

The Forces and Pressures of Balloon Flight

by William G. Phillips

Did you ever wonder what the forces inside of your balloon were like? Sure, we all know that hot air rises and if you capture hot air in bag, the bag goes up with it. People talk about pressures, forces, loads, strength of materials, etc. but on a detailed level, what really is happening to make your balloon fly? If balloons have pressure in them, then why don't they deflate themselves like a small rubber blow-up balloon? Since we don't tie off our balloon throats why doesn't the high pressure air escape?

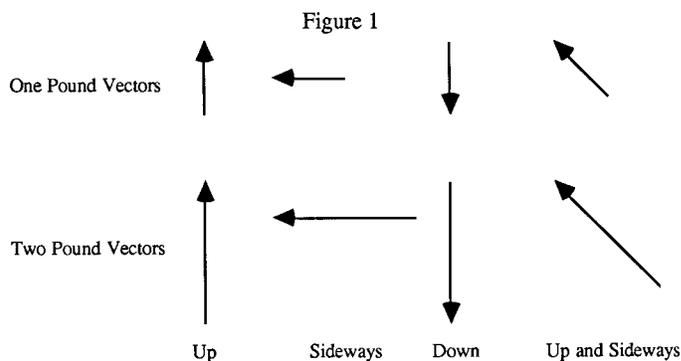
It's sort of obvious that there's pressure in a hot air balloon. Just pull on the vent and feel the resistance. If you pack more people into the gondola and a few more bottles of champagne, the vent is harder to work! That means that the pressure went up. The higher pressure applies higher force on the vent to keep it sealed. This pressure in the balloon can't be distributed uniformly over the entire envelope. If it were, there would be a pressure differential between the throat and the atmosphere. In that case all of the air would come roaring out of the throat and deflate the balloon. An additional clue to the nonuniformity in pressure can be gleaned from the flight manual. You're allowed good sized tears near the throat but only tiny ones above the equator. That's because the loss of hot air is greater for the same sized hole the higher you go in the balloon.

A Few Definitions

If we're going to talk about pressure we all need to agree on *how* we talk about it. Pressure is the measure of force exerted on a given area. If I apply a *force* of 10 pounds uniformly over a square foot of cloth, then we say the *pressure* is 10 pounds per square foot. If I distribute the same force over 2 square feet then we could say we have a pressure of 10 pounds on 2 square feet or simply 5 pounds per square foot. So pressure is the force exerted on something divided by the area of that something, i.e. force per unit area.

Well, all that is nice but what is *force*? Everyone probably thinks that they already know what force is, and maybe they do, but we should define a couple of things anyway. If you hold onto a bottle of champagne it applies a force to your hand of a couple pounds-toward the earth. If you strap a bunch of helium-filled balloons to your wrist you might get 2 pounds force again but-toward the sky. So when we talk about force, we always

need to talk about direction too! We conveniently do this on paper by drawing arrows (called vectors). (Figure 1) When we draw these arrows their length represents the amount of their magnitude. Their direction, of course, represents their direction. For example a 2-pound upward force is drawn twice as long as a 1-pound upward force, a 3-pound force 3 times longer, and so on.



Only one more concept and we can get back to balloon talk. This concerns the up and sideways vector. If I pull a kid's wagon with an up and sideways force, I can accomplish the same thing by making 2 separate forces at 90 degrees to each other which are equivalent. (Figure 2)

In the second part of the picture I have reduced the up and sideways force to 2 equivalent forces called components and the kid in the wagon will never know the difference. Any force can be replaced by substituting other equivalent forces for it. This is a powerful concept because it allows us to really see along which directions these forces are pushing things. Now, since pressure is force per unit area and force has two intrinsic attributes, i.e. direction and magnitude, pressure also has direction and magnitude.

About Pressure

Anyone who has ever snorkeled or SCUBA dived knows that you have to clear your ears as you go down to greater depths.

That's because the water pressure increases with depth. Since the water pressure doubles if you double your depth and triples if you triple your depth, we say that the pressure increases linearly. What this really means is that if you draw a graph of pressure vs. depth, you get a straight line (Figure 3). Now let's fill a can with water and look at the pressure differential (Figure 4) between the inside of the can and the outside world (Throughout most of the remainder of this article I will use the term "Pressure" to imply "Pressure Differential"). The pressure is zero just at the surface "A". The pressure at "B" is an amount half way between zero and "C" and the pressure at "C" is twice that at "B". Let's reshape our can a little bit and fill it again with water (Figure 5). The pressure at "A" is zero, at "B" is 1/2 "C" and at "C" is twice "B" again.

Looking at figures 4 and 5, we notice a couple of things. First, the shape of the can has nothing to do with the increase in pressure with depth! This makes sense because you will experience the same pressure under 10 feet of water whether it's in a small pool, a big pool, or in the ocean. Secondly, the pressure at the top of the can is the same as that of the outside environment. Hence, although the pressure increases as we go down in the can, there is no force trying to throw the water out the top of the can because we're back to neutral at the top.

Let's take the same bulbous shaped can and fill it with cold dense air. Well, it behaves about the same as it did with water. The pressure produced by the weight of those cold dense molecules of air pushing down on one another increases with depth. If we try to draw the pressure and associated vectors in one picture they look something like figure 6. Both the pressure and associated force vectors start small at the top and get larger toward the bottom. It's because of these forces that the can weighs more, full of cold dense air, than it would with normal temperature air in it. The areas of downward forces have effectively increased the weight!

Well, you can see where all of this is leading. Let's turn the can around fill it with hot not-very-dense air and we'll get a similar pressure distribution (Figure 7). Here again, the pressure at the throat is zero and increases as you go up toward the crown due to all of the hot little molecules pushing up on each other. Unlike water, however, air is somewhat compressible. You don't quite get nice linear behavior in pressure with height above the throat (For you purists, the pressure differential gradient in a balloon is exponential just like the Earth's atmosphere). For our purposes though, we will assume it to be linear. This will work well enough to give us some nice approximations.

Lift

When I first drew the picture in figure 7, I noticed that all pressure vectors below the equator have downward components. What this means is that all pressure pushing on the cloth below the equator is effectively increasing the weight of the balloon. Only the forces above the equator help lift.

One lonely night I decided to crank up my computer and grind out just what was happening. Since the balloons we fly are practically spherical, I started with a perfectly spherical shape (the spherical shape makes the math **ALOT** easier!). I also assumed a linear increase in pressure from the throat to the crown. To begin with, I calculated the sums of the vertical components

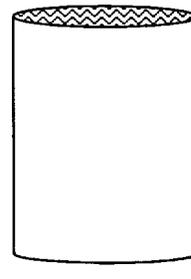
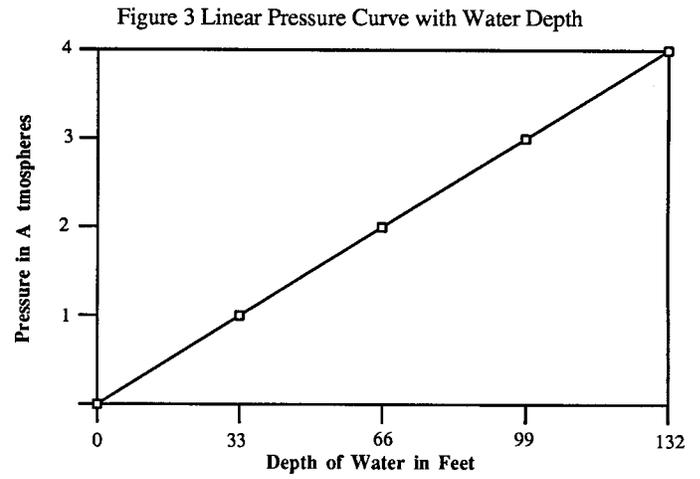


Figure 4

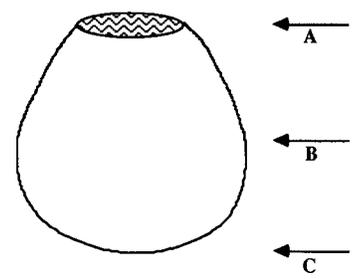


Figure 5

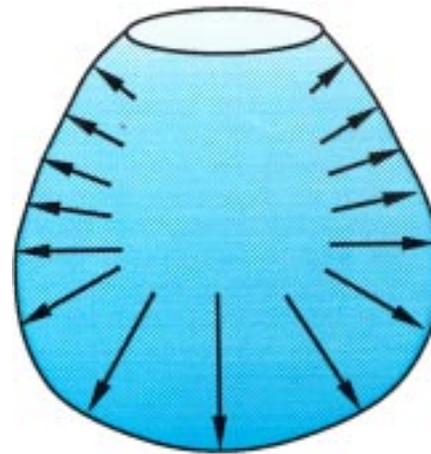


Figure 6

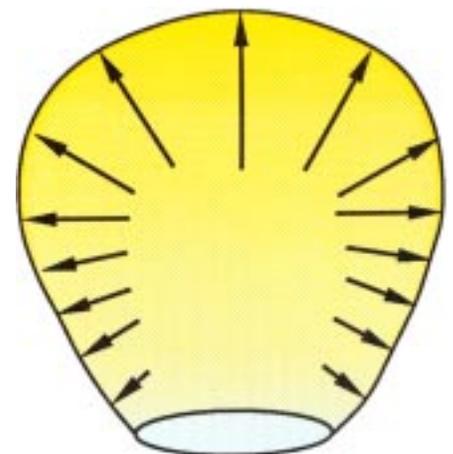


Figure 7

of force at each level of the envelope. This was accomplished by breaking the sphere up into many narrow bands similar to the 2 shown in figure 8 and using a little trigonometry.

Notice figure 9 that, because the balloon is symmetrical, each horizontal vector component has an exact opposite on the other side of the envelope. Thus, all of these horizontal forces effectively cancel each other. This is intuitively reasonable since an inflated balloon has no tendency to want to move sideways on its own! The vertical components, however, are larger in the upper portion of the balloon thus outweighing their negative lower counterparts. This antisymmetric property is what produces our lift. The actual vertical force on each of these bands can be calculated by simply multiplying the vertical component of pressure (force per unit area) by the surface area of the band (area).

Assuming a 60-foot diameter balloon and subdividing the envelope into 60 narrow bands (one for each foot of height), I calculated the force on each, and produced the following plot (Figure 10). This curve is based on lifting a 1000-pound gross load. The horizontal axis of the plot is a measure of the height above the throat (the throat was assumed to be the bottom point of the sphere). The vertical axis is the total lifting force in pounds produced by that particular band on the envelope.

An interesting point of geometry is that each band has the same surface area although the bands vary in shape and size (188 square feet). In fact at the crown the band becomes a cap just like a parachute top. The proof of this is a little complicated

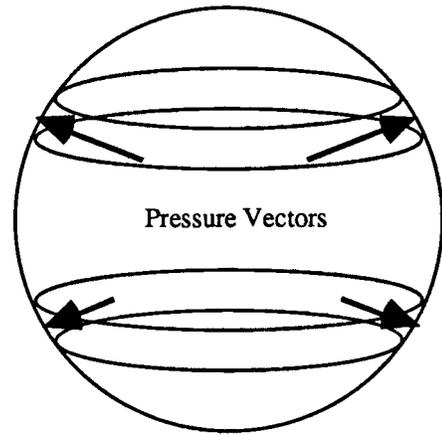
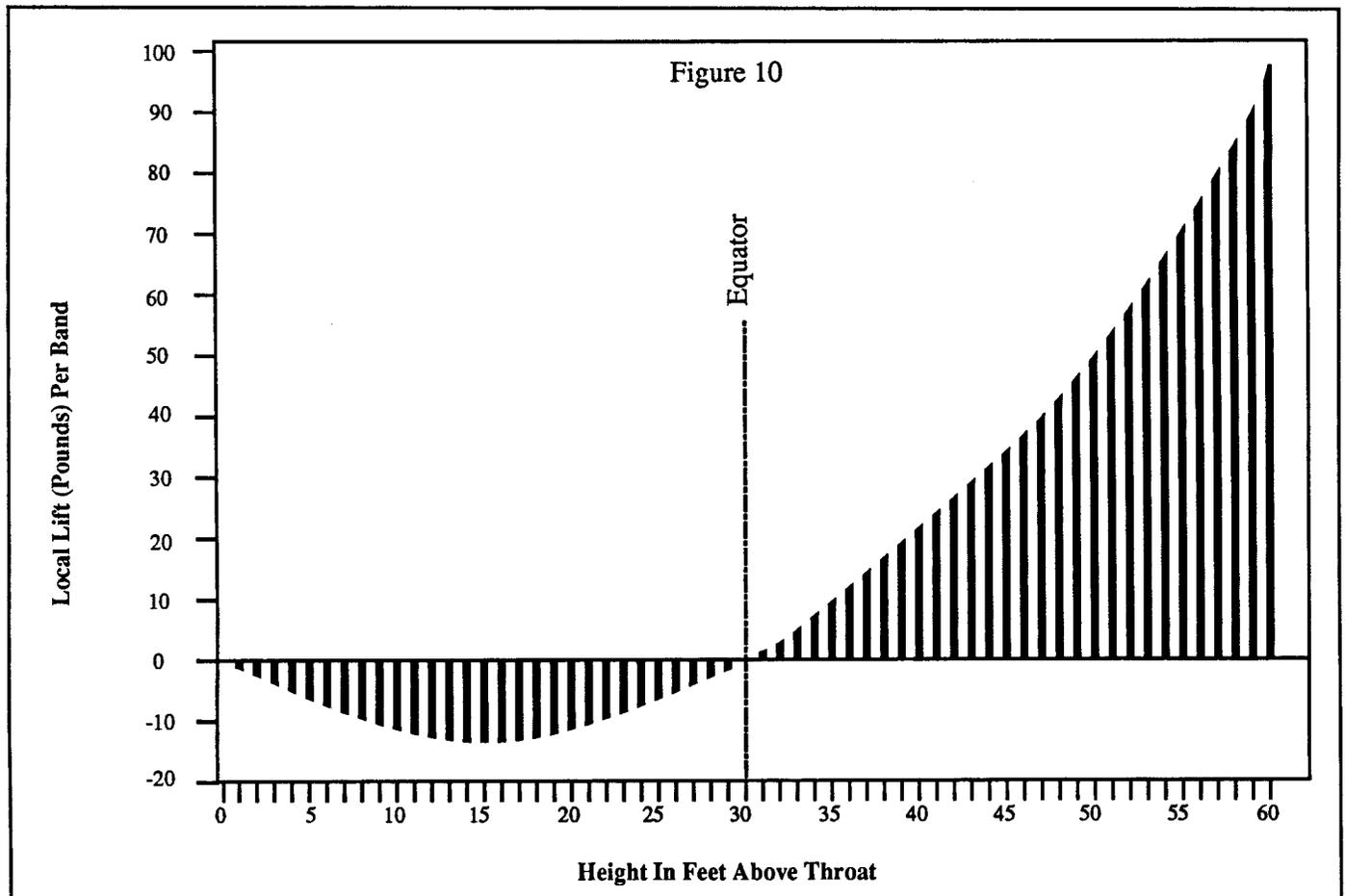
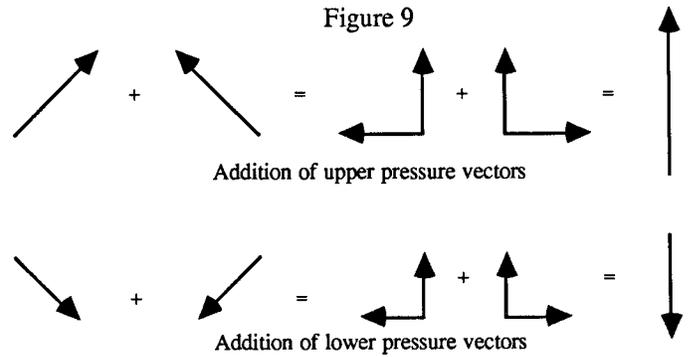
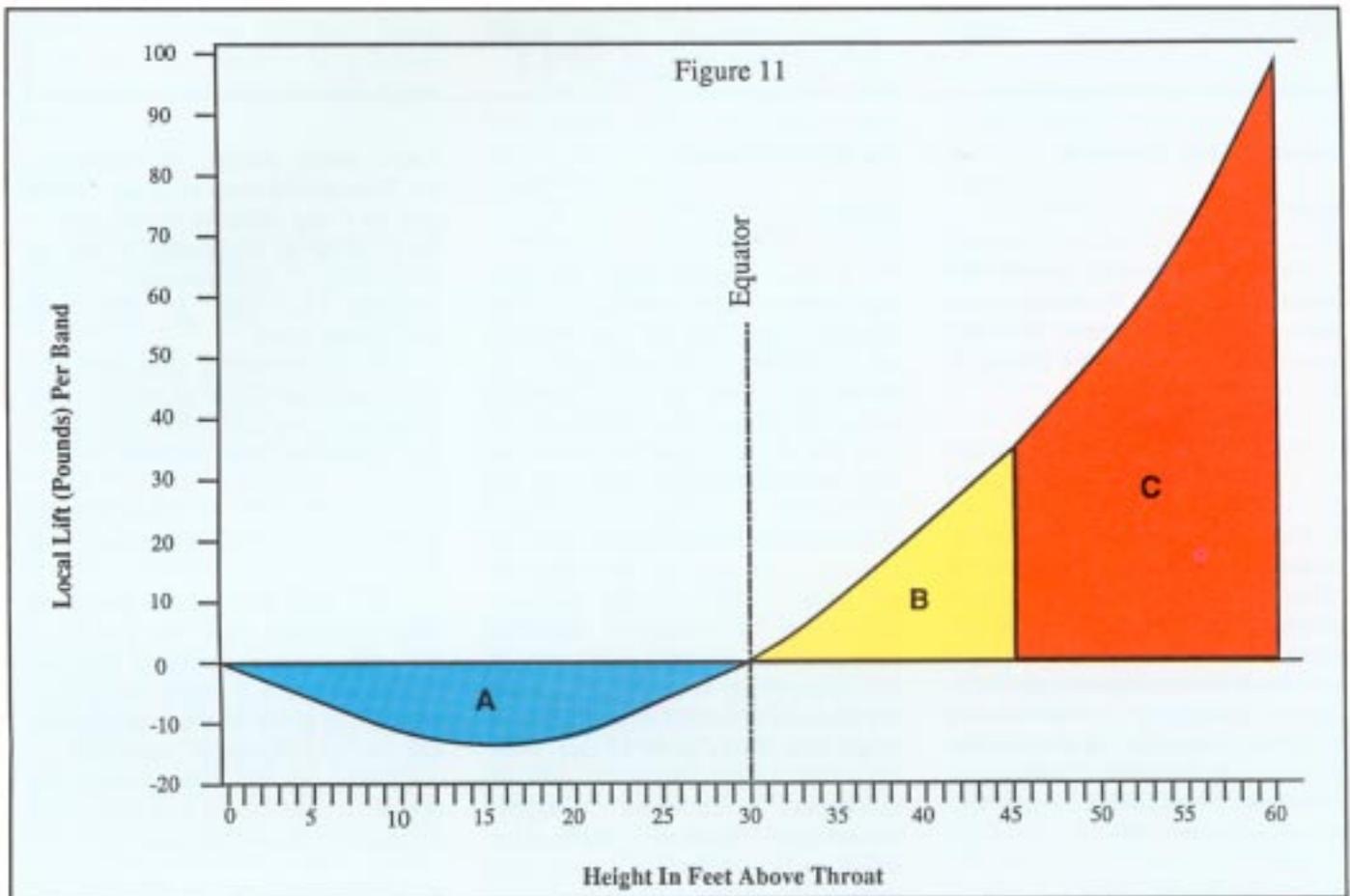


Figure 8





for the scope of this article.

To understand the curve in figure 10, let's start at the throat. Here the internal pressure of the balloon is the same as the external atmospheric pressure, the differential is zero. Therefore the forces near the throat are zero. As we move up the side of the balloon the pressure increases. However, all vertical components of the force point downward and oppose lift. These forces act as apparent extra weight! As we reach the equator we've got more pressure, but all vectors are pointing horizontally, i.e. no vertical components. Moving upward from the equator we begin to get positive lift since the pressure vectors start pointing slightly upward. Then as we move near the crown the vectors almost point straight up and the pressures in the balloon are at their highest.

So, there you have it! The way the forces behave to lift a balloon envelope. The curve in figure 10 was very interesting to me the first time that I generated it. It shows that the lower half of the balloon actually produces negative lift (equivalent to extra weight). When you see things like this you might ask: "Why not just get rid of the lower half of the envelope?" Well, if you did that, the pressure at the equator would be zero. Remember that the pressure starts building from the throat up. You need good pressure by the time the vectors start turning up just above the equator. Hence, the bottom of the balloon is needed to trap the air which creates the higher pressures in the top.

Going a step further, we can sum up the total increase in weight of the balloon due to down-sloping forces. This is equivalent to the shaded area between the curve and the zero local lift

line (area "A" in figure 11). It turns out that this total downward force for a spherical balloon is exactly compensated by the upward force produced by the area of the balloon beginning at the equator and ending 3/4 the way up the balloon (area "B" figure 11). The next area (area "C" in figure 11) produces all of the usable lift.

Isn't that interesting though! What all of this means is that the balloon envelope, from the throat to a point 3/4 the height of the balloon, produces no net lift! When we get up the envelope 3/4 of the way to the crown only then do we start to get usable lifting forces.

Next, we might like to look at the magnitude of the forces in each of these regions. In working this calculation I made the assumption that I needed to lift 1000 pounds (gross load). For this case the downward force produced by area "A" is 250 pounds, the upward force produced by area "B" is 250 pounds, and area "C" generates 1000 pounds of residual lift.

By knowing how to think about these forces, those of you who like to do some figuring for home balloon designs can do some quick and dirty calculations to approximate the forces in the tops of your balloons. The first thing you have to do is figure out the surface area of your design that supports the load, i.e. where the vectors point up. Then determine how much load you want to carry, and divide the two, i.e. *LOAD* (pounds) divided by *AREA* (square feet) equals pressure (pounds/square foot). In most cases the result isn't quite exact for a couple of reasons. First, you're neglecting forces that don't point up, and second, you're assuming a uniform pressure distribution. Even if this

technique isn't perfect you'll find, though, that it gives you a pretty good approximation.

Just for fun let's grind this calculation out for our spherical balloon. Since the top 1/4 of the envelope supports all of the weight and we have a 60-foot diameter, the surface area of that section is

$$4\pi R^2 = \text{Surface Area of a Sphere}$$

$1/4(4)\pi R^2 = \text{Area of top 1/4 of the Balloon where } \pi=3.14,$
and R (radius) = 30 feet. So, the two 4's cancel each other and
 $=3.14 (30) (30) = 2826$ square feet.

(lets call it 2800). If we need to lift 1000 pounds gross load then all 1000 pounds is distributed on this 2800 square feet of fabric which means we need a pressure differential of

$$1000 \text{ lb}/2800 \text{ ft}^2 = .36 \text{ lb}/\text{ft}^2$$

or about 5.7 ounces per square foot. Because the pressure in the top isn't really constant the real values range from about 5 ounces per square foot at the 3/4 mark to about 7 ounces per square foot at the crown. As you can see, though, if you're just trying to get an idea of the forces (within a half pound or so), this method works real well.

Let's consider a different geometric example for those of you who might like to fly a can shape (Figure 12). For a good comparison let's build a balloon of the same height and cubic

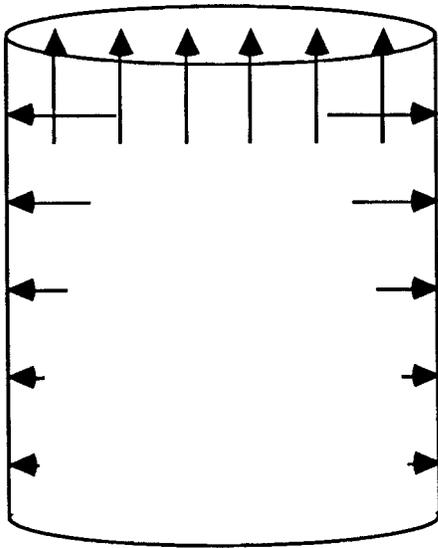


Figure 12

volume as our spherical example (113,000 cubic feet). To do this we make a cylinder 60 feet high and 49 feet across. Here the side vectors point horizontally all the way up the balloon. Only the top area makes lift to use for flight. A simple calculation shows the lifting area (the lid) to be 1883 square feet. If we want to carry the same 1000-pound load this fabric must support a pressure of

$$1000 \text{ lb}/1883 \text{ ft}^2 = .53 \text{ lb}/\text{ft}^2 = 8.5 \text{ oz}/\text{ft}^2$$

That's an increase of 2 to 3 ounces per square foot over a sphere. So you can see as we deviate from the spherical shape things can get worse. To fly this can, the pilot would have to run hotter to generate the higher pressures. This reduces fabric life and uses more fuel, but there is a price for everything. I person-

ally like to see the fun new shapes and designs being built!

Epilogue

After my first article on *The Physics of Lift in Hot Air Ballooning (Balloon Life, May 86)* I received many letters from home designers and other very interesting people. That correspondence stimulated me to write this article.

It's wonderful to live in time when we can fly! Happy Heights!

*This article originally appeared in **Balloon Life** February 1987. William G. Phillips, Research Physicist, Science and Aviation Consultants Inc., Las Vegas, Nevada.*