit better on the slender road tires. Schrader valves by comparison are much more stout, but also more robust. They are the usual standard for American bike tires and are found in almost all off-road bikes and car tires. Connections are available that can adapt Schrader valves to work with

connections for Presta valves and vice versa, but ideally, our product would be able to use one connection to fit both of these standards. One possibility that the group had worked with was manufacturing a valve that one could either switch between the two standards (some sort of rotating device with several connectors attached) or something made through rapid prototyping that would be able to fit both valves. In fact, this is not necessary since there is a commercially available valve on the market made by Topeak known as the Smart Head. This is a single connection that will fit both Presta and Schrader valves and costs about $10.

Figure 25: Smart Head Connector

Other than Presta and Schrader valves, there are not many concerns for air connections going into our inflatables. The only other standard is the needle connector used to fill athletic balls. These connectors are very inexpensive and can be bought

for around 36 cents apiece. They fit into most kinds of clamping chucks as you would find on your typical hand pump or air compressor. They should then fit into the Smart Head device as well, thereby removing our need for a separate clamping chuck connection. This has not been confirmed yet, but will be tested upon actual construction of the pump. Should the needles not fit, it is a simple matter to produce another output line with a clamping chuck that would fit the needles. As stated earlier, many air compressors used to fill tires and balls come equipped with a clamping chuck. These are typically designed to fit Schrader valves in America. For our purposes, we can have a tube that will be able to attach to a clamping chuck or just use the option of screwing the compressor directly into our threaded connection if it does not come with a chuck.

2.3 Tubing

The tubing involved with this design is what creates the path for the air to flow through the product connecting the input with the output, running through the solenoid valve that controls the flow of air and through the pressure transducer that is ultimately responsible for controlling the solenoid. Since the candidate solenoid valves for our design come with 1/4" connections, it is only logical for our tubing to have 1/4" connections and diameter. The issue with tubing, however, is not the size (as that is more or less determined by the other components of the product) but

the material to make it from. It must be airtight, be able to withstand up to 100 psi, and be durable. One aspect of our overall design is that the product should be robust, being able to withstand minor elemental hazards. Whatever material chosen for the tubing, it should be able to resist water damage and corrosion as well as resist tearing and wear. One idea for the inner tubing that would have dealt with some of these issues was to make the inside passage a machined metal tube. However, this causes problems as it solves them since it would be very difficult to match the metal tubing with the connections on the solenoid valve and on the pressure transducer. Overall, it is simpler to just run tubing with the proper connections through the casing of the device. There are three main different types of air hose on the market: braided, PVC, and Rubber. Braided air hoses are usually used for bicycle pumps and airbrushes and the cost about $1.00/ft. PVC and Rubber hoses are the higher-end hoses and are typically found in more industrial uses. They cost $2.50 and $3.30/ft, respectively. Rubber and PVC hoses have higher pressure ratings than braided hoses (300 psi compared to 100 psi) and due to their material, are less susceptible to the elements and to wear. Braided hose will fray and begin to fall apart more easily when put to vigorous use, but it may be overkill to use an industrial rated hose in the application of our product. Table 2, a decision matrix, will help with making this decision.

Figure 26: PVC, Rubber, and Braided Hosing

The first table weights all of the properties of the hoses against the other properties to decide which properties are ultimately the most important by assigning a weight factor (w). The second table diplays a rating in each of the properties for each hose to be normalized against the highest rating in the third table for the normalizing factor (b). The final table sums wibi for all material properties for each hose type to give the ultimate weight for each hose. The hose with the highest rating should be the best decision for our product.

	Weather Resist	Cost	Wear Resist	Pressure Rating	weight factor
Resist		2	1	1	4
	3		2	2	7
sist	1	1		1	3
Rating	1	2	1		4

	Weather Resist(1-3)	Cost/ft	Wear Resist(1-3)	Pressure Rating
	3	2.5	2	300
	3	3.5	3	300
	1	1	1	100
ing Factor(beta)				
	100	40	66.66666667	100
	100	28.57142857	100	100
	33.30	100	33.33333333	33.33333333
ighting				
	1280			
	1300			
	1066.533333			

The results from the decision matrix point to the Rubber tubing to be the best choice for this application with the PVC tubing in a very close second. Rubber tubing is very expensive and since this decision matrix is relatively subjective, in this case it would be wise to go with the PVC tubing over the rubber since ultimately, the product does not require that level of tubing. Braided should be considered a back-up choice in case the PVC does not work out, but PVC should provide the best fit of robustness and functionality for the design.

3. Conclusion

After weighing the different possibilities available to the design and studying

what connectors and tubing were available for use in our product, the design of the connection system to the air source and inflatables took shape. Several types of connectors were reviewed, from threaded NPT connectors in a variety of sizes ranging from 1/8" to 5/8" to quick-connect couplings that provide a small amount of convenience at an increased price. Based on the requirements of the solenoid valve, 1/4" connectors and hose diameters were chosen. This will make interfacing between all of the components easier especially since 1/4" is a more widely used standard than 1/8" in bike pumps and the like. For inflating connectors, after research, it was found that one connector would handle just about every kind of valve we are seeking to address. This is the Smart Head Connector from Topeak. It fits Schrader and Presta valves and may be able to handle needle inflators as well, although that much needs to be tested before we decide whether or not we want a hose with a regular clamping chuck to accommodate those as well. One of the final considerations was tubing. After employing a decision matrix to weight the main material qualities of PVC, Rubber, and Braided hosing, rubber hosing turned out to be the best balance of cost, robustness, and functionality. However, given the general subjectivity of the decision matrix, it is probably best to go on instinct and not choose Rubber hosing over PVC in this case. Rubber hosing is very high-end and meant truly high pressure, high power, pneumatic systems. PVC should suit the needs of the design

as well as rubber.

3.5 Trade Study: Housing

October 5, 2004

- Statement of Purpose:

  The functionality of the proposed "smart air pump" focuses primarily on well-designed interfaces between the proposed valve structure and existing air pumps and inflatables, on the accurate and frequent evaluation of air pressure within the system, and on the successful regulation of the supply air stream, with the overall goal being the achievement of a precise, user-defined vessel inflation pressure. Successful implementation of this design requires consideration of many subsystems and components, including pressure transducers, standardized pneumatic tubing and hardware, reliable and long-lasting electronics systems, and precise are diversion systems. However, successful implementation of a system's functionality does not necessarily guarantee success for its marketability. In this second arena, features above and beyond the bare minimum of expected performance figure prominently in a product's overall success. The housing of a system, which, considered as an individual subsystem, effects the performance of every other subsystem, demands in-depth consideration for

the product's success. The housing serves to protect the potentially fragile individual components from lifetime abuse, the elements, and inevitable environmental harshness. Despite the need for simple protection, however, the housing must not impose undue drawbacks to the system's performance, nor add unmarketable defects to the system. Obvious considerations in the design of a product's housing involve a balance between sufficient system strength and cost, weight, and manufacturability. A truly successful design would strike a balance between what the system needs and what the user wants. It is the purpose of this trade study to investigate the relationships between specified durability design requirements (namely, that the system withstand a 5' drop without fracturing, while remaining as close to the 7" x 4" x 2" target dimensions specified) and the undesired effects materials impose on their completion. This study will first minimize examine the problem of package size, minimizing the required component "envelope". A simple housing of unknown wall thickness will be designed around this volume. Next, several engineering materials suitable for product housing will be considered and minimum wall thicknesses selected, based on the design requirements, solid mechanics, material science, and some impact and fracture mechanics. Finally, using theories of design, each individual housing design will be evaluated based on its cost, mass, machin-

ability, and volume. The goal is a lightweight, cost-efficient, manufacturable, and durable housing.

- Design Variables:

  The design of this simple system housing uses two design variables. The first variable is the system layout. The broad functional problem of the system has already been solved: the system will consist of hardware to mate with existing pumps and vessels, a device for controlling the air flow, a device for measuring the air flow, some internal air conduit, and an electrical/control package. These elements form the "envelope" which the housing must enclose. Layout of these components, while having little effect on the air-regulation performance of the system, will have a significant impact on the shape, and consequently the design, of the housing. Already, the component layout is subject to the 7" x 4" x 2" target system dimensions constraint and has contributed to the weight of the system, which was constrained to remain under 5 lbf. In addition, qualitative constraints govern the layout, as user-interface components cannot be buried deep within a hardware system. The other design variable is the material selection. While the shape of the housing assembly is determined by the component layout, the size and wall thickness are determined by the material used. The housing material must be able to withstand the impact of a 5' drop

without fracturing. With the force magnitude thus determined, the material properties will determine an adequate wall thickness for each material. This in turn will determine the weight of the housing which contributes to the 5 lbf maximum, as well as the overall system size constraint. The choice of material has extended ramifications on many other characteristics of the housing system.

- State Variables:

  As a result of selecting a particular set of design variables, the system's state variables are indirectly determined. System geometry will be determined by the layout of the components. Wall thickness is governed by both the properties of the selected material and the geometry of the system as determined by the component layout. This wall thickness, together with the material properties, will determine the final outer dimensions of the entire pump system, as well as the overall weight of the system. Selection of material has a direct effect on the toughness of the material (actually a design constraint), on the material cost, and on the manufacturability/cost of processing for the housing. Again, these indirectly changed variables have desired constraints imposed on them, namely that the outer dimensions of the system be minimized and preferably no greater than 7" x 4" x 2", and that the overall system weight be minimized and

no greater than 5 lbf. In addition, as-of-yet un-quantified expectations exist, namely that the system cost (and thus the housing cost) be minimized and that the material selection not impose an undue hardship on manufacturability.

- Measures of Merit:

  Evaluation of the system involves selecting individual measures of merit of the system and evaluating how well they conformed to the constraints and desired performance of the system. In the case of the pump housing, system dimensions, cost, weight, and machinability will be considered in the evaluation of how successful a design is. Successful fulfillment of the durability constraint is a pass/no-pass variable and thus will not be used for evaluation. Designs not passing the durability requirement will not be considered. Performance data from each design will be compared to design constraints and goals. A successful design will be aimed at minimizing the system dimensions, minimizing the cost, minimizing the mass, and maximizing the machinability, while continuing to satisfy minimum size, weight, and durability constraints. Using theories of design, these measures of merit will be combined towards the selection of the optimum considered design.

- Description of Tools:

  This problem of housing design touches many fields within engineering, among

them design theory, solid mechanics, material science, manufacturing, finite element analysis, shock and vibration, impact, and fracture mechanics. The scope of this study is necessarily limited by both the short duration of product development and by the lack of any expertise of the author within many of these fields. As such, significant approximations of true theory and correct engineering practice were necessitated if this design aspect was to have been addressed at all. The author lacks any experience in finite element analysis, shock and vibration, and fracture mechanics, and has only marginal knowledge of material science. Due to the scope of this project, the scope of these subjects, and the time constraints of the project, finite element analysis was completely abandoned and design for shock, vibration, and fracture mechanics was approximated through basic solid mechanics and dynamics. Theories drawing from design and material science have been incorporated wherever possible. The component layout was achieved by modeling the large components within a computer-aided-design program (Pro/E [9]) and arranging the components manually. Automated optimization using Matlab or other optimization software would have been ideal, but the complexity of the system and the existence of unquantifiable constraints as mentioned above made the programming and execution of such an optimization code infeasible from a

time and complexity standpoint. Once the component layout was established, standard geometry dictated the dimensions of the housing's inner cavity. From this geometry, a wall thickness, t, was assumed for each case and formulas for housing face area and housing material volume were calculated. Assuming the components' masses totaled approximately 1.5 lbf (as based on data from other trade studies), the mass of the system was derived in terms of the mass of the components, the material density, and the housing material volume thusly:

$$m = 0.0466lbm + \rho V \tag{37}$$

Analysis of the falling system formed the backbone for design selection. It was assumed that the system fell from a height of 5' with no significant forces besides gravity acting on it. Employing the law of conservation of energy [11] and equating the potential energy before the fall with the kinetic energy upon striking the ground the terminal velocity of the object was calculated. At this point, impact theory would have been employed, if feasible. Instead, basic physics and dynamics were employed to approximately calculate the impact force. The deceleration of the system was first calculated as the change in velocity over the period of deceleration, which was assumed to be 0.1 s. This large value of Δt was assumed, given that the true stiffness of the structure was not known. From this deceleration and the mass of the system, the impact

force was calculated using Newtonian physics. By multiplying this impact force by an impact factor of 3, the pulse shape of the impact force was accounted for. This technique acted as an approximation of shock and vibration theory which is unknown by the author. Finally, the force was multiplied by a safety factor of two as a standard safety design technique, yielding:

$$F = s_n n_i (0.466 lbm + \rho V) \frac{\sqrt{2gh}}{\Delta t} \tag{38}$$

where s_n is the safety factor, n_i is the impact factor, r is the material density, V is the material volume, g is the gravitational acceleration, h is the height of drop, and Δt is the period of deceleration. It was assumed that upon impact, the bottom face of the system would be perfectly parallel to the ground and sufficiently elastic enough to "balloon", transferring the force of the impact through the four walls perpendicular to the ground. This assumption was made as the techniques of finite element analysis, which are necessary to truly analyze the stresses within this body, are infeasible at this time. Furthermore, various tables [12] of stress concentrations offered no satisfactory general equations for the stresses within a flat plate, and most approximations erred by up to 30%. Thus, simple solid mechanics [7] was employed. The impact force was divided by the "web" area of the four walls, resulting in a tensile stress. In each component configuration, the smallest cross-sectional area was selected,

as this would produce the highest and most critical tensile stresses. To satisfy the requirement that the walls not fracture, this calculated tensile stress (still a function of the wall thickness) was equated with the true ultimate tensile stress for the material and the critical wall thickness solved for:

$$\sigma = \frac{F_{impact}}{Area} < \sigma_t \tag{39}$$

Now with the system geometry fully defined, the final system dimensions and system weights were calculated. Final evaluation involved examining the system's measures of merit. A weighted possibility index chart was constructed, from which the weighting factors, w, for each measure of merit were determined. Next, the measures of merit were scaled using techniques from design methodology [1] , according to

$$\beta = \frac{numericalvalueofproperty}{largestvalueunderconsideration} \times 100 \tag{40}$$

and

$$\beta = \frac{smallestvalueunderconsideration}{numericalvalueofproperty} \times 100 \tag{41}$$

Next, the material performance index was calculated for each configuration, based on

$$\gamma = \Sigma \beta_i \omega_i \tag{42}$$

and the optimal material/configuration design was calculated.

Results

The three component configurations in Figure 27 were chosen as candidates for an optimum design. Each of these three configurations possesses geometric

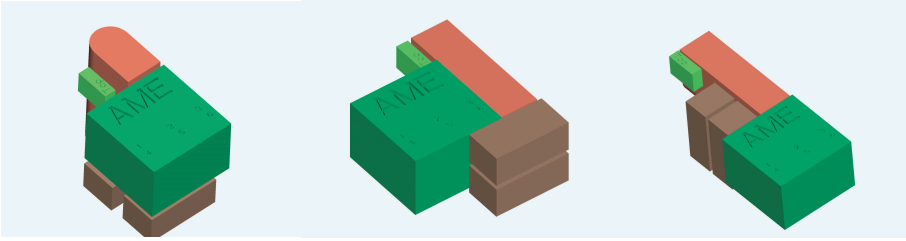


Figure 27: Possible Housing Configurations

characteristics determining the load caused by the housing weight and the ultimate allowable tensile stress for the structure. These characteristics are outlined in 3.5.

	Configuration 1	**Configuration 2**	**Configuration 3**
Critical face area	$4t^2+14.55t$	$4t^2+17.35t$	$4t^2+11.3t$
Housing volume	$8t^3+50.2t^2+102.4t$	$8t^3+57.8t^2+137.8t$	$8t^3+51.7t^2+98.1t$

Table 1: Volume and Area Comparisons

Materials considered for use in the housing were selected based upon past applications of those materials [10] . Polymers were selected which were used in durable and light-weight applications, such as sporting equipment and toys, while widely available and cheap metals such as aluminum and steel were con-

sidered for their availability and cost. The key mechanical characteristics of these materials are summarized later. Implementation of the conservation of energy for velocity calculations, and the assumptions outlined above for simulation of shock and impulse systems yielded the following equation for the impact force:

$$F = 300.93lbf + 6459.96\rho V \tag{43}$$

Dividing this force by the critical cross-sectional area listed in Table 1 allowed the calculation of the critical wall thickness, t. This, in turn, led to the calculation of the final system dimensions and system mass. These measures of merit are presented in the three tables below.

	Wall thickness (in)	Volume (in^3)	Mass (lbm)
Aluminum	0.000582	0.0596	0.052441
Steel	0.000417	0.0427	0.058727
ABS	0.0159	1.641	0.11224
Polycarbonate	0.00549	0.564	0.06916
Polystyrene	0.0143	1.475	0.1056
ASA	0.00922	0.948	0.08452

Table 2

	Wall thickness (in)	Volume (in^3)	Mass (lbm)
Aluminum	0.000248	0.0342	0.049952
Steel	0.000181	0.0249	0.053672
ABS	0.0163	2.262	0.13708
Polycarbonate	0.00491	0.678	0.07372
Polystyrene	0.0143	1.982	0.12588
ASA	0.00863	1.194	0.09436

Table 3

	Wall thickness (in)	Volume (in^3)	Mass (lbm)
Aluminum	0.000772	0.0758	0.054028
Steel	0.000572	0.0561	0.062532
ABS	0.0305	3.04	0.1682
Polycarbonate	0.00796	0.784	0.07796
Polystyrene	0.0261	2.596	0.15044
ASA	0.0146	1.443	0.10432

Table 4

In addition, the cost and manufacturability measures of merit were included in the final material performance index table. These results were normalized and a weighted possibility index chart was constructed, resulting in weighting factors for each measure of merit. Multiplying the normalized values by these measures of merit and summing these quantities for each design produced the material selection indices summarized in Table 5.

Design Variable Combination	Material Performance Index
Configuration 1, Aluminum	68.60738
Configuration 2, Aluminum	68.86784
Configuration 3, Aluminum	68.91513
Configuration 1, Steel	83.09873
Configuration 2, Steel	**84.68965**
Configuration 3, Steel	82.17888
Configuration 1, ABS	51.3018
Configuration 2, ABS	47.66338
Configuration 3, ABS	46.20794
Configuration 1, Polycarbonate	61.25915
Configuration 2, Polycarbonate	57.94828
Configuration 3, Polycarbonate	58.80857
Configuration 1, Polystyrene	55.13101
Configuration 2, Polystyrene	51.62717
Configuration 3, Polystyrene	50.31409
Configuration 1, ASA	55.77595
Configuration 2, ASA	52.35696
Configuration 3, ASA	52.09539

Table 5

The materials performance index evaluates not only the performance of the design with respect to an individual measure of merit, but rather combines all measures of merit, emphasizing those of greater importance to the consumer. Thus, the design with the highest performance index is the design with the most successful measures of merit and thus the optimum.

- Discussion of Results:

  The author maintains that the overall approach to this problem is sound. The housing design is an important product facet, worth of scrutiny. That said, the questionable results of this modified approach suggest serious flaws, largely

stemming from a lack of familiarity in the area of finite element analysis and shock and vibration. Research on the properties and behavior of plastics and familiar metals is familiar territory and likely not the source of large error. Rather analysis of the impact force with the many and broad assumptions making it possible creates a significant and fundamental uncertainty in the results. Examination of the calculated wall thicknesses in Tables 2-4 reveals that all designs would have housings with impractically thin walls (a "reality-check" expected wall thicknesses on the order of 0.10 in). The wall thickness is merely a state variable, resulting from the choice of design variable combinations. However, it is used to generate values for two of the four measures of merit, namely the system dimensions and system mass. Thus, any error in the calculation of the wall thickness, of which there is a significant certainty, will have escalated effects on the calculation of the material performance index and final design selection. Supposing the presented theory is sound, the optimum design would be a system in the second configuration with a steel housing. Examination of the measures of merit for configuration two, found in Appendix 4, reveals that three out of four of this design's measures of merit lie within the 90th percentile, or achieve a perfect score. Thus, in comparison to other material designs of configuration two, no other design combination had

as low a volume nor as low a cost index. This design's major drawback is its machinability, as designs of this type would be less convenient to mass-produce out of steel. Were a more traditional appliance style desired, one which was housed in plastic, the polycarbonate configuration one design would prove optimal. Drawbacks to this design are its comparatively large housing size and its higher cost.

- Discussion of the Influence of the Results:

  There exists much room for refinement in this evaluation, both on the theoretical level and on the consumer level. Truly accurate and optimized housing design demands the use of finite element analysis, as well as a thorough understanding of the forces imposed on the housing, be they steady and distributed loads or impulse loading. On the customer level, in-depth surveys should be conducted to truly pinpoint the relative importance of the measures of merit to the consumers. Through further education and surveying, an accurate model of the housing system can be developed. Serious doubt of this trade study's results exists, both due to an acceptance of the theoretical limitations and from a "reality check" analysis of the resulting numbers (expected wall thickness values ranged around 0.10 in). As such, it is unlikely that the current results of this study will result in significant implementation in prototype or final design.

Further and guided investigation into impact theory and plate mechanics will benefit this analysis in the future and generate a truly optimal design.

3.6 Critical Design Review Slides

3.7 CAD Models

The Aura Valve is composed of two main subassemblies: The electrical subassembly and the mechanical subassembly. The electrical subassembly consists of the electrical components including the Mini-Max controller, the pressure transducer, the push buttons, and the LCD screen. These components control the logical function of the device and are directly tied into the second subassembly, the mechanical subassembly. This consists of all the pipe fittings, the tubing, solenoid valve and the pump head. Its function is to allow passage of air from the air supply to the vessel and divert the flow if the vessel is filled. The following pages include detailed CAD drawings and assembly configurations of the final proposed Aura Valve design, as well as a cost accounting sheet of project expenses.

Team Unum Accounting

Date Ordered	Date Rec'd	Description	Part ID	Company	Price	S/H	Initials	Paid By
7-Oct-04	12-Oct-04	Pressure Sensor	Motorola MPX5700GP-ND	www.Digikey.com	$18.19	$8.39	FMB	Frankie
13-Oct-04	26-Oct-04	Solenoid Valve	8320G184 Asco	Coastal Supply	$84.50	$0.00	JRV	donation
12-Oct-04	15-Oct-04	Parallel LCD, 20x4	277376	Jameco	$23.29	$8.93	CJT	Chris
12-Oct-04	15-Oct-04	Pushbutton (6)	26622	Jameco	$3.30	$0.00	CJT	Chris
12-Oct-04	15-Oct-04	Switch, SLD	202972	Jameco	$0.20	$0.00	CJT	Chris
12-Oct-04	15-Oct-04	Heat Sink (2)	158051	Jameco	$0.78	$0.00	CJT	Chris
12-Oct-04	15-Oct-04	Jack, DC, Male, 2.1 mm	101178	Jameco	$0.49	$0.00	CJT	Chris
12-Oct-04	15-Oct-04	Plug, DC, Female, 2.1 mm	138587	Jameco	$0.79	$0.00	CJT	Chris
12-Oct-04	15-Oct-04	Plug, DC, Female, 2.1 mm	147328	Jameco	$0.69	$0.00	CJT	Chris
12-Oct-04	15-Oct-04	Plug, DC, Female, 2.5 mm	147336	Jameco	$0.75	$0.00	CJT	Chris
12-Oct-04	15-Oct-04	AC/DC Converter, 24 V	102285	Jameco	$7.95	$0.00	CJT	Chris
26-Oct-04	30-Oct-04	AC/DC Converter, 12 V	15368	Jameco	$6.49	$6.94	CJT	Chris
26-Oct-04	30-Oct-04	Relay, 5 V	106462	Jameco	$2.15	$0.00	CJT	Chris
26-Oct-04	27-Oct-04	PVC Multipurpose Airhose	Parker 49697808	MSC	$1.56	$0.00	JJH	Jim
26-Oct-04	27-Oct-04	Female NPTF Hose Barbs	Parker 79870606	MSC	$2.04	$0.00	JJH	Jim
26-Oct-04	27-Oct-04	Worm-Drive Clamps SAE 8	Tridon 48706097	MSC	$4.10	$0.00	JJH	Jim
26-Oct-04	27-Oct-04	Male NPTF Hose Barbs	Parker 79870002	MSC	$3.76	$0.00	JJH	Jim
5-Nov-04	10-Nov-04	Smart Head Valve		Topeak	$14.95	$5.00	JJH	Jim
10-Nov-04	12-Nov-04	5/8" Dia 2011 Aluminum Stoc	88615K31	McMaster	$15.50	$4.00	TDC	Tim
12-Nov-04	12-Nov-04	25' 0.25" Polyethylene Tubing		Lowe's	$1.70	$0.00	TDC	Tim
12-Nov-04	12-Nov-04	Teflon Tape		Lowe's	$2.63	$0.00	TDC	Tim
12-Nov-04	12-Nov-04	Female Pipe Tee		Lowe's	$1.99	$0.00	TDC	Tim
12-Nov-04	12-Nov-04	1/8" Barb Male Fitting		Lowe's	$2.96	$0.00	TDC	Tim
12-Nov-04	12-Nov-04	3/16" Barb Male Fitting		Lowe's	$0.89	$0.00	TDC	Tim
12-Nov-04	12-Nov-04	1.5" Brass Pipe Nipple		Lowe's	$0.79	$0.00	TDC	Tim
12-Nov-04	12-Nov-04	Close Brass Pipe Nipple		Lowe's	$0.59	$0.00	TDC	Tim
12-Nov-04	12-Nov-04	1/4" Pipe Clamps		Lowe's	$1.41	$0.00	TDC	Tim
28-Oct-04	3-Nov-04	LCD 242	705	BiPom	$24.95	$10.00	CJT	Chris
15-Nov-04	23-Nov-04	FDM Housing Shells		ND CAM	$70.00	$0.00	TDC	ND
23-Nov-04	23-Nov-04	Fasteners		Lowe's	$0.70	$0.00	TDC	Tim
Totals					**Parts**	**S/H**	**Total Costs**	
					$300.09	$43.26	**$343.35**	

Itemized List of Prototype Development Expenses

References

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