Manned suborbital spacecraft missions

Aspirepace technical papers

Author: Rick Newlands

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Introduction

This paper includes previous papers ‘Suborbital re-entry’ and ‘Launching spaceplanes from a winged carrier aircraft’.

As time passes and technology improves, more and more commercial companies and amateur groups are getting interested in going into space, either for space tourism or to simply enjoy a few minutes of ‘zero-gravity’.

Getting into orbit is still very challenging, but simply getting a craft just above the Kármán line of 100 kilometres (i.e. officially into space) is much easier. It’s actually 7/8ths easier, as it requires only $1/8^{th}$ of the propellant and $1/8^{th}$ of the **delta V**.

But getting the spacecraft back safely requires care, and some radical vehicle designs, because the gees suffered during re-entry can be *much higher* than for an orbital re-entry.

This paper describes suitable spacecraft to perform such a **suborbital** mission with examples given of one-person craft; launch, ascent, and eventual re-entry. Both winged and non-winged craft are discussed, although the boundaries between the two blur during re-entry because wings at very high **angles of attack** are more drag-devices than anything else.

With modern composite materials, and advances in computational fluid mechanics, a low-energy mission at low **dynamic pressure** can be designed safely.

Words in **bold** appear in the Glossary at the end of the document.

Note I’ll sometimes use Newton’s fluxion notation: using a dot above a letter to denote derivative with respect to time, i.e. $\dot{\phi} = \frac{d\phi}{dt}$

Mission

Space is officially deemed to start at 100 Km above sea-level.

Scotland from 120 Km apogee

To reach this altitude on a purely vertical ascent requires the craft to attain only about 1.6 Km/sec **delta-V** at burnout, which can be achieved with a surprisingly small amount of rocket propellant: a **mass ratio** as low as 2

The ensuing re-entry will begin at around 70 Km, although nothing much will happen until the air begins to 'bite' at around 45 Km.

Equivalent Airspeed (EAS)

The concept of Equivalent Airspeed (EAS) has fundamental consequences for several aspects of a suborbital spacecraft's flight (reference 1), and so will be introduced here at the outset. I'll slant this explanation in terms of an aircraft, but it applies equally well to a non-winged re-entry capsule.

The density of the atmosphere decreases with altitude, which means from the **Lift equation** that an aircraft must fly faster (at the same angle of attack) to achieve the same lift at altitude as opposed to if it were flying at sea-level.

The aerodynamics of the aircraft will dictate several key airspeeds such as best glide airspeed, best climb airspeed, and above all, maximum safe airspeed that the structure can withstand, and the pilot will want to know how these airspeeds increase with increasing altitude.

Altitude-Equivalent Airspeed performs the conversion for him; if he flies at 100 Knots Equivalent airspeed, then the aircraft will perform the same as if it were flying at a True (actual) airspeed (TAS) of 100 Knots at sea-level: the aerodynamic loads on the vehicle (lift, drag, **dynamic** or 'hull' pressure) will be 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)

Upon canceling:

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

where $\frac{\rho_{at\ altitude}}{\rho_{at\ sea\ level}}$ is known as the relative density σ

It would be convenient for the pilot if his Airspeed Indicator showed Equivalent airspeed rather than True airspeed, and happily it so happens that the mechanics of a traditional Airspeed Indicator do exactly that.

The problem for spaceplanes occur when pitching manoeuvres are performed at very high altitudes: the aerodynamics (available Lift) depend on Equivalent airspeed, whereas the G's pulled during the *pull-up manoeuvre* (see later) depend upon the True airspeed, which is very much higher than the EAS at very high altitudes.

Equivalent airspeed is useful for calculating the aerodynamic forces on the spacecraft hull. The forces on a spacecraft travelling at 100 knots EAS at any altitude will be the same as if it were travelling at 100 knots at sea-level (though care has to be taken to take Mach number changes in aerodynamics into account).

Another parameter often used to calculate hull forces is **dynamic pressure** *q*. This is related to Equivalent airspeed as:

$$q = \frac{1}{2}\rho_{Sea\_level}V_{EAS}^2$$

The Mach problem

From the above, you can deduce that high altitude flight/high altitude launch reduces Equivalent airspeed; a good thing.

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, 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 vehicle needs wings/fins and a nosecone designed for supersonic flight. This is a particular problem for boost 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 boost glider off a balloon, it can easily hit Mach 1 before it pulls out into a glide.

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

Launch and ascent: ground-launched or air-launched?

Copenhagen Suborbitals are a talented bunch of engineers intending to launch one person on a non-winged rocket vehicle. They intend launching from sea-level, but are dolefully aware that small rocket vehicles launched from sea-level suffer from a *much* higher waste of propellant combatting drag than larger vehicles do (as a percentage of launch propellant mass).

The only solution is to use much more propellant, and to keep the vehicle cross-sectional area (see the **drag equation**) as low as possible. In Copsub's case this means that the passenger gets squeezed uncomfortably into a narrow-diameter fuselage.

This requirement for more propellant results in big propellant tanks and hence a big spaceship. Bristol Spaceplanes' 'Ascender' spaceplane is large considering it only ascends two people to just over 100 Km.

Another problem with sea-level launch is that the Equivalent airspeed/dynamic pressure gets exceedingly large during ascent. This requires a sturdy airframe, and heat-protection, all of which weigh a lot.

Vertical ground launch

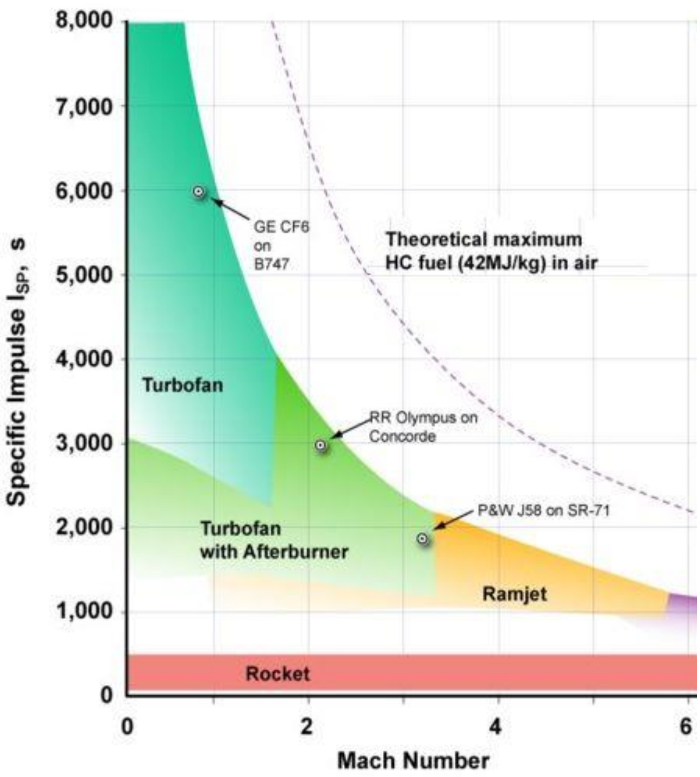
A final problem with sea-level/ground-level launch is that if something goes wrong on a non-winged rocket, chances of the pilot getting out alive and activating a parachute before impacting the ground are slim. Some sort of escape rocket is his/her only chance. And anyone who bails-out above Mach 1 at low altitude will quickly get torn apart.

Horizontal ground launch

A winged vehicle taking off from a runway or sled track has many more abort options, but there still remains the high Equivalent airspeeds during ascent requiring excessive rocket propellant.

One solution that appears at first glance to reduce this propellant load is to use jet engines for the initial climb to altitude.

A metric commonly used to compare rockets and jets is **Specific impulse** (Isp).The following graph shows Isp versus Mach number for jets and rockets.



Specific impulse of various engines (Wikipedia)

Jets have a high Isp, which is unsurprising as unlike rockets they don't need to carry their oxidiser onboard the vehicle.

As the speed gain (**delta V**) that the spacecraft achieves is directly proportional to the engine Isp then it would appear to be a foregone conclusion that a spaceplane should use jet engines for the low airspeed part of the ascent as Bristol Spaceplane's Ascender spaceplane does.

However, it's not so clear-cut:

Firstly, jet engines are much heavier per Newton of thrust produced (lower thrust-to-weight ratio) so that over a short point-to-point distance or rapid vertical climb, a rocket is actually the better choice in terms of reducing vehicle mass.

Secondly, the effect of altitude on jet thrust is a function of air density, which is proportional to pressure and inversely proportional to temperature. The higher you go the less air pressure there is and the colder it gets. As pressure decreases thrust decreases, but as temperature decreases thrust increases. However, the pressure drops off faster than the temperature so that there is actually a drop off in thrust with altitude.

At about 36,000 feet altitude (the Tropopause) the temperature stops falling and remains constant while the pressure continues to fall. As a result, the thrust will drop off more rapidly with height above this altitude, so this limits the altitude that the standard jet provides a useful amount of thrust to around 50,000 feet.

Useful thrust can be maintained to higher altitudes by the injection of liquid oxygen plus water into the engine intake (or liquefied air or nitrous oxide) but this requires modification of the engine control software and the carriage of this propellant onboard.

Above Mach 1, the jet needs a variable geometry inlet to function efficiently, which is a large and heavy piece of equipment.

Once the jet has finished providing useful thrust and is shut down in favour of the rocket engine at altitude, the jet then becomes dead weight that has to be hauled into space.

There is also the issue of keeping the jet engine ‘happy’: the jet is lubricated and cooled by oil and grease, which will out-gas (flash evaporate) above a certain high altitude rendering the jet unusable upon descent into the atmosphere again. The jet fuel will likewise out-gas. The jet must also be protected from the heat of re-entry somehow. Furthermore, Sgobba points out that the bearings of jet engines can shatter under the vibration of the rocket engine when it fires. All these suggest that the jet has to be encased inside a pressurised, vibration isolated, duct inside the spaceplane.

Benefits of air launch

Launching your spacecraft from a high altitude aircraft/balloon makes much more sense. Propellant mass and Equivalent airspeeds are significantly lower, and there’s time to do something if the mission goes awry before hitting the ground.

- The spaceplane is already flying if dropped from an aircraft so full aerodynamic control is available (not reliant on thrust vectoring).
- The launch occurs above the Troposphere, i.e. above the weather.
- The winged carrier aircraft is effectively the first stage; the height gained by the carrier raises the spaceplane’s **apogee.**
- The high altitude *greatly* reduces the **drag** on the spaceplane which raises the apogee even more: the effect on apogee for a suborbital mission type (a) spaceplane is dramatic.
- Atmospheric pressure is reduced at altitude: less back-pressure on the rocket nozzle improves its thrust and so raises apogee.
- Expensive launchsite infrastructure is no longer required (e.g. launchpad and bunkers).
- Operational flexibility: can fly to a wide choice of launch locations.
- Large number of abort options: e.g. if the mission had to be aborted then there would be time to dump the liquid propellants before landing.
- The rocket portion of the flight can occur over the sea (lowest number of people underneath).
- The rocket engine need not be throttlable due to the launch occurring at high altitude and so avoiding a large peak **dynamic pressure** (see ‘transonic punch’ section later).
- The rocket engine need not be vectorable (suborbital mission) as the trajectory can be altered by purely aerodynamic means.

Actually, the reduction in **drag loss** is significant. As the air is thinner (reduced density) at altitude, one can then make the spaceplane fuselage much fatter yet still achieve a low drag loss. A fat fuselage is a lot lighter (low bending moments, see later section on structures) especially with a wing on it. Remember the Interim Hotol that was going to be launched off an Antonov at altitude? It was really fat.

Fat fuselages hold propellant tanks better (can be spherical tanks) and give room for low-density propellants such as nitrous oxide or liquid hydrogen that need very large tanks (‘flying gassometers’).

Also, there's a big increase in first stage **Specific impulse** because of the reduced atmospheric back-pressure at altitude; larger nozzle exit bells can be used. Also, this allows you to use lower combustion chamber pressures, which saves engine mass.

In Britain, there simply isn't enough empty land anywhere to launch a rocket from the ground to 100 Km, because you'd need a 100 Km wide no-go area for public safety; air-launch is therefore the only option in Britain. The rocket portion of flight can occur over the sea (lowest number of people underneath).

An air launch has a better public perception: aircraft/balloons are seen as 'less dangerous' than rockets. Recovery would be on land or sea.

Air launch technique

Then we need to decide on a viable air launch technique.

The spacecraft could be dropped from a carrier aircraft.

Unfortunately, an aircraft can only tow or carry a spacecraft to around 50,000 feet altitude with conventional jet engines, although it's possible to increase the performance of the jets by injecting a proportion of liquefied air into their intakes. To limit Equivalent airspeed during rocket ascent to a low value requires a launch above 70,000 feet.

70,000 feet mandates the use of a gas balloon to initially ascend the spacecraft.

Launch rail

Having decided on a balloon, the method of launch requires consideration. Ground-launched rockets often use a launch rail; a mechanical guide which restrains rotation of the rocket until its fins/wings reach flying speed, around 30 Knots Equivalent airspeed (EAS).

However, air density at 70,000 feet is only 6% of that at sea-level, therefore 30 Knots EAS = 125 Knots TAS. To reach 125 knots TAS at a constant 4g acceleration requires 52 metres (172 feet) of launch-rail (see appendix 1). This size of launch-rail would be too heavy to be carried by a balloon.

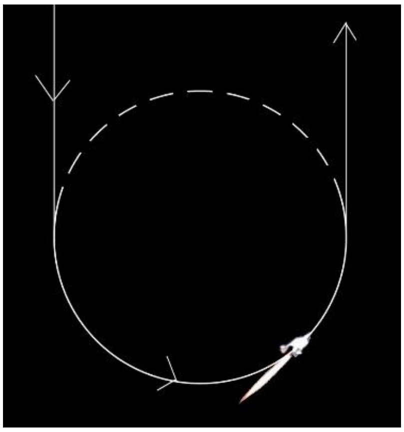
What will happen if we try to launch our vehicle from a short launcher at high altitude? Its wings/fins will be useless (no aerodynamic forces from either wings/fins or nosecone), so the vehicle will be at the mercy of the only remaining effects: tiny non-asymmetries that crop up in the manufacture of 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?

Vertical drop

One option to dispense with a launch rail is simply to drop the spacecraft from the balloon.

For a non-winged rocket vehicle, the rocket engine should be ignited the instant the vehicle is released from the balloon. Some form of thrust vectoring is required as fins haven't yet reached flying speed (and if they had, the rocket would flip over to point nose-first at the ground).

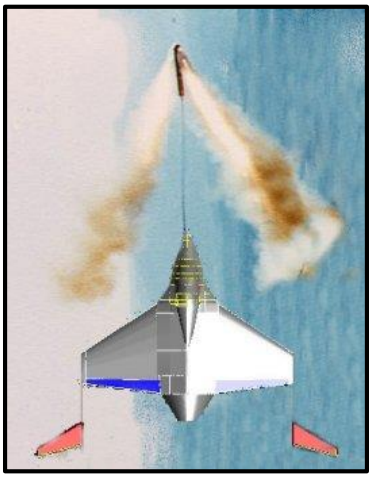
You might decide that for a winged vehicle, let it drop for some distance then ignite the rocket engine once fin/wings flying speed has been reached. Then perform a pull-up manoeuvre up to the vertical.



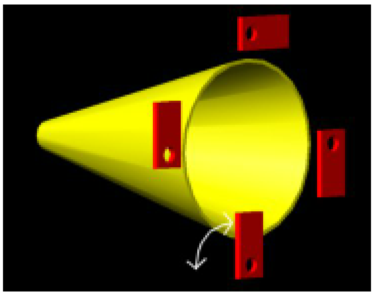
Unfortunately, analysis shows (see appendix 1) that the low density at these altitudes results in an excessively large radius of the semi-circle linking vertical descent to vertical ascent, which results in a high centrifugal gee load and large drag loss This high gee load manoeuvre wastes excessive propellant: up to 1/6 of the propellant onboard is wasted to lift-induced drag according to simulations.

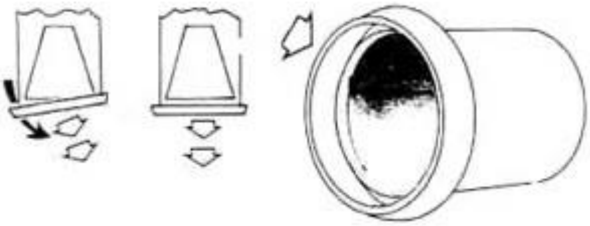
So the remaining choice is a vertical ascent immediately upon release from the balloon, which requires some sort of steering mechanism (and a kink in the initial trajectory in order to miss the balloon).

Two choices present themselves: 1) spin stabilisation, and 2) thrust vectoring.



1) The spin-rate required to produce sufficient ‘gyroscopic stability’ would be unpleasant to say the least for the spacecraft occupant. A better option is to move the spinning component off the spacecraft: a separate spin-stabilised stage which is linked to the spacecraft by a tow-line. Such a mechanism is used on a tractor rocket device used to pull pilots free of aircraft. It resembles a Catherine-wheel: several solid motors spin it up. 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 device only needs to achieve 125 Knots TAS at 70,000 feet to allow the wings/fins to attain operational speed, and then is jettisoned. Then the main spacecraft engine is fired.
2) At higher altitudes, the much higher True airspeed required for the wings/fins to attain operational speed would require an excessively large spinning device. Also, Equivalent airspeed could drop too low for aerodynamic control towards the end of the ascent. Some form of traditional thrust vectoring device is needed. However, the cost and complexity of thrust-vectoring systems varies enormously. The cheapest and simplest method that has been considered consists of swinging heatproof obstructions into the nozzle exhaust. These ‘jet tabs’ cause a blockaging effect and create shockwaves; these bend the rocket exhaust sideways slightly to give the required vectoring. Four jet-tabs arranged 90 degrees apart around the nozzle provide steering in all directions. The other method considered is a jetavator: a gimballed ring positioned around the circumference of the nozzle exit. This creates thrust loss only when tilted.





The balloon

It is a requirement to keep the Equivalent airspeed during rocket ascent very low. If, for example, ascent starts from a height of 35 kilometres up (115 thousand feet) then the maximum Equivalent airspeed during ascent is only 60 knots.

A rocket fired from a balloon is known as a rockoon system.

To get the spacecraft plus fuelled rocket booster to very high altitude up requires a large balloon.

Consider hydrogen (see our paper 'Launching rockets from a high altitude balloon' on the Aspirespace website, 'technical papers' webpage). Most modern balloonists use helium, even though it doesn't lift so well requiring a bigger balloon. Helium is becoming scarce and so helium's currently *very* expensive, and will only get ever more expensive, unlike hydrogen which is cheap, and is getting cheaper. The required balloon could require hundreds of thousands of pounds sterling worth of helium.

Many European balloonists are switching to hydrogen balloons.

As it happens, the U.K. has experience of large balloon projects. While it is true that the Qinetiq One helium balloon burst upon inflation, that was caused by manufacturing defects in the balloon canopy: easily rectified by better quality control.

The balloon would be launched from a quarry or from a boat, at sunrise when the winds are light.

For the mechanics of launching a large balloon see the Red Bull Stratos website www.redbullstratos.com

Ascent

This paper assumes a vertical ascent to just over 100 Km. A non-vertical ascent incurs more propellant and a higher re-entry airspeed.

If the launch occurs at 70,000 feet or lower, then there will still be a high enough Equivalent airspeed at engine burnout for wings/fins to stabilise the ascent whilst the engine is firing. If launch altitude is higher, Equivalent airspeed will drop too low for aerodynamic stabilisation to work by the time burnout is reached.

Re-entry

What goes up suborbitally, must come down. After a vertical fall from around 100 Km apogee, the spacecraft encounters the atmosphere at an airspeed around Mach 3.

There are two vehicle design aspects to re-entry:

1) Dealing with the aerodynamic heating.

2) Mitigating the g-deceleration.

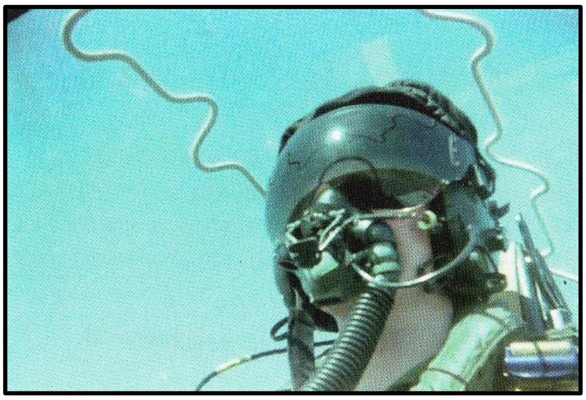
Concerning 1, Peak **Mach number** during re-entry is just over three, so heating isn't an issue. Simply use heatproof materials for the nosecap and wing/fin leading edges such as high-temperature resins or stainless steel edges.

As for 2, the gees suffered are, however, a major design issue. Get the design wrong and you could pull 10 gees.

The problem is the *angle of entry* which is the angle that the craft's trajectory encounters the atmosphere. Orbital craft encounter the atmosphere at a very shallow angle (around 4 degrees), so should be able to perform their re-entry at high altitude where the atmosphere is thin.

Suborbital craft descending vertically slam into the atmosphere at an angle of entry of 90 degrees, so can quickly descend into the thick lower atmosphere whilst still at very high airspeed. This feels like hitting a brick wall. So paradoxically, suborbital re-entries can suffer much higher gees than orbital re-entries.

Life support



At altitudes above 10,000 feet, some form of life support is required (supplemental oxygen). As altitudes increase, life support requirements become more onerous.

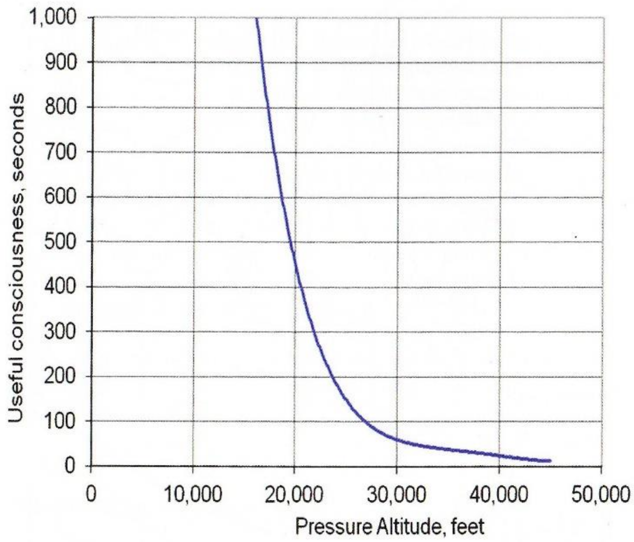
By 33,700 feet altitude, the pilot has to breathe pure oxygen (typically through a mask).

Above 39,500 feet, pure oxygen alone isn't enough; there has to be sufficient pressure inside and outside the lungs for the lungs to be able to absorb oxygen.

This requires that the spacecraft cabin is pressurized with some gas to a pressure equal to atmospheric pressure below (preferably significantly below) an altitude of 39,500 feet.

One other consideration, often overlooked, is the need to keep the cabin temperature constant; around 20 degrees C is preferable. Hypothermia or heatstroke can be fatal. A spacecraft cabin ascending on a balloon can be cooked by the Sun and the heat produced by the pilot's body.

Protection from Space



Typical adult useful consciousness time at various altitudes

What are the dangers of exposure to Space? Depressurisation at high altitude carries the following risks:

Lack of oxygen (hypoxia), which can cause rapid loss of consciousness, depending on the altitude at which the depressurisation occurs. The pilot shall wear an oxygen mask.

Decompression illness at altitudes over 18,000 feet. Nitrogen bubbles out of the blood and causes 'the bends'. The pilot will counter this by pre-breathing oxygen for a few hours before liftoff to purge the blood of dissolved nitrogen. However, above 50,000 feet it's unlikely to offer effective protection.

Ebullism, the spontaneous change of liquid water to water vapour in body tissues at an ambient pressure below 63 millibars. This can occur at altitudes over approximately 63,000 feet and rapidly lead to damage to the lungs and surrounding tissues. If the integrity of the pressurised cabin is breached, it's essential to maintain the pressure sufficiently high to prevent ebullism and to ensure that the gas composition maximises the chances of injury-free survival. The risk increases with the area of the breach. The pilot may consider carrying a 'repair kit' to quickly plug small leaks, plus a gas supply to keep the cabin at a low pressure during emergency descent to lower altitudes.

Barotrauma, which is damage to body tissues from a change in pressure. If the capsule depressurises rapidly, the pressure differential between gas in the cabin and gas in the lung could become so great that it may tear lung tissue. This would mean air would leak into the chest (pneumothorax or pneumomediastinum) and gas could get into the tissues (mediastinal emphysema) or circulation, known as arterial gas embolism.

In the event of a depressurisation, medical personnel trained in the treatment of the consequences of decompression at high altitudes would need to be available on the ground to assess and treat the pilot immediately on landing, and specialist medical equipment may be required. For example, Scotland has treatment centres for North sea oil divers on the East coast.

Radiation, Over and above Cosmic rays, a solar flare/storm from the Sun could bathe the pilot in an unacceptably high level of radiation. Generally, various organisations can give a half-hour's warning of a solar flare (though not always). The best protection is an onboard radiation detector. If the reading becomes too high, abort the ascent and get down to low altitude as quickly as possible.

Part 1: ballistic (non-winged) launch and ascent

Accomplishing ascent to just over the Kármán line (100 kilometres apogee) involves squeezing the occupant into some sort of pressurized capsule riding atop a rocket.

This is a traditional approach - the early astronauts rode atop converted missiles - but it doesn't mean that it's a good idea. It never was, it was just an excuse to showcase ballistic missile guidance accuracy to the enemy. As David Ashford says "If I want to send my grannie on a world cruise, I don't tie her to a torpedo."

Launching from a balloon/aircraft at high altitude makes considerably more sense than the highly dangerous practice of ground-level launch, simply because there's time to sort out any problems before hitting the ground and the rocket exploding.

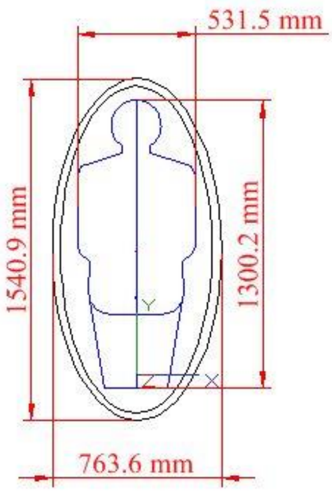
Another major benefit of a high altitude launch is the significantly reduced Equivalent airspeeds during ascent. This causes a major reduction in **drag loss**.

For these reasons, the launch should occur at as high an altitude as possible. If ascent starts from a balloon at an altitude of 35 kilometres (115 thousand feet) then the maximum Equivalent airspeed during ascent is only around 60 knots.

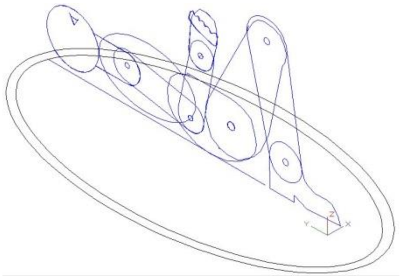
Capsule layout

Reduced Equivalent airspeeds during ascent from a launch at altitude allows the use of a considerably fatter capsule diameter which is much less uncomfortable for the occupant, especially under high gee.

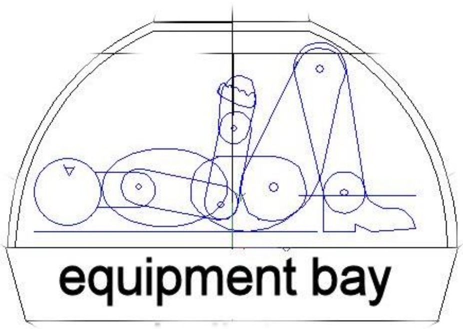
Peak gees during an efficient (low **gravity loss**) suborbital ascent to just over 100 kilometres are about four at rocket engine burnout. This dictates that the capsule occupant has to be lying on his/her back. (Standing upright would give a thin capsule with reduced drag, but I'm sure the occupant would black out even with an advanced gee suit.)



A simple shape that encloses a human (6 foot tall here with knees bent) with minimum capsule planform area is an ellipse:



This gives an elliptical capsule:



Part 2: winged launch and ascent

A microlight spacecraft

Recently, the U.K. Civil Aviation Authority (CAA) have perhaps unwisely decided to de-regulate single-seat microlights. This means that single-seat microlights don't need to comply with build regulations: civil design code BCAR Section S microlight (although it would be foolish not to comply for safety reasons), and don't require a permit to fly/annual inspection.

This opens up the range of single-seat microlights to encompass simple one-person boost-gliders, something the CAA would have previously baulked at.

With modern composite materials, and advances in computational fluid mechanics, a low-energy mission at low Equivalent airspeed/low dynamic pressure can be designed safely.

Microlight definition

The U.K. definition of a microlight aircraft is as follows:

1. Maximum all-up mass (including pilot) less than or equal to 300 kg (450 kg for 2-seaters). Extra mass is conceded for fitting of ballistic parachutes.
2. Stall speed/minimum landing speed (in the landing configuration) less than or equal to 35 knots Calibrated airspeed (CAS).
3. Maximum achievable airspeed in level flight less than or equal to 100 knots Calibrated airspeed (CAS).

Dealing with definition 1, it could be argued that a boost-glider is a different type of vehicle (a rocket) during vertical rocket ascent, so rocket propellant mass needn't be counted in the Maximum all-up mass calculation.

Definition 2 is simply a question of wingloading after all propellant has burnt out/ been jettisoned.

Definition 3 is rather a soft limit; modern microlights regularly exceed it. Note that the airspeed is Calibrated airspeed (Equivalent airspeed). Equivalent airspeed can be low whilst True airspeed is high at very high altitudes (see ealier). Also note this is level flight speed, not speed during vertical ascent.

So, with a bit of haggling, a single-seat boost glider can be squeezed into the CAA category of deregulated single-seat microlight.

It would be prudent to adopt relevant sections from design codes for larger and faster aircraft, such as JAR 23 and CS VLA (very light aircraft) where they pertain to subjects such as pressurised cockpits.

Launch

The first question is whether the spaceplane will launch from the ground, or whether it will be towed or carried to some launch altitude.

Ground launch from a runway (i.e. horizontal takeoff) is immeasurably safer than vertical launch from the ground, and many spaceplane designers are going for this option. However, the Equivalent airspeeds during ascent become onerously large which requires a sturdy airframe and a large requirement for propellant just to combat drag.

The requirement of a carrier aircraft is to get the spacecraft to as high an altitude as possible to save on propellant. For a spaceplane, it's also worth releasing it at a reasonable forward airspeed.

To attain high altitude requires high-performance wings of high **aspect ratio**, and the use of jet engines. Neither of these are required later on in the mission, and so are dead-weight that should be jettisoned at launch altitude: Spaceship 2 parts from its high-lift jet-powered carrier aircraft at around 45,000 feet.

The exact launch altitude is dictated by the following constraints:

We want a low equivalent airspeed throughout rocket ascent to minimize **drag losses**, and to reduce **dynamic pressure**, which will reduce the structural weight required: a maximum of 140 knots EAS (typical light aircraft airspeeds) can be achieved by starting high enough up.

It would be useful to have high enough EAS's for aerodynamic control right up until motor burnout, which dictates a minimum of around 30 knots EAS at burnout: this dictates the maximum start altitude.

Trajectory simulations of the rocket ascent show that these constraints dictate a best launch altitude of around 70,000 feet.

Avoiding collision during separation

When the spaceplane separates from the carrier aircraft, there is a risk of re-contact (collision). This risk increases both with EAS (aerodynamic loads) and the square of TAS (kinetic energy) so both should be minimised.

Certainly, separation should never be attempted at supersonic airspeeds: not only are the airspeeds higher, but shockwaves bounce between the two craft giving rise to aerodynamic forces that can cause unforeseen pitching moments which could pitch one vehicle into the other. (There were many studies in the 1960's that involved supersonic separation, but we now know they were fraught with danger).

A separation should get the carrier aircraft as far away from the spaceplane in the shortest time so as to minimise the danger of spaceplane engine explosion causing shrapnel to impact the carrier aircraft. (Having said that, a rocket engine designed to loft passengers shouldn't ever explode.)

The spaceplane is restricted in roll angle (in order not to waste airspeed as it's heavy with fuel) but the carrier aircraft is now free of its load and so is highly manoeuverable: it should bunt (pull negative gee) to get well below the spaceplane, whilst banking at maximum bank angle until it's flying away at full speed at 90 degrees from the heading of the spaceplane.

The ascent pull-up manoeuvre

After release from a carrier aircraft, a spaceplane will stabilise into a descending glide, and then ignite its rocket engine, whereas a spaceplane that has powered itself to altitude by jet engine will be in a very shallow climb when it lights its rocket.

Whether climbing or descending, the craft will be flying near-horizontally, and needs to perform quarter of a loop under rocket power to attain a vertical ascent.

The Spaceplane will be laden with propellant, and so will require a lot of lift from its wings to perform the pull-up. From the **Lift equation** this dictates a reasonable wing area (*S*) if high Equivalent airspeeds are to be avoided.

High EAS's *should* be avoided, because the high altitude means that high EAS's mean high True airspeeds, which results (see appendix 1) in the physical size of the circle becoming excessively large at high altitudes.

For example, if a spaceplane is dropped vertically off of a helium balloon at 70,000 feet then simulations show that 1/6th of the propellant is lost to drag while performing the pull-up manoeuvre to a vertical climb. This dictates that the spaceplane should instead rise vertically from the bottom of a rope tied under the balloon.

This loss is obviously less for spaceplanes starting in a gentle glide rather than a vertical plummet, but the loss is still surprisingly significant. The higher the **wing loading**, the faster the TAS, or the higher the lift coefficient has to be and so the **induced drag** is larger (which increases with lift coefficient), so a low wing loading is preferable.

The X15 with its very high wing loading lost vast amounts of propellant during pull-up. It also lost several thousand feet altitude before beginning the pull-up.

The Russians took a novel approach with their MAKS spaceplane proposal: the Antonov airliner it was launched from was to fire a small rocket in its tail to perform the pull-up manoeuvre to a 70 degree climb with the Antonov and spaceplane still attached to each other! This wouldn't require a terribly powerful rocket, and the pull-up propellant is carried by the carrier aircraft rather than the spaceplane. The high-performance/low wing loading wings of the carrier were therefore to be used for the pull-up manoeuvre.

The pull-up manoeuvre is limited to 2 to 3 G's due to airframe and wing structural limits and takes about 1 minute to reach a climb-out angle above 45 degrees nose-up. During the pull-up maneuver, the launch vehicle is subjected to both high sideways bending moments as well as high dynamic pressure.

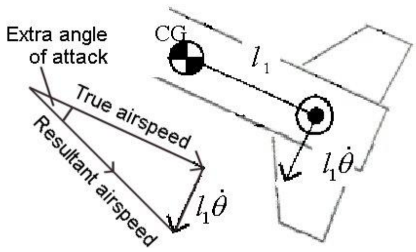
Aerodynamic damping

As the ascent progresses, the pilot will notice an unfamiliar aspect coming into the craft's handling (if he hasn't prepared himself on a flight simulator).

At low altitudes, aircraft have good Dynamic stability (see our paper 'rocketry Aerodynamics' chapter 4 on the Aspire website).

Rotations about the CG ($\dot{\theta}$ = rotation rate) cause an extra angle of attack on the fins/tailplane/wingtips which resists the rotation, and damps it out. This is known as 'aerodynamic damping'.

This damping *decreases* as *True* airspeed increases:



Extra angle of attack = $\tan^{-1}\left(\frac{l_1\dot{\theta}}{V_{TAS}}\right) \cong \left(\frac{l_1\dot{\theta}}{V_{TAS}}\right)$

So at very high altitudes (low EAS but high TAS) *there is no rotational damping.*

This causes some problems:

- The Spaceplane becomes difficult to fly, because there is no damping to prevent high rates of rotation from building up, it feels like driving on ice.
- There is no damping to oppose the natural aircraft oscillation in pitch: 'porpoising', or the oscillation in yaw: 'shakin' that ass'.

- One real danger is the lack of roll damping; a rapid roll rate can quickly build up: ‘corkscrewing’, as happened to Spaceship One on one of its prizewinning flights just prior to burnout.

Solutions to the lack of aerodynamic damping are to make slow, gentle control inputs, and to introduce a large degree of Static stability (see our paper ‘Rocketry aerodynamics’ chapter 4 on the Aspire website) to reduce the amplitudes of ‘porpoising’ and ‘ass shaking’ oscillations.

Introduce rotation rate sensors (rate gyros) into the control servos as negative feedback to limit rotation. This type of rate feedback is now being incorporated into radio-controlled aircraft using MEMS gyros to make them easier to fly.

Part 3: ballistic (non-winged) re-entry

While I strongly feel that a winged vehicle is the best option for accomplishing ascent to just over the Kármán line (100 kilometres apogee) followed by re-entry, many groups want to opt for the traditional vertically-launched rocket vehicle with manned capsule. There then follows the problem of providing some device to produce *enough* drag (see below) to *reduce* the re-entry gee load to tolerable levels.

The drag requirement

From Newton's 2nd law, the deceleration a produced by the re-entry capsule's parachute's drag force is:

$$a = \frac{F_{drag}}{m}$$ where *m* is the mass of the re-entry capsule (plus parachute mass).

From the Drag equation:

$$a = \frac{F_{drag}}{m} = \frac{\frac{1}{2}\rho V^2 S\, C_D}{m} = \frac{\frac{1}{2}\rho V^2}{\beta} \quad or = \frac{\frac{1}{2}\rho V^2\, C_D}{CL}$$

where β is known as the ballistic coefficient: $\beta = \frac{m}{S\, C_D}$ (which clearly isn't a coefficient)

and *CL* is known as the canopy loading (related to an aircraft's **wing loading**): $CL = \frac{m}{S}$

S is the 'chute's **planform area** (projected area).

So to produce a low deceleration requires a high ballistic coefficient or high canopy loading, *or so you'd think!* But note the occurrence of the atmospheric density ρ in the above equation: that has a *very* big influence on the re-entry as we shall see shortly, and turns this result on its head.

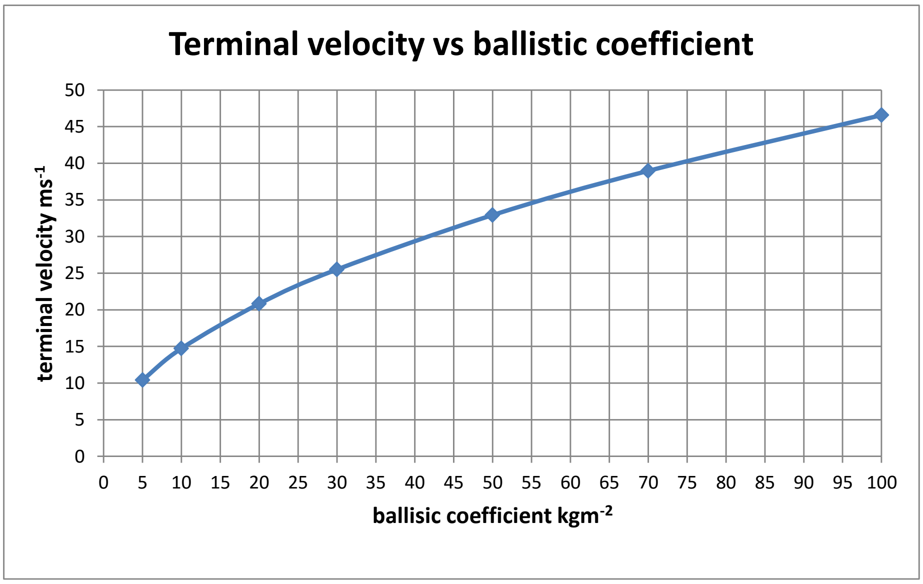
After re-entry, the capsule will eventually settle down to fall at a fixed terminal velocity where the drag *D* is equal to its weight *W* (including the weight of the 'chute) and so:

$$W = mg = D = \frac{1}{2}\rho V^2 S\, C_D$$

Rearranging, the descent airspeed (terminal velocity) is then:

$$V = \sqrt{\frac{mg}{\frac{1}{2}\rho S\, C_D}} = \sqrt{\beta\left(\frac{2g}{\rho}\right)} \quad or \quad \sqrt{CL\left(\frac{2g}{\rho\, C_D}\right)}$$

So the lower the ballistic coefficient or canopy loading, the slower the capsule descends. With suitably low ballistic coefficient or canopy loading, the terminal velocity is subsonic (below Mach 1) which makes selection of the landing parachutes easier:



The 'chute size paradox

I discovered this back in the '90s when I simulated suborbital re-entries of our Aspire 2 vehicle. I tried to recover Aspire 2 using supersonic parachutes, and after running numerous sims I found something very surprising.

Very strangely, as I increased the size of the parachute (increasing canopy area *S*), the gees suffered during re-entry *went down* instead of up. This was very odd, because at sea-level, the bigger the 'chute, the bigger is *S*, so the bigger the drag force it causes: a larger force should produce a *larger* deceleration (Newton's 2nd law) as we saw above.

Such is the beauty of sims, they sometimes throw something unexpected at you. After checking for sim program bugs, I had to concede that the weird result still remained, and I then investigated what was going on:

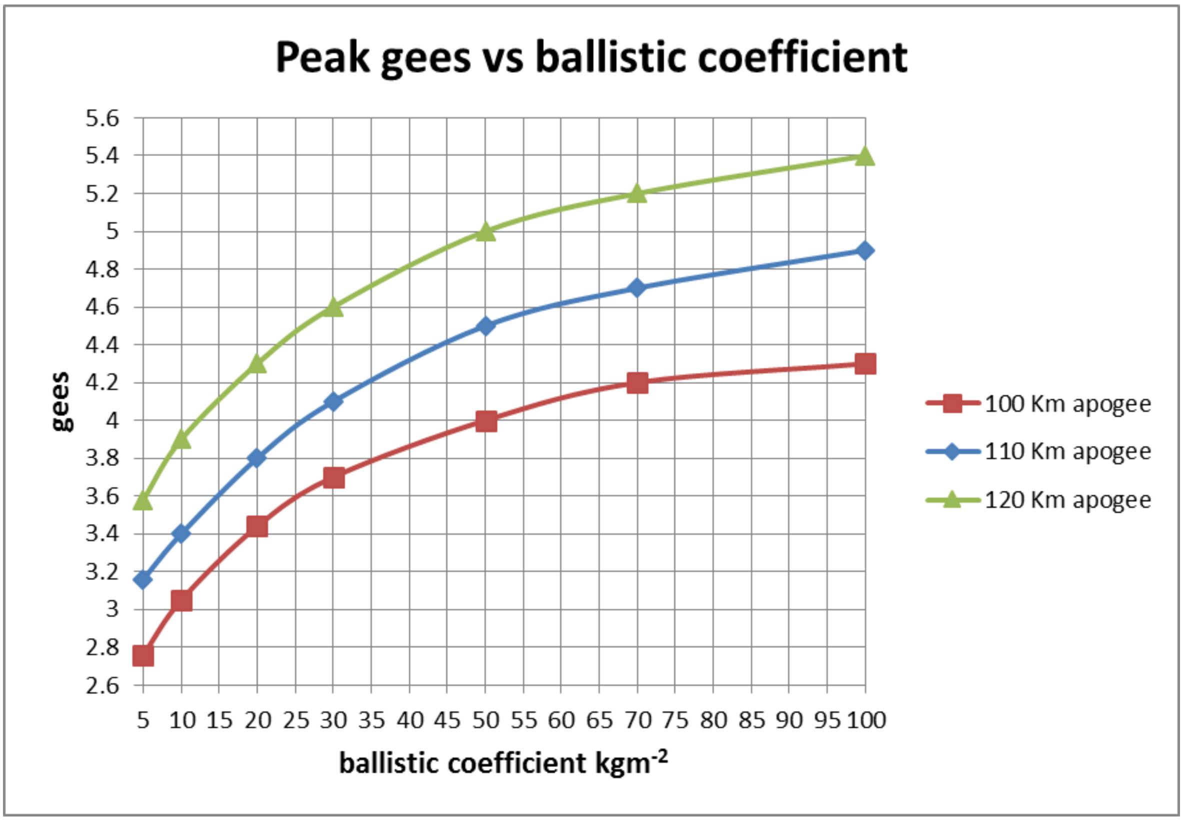
The explanation is that larger drag areas are able to provide a drag force much higher up in the atmosphere: the larger area compensates for the much lower air density at altitude (see the **Drag equation**).

Producing usable drag higher up reduced the gees because the atmosphere doesn't thicken linearly with decreasing altitude, it increases *exponentially* with decreasing altitude.

So the *rate* at which the atmosphere is thickening around the craft as it descends at some vertical velocity is much gentler higher up, so if re-entry is performed higher up, then the deceleration to low speed is spread-out over a much larger vertical 'braking' distance, which lowers the gees.

On top of this there's the simple issue that there's less height to fall between 100 Km and the top of the atmosphere compared with 100 Km to the lower atmosphere: you simply haven't built up so much speed.

Here's a graph of my sim results for a capsule with fixed C_D versus Mach number descending vertically from various apogees:

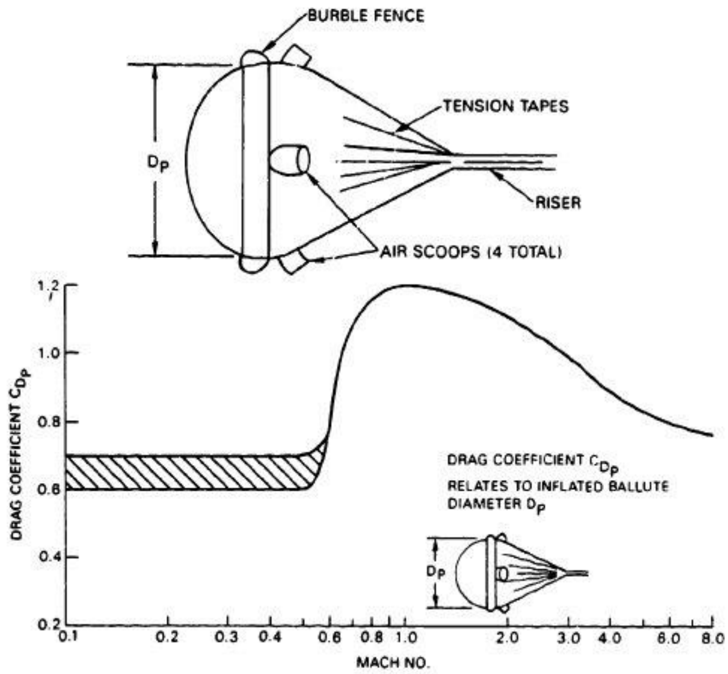


So suborbital craft should *maximise* drag area, and should get this drag working as soon as possible after **apogee**, i.e. deploy your 'chute as high up as possible. This is a problem, because conventional 'chutes, even supersonic ones, require a moderate air density to open properly, but we need their drag much earlier in the re-entry.

The lower the ballistic coefficient or canopy loading, the lower the gees, as this graph shows, it's quite possible to keep the gees less than 4 with a moderately large 'chute.

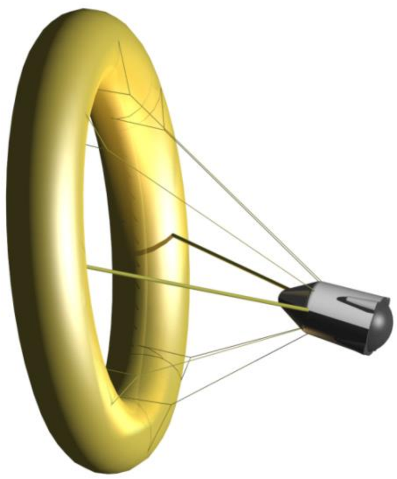
Ballutes

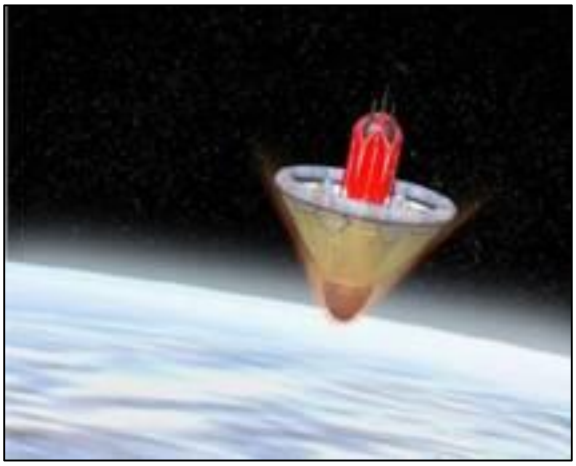
Inflatable high-Mach number ‘chutes have been designed and tested, known as ‘ballutes’:



Drag Coefficient Versus Mach Number for Goodyear Ballute.

These can be inflated at very high altitudes, or even in space.





They’re constructed of typical parachute fabric, but coated with an outer layer of rubber for gas-tightness, and the rubber ablates to carry away the heat of re-entry. (Very high Mach number ballutes are woven of stainless steel cloth coated in rubber ablative).

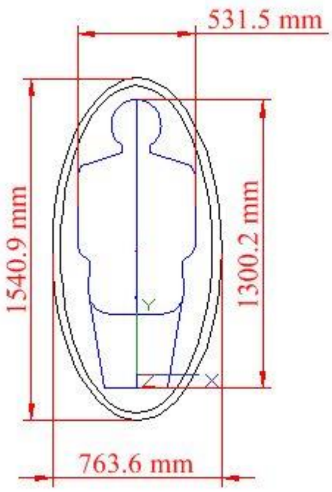
Note that a blunt-based capsule design such as the Apollo or Mercury re-entry capsule doesn’t have enough drag area to keep the gees low during suborbital re-entry.

Design of a manned capsule

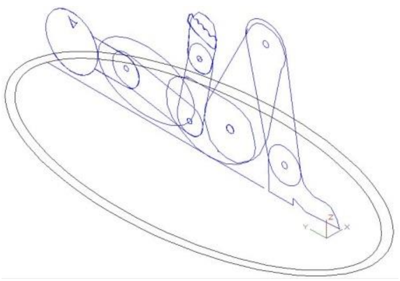
So the requirement for a manned capsule is for low drag during ascent (low **planform area**), but a ballistic coefficient of 50 kg/m^2 or less during re-entry.

Layout

A simple shape that encloses a human (6 foot tall here with knees bent) with minimum capsule planform area is an ellipse:



The area of an ellipse is: $S = \pi ab$ where *a* and *b* are half the lengths of the major and minor axes. So from the drawing, the capsule has a planform area of 0.92 m^2

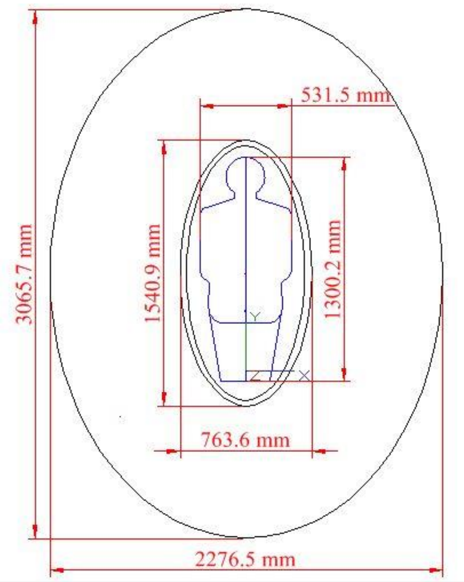


Ballute area

If we assume that the capsule has a mass of 300 kg (fibreglass double-hull) with occupant, and has an average drag coefficient of 1.1 at around Mach 2 (the Mach at peak gees, max Mach is 3.1) then the required planform area for a ballistic coefficient of 50 kg/m^2 is:

$$S = \frac{m}{\beta\, C_D} = \frac{300}{50\times1.1} = 5.46 \text{ m}^2$$

This area is shown by the outer nearly-ellipse here, which has approximate area:



$$S = \pi(a + x)(b + x)$$

where *x* is the width of the skirt and a and *b* are as above.

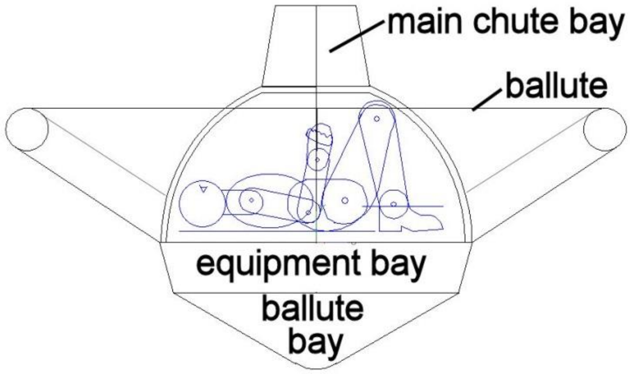
This extra area is most easily provided by an inflatable skirt of some description: an attached ballute. Not only does this provide the required planform area but at minimal extra mass, but it also can act as a flotation device if the capsule lands in the sea.

Stability

The Apollo or Mercury re-entry capsules had a shape that was not aerodynamically stable; they required constant use of nose thrusters to stay upright. Without thrusters they'd pinwheel uncontrollably.

There are two simple ways to make our capsule stable. One is to add 'feathers': the tailbooms added to Rutan's Spaceship One, and the other method is to arrange the ballute skirt as a shallow cone whilst keeping the capsule centre of gravity low down.

This second method is sketched here:

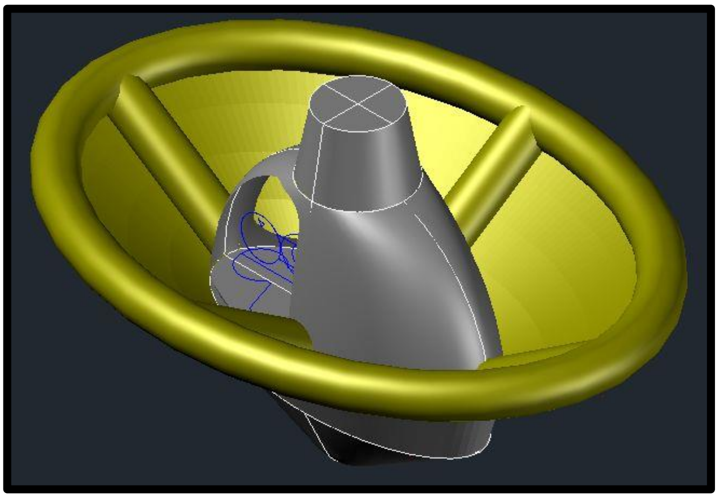


An inflatable elliptical tube runs round the rim of the fabric skirt with eight radial support tubes (four are shown), and an inner elliptical tube (not shown) at the inner ends of the radial tubes.

Heavy equipment such as life support is mounted in the underfloor equipment bay to keep the CG low.

Not shown are steel cables attached to the skirt rim to prevent the skirt popping inside-out during re-entry.

This design is based on several NASA studies of inflatable shallow-cone ballutes, as well as the original design for the DaVinci project X-prize entry conical ballute which is the right-hand picture shown in the 'ballutes' section above.



You may be of the opinion, based on your experience of kid's inflatable paddling pools and bouncy castles, that inflatables are intrinsically floppy. However, it's all about the pressure used for inflation, these are at *very* low pressure.

I'm the owner of one of the new generation of inflatable tents: a rubber tube of about 10 cm diameter is encased in a tough, unstretching fabric sleeve. The sleeve is tailored so that when the rubber tube is inflated, a semi-circular arch is created. When inflated to 12 psi (0.8 bar) an arch of over 2 metre radius is created from this mere 10 cm diameter tube, and I can testify that the tube is as rigid as an inflated bicycle tyre.

A slightly higher inflation pressure is enough to rigidify the ballute to withstand the peak Equivalent airspeed of 116 knots (60 metres per second) that occurs during the descent of this capsule. A larger ballute planform area will reduce this peak airspeed accordingly.

Main ‘chutes

The main landing ‘chutes are stored in a container at the top of the capsule. A pilot ‘chute is fired from a mortar to get it clear of the stagnant wake behind the ballute, and this pilot ‘chute extracts the main ‘chutes.

Landing speed depends on canopy loading (vertical landing). The lower this is, the lower the landing speed.

Part 4: winged re-entry

Re-entry drag area

The same 'chute size paradox described in part 3 also applies to winged suborbital craft: we must provide them with enough drag area to reduce the gees. This goes against every aircraft designer's wish to *reduce* drag!

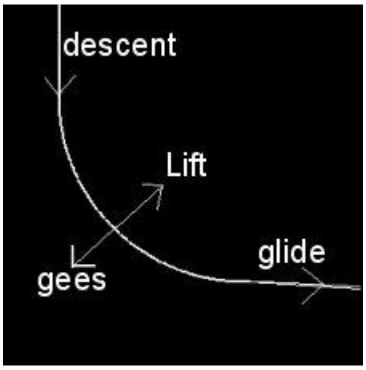
As Burt Rutan knows (and see reference 1), the way to do this is to have a large wing area, and to push these wings through the air at absurdly large angles of attack (around 90 degrees) so that the wings are really just drag devices.

In part 3 I introduced **canopy loading**. The aircraft equivalent is **wing loading**, and as with canopy loading, the lower the **wing loading**, the lower the gees. Burt has reduced his gees to a peak of around 4.5 with Spaceship 2, whereas I've reduced the peak to 3 gees by using a lower wing loading for my Swift spaceplane (see example B later), accepting that larger wings weigh more and cause more drag during ascent.

The re-entry pull-up manoeuvre

The main difference between a non-winged suborbital re-entry and a winged one is that the winged craft has to start with a vertical plummet then eventually settle down into a shallow near-horizontal glide.

Once again, my simulations show that it's important to perform this manoeuvre as high up in the atmosphere as possible, to mitigate both the gees suffered, and also the peak **dynamic pressure** (max aerodynamic loads). So it should be combined with the re-entry.



To perform this pull-up manoeuvre high up requires a lot of Lift. From the **Lift equation**, as the air density is low, and the airspeed moderate, then the craft has to be designed to generate a high lift coefficient and have a large wing area for its weight (low wing loading).

The lift is reacting the 'centrifugal force' from the turn, however the outcome is different from the ascent pull-up manoeuvre. In this case we're adding very large drag area into the mix, which reduces the True airspeed and so reduces the centrifugal gees (which vary with True airspeed).

It so happens that for delta-winged craft operating at supersonic airspeeds, peak lift occurs at around 60 degrees angle of attack, and at that angle, the drag from the wings is nearly the maximum value you'd get at 90 degrees angle of attack. So an angle of attack of 60 degrees satisfies both requirements for the re-entry, and re-entry pull-up manoeuvre.

Two trajectories: a low angle of attack pull-up

To illustrate the effectiveness of the high-altitude re-entry pull-up manoeuvre combined with high drag area, here are the results of two sims of a generic delta-wing vehicle (reference 3) with a wing loading of 294 N/m^2 re-entering suborbitally from an apogee of 100 Km.

1) In this 1st instance, we'll keep the angle of attack low, no more than 14 degrees. Consequently, the drag is low.

During the pull-up manoeuvre, I had to progressively reduce angle of attack in order to keep the gees less than 6 (due mostly to centrifugal force), but due to the very large radius of the pull-up manoeuvre to horizontal glide I began to run out of sky.

Peak re-entry happened about 60,000 feet up, which is frankly very low to be doing those sort of speeds (Mach 3 ish), you're going to get a very hot and heavy structure because **dynamic pressure** was high.

The 6 gees occurred over an uncomfortably long time period, the occupants wouldn't like that at all.

2) I then performed the same re-entry but reducing the angle of attack still further to limit the gees to 4, and something nasty happened: the gees became 5 at zero angle of attack, i.e. all the gees were due to **profile drag**, and were acting along the fuselage axis, which would be nasty for the passengers (eyeballs-out gees) due to the direction of the drag (straight backwards).

This happened because I was slamming into the thick lower atmosphere at high airspeed. And I pretty-much ran out of sky: the pull-up circle was so large that I nearly hit the ground. **Dynamic pressures** at this low altitude were exceedingly high.

Is there any way we can improve on this?

It turns out that there is: if we can produce a large amount of drag, then we rob the vehicle of True airspeed, and so as centrifugal force is proportional to the square of True airspeed, the centrifugal force during the pull-up will be less.

However, we need to produce the same order of drag as a high angle of attack re-entry, which is an awful lot!

One way to do this is to deploy a moderately large braking parachute (i.e. a ballute) trailing behind the vehicle at a far enough distance behind it to be in clean air. Another way to do it is to deploy very large airbrakes on the vehicle (we're talking barn door here).

We're now effectively performing the same re-entry as a non-winged vehicle, and the result is the same: more drag is better.

However much drag we produce, this method is still inferior to a high angle of attack re-entry as we're not producing nearly so much lift to reduce the angle of entry at the beginning of re-entry. This is reflected in the fact that peak re-entry occurs at lower altitude, so dynamic pressures are higher.

Simulation shows that the minimum drag increment that will produce a viable re-entry is around 0.3 based upon wing area (for the above vehicle). This gives a peak re-entry altitude of around 80,000 feet.

But this re-entry method produces a very unpleasant direction of the g-vector: the occupants are going to be uncomfortable (eyeballs-out gees) due to the direction of the drag (straight backwards): this re-entry ethos would have the occupants feeling that they were in a building with the cockpit as the lower floor below them: they'd effectively be trying to either stand up, or hang horizontally facing 'down', under high gees, which would be most unpleasant.

For the pilot, it'd feel like a prolonged carrier landing. Not pleasant.

However, if using airbrakes, this re-entry option is easier to implement than configuring the vehicle for very high angle of attack flight (see below).

Two trajectories: a high angle of attack pull-up

Using the same vehicle, I then performed the same re-entry but at 57 degrees angle of attack (highest lift with high drag). Peak re-entry occurred at double the altitude: 120,000 feet.

True airspeeds were considerably lower, and the vehicle went subsonic at the end of the pull-up manoeuvre to horizontal glide. Ergo, it wouldn't get hot at all.

By progressively reducing angle of attack towards the end of the re-entry I could keep the gees less than three for not much loss of altitude. Dynamic pressures remained low.

The large pitch angle necessary to get the high angle of attack orients the g-vector down into the seat which is much more comfortable for the occupants.

Basically, it's the combination of high lift with high drag that wins out. Even if severe angles of attack of 60 degrees aren't achievable by your vehicle, strive for as high an angle as you can manage, especially at the beginning of re-entry when the trajectory is still fast and steep, as every extra degree helps.

Reducing the gees: the bottom line

In summary, to reduce re-entry gees: increase drag, increase lift, decrease wing loading. Any of these alone helps, but all three in combination gives the lowest gees.

The X-15 hypersonic research aircraft was able to re-enter at 30 degrees angle of attack (it had conventional wings) by removing the lower vertical tail. This generated moderate lift, but low drag, therefore dive brakes (drag brakes) had to be used to reduce airspeed.

Adding horizontal velocity

To reduce the gees of either low angle of attack or high angle of attack re-entries, we can add a horizontal velocity vector to the vertical velocity at the start of re-entry by flying a non-vertical ascent.

I've simmed this for winged 1st stages of launchers: yes, a horizontal velocity does ease re-entry gees due to the lower angle of entry, but you do need rather a lot of it. A subsonic vehicle will require just over 1 Km/sec to reach above 100 Km. Adding another 1 Km/sec sideways reduces the angle of entry which makes a big difference to re-entry gees. However, re-entry then occurs at Mach 7 so the craft gets very hot.

You then also have the problem that the craft lands a long way downrange.

Basically, this is a poor option, and it needs double the amount of propellant.

High angle of attack stabilisation

If the angle of attack remains low, then a conventional tailplane can be used to stabilise the aircraft. But if a very high angle of attack is required, a tailplane cannot be used. How can we then stabilise a supersonic aircraft at very high angle of attack?

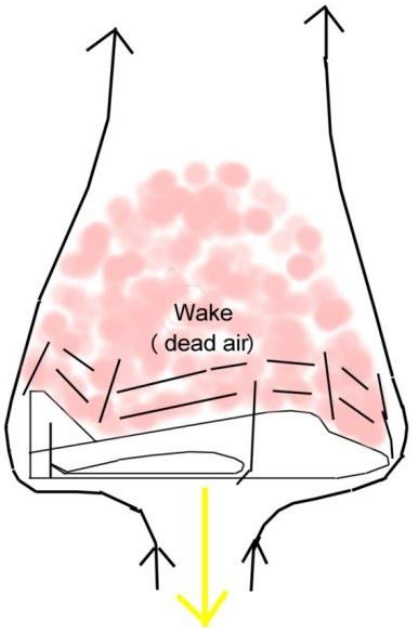
The first question to answer is this: in the absence of a supersonic wind-tunnel, how can we be sure that whatever scheme we devise will work at supersonic airspeeds?

Actually, despite the shockwaves and expansion fans (see our paper 'supersonics and waveriding' on the Aspire website), supersonic flow is very similar to subsonic flow: fins are fins, an angle of attack on a wing or fin gives lift, and lee surfaces are in suction or dead air.

I hadn't appreciated the depth of the similarities until a saw an old NASA film where they tested free-flying models of ***hypersonic*** vehicles in a low ***subsonic*** windtunnel. (If you haven't seen this film: reference 5, it's very illuminating.) The researchers knew that if it was stable at low speed, it'd most likely be stable at high speed.

So we can test candidate supersonic methods for stabilising a winged craft by building and flying simple low-speed scale models.

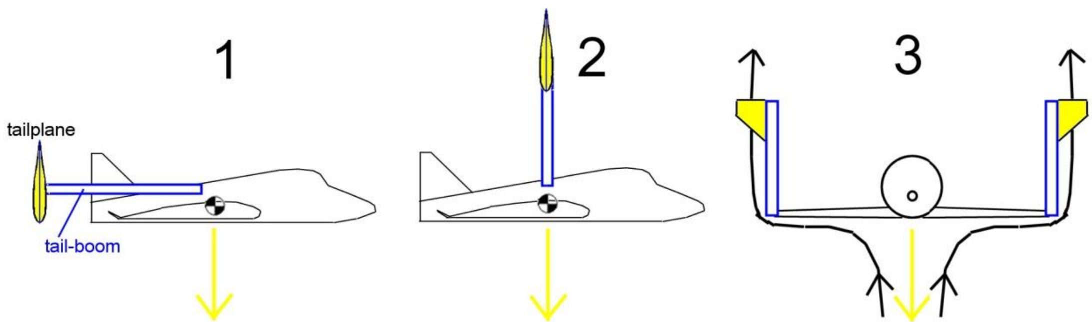
(The footage in reference 5 was filmed in a NASA Langley vertical wind tunnel, known as a spin tunnel. Britain's RAE used to have one but it's probably dead, as Thatcher's government broke up the RAE and sold it for scrap.)



I toyed with the idea of adding stabilising parachutes to a delta-winged craft to orient it very nose-up but there was a problem. The lee of a supersonic vehicle is a large region of dead (stagnant) air. You need a very long rope to get the parachute far enough downstream to avoid this dead wake, and suppose the parachute didn't open?

Next, I wondered whether a tailplane could be made to hold this very high attitude but again there were problems: the conventional site for a tailplane is on a boom at the rear of the vehicle.

But for a very high angle of attack that just won't work, the tailplane is in the wrong place (picture 1 below), the tailplane drag will just swing the vehicle around its C.G. It needs to be on a boom aligned with the airflow (picture 2) which would be a pole sticking awkwardly out of the middle of the fuselage.



But this would mean that the tailplane would be in the dead air of the wake; it wouldn't work.

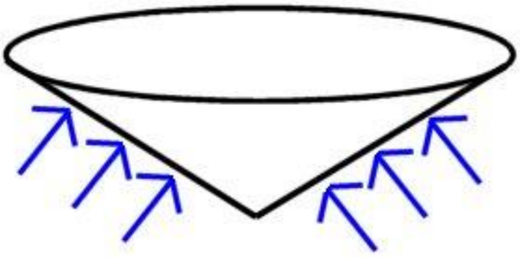
At this point I gave up, but Burt Rutan didn't. He realised that he could modify the tailboom of picture 2 by splitting it in two and bolting it to the wingtips. As the front view of picture 3 above shows, the tailfins are now in the moving air flowing past the vehicle so will function properly. And that's why Burt is a genius! He refers to the pivoting split tailbooms as 'feathers' as he was inspired by the feathers on a shuttlecock.

I've adopted these feathers for my Swift one-man spaceplane design (see example B later) in honour of Burt Rutan, as they're a very ingenious solution.

The XCOR team have taken a different approach with their Lynx suborbital spaceplane.

Note how the nose section is canted upwards relative to the rest of the vehicle.

This is to give 'biconic stability' to the vehicle: it wants to sit at a high angle of attack just as a shallow cone would.



In the picture here, if the cone rotates right or left then that side of the cone hits the airflow at a shallower angle which produces more force to counteract the rotation:

This is the same as the Lynx pitching up or down at 90 degrees angle of attack.

Their windtunnel results confirm their plan (as does the footage of reference 5: a folded delta versus a flat delta) although I'm not sure how they intend to transition between low and high angle of attack, perhaps using thrusters.

Movement of the centre of pressure

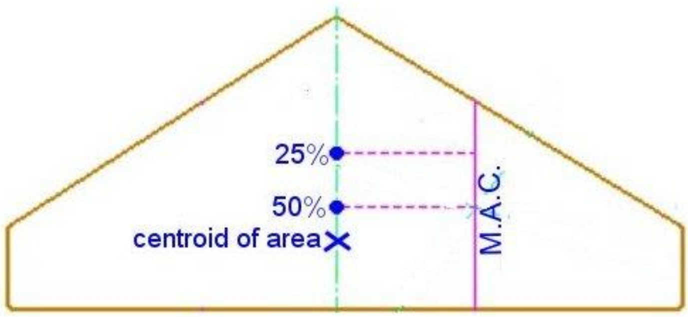
Looking at the picture of Spaceship 2 here, notice how the rear of the wings are folded upwards with the tailbooms (the 'feathers').

This is done because the **centre of pressure** of delta-wings moves rearward at very high angle of attack which would make Spaceship 2 very nose-heavy at high angle of attack.

See appendix 2 for details of how to derive the following geometric positions:

As the re-entry begins, the centre of pressure starts rearward at the **centroid of planform area** at the initial very high angle of attack.

Then as angle of attack is reduced, it moves to the 50% **mean aerodynamic chord** (MAC) position at **supersonic** airspeeds.



Then apart from some positional wobbles in the **transonic zone**, it moves to the 25% mean aerodynamic chord position at **subsonic** airspeeds and low angles of attack.

I should mention that this centre of pressure travel is less for delta-wings than for other aircraft wing shapes which is the main reason that deltas are so popular for supersonic aircraft that have to go subsonic for takeoff and landing, but the travel still has to be dealt with.

Looking at the picture of Spaceship 2 above, Instead of somehow moving the entire wing forward to compensate for the rearward movement of the centre of pressure as angle of attack is increased from low to high, Burt Rutan has instead effectively removed the rear of the wings (by folding them up) to move the centre of pressure forward.

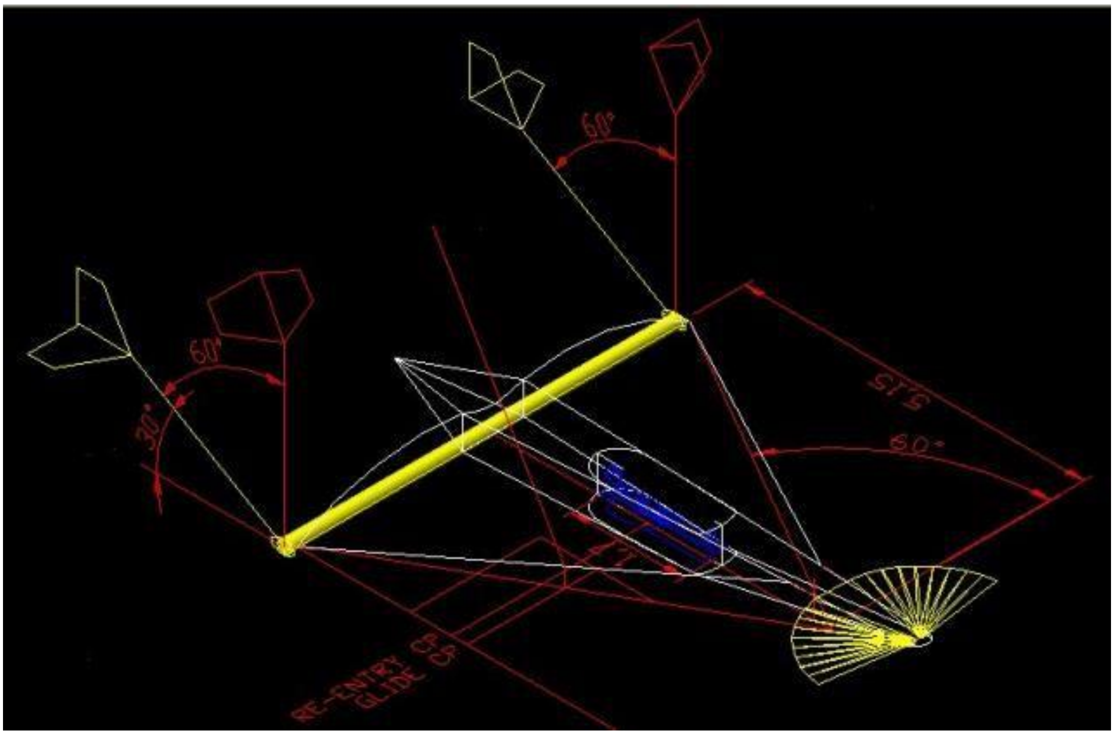
If Burt Rutan hadn't moved the centre of pressure forwards then the torque that the horizontal fins on his movable 'feathers' would need to supply to keep the nose up would be large. Burt preferred much less of a torque requirement so that small and lightweight pneumatic actuators could move the feathers (though their lack of torque may have contributed to the 2014 break-up of Spaceship 2 during flight testing).

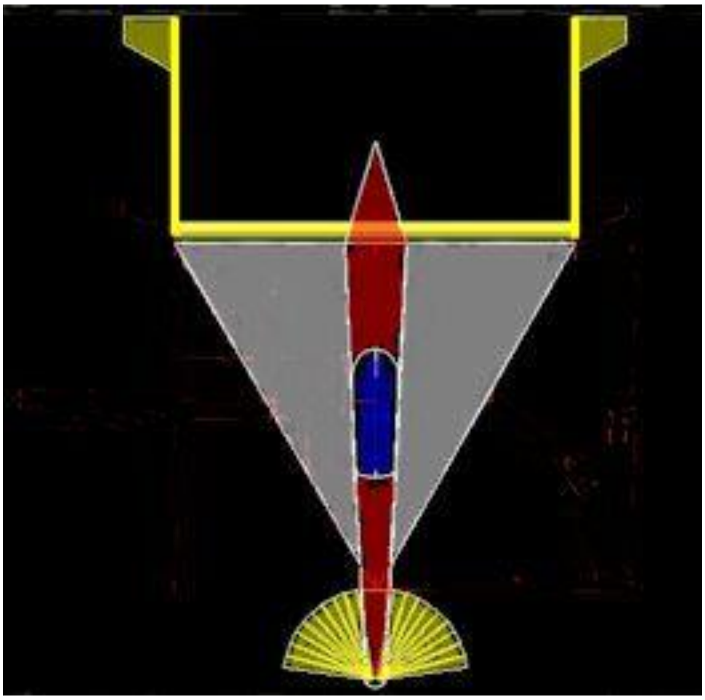
Personally, I don't like this folded-wing concept except insomuch as it's mechanically simple. It's possible to move the centre of pressure forwards in other ways (or alternatively move the centre of gravity backwards).

It's possible to deploy horizontal aerodynamic surfaces at the nose to increase nosewards planform area to move the centre of pressure forwards, though in truth these do have to be rather large in area. And these additions do add a further level of complexity (something else that can go wrong). Having said that, adding nose area instead of removing tailwards area increases planform area instead of reducing it, which helps reduce the gees.

This is the method I've adopted for my 'Spacelouge' boost glider. It deploys angel-wing shaped canards to move the centre of pressure forwards.

Spacelouge in ‘angel mode’ (the yellow-fan-like nose canard):

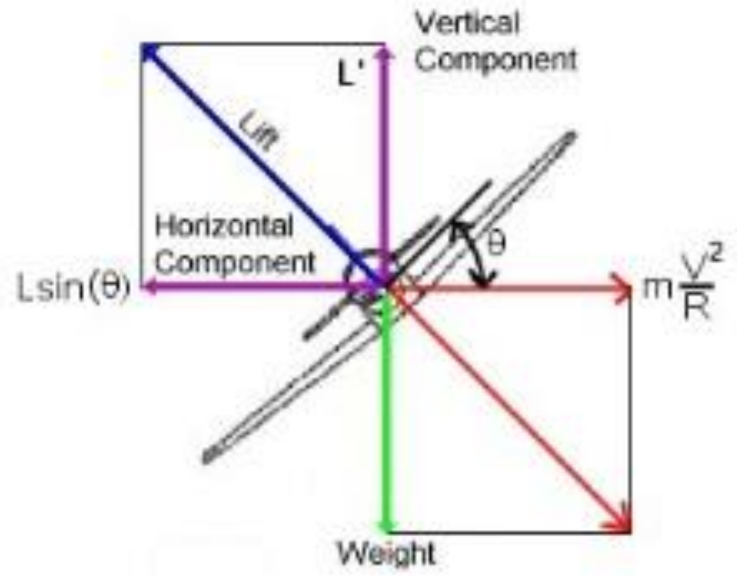




Boost glider: gliding turn

For a 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:

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

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

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

By inserting the relative density σ into this equation we get:

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

If the launch is to take place at a typical 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.

Landing

Landing speed depends on **wing loading** (horizontal landing). The lower this is, the lower the landing speed.

A sensible landing wing loading can be calculated using *cubic wing loading*, (reference 4) which is an extension to wing loading that takes the physical scale of the vehicle into account. It is vehicle weight per square metre of wing area (*S*) per metre (i.e. of vehicle length):

$$cubic\ wing\ loading = \frac{W}{S^{1.5}}$$

Sensible cubic wing loadings would be between 49 and 245 N/m^3, which will apply for any size from 1 metre radio controlled models up to Space Shuttle sizes and beyond. Typical light aircraft landing performance (scaled rate of descent) comes from a cubic wing loading of around 147 N/m^3. (See our paper 'winged rockets and boost gliders' downloadable from the Aspire website.)

To convert from wing loading to cubic wing loading, divide wing loading by the square root of wing area:

$$cubic\ wing\ loading = \frac{W}{S^{1.5}} = \frac{\frac{W}{S}}{\sqrt{S}}$$

Our Swift suborbital spaceplane (see example B later) has a cubic wing loading of 49 N/m^3 (glider performance) as we want a particularly low landing speed as well as particularly low re-entry gees.

It's also worth pointing out that most re-entry vehicles don't take off from a runway. Burt Rutan's Spaceship 1 and Spaceship 2 don't, so Burt saw no need for them to have a full set of undercarriage wheels. His nosewheel is replaced by a simple skid which not only helps braking during landing, but doesn't mind getting hot as a tyre would mind, as it's near the hot nosecap. You could replace all three wheels by skids.

Example A: a non-winged vehicle

The launch vehicle

The rocket vehicle that can launch the capsule described in parts 1 and 3 would typically be a single-stage vehicle.

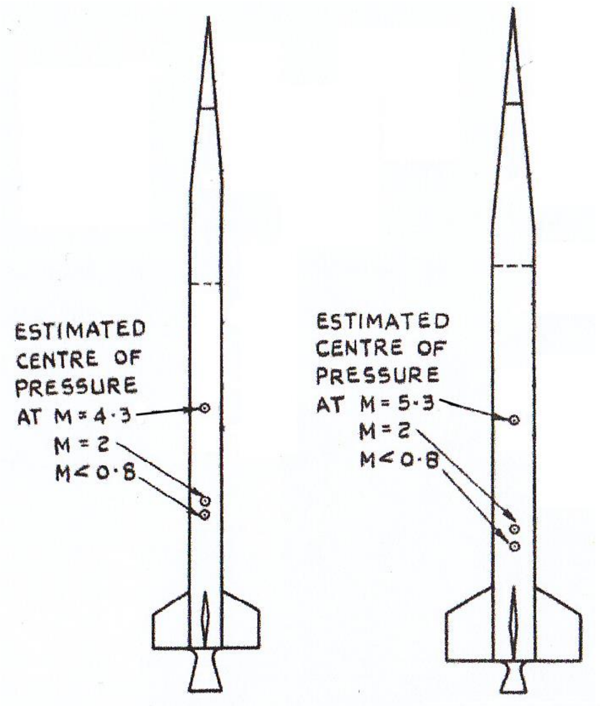
It could have a diameter equal to the minor axis of the capsule ellipse (0.764 metres diameter) with a conical fairing for the major axis of the ellipse.

As the major axis of the ellipse is larger than the minor axis, then assuming the vehicle had four fins, one pair of fins would need to be larger than the other pair. Also, the pitch axis moment of inertia would be larger than the yaw axis moment of inertia.

Or, if launched from a balloon at very high altitude (35 Km, 115,000 feet) **drag loss** isn't an issue so the propellant tank could be a simple mass-efficient sphere, giving a rather fat rocket vehicle.

Some form of thrust vectoring as described in the 'Launch and ascent: ground-launched or air-launched?' section will be required.

Care must be taken sizing the fins, as the **centre of pressure** of a rocket moves forward as Mach number climbs due the disproportionate increase in lift of the nose/capsule compared to the fins:



Example B: winged vehicle – the Swift

Introduction

The Aspirespace Swift is a single-seat light aircraft (hopefully a microlight) boost glider with an onboard nitrous oxide hybrid propulsion system. It is in effect a single-seat repeat of the Spaceship One mission, although is launched from a gas balloon at high altitude. The original Swift design was devised as a test-vehicle for a proposed entrant to the Ansari X-prize.

The craft will use an uprated version of our nitrous oxide hybrids, and will be launched off the north coast of Scotland, to re-enter and glide to any airstrip or beach within glide range.

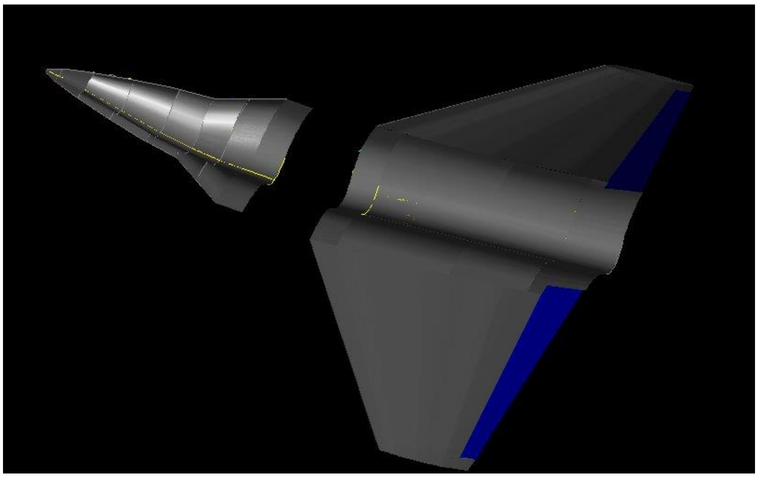
Initial simulations show that a mere 500 litres of nitrous oxide, which equates to a spherical tank about one metre diameter, is enough to reach Space. Better zero-lift drag data will firm-up this initial estimate.

The Swift incorporates sharp nose and leading-edges, and underside concavity, in order to waveride during the pull-up manoeuvre from vertical fall to horizontal glide during re-entry: maximising supersonic lift significantly reduces the re-entry 'gees' suffered, as well as the maximum airspeeds and heating encountered. (See our paper ‘Supersonics and waveriding’ on the Aspirespace website.)

Swift re-enters about Mach 3.3 at very high angle of attack, so decelerates rapidly. Therefore only during the initial phase of re-entry is the **Mach number** high enough to maintain a shockwave attached to the wing leading edges: ‘waveriding’. However, we have it on reliable authority from Leo Townend, a waverider expert, that even after the shockwave detaches, an aircraft with underside concavity will still develop a higher lift coefficient than one that has none.

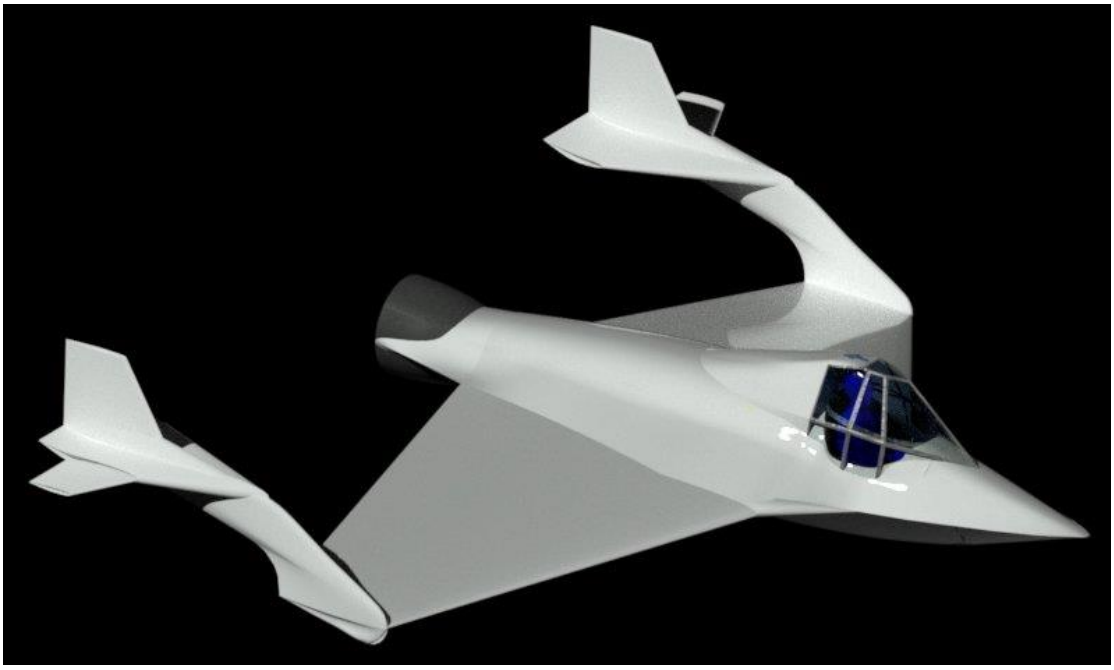
Vehicle design

- Use Waverider configuration to maximise re-entry lift to minimise gee loads and re-entry heating.
- Conic-flow derived Waverider at the front, mated to a ‘Caret’ Waverider at the rear.
- Gives a double-delta wing planform: this shape is stable over the whole speed-range.
- Forward Waverider has highly swept leading-edges to produce strong vortices to energize the vortices lifting the main wing at moderate angle of attack (prevents sharp aerofoil stall of main wing during landing.)
- Küchemann rule-of-thumb: every 5 degrees of wing leading-edge sweepback has the same stabilising effect as 1 degree of dihedral, therefore Swift has positive *effective* dihedral despite its anhedral (negative dihedral).
- Küchemann rule-of-thumb verified by numerous low-speed free-flight models (ASTRA, STAAR, Aspirespace)



Underside view of Swift components

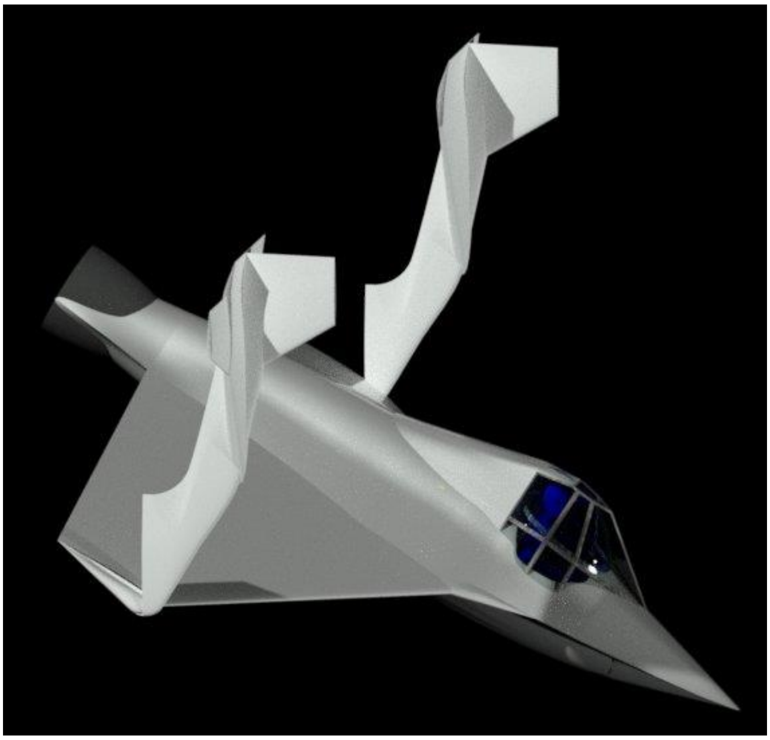
Aspirespace have incorporated stabilising 'feathers' as on Spaceship One which was designed by Burt Rutan to allow an auto-stable ‘hands free’ re-entry. Aspirespace didn't invent the parachute either, but it would be foolish not to have one; both Rutan's feathers and the parachute are fundamental additions that greatly enhance safety on this type of vehicle.



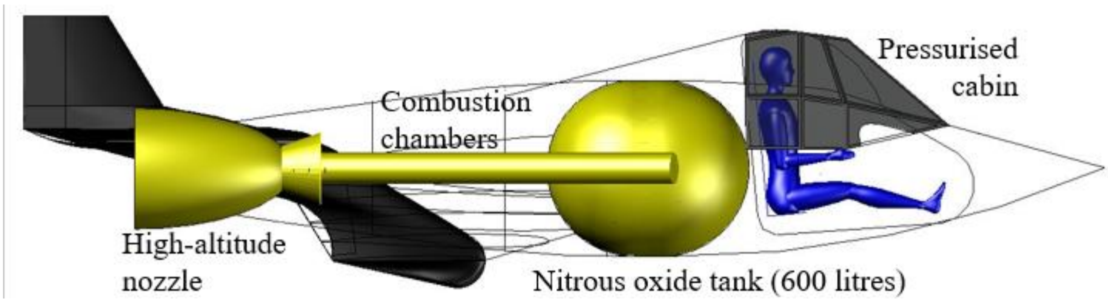
Re-entry

‘Rutan feathers’ are raised to give an angle of attack of around 60 degrees to maximise supersonic lift.

Simulations suggest maximum of 4.5 gee’s at Mach 3 when pulling out of near-vertical re-entry to commence subsonic near-horizontal glide.



Swift internals



Design parameters

- Conservative aerodynamic model (higher fuselage drag, lower Cl max) based on windtunnel data of Japanese aerospaceplane study.
- Use electric 'Rutan feathers' controls for ascent and re-entry.
- Use separate conventional controls (rudder and elevons) once craft has descended to normal air-traffic altitudes, and for landing.
- Minimise gee loads: *large* wing area (low **wingloading**) actually *reduces* the gee's because re-entry occurs at a much higher altitude where the air is thinner. Post-burnout wing-loading of 196 N/m^2, 20 kg/m^2
- Baseline **planform area** 20 m^2.

Launch altitude

- Want low EAS throughout rocket ascent: maximum of 140 knots (typical light aircraft airspeeds)
- Want high enough EAS for aerodynamic control right up until motor burnout (minimum of around 30 knots at burnout)
- Want high enough TAS at burnout to reach 120 Km apogee (assumes 4 gee max thrust)
- These constraints dictate a launch altitude of about 70,000 feet (from trajectory sims).

Example C: winged vehicle – the Spacedare

Introduction

Aspirespace were tasked to design a boost-glider that could enable a pilot suffering from severe M.E. (CFS) to enter space and glide back down.

This can be done safely, and cheaply, due to new advances in technology that weren't available 60 years ago during the space race.

The mission is detailed on the website: www.reactionforme.org.uk

Sufferers of M.E. are physically disabled. The dichotomy of a house-bound M.E. sufferer becoming an astronaut is bound to raise the awareness of M.E. and generate substantial media coverage which is the point of the mission: to make a lot of noise (sic) to get M.E. into the popular media and show that M.E. sufferers actively try to get around their illness to lead a goal-orientated life like everyone else.

M.E.

- Very debilitating illness characterised by physical and mental exhaustion, pain, poor cognition, and extreme fatigue.
- Sometimes known as Chronic Fatigue Syndrome (CFS).
- Most sufferers recover after several years, but some don't.
- For decades, wrongly diagnosed as a psychiatric illness.
- Latest research shows that inflammation of the lower brain caused by a malfunctioning immune system (auto-immune disease) is the most likely prognosis.
- Officially, strikes one in 100 of the population. Unofficially, much higher occurrence.
- Gets very little press: this mission aims to change that.

<u>Mission parameters defined by the illness</u>

1) Orthostatic intolerance: the pilot's cardiovascular system has been affected by his illness and the distribution of blood pressure around his body is awry: he can't sit upright for long. He won't be able to take high gee acceleration unless he's lying with his back flat, and he can't sit upright for more than 30 minutes. That's enough time to just reach space and immediately fall down again (around 10 minutes), but not for the two-hour balloon ascent to 35 kilometres (115,000 feet), nor the leisurely descent after re-entry. Solution: design a craft where he can remain flat as in bed.
2) The pilot's arms are rather weak. Solution: use electrically power-assisted controls.

3) The spacecraft occupant used to be a pilot, but he's out of practice, and his reaction time isn't what it was. Solution: make something small and easy to fly and easy to land.

Not many aircraft have been flown lying on your back (though there have been some, you use T.V. cameras to see where you're flying) but there's a basic geometry problem: a vertically ascending rocket but with a horizontally-inclined bed lying across it. Not very aerodynamic, but you can get away with it if you start at the top of the atmosphere to avoid **drag loss**.

Mission

'Spacedare' is a one-man microlight spaceglider (boost-glider) that the pilot will fly lying flat on his back then on his stomach because he can't sit up for very long. Lying flat allows healthy people to withstand up to 20 gees of acceleration, so he should easily be able to withstand the 4 gees during rocket ascent and the 5 gees of re-entry.

Spacedare is so-named because on the way down the pilot lies prone on his stomach like the pilots in the venerable old British Dan Dare comic, or a hanglider pilot.

- Keep Equivalent airspeeds (EAS) low to reduce structural and aero heating requirements: requires launch and re-entry at very high altitudes.
- High altitude launch from large gas balloon (at 115,000 feet) allows high-drag configuration during ascent (bed lying normal to airflow): maximum ascent EAS only 65 knots.
- High-drag shape during re-entry (ballistic coefficient of 46 kg/m^2) reduces peak EAS: 117 knots (Mach 3.3) and limits g-load to 4.8
- Deceleration to subsonic speed at end of re-entry (terminal velocity of 55 knots EAS at 70,000 feet).
- Reconfigure craft geometry for subsonic glide post-re-entry: moderate aspect ratio double-delta wing planform.
- Low wing-loading: 390 N/m^2, 40 kg/m^2, 8 lb/ft^2 (typical of U.K. microlight category) for low landing speed (35 knots) on grass strip or sand beach.

The mission was simulated using bespoke spacecraft design and trajectory simulation software. The pilot doesn't want to suffer more than 5 gees during re-entry due to his debilitated state. Falling vertically from 120 kilometres apogee dictates that he needs at least 1 square metre of parachute area for every 45 kilos of spacecraft mass (counterintuitively, the bigger the parachute, the less the gees you suffer, which is the complete inverse of what happens at sea level.)

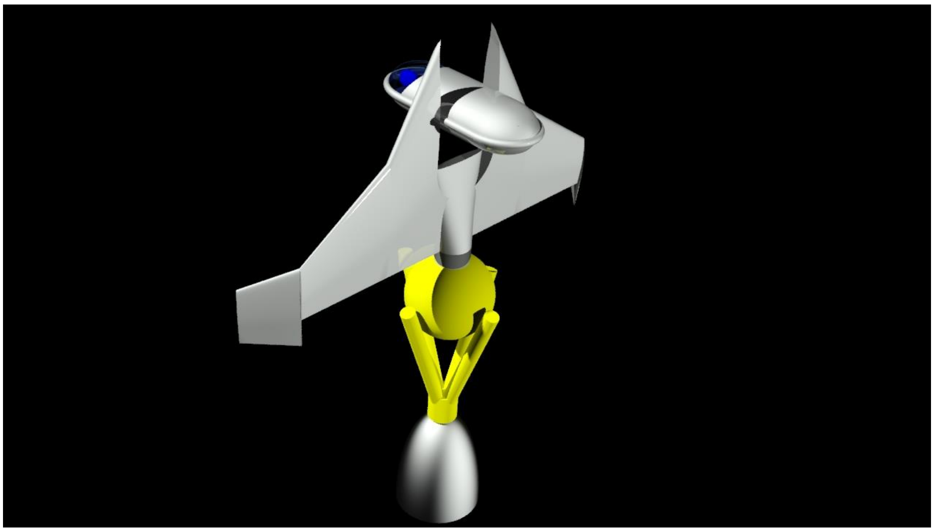
With this acreage of parachute, the pilot will perform re-entry very high up in the atmosphere (re-entry will be finished well before he descends into busy airspace), so although he'll commence re-entry at Mach 3.3, the spacecraft will only feel as if it's flying at 117 knots at sea level (peak Equivalent airspeed of 117 knots), which will soon settle down to a steady glide at 55 knots Equivalent airspeed.

There are many shapes of supersonic parachutes suitable for re-entry. The American Charles Pooley described the use of large airbrakes to slow a spacecraft back in 2005. Friends at Booster Space Industries have adopted this idea, as have I: the airbrakes will be deployed using electric motors.

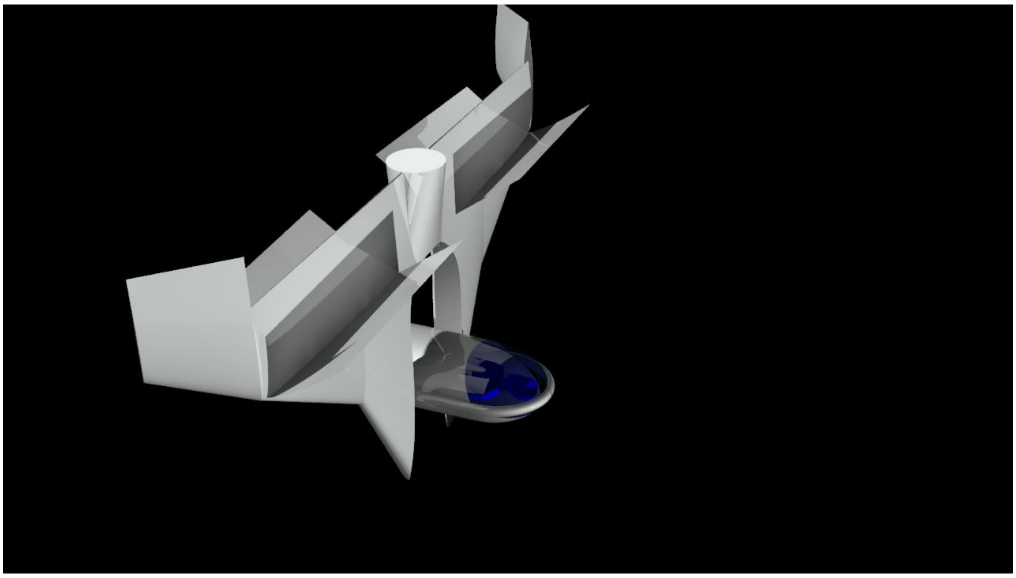
First model

In order to gauge geometries and basic stability, I constructed a simple balsa and card flying model. Interestingly, if it flies in a stable orientation subsonically (which it did), it's a good indication that it'll work at Mach 3 as well, as the laws of aerodynamic stability change only slightly at supersonic airspeeds. I then built a larger balsa and plastic model which is shown below.

This picture shows the Spacedare during ascent. The pilot is lying flat on his back looking skyward, as a not very large rocket (not shown) pushes him from below. The wings are vertical underneath him, hitting the airflow at the angle of attack that generates zero lift (This could be zero degrees if one choose a symmetrical aerofoil).



During descent/re-entry, an electric motor slowly rotates the cockpit 180 degrees about the pilot's middle so that he's still facing skyward but the wings are now above him (you're now looking at his back here).



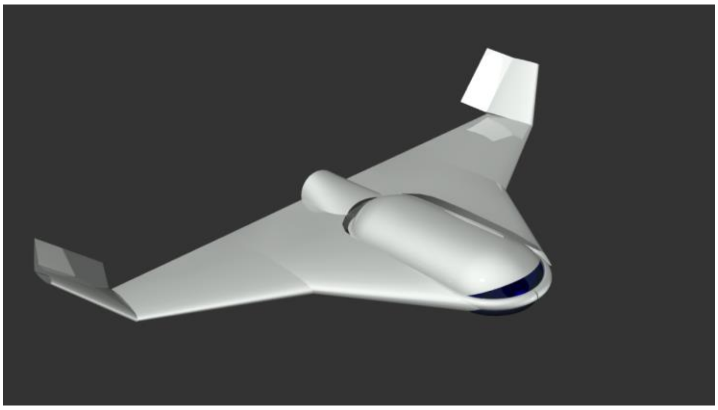
Now the drag of the sideways cockpit is a help rather than a hindrance, its area adds much useful drag.

Four large airbrakes deploy to create large drag during re-entry, and to make the craft auto-stable like a shuttlecock: the pilot doesn't need to touch the controls, instead just lie back and take the five gees.

The underside of the cockpit is a heatshield: it uses high-temperature resin, and the pilot is insulated from it.

The booster rocket has long since departed to parachute separately down into the sea.

Just after re-entry, the cockpit rotates 90 degrees so that the wings and pilot are both aligned (he's now lying on his stomach in a harness), and the craft becomes a simple delta-wing glider which gently descends to Earth to land on a beach or grass runway.



The full-size glider would employ composite sandwich construction, using high-temperature resistant resin.

As the cockpit rotates, it will cause sideways lift forces. The airbrakes on the upper and lower surfaces can be moved independently to aerodynamically counterbalance this lift force to prevent the craft pinwheeling.

Turbulator strips on the leading edges of the wings counter the effects of flying at very high altitudes (low Reynolds numbers) which can otherwise cause the airflow over the upper surface of the wing to separate when you don't want it to.

Burble fences (raised strips around the larger circumference of the capsule) position flow separation around the capsule to prevent asymmetric Von Kármán vortex shedding which would generate large side-loads.

General post-re-entry steering is done by electrically-actuated elevons on the wingtip fins. The pilot shall then be flying 'VFR' (visual flight rules) which means he has to steer clear of cloud and fog.

To allow the pilot to get the best view when in Space, there will be compressed-gas thrusters at the nose and wingtips to orient into the correct orientation.

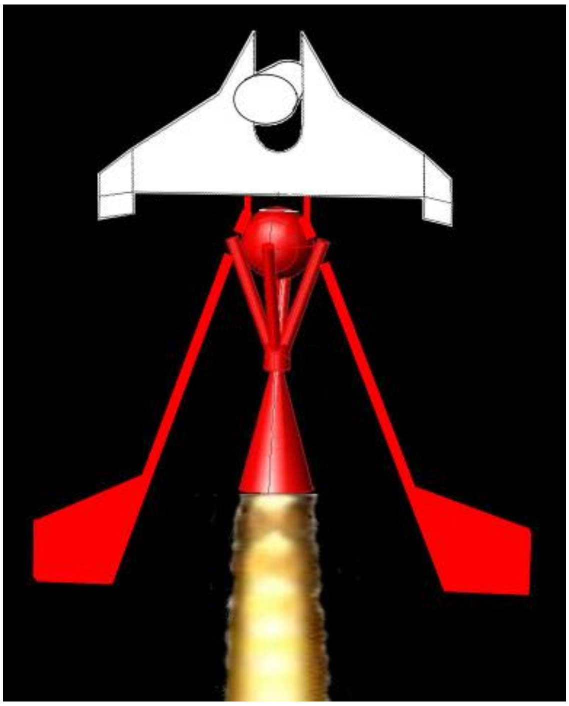
Re-entry

Infrared cameras will monitor the outside of the craft and warn of any hotspots forming.

Should the airbrakes fail to deploy, there is still enough drag area to slow down, although the gees will rise to uncomfortable levels. The pilot even successfully re-enter with the capsule the wrong way up as in ascent mode, though it'll be seriously unpleasant.

The booster rocket

The rocket is a nitrous oxide and high-density polyethylene plastic hybrid engine, as this is a particularly safe propellant combination, and Aspirespace have much experience with this type of engine.



For more information on hybrids, see the Aspirespace website www.aspirespace.org.uk

Nitrous oxide self-pressurises due to a high vapour pressure at room temperature therefore no pump is required.

So the booster is simply a big spherical tank of nitrous (around 460 litres) which feeds four tubes of plastic, that burn and their exhaust is carried into one common nozzle. Just one nozzle is better than several incase one of the several breaks and stops thrusting.

The propellant tank may appear small, but the propellant requirement to reach 120 Km from 35 Km is surprisingly low.

Just after ignition, the rocket engine delivers a peak thrust of 22 kiloNewtons.

Then the thrust slowly decreases throughout the burn as the tank empties. This decreasing thrust is another handy feature of nitrous hybrids as it keeps the gees from getting too high during ascent. All the while during the burn the booster gets progressively lighter as propellant is used up: The gees would increase dangerously if the thrust didn't decrease to match the decreasing booster mass. Peak gees are four gees just before engine burnout.

The booster is jettisoned at high altitude and parachutes back down.

Thrust vectoring

At the high altitudes the rocket will be firing at, trajectory control by simple fins don't work due to too low an Equivalent airspeed. Some form of vectoring the thrust is required as described earlier.

Rocket performance

- Vacuum specific impulse = 270 seconds
- Launch altitude 35 Kilometres (near-vacuum conditions)
- Delta V requirement = 1275 plus 491 gravity loss = 1766 metres/sec gross
- Required Mass ratio = 2
- Propellant mass = empty mass = approx 360 kg
- Total impulse 843900 Newton seconds (T-class)

Glossary:

Angle of attack: α (or Angle of Incidence)

This is usually referred to as 'alpha', and corresponds to the angle between the incoming airflow direction (usually the **Freestream** direction) and some vehicle or fin datum.

Apogee:

The highest point in an orbit or suborbit. From the Latin Apo Geos: furthest from Earth.

Aspect ratio AR:

A wing or fin's wingspan divided by its width (or mean chord).

Boost-glider:

A glider that is near-vertically rocket-boosted to altitude. After the rocket has burnt out, the aircraft glides back to Earth.

Canopy loading:

Is the mass of the retarded object divided by its parachute cross-sectional area.

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 vehicle's surface where the average of all the aerodynamic pressure forces from the nose, body, and wings/fins act. This must be behind the Centre of Gravity (CG) for stability.

Centroid of planform area:

Taking the fore-aft direction as the x-axis, the centroid of **planform** area is a centroid of the first moment of planform area: it's not just the area distribution that is important, but how far a particular region of area is along the x-axis. Therefore a horizontal tailplane's effectiveness is not just due to its area, but also its x-axis distance.

The formula to calculate the centroid of planform area is thus: $\frac{\int_0^x x\,da}{\int_0^x da}$

where *x* is measured from a convenient reference point such as the nosetip.

Delta-V (ΔV):

Change of velocity of a spacecraft.

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: $D = \frac{1}{2}\rho \cdot V^2 S C_D$ (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.

Drag loss: To avoid **gravity loss** you might think that it’s a good idea to pick a huge thrust, many times greater than your weight. But then your speed will quickly get very fast whilst you’re still low down in the atmosphere. The fast speed in thick air will cause enormous drag and you’ll waste a lot of propellant combating it. Drag loss is the loss of energy (delta V) caused by drag, which is equal to the drag divided by the vehicle mass, integrated with respect to time.

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).

Freestream (flowfield): ∞

The undisturbed airflow at a large (‘infinite’) upstream distance ahead of the **vehicle,** i.e. not **local.** For example, freestream **Mach number** is Mach number for the whole vehicle as we’d usually understand it, and not the **local** Mach number around the nosecone or fins.

Freestream **properties** have the subscript ∞, and are those of the atmosphere.

Gravity loss: if you pick a thrust that is exactly equal to your weight, then you will just hover in mid-air. You won’t have gained any height by the time your propellants have all been used up (burnout).
You’ve lost all that propellant just combating gravity without gaining any height. If your thrust is just a tiny bit higher than your weight, then similarly, you won’t rise very far by burnout. You’ll still get a huge gravity loss.

Hypersonic:
A **supersonic** airspeed fast enough that the airflow molecules begin to break up upon encountering the aircraft, giving rise to chemical effects within the airflow. Generally taken to be an airspeed faster than **Mach** five to seven.

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*':

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

Mass ratio:

The initial mass of the vehicle (at launch) divided by the final mass of the vehicle (i.e. at engine burnout). (Note that Sutton alone has this ratio the other way up.) This ratio is dictated by how much of the initial mass is propellant: the smaller the mass of tankage and structure compared to the initial mass of propellant then the higher this ratio will be.

This ratio directly determines the eventual **delta V** of the vehicle: the larger the ratio, the higher the delta V, as shown by the rocket equation:

$$\Delta V = V_e \ln\left(\frac{m_{initial}}{m_{final}}\right)$$

where V_e is the rocket's effective exhaust velocity and *ln* is the natural logarithm.

Mean aerodynamic chord (MAC):

Physically, the MAC is the chord of a rectangular wing, which has the same area, aerodynamic force and position of the center of pressure at a given angle of attack as the given wing has. Simply stated, MAC is the width of an equivalent rectangular wing in given conditions.

Planform area:

The area within the vehicle's or parachute's outline as seen from directly above.

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.

Reference area (S):
See **Drag (equation)**

Specific impulse (ISP):

The thrust generated per unit propellant weight flow rate (mass flow rate times 1 gee). This is similar in usefulness to the 'miles to the gallon' metric of cars.

Suborbital:

A trajectory that doesn't have enough energy to sustain an orbit.

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

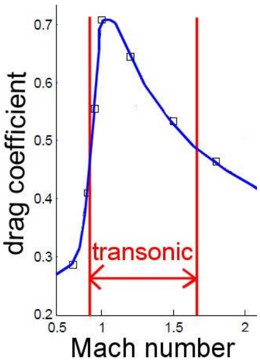
Supersonic:
Vehicle airspeed is above Mach 1 (see **Mach number**).

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, i.e. are 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.

Wing loading:

Is the weight of the aircraft (assuming 1 gee) divided by its wing area. From the **Lift equation** above, if the aircraft is flying horizontally then the Lift is equal to the aircraft's weight and so:

$$W = L = \frac{1}{2}\rho V^2 S\, C_L$$

The airspeed that the aircraft has to fly at is then: $V^2 = \dfrac{W}{\frac{1}{2}\rho S C_L}$ = wing loading $\dfrac{2}{\rho C_L}$

so the higher the wing loading, the faster the aircraft has to fly.

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Ref. 3: 'Experimental studies on aerodynamic characteristics of SSTO vehicle at subsonic to hypersonic speeds', Nomura, Hozumi, Kawamoto, Miyamoto. Proceedings of the 16th international symposium on space technology and science, Sapporo 1988

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Ref. 7: 'Initial airworthiness', G. Gratton, Springer, 2015

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Ref. 9: 'Aerodynamics for Engineering students' by Houghton and Carruthers.

Ref. 10: 'University Physics' by Sears, Zemansky, and Young. Addison Wesley publishing Co.

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Appendix 1: vertical drop from a balloon and pull-up

Assuming no **induced drag**, the vertically downwards acceleration of a body dropped from a balloon 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 vertical distance.

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

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

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

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:

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

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

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:

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

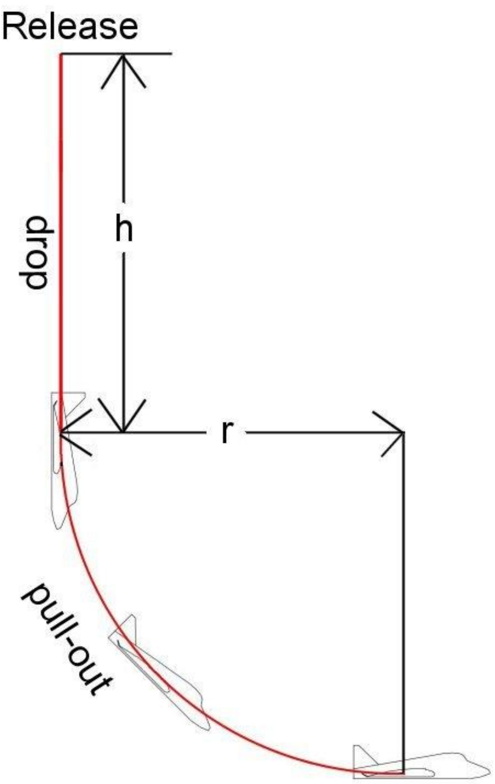
so the height of this drop is:

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

Now if we substitute Equivalent airspeed into this equation we get:

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

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



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

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.

Pull-up to the horizontal

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:

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

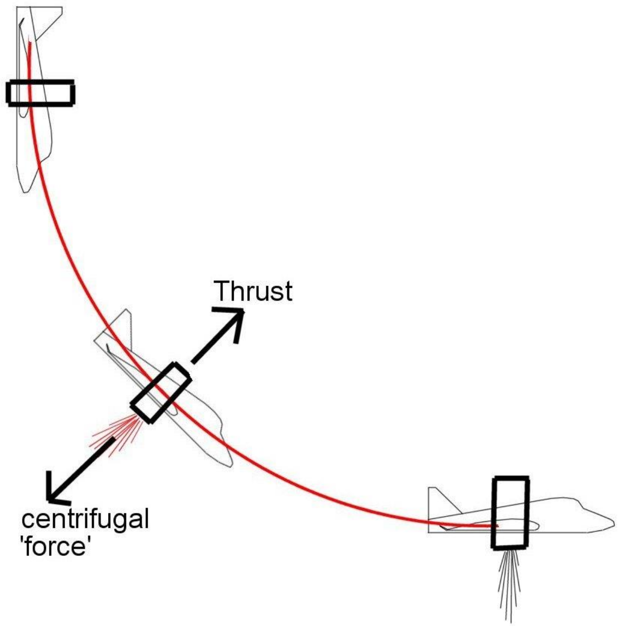
Yet again the size of the circle is inversely proportional to the density at altitude, so yet again, the circle will be 71.6 times larger at 100,000 feet altitude.

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 (a **drag loss**).

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:

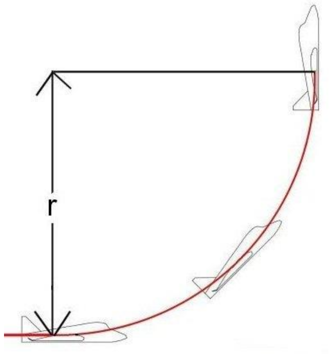


This was found to require less propellant to complete the pull-up manoeuvre than if the rocket was firing rearwards out of the glider.

Pull-up to vertical ascent

As the spaceplane is typically released into a horizontal flightpath or gently descending glide, it is then necessary perform the pull-up manoeuvre from near-horizontal glide to vertical ascent.

Again, assume that the pull-up manoeuvre is a vertical circle of radius '*r*' where the lift force reacts the 'centrifugal' radial force.



The radial force is equal to $\frac{mV_{TAS}^2}{r}$ where *m* is the mass of the spaceplane. Rearranging:

$$r = \frac{mV_{TAS}^2}{radial\ force} = \frac{mV_{TAS}^2}{\frac{1}{2}\rho_{at\_altitude}V_{TAS}^2SC_L}$$

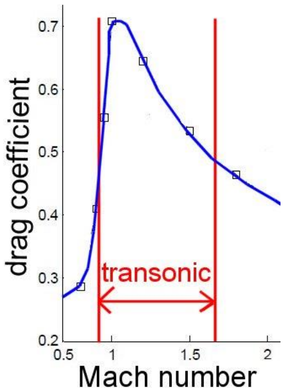
$$= \frac{2m}{\rho_{at\_altitude}SC_L}$$

So the size '*r*' of the circle is inversely proportional to the density at altitude; it can get very large at high altitudes.

During the pull-up manoeuvre, the spaceplane is combatting drag all of the time, so energy is continually being lost (**drag loss**).

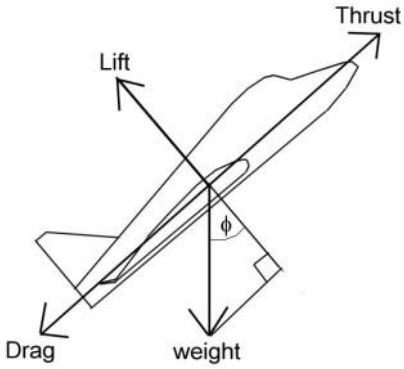
Pulling a tighter circle requires combatting higher centrifugal 'force' so more lift is required which causes higher **induced drag**, but the circumference of the circle is smaller so **drag loss** may be reduced. Pulling a larger circle causes the circumference of the circle to get large, so more energy is lost to **profile drag** and more time is spent at lower altitude where the rocket thrust suffers. Either way, a lot of energy is lost, but this is unavoidable. Only a simulation will tell you the optimum radius '*r*' which minimizes energy loss.

Transonic punch-through



Reaching **supersonic** airspeed (which is unavoidable for even a suborbital vehicle) will involve punching through the **transonic drag rise** airspeed range. This should be done as quickly as possible so as not to incur a large **drag loss**.

The force vector diagram for an ascending aircraft is:



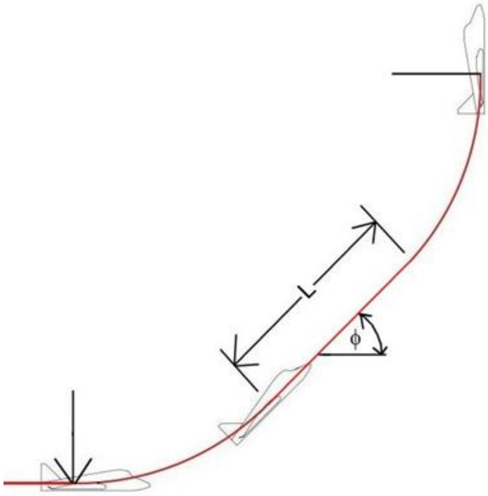
A component of the weight is counteracting the thrust, so is reducing the overall acceleration along the flight path:

$$acceleration = \frac{F}{m} = T - D - W\sin\phi$$

If the thrust/weight ratio of the vehicle is not large enough, and the flight path angle ϕ is large, then the acceleration can become too low to punch through the transonic drag rise quickly, and propellant is wasted as **drag loss**.

So during the pull-up to a vertical trajectory, it may be necessary to modify the simple circular pull-up by adding a section of ascent at constant flight path angle.

The punch through the **transonic zone** occurs during this section, and then the circular pull-up continues immediately the drag peak is past.



Flying at constant ϕ removes the centrifugal load so that the lift requirement is lower. This reduces the **induced drag** to increase the acceleration.

The higher the vehicle's thrust-to-weight ratio, the larger angle ϕ can be, though the relationship isn't linear. Once ϕ reaches about 70 degrees, then the weight component in the above vector diagram won't grow much larger due to the sine function, and the simple circular pull-up is the most efficient trajectory.

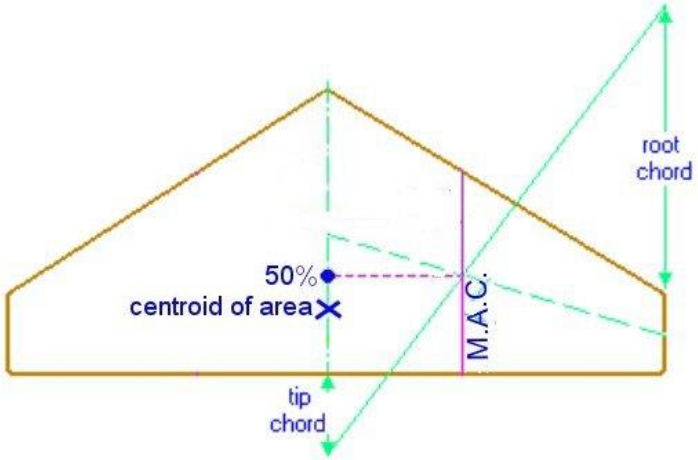
Note that the simple circular pull-up incurs the lowest peak EAS, particularly if the entire pull-up occurs subsonically. As the angle of the straight section of the trajectory lowers, the peak EAS increases, and EAS^2 increases dramatically (from the **drag equation**, aerodynamic loadings vary with the square of airspeed). This requires a stronger therefore heavier structure. So in a nutshell, don't install too low a thrust-to-weight ratio engine, the higher the better.

Appendix 2: geometric positions on a delta wing

In part 4 we looked at the movement of **centre of pressure** on a delta wing. This CP could end up at the ¼ or ½ chord position of the **mean aerodynamic chord**, or could end up at the centroid of area at 90 degrees angle of attack.

This sketch shows a simple geometric method for obtaining the mean aerodynamic chord: draw the root chord and tip chord lengths onto the ends of the tip chord and root chords.

Where a line joining the ends of these crosses the half-chord line gives the spanwise position of the mean aerodynamic chord.



Note that the centroid of area *isn't* the same thing as the centre of area. The amount of wing area behind the centroid of area is *not* equal to the amount of wing area ahead of the centroid of area.

It's more involved than that: as well as taking area into account, the centroid calculation also takes into account how far forward or aft each section of area is. Thus adding a canard that is small in area but is far forwards will move the centroid noticeably forwards as it's the product of area and forwards distance that counts.

Thus the integral that calculates centroid of area is: centroid = $\frac{\int xdA}{\int da} = \frac{\int xdA}{A}$

where fore-aft distance x is measured from a convenient point such as the nosetip or wing apex.

This equation is identical to the centre of gravity calculation of a uniformly thin lamina. This means that simply cutting out the planform shape from stiff card will give the centroid of area as the balance point (CG) of the card shape.

For the above shape of delta wing (a cropped delta) reference 6 gives the position of the centroid of area as:

$$\frac{x_{ca}}{root\ chord} = \frac{2+2\lambda-\lambda^2}{3(1+\lambda)} \quad \text{where } \lambda = \frac{tip\ chord}{root\ chord}$$

and where *Xca* is measured aft of the wing apex.