Launching rockets from a high altitude balloon

Introduction

The idea of launching a rocket vehicle from a high altitude balloon is an old idea (it was done back in the 1950's) but is coming back into fashion for amateur rocket flights. The plan is to use a weather-balloon effectively as the first stage; the height gained by the balloon raises the rocket's apogee, and furthermore the high altitude greatly reduces the drag on the rocket which raises the apogee even more: effectively switching the drag off raises the apogee around *nine-fold!*
This system is sometimes known as a 'rockoon', which sounds like a cartoon character.

However, what is often not appreciated is that the very rarefied atmosphere at typical helium balloon peak altitudes fundamentally alters the aerodynamics of the launch of the rocket. Traditional ground-level launching techniques *simply won't work!*

I'd like to thank Aspire member Jim Sadler, and Cambridge University Spaceflight's Ed Moore, for their advice on hydrogen weatherballoons.

Words in **bold** are listed in the glossary at the end of the paper.

1: Equivalent airspeed

There are several ways to describe the aerodynamic effects of high altitudes such as the use of **dynamic pressure**. However, a particularly useful measure of altitude is Equivalent airspeed (known to aircraft pilots as Indicated airspeed).

The density of the atmosphere decreases with altitude, which means from the **lift equation** that a rocket must fly faster to achieve the same stabilising lift force from its fins at altitude as opposed to if it were flying at sea-level.
For example, there's a minimum airspeed at sea-level that the rocket can leave its launch rail and be aerodynamically stabilized. What would that airspeed be at higher altitude?
Equivalent airspeed (EAS) performs the conversion: if the rocket flies at 10 Knots Equivalent airspeed at any altitude, then the rocket's fins will behave the same as if they were flying at a True (actual) airspeed (TAS) of 10 Knots at sea-level: infact all the aerodynamic loads on the rocket (lift, drag, **dynamic pressure** or 'hull' pressure) will be the same whatever altitude the rocket is flying at if the Equivalent airspeed is the same.

The conversion factor from True airspeed to Equivalent airspeed comes directly from the **lift equation:**

$$\frac{1}{2}\rho_{Sea\_level}V_{EAS}^2 SC_L = \frac{1}{2}\rho_{at\_altitude}V_{TAS}^2 SC_L$$ (ρ = atmospheric density) (equ. 1.1)

Upon canceling:

$$\rho_{Sea\_level}V_{EAS}^2 = \rho_{at\_altitude}V_{TAS}^2 \quad or \quad V_{EAS} = V_{TAS}\sqrt{\frac{\rho_{at\ altitude}}{\rho_{at\ sea\ level}}}$$ (equ. 1.2)

where $\frac{\rho_{at\ altitude}}{\rho_{at\ sea\ level}}$ is known as the *relative density* σ. Its value at a typical helium balloon altitude of 100,000 feet above sea-level is: $\sigma = \frac{0.01710}{1.225} = \frac{1}{71.6}$

When we launch rockets from a balloon at this altitude, this number 71.6 will crop up again and again. So note for now that it's quite a large number.

Equation 1.2 shows us the problem we face if we want to launch a rocket off a balloon at high altitude using a good old fashioned launch rod or launch rail.

Suppose the minimum airspeed for the fins to work effectively on a typical rocket is '*V'* metres per second at sea level, so that the launcher has to be long enough to allow the rocket to attain '*V'* metres per second Equivalent airspeed as it leaves the end of the launcher at high altitude.

Suppose, for easy calculation, that the rocket's boost acceleration '*a*' is nearly constant as it rides up the launch rail, and upon launch, the thrust is much larger than the drag so that the drag can be ignored. Using high school physics equation $V^2 = U^2 + 2aL$ where initial speed $U^2 = 0$ allows us to calculate the required length L of launch rail as:

$$L = \frac{V_{TAS}^2}{2a} \quad \text{(equ. 1.3)}$$

(For a more detailed method that includes drag see the method of appendix 1 though the conclusion is the same.)

Substituting equation 1.2 into equation 1.3 allows us to calculate the effect of the actual True airspeed at high altitude by including the relative density σ:

$$L = \frac{V_{EAS}^2}{2a}\left(\frac{1}{\sigma}\right) \quad \text{(equ. 1.4)}$$

Now if the launch is to take place at a typical helium balloon altitude of 100,000 feet above sea-level, then: $\frac{1}{\sigma} = \frac{1.225}{0.01710} = 71.6$

Therefore from equation 1.4, the launcher must be *71.6 times as long* as the launcher at sea-level to guarantee that the rocket leaves the launcher with the same Equivalent airspeed, which is one hellova long launcher! (It simply can't be done as the launcher must remain lightweight so that the balloon can loft it.)

What will happen if we try to launch our vehicle from a short launcher at high altitude? Its fins will be useless (no aerodynamic forces from either fins or nosecone), so the vehicle will be at the mercy of the only remaining effects: tiny non-asymmetries that crop up in the manufacture of the nozzle. A tiny asymmetry times a large boost thrust equals a moderate turning moment that will pinwheel the vehicle end-over-end about its **CG**, be it a standard rocket shape or a boost-glider. Can you guarantee that the thrust line of action passes through the CG to fractions of a millimetre precision? No you can't.

2: Alternative launch methods

So launch rails and launch towers simply won't work at high altitudes (especially as they have to be rigidly fixed to the ground) so what are the alternatives?

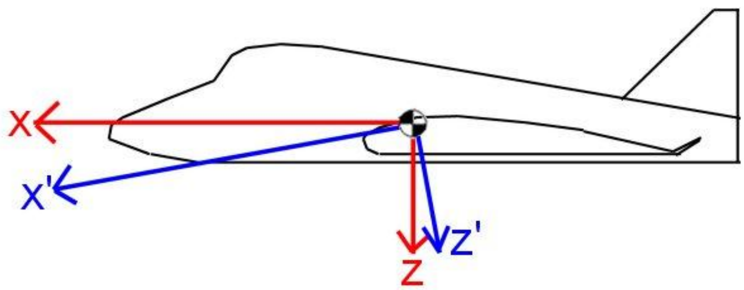
Vectored thrust

The Germans faced a similar problem during World War 2 with their V2 rocket and Natter vertical-takeoff rocket aircraft: the vehicles were too physically large to allow the use of a launch tower. They solved the problem by introducing steerable vanes into the rocket exhaust which steered (vectored) the thrust and were driven by a gyroscope to give artificial stability to the rocket.
Vectored thrust (or puffer jets: reaction control system) is one option, but it certainly isn't simple nor particularly lightweight on small rockets, especially for solid rocket motors.

Spin-stabilisation
I prefer spin-stabilisation at launch, simply pre-spin the rocket just before launch to get ‘gyroscopic’ (spinning top) stability which is effective at any altitude, but this has its own problems:
Obviously, only axisymmetric (cylindrically symmetric) vehicle shapes such as traditional launch vehicle shapes can be spin-stabilised.
Boost-gliders are most definitely *not* axisymmetric, so if you try to spin-stabilise them their axis of spin will wobble around (known as precession and nutation): they’ll go into a wobbling sort of flat spin from which they won’t recover.

The rotational inertia of a spinning object is described by the three moments of inertia Ixx, Iyy, and Izz (one for each of the three vehicle axes x, y, z) but it can also include products of inertia Ixy, Ixz, Iyz which describe mass imbalances.
For example, a boost-glider which has aeroplane-like symmetry has two of the products of inertia Ixy = Ixz = 0, but also has a non-zero product of inertia Ixz (x = noseward from CG, y= wing spanward from CG, z = downwards below CG).

Now it so happens that it is always possible, for any body shape, to find a 3-axis body axes orientation such that the products of inertia are all zero. In this case, the axes are called the Principal axes, and you can certainly spin the body about one of these Principal axes without the body wobbling (precessing).
For a boost-glider, the x’ and z’ Principal axes will be in the plane as the x and z axes, with the y and y’ axes the same. What this means is that you could spin the boost-glider about either its x’ or z’ Principal axis (or even its y’ axis) and it wouldn’t wobble.



But finding the Principal axes is mathematically hard, and you need very accurate data for the inertias and masses of your vehicle. If you were even a degree off the Principal axis it would wobble as it spun.
And don’t forget that once aerodynamics comes into play, the spin could go anywhere!

A traditional cylindrical-body rocket vehicle shape may look axisymmetric so that the Principal axes are also the axes of symmetry, but it may not be inside: internal avionics, batteries, and parachutes will have to be restrained and positioned to keep the balance, which can be a real pain. We’ll have to take care to *dynamically balance* our rocket just as a car’s wheel has to be balanced by adding weights to it to align the Principal axes with the spin axis. Professional rocketeers use instrumented spin-tables to check the dynamic balance of their spin-stabilised rockets just as tyre shops do.

From Ref. 3 the equation governing the rotation of a spin-stabilised rocket is:

$I\dot{\omega} = T\,r\sin(\tau) - \dot{m}\omega r^2$ (equ. 2.2)

where I is the moment of inertia about the spin axis, *T* is the spin rocket’s thrust, $\dot{\omega}$ is the angular acceleration, ω is the angular velocity (the spin rate), *r* is the distance from the spin axis to the centre of the spin rocket nozzle exit, and τ is the cant of the spin rocket nozzle from the spin axis (0 to 90 degrees).

The final term in equation 2.2 involving the spin rocket's nozzle mass flow rate $\dot{m}$ is a 'jet damping' effect which reduces the angular acceleration (See our paper 'A dynamic stability rocket simulator' Appendix 2 for a derivation of the jet-damping term).

The mass flowrate $\dot{m}$ can be estimated as: $\dot{m} = \frac{Thrust}{effective\ exhaust\ velocity}$

where $effective\ exhaust\ velocity \cong \frac{total\ impulse}{total\ propellant\ mass}$

Note that in a lot of cases, the jet damping term is small compared to the thrust term and can be neglected (such as when ωr^2 is small).

Tractor rockets

We can go a stage further by divorcing the rocket motor from our vehicle. A tractor rocket connects the rocket to the vehicle via a rod or rope. This lets us spin-stabilise the rocket motor whilst not having to spin the vehicle (by the use of a swivel link). This is particularly useful for launching non-axisymmetric vehicles such as human-shaped dolls or boost-gliders. The multiple rocket nozzles have to be canted out at around 45 degrees from the direction of flight to prevent their exhaust toasting the vehicle being pulled behind it. The tractor rocket separates from the vehicle at rocket burnout.

A tractor rocket system was devised by legendary aero engineer and test-pilot Robert Stanley as a means of escape for aircraft pilots. Here's an actual test of the Stanley 'Yankee extraction system' tractor rocket fitted to the American Air Force A-1 Skyraiders:

Stanley's 'Yankee' system fired an expulsion tube, (see our paper "Recovery system design for large rockets") which cannoned the as-yet unlit tractor rocket vertically at 35 metres per second up out of the cockpit.

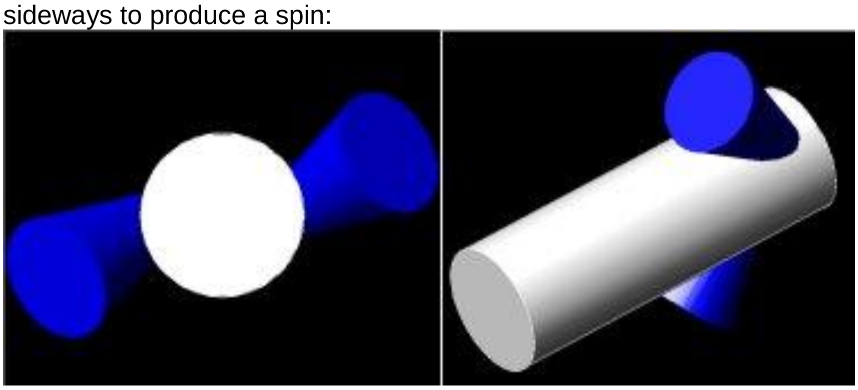
The tractor rocket was attached to the crewman via 3 metre long nylon towlines attached to the parachute harness of the crewman.

Then the spin stabilized tractor rocket was ignited when the towlines reached full stretch, providing 8.9 kN of thrust (quite a lot!)
Then the tractor rocket extracted the crewmember and his parachute.
This system was credited with saving over 150 lives during the Vietnam War.

This picture shows a test of the Stanley Yankee system pulling a life-sized dummy out of an airlock hatch. This was proposed as a crew escape system for the Space Shuttle. (The test-rocket was fired over a cliff here.)
Sadly, the video has been lost to history, but (and I saw it) the tractor rocket was spin-stabilised at high RPM by canting the rocket's thrust lines off the axis of its symmetry.

Shuttle crew escape systems (CES) rocket test at Hurricane Mesa, Utah

Here's a sketch of the Yankee tractor rocket, showing the two nozzles (in blue) that are angled out at 45 degrees from the long axis of the rocketmotor casing, but are also canted out sideways to produce a spin:



Note that the nozzles are forward of the rocket's CG, and that the towline attachment point is behind the rocket's CG.
This tractor rocket reaches peak thrust in only 0.03 seconds after ignition, so that there is no danger of the towline rebounding once it reaches full stretch.

I've launched some basic tractor rocket experiments as I want to use such a system for my Swift personal spaceplane boost-glider (see our website's 'spaceplanes' section).

These pictures show my 'pidgeon' system (so-named after a type of pyrotechnic) which consists of a hexagonal wooden disc which is spun-up by turning motors (low thrust, long duration motors). The disc is pierced by three high-thrust C-class lift motors that provide the tractive thrust, and the whole assembly rotates about a central plastic tube which is its axle and to which the string is attached to for towing an object into the air.

The first time I tried this, I used three high-thrust B-class motors as the spin motors. The ensuing RPM was slightly colossal: the pidgeon disintegrated due to centrifugal forces, and all three nozzles of the lift motors were also flung out due to centrifugal forces!
So be warned, use only very low thrust spin motors, or cant them only a few degrees to create spin: a very slight turning moment is all that is required.

3: The Mach problem

Equivalent airspeed lets us predict the aerodynamics at altitude, but there's another factor to consider. We've seen that low Equivalent airspeeds translate into large True airspeeds at very high altitudes. Unfortunately, Mach number is defined by True airspeed. This means that our rocket vehicle very quickly goes **supersonic** when launched at very high altitude, the majority of the flight is supersonic.
For example, at 100,000 feet above sea-level, equation 1.2 shows that the True airspeed is 8.5 times the Equivalent airspeed, and not only that, but the speed of sound is lower at 100,000 feet (302 metres per sec) than it is at sea-level (340 metres per sec). This means that an Equivalent airspeed of only 35.5 metres per second (69 knots) is Mach 1 at 100,000 feet altitude.
So your rocket needs fins and a nosecone designed for supersonic flight.

This is a particular problem for gliders launched from a high altitude balloon: you need to use a wing aerofoil section that remains effective at high **subsonic** airspeeds, such as the 'supercritical' aerofoils which delay **transonic** effects. Simply dropping a glider off a balloon, it can easily hit Mach 1 before it pulls out into a glide.

Note that the rocket vehicle may well be supersonic when it re-enters the atmosphere so a supersonic drogue must be used: a conventional drogue will simply collapse.

4: Eating a lot of sky

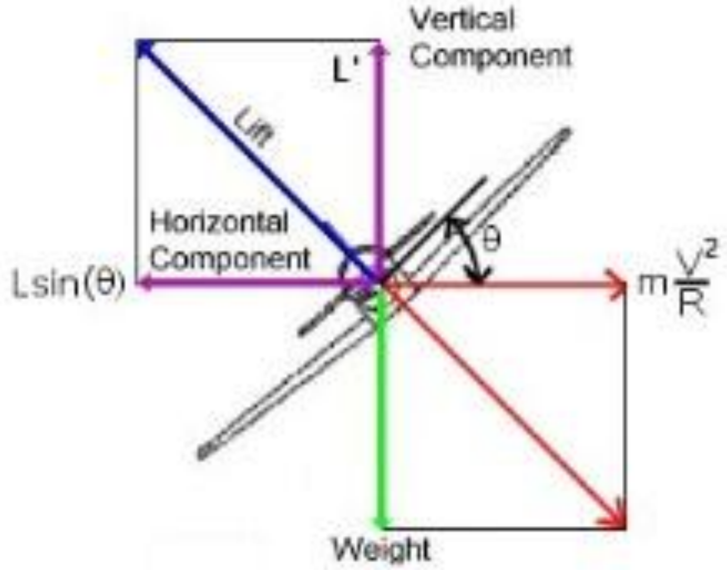
Parachute drift

Obviously, when launching a rocket from a high altitude balloon, it'll drift an enormous distance under its eventual parachute, even if Close Proximity Recovery (CPR, the use of a small drogue for most of the descent) is used, as the winds at high altitude can be fast, particularly the jet streams. Radio tracking is essential.

Boost glider: gliding turn

Things are somewhat worse for a glider or boost glider launched from a high altitude balloon. Even a low Equivalent airspeed translates into a high True airspeed, so a lot of ground can be covered during gliding descent.

One can therefore command the glider to descend in a circle or figure-of-eight to minimise glide distance, but there's a problem: the radius of the glider's turning circle is determined by the centrifugal force generated during the turn, which depends upon True airspeed. So at high altitudes (high True airspeeds) the turning circle can get very large indeed.



Here's the vector diagram for an aircraft in a 45 degree banked turn (and therefore pulling 1.41 gees).

At 45 degrees, the horizontal component of the lift happens to be numerically equal to the weight of the aircraft, therefore:

$$mg = L\sin\theta = m\left(\frac{V_{TAS}^2}{R}\right)$$

(equ. 4.1)

The equation determining the turn radius *R* (metres) is therefore:

$R = \frac{V_{TAS}^2}{g}$ (equ. 4.2) where *g* is 9.81 (assuming the airspeeds are in metres per second.)

By inserting equation 1.2 (including the relative density σ) into equation 4.2 we get:

$$R = \frac{V_{EAS}^2}{g}\left(\frac{1}{\sigma}\right)$$ (equ. 4.3)

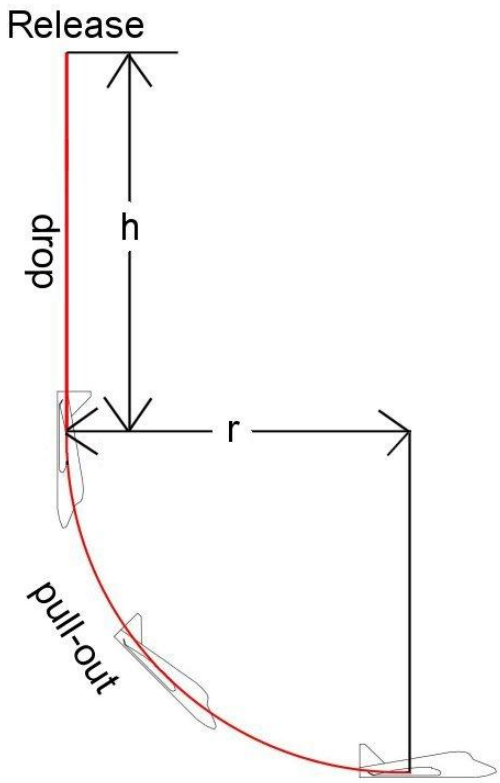
where we discovered earlier that if the launch is to take place at a typical helium balloon altitude of 100,000 feet above sea-level, then: $\frac{1}{\sigma} = \frac{1.225}{0.01710} = 71.6$

Or in other words, the glider's turning circle is *71.6 times larger* than it would be at sea-level.

With such a large turning circle it could well be that the glider simply can't turn as smartly as its autopilot requests it to do, so that the autopilot then fails to keep the glider on-track.
It would be better to just circle down into the lower atmosphere where the turning circle is much smaller before trying to follow a set course.

Boost-glider: drop and pull-up

A similar problem occurs when a glider is dropped vertically from a high altitude balloon. The ensuing pull-up manoeuvre from vertical plummet into a near-horizontal glide is pretty-much a quarter of a circle, and for the same reasons this can be an enormous circle at high altitudes.



The manoeuvre starts with a drop from the balloon, where the glider falls vertically (and hopefully nose-first) until it reaches a high enough airspeed to perform the pull-up.
To build up airspeed as quickly as possible, the glider should be trimmed for minimum drag which means reducing **induced drag** to zero by trimming for zero lift from the wings during the drop.

The height of this drop is: $h = \frac{m}{\rho S C_D} \ln\left(\frac{W}{W - \frac{1}{2}\rho\, V_{pull-up}^2\, S\, C_D}\right)$

(equ. 4.4)

where W is the glider's weight, m is its mass, S and C_D come from the **drag equation**.

ln( ) is the natural logarithm. (See appendix 1 for derivation of this solution).

Now if we substitute equation 1.2 into equation 4.4 we get:

$$h = \frac{m}{\rho S C_D} \ln\left(\frac{W}{W - \frac{1}{2} S\, \rho_{sea\_level} V_{EAS}^2 C_D}\right) \quad \text{(equ. 4.5)}$$

Where V_{EAS} is the Equivalent airspeed at pull-up.

The ln( ) term is now constant, so h varies only with the 1st term in the equation, i.e. inversely proportionally with the density at altitude ρ.

Now if the launch is to take place at a typical helium balloon altitude of 100,000 feet above sea-level, then: $\sigma = \frac{0.01710}{1.225} = \frac{1}{71.6}$

Therefore *the drop will have to be 71.6 times longer* at 100,000 feet than at sea-level. This is perhaps not much for a small model glider, but gets significant for bigger models or full-sized gliders.

At the end of the drop, the glider reaches a flyable airspeed, enough to perform the pull-up from vertical plummet to near-horizontal glide.
Assume that the pull-up manoeuvre is a vertical circle as shown above where the lift force reacts the 'centrifugal' radial force.

The radial force is equal to $\frac{m V_{TAS}^2}{r}$ where *m* is the mass of the glider and radius *r* is the radius of the circle. Rearranging:

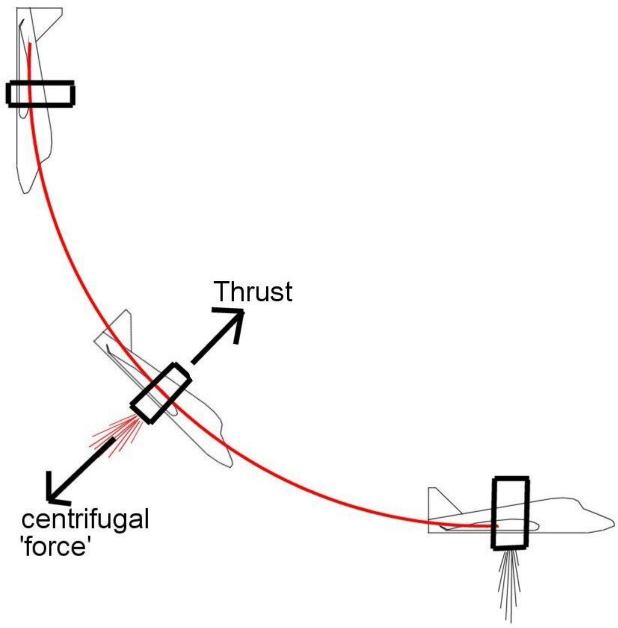
$$r = \frac{mV_{TAS}^2}{radial\ force} = \frac{mV_{TAS}^2}{\frac{1}{2}\rho_{at\_altitude}V_{TAS}^2 SC_L} = \frac{2m}{\rho_{at\_altitude}SC_L} \qquad \text{(equ. 4.5)}$$

Yet again the size of the circle is inversely proportional to the density at altitude, so yet again, the circle will be 71.6 times larger at 100,000 feet altitude.

During the drop and pull-up manoeuvre, the glider is combatting drag all of the time, so energy (height and speed) is continually being lost. Pulling a tighter circle requires combatting higher centrifugal 'force' so more lift is required which causes higher **induced drag**. Pulling a larger circle causes the circumference of the circle to get large, so more energy is lost to **profile drag** and the height loss is large. Either way, a drop followed by a pull-up is an inefficient manoeuvre at very high altitude: a lot of energy is lost to drag.

Suppose that a rocket engine is fired on the boost-glider when it completes the pull-up so that it then performs more of a pull-up circle into a vertical climb. Then some of the propellant will be lost to drag.
For example, if a boost-glider is dropped vertically downwards off of a helium balloon at 70,000 feet then my simulations show that 1/6th of the propellant needed to reach an apogee of 100 Km is lost to drag while performing the pull-up manoeuvre to a vertical climb. That's a large loss of propellant.

One model glider dropped vertically off a balloon (reference 4) had a solid rocket motor fixed at its CG and pointing down through the bottom of the model (through the 'floor'). This motor was used to combat the centrifugal force during pull-up to greatly reduce the pull-up circle's radius:



This was found to require less propellant to complete the pull-up manoeuvre than if the rocket was firing rearwards out of the glider.

<u>Boost-glider: pull-up to vertical ascent</u>
Obviously, if the glider is powered, we'll want to continue the pull-up circle until the boost glider is ascending vertically.
However, if the boost glider is still subsonic by the time it's flying horizontal, then reaching supersonic airspeed will involve punching through the **transonic drag rise** during the pull-up to the vertical. In certain cases, a simple circular pull-up trajectory is inefficient (wastes too much propellant during the punch) so will have to be modified. See our article "Launching spaceplanes from a winged carrier aircraft" for details.

5: transonic cheat

I almost hesitate to mention this due to the tricky practicalities, but I've realised that there is a way to avoid the **transonic drag rise** entirely.
The speed of sound in hydrogen and helium is several times faster than in air (3 times faster in helium, 4 times faster in hydrogen).
Fire the rocket vehicle right through the bottom of the balloon. Arrange for the vehicle to just be at the onset of the drag rise (at around Mach 0.9 in air) as it enters the balloon, and then arrange the acceleration within the balloon to be sufficient such that the drag rise is past just as the vehicle exits the top of the balloon (at around Mach 1.2 or higher in air).
Within the balloon, the hydrogen or helium gas will lower the Mach number by a factor of 4 or 3 so that the **transonic zone** is missed entirely.
Please try this, I'd love to know if it works!

6: Thermal issues

At low altitudes, the dense atmosphere shields us from the glare of the Sun, so that the temperature of a surface exposed to direct sunlight isn't a lot greater than the temperature in shadow.
But at very high altitudes, the difference between sunlight and shadow can be extremely large: surfaces in sunlight can cook, whilst those in shadow can freeze, and the physical colour of the surface can strongly affect its temperature.

Amateurs lofting electronics to very high altitudes on balloons tend to encase the electronics in a thick layer of Styrofoam, so that the interior of the foam box remains at roughly room temperature; warmed by the heat coming off the electronics.

7: Ignition woes

It would be very embarrassing if you got your rocket vehicle to very high altitude on a balloon but then the rocket failed to ignite!

Below about 20,000 feet, air contributes significantly to the heat transfer from the igniter to the rocket propellant.
Above that altitude there is significantly lower assisted convective and conductive heat transfer, so a much more energetic igniter is required to set off the propellant than at sea level.

It's been reported that several rocket vehicles have suffered ejection charge failures at very high altitude. It's not clear why but it's thought that the near-vacuum of very high altitudes is preventing the propagation of heat/flame across the loose pile of expulsion powder; the bulk of the powder doesn't burn. Black powder, like other propellants, has what is called a "deflagration limit" which is a minimum pressure at which combustion is barely self-sustaining. If the pressure is too low, combustion will cease or be erratic at best.

The first way to correct this problem is used on military and civilian high altitude rockets: they use sealed canisters to contain the powder, containing ground-level pressure air with burst diaphragms, for motor igniters and deployment devices. The container is designed to burst at a set pressure when the powder burns and expands.
Whatever material is chosen for the burst diaphragm should be tested to make sure it will break at a 20 psi overpressure to prevent fragment damage to the rocket, since confined black powder can generate 25,000 psi pressure or higher.

A second, though heavier, option is to use pressurised carbon dioxide (CO_2) to power the recovery system.

8: Hydrogen

At first sight it is *obvious* that a balloon containing a very flammable gas is very dangerous. So today helium, which is non-flammable, has almost completely replaced hydrogen for filling balloons and airships.
However, just because something is obvious does not mean that it is true. Helium is very expensive and will only get more expensive as the world's supply runs out. Hydrogen is much cheaper, and will get progressively cheaper as hydrogen-fuelled transport increases.

The World's first hydrogen-filled airship made its first flight in 1852. More than a hundred and fifty years later the Hindenburg disaster is still the *only* accident to *any* airship involving the death of a passenger. The facts simply do not support the idea that hydrogen-filled balloons and airships are very dangerous.

The Hindenburg disaster was a case of structural breakup in strong winds coupled with the political decision to use a certain type of exceedingly flammable paint for the skin of the aircraft. The ensuing hydrogen fire (note: not an explosion) was the end result of a chain of catastrophic occurrences. Most of the passengers and crew got away safely.

Barry Gray (Reference 5) puts hydrogen into perspective:
"The danger with flammable gases is not fire but explosion, where the gas has *first* escaped to mix with the air and *then* the mixture of gas and air has become ignited. But hydrogen is very much lighter than air, and hydrogen escaping from an *airborne* balloon will disperse very rapidly indeed and never build up around the balloon to form an explosive concentration."

If the balloon bursts and there's ignition, there still isn't much mixing with oxygen so it's not so much a pop as a thwumph (which is the technical term). The hydrogen burns upwards and quickly. The bad thing is if the latex catches fire (which it doesn't always) and then falls back down onto something. A rockoon launch would have a good physical separation between balloon filling and rocket/gondola prep, which would help, but some sort of remote gas shut-off, to safe the filling area in the event of a burn, would help too.

Here is a video of a deliberately induced hydrogen balloon ignition which backs up the above remarks. There is no explosion: http://www.youtube.com/watch?v=cQvpK9cl0No

Almost all balloon accidents involving hydrogen fires have taken place on the ground at the time the balloon was being filled; in fact they have really involved cylinders containing hydrogen rather than balloons filled with it.
By improving the conductivity of the whole system (fabric and lines) to prevent static electrical charges, the dangers can be reduced to a tolerable level.

Surely mixing rockets with hydrogen is dangerous? Well of course many rockets employ hydrogen. What we must do is not let an internal pocket of hydrogen and air be ignited within the balloon, which is easy to prevent.

It could be considered unwise to ignite the rocket after the balloon had burst due to excessive altitude. Again, this is easily preventable.
The rocket ignition would not ignite the hydrogen, as the rocket vehicle would be falling rapidly whilst the hydrogen would be ascending. It would be the ensuing vertical flight through the cloud of hydrogen that would ignite it. There might be a fireball, but it would have no teeth: the overpressure caused would be marginal. The speed of ascent of the rocket vehicle through the fireball would be swift enough not to cause any noticeable temperature rise on the rocket vehicle: it would look dramatic, but like a motorcyclist jumping through a flaming hoop it wouldn't be.

Ed Moore of CUSF reckons that he wouldn't have issues using hydrogen in rockoon systems, so long as basic safety is observed with the fill rig, such as grounding the equipment. He's heard of fillers wearing flash jackets too, though in all the hydrogen weather balloons he'd seen inflated, precautions were nothing more than a decent pair of goggles, gloves and long sleeves.

It should be noted that the use of hydrogen aboard ships is no longer permitted under the general conditions imposed for marine insurance. This would obviously be a problem for ship-launched balloons, which is often done in order that the ship steams downwind at the wind speed so as to zero the sideways drag loads on the balloon from the wind.

<u>Excerpts from Ref. 6: safety guidelines (hydrogen balloons)</u>

Protection Zone / Inflation area
The protection zone has to be cordoned off, visible signs, which indicate that smoking is prohibited, have to be placed. All possible ignition sources have to be excluded. Persons that are not authorized have to be kept away from the inflation place. The same is true for moving or standing motor vehicles.

Inflation
Pilot, balloon master, and inflation aides have to be informed about the hazards and safety instructions when using hydrogen. They must be familiar with the local conditions. The inflation personnel must wear clothes and shoes that are antistatic.

Inflation tubes.
The inflation tubes must be conductive and leak-proof. The main closing valve always has to be staffed. The person in charge has to be in visual contract with the pilot or balloon master all of the time. Two fire extinguishers (powder) with a minimum content of 12 kg have to be within reach.

Explosion Protection
Minimum safety distances (weather balloons)
- 10 meters between inflation socket and protection zone.
- 6 meters around the balloon. Only explosion safe lamps and tools may be used.

Launch
When there is evidence of an approaching thunderstorm the inflation process must be immediately stopped. If necessary the envelope can be deflated with the help of the quick deflation system (parachute). Starting is prohibited when there is a storm front approaching.

Flight
When the risk of a thunderstorm becomes manifest during the flight or a thunderstorm is already in full swing, immediately landing is inevitable.

Deflation
Be cautious while deflating: friction and motion of the envelope can lead to electrostatic charge. For deflation the same rules apply as for inflation concerning the distances, the clothing and ignition sources.

Action in case of gas fires
If possible, extinguish the flame by immediately closing the gas supply line. If this is not possible, leave the gas fire burning until the fire fighters arrive, because there is always a risk of re-ignition after the flame has been extinguished.
Balloons that are filled with hydrogen burn without pressure and with a high darting flame. Remains of the burning envelope falling down can be a potential threat to people standing nearby. Special caution is required in cast of the burning of the balloon envelope that is filled with gas and air. Deflagration can suddenly turn into a detonation with a pressure and heat effect.

As one of the precautions against explosion, an antistatic agent may also be added during the manufacture of balloons intended to be filled with hydrogen.

Glossary:

Centre of Gravity, centre of mass (CG):
The point within the vehicle that is the centroid of mass, the balance point.

Centre of Pressure (CP):
The point on the rocket's surface where the average of all the aerodynamic pressure forces from the nose, body, and fins act. This must be behind the Centre of Gravity (CG) by at least one **Calibre** for stability.

Drag (equation):
Drag, or 'air resistance', is the retarding force experienced by bodies travelling through a fluid (gas or liquid).
The equation used to calculate drag is simply the *drag coefficient,* C_D, times **dynamic pressure**, times some reference area '*S*', i.e: $D = \frac{1}{2} \rho V^2 S C_D$ (ρ = atmospheric density.)
For the rocket vehicle, this reference area '*S*' is the maximum cross-sectional area of the fuselage (ignoring the fins or small, local structures), whereas for aircraft, it's the total wing area.

Dynamic pressure: (q)
All aerodynamic forces scale directly with the kinetic energy term: $\frac{1}{2}\rho V^2$
ρ being volume-specific mass or air density, and V = flow velocity.
This kinetic energy term is called Dynamic Pressure (q), to distinguish it from its Potential energy counterpart of static pressure (P).

Induced drag:
The drag caused by lift (predominately from the wings) so is proportional to the lift coefficient C_L i.e.
$C_{D\_induced} \propto C_L$
For traditional aircraft shapes (long slender wings) $C_{D\_induced} = kC_L^2$ where k is a constant.
From the **lift equation**, as an aircraft gains airspeed (V^2 increases) then less lift coefficient is needed to maintain flight (keep lift constant) therefore the induced drag actually decreases with increasing V^2.

Lift (equation):
Lift is a force generated by aircraft at right-angles to their flightpath.
The equation used to calculate lift is simply the *lift coefficient,* C_L, times **dynamic pressure**, times some reference area '*S*', i.e: $L = \frac{1}{2} \rho V^2 S\, C_L$ (ρ = atmospheric density.)
For aircraft, this reference area 'S' is the total wing area.

Mach number:
The vehicle's airspeed V compared to the speed of sound '*a*':

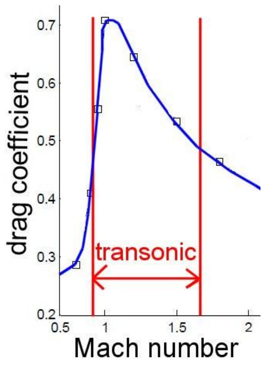
$$M = \frac{V}{a}$$

Profile drag (also known as Form drag):
The drag of the fuselage etc, i.e. separate from the **induced drag**. Profile drag is proportional to the square of the airspeed: $D_{profile} = \frac{1}{2} \rho V^2 S C_{D\_profile}$ where $C_{D\_profile}$ is a constant.

Subsonic:
Vehicle airspeed is below Mach 1 (see **Mach number**).

Supersonic:
Vehicle airspeed is above Mach 1 (see **Mach number**).

Transonic (zone):
Above a **freestream Mach number** of about 0.7, certain parts of the **local** flow around the nose and fins will hit a local Mach of above 1.0, **supersonic**.
Similarly, up to a freestream Mach number of about 1.4, certain parts of the local flow around the nose and boat-tail are still **subsonic**.
The transonic zone is this freestream Mach number region where there is a mix of subsonic and supersonic flow. This mixture makes predicting the aerodynamics of the zone difficult and inexact.



Transonic drag rise:
Peak **profile drag** occurs within the transonic zone at around Mach 1. This drag peak is very large so requires a high thrust to 'punch' through it to reach supersonic speed.

Vehicle: (the)
A stationary object immersed in a moving airflow, or an object moving through stationary air. (Aerodynamically, these two situations are identical in every respect.)
Here, the vehicle is a rocket-vehicle.

References:

Ref. 1: 'Aerodynamics for Engineering students' by Houghton and Carruthers.

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Ref. 4: 'High altitude balloon-launched aircraft: a piloted simulation study' Murray, Moes, Norlin, NASA Dryden flight research facility, AIAA-93-1019

Ref. 5: 'Hydrogen, helium, the Hindenburg, airship safety and the future' by Barry Gray, http://www.barrygray.pwp.blueyonder.co.uk/Tutoring/BSaft.html

Ref. 6: 'Hazards and safety when using hydrogen'
http://www.gasballooning.net/Hydrogen%20Safety.htm

Ref. 7: UK high altitude society website: http://ukhas.org.uk/

Shuttle escape picture:
http://www.nasaimages.org/luna/servlet/detail/nasaNAS~7~7~37854~141704:Shuttle-crew-escape-systems--CES--r

Appendix 1: derivation of vertical drop

Assuming no induced drag, the vertically downwards acceleration during the drop is:

$a = \frac{W-D}{m}$ where *W* is the glider's weight, and *m* is its mass.

D is its drag, which is proportional to V_{TAS}^2

Now $a = \frac{dV}{dt}$ and by using the chain rule of differentiation: $\frac{dV}{dt} = \frac{dV}{dx}\frac{dx}{dt} = V\frac{dV}{dx}$

where *x* is downwards distance.

Thus: $\frac{W-D}{m} = V\frac{dV}{dx}$ which on rearranging gives: $dx = \left(\frac{m}{W-D}\right)VdV$

Now $D = \frac{1}{2}\rho\, V^2 S\, C_D$ (see the **drag equation**) therefore: $dx = \left(\frac{m}{W-\frac{1}{2}\rho\, V^2 S\, C_D}\right)VdV$

Integrating gives: $x = \int_0^{V_{pull-up}} \left(\frac{m}{W-\frac{1}{2}\rho\, V^2 S\, C_D}\right)VdV$

Using the substitution: $U = W - \frac{1}{2}\rho\, V^2 S\, C_D$ then differentiating: $dU = -\rho\, S\, C_D V\, dV$

And therefore:

$$x = -\frac{m}{\rho\, S\, C_D}\int_{U_1}^{U_2}\left(\frac{1}{U}\right)dU = -\frac{m}{\rho\, S\, C_D}[\ln(U)]_{U_1}^{U_2} = -\frac{m}{\rho\, S\, C_D}(\ln(U_2) - \ln(U_1))$$

$$= -\frac{m}{\rho\, S\, C_D} ln\left(\frac{U_2}{U_1}\right) = \frac{m}{\rho\, S\, C_D} ln\left(\frac{U_1}{U_2}\right)$$

where ln( ) is the natural logarithm.

Substituting back for V using the above $U = W - \frac{1}{2}\rho\, V^2 S\, C_D$ where V_1 is zero gives:

$$x = \frac{m}{\rho S C_D}\ln\left(\frac{W}{W-\frac{1}{2}\rho\, V_{pull-up}^2\, S\, C_D}\right)$$