Pressure Meter
Engineering World Health

Final Report

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Abstract

The pressure of the gasses provided by anesthesia machines, ventilators, and other similar hospital equipment must be measured in order to avoid unsafe conditions for patients. Generally this is done with an internal gas pressure meter, but in third world countries the machines are not always advanced and may required an external device for this purpose. Engineering World Health (EWH), an organization that provides medical equipment to underserved areas of the world, is in need of a device like this. The most important limitation of this design is cost. Once background research was completed and a design matrix was constructed, a strain gage design was selected. This led to the construction of calibration curves and selection of suitable op amps, resistors and potentiometers. In the future, the project will consist of writing a proposal for EWH, improving the pricing and size of the device and finally its mass production.

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Background Information

Engineering World Health (EWH) is an organization of engineers, scientists, doctors, students, and other people who are interested in making a difference in disadvantaged areas of the world. It supplies appropriate medical technology to third world countries and other underserved areas in order to provide adequate medical care for the people living in these regions. (Engineering World Health (1), n.d.)

EWH has a program in which it sets specifications for certain devices that would be useful in medical care in these areas, and then accepts designs for these devices. If the designs meet all the requirements and are approved, EWH provides $150 for prototype production. Eventually, if the device is mass-produced for use in a third world country, the design group can accompany EWH members to distribute the device. (Engineering World Health (2), n.d.)

The Engineering World Health website (http://ewh.org) has specifications for each of the devices, including the gas pressure meter. The limiting factor of the design for this device is going to be the cost, which tends to be the case for most of the EWH projects. Also, generally gas pressure is measured with a pressure meter found within the machines that provide the pressure, but in third world countries the machines are not always advanced and may require an external device to read the pressure

Problem Statement

Our task is to design a gas pressure meter to be used in third world countries and to be distributed by Engineering World Health. The pressure meter will be used to measure the pressure of oxygen, medical air, and carbon dioxide and must be compatible with several different machines, including ventilators and anesthesia machines. The pressure leaving the machines will be measured and displayed using a digital readout. Generally ventilators and anesthesia machines used in hospitals today contain an internal device that measures pressure, but since this device will be used in a different setting, the machines may not be as “up-to-date” and may require an external device to read the pressure. (Backes, W., personal communication, February 28, 2007).

Constraints

This device must abide by several constraints in order to be a plausible solution. Several of these constraints were explicitly defined by EWH, and the rest were left to the group to research.

With regards to functionality, EWH has specified that the device must be able to measure pressure to within at least 10% of its true value, while 1% is optimal. The device needs to have a continuous readout, which means that the measurement system must be continuous as well. Also, the readout must be digital, which could be beneficial to the accuracy of the device by removing error produced by the person reading the display. Dimensions must be 4 inches by 4 inches by 1 inch for a device with only one segment, or 1 inch by 4 inches by 1 inch for a device with several segments.

EWH has specified that the device will be used to measure medical gasses, such as O_2, CO_2, and medical air. However, the range of pressures that the device will be required to measure was not defined. With the help of clinical engineers from the University of Wisconsin Hospital, the group found that pressures between -35 mm of Hg and +75 mm of Hg would be optimal.

Since the device will potentially be used with technologically "out-of-date" machines, there is no specific form factor to reference for the design. The device must therefore be flexible in its ability to compensate for different connections (e.g. hose barb, locking ring, quick release). The device must also be reusable and autoclave compatible, though this method of sanitation may not be necessary and will be discussed with EWH at a later date. The final specification is the cost; in quantities of 500, the devices needs to cost less than two dollars each, including packaging, but not including the cost of manufacturing.

Several other safety requirements were not specified by EWH, but should still be taken into consideration when designing the device. The materials that are used, along with being autoclavable, must be nontoxic and should not shed any sort of debris. Also, since the device will be directly linked to the airflow going to the patient, the design of the device should not block the airways in the case of a malfunction. Weight was not specified, and will probably not pose a significant constraint on the design.

Current Technology

There are many forms of pressure measurement in use today for various applications. These tools are known as pressure or gas gauges. Pressure is most commonly thought of as the relationship between the amount of force and the area on which it is exerted. This is the basis for the equation Pressure = Force/Area. Most measurement devices incorporate this concept in some way, and make measurements with some reference to a zero point (usually atmospheric pressure). There are also two types of pressures considered – static pressures and dynamic pressures. Static pressures are exerted in all directions, like from gas and fluids. Flow produces pressures parallel to its direction and is usually referenced as dynamic pressure. These two differ in the way that they are measured. Since static is constant in all directions, the measurement device may be positioned anywhere. Dynamic pressures are measured in a more complex fashion, using references to other pressures. However, since dynamic pressures are less important in this design, they will not be considered in depth.

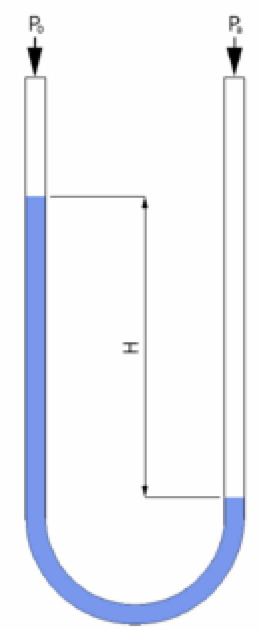

Figure 1: Diagram of a monometer. Pa represents the unknown pressure, and Po represents the reference pressure. (Wikipedia.org, n.d.)

One of the most primitive forms of pressure measurement is the monometer. It utilizes a U-shaped column filled with some liquid, typically mercury or water (Figure 1). The pressure of one side of the column is used as a reference and compared to the pressure of the other side, using the difference in heights as a measurement. The pressure displaces the liquid until the liquid's weight compensates and reaches equilibrium. This is a superior method for analog analysis.

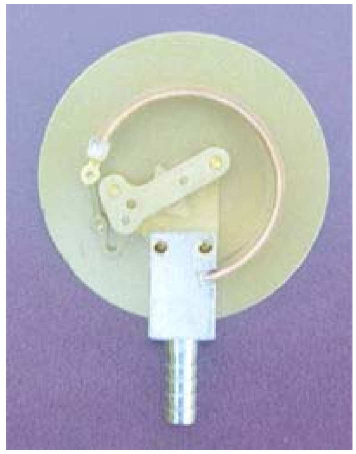

Figure 2: Backside view of a Bourdon Gauge. (Wikipedia.org, n.d.)

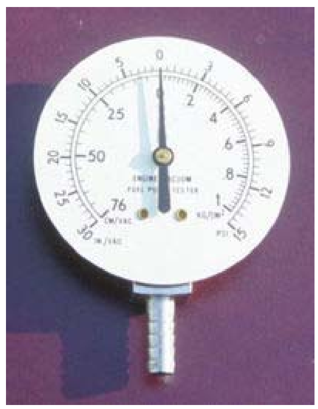

Figure 3: Frontside view of a Bourdon Gauge. (Wikipedia.org, n.d.)

Another common form of measurement is called the bourdon gauge. It involves a coiled tube connected to a port that's exposed to a changing pressure (Figures 2 and 3). As the pressure increases, the tub straightens out, rotating a gear train connected to a dial. The stronger pressure extends the tube farther and the dial is rotated. This is another gauge that is primarily used in analog pressure analysis.

The most commonly used digital pressure detector is a strain gauge. An example is the foil strain gauge. As the foil is deformed by pressure, the resistance across it changes. Using a Wheatstone bridge, this unknown resistance can be measured and converted into a voltage. With a gauge factor and the change in voltage, different pressures can be analyzed digitally.

Preliminary Designs

Propeller Design

This design uses the relationship between the velocity of flow, its density, and the area of a cylinder as described by Bernoulli's equation. The main part of the design consists of a cylinder of known diameter with an axial fan mounted to its center. It is important that the cylinder is long enough so that moving air has enough time to stabilize after experiencing turbulence from the change in tube diameter between the medical equipment and the device. Each device will be calibrated with various known pressures throughout the range of the required pressures outlined in the constraints section. Once a calibration curve is created, a known voltage will indicate an unknown pressure.

One of the pros of this device is its simple design. It will not be complicated to produce, and the components should be relatively easy to find. None of the pieces are excessively expensive.

One of the cons of this design, however, is that it requires flow. Pressure does not necessarily require flow, so in some cases this design might not function properly. Also, each device will need to be calibrated separately. One final downside is the possibility of the blockage of a patient's airway due to malfunction of the fan.

Piezoelectic Design

This design is based on the utilization of a special material that is able to convert a mechanical signal into an electrical signal. The material that can accomplish this is a piezoelectric material. This material responds to a mechanical stimulus with a voltage output and to an electrical signal with a mechanical change in shape. A flap of this material would be placed on the interior of a tube that is connected to the machine in which we need to measure pressure. When the gas from the machine flows through the tube the pressure from the gas will deform the material, outputting a voltage which we could convert to a pressure through calibration.

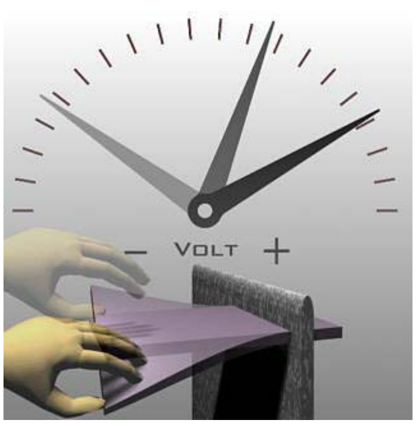

Figure 4: Depiction of the piezoelectric material behavior. As material is deformed there is a change in voltage. (Design inSite, n.d.)

One of the pros of this design is that it would be more accurate than the propeller design. Also, it would reduce the number of circuitry components because it acts as its own transducer, meaning that it would only be necessary to digitize the voltage output *and* display the results.

The biggest problem with this design is that it will be very expensive because the piezoelectric material can be very costly, at least $100, which is far from our budget constraints. Also, the piezoelectric material can only detect changes in pressure, and would not be able to measure static pressures.

Design Matrix

Once the designs were narrowed down to final three options – piezoelectric, propeller, and strain gauge – they were evaluated using a design matrix. Each design was evaluated in six different categories, which included patient safety, cost, size, ease of production, durability and client requirements. Since three of these categories – patient safety, cost and client requirements – are the most important, they were weighed on a scale from 1 to 10 (1 being the worst to 10 being the best). The rest of the categories – size, ease of production and durability – were considered on a scale from 1 to 5 (1 being the worst and 5 being the best). The piezoelectric design came out with 27, the propeller design came out with 31, and the strain gauge design came out with 40 points. Based on this evaluation, the design chosen for further pursuit was the strain gauge design. Figure 6 shows this design matrix.

Design	Piezoeletric	Propeller	Strain gauge
Patient safety (10)	**8**	**6**	**8**
Cost (10)	**4**	**8**	**10**
Client requirements (10)	**6**	**6**	**10**
Size (5)	3	3	4
Ease of production (5)	3	3	4
Durability (5)	3	5	4
Total (45)	**27**	**31**	**40**

Table 1: Design matrix of our three design alternatives. The strain gauge design won out getting 40 total points.

Final Design

After making a design matrix, the third design option, a strain gauge device, was chosen as the final design. This design uses a strain gauge as the pressure transducer to change the pressure signal into a voltage signal. The first step towards making this device was splitting the design into two parts: transducer circuit and digital display. This allowed efficient work and kept the project moving ahead with full force.

This design is based on basic principles of circuitry and is able to use mechanical pressure to transducer and electrical signal. The basic circuit component at the heart of the strain is the wheatstone bridge shown below in figure 5. Using known resistances of three resistors, an unknown voltage can be found over the fourth resistor, labeled Rc in figure 5 below. Through calibration with known pressures a voltage output can be equated to pressure.

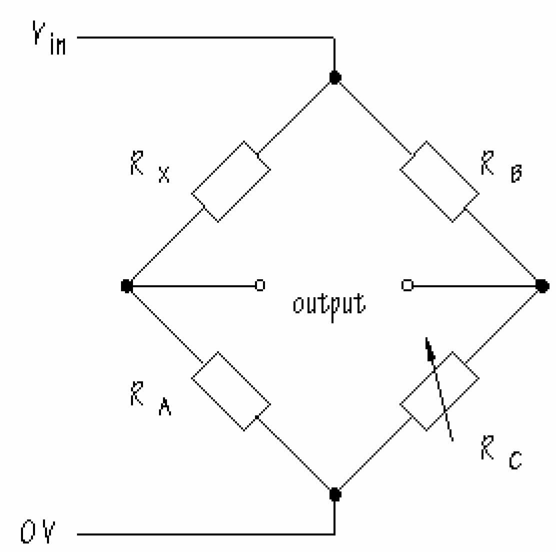

Figure 5: Depiction of a wheatstone bridge. Using three known resistors, a change in voltage can be determined off of a fourth resistor based on the mechanical stimulus it receives. (Westminster School Intranet, n.d.)

One advantage of this design is that it is very accurate. This would provide the best chance of reaching the goal of 1% of the true value of pressure. Also, this design can be relatively inexpensive compared to the other two because these pressure transducers are already commercially available. Furthermore, this is the only design that is able to measure static pressure, which is a major advantage over the other designs.

The major con of this design is that it has a lot of circuitry components, which increases the probability of failure in any single component of the circuit.

With the help of Amit Nimunkar and John Webster regarding the circuit design, a design was chosen that utilizes a pressure transducing circuit used in a BME 310 lab. The circuit diagram is shown in Figure 6. This circuit was then modified to meet the expectations in terms of voltage and accuracy. The next step involved creating calibration curves using known pressure so that based on the voltage output received pressure input from a simple equation could be calculated. This process is detailed in the testing section. The strain gauge used in this application, although too expensive for our application, is very accurate and a good choice for a proof-of-concept first prototype. A detailed description of the strain gauge used for the first prototype can be seen at this location: http://www.utahmed.com/intran.htm.

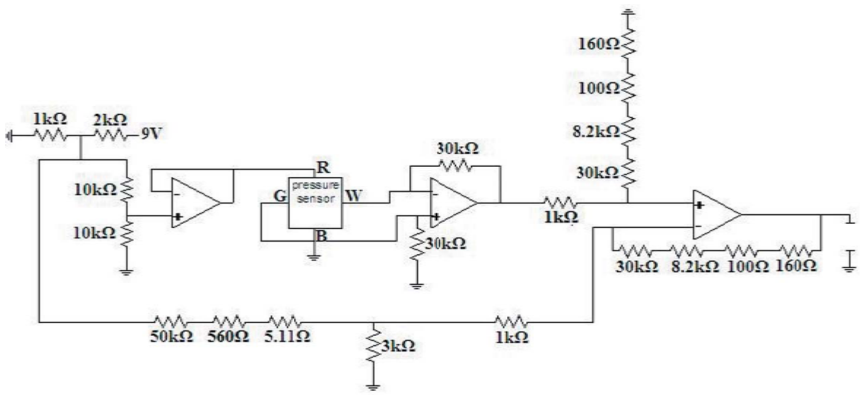

Figure 6: Circuit diagram for the prototype pressure transducer using a strain gauge.

Since the design required a digital display, one of the main design problems was finding a way to convert analog signals to digital and displaying the digital signal once it is obtained. This process was also a source of many problems during the design process. After some research, it was determined that the analog signal would be converted to a digital signal using a simple AD converter. These can be commercially bought and are very inexpensive. From here the signal can be displayed using an LED or an LCD screen. Both the AD converter and an LCD screen were purchased from Allied

Electronics to be implemented in the transduction circuit. It was later found that the LCD needed a driver and a controller to function properly. After consulting Professor Willis Tompkins about using a microcontroller system it became apparent that this would be too expensive for the budget constraints in our project. This problem was solved through the use of a digital voltmeter to display the output voltage and accounting for the parts of the calibration curve within the circuit itself. This would be accomplished by adjusting the circuit voltages and resistor values so that the output voltage is equal to the pressure input value. For example, if the pressure value is 70 mmHg, the voltmeter will display 70 mV. The cost of the digital voltmeter will be the ultimate determinant of the efficacy of this design solution. The best prospect for an inexpensive, accurate digital voltmeter is to use a build-your-own voltmeter instruction site as found at this location: http://www.electronics-lab.com/projects/test/014/.

Cost Analysis

Because of the stringent cost specifications set forth by Engineering World Health, the biggest challenge in the upcoming semesters will be reducing the overall cost of the design. Currently the total estimated cost of one device is $43.10, which is well over the $5 individual cost allowed in the specifications.

The circuit utilizes a combination of several resistors purchased from the University of Wisconsin Electrical and Computer Engineering Parts Shop for a total of $2. The op-amps used in the circuit were also purchased at the Parts Shop and totaled $0.60. A 9-Volt battery used in the design costs $0.50, and can be purchased at Walgreen’s or Target. The strain gauge is the most expensive component of the design, and costs $35. The strain gauge used in the prototype was borrowed from a bioinstrumentation lab in the UW College of Engineering, but can be found and purchased at http://www.utahmed.com/intran.htm. The digital display will consist of parts from a build-your-own voltmeter kit and costs $5 from http://www.electronics-lab.com/projects/test/014/.

Testing

Testing was done often in the design and construction process. It was used to evaluate the performance of a current circuit before additions were made. The first test was administered with a low accuracy Bourdon gauge to observe the linearity between the pressure input and the voltage output. If the circuit would have been obviously nonlinear in the desired range, the design would have been abandoned. Even with this poor quality test equipment the linearity was very apparent, with an average standard deviation between trials of .5%.

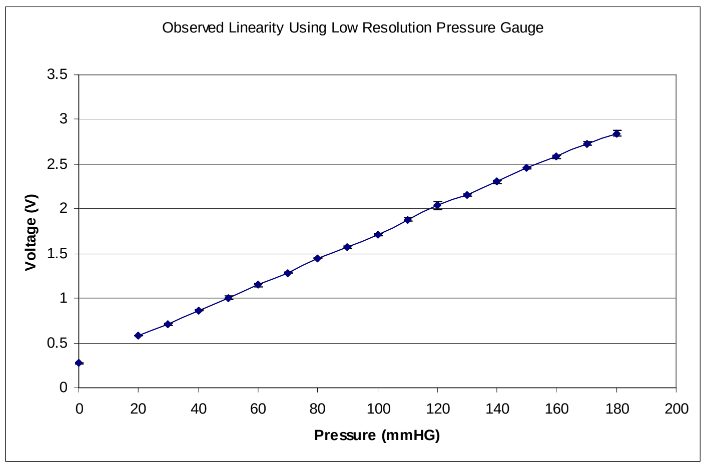

Figure 7: Preliminary observation of circuit linearity. Standard deviation lines are present, but difficult to see.

The next step in testing involved the selection of proper resistors following the Wheatstone bridge (See Figure 6). A more accurate pressure source was used, specifically the KAL 84 electronic pressure calibrator which was borrowed from one of the professors in the department. It had

Voltage (V),	Average

Resistance (Ohms)	Standard Deviation
7.5, 68k	9.32E-4
3, 68k	3.02E-2
3, 51k	5.05E-4
3, 30k	1.67E-4
3, 10k	1.73E-2

Table 2: Average standard deviation of voltage output from varying resistors following Wheatstone bridge as well as varying voltage inputs.

significant figures to one one-hundredth. The resistors tested ranged from 10k from 68k, as well the voltage inputs 3k and 7.5k. Only one test case involved an input of 7.5V because the final product would likely use a lower voltage, closer to 3V. 7.5V was only used as a reference. The average standard deviation of each grouping was used to assess the resistors performance. These values can be seen in (Table 1)

The lowest average standard deviation came from two 30k resistors with a 3V input, so they were chosen for the circuit. After the potentiometer was integrated and the resistance was calibrated to produce a voltage offset of zero, one final set of tests were taken to again evaluate the average standard deviation of the

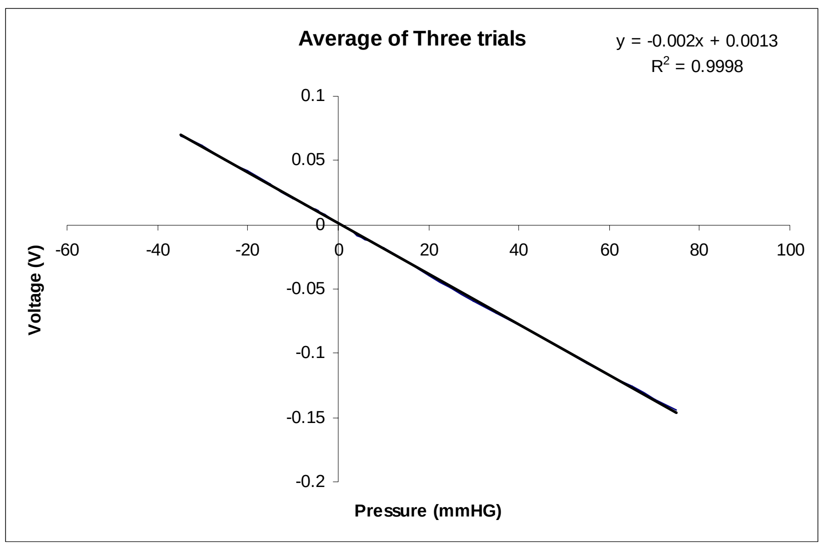

Figure 8: Relationship between pressure and voltage output of final circuit design.

circuit. Again the KAL 84 electronic pressure calibrator was used. This time the pressures were extended into the negative direction, since in the preliminary design stage it was decided that ranges needed to extend from -35mmHg to 75mmHg. Acquisition pressures began at -35 to -5 in increments of 5, then to +5 in increments of 1, then to 75 in increments of 5. The standard deviation was slightly higher (4.87E-4) but still well under the requirements. Similarly, the graph was still very linear (See Figure 8).

It should be noted that in previous test, the absolute voltage average was observed, so the slope of the graph was have been positive. Here, since negative pressures were observed, it became necessary to observe a signed voltage.

Future work

This being the first of a three-semester project, next semester the group will focus on improving the design, creating a better prototype and submitting a proposal. The final semester will focus on improving fine details and implementing our design for distribution in a third world country.

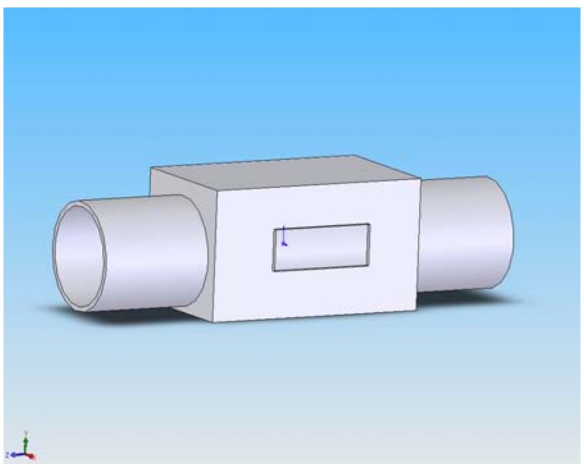

Figure 9: Schematic of the final prototype. This device will feature a box that houses the circuitry, a display and connection pieces to the anesthesia machine.

In terms of the circuit design, one thing that needs to be modified is the display of the proper signal that directly indicates the input pressure. This will most likely be accomplished using the build-your-own voltmeter instructions referenced in the final design section of the paper. The next step with the circuit will be to decrease the costs and in particular decrease the cost of the strain gauge. By the end of next semester the group will have a printed circuit board (PCB) and a prototype that looks like the schematic shown in Figure 9.

By the end of next semester the proposal for EWH will be finished and submitted. EWH requires that the group have documented contact with a clinical engineer in a third world country in order for proposal to be submitted. These clinical engineering contacts are distributed to design groups in the fall semester only and therefore the proposal could not be submitted this semester.

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Appendix: *Product Design Specifications*

Gas Pressure Meter (Engineering World Health)

Problem Statement

Our project goal is to develop a device that can measure the pressure of a gas (either oxygen, medical air or CO2) in medically useful ranges. This device must be mass producible within the specified cost range, and will be used in third-world countries.

Engineering World Health Requirements

- Final cost of <$5 in quantities of 5
- Size: for continuous readout – 4x4x1 or for single readout – 1x4x1
- Measurement of medically useful ranges (post-regulation, such as in ventilators, anesthesia machines, etc.) to within 10% of the measured value
- Measurements of CO_2, oxygen, and medical air
- Digital readout
- Various connections (such as hose barb, locking ring, quick release, etc.

Design Requirements

1. Physical and Operational Characteristics

a. *Performance requirements*: This device must be able to measure gas pressures as they are about to enter the patient. The range in pressures should be medically useful. These gasses will include Oxygen, Carbon Dioxide, as well as other types of medical gasses.

b. *Safety*: The device should be made out of non-toxic material. Any electronics used should be properly insulated.

c. *Accuracy and Reliability*: Minimum performance should be able to measure within 10% of actual value. Superior performance should allow for measurements within 1% of actual values.

d. *Life in Service*: The device should be autoclavable. It is not disposable.

e. *Shelf Life*: It should last through several uses.

f. *Operating Environment*: The device will be used in the hospitals of third-world countries. The hospital technology may be out-dated so the device must function in a variety of environments and support the greatest range of connection flexibility possible. The device should not depend on other, potentially unavailable tools.

g. *Ergonomics:* Function and reliability are most important. Look and feel of this device is a secondary consideration.

h. *Size*: A continuous readout must stay within 4x4x1in, while a single readout device must stay within 1x4x1in. These dimensions may apply to a device in parts or a fully constructed one.

i. *Weight*: Weight was not specified, but given the dimensions the device will stay under 12oz.

j. *Materials*: Materials should be non-corrosive, non-toxic, inexpensive and sturdy.

k. *Aesthetics, Appearance, and Finish*: The readout must be digital.

2. Production Characteristics

a. *Quantity*: Price specifications were provided for quantities between 5 and 500.

b. *Target Product Cost*: For a quantity of 5 the price should be less than $5 and for a quantity of 500, it should be less than $2.