Design of Mechanical Arterial Simulator

by

Lauren Chai

Submitted to the
Department of Mechanical Engineering
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ABSTRACT

A force controlled ultrasound probe is being explored as a new method of measuring blood pressure. An arterial simulator was designed and built for experiments. For this simulator, the vessels and bulk material were designed to meet the specifications of literature values of the physical dimensions and elastic modulus of carotid and brachial arteries and bulk surrounding the arteries. This was done through the use of a PVA cyrogel and Thermo rubber- mineral oil solution as the materials for the vessel and bulk material respectively. The concentration of the ingredients and the number of freeze thaw cycle of the cyrogel control the elasticity of the two materials. Custom molds were fabricated to the desired physical dimensions. Upon integration of the vessel and bulk, the vessel was connected to a network of hoses and a pump. The pump is a diaphragm pump whose volume/stroke and speed can be independently controlled to simulate the pulsing of a real human heart. Measurements were taken of the force applied to the probe for static pressures to demonstrate the force varying linearly with pressure. Further measurements were taken with fluid flowing through the vessel at various probe heights to demonstrate how force and thus pressure vary with height and to demonstrate that the probe can detect the waveforms that result from the vessels pulsing with each stroke of the diaphragm pump.

Thesis Supervisor: Dr. Brian W. Anthony
Tile: Research Scientist, LMP

I would like to thank Brian Anthony for his support and feedback throughout this project as well as Matthew Gilbertson, Bill Vannah, Aaron Zakrzewski and Shih-Yu Sun for their feedback and collaboration.

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Chapter 1

Introduction

1.1 Background

The standard for measuring blood pressure is the use of a sphygmomanometer whose cuff exerts pressure onto the brachial artery. The cuff wraps around the upper arm and inflates until blood flow is completely cut off. Then, the cuff is deflated until blood begins to flow again (systolic pressure) and further until the artery once again pulsates (diastolic). For the average healthy adult, cutting off the blood flow like this is at most mildly unpleasant. For those with much weaker blood pressure, such as elderly and post-operative patients, the cutting off of blood flow is extremely uncomfortable and can lead to bruising and disturbing sleep.

A force-controlled ultrasound probe [13] is being explored as an alternative way to measure blood pressure, its main features being that it does not require blood to be completely stopped. The theory behind this method is that if one can measure the force needed to compress an artery and see via ultrasound how the artery responds to an external force, one should be able to derive the internal blood pressure from the resistance of the artery to the external force assuming the other physical properties can be derived or measured somehow (e.g. the elasticity of the artery wall and surrounding tissue).

Various components of this method have already been developed by The Computational Instrumentation Lab - a force controlled probe developed by Matthew Gilbertson [13] will be used to measure the force exerted by the probe, and elastography numerical models are being developed by Aaron Zakrzewski. For this thesis, we develop a physical model in which all the physical properties can be known/controlled in order to confirm the elastography models. This was done by first examining the static and dynamic factors of the arterial blood waveform, or the factors that contribute to the internal fluid pressure of the artery and how that waveform looks over time. Then each component was designed and manufactured to make a static model before a pump was introduced to make a complete pulsating artery that could be used to develop and validate a method to measure blood pressure.

1.2 Outline

This report is has been divided into six chapters

- Chapter 1: Arterial system: physical components and characteristics
- Chapter 2: Physical characteristics of the arteries and development of working replica.

- Chapter 3: Physical characteristics of the bulk surrounding artery and developement of working replica.
- Chapter 4: Dynamic model schematic and pump selection.
- Chapter 5: System performance
- Chapter 6: Conclusion and future work

Chapter 2

Arterial system: physical components and characteristics

The system components were determined by looking at the structural loop in a cross section of the arm during a blood pressure measurement (Figure 2.1). The probe and bone are approximated as infinitely stiff while the bulk, artery wall and blood have some associated finite stiffness.

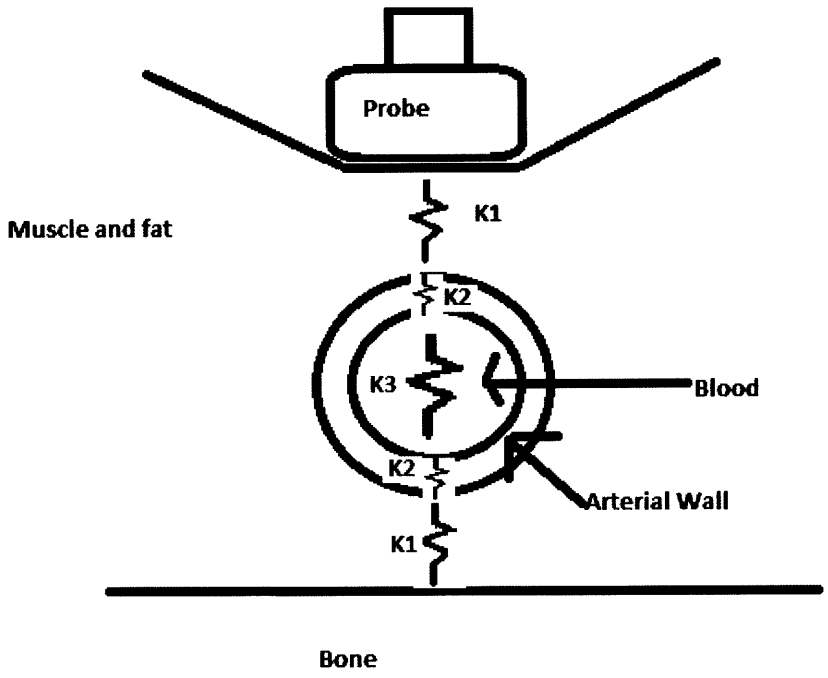

Figure 2.1: Structural Loop of probe pressing down on artery. The probe and bone are assumed infinitely stiff compared to the other components whose labels are described in Table 2.1.

From Figure 2.1, one can see that between the probe and bone, if one knows the physical characteristics of the bulk (muscle and fat) and the arterial wall, one may be able to estimate the blood pressure from the force measured by the probe and estimate the strain of the arterial walls. The components of the system, as well as the properties being controlled have been summarized Table 2.2.

TABLE 2.1: Description of Labels in Structural Loop from Figure 2.1

Label	Component(s)
K1	Bulk Elasticity
K2	Artery Replica Elasticity
K3	Elasticity Associated with Blood Pressue

TABLE 2.2: Simulator Components and Dependent Properties

Body Part	Component(s)	Dependent Physical Properties
Muscle, fat	Bulk Replica	bulk elasticity, vessel depth
Artery	Artery Replica	Vessel outer diameter, wall thickness
Blood	internal pressure	fluid resistances of piping, fluid flow

Chapter 3

Physical characteristics of the arteries and developement of working replica

3.1 Literature values: artery dimensions

The human body varies widely from individual to individual and so likewise the physical the dimensions of the vessels such as the elasticity, thickness and diameter also vary. Actually, these properties are also telling of the health of the individual. Elasticity decreases with age. Significant health problems may result from the internal diameter of the vessel being reduced to the point of no blood flow by plaque and decreasing elasticity. Many studies have been conducted into how these values vary among the population to produce the following values:

- vessel elasticity: 70-100kPa[6]
- wall thickness: approx 0.2-0.4 mm (brachial)[4] and approx 0.65-0.95mm(Carotid)[8]
- artery diameter: 4.1 to 4.3 mm ($\pm$ 0.6 mm)[4]for brachial arteries; 6-8 mm ([9]) for carotid arteries.

For the artery replica, the goal is to be able to consistently fabricate these dimensions and control variations.

3.2 Artery Material: Polyvinyl Alcohol Cyrogel

In order to control these dimensions, Polyvinyl Alcohol Cyrogel (developed by Hoskins, et al[1], Poepping et al[2] and King et al[6]) has been chosen as the material for the vessels. It is a solution that can be cast around a negative mold before being frozen. Once defrosted, the cyrogel is compliant but solid. Thus, I can control the vessel diameter and wall thickness. The elasticity is controlled by the concentration of PVA and the number of times the PVA is frozen. The process plan is described in Table 3.2. A complete list of hardware and materials in Table 3.1. Each batch (using the version 2 molds) consists of the vessels from the final wax molds (which yields 4 vessels of dimensions described in Table 3.3) and a sample for compression tests (5cm height, 5 cm diameter). For one complete batch at 10% PVA, one needs 725 ml distilled water and 80.5 g PVA.

It is very important after mixing that the bubbles be allowed to rise out completely. For our tests, we require a 6 inch vessel segment in which there are no bubbles (which

TABLE 3.1: Summary of materials and hardware for manufacturing PVA cyrogel

Category	Components
Hardware	• Hot Plate • Freezer • 1 L Glass Beaker • Plastic food wrap • pot (large enough to hold 1 L beaker) • stirrer • water (water bath) • freezer
Materials	• Polyvinyl Alcohol (see Appendix for MSDS) • Graphite powder • distilled water

create holes that leak). The elasticity of the cyrogel is varied by the number of freeze thaw cycles. Three freeze-thaw cycles are enough to get within the expected range of elasticity of 24-135 kPa (by King et al [6]), with more freeze cycles expected to increase the stiffness. A sample (5 cm diameter, 5 cm height) was made at 10% PVA and three freeze cycles and subjected in compression tests to produce a Young's Modulus of 23.6 kPa (See Figure 3.1).

TABLE 3.2: Process plan for manufacturing of PVA cyrogel

Process	Material	Measurement	Notes
Mix PVA in distilled water	Polyvinyl Alcohol, distilled water, beaker	PVA is 10-15% of the total weight of the solution	Do not turn on the heat until there is an constant, clump-free suspension.
Cover beaker containing solution with plastic wrap and place in a water bath. Turn on heat	plastic food wrap, water bath (hot plate, pot, water, stirrer, thermometer)	Temperture of water bath is at about 70-80 C	Hot plate is on medium-low. The plastic food wrap is used to reduce the evaporation of the water. Mix every minute to break up clumps. PVA is fully dissolved when mixture has the consistency of honey and there are no clumps
Tun off heat. Add carbon to the solution.	carbon graphite	Carbon is 1% of final weight.	N/A
Leave the solution to cool to room temperature and bubbles to rise out.	N/A	Cool to room temperature (about 21 C)	Cooling takes anywhere from 2 - 6 hours. It is very important that the solution is allowed to cool as this will affect how evenly the PVA will freeze and the true freeze time of the PVA solution.
Pour into molds and allow bubbles to rise out before freezing. Keep molds upright throughout entire process. Cover mold bottom with plastic food wrap.	Plastic food wrap	N/A	Settling time is dependent on many factors such as the viscosity of the solution and how much resistance there is in the molds to the bubbles rising out. An accurate number is dependent on the mold. For the wax molds used, this process takes about 20 minutes and PVA solution needs to be constantly added. The wax blocks have wells to make this process easier.
Freeze and defrost as needed.	Freezer	Freeze time is 12 hours and defrost time is 12 hours	N/A
Open mold and slide vessels carefully off rods.	N/A	N/A	N/A

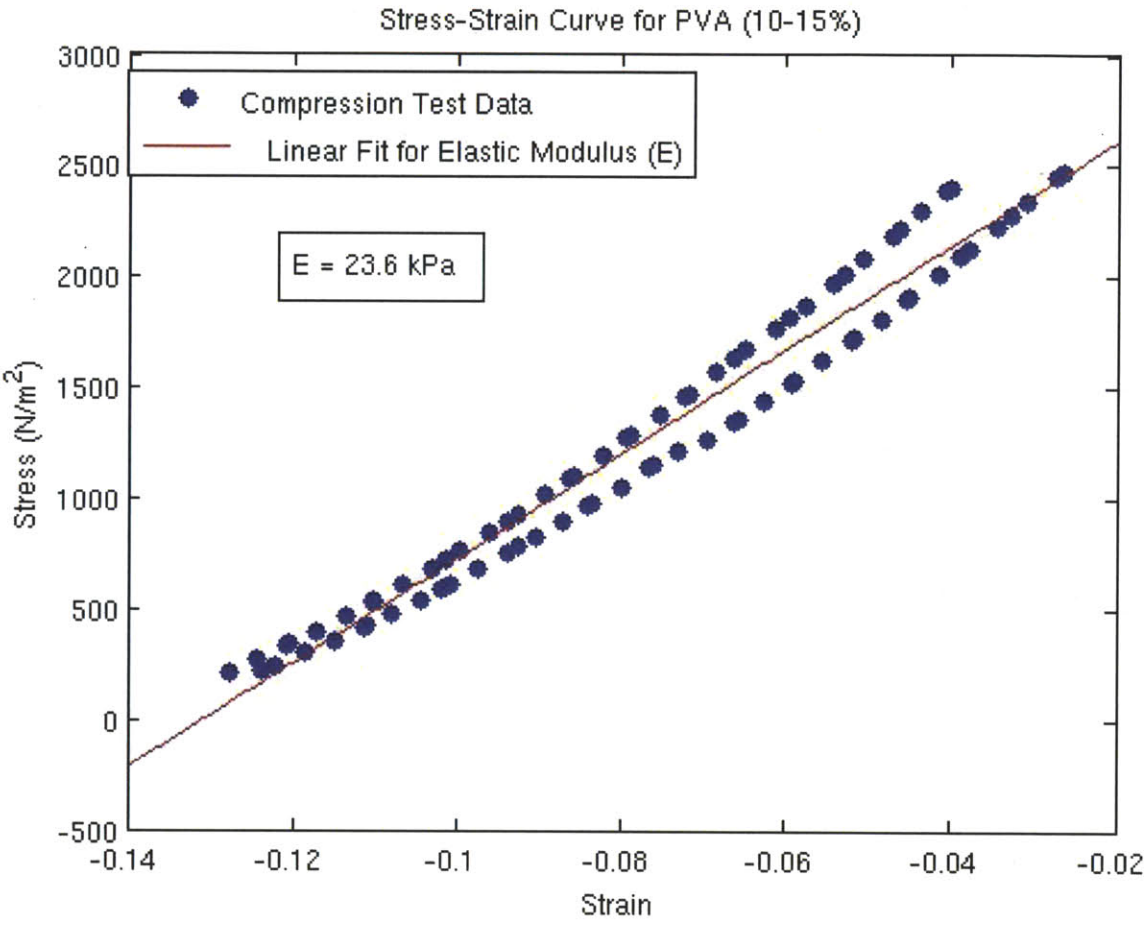

Figure 3.1: Stress Strain Curve from Compression tests of PVA sample (10-15% PVA). The two lines of blue dots represent two cycles of the compression test in the instron testing machine.

3.3 Artery Molds

3.3.1 Version 1- Single Teflon tubes

The first molds were teflon pipes of 6 inches in length in which a metal rod was suspended and sealed by two O-rings (Figure 3.2). Teflon was chosen as the material for the mold for its low friction. It was sufficient as a first pass at manufacturing the vessels, but had some design flaws:

- Single teflon tubes were cumbersome to maintain upright during settling process.
- Required constant supervision and use of syringe to fill tube as bubbles rose out and solution leaked out.
- Vessels had to be pulled out lengthwise from mold, resulting in them sometimes tearing if one was not careful.
- Since the molds had to be laid on their sides during freezing, the vessels had noticeable variation in wall thickness along length

Figure 3.2: Figure showing first version of Artery molds. The rod is held in place by o-rings on the sides of the tube.

3.3.2 Version 2- Clamshell Wax Blocks

The second molds were larger blocks made of machinable wax. Two halves are machined and held together by bolts. Its features include longer vessels, clam shell design for easy removal, wells at the top and steady base for standing upright to aid both settling and freezing. Additionally, the blocks have the ability to cast multiple vessels at the same time, with inner diameter and wall thickness easily varied by the inner tube diameter and dimensions of well caps. Figures 3.3 and 3.4 show the inside of the mold and the wells top of the closed mold.

Figure 3.3: Picture of Wax Molds for Artery phantom. The diameter of the cylindrical cutouts down the length determine the outer diameter of the vessel. Bolts clamp the two sides together and dowel pins maintain alignment.

Since these molds use hard caps instead of o-rings, they have a problem of leaking at the bottom. For this reason, the wax blocks were made to be extra long (10 inches) resulting in vessels that are consistently over 6 inches in length (range has been from 6-8 inches). The bottom of the wax block also needed to be wrapped with plastic food wrap for easier clean up.

Figure 3.5 shows a typical set of vessels from these blocks.

TABLE 3.3: Version 2 mold vessel descriptions and dimensions

Vessel	Replica of	Outer Diameter	Inner Diameter (Wall Thickness)
A	Brachial Artery	0.25 "	1/8" (1/8")
B	Brachial Artery	15/64"	1/8" (7/64")
C	Carotid Artery	3/8 "	(1/8")
D	Carotid Artery	1/2"	(1/8")

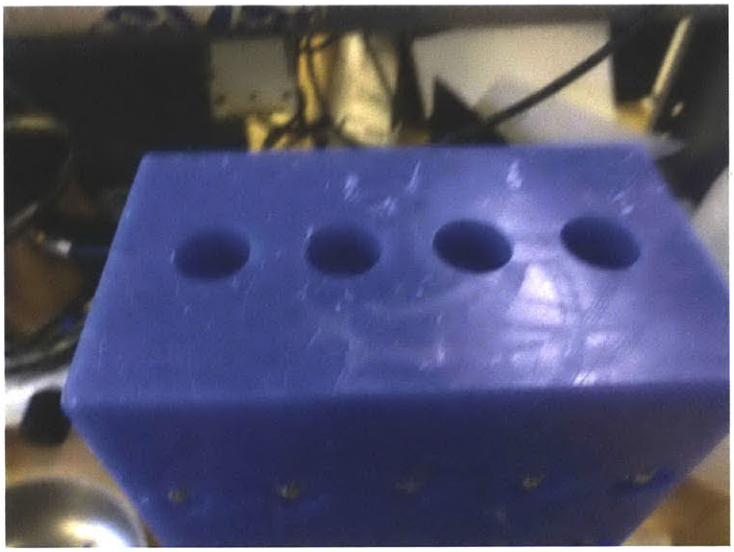

Figure 3.4: Picture of top of closed Wax Molds for Artery phantom (the bottom is identical) showing the wells. Caps fit into these wells to both hold a rod which sets the inner diameter of the vessel and to seal the wax blocks.

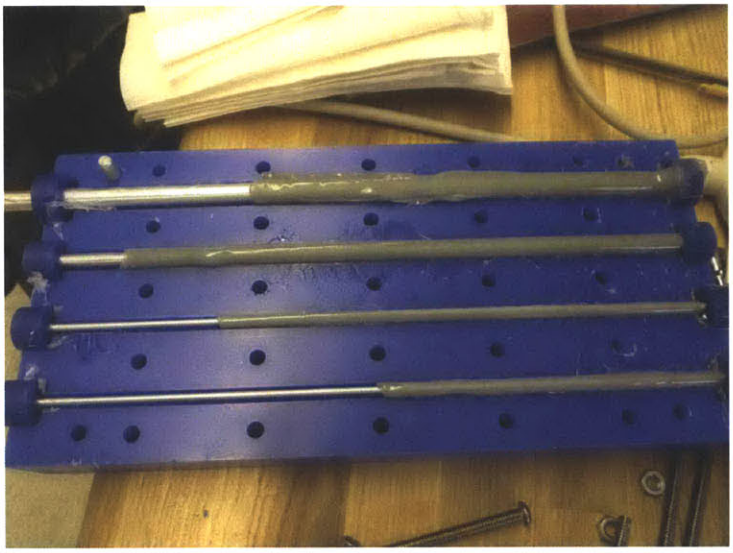

Figure 3.5: Finished Arteries in Wax Molds. See Table 3.3 for dimensions.

3.4 Storage of Artery Replicas and Lifetime

Storing the arteries has two goals: reduce the growth of fungus in the water based solution, and preventing dessication. The artery replicas were first stored in wet paper towels but the paper towels themselves also quickly dried out. Storing the arteries in water risked them absorbing more of the water and losing knowledge of their physical properties. The solution was to store the arteries in the same mineral oil used in manufacturing of the bulk replicas, preventing dessication and inhibiting the growth of mold. Any residue oil on the artery does not impact the full assembly since the artery will be surrounded by the same mineral oil in the bulk material. Nevertheless, the lifetime of

the arteries is about 2 weeks, dependent on the growth of mold.

Chapter 4

Physical Characteristics of the bulk surrounding artery and developement of working replica.

4.1 Bulk Dimensions

To simulate muscle and fat, the bulk replica should have an elasticity of 3-6kPa[7] and vessel depth of 0.5 to 2cm as determined from ultrasound scans. Thus the material chosen was a solution of mineral oil and Kraton thermoformed rubber copolymer (TPR) (5% of the mineral oil weight) developed by Oudry et al[3]. The method is described in Table 4.2 and a complete list of materials and hardware is described in Table 4.1. Amount of bulk material for a particular mold was determined by calculating the volume of the mold and using the matlab program GramTPR.m (see Appendix 3) to compute the weight of TPR copolymer needed. The input is the volume of bulk needed (also the volume of the mineral oil used). The output is the grams of TPR copolymer needed for 5% of the weight of mineral oil.

Compression tests of a sample (5 cm diameter, 5 cm height as seen in Figure 4.1) show the expected young's modulus of 4.99 and 5.25 kPa for 4 and 5 % copolymer in oil respectively. See Figures 4.2 and 4.3.

TABLE 4.1: Summary of materials and hardware for manufacturing PVA cyrogel

Category	Components
Hardware	• hot plate • oven • 1 L glass beaker • pot (large enough to hold 1 L beaker) • vegetable oil (oil bath) • stirrer • mold • thermometer • oven mitts
Materials	• Kraton ThermoRubber Copolymer (see Appendix for MSDS) • Clarion White Mineral Oil Food Grade 90 (see Appendix for MSDS)

Figure 4.1: Sample of TPR Copolymer used in Compression Tests.

TABLE 4.2: Process plan for manufacturing TPR copolymer-mineral oil solution

Process	Material	Measurement	Notes
Preheat Mold	Mold	Preheat at 130 C, boiling temperature of the solution during manufacturing.	Preheating the mold is necessary to facilitating the rise of bubbles out of mixture after the solution is poured.
Mix TPR in oil in beaker until consistent suspension is formed.	TPR Copolymer, beaker, mineral oil	Replicas so far have used TPR copolymer of 4-5% weight of the oil.	Heat should not be turned on before suspension is consistent and there are no more clumps. Any clumps will melt together and not dissolve in oil
Place beaker in oil bath. Heat until oil bath is at 130 degrees Celcius	Oil Bath (Vegetable oil, hot plate, pot, stirrer)	130 C for the boiling temperature.	Going too far above 130 degrees Celcius burns the oil and creates a lot of smoke
Continue heating until the TPR fully dissolves in mineral oil	N/A	A mixture of 700 ml of mineral oil with TPR copolymer amounting to 5% of oil weight takes 1 hr to dissolve.	The phases of the solution are suspension → stringed clumps → finely mashed jello → formation of a large clump→ viscous fluid with consistency of honey. Final version uses two batches of 700 ml each. First layer must be kept molten in oven else the seam between batches is visble on ultrasound. See Figure 4.8.
Pour into mold and bake at 130 degrees until bubbles rise out	preheated molds	130 degrees celcius is the baking temperature.	While it is possible to go for a lower baking temperature, the closer you are to the ideal temperature, the more molten the solution is and thus the quicker the bubble rise out. If possible, use a metal mold with smooth sides as there are less nucleation sites for bubble formation.
Remove from oven	N/A	N/A	Time to remove from oven is dependent on how long it takes the bubbles to rise out. This can be anywhere from 15 minutes (version 3 mold) to several hours (version 1 mold). While bubbles in the vessels make the vessels useless, bubbles in the bulk replica only create shadows. Therefore, it is permissible for there to be some bubbles, so long as they are well away from the area where the artery is inserted.

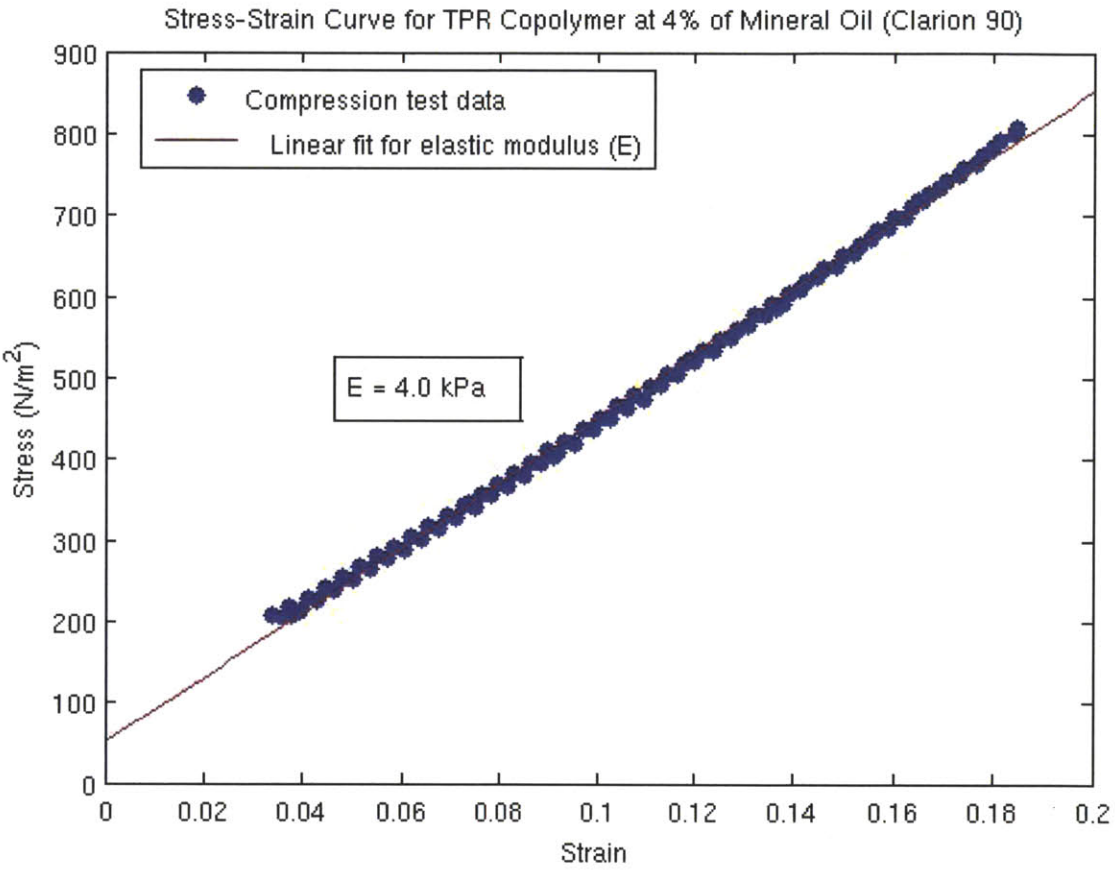

Figure 4.2: Stress Strain Curve for TPR Gelatin (4% Copolymer). The two lines of blue dots represent two cycles of the compression test in the instron testing machine.

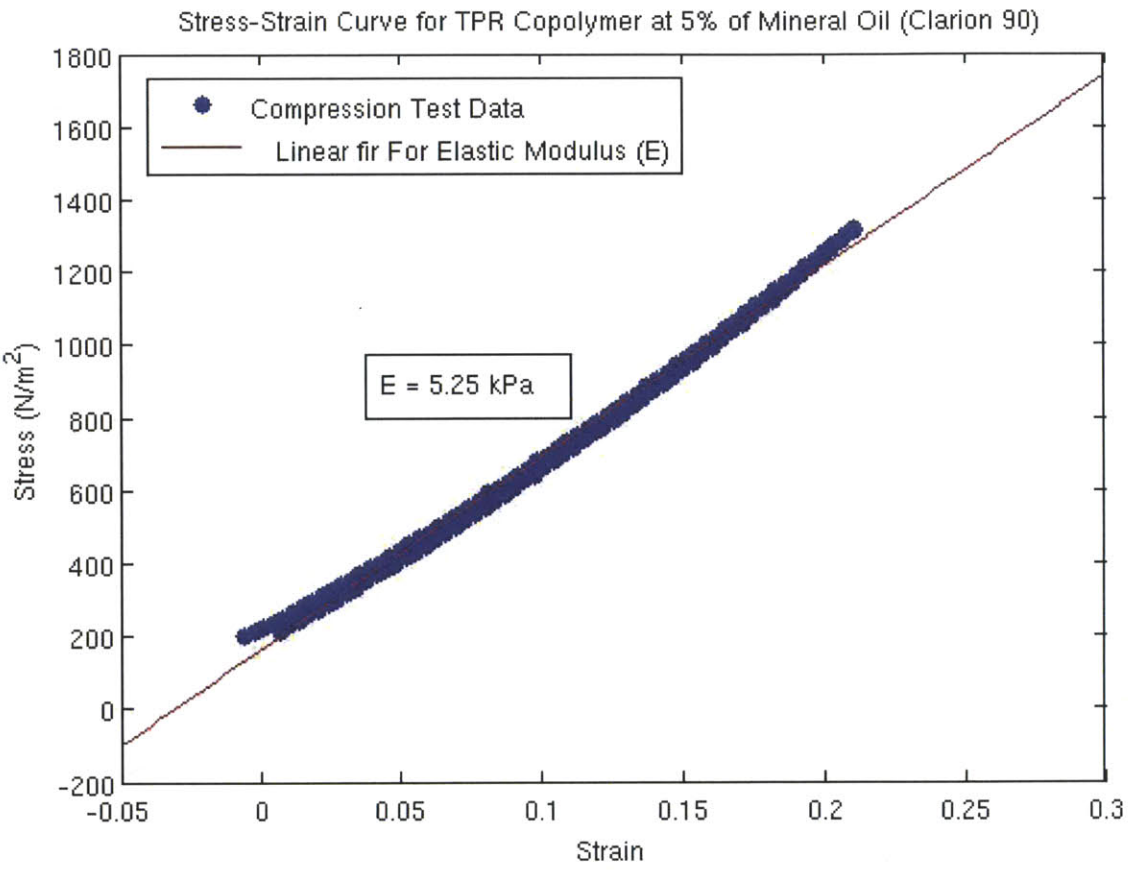

Figure 4.3: Stress Strain Curve for TPR sample (5% Copolymer). The two lines of blue dots represent two cycles of the compression test in the instron testing machine.

4.2 Bulk Mold

4.2.1 Version 1 - Single teflon tubes

The first version of the mold had dimensions of 1-3/4" diameter, and 7 " as described in Table 4.4.

TABLE 4.4: Bulk Replica Dimensions

	Bone to Skin Distance	upper Arm Length
Measured	2" ± 0.5 "	6.5 " ± 1"
Replica	1-3/4" ± 0.1"	6-3/4 ± 0.1"

Figure 4.4: First Mold for Bulk material. Caps on the end have holes for holding a rod to create a negative for the artery in the bulk replica.

In this mold, the bulk material was to be cast around the vessel. However, the high temperature of fluid TPR mixture (about 130 degress Celcius) boiled away the cyrogel as seen in Figure 4.5.

4.2.2 Version 2 - Clamshell

The next version was to cast the bulk separately in a clam shell design. The mold is a much larger version of that in version 3 (See Figure 4.10). The dimensions of this version changed from a round cylinder to that of a block. The dimensions were chosen to initially isolate the vessel from any edge effects via Saint Venant's Principle, and leave room for selectively adding other features such as bone.

Tests revealed two important observations. Tests with a probe showed that the dimensions of version 2 were unnecessarily large due to how compliant the bulk material was (See Figure 4.7) . The second important observation was that the seam between the two halves was extremely visible in ultrasound as seen in Figure 4.8.

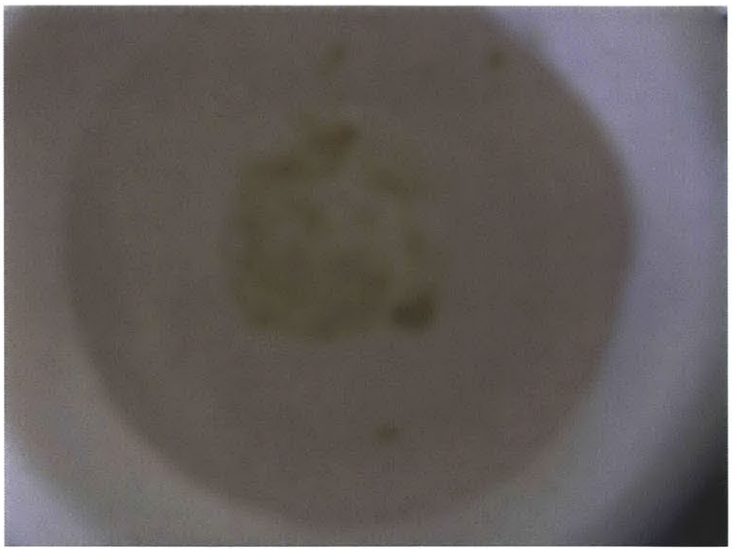

Figure 4.5: Results after first combination of vessel and artery. The bubbles are from the vessel as it boiled away from the heat of the fluid bulk, leaving behind a brown residue.

	Characteristic Dimension	Desired Result	Mold Dimension
Height (each half)	artery dimension = 0.25"	5 times greater than artery diameter to negate effect of bone.	1.5" ± 0.1
Length	Probe width = 2"	3 times larger than probe dimension in both directions (6+6+2=14")	14" ±
Width	Probe thickness = 0.5"	3 times larger than probe dimension in both directions with 2-1/4" space to move probe along vessel length"	5-3/4 ± 0.1

TABLE 4.5: Bulk Mold Dimensions

4.2.3 Version 3 - Single piece

This version was now a single piece and reduced in size to a length of 10 inches (from 14 inches) in order to fit the mold into the conventional toaster oven used to bake the mold and so that less of the bulk material needed to be made per mold. Various ideas were also developed to address the problem of inserting the vessel into the bulk. One idea was to leave the hollow vessel cylinder in mold (used to make space for vessel), and string vessel through the much stiffer cylinder, before removing the cylinder. However, in the course of trying this, it was discovered that the bulk material was both elastic and robust enough such that the bulk could be stretched enough to allow the vessel to be pushed through by hand. The mold can be seen in Figure 4.10. Volume of material needed is about 1400 ml. This can be done in two batches so long as the first layer

Figure 4.6: Figure showing Version 2 of bulk replica, 14 inches in length. The ruler, showing scale, is 12 inches.

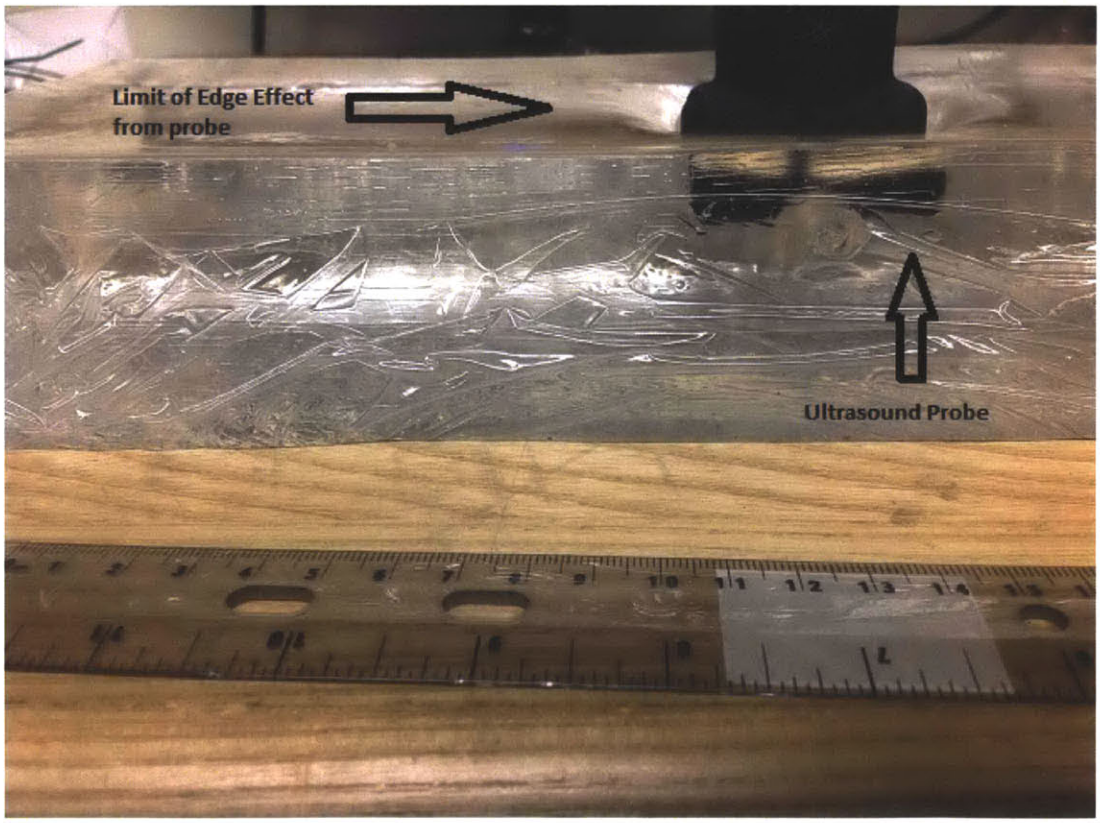

Figure 4.7: Figure showing actual limits of edge effects.

is kept molten in the oven, otherwise the seam between layers is visible on ultrasound. Typical dissolve time for 700 ml is about 1 hr and it takes about 10-15 minutes for bubbles to rise out of the version 3 mold.

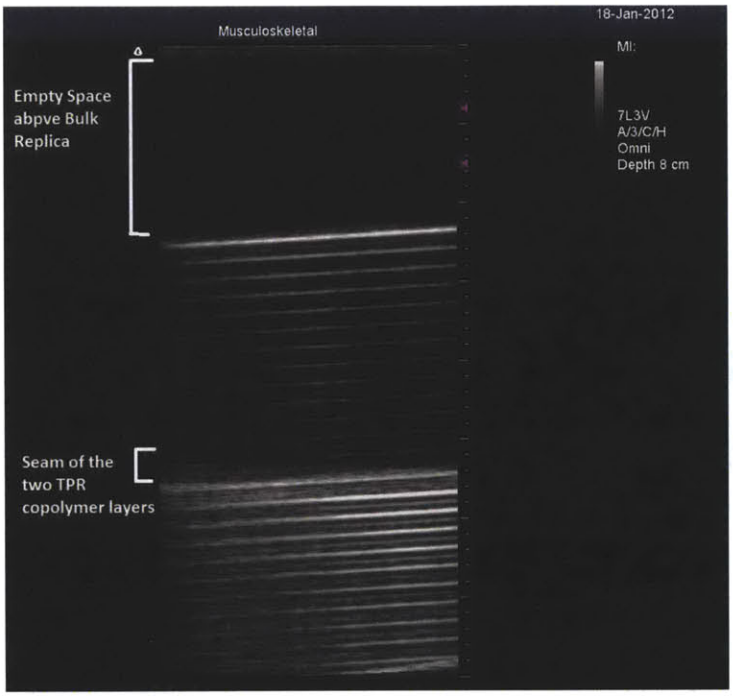

Figure 4.8: Figure showing seam between halves of clamshell in ultrasound. The series of lines in bottom half are reflections from the mold's aluminum base. The ultrasound image side borders are the limits of the probe, not the replica.

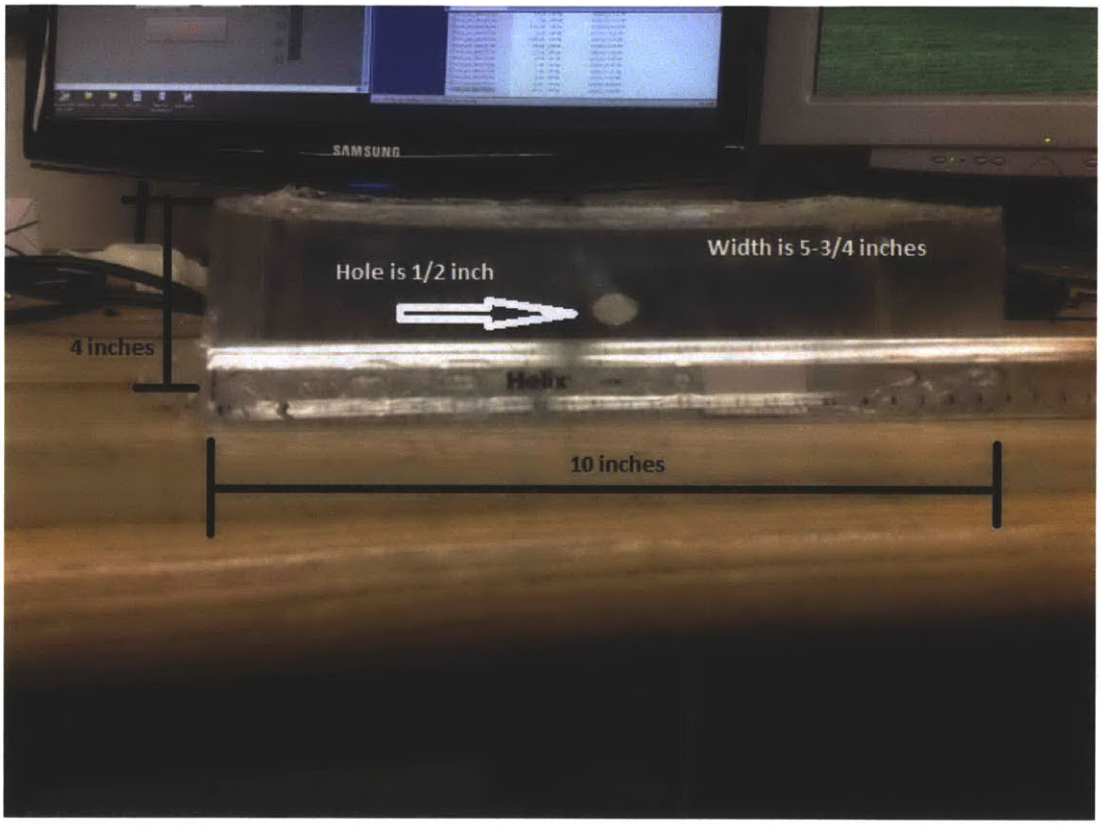

Figure 4.9: Figure showing dimensions of replica version 3. The length was reduced from 14 to 10 inches. The ruler, showing scale, is 12 inches.

4 inches

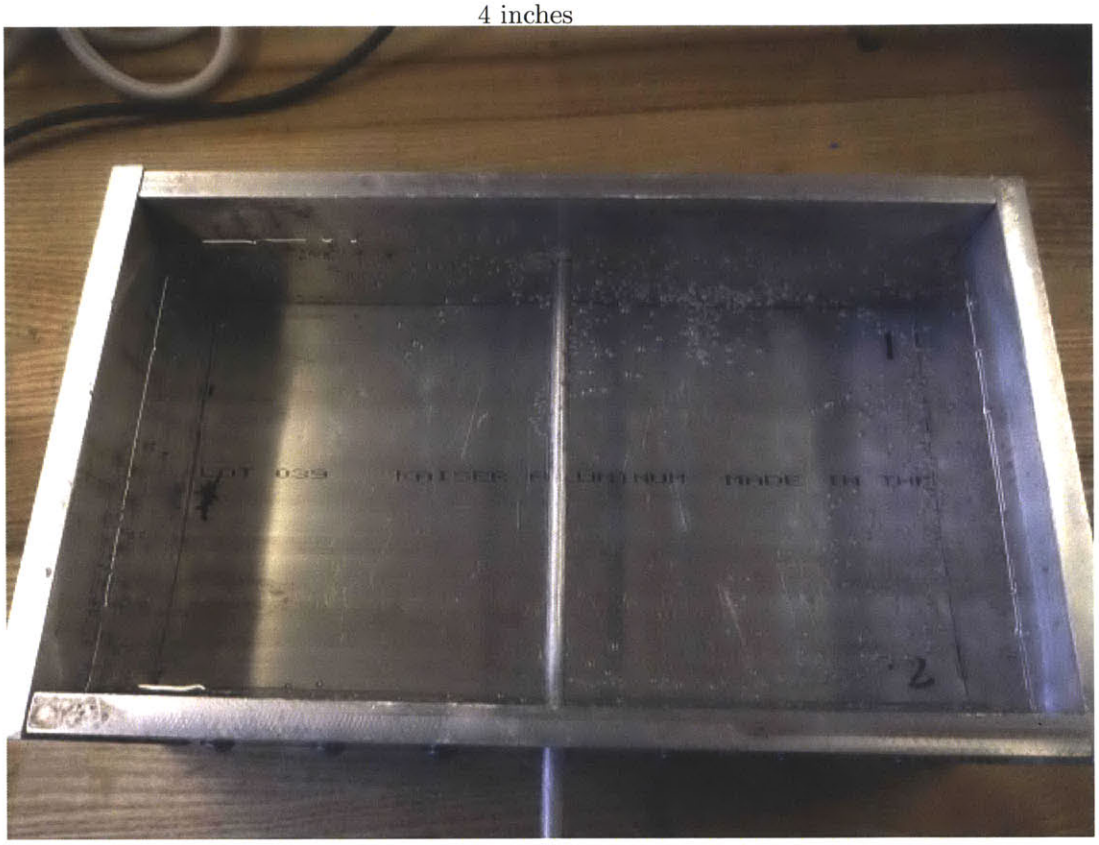

Figure 4.10: Mold for bulk material. The side walls each have a hole to hold a rod that forms the negative for the artery.

4.3 Integrating the artery and bulk replicas

Table 4.6 describes how to integrate the artery replica and the bulk replica.

TABLE 4.6: Table describing how to insert vessel into bulk replica

Step	Description	Image
Step 1	One End of cavity in bulk Replica is stretch and vessel gently pushed through.	
Step 2	Hand reaches through to other side to both stretch middle and guid vessel to other end of cavity.	

Figure 4.11 shows the integrated arterial simulator.

The ends of the vessel are attached to two hose fittings (clamped on by rubber rings made from long party balloons) and the vessel and hose were filled with water. Figures 4.12, 4.13, 4.14 and 4.15 show ultrasound images of cross-sectional and lengthwise views of the vessel. Figure 4.16 shows an image with a bubble inserted to highlight the artery walls. These figures are for the simulated briachial artery.

The blurring at the edges of the arterial walls in Figure 4.16 are about 10-20% of the inner diameter. It is unclear if they are shadows or features. Due to how proportionally large they are to the artery diameter, the decision was made to move from examination of the brachial artery to the carotid artery in which these shadows will have a much smaller impact.

As discussed earlier, the TPR bulk replica is extrelely durable. However, the vessels are easily torn. Because of this, a lot of care must be taken when clamping the vessels onto the hose fittings. External forces that might jolt the hose fittings risk tearing the vessels risk tearing the vessel. To mitigate this (beyond careful set up), the vessel is cut slightly shorter (about 1 inch) than the width of the bulk replica so that the ends of the bulk hold the hose fittings in place. This becomes more important later during actual measurements since the orientation of the hose fittings, if extreme enough, will influence the pressure readout from the pressure gauge used to measure internal fluid pressure.

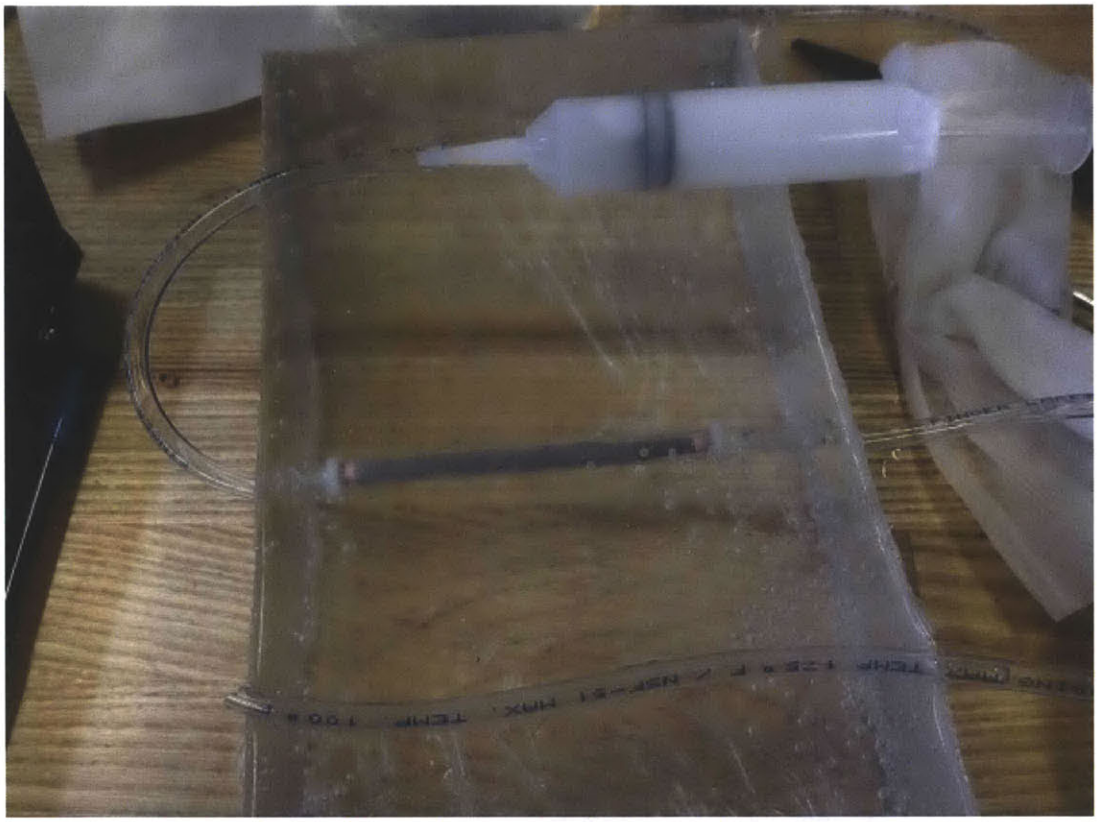

Figure 4.11: Figure showing successful integration of the bulk and cyrogel.

Figure 4.12: Ultrasound Cross section of simulator with no compression.

4.4 Storage of Bulk Replica and Lifetime

The storage lifetime of the bulk replicas, according to Oudry et al[3], is at least 14 months with little change in overall physical properties. There is some minimal change

Figure 4.13: Ultrasound Cross section of simulator with compression.

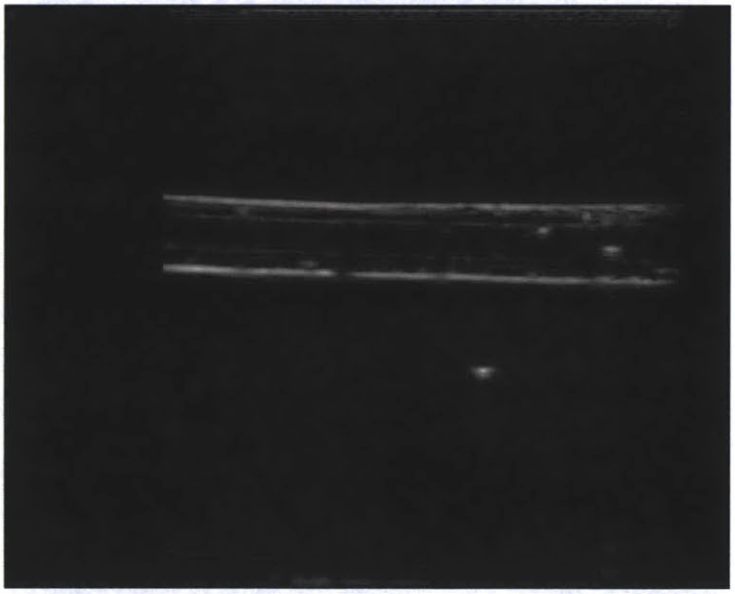

Figure 4.14: Ultrasound Length view of simulator with no compression.

in elastic modulus, but this might be attributed to the issue of mineral oil is easily absorbed from the TPR-mineral oil solids. For this reason, the bulk replicas are all stored wraped in plastic food wrap. They can be then left on an open air shelf, being extremely robust and difficult to tear.

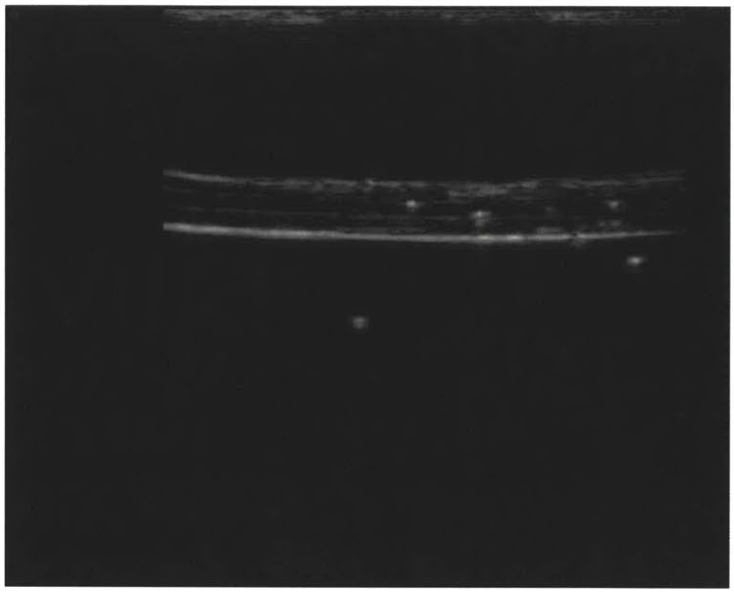

Figure 4.15: Ultrasound Length view of simulator with compression.

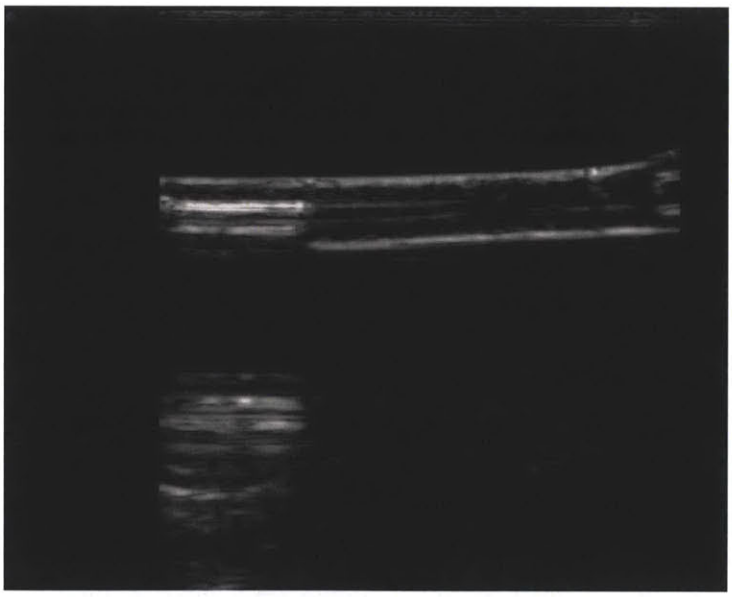

Figure 4.16: Ultrasound Length view of simulator with bubble injected to highlight artery walls. The artery size used is that of a brachial artery. A significant portion of the vessel is taken up by the blurring by the bubble.

Chapter 5

Dynamic Model

5.1 Dynamic Properties and Theoretical Model

The model used for the artery network is that of an electical circuit, where the resistances are determined by Ohm's Law.

$$\frac{V}{I} = R \tag{5.1}$$

This fluid equivalent where pressure $\rightarrow$ voltage, flow rate $\rightarrow$ amps, fluid resistance $\rightarrow$ electrical resistance:

$$\frac{P}{Q} = R \tag{5.2}$$

These equations were applied to the study conducted by Morgen and Hosking [12] measuring the blood pressure waveform at rest and exercise. The results in Table 5.1 show the maximum and minimum pressures from the data collected by Morgen and Hosking [12] where the last column shows the 'resistance' calculated from the results of the study using Ohm's Law(assuming that the heart has consistent volume/stroke). The basal pressure is the minimum pressure of the waveform and the maximum pressure is the peak. The largest difference between the two differences is 4 mmHg-sec/(unit volume/heartstroke), which is about 11% of the smaller of the two differences between the max and min resistances (100 and 65 mmHg-sec/(unit volume/heartstroke)). Thus the model of the artery network is expected to give a consistent distinction between the peaks of the waveform.

TABLE 5.1: Maximum and minimum pressures from blood pressure waveform [12] and calculated resistances.

State	Basal Pressure (mmHg) +/- 5	Maximum Pressure (mmHg) +/- 5	Period (sec) +/- 0.02	Calculated Resistance via Ohm's Law (mmHg-sec/(unit volume/heat stroke))
Rest	65	100	1	65 (basal) 100 (max)
Exercise	80	130	0.8	64 (basal) , 104(max)

5.2 Building the Beating Heart

5.2.1 Selection of Pump

Diaphragm pumps are frequently used for simulating hearts in medicine due to constant flow rate. Research has shown [10] [11] that for blood flow in the common carotid artery, for pressure range is 60-120 mmHg (1.16 - 2.32 psi), the flow rate is 250-600 ml/min. Based on availability and pump characteristics, the pump C-6250HV-115VAC by Blue-White Industries was chosen with maximum flow rate of 2,070 ml/min for 250 strokes per min and maximum pressure of 5 psi. The pump has control over volume/stroke but no speed control. We introduced speed control by attaching the pump motor to an external DC motor to enable pump speed control by adjusting the voltage applied to the motor. The pump has a maximum of 8.3 ml/stroke or maximum 500 ml per min at 60 beats per minute which can be reduced by a setting on the pump.

Chapter 6

System performance

Figure 6.2 shows the flow diagram for the hardware for the tests run and Figure 6.1 is the final hardware setup. A force probe connects the ultrasound probe (by Terason) to the stand which can measure vertical displacements of the ultrasound probe. The force probe data is coverted to digital from analog via a Lab-Jack U3-HV (12 bit ADC) and displayed in the prgram Lab-View. The pressure data was collected by the pressure gauge attached to the hose network near the entrance to the artery. For the first static and dynamic tests, strokes/min was to kept to 70-80 strokes/min.

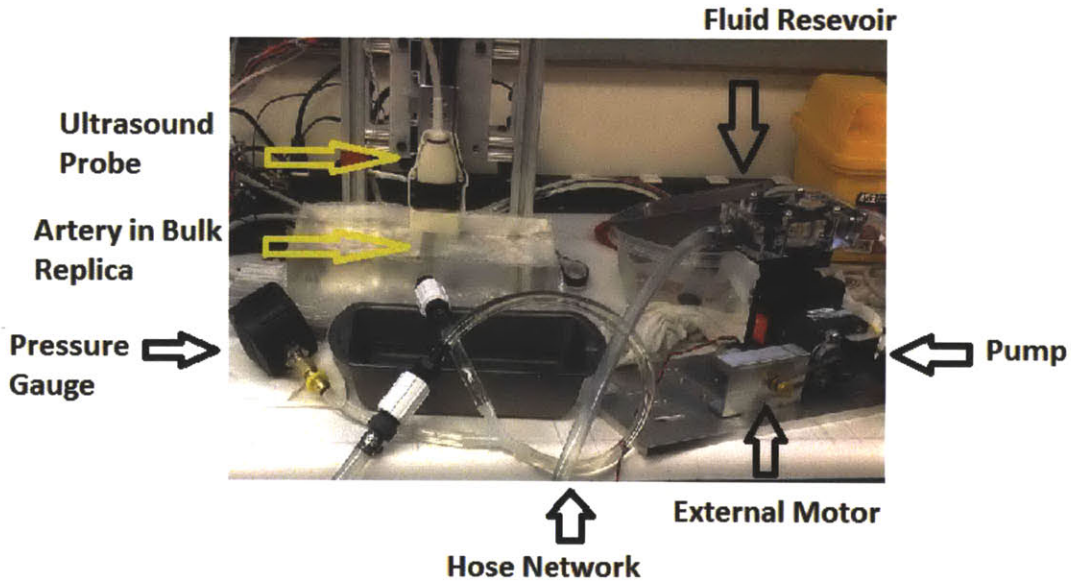

Figure 6.1: Figure showing Final Hardware Schematic of setup.

6.1 Static and Dynamic Results

The first test was to check how the vessel diameter and force output on the probe would respond to increases in pressure. The probe was held at a constant position and a vertical hose connected to the artery replica was gradually filled with water as images

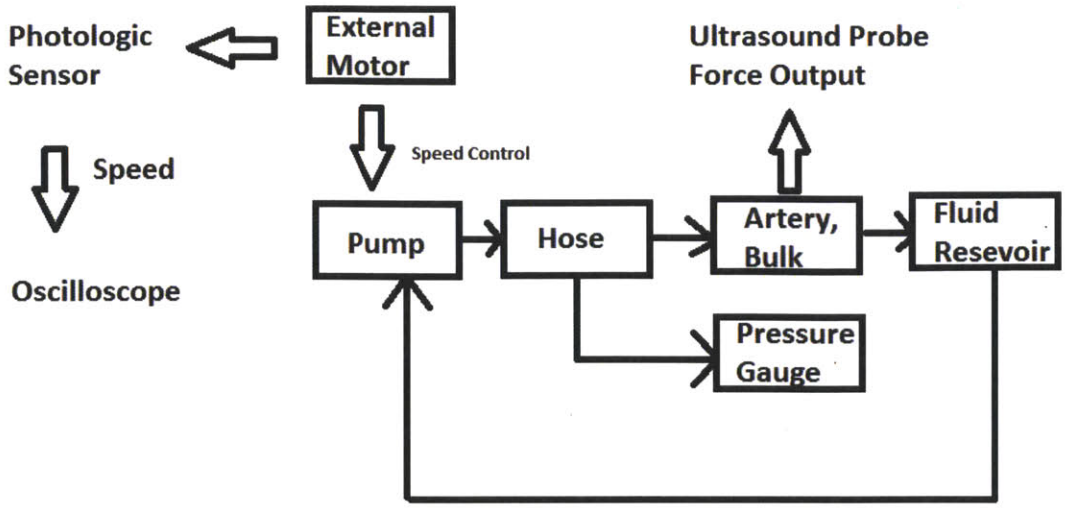

Figure 6.2: Flow Diagram of Hardware.

and force and pressure measurements were recorded. The results are summarized in Table 6.1 and the linear relationship of force as a function of pressure is seen in Figure 6.3. The graph shows that as the internal pressure of the vessel increased, so did the force on the probe.

TABLE 6.1: Results and Images from Static Tests at constant displacement. As Fluid Pressue increases, so does the vessel perimeter and force on probe.

Pressure(psi)	Force (N)	Image
0.43	0.35	
0.217	0.375	
0.326	0.41	
0.46	0.44	

The pump was then turned on at approximately 70 beats per minute. With the pump output constant, the probe was held at 4 different vertical positions to see how distinct the resulting force will be. As expected, as the probe height decreased, the average force measured from the vessel increased, indicating increasing internal pressure as seen in Figure 6.4.

However, the actual waveform is difficult to distinguish as the limit of the resolution

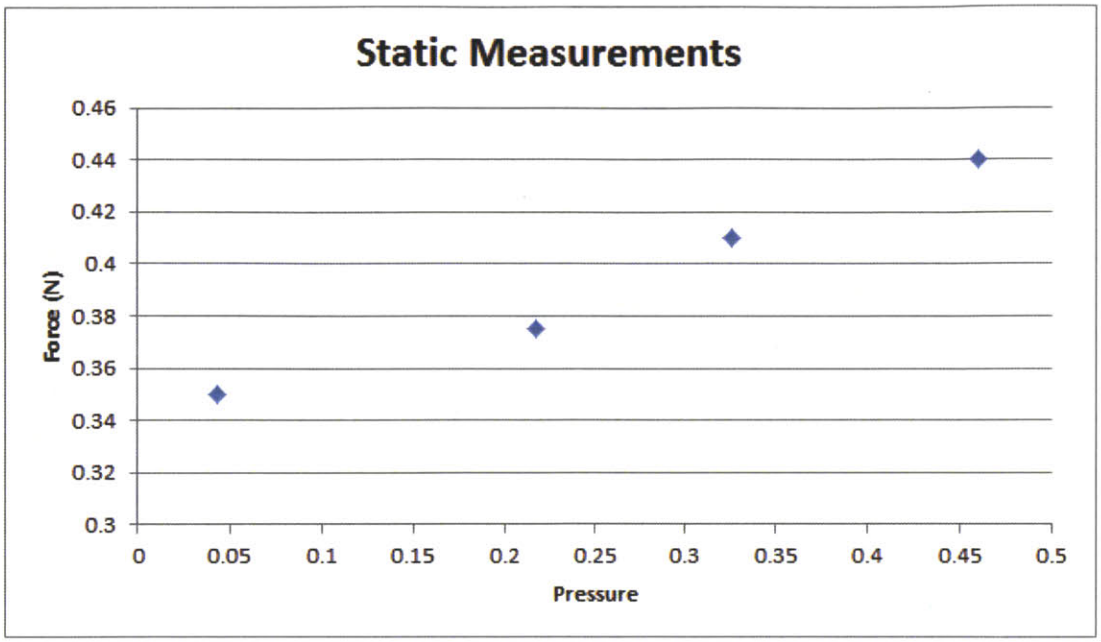

Figure 6.3: Figure showing results of static measurements. Force on Probe increases linearly with Pressure as expected.

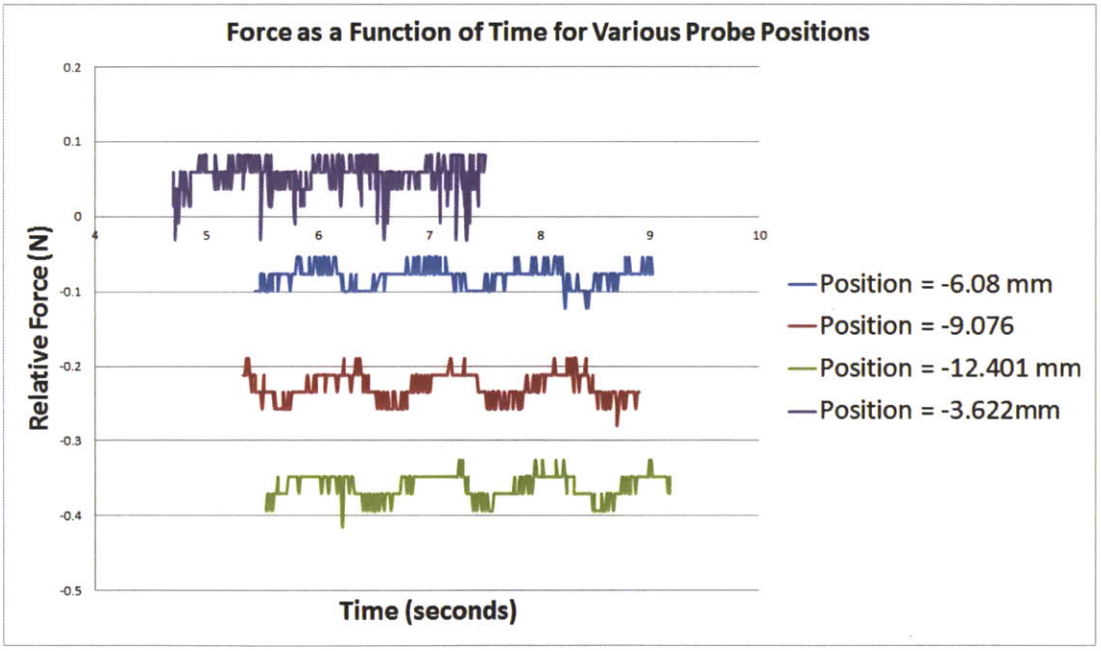

Figure 6.4: Figure showing dynamic waveforms from beating artery. As probe height decreased, force measured increased. Also, less distinguishable are the waveforms of the force as the vessel pulsed.

of the ADC seems to have been reached. In the middle of the range at position -9.076 mm, the peaks of the waveform are clearer than at position -6.08mm.

Chapter 7

Conclusion and future work

A mechanical arterial simulator was designed and built to mimic the physical properties of the components of the structural loop in a blood pressure measurements. A PVA cyrogel and TPR-coplymer-mineral oil solution were teh materials used to replicate the vessel and bulk materials respectively. Having demonstrated that the arterial simulator can detect the waveform of a beating artery sufficiently enough to distinguish between various probe heights and can begin to show the peaks of the waveform, the next steps are

- More finely calibrate force probe for cleaner data.
- Attach photologic sensor to motor to measure speed and flow output.
- Validate results with numerical simulator.
- Compare data with clinical data.

Appendix A

Replica Materials Data Sheets

Clarion® Food Grade White Mineral Oil 90

Material Safety Data Sheet

CITGO Petroleum Corporation
P.O. Box 4689
Houston, TX 77210

MSDS No. 633509009
Revision Date 11/18/2010

IMPORTANT: Read this MSDS before handling or disposing of this product and pass this information on to employees, customers and users of this product.

Hazard Rankings

	HMIS	NFPA
Health Hazard	0	0
Fire Hazard	1	1
Reactivity	0	0

* = Chronic Health Hazard

Protective Equipment

Minimum Recommended
See Section 8 for Details

Emergency Overview

Physical State Liquid.
Color Colorless. **Odor** Odorless.

WARNING:
Aspiration hazard if swallowed.
If liquid material enters the lungs, it can cause severe damage.
Do not taste or swallow.
If swallowed, do not induce vomiting.
Spills may create a slipping hazard.

SECTION 1. PRODUCT IDENTIFICATION

Trade Name	Clarion® Food Grade White Mineral Oil 90	**Technical Contact**	(800) 248-4684
Product Number	633509009	**Medical Emergency**	(832) 486-4700
CAS Number	8042-47-5	**CHEMTREC Emergency (United States Only)**	(800) 424-9300
Product Family	White mineral oil		
Synonyms	White mineral oil; CITGO® Material Code: 633509001		

SECTION 2. COMPOSITION (TYPICAL)

Component Name(s)	CAS Registry No.	Concentration (%)
White mineral oil	8042-47-5	100
di alpha tocopherol (Vitamin E) (Stabilizer)	59-02-9	<0.1

SECTION 3. HAZARDS IDENTIFICATION

Also see Emergency Overview and Hazard Ratings on the top of Page 1 of this MSDS.

Major Route(s) of Entry Not applicable.

Signs and Symptoms of Acute Exposure

Inhalation No significant adverse health effects are expected to occur upon short-term exposure.

Eye Contact Minimal eye irritation may result from short-term contact with liquid, mist, and/or vapor.

Skin Contact No significant irritation is expected to occur upon short-term exposure.

Ingestion

	Ingestion can cause a laxative effect. If liquid material enters into the lungs, it can cause severe damage.
Chronic Health Effects Summary	Repeated or prolonged inhalation of petroleum-based mineral oil mists at concentrations above applicable workplace exposure levels can cause respiratory irritation or other pulmonary effects.
Conditions Aggravated by Exposure	None known.
Target Organs	No target organ effects are anticipated.
Carcinogenic Potential	This product is not known to contain any components at concentrations above 0.1% which are considered carcinogenic by OSHA, IARC or NTP.

OSHA Hazard Classification is indicated by an "X" in the box adjacent to the hazard title. If no "X" is present, the product does not exhibit the hazard as defined in the OSHA Hazard Communication Standard (29 CFR 1910.1200).

OSHA Health Hazard Classification				OSHA Physical Hazard Classification					
Irritant		Sensitizer		Combustible		Explosive		Pyrophoric	
Toxic		Highly Toxic		Flammable		Oxidizer		Water-reactive	
Corrosive		Carcinogenic		Compressed Gas		Organic Peroxide		Unstable	

SECTION 4. FIRST AID MEASURES

Take proper precautions to ensure your own health and safety before attempting rescue or providing first aid. For more specific information, refer to Exposure Controls and Personal Protection in Section 8 of this MSDS.

Inhalation	Vaporization is not expected at ambient temperatures. This material is not expected to cause inhalation-related disorders under anticipated conditions of use. In case of overexposure, move the person to fresh air.
Eye Contact	Check for and remove contact lenses. Flush eyes with cool, clean, low-pressure water while occasionally lifting and lowering eyelids. Seek medical attention if excessive tearing, redness, or pain persists.
Skin Contact	If burned by hot material, cool skin by quenching with large amounts of cool water. For contact with product at ambient temperatures, remove contaminated shoes and clothing. Wipe off excess material. Wash exposed skin with mild soap and water. Seek medical attention if tissue appears damaged or if pain or irritation persists. Thoroughly clean contaminated clothing before reuse. Clean or discard contaminated leather goods. If material is injected under the skin, seek medical attention immediately.
Ingestion	Do not induce vomiting. If spontaneous vomiting is about to occur, place victim's head below knees. If victim is drowsy or unconscious, place on the left side with head down. Never give anything by mouth to a person who is not fully conscious. Do not leave victim unattended. Seek medical attention immediately.
Notes to Physician	SKIN: In the event of injection in underlying tissue, immediate treatment should include extensive incision, debridement and saline irrigation. Inadequate treatment can result in ischemia and gangrene. Early symptoms may be minimal. INGESTION: If ingested, this material presents a significant aspiration and chemical pneumonitis hazard. Induction of emesis is not recommended. Consider activated charcoal and/or gastric lavage. If patient is obtunded, protect the airway by cuffed endotracheal intubation or by placement of the body in a Trendelenburg and left lateral decubitus position.

SECTION 5. FIRE FIGHTING MEASURES

NFPA Flammability Classification NFPA Class-IIIB combustible material.

Flash Point Open cup: 190°C (374°F) (Cleveland.).

Lower Flammable Limit No data. **Upper Flammable Limit** No data.

Autoignition Temperature Not available.

Hazardous Combustion Products Carbon dioxide, carbon monoxide, smoke, fumes, and unburned hydrocarbons.

Special Properties This material can burn but will not readily ignite. This material will release vapors when heated above the flash point temperature that can ignite when exposed to a source of ignition. In enclosed spaces, heated vapor can ignite with explosive force. Mists or sprays may burn at temperatures below the flash point.

Extinguishing Media Use dry chemical, foam, carbon dioxide or water fog. Water or foam may cause frothing. Carbon dioxide and inert gas can displace oxygen. Use caution when applying carbon dioxide or inert gas in confined spaces.

Protection of Fire Fighters Firefighters must use full bunker gear including NIOSH-approved positive pressure self-contained breathing apparatus to protect against potential hazardous combustion or decomposition products and oxygen deficiencies.

SECTION 6. ACCIDENTAL RELEASE MEASURES

Take proper precautions to ensure your own health and safety before attempting spill control or clean-up. For more specific information, refer to the Emergency Overview on Page 1, Exposure Controls and Personal Protection in Section 8 and Disposal Considerations in Section 13 of this MSDS.

Do not touch damaged containers or spilled material unless wearing appropriate protective equipment. Slipping hazard; do not walk through spilled material. Stop leak if you can do so without risk. For small spills, absorb or cover with dry earth, sand, or other inert non-combustible absorbent material and place into waste containers for later disposal. Contain large spills to maximize product recovery or disposal. Prevent entry into waterways or sewers. In urban area, cleanup spill as soon as possible. In natural environments, seek cleanup advice from specialists to minimize physical habitat damage. This material will float on water. Absorbent pads and similar materials can be used. Comply with all laws and regulations.

SECTION 7. HANDLING AND STORAGE

Handling Keep containers closed and do not handle or store near heat, sparks, or any other potential ignition sources. Avoid contact with oxidizing agents. Never siphon by mouth. Avoid contact with eyes, skin, and clothing. Avoid contamination and extreme temperatures.

Empty containers may contain product residues that can ignite with explosive force. Drain and purge equipment, as necessary, to remove material residues. Follow proper entry procedures, including compliance with 29 CFR 1910.146 prior to entering confined spaces such as tanks or pits. Use appropriate respiratory protection when concentrations exceed any established occupational exposure level (See Section 8). Promptly remove contaminated clothing. Wash exposed skin thoroughly with soap and water after handling.

Do not pressurize, cut, weld, braze solder, drill, grind or expose containers to flames, sparks, heat or other potential ignition sources. Protect containers against physical damage. Consult appropriate federal, state and local authorities before reusing, reconditioning, reclaiming, recycling or disposing of empty containers and/or waste residues of this product.

Storage

Keep container tightly closed. Store in a cool, dry, well-ventilated area. Store only in approved containers. Do not store with strong oxidizing agents. Do not store at elevated temperatures. Avoid storing product in direct sunlight for extended periods of time. Storage area must meet OSHA requirements and applicable fire codes. Consult appropriate federal, state and local authorities before reusing, reconditioning, reclaiming, recycling or disposing of empty containers or waste residues of this product.

SECTION 8. EXPOSURE CONTROLS AND PERSONAL PROTECTION

Engineering Controls

Provide exhaust ventilation or other engineering controls to keep the airborne concentrations of mists and/or vapors below the recommended exposure limits (see below). An eye wash station and safety shower should be located near the work-station.

Personal Protective Equipment

Personal protective equipment should be selected based upon the conditions under which this material is used. A hazard assessment of the work area for PPE requirements should be conducted by a qualified professional pursuant to OSHA regulations. The following pictograms represent the minimum requirements for personal protective equipment. For certain operations, additional PPE may be required.

Eye Protection

Safety glasses equipped with side shields are recommended as minimum protection in industrial settings. Wear goggles if splashing or spraying is anticipated. Wear goggles and face shield if material is heated above 125°F (51°C). Have suitable eye wash water available.

Hand Protection

None required for incidental contact. Use gloves constructed of chemical resistant materials such as heavy nitrile rubber if frequent or prolonged contact is expected. Use heat-protective gloves when handling product at elevated temperatures.

Body Protection

Use clean protective clothing if splashing or spraying conditions are present. Protective clothing may include long-sleeve outer garment, apron, or lab coat. If significant contact occurs, remove oil-contaminated clothing as soon as possible and promptly shower. Launder contaminated clothing before reuse or discard. Wear heat protective boots and protective clothing when handling material at elevated temperatures.

Respiratory Protection

The need for respiratory protection is not anticipated under normal use conditions and with adequate ventilation. If elevated airborne concentrations above applicable workplace exposure levels are anticipated, a NIOSH-approved organic vapor respirator equipped with a dust/mist prefilter should be used. Protection factors vary depending upon the type of respirator used. Respirators should be used in accordance with OSHA requirements (29 CFR 1910.134).

General Comments

Use good personal hygiene practices. Wash hands and other exposed skin areas with plenty of mild soap and water before eating, drinking, smoking, use of toilet facilities, or leaving work. DO NOT use gasoline, kerosene, solvents or harsh abrasives as skin cleaners. Since specific exposure standards/control limits have not been established for this product, the "Oil Mist, Mineral" exposure limits shown below are suggested as minimum control guidelines.

Occupational Exposure Guidelines

Substance	Applicable Workplace Exposure Levels
Oil, Mineral (Mist)	**ACGIH (United States).** TWA: 5 mg/m^3 STEL: 10 mg/m^3 **OSHA (United States).** TWA: 5 mg/m^3

SECTION 9. PHYSICAL AND CHEMICAL PROPERTIES (TYPICAL)

Physical State	Liquid.	**Color**	Colorless.	**Odor**	Odorless.
Specific Gravity	0.85 (Water = 1)	**pH**	Not applicable	**Vapor Density**	>1 (Air = 1)
Boiling Range	Not available.			**Melting/Freezing Point**	Not available.
Vapor Pressure	<0.01 kPa (<0.1 mm Hg) (at 20°C)			**Volatility**	AP 30 g/l VOC (w/v)
Solubility in Water	Negligible solubility in cold water.			**Viscosity (cSt @ 40°C)**	16
Flash Point	Open cup: 190°C (374°F) (Cleveland.).				
Additional Properties	Gravity, °API (ASTM D287) = 33.4 @ 60° F Density = 7.14 Lbs/gal. Viscosity (ASTM D2161) = 87 SUS @ 100° F				

SECTION 10. STABILITY AND REACTIVITY

Chemical Stability Stable. **Hazardous Polymerization** Not expected to occur.

Conditions to Avoid Keep away from extreme heat, sparks, open flame, and strongly oxidizing conditions.

Materials Incompatibility Strong oxidizers.

Hazardous Decomposition Products No additional hazardous decomposition products were identified other than the combustion products identified in Section 5 of this MSDS.

SECTION 11. TOXICOLOGICAL INFORMATION

For other health-related information, refer to the Emergency Overview on Page 1 and the Hazards Identification in Section 3 of this MSDS.

Toxicity Data

White mineral oil

ORAL (LD50): Acute: >5000 mg/kg [Rat].
DERMAL (LD50): Acute: >2000 mg/kg [Rabbit].

Low-viscosity and High-viscosity White Mineral Oils:
DRAIZE EYE, Acute: Non-irritating [Rabbit].
DRAIZE DERMAL, Acute: Non-irritating [Rabbit].
BUEHLER, Acute: Non-sensitizing [Guinea Pig].
28-Day DERMAL, Sub-Chronic: Non-irritating [Rabbit].
104-Week DERMAL, Chronic: No skin tumors at site of application [Mouse].
MUTAGENICITY:
Modified Ames Assay: Negative [Salmonella typhimurium].
in-vitro Lymphoma Assay: Negative or no toxicity [Mouse].

Lifetime mouse skin painting studies indicated that white mineral oils are not mutagenic or carcinogenic. Mineral oil mists derived from highly refined oils are reported to have low acute and sub-acute toxicities in animals. Effects from single and short-term repeated exposures to high concentrations of mineral oil mists well above applicable workplace exposure levels include lung inflammatory reaction, lipoid granuloma formation and lipoid pneumonia. In acute and sub-acute studies involving exposures to lower concentrations of mineral oil mists at or near current work place exposure levels produced no significant toxicological effects. In long term studies (up to two years) no carcinogenic effects have been reported in any animal

species tested.

SECTION 12. ECOLOGICAL INFORMATION

Ecotoxicity

Analysis for ecological effects has not been conducted on this product. However, if spilled, this product and any contaminated soil or water may be harmful to human, animal, and aquatic life. Also, the coating action associated with petroleum and petroleum products can be harmful or fatal to aquatic life and waterfowl.

Environmental Fate

Biodegradability: Inherently biodegradable in aerobic conditions.

Partition Coefficient (log Kow): >6 (based on similar materials)

Photodegradation: Based on similar materials, this product will have little or no tendency to partition to air. Hydrocarbons from this product which do partition to air are expected to rapidly photodegrade.

Stability in Water: Not readily susceptible to hydrolysis under aquatic conditions.

Distribution: Principally to soil and sediment. Petroleum-based (mineral) lubricating oils normally will float on water. In stagnant or slow-flowing waterways, an oil layer can cover a large surface area. As a result, this oil layer might limit or eliminate natural atmospheric oxygen transport into the water. With time, if not removed, oxygen depletion in the waterway may be sufficient to cause a fish kill or create an anaerobic environment.

SECTION 13. DISPOSAL CONSIDERATIONS

Hazard characteristic and regulatory waste stream classification can change with product use. Accordingly, it is the responsibility of the user to determine the proper storage, transportation, treatment and/or disposal methodologies for spent materials and residues at the time of disposition.

Conditions of use may cause this material to become a "hazardous waste", as defined by federal or state regulations. It is the responsibility of the user to determine if the material is a "hazardous waste" at the time of disposal. Transportation, treatment, storage, and disposal of waste material must be conducted in accordance with RCRA regulations (see 40 CFR 260 through 40 CFR 271). State and/or local regulations may be more restrictive. Contact your regional US EPA office for guidance concerning case specific disposal issues. Empty drums and pails retain residue. DO NOT pressurize, cut, weld, braze, solder, drill, grind, or expose this product's empty container to heat, flame, or other ignition sources. DO NOT attempt to clean it. Empty drums and pails should be drained completely, properly bunged or sealed, and promptly sent to a reconditioner.

SECTION 14. TRANSPORT INFORMATION

SECTION 15. REGULATORY INFORMATION

TSCA Inventory	This product and/or its components are listed on the Toxic Substances Control Act (TSCA) inventory.
SARA 302/304 Emergency Planning and Notification	The Superfund Amendments and Reauthorization Act of 1986 (SARA) Title III requires facilities subject to Subparts 302 and 304 to submit emergency planning and notification information based on Threshold Planning Quantities (TPQs) and Reportable Quantities (RQs) for "Extremely Hazardous Substances" listed in 40 CFR 302.4 and 40 CFR 355. No components were identified.
SARA 311/312 Hazard Identification	The Superfund Amendments and Reauthorization Act of 1986 (SARA) Title III requires facilities subject to this subpart to submit aggregate information on chemicals by "Hazard Category" as defined in 40 CFR 370.2. This material would be classified under the following hazard categories: No SARA 311/312 hazard categories identified.
SARA 313 Toxic Chemical Notification and Release Reporting	This product contains the following components in concentrations above *de minimis* levels that are listed as toxic chemicals in 40 CFR Part 372 pursuant to the requirements of Section 313 of SARA: No components were identified.
CERCLA	The Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) requires notification of the National Response Center concerning release of quantities of "hazardous substances" equal to or greater than the reportable quantities (RQ's) listed in 40 CFR 302.4. As defined by CERCLA, the term "hazardous substance" does not include petroleum, including crude oil or any fraction thereof which is not otherwise specifically designated in 40 CFR 302.4. This product or refinery stream is not known to contain chemical substances subject to this statute. However, it is recommended that you contact state and local authorities to determine if there are any other reporting requirements in the event of a spill.
Clean Water Act (CWA)	This material is classified as an oil under Section 311 of the Clean Water Act (CWA) and the Oil Pollution Act of 1990 (OPA). Discharges or spills which produce a visible sheen on waters of the United States, their adjoining shorelines, or into conduits leading to surface waters must be reported to the EPA's National Response Center at (800) 424-8802.
California Proposition 65	This product is not known to contain any components for which the State of California has found to cause cancer, birth defects or other reproductive harm.
New Jersey Right-to-Know Label	Petroleum Oil
Additional Regulatory Remarks	Federal Hazardous Substances Act, related statutes, and Consumer Product Safety Commission regulations, as defined by 16 CFR 1500.14(b)(3) and 1500.83(a)(13): This product contains "Petroleum Distillates" which may require special labeling if distributed in a manner intended or packaged in a form suitable for use in the household or by children. Precautionary label dialogue should display the following: **DANGER: Contains Petroleum Distillates! Harmful or fatal if swallowed! Call Physician Immediately. KEEP OUT OF REACH OF CHILDREN!**

SECTION 16. OTHER INFORMATION

Refer to the top of Page 1 for the HMIS and NFPA Hazard Ratings for this product.

REVISION INFORMATION

Version Number	1.7
Revision Date	11/18/2010
Print Date	Printed on 11/18/2010.

ABBREVIATIONS

AP: Approximately EQ: Equal >: Greater Than <: Less Than NA: Not Applicable ND: No Data NE: Not Establishe

ACGIH: American Conference of Governmental Industrial Hygienist: AIHA: American Industrial Hygiene Associatior

IARC: International Agency for Research on Cancer NTP: National Toxicology Program

NIOSH: National Institute of Occupational Safety and Health OSHA: Occupational Safety and Health Administration

NPCA: National Paint and Coating Manufacturers Association HMIS: Hazardous Materials Information System

NFPA: National Fire Protection Association EPA: US Environmental Protection Agency

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***** END OF MSDS *****

K0061 Europe 9/28/2009	Kraton® G1651 E Polymer	Data Document

Identifier : K061DDc09E

Description

Kraton G1651 E is a clear, linear triblock copolymer based on styrene and ethylene/butylene, S-E/B-S, with bound styrene of 31.5% mass. It is supplied from Europe in the physical forms identified below.

- Kraton G1651 EU - supplied as undusted fluffy crumb
- Kraton G1651 ES - supplied as fluffy crumb dusted with amorphous silica

Kraton G1651 E is used as a base material for compound formulations and as a modifier of thermoplastics. The inherent stability of the mid block suggests the use of this product in applications that must withstand weathering and high processing temperatures.

Sales Specifications

Property	Test Method	Units	Sales Specification Range	Notes
Polystyrene Content	KM 03	%m	30.0 TO 33.0	
Total Extractables	KM 05	%m	<= 1.6	
Antioxidant Content	KM 08	%m	>= 0.03	
Volatile Matter	KM 04	%m	<= 0.5	
Ash (ES)	ISO 247	%m	0.3 TO 0.5	

Typical Properties (These are typical values and may not routinely be measured on finished product)

Property	Test Method	Units	Typical Value	Notes
Solution Viscosity	KM06	Pa.s	1.5	a
Specific Gravity	ISO 2781		0.91	

a Measured on 10% m/m solution in toluene at 25°C using a Brookfield viscometer LVT model

Packaging

End Use Requirements

If the finished article is intended for use in food contact and packaging applications, toys, or human contact areas, manufacturers of the final product should observe all relevant regulations. Some of these regulations require tests to be carried out on the final product, e.g. migration. These are the responsibility of the final product manufacturer.
Information on the food packaging clearances of individual products is available from Kraton Polymers.

Medical, Healthcare and Cosmetic Applications and Trademark Usage

Kraton Polymers products should not be used in any devices or materials intended for implantation in the human body as defined by the U.S. Food and Drug Administration under 21 CFR 812.3(d) and 21 CFR 860.3(d).
Kraton Polymers products may, in certain circumstances, be used in the following products or applications with prior written approval for each specific product or applicaton:

a. Cosmetics (exclusive of packaging or delivery applications).
b. Drugs and other Pharmaceuticals (exclusive of packaging or delivery applications).

Kraton Polymers trade names, trademarks, logos or other similar identifying characteristics should not be used in the manufacture, sale, or promotion of cosmetics, drugs, and pharmaceutical products or other medical/healthcare applications or materials.
Kraton Polymers has no specific expertise in these markets and applications, and does not intend to perform testing, clinical studies or other investigations of the suitability of its products for specific applications.
Each customer or user of Kraton Polymers products is solely responsible for determining the suitability of the materials it selects for the intended purpose and acknowledges that it has not relied on any representations of Kraton Polymers regarding suitability for use in its intended cosmetics, drugs, pharmaceutical products or materials.
Please contact your Kraton Polymers Sales Representative for more details before using our products in these specific applications.

Safety and Handling Precautions

Read the Safety Data Sheet carefully and thoroughly before beginning any work. Additional information relating to the health, safety, storage, handling and processing of Kraton Polymers products can be found in "Health and Safety Aspects of Kraton D and Kraton G Polymers" (Document K0155), available from your local Sales Representative or the company website. Kraton Polymers also recommends that customers or users consult other sources of safety information, for example, the current edition of the "Code of Practice on the Toxicity and Safe Handling of Rubber Chemicals," British Rubber Manufacturers Association Limited.
Kraton Polymers products and compounds can accumulate electrostatic charges when rubbed, chafed or abraded. Processing and storage equipment for use with Kraton Polymers products should provide a means of dissipating any charges that may develop.

When processing Kraton Polymers products, maintain a fire watch if the material reaches 225°C (437°F) for Kraton IR and Kraton D (polymers and compounds), and 280°C (536°F) for Kraton G (polymers and compounds). The temperatures listed above are indicated only for safety reasons (risk of fire and product degradation) and are not necessarily recommended for processing. Degradation of the polymer (polymer breakdown) will start at lower temperatures depending on the specific processing conditions. Therefore, operating below these temperatures does not guarantee the absence of product degradation.

Kraton Polymers products (the neat resin or the base product) are high molecular weight polymers which are non-toxic and biologically inactive.

Warranty

The information contained in this publication is, to the best of Kraton Polymers' knowledge, true and accurate, but any recommendations or suggestions that may be made are without guarantee, since the conditions of use and storage are beyond Kraton Polymers' control. The customer understands that it shall make its own assessment to determine the suitability of a Kraton Polymers product for a particular purpose. Further, nothing contained herein shall be construed as a recommendation to use any Kraton Polymers product in conflict with existing patents. All products purchased from or supplied by Kraton Polymers are subject to terms and conditions set out in the applicable contract, order acknowledgement and/or bill of lading. Kraton Polymers warrants only that its products will meet those specifications designated therein.
KRATON POLYMERS MAKES NO OTHER WARRANTY REGARDING ITS PRODUCT, EITHER EXPRESS OR IMPLIED, INCLUDING MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE; OR THAT THE USE OF SUCH INFORMATION OR KRATON POLYMERS PRODUCT WILL NOT INFRINGE ANY PATENT.

For further information:		**In Asia Pacific**	
USA Tel (toll free):	+1-800-4-Kraton (+1 800-457-2866)	Tel Japan	+81-3-3769-5990
USA Tel:	+1-281-504-4950	Hong Kong	+852-250-80-657
USA Fax:	+1-281-504-4953	Taiwan	+886-2-2545-1538
In Europe / Africa		China	+86-21-6289-6161
Europe Fax:	+44-(0)1244 405 949	South East Asia / India	+91-11-2923-0324
In South America		Australia	+61-41-937-5055
Fax:	+55-(0)19-3874-7275	Or contact your local Kraton Polymers Representative **Visit us at www.kraton.com** **Email info@kraton.com**	

Material Safety Data Sheet

acc. to OSHA and ANSI

Printing date 12/19/2007 Reviewed on 02/01/2007

1 Identification of substance:

Product details:

Product name: Polyvinyl alcohol, 98-99% hydrolyzed, high molecular weight

Stock number: 41243

Manufacturer/Supplier:
Alfa Aesar, A Johnson Matthey Company
Johnson Matthey Catalog Company, Inc.
30 Bond Street
Ward Hill, MA 01835-8099
Emergency Phone: (978) 521-6300
CHEMTREC: (800) 424-9300
Web Site: www.alfa.com

Information Department: Health, Safety and Environmental Department
Emergency information:
During normal hours the Health, Safety and Environmental Department.
After normal hours call Chemtrec at (800) 424-9300.

2 Composition/Data on components:

Chemical characterization:
Description: (CAS#)
Polyvinyl alcohol, 98-99% hydrolyzed, high molecular weight
(CAS# 9002-89-5), 100%

3 Hazards identification

Hazard description: Not applicable
Information pertaining to particular dangers for man and environment
Not applicable
Classification system
HMIS ratings (scale 0-4)
(Hazardous Materials Identification System)

HEALTH	0
FIRE	1
REACTIVITY	0

Health (acute effects) = 0
Flammability = 1
Reactivity = 0

4 First aid measures

After inhalation
Supply fresh air. If required, provide artificial respiration. Keep patient warm.
Seek immediate medical advice.
After skin contact
Immediately wash with water and soap and rinse thoroughly.
Seek immediate medical advice.
After eye contact
Rinse opened eye for several minutes under running water. Then consult a doctor.
After swallowing Seek medical treatment.

(Contd. on page 2)

Material Safety Data Sheet
acc. to OSHA and ANSI

Printing date 12/19/2007 Reviewed on 02/01/2007

Product name: Polyvinyl alcohol, 98-99% hydrolyzed, high molecular weight

(Contd. of page 1)

5 Fire fighting measures

Suitable extinguishing agents
Carbon dioxide, extinguishing powder or water spray. Fight larger fires with water spray or alcohol resistant foam.
Special hazards caused by the material, its products of combustion or resulting gases:
In case of fire, the following can be released:
Carbon monoxide (CO)
Protective equipment:
Wear self-contained respirator.
Wear fully protective impervious suit.

6 Accidental release measures

Person-related safety precautions:
Wear protective equipment. Keep unprotected persons away.
Ensure adequate ventilation
Measures for environmental protection:
Do not allow material to be released to the environment without proper governmental permits.
Measures for cleaning/collecting: Pick up mechanically.
Additional information:
See Section 7 for information on safe handling
See Section 8 for information on personal protection equipment.
See Section 13 for disposal information.

7 Handling and storage

Handling
Information for safe handling:
Keep container tightly sealed.
Store in cool, dry place in tightly closed containers.
No special precautions are necessary if used correctly.
Information about protection against explosions and fires:
Keep ignition sources away.
Protect from heat.

Storage
Requirements to be met by storerooms and receptacles:
No special requirements.
Information about storage in one common storage facility:
Store away from oxidizing agents.
Further information about storage conditions:
Keep container tightly sealed.
Store in cool, dry conditions in well sealed containers.

8 Exposure controls and personal protection

Additional information about design of technical systems:
Properly operating chemical fume hood designed for hazardous chemicals and having an average face velocity of at least 100 feet per minute.

Components with limit values that require monitoring at the workplace:
Not required.
Additional information: No data

(Contd. on page 3)

Material Safety Data Sheet
acc. to OSHA and ANSI

Printing date 12/19/2007 Reviewed on 02/01/2007

Product name: Polyvinyl alcohol, 98-99% hydrolyzed, high molecular weight

(Contd. of page 2)

Personal protective equipment
General protective and hygienic measures
The usual precautionary measures for handling chemicals should be followed.
Keep away from foodstuffs, beverages and feed.
Remove all soiled and contaminated clothing immediately.
Wash hands before breaks and at the end of work.
Breathing equipment:
Use suitable respirator when high concentrations are present.
Protection of hands: Impervious gloves
Eye protection: Safety glasses
Body protection: Protective work clothing.

9 Physical and chemical properties:

General Information	
Form:	Powder
Color:	White Cream colored
Odor:	Odorless
Change in condition	
Melting point/Melting range:	200°C (392°F) ((dec))
Boiling point/Boiling range:	Not determined
Sublimation temperature / start:	Not determined
Flash point:	79°C (174°F)
Flammability (solid, gaseous)	Product is not flammable.
Ignition temperature:	Not determined
Decomposition temperature:	Not determined
Danger of explosion:	The material is not explosive but the formation of explosive dust/air mixtures may be possible.
Explosion limits:	
Lower:	Not determined
Upper:	Not determined
Vapor pressure:	Not determined
Density at 20°C (68°F):	1.26 g/cm³
Solubility in / Miscibility with	
Water:	Partly soluble

10 Stability and reactivity

Thermal decomposition / conditions to be avoided:
Decomposition will not occur if used and stored according to specifications.
Materials to be avoided: Oxidizing agents
Dangerous reactions No dangerous reactions known
Dangerous products of decomposition: Carbon monoxide and carbon dioxide

(Contd. on page 4)

Material Safety Data Sheet
acc. to OSHA and ANSI

Printing date 12/19/2007 Reviewed on 02/01/2007

Product name: Polyvinyl alcohol, 98-99% hydrolyzed, high molecular weight

(Contd. of page 3)

11 Toxicological information

Acute toxicity:

LD/LC50 values that are relevant for classification:		
Oral	LD50	18750 mg/kg (gpg) 14270 mg/kg (mus) 23854 mg/kg (rat)

Primary irritant effect:
on the skin: May cause irritation
on the eye: May cause irritation
Sensitization: No sensitizing effects known.
Other information (about experimental toxicology):
Tumorigenic effects have been observed on tests with laboratory animals.
Carcinogenic effects have been observed on tests with laboratory animals.
Subacute to chronic toxicity:
Effects in experimental animals via subcutaneous route include anemia, hypertension, vascular lesions, hypertrophy of the heart and kidneys, renal pathology and increased thyroid weight.
Additional toxicological information:
To the best of our knowledge the acute and chronic toxicity of this substance is not fully known.
IARC-3: Not classifiable as to carcinogenicity to humans.
The Registry of Toxic Effects of Chemical Substances (RTECS) contains tumorigenic and/or carcinogenic and/or neoplastic data for components in this product.

12 Ecological information:

General notes:
Do not allow undiluted product or large quantities of it to reach ground water, water course or sewage system.
Do not allow material to be released to the environment without proper governmental permits.

13 Disposal considerations

Product:
Recommendation
Consult state, local or national regulations to ensure proper disposal.

Uncleaned packagings:
Recommendation: Disposal must be made according to official regulations.

14 Transport information

Not a hazardous material for transportation.

DOT regulations:
Hazard class: None

Land transport ADR/RID (cross-border)
ADR/RID class: None

Maritime transport IMDG:
IMDG Class: None

(Contd. on page 5)

Appendix B

Pump and Motor Datasheets

Blue-White® Industries, Ltd.

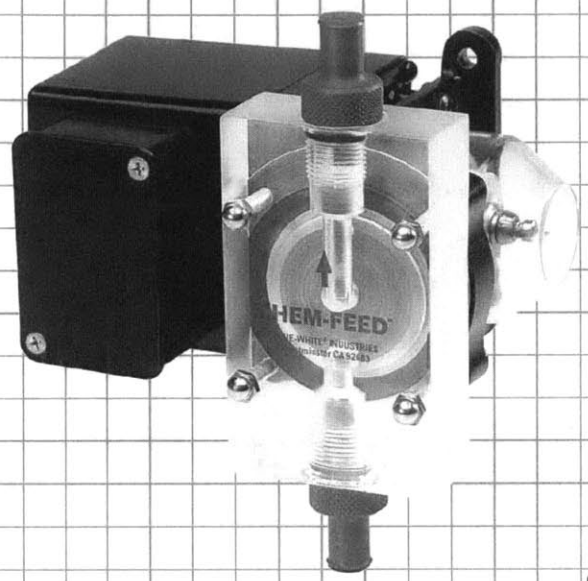
CHEM-FEED® Diaphragm Metering Pumps

Engineering and Technical Data

C-600HV

Fixed Speed

Mechanical Cam Output Adjustment



Features:

- All ball bearing, permanently lubricated gear motor for smooth, quiet, powerful operation.
- Solid, clear acrylic pump head with large high-output diaphragm.
- EP diaphragm.
- Outputs to 791 GPD.
- Output pressures to 20 PSI.
- Stroke adjustment from 4-100% permits accurate small injections at a high rate per minute. 27:1 turndown
- Durable metal epoxy coated construction.
- PVC suction strainer with removable polypropylene filter screen.
- Includes 1/2" ID clear PVC suction and discharge tubing, PVC Injection fitting and all mounting hardware.

Specifications:

Max. working pressure: .....20 psig (1.4 bar)
Max. fluid temperature: .....130° F (54° C)
Max. ambient temperature: ..14° to 110° F/ -10° to 43° C
Maximum viscosity: .....1,000 Centipoise
Maximum suction lift: .....10 ft. Water 0 psig
Output adjustment range: ....4-100% stroke length
Duty cycle:.....Continuous
Enclosure: .....NEMA type 1, (IP20)

Voltage (amp draw): .....115VAC/60Hz, 1ph (.74 amp max)
230VAC/60Hz, 1ph (.36 amp max)
220VAC/50Hz, 1ph (.31 amp max)
24VAC/60Hz, 1ph (3.40 amp max)
12VDC (3.00 amp max)
24VDC (1.50 amp max)
Power Connection: .....Junction box for field wiring
Approximate shipping wt: ...8 lb. (3.6 kg)

Materials of Construction:

Wetted components:

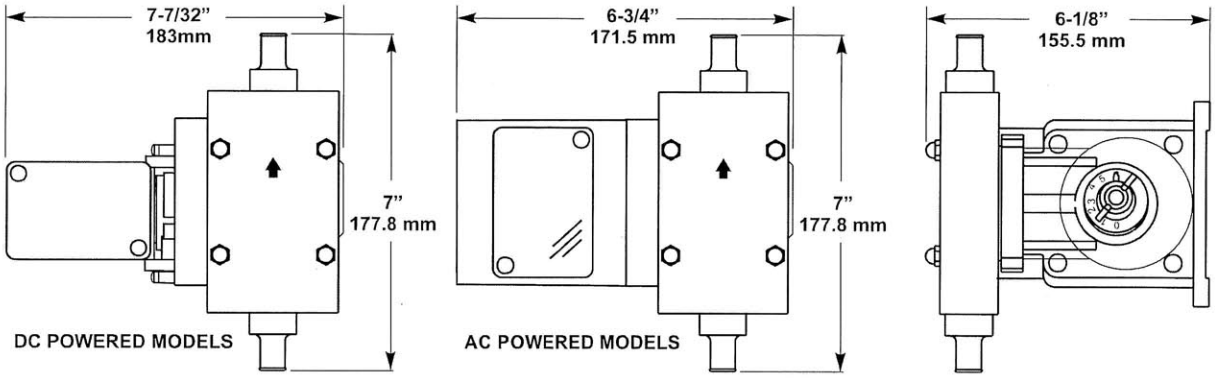
Pump Head:.....Acrylic (optional Teflon)
Pump Head Inlet/outlet Valves:
Tube adapters: .....PVC
Valve Poppit: .....EP (optional Viton)
Adapter O-ring: .....EP (optional Viton)
Poppit spring:.....Hastelloy C-276

Suction Tubing:.....Clear PVC
Discharge Tubing:.....Clear PVC
Suction Strainer:
Body & Tubing adapter:.....PVC
Strainer: .....Polypropylene
Injection Fitting: .....PVC

Blue-White Industries, Ltd.

CHEM-FEED® Diaphragm Metering Pumps

Dimensions:



Model Number Matrix:

MODEL C-6 [ ] [HV] - [ ]

Maximum Motor RPM
60 = 60 RPM
125 = 125 RPM
250 = 250 RPM

Pump Head / Wet Parts
P = Heavy duty cartridge style polypropylene head
HV = High volume output acrylic head

Power Supply Voltage
115VAC = 115V60Hz
220VAC = 220V50Hz (20% less output)
230VAC = 230V60Hz
24VAC = 24V60Hz
12VDC = 12V DC
24VDC = 24V DC

Flow rate and pressure capacities:

AC powered models:

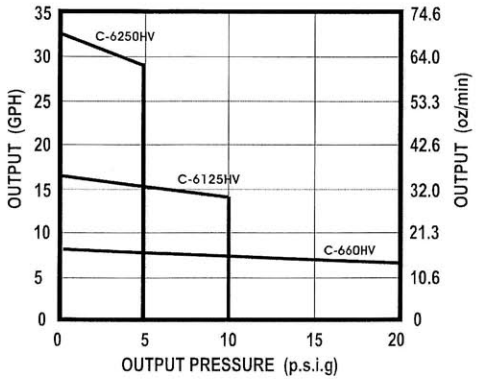
Max Output at 0 PSI				Strokes	Max	115V/60Hz	230V/60Hz	220V/50Hz*
GPD	GPH	LPH	OZ/MIN	Per minute	PSI	Model Number	Model Number	Model Number
189	7.8	29.5	16.8	60	20	C-660HV-115VAC	C-660HV-230VAC	C-660HV-220VAC
398	16.5	32.4	35.3	125	10	C-6125HV-115VAC	C-6125HV-230VAC	C-6125HV-220VAC
791	32.9	124.5	70.3	250	5	C-6250HV-115VAC	C-6250HV-230VAC	C-6250HV-220VAC

*** Note: 220V/50Hz models deliver approximately 20% less output.**

DC powered models:

Max Output at 0 PSI				Strokes	Max	12V DC	24V DC
GPD	GPH	LPH	OZ/MIN	Per minute	PSI	Model Number	Model Number
268	11.2	42.4	23.8	60	20	C-660HV-12VDC	C-660HV-24VDC
568	23.7	89.7	50.5	125	10	C-6125HV-12VDC	C-6125HV-24VDC
1,129	47.1	178.3	100.4	250	5	C-6250HV-12VDC	C-6250HV-24VDC

Maximum Output vs. Pressure Curve



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Technical data sheet #85000-056 rev.092205

PittmanExpress™

GM8712-11

Lo-Cog® DC Gearmotor

Assembly Data	Symbol	Units	Value	
Reference Voltage	E	V	19.1	
No-Load Speed	S_{NL}	rpm (rad/s)	1,227	(128)
Continuous Torque (Max.)[1]	T_C	oz-in (N-m)	6.0	(4.2E-02)
Peak Torque (Stall)[2]	T_{PK}	oz-in (N-m)	26	(1.8E-01)
Weight	W_M	oz (g)	6.8	(194)
Motor Data				
Torque Constant	K_T	oz-in/A (N-m/A)	3.06	(2.16E-02)
Back-EMF Constant	K_E	V/krpm (V/rad/s)	2.27	(2.16E-02)
Resistance	R_T	Ω	10.8	
Inductance	L	mH	5.40	
No-Load Current	I_{NL}	A	0.14	
Peak Current (Stall)[2]	I_P	A	1.76	
Motor Constant	K_M	oz-in/√W (N-m/√W)	0.93	(6.57E-03)
Friction Torque	T_F	oz-in (N-m)	0.35	(2.5E-03)
Rotor Inertia	J_M	oz-in-s^2 (kg-m^2)	1.3E-04	(9.2E-07)
Electrical Time Constant	τ_E	ms	0.50	
Mechanical Time Constant	τ_M	ms	21.5	
Viscous Damping	D	oz-in/krpm (N-m-s)	0.009	(5.9E-07)
Damping Constant	K_D	oz-in/krpm (N-m-s)	0.64	(4.3E-05)
Maximum Winding Temperature	θ_{MAX}	°F (°C)	311	(155)
Thermal Impedance	R_{TH}	°F/watt (°C/watt)	75.9	(24.4)
Thermal Time Constant	τ_{TH}	min	7.8	
Gearbox Data				
Reduction Ratio			6.3	
Efficiency			0.81	
Maximum Allowable Torque		oz-in (N-m)	100	(0.71)
Encoder Data				

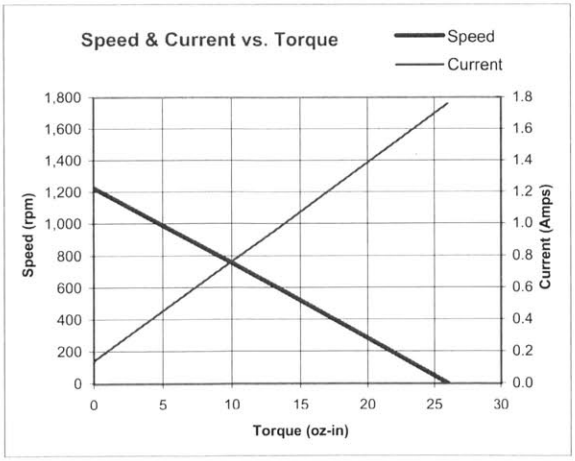
1 - Specified at max. winding temperature at 25°C ambient without heat sink. 2 - Theoretical values supplied for reference only.

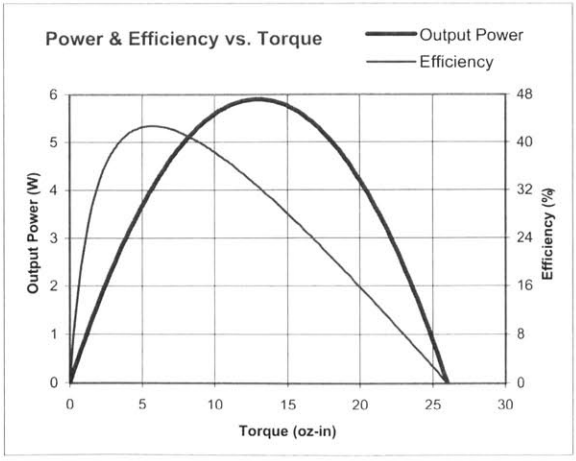
Included Features

2-Pole Stator
Ceramic Magnets
Heavy-Guage Steel Housing
7-Slot Armature
Silicon Steel Laminations
Stainless Steel Shaft
Copper-Graphite Brushes
Diamond Turned Commutator
Motor Sleeve Bearings
Output Sleeve Bearing
Standard Gears

Customization Options

Alternate Winding
Sleeve or Ball Bearings
Modified Output Shaft
Custom Cable Assembly
Special Brushes
EMI/RFI Suppression
Alternate Gear Material
Special Lubricant
Optional Encoder
Fail-Safe Brake

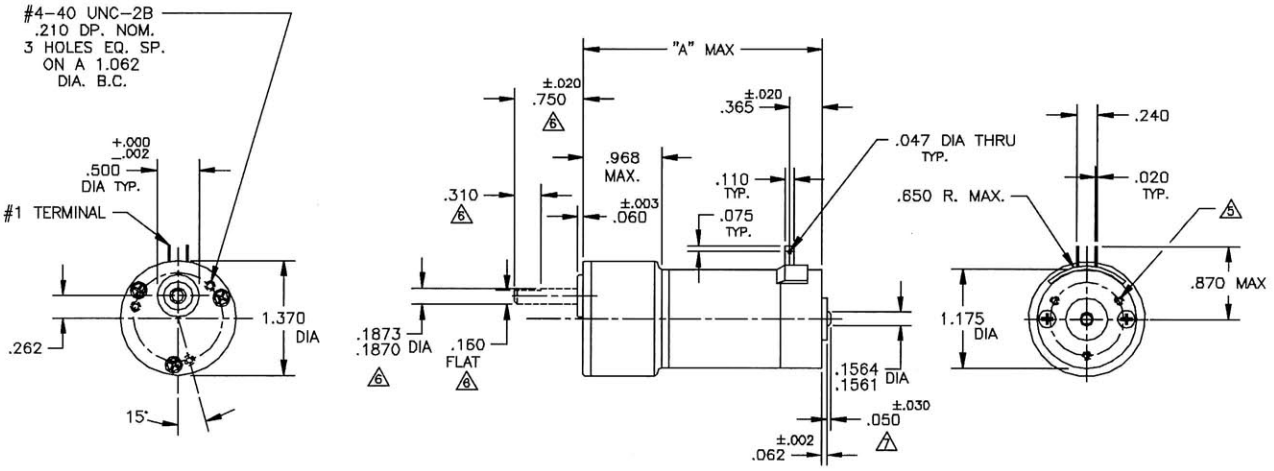




All values are nominal. Specifications subject to change without notice. Graphs are shown for reference only.

PITTMAN, 343 Godshall Drive, Harleysville, PA 19438, Phone: 877-PITTMAN, Fax: 215-256-1338, E-mail: info@pittmannet.com, Web Site: www.pittmannet.com

REVISIONS				
LTR	DESCRIPTION	DRFT/ENGR	DATE	APPR
H	REDRAWN, UPDATED TO CURRENT STD.	DLF	6/28/94	JVM
J	UPDATED TO CURRENT STD.	RJS/RJS		



NOTES:

1. SHAFT ROTATION IS SHOWN WHILE VIEWING MOUNTING END, WITH POSITIVE (+) VOLTAGE APPLIED TO # 1 TERMINAL.
2. TERMINALS ARE PLATED FOR SOLDERING.
3. MAX. GEARBOX TORQUE RATING IS 100 OZ.IN., STANDARD SINTERED GEARS. MAX. GEARBOX TORQUE RATING IS 160 OZ.IN., CUT STEEL GEARS.
4. ENDPLAY .020 MAX. ON OUTPUT SHAFT, .015 MAX. ON MOTOR SHAFT.
5. OPTIONAL MOUNTING PATTERN #2-56 UNC-2B, (3) HOLES EQUALLY SPACED ON A .875 DIA. B.C., .125 MAX. THREAD DEPTH.
6. ALL SHAFT DIMENSIONS SHOWN ARE STD. (10-385). FOR ALL OTHER CONFIGURATIONS REFER TO DATA SHEET FOR PART NUMBERS.
7. OPTIONAL REAR SHAFT EXTENSIONS AVAILABLE.

GEAR RATIO	DIRECTION
187/96:1	CCW
60.5/31:1	CW
19.5/10:1	CCW
6.3:1	CW

3.285	GM87X4
3.035	GM87X3
2.910	GM87X2
"A" MAX.	MODEL NO.

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES ARE:
FRACTION ±1/64 DECIMAL X ±.015 XX ±.010 XXX±.005 ANGLES ±1°
BREAK ALL SHARP EDGES

MATERIAL:

FINISH:

FILE: 150/28

DRAFTED BY	DLF	DATE 6/24/94
ENGINEERED BY	DLF	6/24/94
APPROVED BY	JVM	6/28/94

NEXT ASSY:

USED ON:

PITTMAN

TITLE: OUTLINE & MOUNTING DIMENSIONS GM87XX STD. GEARBOX

DWG. NO. B- 150-28 REV. J

SCALE: D.N.S. SHEET 1 OF 1

Appendix C

Matlab functions

```
function yGram = GramTPR(xml)
%this function takes as input the vol of oil in the beaker
%and determines the TPR needed via weight in pounds

Xgallon = xml*0.000264172052;%convert from ml to gallon
xPound = 7.14*Xgallon; %convert to pounds of oil
yPound = 0.05*xPound;%pounds of TPR needed -> 5% of pounds of oil in beaker
yGram = yPound*453.59237; %convert to grams of TPR needed
```

Chapter 8

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