

# High Altitude Ballooning: A Comprehensive Review

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## ABSTRACT

This will be re-written after the paper is completed

## 1 INTRODUCTION

There has been a recent resurgence of interest in high altitude ballooning from universities, companies, hobbyists, scientists, and the general public. Since November of 2012, over 1,700 amateur balloon launches have been detected by APRS-IS (Gable 2013). These launches have taken place on all continents (save for Antarctica) and have been orchestrated by hundreds of groups.

In this paper, the balloon's ascent and behaviour at altitude is described. Factors affecting balloon buoyancy with altitude are discussed in detail, namely membrane pressure, change in the gravitational constant  $g$  with altitude, and air displacement caused by a solid payload. These factors, in combination, are thought to cause a balloon's free lift to decrease with altitude. One potential application of this natural lift change is the creation of a balloon that becomes neutrally buoyant at high-altitude without the use of a cut-down or other remote lift-altering device. Data from one of our launches is presented to illustrate an experimental example of a neutrally buoyant balloon and compare its observed behaviour with that which is theoretically described.

Finally, a thermodynamic model of high-altitude balloon motion is presented and analyzed.

## 2 BALLOON LIFT

### 2.1 Net Lift

A free-floating balloon is acted upon by three forces along the z-axis. The upwards buoyant force,  $F_B$ , the gravitational force,  $F_g$ , and the drag force,  $F_d$ . These forces can be combined to find the net lift force of the balloon:

$$\Sigma F = F_B - F_g \quad (1)$$

The buoyant force,  $F_B$ , can be calculated by using the Archimedes Equation:

$$F_B = \rho V \quad (2)$$

where  $\rho$  is the density of the displaced fluid in  $kg/m^3$  (air, in the case of the balloon),  $V$  is the volume of the balloon in  $m^3$ , and  $g$  is the acceleration due to gravity in  $m/s^2$ .  $F_B$  is in kilograms, as it is more convenient for our application. The density and pressure of the atmosphere changes

with altitude, causing the buoyant force to change throughout the flight. The data for density and pressure is available in the 1976 US Standard Atmosphere for up to 86 kilometers. The volume of the gas in the balloon can be measured with a flowmeter attached to the gas source.

The gravitational force,  $F_g$ , is the mass of the entire balloon, including the payloads, the balloon itself, and the gas inside the balloon:

$$F_g = m_b - m_p - \left(\frac{n * M}{1000}\right) \quad (3)$$

where  $m_b$  is the mass of the balloon,  $m_p$  is the mass of the payload,  $n$  is the moles of gas in the balloon, and  $M$  is the mass of the gas in grams.

When both of these forces are combined into equation 1, we end up with the net lift, or  $\Sigma F$ . This value can be used for various calculations regarding the balloon.

### 2.2 Change In Lift With Altitude

During several launches, it was observed that the latex balloon was able to reach neutral buoyancy without any manual changes to the balloon. This meant that the net lift of the balloon decreased with altitude, eventually reaching 0. Of the two forces involved in the net lift, only one can change throughout the flight: buoyancy.

Two factors are involved with buoyancy: The volume of the gas and the density of the air. The density of the air changes throughout the flight due to change in altitude. The volume of the gas also changes throughout the flight, and this can be modeled with the ideal gas law.

$$Pv = nRt \quad (4)$$

However, assuming that the pressure inside the balloon is the same as the pressure outside the balloon (the balloon expands to match the pressure), the volume of the balloon changes proportionally to the density of the atmosphere, resulting in no change in lift. This is contradictory to our observations; therefore, there has to be another factor that effects the volume. This is the back pressure of the elastic latex on the gas inside.

Various models exist for sphere rubber shells (also known as rubber balloons), including the Gent model and

the Mooney-Rivlin model. This paper will be focusing on the Mooney-Rivlin model too keep the paper concise.

The modified Mooney-Rivlin model for an incompressible spherical rubber shell is as such:

$$\Delta P = 2\mu \frac{t_0}{r_0} \left( \left( \frac{t_0}{r_0} \right) - \left( \frac{t_0}{r_0} \right)^7 \right) \left( 1 + \frac{1-\alpha}{\alpha} \left( \frac{t_0}{r_0} \right)^2 \right) \quad (5)$$

Where  $\mu$  is the shear modulus,  $\alpha$  is a constant,  $r_0$  is the unstretched radius of the balloon,  $r$  is the inflated radius of the balloon, and  $t_0$  is the thickness of the balloon. Setting  $\alpha$  as 1 results in the neo-Hookean model. While this is useful for small stretches, it does not accurately describe experimental data at high values of strain "Kanner". The values in "Miller" suggest values of  $\frac{10}{11}$  for  $\alpha$  and  $300kPa$  for  $\mu$ .

### 2.3 Neutral Buoyancy

Achieving neutral buoyancy is the foundation of achieving long-distance balloon flight. When a balloon is neutrally buoyant, it is able maintain suspension in the atmosphere and thus be exposed to high-altitude wind currents for a larger duration. Most trans-continental and trans-oceanic flights attain near-neutral buoyancy and maintain it for long periods of time, allowing them to travel long distances for extended periods of time.

Neutral buoyancy is achieved when the forces on the balloon along the z-axis reach a point of equilibrium so that:

$$F = 0 = F_B - F_g \quad (6)$$

Which can be manipulated to show equivalence between buoyant force and gravity:

$$F_B = F_g \quad (7)$$

In practice, this is achieved by filling the balloon with an excess of gas that creates a small net initial upwards force (in excess of gravity) that diminishes over the course of the flight (see Section 2.2).

Initial net upwards lift is critical to the balloon's buoyancy at a target altitude. Adding too much gas at the launch point will cause the balloon to burst before it can become neutrally buoyant. A shortage of initial gas will cause the force of gravity to exceed the buoyant force at the target altitude and cause the balloon to sink.

There is no "magic amount" of extra lift that guarantees neutral buoyancy. The amount of extra lift required is dependent on the size of the balloon, atmospheric conditions, the type of lift gas used, and the mass of the payload.

Our team launched a neutrally-buoyant balloon from Mesquite, Arizona, USA, on August 4, 2013 at 16:29 UTC. Its ascent path is plotted below:

[lht]

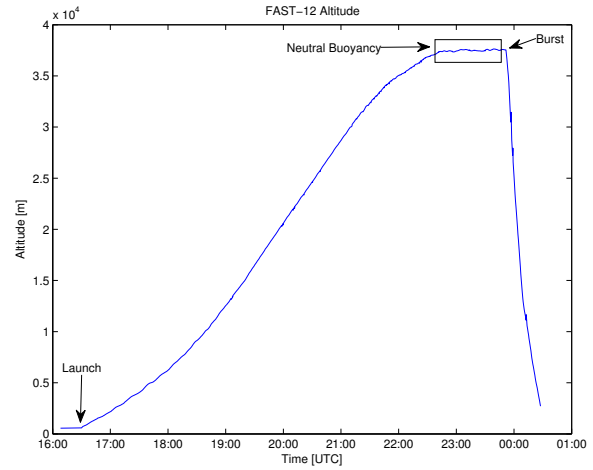


Figure 1. Altitude of neutrally-buoyant balloon vs. time

## 3 BURST ALTITUDE

### 3.1 Balloon Elasticity

## 4 THE EFFECT OF WIND VECTORS ON THE ASCENT AND DESCENT PATHS OF HIGH-ALTITUDE BALLOONS

### 4.1 Experimental Examples

## REFERENCES

Gable J., , 2013, APRS Flightdata