Hydrostatic Hyperbaric Chamber Ventilation System

Miriam J. Sargusingh[1]
NASA Johnson Space Center, Houston, TX, 77058

The hydrostatic hyperbaric chamber (HHC) represents the merger of several technologies in development for NASA aerospace applications, harnessed to directly benefit global health. NASA has significant experience developing composite hyperbaric chambers for a variety of applications. NASA also has researched the application of water-filled vessels to increase tolerance of acceleration forces. The combination of these two applications has resulted in the hydrostatic chamber, which has been conceived as a safe, affordable means of making hyperbaric oxygen therapy (HBOT) available in the developing world for the treatment of a variety of medical conditions. Specifically, HBOT is highly-desired as a possibly curative treatment for Buruli Ulcer, an infectious condition that afflicts children in sub-Saharan Africa. HBOT is simply too expensive and too dangerous to implement in the developing world using standard equipment. The HHC technology changes the paradigm. The HHC differs from standard hyperbaric chambers in that the majority of its volume is filled with water which is pressurized by oxygen being supplied in the portion of the chamber containing the patient's head. This greatly reduces the amount of oxygen required to sustain a hyperbaric atmosphere, thereby making the system more safe and economical to operate. An effort was taken to develop an HHC system to apply HBOT to children that is simple and robust enough to support transport, assembly, maintenance and operation in developing countries. This paper details the concept for an HHC ventilation and pressurization system to provide controlled pressurization and adequate washout of carbon dioxide while the subject is enclosed in the confined space during the administration of the medical treatment. The concept took into consideration operational complexity, safety to the patient and operating personnel, and physiological considerations. The simple schematic, comprised of easily acquired commercial hardware, supports sustainability.

Nomenclature

atm	=	atmosphere, standard
CO_2	=	carbon dioxide
HBOT	=	hyperbaric oxygen therapy
HHC	=	hydrostatic hyperbaric chamber
mm Hg	=	millimeters of mercury
O_2	=	oxygen

I. Introduction

The hydrostatic hyperbaric chamber (HHC) represents the merger of several technologies in development for NASA aerospace applications, harnessed to directly benefit global health. NASA has significant experience developing composite hyperbaric chambers for a variety of applications, including the treatment of medical conditions. NASA also has researched the application of water-filled vessels to increase tolerance of acceleration forces. The combination of these two applications has resulted in the hydrostatic chamber, which has been conceived as a safe, affordable means of making HBOT available in the developing world for the treatment of a variety of medical conditions. Specifically, HBOT is highly-desired as a possibly curative treatment for Buruli Ulcer, an infectious condition that afflicts children in sub-Saharan Africa. HBOT is simply too expensive and too dangerous to implement in the Developing World using standard equipment. The HHC technology changes the paradigm.

---

[1] Systems Engineer, Crew and Thermal Systems Division, 2101 NASA Parkway/EC2

The HHC differs from standard hyperbaric chambers in that the majority of its volume is filled with water. Since water is essentially incompressible, filling the chamber greatly limits the internal volume of compressed gas. This decreases the potential energy contained within the chamber, and decreases the overall energy expenditure needed to operate the chamber. The energy requirements for operating a traditional medical hyperbaric chamber make it too expensive (and too unsafe) to implement in undeveloped locations. In contrast, a hydrostatic hyperbaric chamber could make HBOT a financially viable treatment option for medical conditions in the developing world. Developing a simple hydrostatic hyperbaric system could therefore utilized for compassionate medical care in the Developing World with good effect.

Since the human body is predominantly water, the occupant of a hydrostatic hyperbaric chamber can be made neutrally buoyant. NASA studies have shown that, when subjected to a hyperbaric, hydrostatic pressure, humans are capable of withstanding higher g-loads and vibrations. A personal HHC, or launch pod, would be beneficial in mitigating the injury to crew during launch. With respect to commercial applicability, a lighter and less expensive HHC's could be used to make DCS treatment available on more dive boats. Likewise, a lightweight, low energy system could be applied to mitigate the effects of altitude sickness and provide decompression sickness (DCS) treatment.

The objective of this project is to develop and manufacture a portable single-person hydrostatic hyperbaric chamber (HHC) that can be used to administer HBOT in developing countries.

II. Design Considerations

A. Concept of Operations

A concept of operations (ConOps) was discussed by the design team in order to draw out the design functions, constraints and requirements.

The HHC components will be manufactured/procured in the locality of treatment administration. The HHC will be transported to the medical facility via a readily available form of transportation, for example a pick-up truck. No special equipment will be required and the environment will not be controlled. It is assumed that the form of transportation is not highly reliable, therefore breakdowns may occur in transit causing significant delays. At the medical facility, "normal" medical equipment such as human grade oxygen, breathing masks and plastic oxygen grade tubing will be available. Local technicians will off-load the HHC from the truck to the administration site and assemble the unit. The seat will be adjusted in accordance with the patient's size. The patient will be seated in the HHC and the restraints adjusted and secured. The chamber will be filled with local water to the patient's collar bone. The chamber is closed. The chamber is pressurized with breathing gas to the desired pressure.

The hydrostatic hyperbaric chamber will require a subject to be enclosed in a confined space for about an hour during the administration of the medical treatment. A doctor and support person (e.g. parent) maintains visual contact with the patient. It is expected that the patient may experience convulsions during the treatment and must, therefore, be secured so as not to fall under the water level. The HHC will incorporate a harness to keep the subject from submerging into the water portion of the chamber. If the doctor perceives significant danger to the patient, the treatment is stopped. In an emergency, the chamber is returned to ambient pressure and the water is dumped. The chamber is opened and the patient is removed.

B. Derived requirements

Based on the ConOps, the key design considerations for the HHC were as follows:
- **Safety**: It is NASA policy to protect the public, NASA workforce, high-value equipment and property, and the environment from potential harm as a result of NASA activities and operations by factoring safety as an integral feature of programs, projects, technologies, operations, and facilities. [NPD 8700.1E]
- **Cost**: The upfront cost of the design and manufacture of this system must fall within the project budget
  - Application of this technology to benefit Developing World medical care is contingent on the ability to fund the acquisition and sustaining operation of this system
  - Specialized equipment or personnel must not be required to operate or maintain this system
- **Portability**: This system must be light enough to be assembled manually and small enough to fit in standard modes of transportation available in Developing counties; e.g. a pick-up truck flat bed
- **Reproducibility**: It is a goal to have this technology manufactured directly in third world countries

The following are the key driving requirements were derived for the HHC ventilation system:
- The ventilation system must provide controlled pressurization of the HHC at start up

- The ventilation system must maintain the system at the nominal operating pressure throughout the duration of the procedure
- The ventilation system must mitigate the toxic buildup of CO_2.
- The ventilation system must accommodate movement of the patient (e.g. convulsions)
- The ventilation system must allow for visual monitoring of the patient
- The design must accomodate 5th percentile 5-yr old child through 95th percentile male. The following parameters were taken into consideration when designing the ventilation system:
  - Neutral placement of oral/nasal region
  - Head range of motion
  - Breath capacity
  - Inspiration Rate
  - Tidal Volume
- The design must provide for controlled depressurization at termination of treatment
- The design must accommodate an emergency termination.

III. Design Concept

This ventilation system schematic was intended to be as simple as possible to support operability and maintainability. Figure 1 provides a notional schematic.
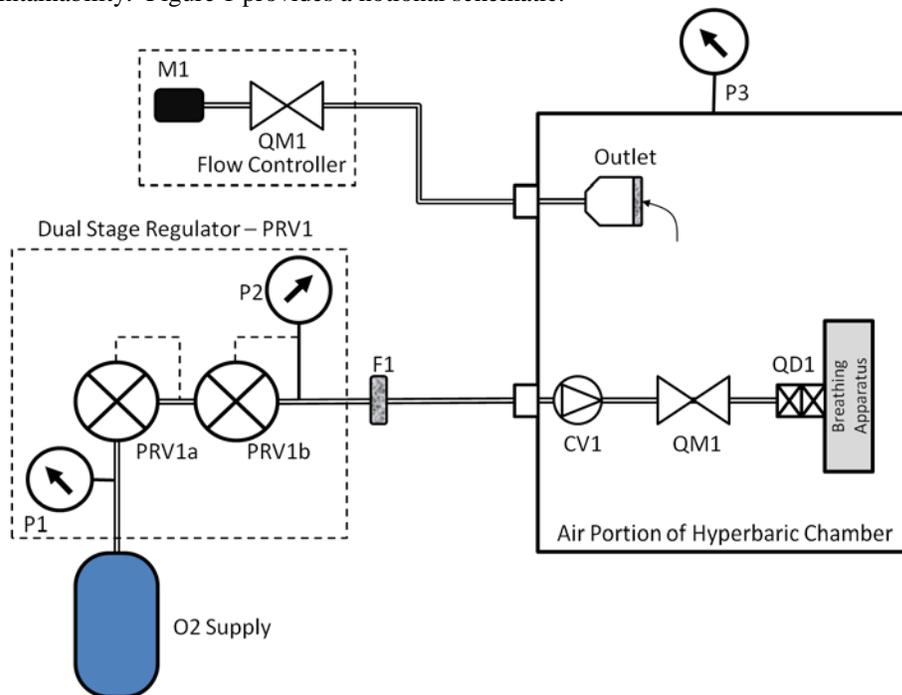

Figure 1. Notional Schematic for an HHC Ventilation System

A. Pressurization System

The general architecture chosen for the ventilation system is one where oxygen is transmitted to the breathing apparatus. This ventilation flow is used to gradually pressurize the system. A back pressure regulator at the outlet maintains the pressure in the chamber throughout the procedure. A manual valve is included at the outlet to depressurize the chamber at the end of the procedure.

It is expected that high pressure oxygen will be available locally. A standard bottle at up to 1000 psi is plumbed to a standard fitting on the HHC. A dual-stage regulator steps the oxygen pressure into the HHC down to an acceptable operating pressure (about 2 atm). An inline flow meter is used to control the flow to the breathing apparatus. A checkvalve prevents back flow of expired air into the oxygen supply line.

A reverse flow regulator is included to support the emergency termination event. In this scenario, a manual valve opens the HHC drain to dump the water from chamber. Without a way for pressure to equalize with the ambient environment, a sub-ambient pressure could be achieved in the chamber posing a risk of decompression sickness to the patient. With certain oxygen delivery methods, there is a risk of incurring a hypoxic environment

until the chamber can be opened. The reverse flow regulator allows ambient air to enter the chamber thereby preventing sub-ambient conditions to occur.

All of the components in the pressurization subsystem are commercially available. A sample parts list is included in Appendix A.

B. Oxygen Delivery Subsystem

The breathing apparatus, or means by which air is delivered to the patient, drives the design of the whole ventilation system. Three ventilation options were evaluated: demand breathing, free volume ventilation (FVV), and directed constant flow (DCF).

Demand breathing systems are used by miners, firefighters and divers (among others). This option provides breathing to the subject via a demand regulator. A suction force created by the lungs during the inhalation motion triggers oxygen flow to the subject. The air is then exhaled to the chamber. A relief valve is used to keep the chamber from over-pressurizing. Since air must be delivered to the patients a varying pressures from 1 to 2 atm, a self-contained underwater breathing apparatus (SCUBA) system is the most relevant commercially available demand breather for the HHC.

In the FVV concept, pure oxygen is directed into the hyperbaric chamber to pressurize the volume. Inlet and outlet flows are then maintained in order to establish a ventilation path in the chamber to mitigate toxic buildup of carbon dioxide. In this scenario, flow must be sufficient to ensure that there is no build-up of CO_2 greater than 5mmHg anywhere in the gas chamber. Significantly more oxygen would be required than with a oral-nasal directed flow.

DCF delivers a constant flow of oxygen directly to the subject's nose and mouth. Excess oxygen and expired air flows to the chamber dome and out through a back-pressure regulator that maintains a constant pressure within the chamber. This option passively ventilates to the chamber dome. One option (DCF1) is to administer oxygen via a pediatric nebulizer mask or standard oxygen mask. An alternate solution is a face directed spray bar. This would maintain a constant flow of air over the patients face.
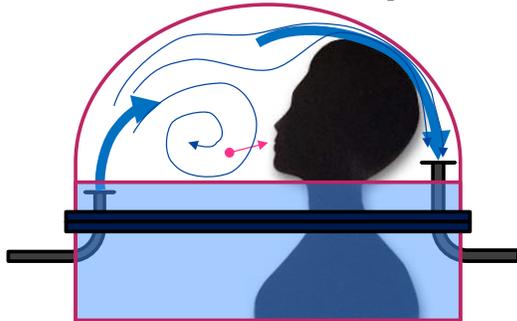

Figure 2. Free Volume Ventilation (FVV).

Figure 4. Directed Constant Flow with Overhead Spray Bar (DCF2).
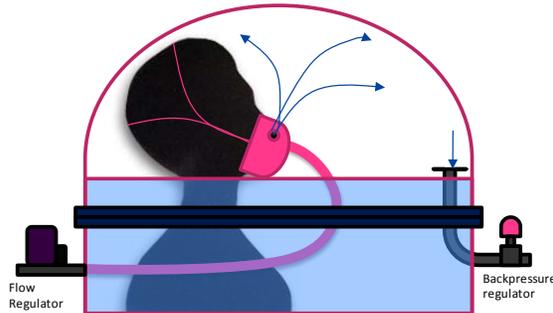

Figure 3. Directed Constant Flow with Oral-Nasal Mask (DCF1).

A multiobjective analysis (reference Kirkwood) was performed using the key design considerations and requirements to establish the evaluation measures. All options meet basic functionality, therefore the functional requirements were not included as evaluation measures. Additionally, none of the four options challenge portability. The preliminary value hierarchy is presented in Figure 5.
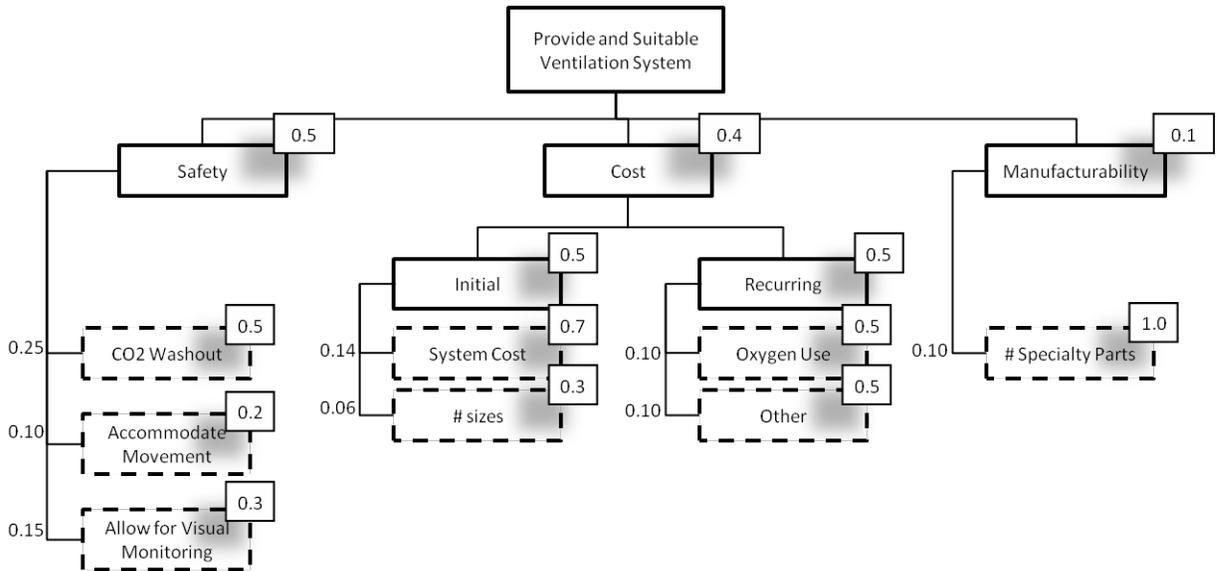
Figure 5. Preliminary Value Hierarchy for Ventilation System Trade Study.

After preliminary analyses of each evaluation measure, it was determined that the options do not provide a significant distinction with respect to CO_2 washout or movement accommodation. No additionally consumables were identified for each of the options to affect recurring costs. Finally, the commercially available equipment was identified to support all options such that no specialty parts would be needed for any option. Four evaluation criteria were then used to score the options. The weights were adjusted to maintain the same relative weights prior to the simplification. The final value hierarchy is shown in Figure 6.
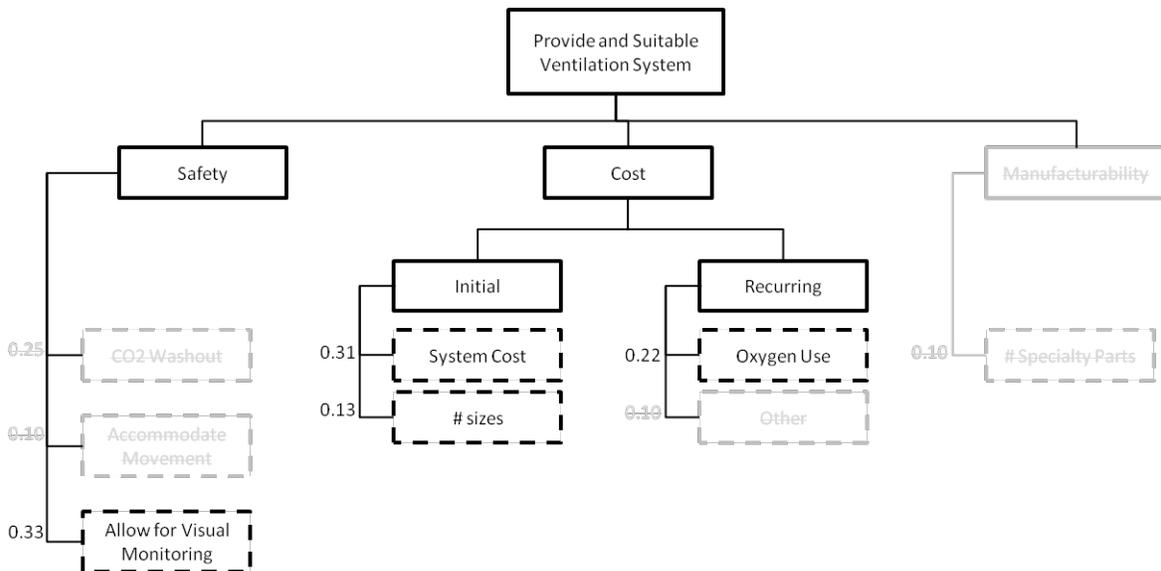
Figure 6. Final HHC Ventilation System Trade Study Value Hierarchy

1. Patient Monitoring
This objective measures the impact to visual monitoring of the patient. Each option was evaluated – one point was given for each visual impediment identified.

American Institute of Aeronautics and Astronautics

The demand breather option requires a full face mask with an attached demand regulator. The oral nasal region of the patient would be completely covered, though clear view of the patients eyes is achieved. Since there is no active ventilation to the chamber, the dome is likely to fog over reducing the care providers ability to visually monitor the patient. There is very little risk that the mask would be displaced during the procedure. This is also low risk of blocking the flow path with spit or vomit. (get a better reference than about.com)

FVV allows for optimal monitoring of the patient since there is no hardware impeding the view of the patient. Additionally, the option allows for flow to be directed to the dome to keep down fogging during the procedure. The flow could be configured to achieve acceptable washout of CO2 (see the figure); some risk of CO2 pockets forming remains (reference Augustine's CO2 washout paper).

Both DCF options require something to be worn by the patient that channels oxygen directly to the nose and mouth region. The DCF1 mask has some impact on the ability to visually monitor the patient as it will cover the oral nasal region of the patient with a translucent plastic. The DCF2 head-mounted spray bay could have a larger impact on patient monitoring. Both options would require some oxygen to be channeled toward the dome to mitigate fogging. Both options will achieve adequate CO2 washout.

2. System Cost

Only the device that delivers the oxygen to the patient was reviewed for this parameter; the infrastructure to provide oxygen to this device is similar for all options. DBA is the most expensive option, followed by DCF2. The FVV option requires nothing more than the basic pressurization infrastructure and therefore is considered to carry no cost. DCF1 requires a very inexpensive oxygen mask.

3. Sizing

Another aspect to cost involves sizing. The options that interface with the patient may need various sizes to accommodate the patient pool. Several units would have to be purchased, increasing the system cost. The FVV option does not interface with the patient and, therefore has no additional cost incurred. The remaining options would require at least 2 sizes to accommodate both child and adult physiology.

4. Oxygen Use

A major aspect of the system's recurring cost is the oxygen usage. The DCF options will require about (need to recalculate) oxygen per hour of treatment to support a small child to average adult, respectively.

<insert oxygen usage calculations>

The DBA will require less than half the gas as the DCF options since oxygen will only be consumed during inhalation. The FVV option will require significantly more oxygen to ensure adequate CO2 washout.

A quick test was performed to demonstrate a small volume hatch concept; inspired CO2 was measured given up up to 10 lpm oxygen at ambient pressure. Adequate CO2 washout could not be achieved in the FVV configuration; directed flow to the oral-nasal region was required. This was was very low fidelity test that should be repeated to validate flow requirements; but the observations correlated to the trend predicted by the analysis.

5. Trade Study Results

The following table shows the scores given for each parameter. FVV is rated to be the best option followed closely by the DCF1 option.

Table 1. Oxygen Supply Trade Scores.

Parameter \ Option	DBA	FVV	DCF1	DCF2
Fogging	1	0	0.5	0.5
Blocked view of nose/mouth	1	0	0.5	0
Blocked view of eyes	0	0	0	1
Raw Score	2	0	1	1.5
Value	**0.5**	**1**	**0.75**	**0.625**
Weighted Safety (.625)	**0.165**	**0.330**	**0.248**	**0.206**
Cost	600(1)	0	2.52(2)	300(3)
Value	**0**	**1**	**0.9958**	**0.5**

Weighted Cost (.131)	**0.000**	**0.310**	**0.309**	**0.155**
Sizing	1	0	1	1
Value	**0**	**1**	**0**	**0**
Weighted Sizing (.056)	**0.000**	**0.130**	**0.000**	**0.000**
O2 Usage	1.5 cfm	>> 3 cfm	3 cfm	3 cfm
Value	**1**	**0**	**0.5**	**0.5**
Weighted Score (.138)	**0.220**	**0.000**	**0.110**	**0.110**
Total Score	**0.385**	**0.770**	**0.666**	**0.471**

1. http://www.scuba.com/scuba-gear-124/029940/Ocean-Reef-Neptune-Space-G.divers-Full-Face-Scuba-Dive-Mask.html
2. http://www.medexsupply.com/respiratory-oxygen-therapy-oxygen-masks-and-tubing-oxygen-masks-hudson-pediatric-aerosol-mask-without-tubing-each-x_pid-8410.html
3. http://store.cyberweld.com/micowehecosy.html

The DCF1 had a significantly lower score due to fogging of the chamber and the need for multiple sizes to support the range of patient physiology. The FVV was at a deficite with respect to oxygen usage. A higher fidelity trade study should be attempted between these two down-selected options taking into consideration the relative impact to cost associated with carrying multiple size masks versus the delta oxygen usage. Finally, these options should be tested in a prototype chamber as the design of the gaseous portion could significant ventilation which will impact. Minizing the oxygen free volume would decrease the flow rate required to maintain optimal ventilation for CO_2 washout and defogging.

IV. Conclusion

A concept for a personal hyperbaric chamber was developed. It is possible to assemble a ventilation system with a readily available parts that is easy to assemble, operate and provides adequate ventilation. Work should continue to develop a prototype and demonstrate the treatment at Johnson Space Center.

Acknowledgments

References

Dr. Locke HHC Presentation
Augustine, et al. CO2 Washout
Kirkwood. Strategic Decision Making – Multiobjective Decision Analysis with Spreadsheets
http://www.scuba.com/scuba-gear-124/029940/Ocean-Reef-Neptune-Space-G.divers-Full-Face-Scuba-Dive-Mask.html
http://www.medexsupply.com/respiratory-oxygen-therapy-oxygen-masks-and-tubing-oxygen-masks-hudson-pediatric-aerosol-mask-without-tubing-each-x_pid-8410.html
http://store.cyberweld.com/micowehecosy.html

Appendix
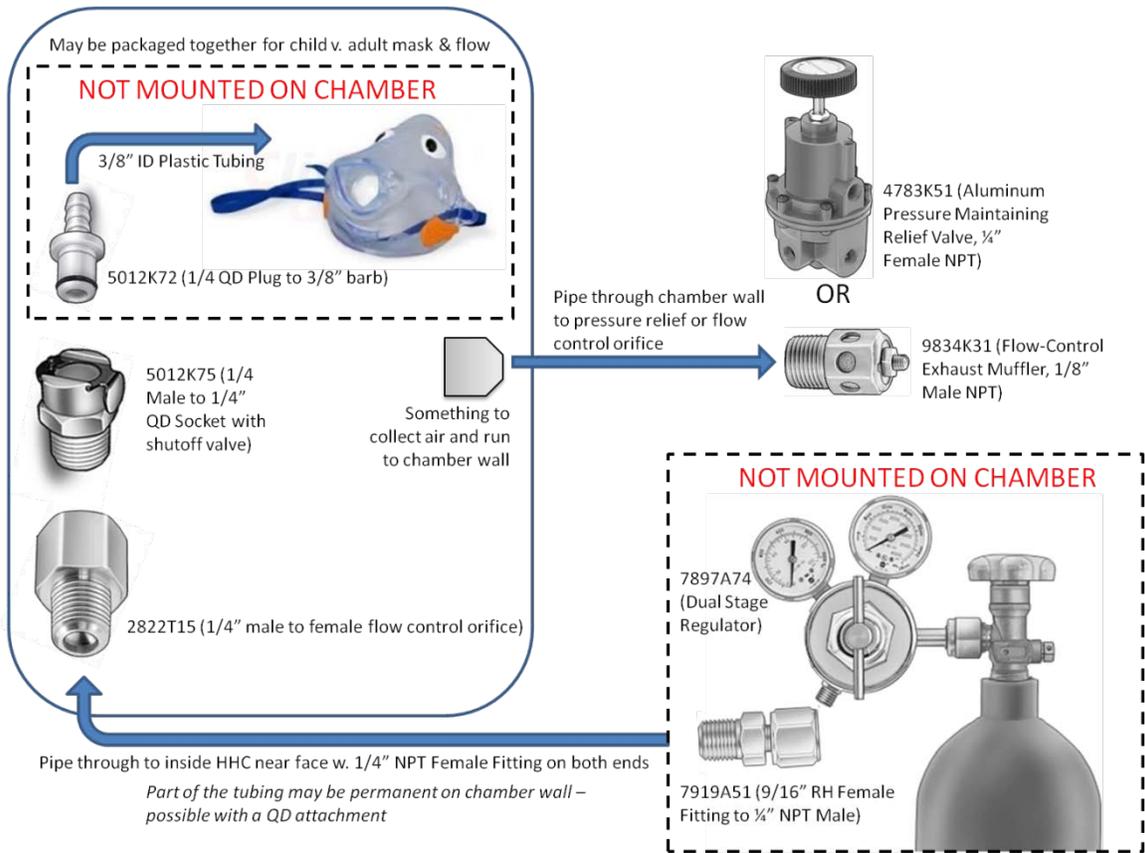
Figure 7. Notional Schematic with Part Numbers. Parts from the McMaster-Carr Equipment catalog were chosen to demonstrate that the system could be assembled and maintained easily.