Lighter Than Air:
Why Do Balloons Float?

(Randy Landsberg, Bill Fisher & Dan Robertson)

INTRODUCTION

We are all familiar with balloons. They are a common sight at birthday parties and other fun events. But there is much more to balloons then just that. Coming in a range of shapes and sizes, balloons have vital applications in all walks of life, from flying machines to planetary exploration, medicine to meteorology; we use balloons for more things then meets the eye.

Source: Robert Friedman

But what makes some balloons float, while others do not? In this lab we will investigate the phenomena of buoyancy, and examine the relationship of buoyancy to floating objects. We will explore what a lazy afternoon floating in the pool has in common with a hot air balloon. Some questions that we will tackle include:

- ? We are all familiar with the idea of floating on water, but why do things that float in water not float in air?
- ? How does the density of an object determine what it will float in?
- ? How can we take advantage of floating to do science?

To answer these questions, this investigation will have three parts. In Parts I and II, we will investigate the effects of heat on density and floating. In Part III we will explore the use of helium for floating.

BACKGROUND

Why does a rock sink when thrown into a lake but a piece of Styrofoam floats?
Why do hot air and helium balloons rise?
What does this have to do with Archimedes?

Floating in air is not a common experience for humans but floating in water, or at least seeing things float in water, is. The physics of floating in both air and water is similar because both air and water behave in similar ways - both are fluids. *A fluid is a substance that flows and conforms to the shape of a container that holds it* (for example, if you pour water, a fluid, into a bucket, the water will take the shape of the bucket, but if you put a rock into a bucket the rock stays the same shape).

When do things float in fluids? What is going on that makes floating happen? **Something will float in a fluid when the force from the fluid pushing up is greater than the force pulling down.** Generally things float when they are less dense than the fluid by which they are surrounded.

The downward force an object feels (F_g) is from gravity, and is equal to the weight of the object. [Technically F_g depends on the mass (m) of the object and the local gravitational force (g) pulling on that mass, but g is essentially constant on the earth.] The downward force depends on how much 'stuff' there is in the object. A kilogram of rock and a kilogram of Styrofoam feel the same downward force, even though one is much denser and smaller then the other. Two kilograms of anything feels twice the downward force as one kilogram of anything. We can express the downward force on an object as:

Downward force = F_g = mass of object (m) x gravitational strength (g) = weight of object

The buoyant force pushing up (F_b) is determined by how much fluid the object displaces. The amount of displacement depends on the object's volume. A bigger object displaces more fluid. Think about taking a bath. What happens to the water level when just your foot is in the tub compared to when you sit in the bath? The buoyant force (F_b) depends on the weight of the fluid displaced by the object. In other words, the volume of fluid that has been pushed aside by the object pushes up with a force that is equal to how hard gravity pulls the fluid down.

Upward force = F_b = mass of fluid displaced (m) x g = weight of fluid displaced

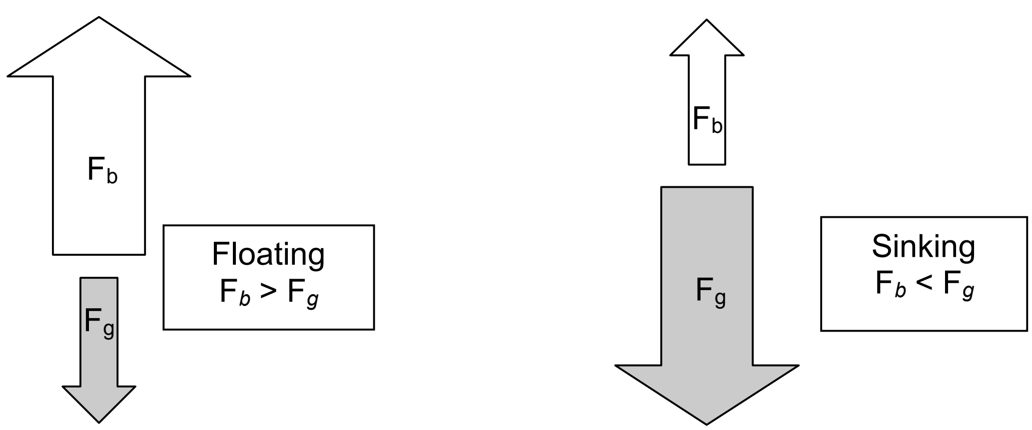
ARCHIMEDES' PRINCIPLE

When a body is fully or partially submerged in a fluid, a buoyant force F_b from the surrounding fluid acts on the body. The force is directed upwards has a magnitude equal to the weight, m x g, of the fluid that has been displaced by the body (Fundamentals of Physics 6th ed, Halliday, Resnick & Walker p. 330)

Net lift is equal to the upward buoyant force minus the downward gravitational force:

$$\textbf{Lift} = F_b - F_g$$

So, just by comparing the upward and downward forces, you can tell if something will be buoyant. That is, **if F_b is bigger than F_g, then the object will float.**



Buoyancy Example: Under Water Soda Bottle Balloon

(from http://www.howstuffworks.com/helium.htm/printable)

Let's say that you take an empty plastic 1-liter soda bottle, sealed tightly. Tie a string around it like you would a balloon, and still holding it, dive to the bottom of a swimming pool. Since the bottle is full of air, you can imagine it will want to rise to the surface. If you sit on the bottom of the pool holding the string, it will act just like a helium balloon in air. If you let go of the string the bottle will quickly rise to the surface of the water.

This soda bottle "balloon" wants to rise in water because water is a fluid, and the 1-liter bottle is **displacing** one liter of that fluid. The bottle and the air in it weigh very little (1 liter of air weighs about a gram, and the bottle is very light as well). However the liter of water it displaces weights about 1,000 grams (2.2 pounds or so). Because the combined weight of the bottle and air is less than the weight of the water it displaces, the bottle floats. This behavior is the law of **buoyancy**.






Buoyancy Example: Helium Flotation

(from http://www.howstuffworks.com/helium.htm/printable)

Helium balloons also work by the law of **buoyancy**. In this case, the helium balloon that you have is floating in a "pool" of air (in a swimming pool you are standing in a "pool of water" perhaps 10 feet deep - in an open field you are at the bottom of a "pool of air" that is many miles deep). The helium balloon displaces an amount of air (just like the empty bottle displaces an amount of water). As long as the weight of the helium plus the balloon fabric is lighter than the air it displaces, the balloon will float in the air.

It turns out that helium is a lot lighter than air. Though the difference is not as great as that between water and air (a liter of water weighs about 1,000 grams, while a liter of air weighs about 1 gram), it is still significant. **Helium weighs 0.1785 grams per liter**. Nitrogen weighs 1.2506 grams per liter. As nitrogen makes up about 80 percent of the air we breathe, 1.25 grams is a good approximation for the weight of a liter of air.

Therefore, if you were to fill a 1-liter soda bottle full of helium, the bottle would weigh about 1 gram less than the same bottle filled with air. That doesn't sound like much, but in large volumes the 1-gram-per-liter difference between air and helium really adds up. That is why blimps and balloons are generally quite large - they have to displace a lot of air to float!

PART I: HOT AIR AND DENSITY, OR, CAN GARBAGE BAGS FLY?

In this part of the lab we will investigate what happens when air is heated, and how this can make things float.

Record your ideas!

In your lab notebook, describe what you think happens to air when it is heated.
What changes?
What might one observe?

Solar Bag

In this outdoor activity we will use sunlight to heat the air inside a "solar bag". A solar bag is essentially a super-sized plastic bag that is 50 feet long.

Materials: Solar Bag, strong string, & sunshine

Record your data!

Step 1 – fill the bag with air – this is a challenge for the group
Step 2 – seal the bag & connect a tether, a long line of string
Step 3 – place the bag in sunlight and observe what happens
Step 4 – *Record you observations in your lab notebook*
Step 5 – *Try to explain what happened*

Demonstration: What happens when air is heated?

(The instructor will perform this demonstration. Your job is to observe and record what happens.) The solar bag provided an example of what can happen when air is heated. In this demonstration we will explore in more detail what happens to air when it is heated up.

Materials: Erlenmeyer flask, stopper, stopper w/ hole, tubing, beaker, thermometer, hot plate & balance

Does heating air make it heavier?
Does heating air change its volume?
Does heating air change its density?

(If you were at YWI 2005, think about the kinetic theory of gases lab)

Record your observations!

In your lab notebook, sketch a picture of both parts of the demonstration. Describe what was done in each part and what conclusions the group made about the effect of heating air on its mass and its volume.

- ? What can you conclude about the density of hot air vs. cool air?
- ? What can you say about the volume & density of the air inside the solar bag before and after it was in the sunshine?
- ? Can you relate this behavior to Archimedes principle?

Record your conclusions!

PART II: BUILDING PAPER BALLOONS

Earlier in the week, if the weather cooperated, you witnessed the launch of a modern hot air balloon. In this portion of this lab we will build our own hot air balloons out of paper. As odd as a paper balloon may sound, it is actually similar to some of the very first hot air balloons ever launched (see sidebar).

> **THE FIRST BALLOON FLIGHT**
>
> The first recorded manned flight of a hot air balloon took place in Paris on November 21, 1783. The balloon, made of paper and silk , was designed by Joseph and Etienne Montgolfier, brothers whose family owned a famous paper company. The flight of "Seraphina" lasted about twenty minutes, reached a height of about 500 feet, and landed a few miles outside of Paris.

Though our paper balloons will be a bit smaller than both modern and historic hot air balloons, they will operate on the same principles. The key is to fill the balloons with something lighter, or more properly less dense, than the surrounding air. We are so accustomed to swimming in air we forget that it is made of atoms and molecules (mostly nitrogen molecules, N_2), that have mass. This fact means that when the air molecules are displaced by an object, they push back with a buoyant force equal to the mass of the volume air pushed aside.

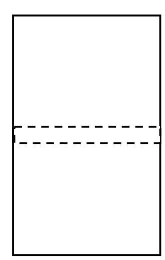
Materials:

- 12 small sheets thin tissue paper
- Glue
- Stapler and staples
- Rulers
- Wire
- Newspaper
- Scissors
- Section patterns
- Heat source (e.g. camping stove)

Source: wikipedia.com

Record your ideas!

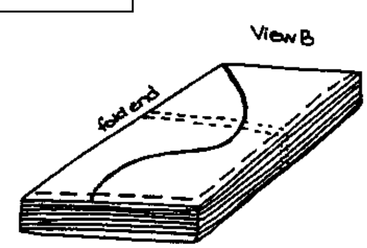
Questions to discuss with your group:
What do you think is important in designing and making a good hot air balloon? Are there things to avoid? Why?



Construction Instructions:

1. Join sheets together on short edge, overlap edges 1cm and glue (use as little glue as possible). Run a thin continuous line and allow glue to dry before you go on. Sheets need to be ~47x51cm

2. Fold the sheets lengthwise, and then stack one on top of the other. Make certain that all the folded edges line up evenly.

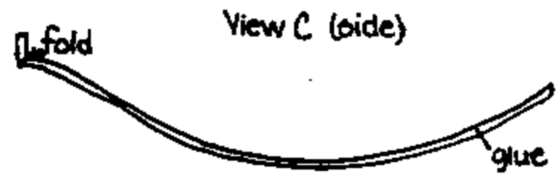


3. Making sure they stay aligned, staple the stacked sheets together along

the three unfolded edges (see view B)
4. Place pattern on top and trace on with a magic marker.

5. Carefully cut out the pattern with sharp scissors.

6. Lay out one of the folded sections on a sheet of newspaper. Run a thin continuous line of glue about 1 cm from the right hand side (see View C).

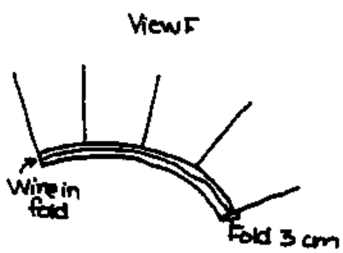


7. Place another folded section on top of the first (View D)

8. Repeat and continue until all six sections are glued together. Put newspaper between the folds to keep them from sticking together.

9. When completely dry, carefully remove the newspaper. Run a line of glue on one of the last edges. Connect that edge with the other free edge. (see View E).

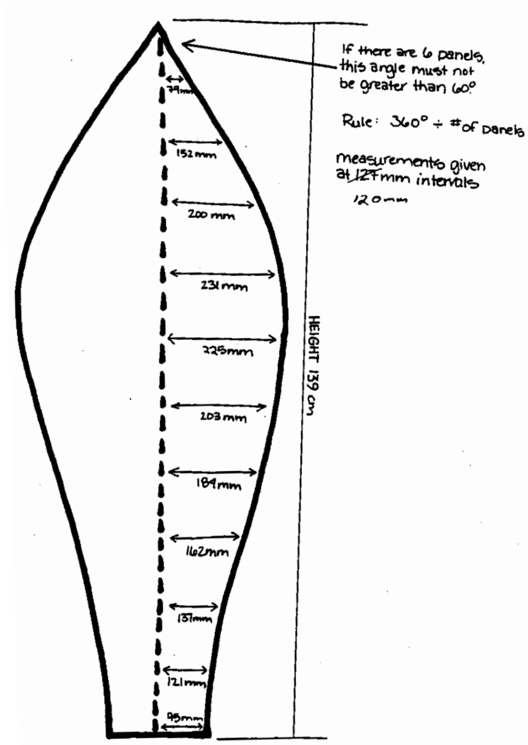
10. Measure the circumference of the bottom opening. Cut a piece of wire 5 cm longer and bend it into a circle the size of the opening and twist the overlap



11. Fold up the bottom 3 cm of the balloon. Place the wire inside the fold, and glue the fold over the wire. (View F)

12. Reinforce the top of the balloon by gluing a 10 cm (diameter) circle on the top.

13. Repair any breaks or tears with patches of tissue paper and glue.



Getting to Launch:
Once the balloons are assembled, weigh each balloon and record the weights.

Then, carefully carry the balloons one at a time to the launch pad.

Time each flight and try to gauge how high the balloons fly.

Record & discuss your observations of the launches:

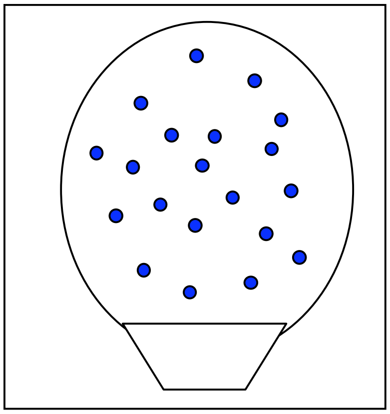
- successful or not
- duration of the flight
- approximate maximum height

Record your results!

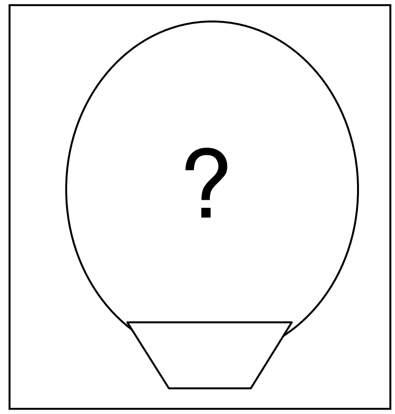
- other observations

Thinking About It…

The picture below on the left is of a hot air balloon, with greatly oversized air molecules, before heating. Using the same idea of oversized air molecules, **sketch in your lab notebook** what a similar air balloon would look like after heating.



Before heating



After heating

How Does It Compare?

Compare your balloon to a typical modern hot air balloon.

? How many times bigger do you think a modern hot air balloon is compared to yours?

DO THE CONVERSION

Cubic feet to liters:
28.317 liters/cubic foot

Liters to cubic feet

MODERN HOT AIR BALLOONS

Typical Height: 80’ tall

Typical Girth: 50’ across

Typical Inflated Volume: 78,000 cubic feet (or about 2,200,000 liters)

Typical Weight of Air Contained: 2 ½ tons (or about 2,270 kg)

The world’s record for altitude in a hot air balloon is 64,997 feet.

The baskets that hang from hot air balloons are all made by hand.

Photo credit: wikipedia.com

PART III: SCALING UP FROM PARTY BALLONS TO SCIENTIFIC PAYLOADS

Record your ideas!

How many helium filled balloons do you think it would take:

- ? *To lift you?*
- ? *To lift as much as a modern hot air balloon?*
- ? *To lift a big telescope?*

Take a guess for each question and record your guesses in your lab notebook.

In this part of the lab we will explore how good your guesses were, and how scientists determine the right size balloon to use for their experiments.

Introduction:

Helium filled balloons are commonly seen at festivities and celebrations. In addition to being used for entertainment purposes, helium filled balloons play an important role in many areas of scientific research. For example, "small" six to eight foot diameter weather balloons are frequently launched to acquire many different types of metrological data. At the South Pole, balloons are launched to monitor the amount of ozone in the atmosphere (see photo). These balloons provide information that other methods such as satellite remote sensing cannot, e.g., the amount of ozone at specific altitudes.

The beauty of a helium balloon as a launch vehicle is that it is simple, has no moving parts, and is relatively inexpensive. They can also go places where humans might not want to. Typical weather balloons contain a small radio transmitter, which is used to send the data back to the researchers.

Much bigger helium balloons are used for larger research projects. Researchers at the University of Chicago use simple balloons for some of the most sophisticated experiments in modern physics. For example, Professor Stephan Meyer flew a telescope named TopHat over Antarctica in the austral summer of 2000-2001. This telescope was designed to look at light from the infant universe, microwave photons that had traveled for about 14 billion years and hold physics secrets of the early universe. As the name suggests, the TopHat telescope sat on top of the balloon rather than hanging underneath it. The reason for this funny geometry is that the experiment was so sensitive that the thin fabric of the balloon itself would have gotten in the way, making it an unwanted source of error (the small balloon in the photo was detached after launch). This summer, Professor Dietrich Muller flew a cosmic ray detector experiment called TRACER (Transition Radiation Array for Cosmic Energetic Radiation) in the Arctic over Sweden.

Supplies/Resources:

- 11 inch Diameter Latex Balloons
- Helium Tank with Low Pressure Regulator (ask an instructor for help using this)
- String
- Paper Clips (many)
- Balance
- Set of Metric Masses (10gm, 20gm, 100gm, 200gm, 500gm, 1,000gm)

Experimental & Computational Challenges:

 # 1 - The Power of Averages Part I (paper clip)

- Determine the weight of one (1) paper clip
- Weigh ten different paper clips, one paper clip at a time, determine the average weight
- Weigh ten paper clips and determine the average weight by dividing by 10
- Compare your results to other groups & estimate the error in the weight

In your lab notebook, make the following data tables and fill them in:

Trial	**Weight One paper clip (g)**
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
Average	

Record your data!

Group	**Weight 10 paper clips (g)**	**Weight one paper clip (g)**
Average		

 # 2 - Determine how much mass one balloon can lift.

- Describe the method that your group develops – be sure to account for everything!
- Compare your results to those of the other groups.

 # 3 - Determine how much mass 2 balloons can lift.

• Describe the method that your group develops.
• Compare your results to those of the other teams.

 # 4 - Determine how much mass 10 balloons can lift.

• Describe the method that your group develops.
• Compare your results to those of the other teams.

 # 5 - The Power of Averages Part II (balloon lift)

- Pool the class data to determine the lift in terms of number of paper clips for:
- One balloon
- Two Balloons
- Ten Balloons
- In each case calculate the lift of one (1) balloon based on the average.

In your lab notebook, make the following data tables and fill them in:

Group	Lift 1 balloon (#paper clips)	Lift 1 balloon (g)
Average		

Group	Lift 2 balloons (#paper clips)	Lift 2 balloons (g)
Average		

Group	Lift 10 balloon (#paper clips)	Lift 10 balloons (g)
Average		

 # 6 - Calculate and then test how many balloons are needed to lift a 20 gram mass.

(Share balloons with other groups for the test)

• Compare your calculation to the experimental results

7 - **Based on your previous results, calculate how many balloons would be needed to lift yourself.** (Note: there are about 2.2 kg in a pound)

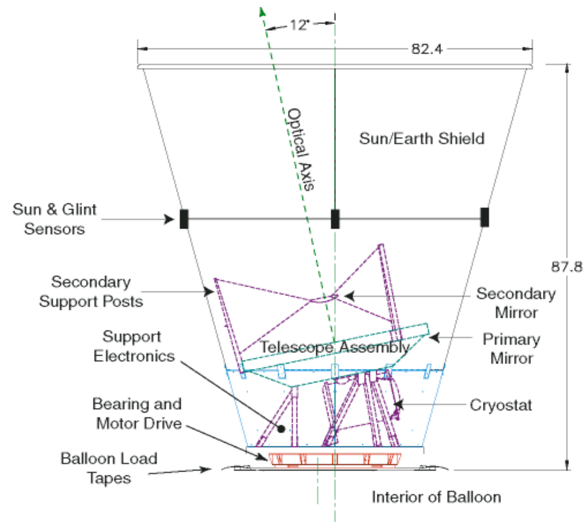
- Show all calculations in your lab notebook.
- Describe you calculation and any assumptions made.
- Compare this answer to your guess at the start of the lab.

 # 8 - Based on the description of the TopHat telescope below, calculate how many helium filled party balloons would be needed to lift the TopHat telescope.

- Describe your calculation & record it in your lab notebook.
- Compare your results to your initial guess.

TOPHAT TELESCOPE

Balloon volume: 56,800 ft^3 at sea level
Balloon volume: 28.4 million ft^3 at float
(at float altitude: $^1/_{500}$ pressure of sea level)
Inflated Height: 335 ft.
Inflated Diameter: 424 ft.
Balloon Weight: 3,600 lbs.
Float Altitude: 118,000 to 130,000 ft.
Top Package Weight: 200 lbs.
Bottom Gondola Weight: 1,500 lbs.
Free Lift: about 10%



 # 9 - Compare the number of balloons that you calculated were needed to lift TopHat and the actual volume of helium used for the TopHat balloon.

- Show your comparison calculation.
- Comment on the difference between sea level and float volumes.
- Calculate the buoyant force (F_b) on the TopHat balloon

HELIUM VOLUMES

TopHat held
56,800 cubic feet at sea level 28.4 million cubic feet at float.

An 11-inch diameter balloon holds between 0.4 and 0.5 cubic feet of helium at sea level.

Record your results!

(Useful info: there are about 28.3 liters/cubic foot and air weighs about 1.25 grams/liter (at sea level and ambient temperature).)

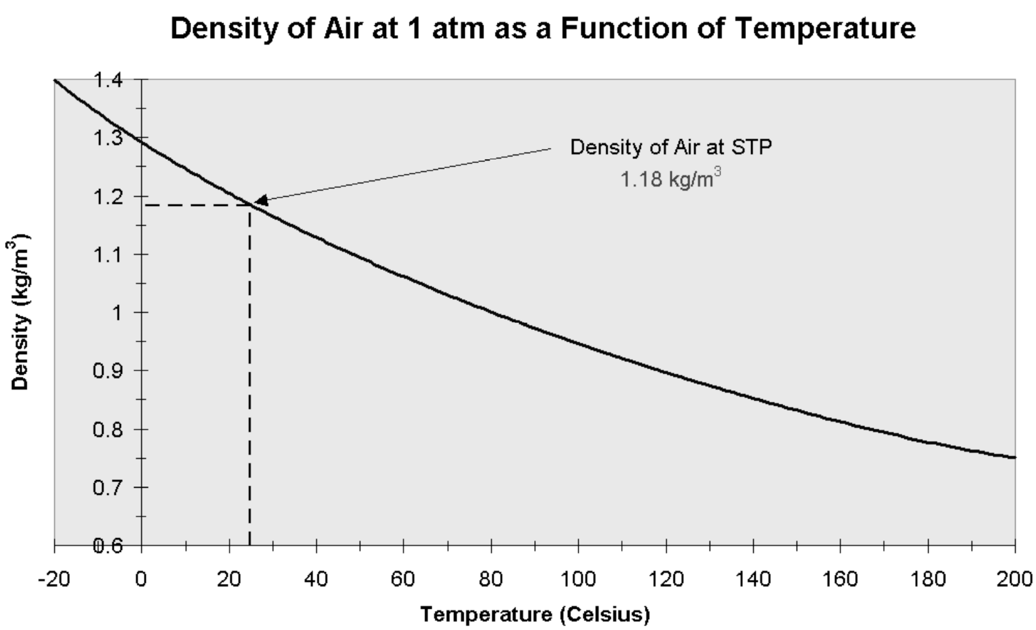
 # 10 – Determine how much all the balloons in the lab can lift

- Count all the inflated balloons for the entire group.
- Calculate how much they can lift (show your calculations in your lab notebook).
- Test your prediction.

IN CONCLUSION…

Well, now you should be experts in getting things to float in the air! We have used a couple different techniques for ensuring floatation, and with each method employed key concepts that come up in other labs as well. **In your lab notebook, write a short paragraph summarizing what you did in this lab and what you learned about floating in air.**

APPENDIX: USEFUL INFORMATION



(Source:http://www.ce.utexas.edu/prof/kinnas/319LAB/Book/CH1/PROPS/GIFS/densair.gif)

Standard Temperature and Pressure: 20 °C and 760 mm Mercury

- Weight of air per liter at STP = 1.20 g/l
- Weight of helium per liter at STP = 0.18 g/l
- Net lift per liter of helium at STP = 1.03 g/l

A typical balloon should provide from 4 to 5 mm of overpressure and reduce lift to .9935 of these figures.

VOLUMES

- Sphere: $(^4/_3)\,\pi\, r^3$
- Cylinder: $\pi\, r^2\, h$