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Fluid Flow Measurement Techniques and Evaluation of the Cardiotherm 500 For *in vitro* Flow Measurements

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UNIVERSITY HONORS PROGRAM

SENIOR PROJECT - APPROVAL

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PROJECT TITLE: Fluid Flow Measurement Techniques and Evaluation of the Cardiotherm 500 For In Vitro Flow Measurements

I have reviewed this completed senior honors thesis with this student and certify that it is a project commensurate with honors level undergraduate research in this field.

Signed: John H Forrester, Faculty Mentor

Date: 5/12/99

Comments (Optional):

Lots of lab work setting up systems. The "experiment" with the Cardiotherm was useful but as in most research, opens up more questions than it answers! Nelson took lots of initiative and learned quite a bit I believe about setting up flow systems.

JHF.

Senior Project

Fluid Flow Measurement Techniques and Evaluation of the Cardiotherm 500 For *in vitro* Flow Measurements

Submitted by
Nelson Chen

May 14, 1999

Fluid Flow Measurement Techniques and Evaluation of the Cardiotherm 500
For *in vitro* Flow Measurements

The accurate measurement of fluid flow and the determination of fluid velocity can be achieved through a variety of methods. These methods include

1. Collection of fluid for a known time, finding the volume rate of flow (Q), and subsequently calculating fluid velocity V=Q/A, A being the flow cross-sectional area. This method is simplest, but its accuracy is limited by the measurement process for Q. It is useful for the verification and calibration of results obtained through other means. A further limitation of this method is that only average flow rates can be obtained, with relatively large time differential Δt's required for reasonable accuracy.
2. Perturbation of a constant signal by the fluid as it moves along. This signal can be electromagnetic or ultrasonic. For an electromagnetic signal, the fluid must be an electrolyte in order to alter the signal.
3. Raising a weight in a specially constructed tube having an increasing cross sectional area, where the height of the weight in the tube corresponds to the flow velocity,
4. Injection of a fluid bolus at a given point at a different temperature T than the fluid being studied, and subsequently monitoring the temperature change and its duration at a location downstream. This approach is that used for the Cardiotherm 500.

Each of the methods is diagrammed below.

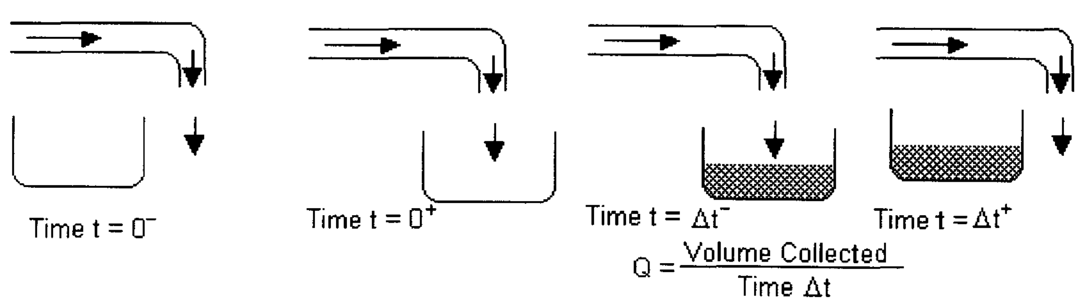


Figure 1. Collection of Fluid for Known Time Δt

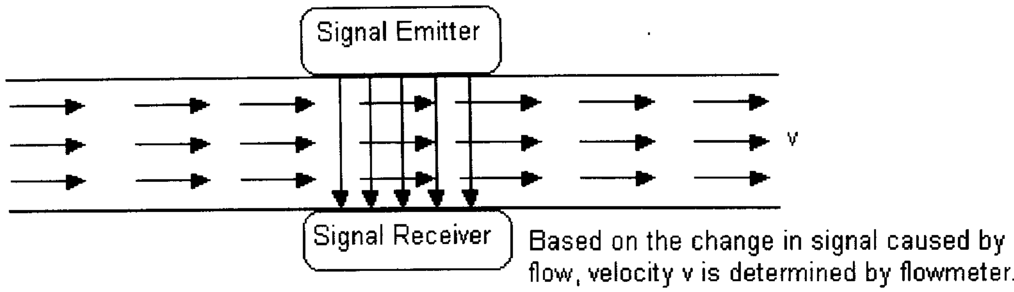


Figure 2. Perturbation of Known Electromagnetic or Ultrasonic Signal

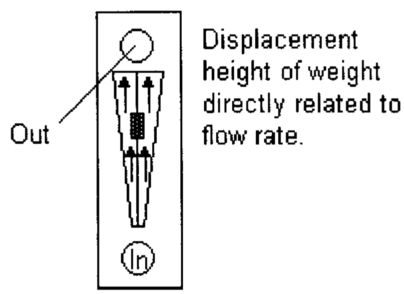


Figure 3. Flowmeter Based on Height Displacement of Known Weight in Special Tube

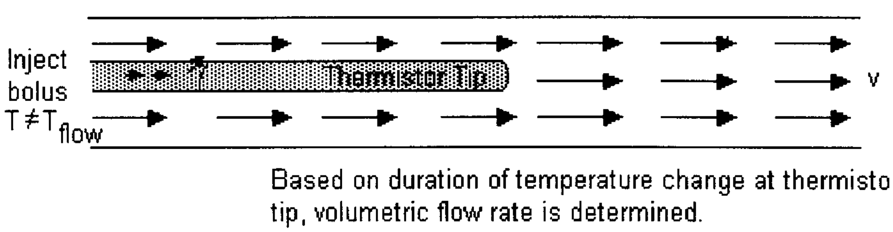
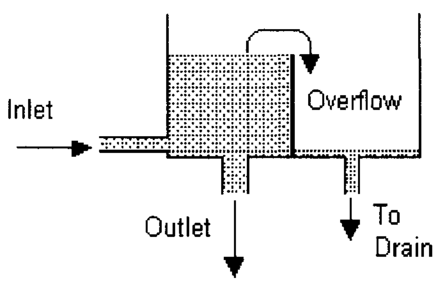


Figure 4. Injection of Fluid Bolus. Catheter (shaded) exaggerated for clarity.

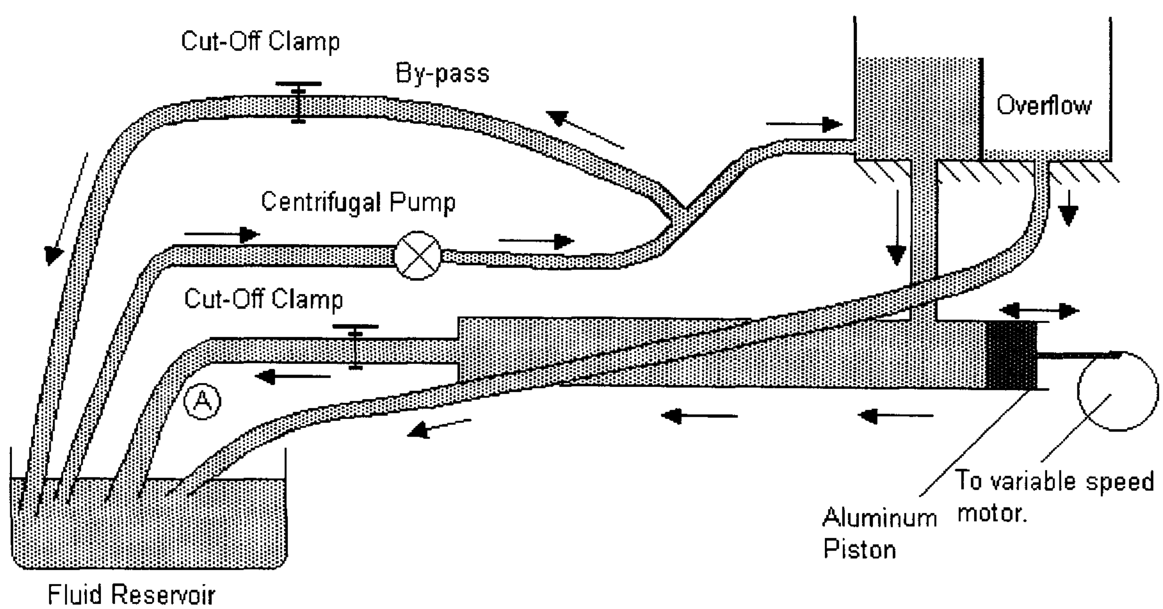
All of these methods were observed and tested for given, established flows, with the emphasis on the Cardiotherm 500. The fluid used for all the testing was water. The Transsonic Ultrasonic Flowmeter based on figure 2 were found to be inaccurate, and The Narco electromagnetic flowmeter (using salt water) was found to be nonfunctional. The height displacement flowmeter was found to function with limited accuracy.

In order to provide a steady flow of water at constant pressure at the entrance to the flow system, and hence constant flow rate, a constant pressure head tank was required. Although large enough reservoirs are theoretically capable of producing near constant pressure, at the flow rates being studied (around 10 L/min) such reservoirs are unwieldy. A small constant head tank was used for a separate pulsatile flow apparatus and is diagrammed below.



The inlet flow volume is purposefully made to be greater than the outlet flow volume, so there is a constant, predictable overflow into the overflow chamber. The amount of fluid in the primary chamber is therefore constant and at a constant height; therefore, the pressure at the outlet remains constant.

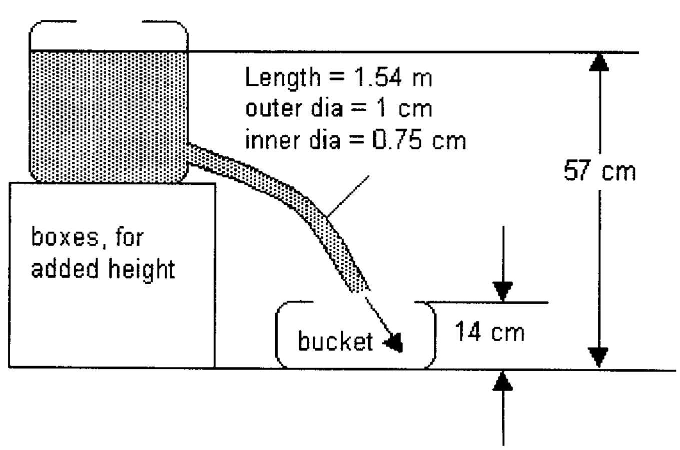
Before working on the Cardiotherm 500, the pulsatile flow apparatus was set up and tested; however, in testing the flowmeters, the system was used simply as a steady flow system. This apparatus provided for the evaluation of the weight displacement flowmeter (Figure 3) and forms the basis for much of the subsequent work in terms of techniques used. The system is diagrammed below.



The primary outlet shown above as A, was the inlet for the flowmeters tested. As the centrifugal pump runs at a single speed, the cut-off clamps were added so adjustments could be made to maintain a constant pressure head without overflowing the overflow compartment. When switched on, the variable speed motor caused the aluminum piston to oscillate back and forth, thereby generating a pulsatile flow. The constant pressure tank used was the small one earlier indicated. Removal of trapped air from within the system to avoid open-channel flow was achieved using a syringe and thin tubing threaded within the apparatus. Various stenoses were subsequently introduced into the system and results tested by other students.

Noteworthy observations from this setup are (1) aluminum corrodes under water at a significant rate, and (2) the presence of even a little air in the centrifugal pump drastically reduces pumping efficiency. It would be beneficial to coat the piston with paint or some other material to retard the corrosion. Other students found that the pulsation produced by the piston could be detected, but only barely with the use of a data recorder.

For the evaluation of the Cardiotherm 500 itself, initially there was difficulty in securing a constant head tank of sufficient size for the flow rates (around 10 L/min) being studied. A 5 gal reservoir was therefore initially used and flow measurements taken. This setup is diagrammed below.



Allowing the water to run out of the tank for 1 min with an initial fluid height as shown, and measuring the amount of fluid flow caught in the bucket yielded the following data.

$Q_{average}$ (L/min) = 1.5, 1.43, 1.44, 1.49

It was noted that the water level in the tank dropped significantly during each of the trials, invalidating the "true reservoir" assumption. It was also observed that even small fluid height variations at the outset, had a significant effect on the average flowrate. Finally, it was noted that the flow rates obtained from this system are far less than the desired 10 L/min ballpark figure.

To reduce the effect of height variations on measured values, it was determined to fill the tank to the brim, where the initial height (now >57 cm) would be visually verified prior to initiating flow. Flow values obtained (run for 1 min, as before) became $Q_{average}$ (L/min) = 1.64, 1.66, 1.71, 1.68. As expected, the initial height difference produced an observable difference in flow rates.

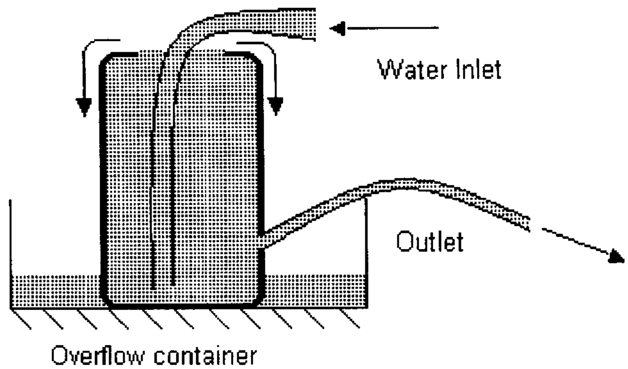
Now, threading the measurement catheter 65 cm into the flow tube with the initial height still to the brim, running for 1 min, yielded the following data. $Q_{average}$ (L/min) = 1.27, 1.26, 1.25.

Summarizing the data obtained,

Q_{avg} (L/min)					Average	Std. Dev
initial (57 cm)	1.5	1.43	1.44	1.49	1.47	0.04
fill to brim (no cath)	1.64	1.66	1.71	1.68	1.67	0.03
fill to brim (cath)	1.27	1.26	1.25		1.26	0.01

It is readily seen that not only does the filling of the container have a significant effect on the flow rate, but also introduction of the catheter based on the data values obtained and their deviations. Therefore, when testing the Cardiotherm 500, the catheter must be kept installed for all measurements to compensate for this effect.

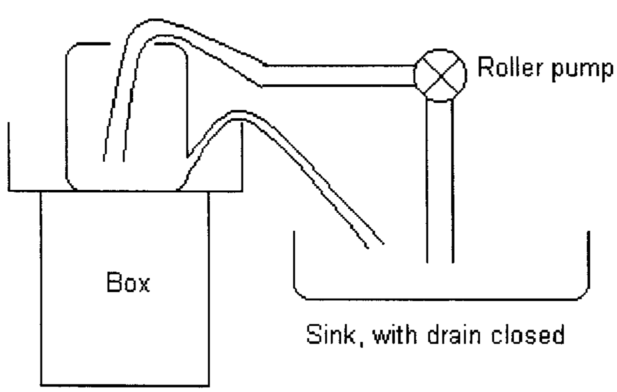
Because the tank fluid height changes a significant amount during the 1 min or so of flow, the pressure developed also changes during the flow. Therefore, the instantaneous flow rate varies throughout the time of measurement and avoids measurement by catching the flow in a bucket for a given time. Since the Cardiotherm 500 measures instantaneous flow rates, or flow rates at a given time t, a constant pressure head is needed in order to obtain an average flow rate that is always equal to the instantaneous flow rate. A new constant head tank, shown below, was improvised.

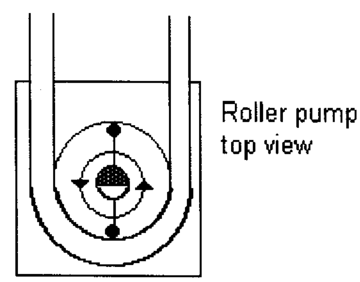


The overflow container was elevated to provide the pressure head through its height. The only drawback to this constant pressure tank was the overflow container not having a ready means of drainage.

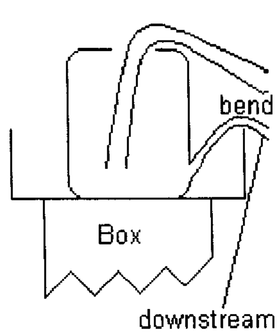
As the cardiotherm requires a warmed fluid, the inlet was connected directly to the faucet, where warm water was readily available. In order to increase the flow rate, a larger diameter tube was used for the outlet. Flow rates of 9.11, 9.11, 8.97, 8.95, 9.06, and 9.57 (Average 9.13 $\pm$ 0.23) L/min were measured with a bucket (Figure 1) with the catheter in the outflow connected to the reservoir.

There was difficulty in maintaining such a constant head due to the overflow container quickly filling with excess water. In order to reduce the rate at which the overflow container filled, a modified closed system was established with a variable speed roller pump. Both the modified system and the pump are diagrammed below.





The overflow container was drained with one or more small diameter siphons back to the sink. It was found that the temperature of the water could be kept close to constant with periodic small additions of warm water. The roller pump was far less susceptible to air than the centrifugal pump, although its maximum output was less.



With this system in place, the Cardiotherm 500 was tested according to the instructions provided. It was noted that the

"Open Catheter" indicator would light whenever there was no flow. When the flow was too hot or cold, "open catheter" would light as well. When the catheter was placed at the bend in the output tube, the Cardiotherm measured 12 L/min for an actual 6 L/min flow rate. The catheter tip was moved to a location upstream to the bend. The move resulted in measured values of 15 L/min, for an actual flow of 7.5 L/min. It was then noted that the injection site upstream was in the tank, rather than the flow tubing. However, moving the catheter downstream way beyond the bend did not improve the results. Neither did elevating the constant head tank to avoid having a bend at all. Variations in injectate temperature and injection speed did not improve the results obtained either.

At this point, it was decided to call technical support at Columbus Instruments. It was reported that for the Cardiotherm 500 to operate properly, several conditions needed to be met.

They are

- A fluid temperature which does not change by more than 0.01 °C; in animals capable of controlling their body temperature (for which the cardiotherm was originally designed) such regulation is naturally achieved
- Power injection (via autoinjector) for an extremely rapid injection
- Injection of the injectate as close to the mixing point as possible, to avoid altering the temperature profile of the flow prior to the mixing area.
- Full turbulence in the flow at the location measured for prompt, thorough mixing.

Even with all of these conditions satisfied, they state the accuracy is still only within 0.5 L/min. The Cardiotherm 500 is better suited for detecting changes in flow rate, rather than measuring absolute values. It is concluded that for *in vitro* flow measurements, satisfying all four of the requirements would be difficult at best, especially maintaining the fluid at a given temperature. With design modifications, the power injection, injection close to the mixing point, and turbulence can be achieved. But even with all these modifications, the use of the Cardiotherm 500 as a useful flowmeter for absolute flow values is tenuous at best.

Acknowledgements

I would like to take this opportunity to thank Dr. John Forrester, who was my faculty mentor and was always around to offer help and suggestions, and for designing many of the setups mentioned. I would also like to thank Dawn Clifford for her help in various experiments. Finally, Ken Thomas was helpful in offering equipment setup and maintenance advice, and for readying the piston in the pulsatile flow apparatus. Technical support at Columbus Instruments, staffed by Dr. Jan Czekajewski, was vital in helping to identify the limitations of the Cardiotherm 500. Without the University Honors program, headed by Dr. Tom Broadhead, this project would not of been possible.

Appendix A

Establishing an Underwater Seal

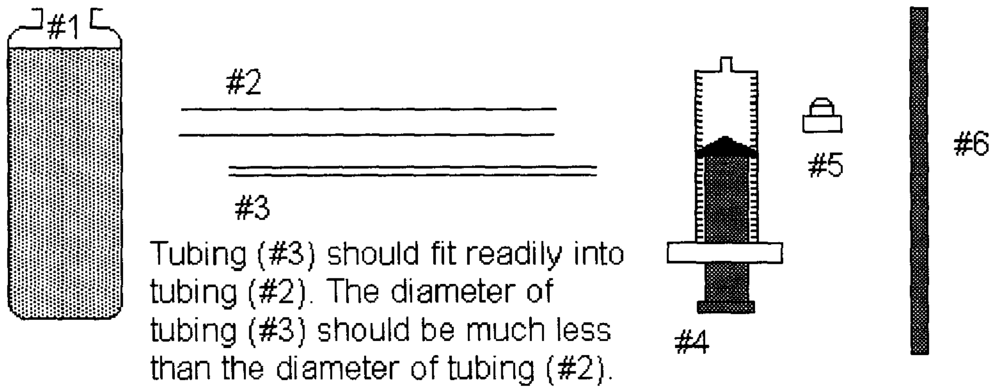
In order to fill the apparatus with water or other liquid completely, and to ensure that the flow completely fills the tubing, an underwater seal is required. If air is present within the system, the flow can quickly degenerate into open channel flow, which behaves completely differently from what is desired.

The most important thing to remember when creating an underwater seal is that water will displace air, when the air is removed and water will quickly fill the void.

Supplies required:

1. a large container, with a narrow opening at the top, filled with seveal liters of water or the other liquid being used to model blood
2. a piece of tubing (large diameter) to connect the seal with the apparatus
3. another piece of tubing (small diameter) which fits within the large diameter tubing, and which slides readily back and forth within the large tubing
4. a large syringe which produces a watertight seal with the end of the small diameter tubing (item #3)
5. a plug which fits the large diameter tubing's end, and can seal it off snugly (in a watertight fashion)
6. Optional, but often extremely helpful, is a thin diameter rigid stick long enough to reach into the container (#1) thoroughly

The supplies are diagrammed below.



Drawings not to scale

To create the seal,

1. Insert the plug (#5) into one end of the large diameter tubing (#2). The plug should create a tight fit.
2. Attach the small diameter tubing (#3) to the tip of the syringe.
3. Insert the other end of the tubing (#3) into the large diameter tubing as far as it will comfortably go.
4. Now take the entire complex, and place the large tubing's open end under water as shown below.

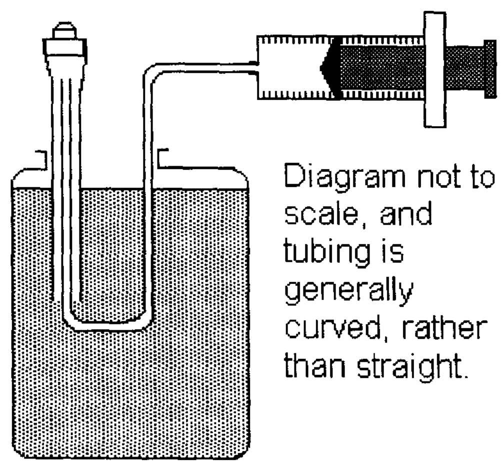


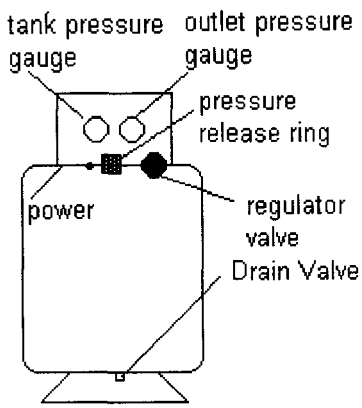
Diagram not to scale, and tubing is generally curved, rather than straight.

5. Draw out the trapped air with the syringe. If the syringe should fill with air, simply remove from the small diameter tubing while pinching the tubing shut and empty. Then reconnect and continue. It will probably be necessary to manipulate the thin tubing to be able to draw out all the trapped air. The use of a thin rod to hold the large diameter tubing probably will be helpful.
6. When all the air is withdrawn, simply withdraw the small diameter tubing completely, taking care that the large diameter tubing does not fall into the fluid container.

The underwater seal can be used as a ready means to drain the fluid container. To do so, simply hold the plugged end below the fluid surface, and remove the plugged end. Replace the end when the fluid reaches a desired level. All that needs to be ensured is that the other end of the tubing remains under water. This technique can also be used to efficiently fill the pulsatile flow apparatus by connecting the outlet to an end of the flow apparatus, leaving only some air pockets to be removed with the syringe and thin tubing.

Appendix B

Operation of the Sears Air Compressor



The Sears air compressor is capable of blowing large quantities of air at high flow rates, or gentle streams of air as desired. This air can be employed for a variety of purposes. The compressor can produce pressures as high as 130 psi, so caution is required in its operation. Below is a guide to the safe operation of the craftsman air compressor.

Safety Checks

- Make sure the tank and its fittings are not corroded, dented, welded to anything, or otherwise weakened prior to use. Be especially careful in the inspection if you have not previously used the compressor.
- Pull on the pressure release ring (located where the regulator and gauges are) firmly to ensure it slides out smoothly. Then release it back to the "closed" position.
- Make sure the compressor is plugged in to a 3-pronged outlet. Ideally, no extension cord is used. However, if an extension cord is employed, then it **has** to be heavy duty, to ensure the motor receives enough power. Do not run anything else from the outlet while using the air compressor.
- Make sure the compressor is not exposed to water. If any part of the compressor is wet, then dry it immediately with a paper towel.
- Remember that if any part of the compressor is malfunctioning, you can and should shut off the air compressor at any time through the power lever.

Charging the Compressor

- Turn the regulator knob to the "closed" position.
- Set the power lever to the "on" position. You should immediately hear the compressor charging.

- Carefully feel the end of the hose attachment to make sure the airflow is closed off. There should be no air flowing out at this time. If there is airflow, make sure the regulator knob is properly closed.
- Allow the compressor to charge to maximum pressure (130 psi). At 130 psi, the compressor will automatically shut off. As an extra safety precaution, it is advisable to maintain a long distance from the compressor while charging (to protect oneself from a very unlikely tank explosion).
- Attach whatever tool needed at the end of the hose. If drying certain equipment, this step may be omitted or a piece of tubing may be attached to the end of the hose.
- Turn the regulator valve to produce the pressure needed at the outlet. The compressor will reengage whenever the pressure produced is insufficient. If necessary, temporarily stop use when the pressure is less than that necessary.

At this point, use the pressurized air to achieve whatever task is at hand. The air can be used for filling containers, drying equipment, operation various tools, and a variety of additional tasks. When switching tools, be sure the regulator valve is shut off and pressure is zero before removing the tool from the hose. Be sure to not direct the air jet at any person or use the compressed air for breathing.

Shutting Down the Compressor- In order to temporarily shut down the compressor, simply switch the power lever to the off position. When done with the air compressor for the day, permanent shutdown (detailed below) is **required** to prevent rust from within and cause an explosion hazard.

- When finished, first switch off the power using the lever.
- Gradually release air from the tank until there remains approximately 20 psi of air within the main tank. The easiest way would be to set the regulator at 20 psi, and allow the airflow to continue until it stops at equilibrium.
- Close the regulator valve

- Now, open the drain valve located at the bottom of the tank by turning the knob to the open position. Air and some water should empty out. When the air has all exited, be sure to close the drain valve.
- Finally, unplug the air compressor (optional).

Appendix C

Producing a siphon

A siphon is related closely to an underwater seal, and it can be used as a convenient way to transfer fluid from one container to another. Just as with an underwater seal, the most important aspect of the siphon is the removal of air from the tubing employed. Once the air is removed, the siphon is ready to be used. A distinction is made here between small diameter siphons (< 0.5 cm) and large diameter siphons because their production technique differs.

For small diameter siphons

A small diameter siphon is produced through evacuating the air within a piece of tubing, and allowing the water to displace the air that was originally present. The air present is best removed with a large syringe.

- Attach the syringe to one end of the tubing
- Place, and hold, the other end under the fluid being moved
- Draw back on the syringe's plunger until the fluid enters the syringe by itself, with no air. If the syringe's capacity is insufficient to remove all the air, then pinch/fold the tubing shut, remove and empty the syringe, and repeat.

For large diameter siphons

A large diameter siphon is made by removing all the air within the tubing as well. However, its size makes air evacuation using a syringe impractical.

- Attach something which will close off one end of the tubing (could be the syringe, although the syringe will not be used further in this procedure)
- Taking a beaker full of fluid, fill the tubing from the other end, allowing the tubing and fluid's weight to force the tubing to become almost vertical. The air bubbles should float out. Their previously occupied volume will be displaced by the fluid.
- Finally, quickly place the open end of the tubing under the fluid being moved and keep it there.

To use the siphons (large or small), simply remove the plug from the closed, while keeping (1) the previously closed end lower then the open end, and (2) the open end fully underneath the fluid being moved. For small diameter siphons, the flow will be a steady trickle, while for large diameter siphons, the flow will be a deluge.