Buoyancy and high altitude ballooning: the Red Bull Stratos mission

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On 14 October 2012, Felix Baumgartner jumped from a capsule suspended beneath a helium-filled balloon that had risen to 39.0 km (128 000 ft) above the New Mexico desert. Baumgartner set several records on this mission.[1]

This article explores the science behind his ascent: buoyancy.

Buoyancy*

All objects have a constant *mass*, but they have a reduced *apparent weight* if they are present in another fluid. Water and air are two common fluids. *Buoyancy* is the upward force that the surrounding fluid exerts on a body: wood floats on water, a helium balloon floats in air.

The apparent weight, *w*, of an object depends on the difference in density, *ρ*, between the fluid and the entity. *V* is the volume of the object and *g* is the force of gravity.

$$w = \left(r_{\text{object}} - r_{\text{fluid}} \right) V\ g \qquad \textbf{1}$$

- if $w > 0$, the object sinks in the fluid
- if $w < 0$, the object is *buoyant* and rises in the fluid
- if $w = 0$, the object is *neutrally buoyant* and floats at that altitude

For complex systems, the object density is the average density. The Red Bull Stratos (RBS) equipment consists of the balloon material, helium, capsule, and Baumgartner himself.

Focussing on gases, the density of a gas depends on several factors: pressure, *P*; molecular mass, *M*; and temperature, *T*. To a good approximation, atmospheric gases approximate an ideal gas, and the density of ideal gases is given by equation **2**.

$$r = \frac{P\,M}{R\,T} \qquad \textbf{2}$$

where *R* is the gas constant: *R* = 0.08314 (L bar)/(mol K)

Equation **2** explains why helium is buoyant in air: the molecular mass of helium, 4.003 g/mol, is less than the average molecular mass of air, 28.96 g/mol.† In the RBS mission, sufficient helium was used to make the average density of all the equipment less that the density of air. That is, the apparent weight of the equipment was negative. Table 1 gives the relevant parameters of the RBS equipment and of the atmospheric conditions.

* Adapted from *Exploring Chemistry*, by Roy Jensen. Background image courtesy of Red Bull Stratos.

† Not related to the Red Bull Stratos mission, but hot air balloons are buoyant because the air temperature inside the balloons is higher, therefore less dense that the surrounding air.

Table 1 Relevant information on the Red Bull Stratos equipment and environmental conditions on mission day.

Equipment[a]		Conditions: ground[b]	
balloon mass	1682 kg (3708 lb)	pressure	0.89 bar
capsule mass	1315 kg (2900 lb)	temperature	287 K (14 °C, 57 °F)
capsule volume	17 m^3 (600 ft^3, estimated)		
mass of Baumgartner & suit	118 kg (260 lb)	**Conditions: 39 km[c]**	
maximum balloon volume	$8.35 \cdot 10^5$ m^3 ($29.5 \cdot 10^6$ ft^3)	pressure	0.0039 bar
volume helium used	$5.1 \cdot 10^3$ m^3 ($1.8 \cdot 10^5$ ft^3)	temperature	266 K (–7 °C, 19 °F)

a. Reference 2. b. Reference 3. c. Reference 4.

The Red Bull Stratos mission

Figure 1 shows the balloon just after launch and approaching the jump altitude. It is clear that the balloon has increased in volume by several orders of magnitude.

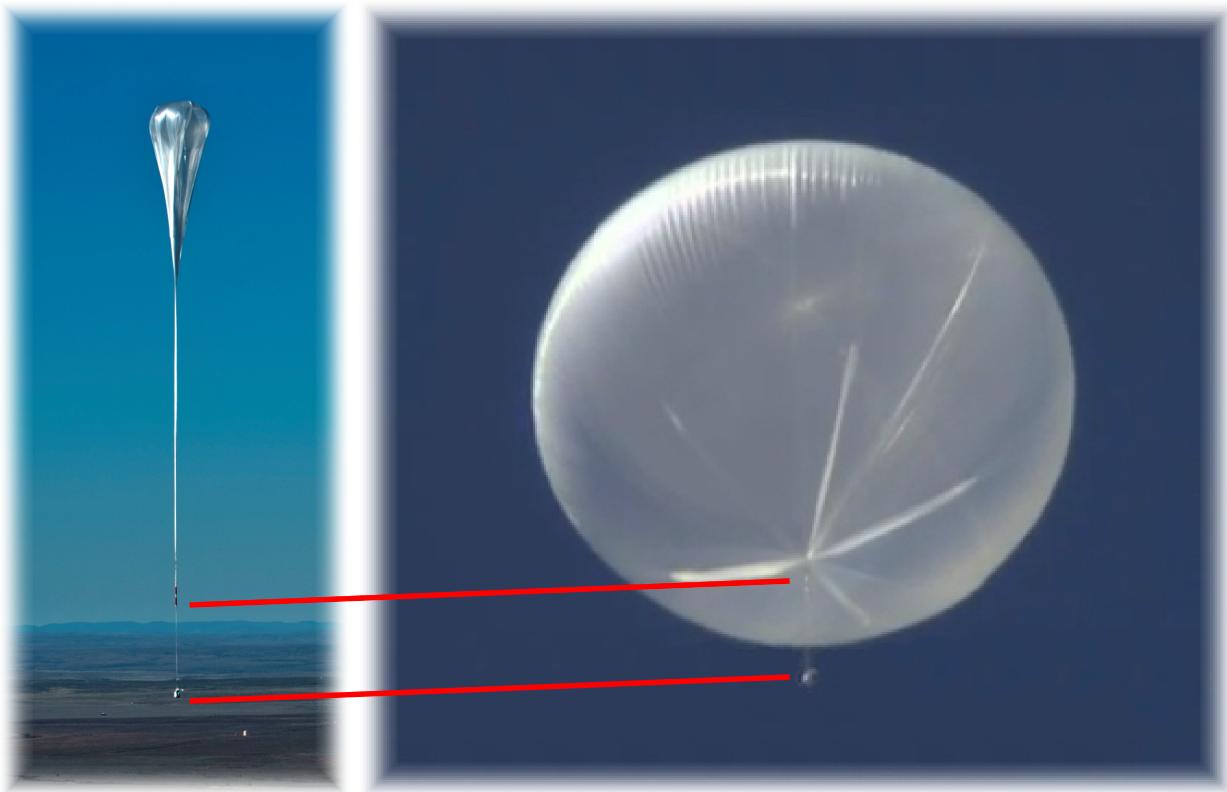

Figure 1 The Red Bull Stratos balloon (left) just after launch from Roswell, NM, and (right) at approximately 38 km altitude. The red lines identify the end of the balloon and the capsule, respectively. The tautness on the right balloon suggests it is full. Images courtesy of Red Bull Stratos.

Density of air and helium

Equation **2** is used to calculate the density of air and helium at ground level and at altitude.

$$r_{\text{air}}^{\text{ground}} = \frac{P\,M}{R\,T} = \frac{0.89\ \text{bar} \cdot 28.96\ \frac{\text{g}}{\text{mol}}}{0.08314\ \frac{\text{L bar}}{\text{mol K}} \cdot 287\ \text{K}} = \boxed{1.0\underline{8}\ \frac{\text{g}}{\text{L}}} \qquad \mathbf{3}$$

$$r_{\text{air}}^{39\ \text{km}} = \frac{P\,M}{R\,T} = \frac{0.0039\ \text{bar} \cdot 28.96\ \frac{\text{g}}{\text{mol}}}{0.08314\ \frac{\text{L bar}}{\text{mol K}} \cdot 266\ \text{K}} = \boxed{0.0051\underline{1}\ \frac{\text{g}}{\text{L}}} \qquad \mathbf{4}$$

$$r_{\text{He}}^{\text{ground}} = \frac{P\,M}{R\,T} = \frac{0.89\ \text{bar} \cdot 4.003\ \frac{\text{g}}{\text{mol}}}{0.08314\ \frac{\text{L bar}}{\text{mol K}} \cdot 287\ \text{K}} = \boxed{0.14\underline{9}\ \frac{\text{g}}{\text{L}}} \qquad \mathbf{5}$$

$$r_{\text{He}}^{39\ \text{km}} = \frac{P\,M}{R\,T} = \frac{0.0039\ \text{bar} \cdot 4.003\ \frac{\text{g}}{\text{mol}}}{0.08314\ \frac{\text{L bar}}{\text{mol K}} \cdot 266\ \text{K}} = \boxed{7.0\underline{6} \cdot 10^{-4}\ \frac{\text{g}}{\text{L}}} \qquad \mathbf{6}$$

In terms of dimensionality, the following units are used interchangeably.

$$\frac{\text{g}}{\text{L}} = \frac{\text{kg}}{\text{m}^3} \qquad \mathbf{7}$$

Density of Red Bull Stratos equipment on the ground

The Red Bull Stratos (RBS) equipment is a composite of the balloon, helium, capsule, and Baumgartner. To determine the density of this complex system, I turn to the fundamental definition of density:

$$density = \frac{mass}{volume} \qquad \mathbf{8}$$

By calculating the total mass and total volume, I can calculate the average density. I assume that the mass of air inside the capsule is negligible compared with the uncertainty in other values. At ground level,

$$\begin{aligned} r_{\text{RBS}}^{\text{ground}} &= \frac{\sum mass}{\sum volume} = \frac{mass_{\text{balloon}} + mass_{\text{helium}} + mass_{\text{capsule}} + mass_{\text{Baumgartner}}}{volume_{\text{balloon}} + volume_{\text{capsule}}} \\ &= \frac{1682\ \text{kg} + \overbrace{\left(0.14\underline{9}\ \frac{\text{kg}}{\text{m}^3} \cdot 51\underline{00}\ \text{m}^3\right)}^{=76\underline{0}\ \text{kg}} + 1315\ \text{kg} + 118\ \text{kg}}{51\underline{00}\ \text{m}^3 + 17\ \text{m}^3} \\ &= \frac{38\underline{75}\ \text{kg}}{51\underline{17}\ \text{m}^3} = \boxed{0.75\underline{7}\ \frac{\text{kg}}{\text{m}^3} = 0.75\underline{7}\ \frac{\text{g}}{\text{L}}} \end{aligned} \qquad \mathbf{9}$$

where the mass of helium is calculated from equation **8**: *mass* = *density* · *volume*

Equation **9** shows that the density of the Red Bull Stratos equipment is less than the density of air ($1.0\underline{8}\ \text{kg/m}^3$ from equation **3**), so the equipment is buoyant in air.

Density of Red Bull Stratos equipment at 39.0 km

The mission video indicates that the capsule ejected 60 kg of ballast during the ascent.

The balloon material is made from 20 µm polyethylene, about the thickness of a dry-cleaning bag or household plastic wrap. Polyethylene and helium are non-polar; so are all the major atmospheric gases (nitrogen, oxygen, and argon). Consequently, all these gases diffuse through polyethylene. In the balloon, helium diffuses out and air diffuses in because of the difference in partial pressures. Helium also escapes through leaks and vents.

To explore what occurred during ascent, I can determine the volume of the balloon assuming no diffusion or leaking. Using the two-state gas equation derived from the ideal gas equation,

$$\frac{P_1 V_1}{n_1 T_1} = \frac{P_2 V_2}{n_2 T_2} \quad \Rightarrow \quad V_2 = \frac{P_1 n_2 T_2}{P_2 n_1 T_1} V_1 \qquad (1 = \text{ground};\ 2 = 39\ \text{km})$$

$$V_2 = \frac{0.89\ \text{bar} \cdot \cancel{n_2} \cdot 266\ \text{K}}{0.0039\ \text{bar} \cdot \cancel{n_1} \cdot 287\ \text{K}} 5100\ \text{m}^3 \qquad \textbf{10}$$

$$= 1.0\underline{8} \cdot 10^6\ \text{m}^3$$

This volume is 29 % greater than the maximum balloon volume in table 1. Clearly, some helium escaped from the balloon. But has air diffused in? If I assume the balloon only contains helium at 39.0 km, I can calculate the density of the equipment.

$$r_{\text{RBS}}^{39\ \text{km}} = \frac{mass_{\text{balloon}} + mass_{\text{helium}} + mass_{\text{capsule}} + mass_{\text{Baumgartner}}}{volume_{\text{balloon}} + volume_{\text{capsule}}}$$

$$= \frac{1682\ \text{kg} + \overbrace{\left(7.0\underline{6} \cdot 10^{-4}\ \tfrac{\text{kg}}{\text{m}^3} \cdot 8.35 \cdot 10^5\ \text{m}^3\right)}^{=590\ \text{kg}} + \overbrace{1255\ \text{kg}}^{(\text{less } 60\ \text{kg})} + 118\ \text{kg}}{8.35 \cdot 10^5\ \text{m}^3 + 17\ \text{m}^3} \qquad \textbf{11}$$

$$= \frac{36\underline{4}5\ \text{kg}}{8.35 \cdot 10^5\ \text{m}^3} = \boxed{= 0.0043\underline{6}\ \frac{\text{kg}}{\text{m}^3} = 0.0043\underline{6}\ \frac{\text{g}}{\text{L}}}$$

The average equipment density from equation **11** is less than the surrounding air calculated in **4**, $0.0051\underline{1}$ kg/m^3. However, the balloon was neutrally buoyant at 39.0 km, so helium must have diffused out and air diffused into the balloon. The amount of air that has diffused in can be calculated by setting the densities equal and calculating the fraction of helium in the balloon.

- let x be the volume of helium in the balloon
- let $8.35 \cdot 10^5\ \text{m}^3 - x$ be the volume of air in the balloon

To determine *x*, I set the density of the equipment equal to the density of air and solve for *x*.

$$\rho_{\text{RBS}}^{39\text{ km}} = \rho_{\text{air}}^{39\text{ km}} = 0.0051\underline{1}\ \frac{\text{g}}{\text{L}} = 0.0051\underline{1}\ \frac{\text{kg}}{\text{m}^3}$$

$$0.0051\underline{1}\ \frac{\text{kg}}{\text{m}^3} = \frac{mass_{\text{balloon}} + mass_{\text{helium}} + mass_{\text{air}} + mass_{\text{capsule}} + mass_{\text{Baumgartner}}}{volume_{\text{balloon}} + volume_{\text{capsule}}}$$

$$= \frac{1682\text{ kg} + \overbrace{7.0\underline{6}\cdot 10^{-4}\ \tfrac{\text{kg}}{\text{m}^3}\cdot x}^{\text{mass of He}} + \overbrace{0.0051\underline{1}\ \tfrac{\text{kg}}{\text{m}^3}\cdot\left(8.35\cdot 10^5\ \text{m}^3 - x\right)}^{\text{mass of air}} + \overset{\text{(less 60 kg)}}{1255\text{ kg}} + 118\text{ kg}}{8.35\cdot 10^5\ \text{m}^3 + 17\ \text{m}^3}$$

$$\vdots$$

$$x = \boxed{6.9\underline{4}\cdot 10^5\ \text{m}^3} \qquad \textbf{12}$$

$6.9\underline{4}\cdot 10^5\ \text{m}^3$ of helium corresponds to 83.$\underline{1}$ % helium and 16.$\underline{9}$ % air in the balloon by volume.

Over-altitude

The Red Bull Stratos team estimated that the balloon would rise to only around 36.6 km (120 000 ft). Possible reasons for the balloon rising further are given below.

1. The team may have assumed that helium and air would diffuse at faster rates. Less helium and more air would increase the density of the gases and decrease the buoyancy of the equipment.
2. The helium inside the balloon may not have thermally equilibrated with the atmosphere. Solar irradiation of the balloon material may have further hindered thermal equilibration. The higher temperature would decrease the density of the gases inside the balloon and increase the buoyancy of the equipment.
3. The temperature at altitude may have been cooler than measured by the RBS capsule. (This is possible, depending on the type of thermometer used.) Using the composition calculated in equation **12**, with all other parameters being unchanged, the apparent weight of the RBS equipment at different ambient temperatures would be

   230 K: $w = -4.7\cdot 10^3$ N (buoyant at lower temperature)

   266 K: $w = 0.0$ N (neutrally buoyant)

   300 K: $w = 3.4\cdot 10^3$ N (sinks at higher temperatures)

References

1. The Red Bull Stratos mission is documented at http://www.RedBullStratos.com
2. Balloon mass from http://www.redbullstratos.com/technology/high-altitude-balloon/
   Capsule mass from http://www.redbullstratos.com/technology/capsule/
   Balloon volume from http://www.redbullstratos.com/gallery/?mediaId=media1968
   Baumbartner and equipment mass from http://www.redbullstratos.com/the-mission/mission-timeline/
   Volume of helium at ground level from http://www.redbull.com/cs/Satellite/en_INT/Article/Red-Bull-Stratos-The-largest-manned-balloon-ever-021243269595978
3. http://www.wunderground.com/history/airport/KROW/2012/10/14/DailyHistory.html?req_city=Roswell&req_state=NM
4. Sensors on-board the capsule recorded external temperature and pressure in real-time. At 39 km, the temperature varied from 263 K to 269 K (–10 °C to –4 °C) and the pressure varied from 0.001 bar to 0.005 bar. An average temperature of 266 K was used in calculations, which also introduces an one percent uncertainty into the results. The pressure uncertainty is too great for the calculations herein. The atmospheric pressure was estimated using the MSIS-E-90 Atmosphere Model using geographical data for Roswell, NM: http://omniweb.gsfc.nasa.gov/vitmo/msis_vitmo.html The model also correctly calculated the ground-level pressure, supporting the accuracy of the model.