# Parachute recovery system design for large rocket vehicles

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## Introduction

Any Engineer who's seen a video taken from onboard an HPR rocket vehicle tends to wince when the parachute recovery system fires. Bits of airframe are tossed all over the sky, and there's usually the ominous 'clonk' of one piece of airframe bouncing off another.

**HPR** rocketeers have followed an evolutionary approach to recovery systems: if it works, who cares how messy it is, and there's the old Engineer's adage, "if it ain't broke, don't fix it".

But by doggedly applying *small model rocketry* parachute recovery system design to ever larger vehicles, the loads occurring when the recovery system deploys are often enormous, by far the largest the vehicle has to deal with.

A properly designed recovery system reduces these loads considerably.

This guide describes the design of recovery systems applicable to HPR class rocket vehicles and larger. As most HPR vehicles use a two-stage **recovery system** (**drogue** and **main 'chute**) I'll concentrate on this method.

Examples of the more common methods and devices used in the parachute industry are given, and parachute industry nomenclature is used, covered in the glossary at the end of the paper.

Words in **bold** are listed in the glossary.

Disclaimer: Aspirespace can't be held responsible for the information contained herein. If your recovery system fails and someone is hurt by a falling vehicle it isn't our fault. Nobody should have been allowed to wander underneath the rocket vehicle's trajectory.

# Part 1: Recovery system design

## The traditional HPR design

The problem is that model rocketeers are very conservative when it comes to **recovery system** design.

They want to be sure the recovery system works in order to save their expensive flight computers, so they almost never experiment with new recovery designs: they're still using designs only suitable for small Estes-powered model rocket vehicles, and simply beef them up to withstand the horribly large loads that then ensue.

Considering the amount of innovation spent on the vehicle as a whole, remarkably little progress has been achieved in recovery system design.

In the early days of Aspirespace I was tasked to devise recovery systems. The world of HPR rocketry was still very new; there was very little information to draw upon, so I researched how the 'big boys' did it, and my research is detailed herein.

Two decades on, I'm appalled to find that almost no technical progress has been made in HPR recovery!

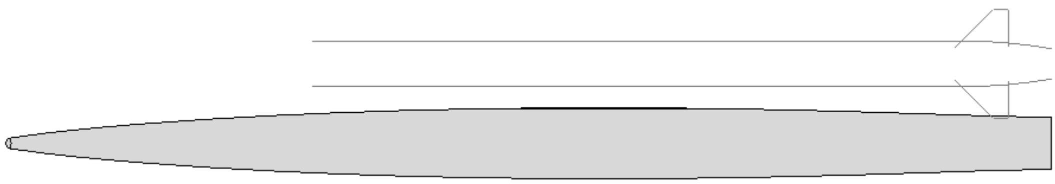
### The issue of scale

Perhaps I'm being unfair; the **model rocket** and HPR world have evolved recovery systems particularly suited to that scale of vehicle (which *does not* mean that it's suitable for larger scales).

The physical thickness of ripstop 'chute **canopy** material, Nomex heatshield material, and **bridal lines**, means that small HPR 'chutes don't package well. They require a proportionately larger internal volume to accommodate the folded 'chute in its bag.

For 'minimum diameter' HPR vehicles (e.g. 54mm diameter fuselages and smaller) the folded main 'chute becomes a very long sausage that requires a very large fraction of the fuselage length to accommodate it. The only way to get such a long, thin 'chute out is to split the fuselage across a diameter and draw it lengthways out of the tube.

Note that with modern 3D printing, traditional rocket vehicles no longer need to have cylindrical fuselages. A proper **Transonic** body of revolution can be twice the diameter of an equivalent tube for the same **drag**:



Any bag that has to contain such a 'chute is also long and very narrow; and due the aforementioned minimum material thicknesses, the system of 'chute-within-bag simply isn't nearly flexible enough to function properly: the 'chute won't come out of the mouth of the bag. Therefore, the entire fuselage diameter is used as the 'chute container instead of a bag. (More on bags later).

Then there's the drag (area) scaling effect: the fact that small rocket vehicles suffer a disproportionately much larger drag than large rockets, and furthermore the fact that they often go **Transonic** at very low altitudes where the **dynamic pressure** is high, which causes a huge drag spike.

This then requires seriously robust fuselage tubes and nosecones for small rocket vehicles to withstand the drag of the nosecone compressing the tube. These small, rigid fuselages and nosecones can then withstand much higher accelerations; it's acceptable to fling these fuselage sections all over the sky. (Until that is, a thin fin meets an upper section of fuselage and punctures it.)

Traditionally, the HPR recovery system comprises splitting the fuselage at a 'coupler' socket joint to let the **drogue** 'chute out.

Typically, the split is far rearwards of the nose, causing the fuselage sections above and below the joint to become aerodynamically unstable: they end up flying sideways-on to the airflow. This is reckoned to aid the deceleration of the vehicle - perhaps it does, but only in a very brutal way, the airframe loads are enormous.

Then the parachutes come out, spewed-out like so much untidy washing out of a spin-drier; canopy and lines all come out together in a mess. Most of the time the 'chute opens, but not always: sometimes the canopy gets tangled in the lines, which isn't good enough.

Then there's the **snatch load**: in parachute design this is the name given to the shock load that occurs when the 'chute **riser** goes taut, and the mass of the 'chute, (which hasn't yet opened) decelerates rapidly. In traditional parachute recovery systems, this snatch load is often equal to or larger than the subsequent opening load when the 'chute opens. It shouldn't be!

More on the snatch load later; bear in mind that scaling effects cause larger 'chutes to have proportionately larger inertia which causes proportionally much larger snatch loads.

With HPR and model rockets, the snatch load can often go through a riser that's bent over the lip of the fuselage joint. This often shears the riser in half, or if the riser remains intact, it cuts a slot down the fuselage like a cheese-wire, which is known in rocketry circles as 'zippering'.

Then the two sections of fuselage are often joined by a length of 'shock' chord. This chord is often very long as this 'makes it more elastic' which is reckoned to lower the recovery loads.

Actually, the opposite is true: the long length gives much more time for the separate bits of fuselage (with their own individual drags) to attain markedly different airspeeds relative to each other, which causes a large shock load when the line finally goes taut. A short length of elastic bungee would be much better.

<u>Alternative design for larger vehicles</u>

How are large, commercial sounding rocket vehicles recovered? Certainly not like HPR's.

For start off, hurling large bits of airframe around is clearly not acceptable: large rocket fuselages can be made much more delicate to reduce their mass, but the downside is that they'd simply fold up if flying sideways.

Also, larger fuselage tubes have proportionally much larger inertia for their size therefore colliding tubes would break up on impact with each other.

For these reasons, the **drogue** 'chute that comprises the first stage of the recovery system is usually fired sideways or rearwards out of the *bottom* of the fuselage: its lines are connected to the <u>base</u> of the vehicle.

Rear-eject is the system used by aircraft and dragsters, and for the same reason: to ensure that the vehicle continues pointing nose-first, and isn't subjected to large angles of attack - and therefore large airframe loads - by going sideways.

Once the vehicle's airspeed has been markedly reduced by one or more drogues, *then* the **main** 'chute can be fired out the nose in the traditional way, although more often it's deployed sideways out of a bay on the side of the vehicle by opening a door.

Larger vehicles can provide proportionally much larger internal volume for their size, therefore folded main 'chutes don't require nearly so high a fraction of fuselage tube length as 'minimum diameter' HPR fuselage main 'chute bays: the folded main 'chute is much squatter (not a sausage).

## Recovery system design philosophies

Having listed the deficiencies of traditional HPR designs, it's time to suggest improvements for larger vehicles, but first a brief reminder of the recovery system ethos:

Recovery system design is very much an exercise in assuming that anything that *can* go wrong *will* go wrong, and then designing all the flaws out of the system.

Aerospace design practices should be used, especially in light of the large loads occurring and the high reliability required of the system. These are:

- **Redundancy**: Try to duplicate vital systems - especially timers and igniters - in case of component failure. If the primary system fails, is there an independent backup system? Obviously, too many backups will lower the overall reliability by adding more components that could go wrong.
- **Engineering factors of safety**: Recovery systems can often be significantly over-strengthened with little increase in mass, so do so.
- **Testing**: Test the system before flight to discover any hidden flaws in the design.
- **Simplicity**: Simplest is always best in terms of reliability - and tends to weigh less - though don't go too far: the traditional HPR design is *too* simple.

As there is only finite internal space and mass to allocate to the recovery system, you have to hypothesise possible failure modes, and then prioritize in terms of likelihood of occurrence.

Only testing will show whether you guessed right.

### The recovery envelope

When parachutes inflate, they exert huge forces down the riser to the **store**.

Being aerodynamic forces, these 'opening loads' vary directly with **dynamic pressure**, which will be a minimum at **apogee**.

Even with the steep trajectories of rocket vehicless fired at near-vertical launch angles, the horizontal airspeed at apogee can be surprisingly large, creating opening loads rising to several kiloNewtons.

The 'recovery envelope' is the range of airspeeds that one designs the recovery system to be able to function over: The higher the allowable opening speed, the less critical is the need to open at apogee, and the more flexible the recovery system can be to deal with malfunctions such as unusually high airspeeds caused by an unexpected flatter trajectory.

Narrow envelopes are very sensitive to opening airspeed prediction, and because of the $V^2$ dependence of drag, a reasonable estimate of recovery system loads requires accurate prediction of the vehicle airspeed at 'chute deployment, which can only be gained from a trajectory simulation that doesn't just model purely vertical ascents (see our paper 'a dynamic rocket simulator' for a suitable sim) but estimates the horizontal speed component too.

It's wise to include the effects of wind and wind gusts on the rocket's trajectory (see our papers 'A Dynamic stability analysis rocket simulator' and 'Rocket vehicle loads and airframe design').

To minimise airspeed, the drogue 'chute must be opened at apogee. Commercial rocketry flight computers such as the RDAS can sense apogee to allow this.

Wide envelopes - by definition, aren't so critical of opening airspeeds - and hence trajectory prediction can be cruder.

Wider envelopes usually require more rugged or complex recovery systems.

<u>Multiple-stage recovery systems</u>

For a soft landing, a main 'chute of large canopy area is required.

When opened even near apogee, such a large 'chute will generate enormous opening loads.

Often these loads are just too high: the structural reinforcing of the rocket vehicle fuselage required to survive these loads adds excessive extra mass.

This is to be avoided as opening loads increase strongly with store mass.

- In a multiple-stage recovery system, a smaller 'chute or drag device is opened first to slow the rocket vehicle down to a lower airspeed that the main 'chute can then be safely opened at.
- When done correctly, the maximum loads generated by any stage's 'chute in a multiple-stage recovery system are considerably less than for a single stage 'chute alone.
- Due to the higher **dynamic pressure** at opening, the initial drag devices - known as **drogues** or 'first stage' 'chutes - can have high **canopy loadings** (small surface areas) and yet still create a reasonable drag.
- Typically, the drogue is opened at apogee. The system then reaches **terminal velocity** and descends fairly rapidly, reaching low altitude in too short a time for wind drift to be significant. The main 'chute is then opened at this low altitude. This is referred to in HPR rocketry as 'Close Proximity Recovery (CPR)' as the rocket vehicle hopefully lands not far from where it was launched.

## <u>The Snatch Load</u>

Whether forcibly expelled (pyrotechnically) or not, by the time a 'chute has travelled to the full extension of the riser, the 'chute has built up a sizable difference in velocity relative to the rocket vehicle it deployed from.

This velocity difference has been increased by the deceleration of the 'chute due to its drag, which will be much higher if the 'chute is allowed to partially open before lines-taut, as in a traditional system. There will be a large momentum built up relative to the rocket-vehicle, due to the drogue's admittedly small mass, multiplied by the difference in velocity. (The less mass the drogue has, the higher its velocity difference tends to be.)

In consequence, when the riser connecting the 'chute to the rocket vehicle finally goes taut, there will be a sudden whip-load down the riser caused by the deceleration of this momentum.

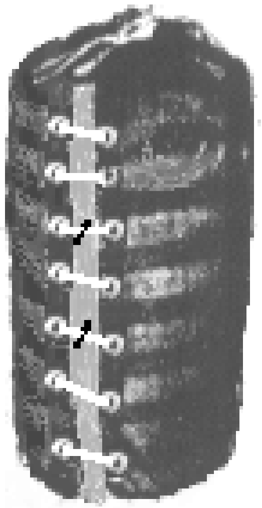
This dynamic ‘twang’ is known as the ‘snatch load’, and if no attempt has been made to restrain the canopy from partially inflating before this snatch load has concluded, this can be the highest load the recovery system has to suffer. You might think that the small mass of the tiny drogues used in HPR rocketry couldn’t produce a significant snatch load, but you’d be surprised!

Reducing the snatch load

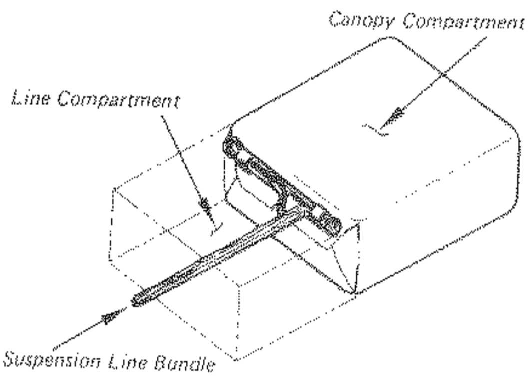
The way to reduce the snatch load is to reduce the difference in airspeed between the ‘chute and the vehicle at lines-taut. Apart from going easy on the amount of expulsion charge used and keeping the riser short, the other way of doing this is to reduce the drag of the ‘chute; keep it tightly compacted until after lines-taut to reduce its drag area by containing it in a ‘deployment bag’ or shell.

The deployment bag

A rucksack-like or sausage-like bag used to contain the packed ‘chute prior to, and during the initial stages of its deployment.



Often, the bag has two compartments that are opened in sequence, to separate the process of the uncoiling of the **bridal lines** from the unfolding of the ‘chute itself. This prevents tangling. The ‘chute and lines are then deployed neatly into the air in an orderly sequence.

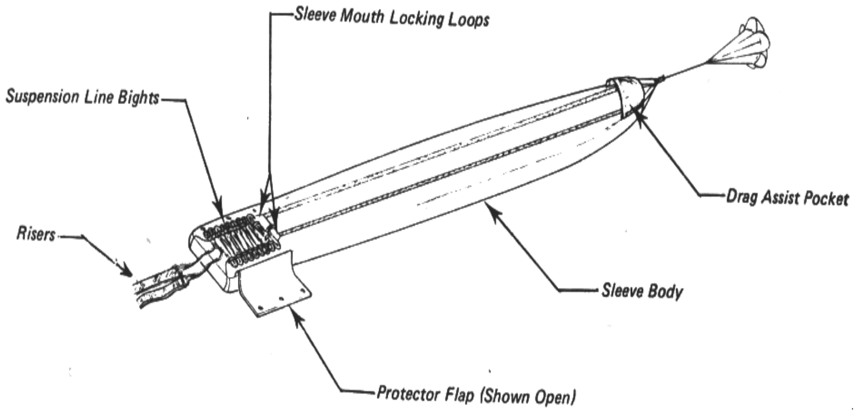



This figure shows line lengths inside such a deployment bag, held tidily in place by loops of elastic until pulled out:

Sometimes the individual lines are stored separate from one another in individual sleeves, again to prevent tangling.

If the lines are extracted first, this is referred to as 'lines first' deployment. The opposite is a 'canopy first' deployment, but this is best avoided as the deployment is messy and the loads are large.

This figure shows a drogue-deployed 'quarter bag' i.e. only the lines are enclosed in a bag while the canopy is inside a sleeve, which gets concertina'd, then stored under a protector flap as shown.




You can buy simple deployment bags from rocketry vendors, though the smaller they are the less flexible they are so don't work effectively. These bags are often fire-resistant Nomex, to shield the 'chute from the heat of the **expulsion charge**.

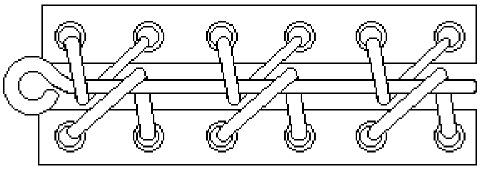
Compression packing (of the deployment bag)

Compression packing by whatever method, is often used for large aerospace parachutes. The Apollo re-entry capsule main 'chutes were compressed to the density of oak in a hydraulic press for compact storage.

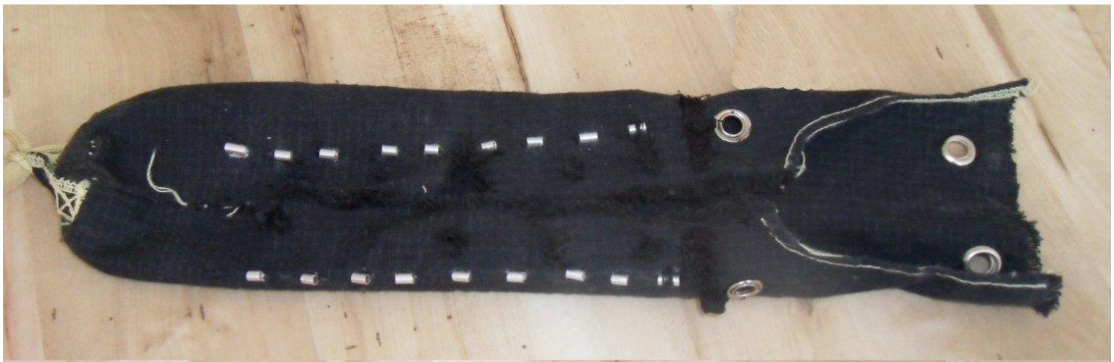
- A 'chute deployed from a compressed deployment bag of reduced cross-sectional area, and hence reduced drag, suffers a greatly decreased snatch force.
- A compressed 'chute takes up *much* less volume.
- If decelerated too violently, a 'chute's inertia acting on itself can throw its neat folding (vital for clean deployment) into disarray. If the 'chute is tightly restrained by a compressed deployment bag, then much higher decelerations can be withstood.

Should you wish to make a compressible deployment bag, the method of lace packing has been found to be the easiest to construct, wherein just as on a shoe, laces threaded through eyelets sewn onto the bag are tightly pulled. The laces are then cut at deployment time by **line cutters**.

Or, the lacing is laced around a release-pin as shown here in such a way that pulling the wire pin out opens the bag.



As I found out the hard way, this system doesn't work for small main 'chutes within 'minimum diameter' HPR airframes because the number of lace loops becomes excessive for such long, thin 'chute bags resulting in a high release-pin friction. I used metal hoops instead of lacing to reduce the friction:

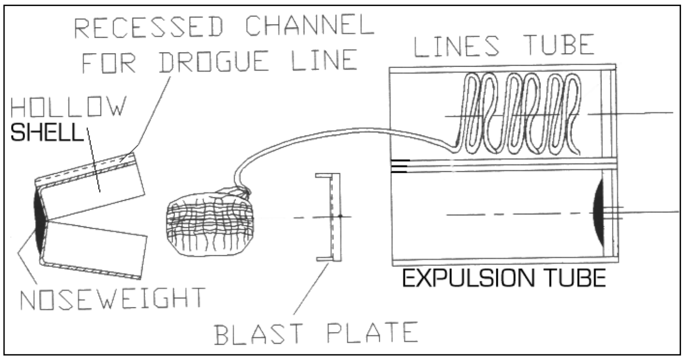


With larger vehicles, the length-to-diameter of the bag reduces, reducing the release pin friction, and also the drag force available from the drogue to pull the release pin increases greatly. I tried this system on a 'minimum diameter' 54 mm diameter fuselage vehicle, and it didn't work. But, I've also tried it on a much wider main 'chute bay where it *did* work: size dictates the success of this system.

<u>The drogue-shell</u>

The drogue-shell system tends to be a more reliable system for drogue deployment from a vehicle travelling at high subsonic or supersonic airspeeds.

(The mass of the shell can get excessive for main 'chute applications, hence the name.)



This system is basically an expulsion-tube wherein the 'chute is compressed into a hollow shell-like container sealed by a blast-plate.

The shell sides can be hinged at the nose to eventually split apart as shown, but are closed and locked by the blastplate during expulsion.

The 'shell' has nose-weight, to give it enough momentum and aerodynamic stability to clear the fins if fired sideways out of the fuselage, or to clear the vehicle's base wake region of dead air if fired rearwards.

Pros:

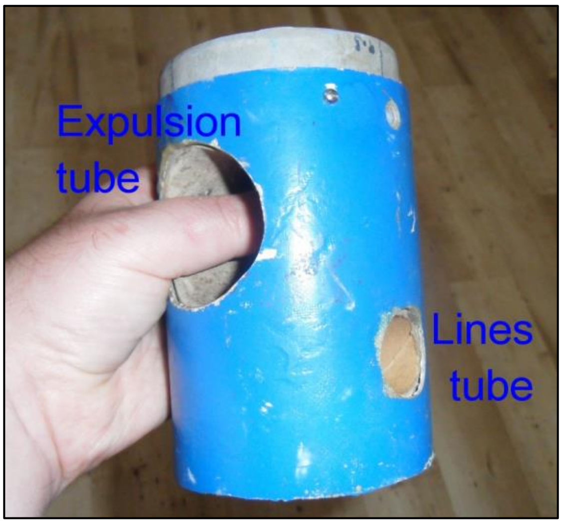
- The drogue can be tightly packed inside the shell, keeping its cross-sectional area to a minimum, which is important for reducing the snatch-load.
- The shell encloses the drogue, and can be made of insulated material to shield the drogue from the heat of expulsion.
- This system has been tried successfully on all sizes of vehicle: model rocket, small HPR, and much larger.

Cons:

- Slightly higher complexity.
- The shell is jettisoned completely, so it *must* be designed to have a low terminal velocity for the safety of people on the ground below: fit it with its own streamer if necessary.

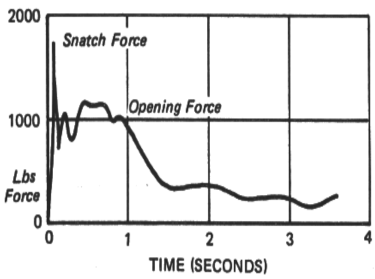
While it would initially appear that a weighty drogue-shell would generate a higher snatch load, the shell parts company with the drogue before the maximum snatch load can build up, and of course, the shell keeps the drag area low.

Here's the drogue shell expulsion tube and lines tube for our Aspire ADV1 rocket vehicle:

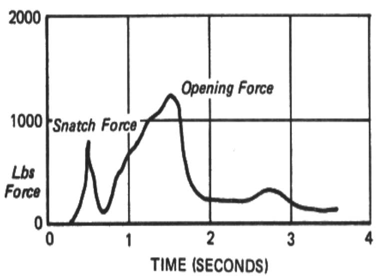



Few properly-designed recovery systems fail because of the snatch load.

With the use of a drogue-shell or deployment bag, the snatch-load will be equal to or more likely less than the **opening shock load** (when the 'chute opens) as shown in these comparative graphs:




a) Without Deployment Bag (Canopy-First Deployment)




b) With Deployment Bag (Lines-First Deployment)

In a poorly-designed traditional system however, the snatch load might be several times higher than the opening load.

The snatch load will cause inertial loads on any devices attached directly to the ‘chute canopy: these must be secure or they'll tear off.

If an auxiliary or previous stage's ‘chute is used to haul out another ‘chute, there must be a deliberately 'weak' link connecting them that's designed to break when the latter stage’s riser goes taut, otherwise the drag of the actuating ‘chute (and its mass, and the mass of air captured within it) will seriously increase the snatch load if it stays permanently attached.

A better design is to have the previous stage’s ‘chute pull the shell or deployment bag off of the subsequent ‘chute, though the length of riser between previous stage ‘chute and this bag mustn't be too long, or high snatch loads will be generated due to excessive relative velocity.

Similarly, the canopy must exit the bag or shell with little friction or the bag/shell will pull on the canopy, increasing the snatch load: this is a problem for small bags and small ‘chutes.

One important factor in determining the snatch load is the energy-absorbing properties of the riser and bridal lines.

Note that a brand-new rope will stretch and absorb a lot of the energy, whereas a used rope is already partially permanently deformed, and so is effectively more rigid. It will break more easily, or will transmit more of the snatch load to the rest of the recovery system.

Snatch-load prediction: (as used by a parachute load-prediction program)
This can be calculated on a spreadsheet, but it’s easier if programmed.

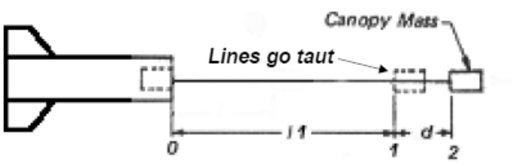
I strongly advise using a better method of integration than the simple Euler method to obtain the velocities and displacements during a parachute deployment, as simple integrations tend to numerically explode under large or sudden accelerations: 2nd or higher-order Runge-Kutta integration methods are suitably stable.

Subject to the following restrictions, a 1-dimensional analysis can be used:

- The deployment is reasonably parallel to the airflow (not transverse) so that the ‘chute’s deployment trajectory is pretty much a straight line, i.e. deployed rearwards to the direction of flight.
- The ‘chute is packed into a deployment bag or drogue shell to reduce its drag to a small value compared to its mass.
- The canopy slides easily out of any drogue shell or deployment bag as soon as the lines go taut.

In the following diagram, the remaining section of vehicle is travelling in a tail-first attitude to the left.

After going taut (at point 1) the suspension lines and riser stretch as the ‘chute decelerates relative to the vehicle, and the ‘chute canopy momentarily comes to rest at some maximum stretch (point 2) before rebounding.



To analyse this situation, a traditional loads analysis doesn't work because the loads are changing rapidly with time (they are a 'dynamic system') and the problem becomes intractable. Instead, you need to perform an energy analysis, as this can capture the dynamics of the stretch and rebound. This is the preferred method used by the parachute industry.

The Snatch load *Fs* can be calculated by comparing the work done in stretching the bridal lines/riser bundle the distance *d,* to the drop in Kinetic energy (*K.E.*) of the system between points 1 and 2.

$$\Delta work = \Delta K.E.$$

Recall that Work is the integral of force *F* with distance *x*, thus:

$$\int_1^2 \frac{dF}{dx}\, dx = \Delta K.E.$$

From the law of conservation of momentum between 1 and 2, when the rocket-vehicle and 'chute have reached a common velocity at point 2 in the diagram, this velocity is:

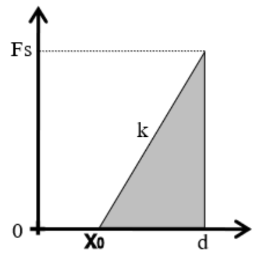
$$V_2 = \frac{m_r V_r + m_c V_c}{m_r + V_c}$$

where *m* =mass, *V* = velocity, subscript *r* = rocket-vehicle and subscript *c* = 'chute canopy.

Approximating the actual stretch force versus distance graph of the combination of lines *and* riser as a linear function gives a good enough result in practice:

$$\int_1^2 \frac{dF}{dx}\, dx = {}^1\!/_2\, F_s(d - x_0) = {}^1\!/_2\, k(d - x_0)^2$$

where: $k = \frac{F_S}{(d - x_0)}$ is the effective 'spring constant', and $\frac{dF}{dx}$ is the gradient of the force versus distance graph shown here:




Note the offset $x_0$: this is used to obtain a better line-fit to data from many synthetic textiles, such as the used webbing strain graph (b) below. In the ideal case, or for steel cable, $x_0$ would be equal to zero.

The energy equation is then: (left-hand side = point 1, right hand side = point 2)

$$\frac{m_r V_r^2}{2} + \frac{m_c V_c^2}{2} + 0 = \frac{(m_r + m_c)V_2^2}{2} + \frac{k(d - x_0)^2}{2}$$

Rearranging and substituting for $F$, this gives the snatch load:

$$F_s = \Delta V_{\max} \sqrt{k \frac{m_r m_c}{m_r + m_c}}$$

where $\Delta V_{max}$ is the maximum velocity reached by the 'chute canopy *relative to the rocket vehicle* at point 1, and is equal to: $V_b - V_c$. This can be simulated based on the on the expulsion tube exit speed of the 'chute, and the subsequent deceleration of the deployment bag or drogue shell due to its drag.

This equation reduces to:

$$F_s = \Delta V_{\max} \sqrt{k\, m_c}$$

if the mass of the 'chute canopy is much less than the mass of the rocket-vehicle. ($m_c << m_r$)

These equations assume that the masses of the riser and bridal lines are negligible compared to the mass of the canopy, which may not be correct.

As a rough approximation, one can assume that the riser mass and mass of the bridal lines are roughly equal, so that the centre of mass of the combined riser and lines can be taken to be halfway between vehicle and 'chute.

From geometry, this centre of mass is therefore travelling at:

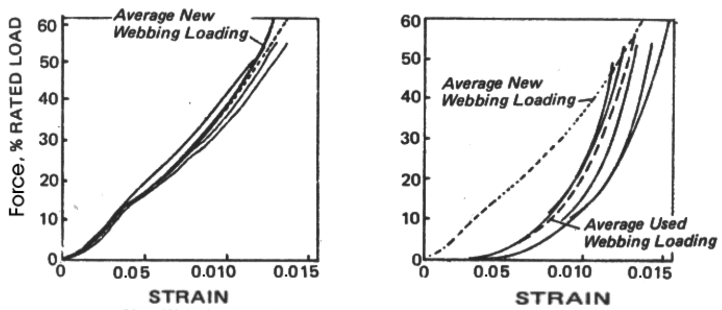
$\frac{1}{2} (V_b - V_c) = \frac{1}{2} \Delta V_{max}$ when the lines go taut, and so has a momentum of

$\frac{1}{2} \Delta V_{max} (m_{riser} + m_{lines})$

so in the above equation, substitute $\left[ m_c + \frac{m_{riser} + m_{lines}}{2} \right]$ for $m_c$.

Ropes analyses

To obtain a value for spring constant $k$ in the equations above, the following force versus strain **(ε)** graphs are broadly representative of nylon chords and webbing:




a. New Webbing Loading

b. Used Webbing Loading

Multiply the strain axis by $l_1$, the unstretched line length:

$$k = \frac{dF}{dx} = \frac{dF}{l_1\, d\varepsilon}$$

Note that the area under an average ‘used rope’ curve is much less than the area under the new rope, i.e. the energy-absorbing properties of a rope are less after the first stretch, so a used rope dissipates a snatch or **opening shock load** less**,** therefore those loads will affect the store more.

To select spring constant $k$ for an old rope, use the gradient of a tangent to the curve for the range of working loads designed for.

I.e. it would be wise to construct the riser from ‘rope that is twice as strong as will be required, so one would use the value of $k$ derived from the tangent to the 50% rated load point in the above graph (b), whereas if one wanted to work out the failure load of the system, (i.e. the load that would just snap the riser), use the higher value of $k$ at the 100% rated load point.

(In the above graphs, the 50% and 100% gradients are probably similar, but if you were using a safety-factor of 5, the gradient at the 20% load is lower.)

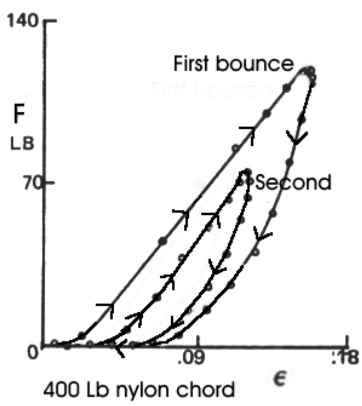
Note that you’ll get higher $k$ values for an old rope, which in the equations for $F_s$ above gives higher snatch loads as expected.

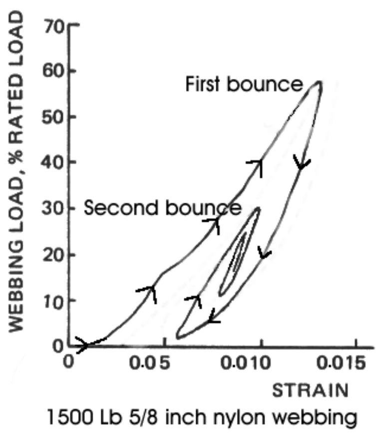
For ropes bundled in parallel (bridal lines), simply add the $k$'s of each rope together, whereas for ropes in series (e.g. riser connected to bridal line/s) add the $k$'s as:

$1/k_{total} = 1/k_1 + 1/k_2 + ...$

Impact loads

The above spring constant graphs were plotted by gently hanging successively heavy weights off of a rope. *However* materials behave differently under sudden impact-loadings such as snatch loadings (and also **opening shock loads**, see below).




The following graphs were obtained by dropping a heavy mass on the end of a new riser: (ε varies with vertical distance).

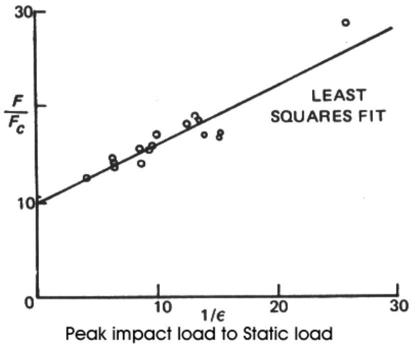
The $k$ values due to impact loads in these graphs are actually higher than the static-load graphs shown above.

This is due to the visco-elastic properties of polymers, wherein the e.g. nylon fibres actually get stiffer as the loading rate increases.

If dynamic load/strain data isn't available for your particular riser or bridal line but static data is, the following empirical curve of peak dynamic load '$F$' to static load '$F_c$' versus the **inverse** of strain can be used to correct your data: (note the large corrections).

This curve was averaged for a wide range of impact speeds on a nylon bridal line, but should be okay for most polymer ropes.

You can then re-plot the force-strain graph to estimate $k$ as before, by re-scaling the y-axis by the factor $F/F_c$ at the (inverse of) the strain that occurred at $F_c$.




Testing

It needs to be said that a lot of the above mathematical and graphical analyses can be replaced by recording the force versus time results of suitably inventive testing methods. For example, one can use an Arduino or Raspberry Pi reading a strain-gauge, or either of these or an RDAS reading acceleration.

## **The opening shock load**

Some milliseconds after the snatch load peak is past, the canopy opens. (If a drogue-shell was used, the drogue has just been pulled free of the shell as the shell's inertia kept it going.)

The 'chute rapidly fills and inflates, creating a momentary peak drag load known as the opening shock load: this peak can be two or three times the eventual steady drag of the 'chute and is caused by the mouth of the canopy swallowing a mass of air which it then decelerates.

Infinite mass assumption

The unsteady aero/fabric/mass dynamics of this opening process confounds researchers even today, as the mathematical modelling requirements are excessive.

What *is* known is that if the 'chute's **canopy loading** is higher than about 1400 N/m$^2$ then the parachute-rocket vehicle system won't decelerate noticeably during the period of canopy inflation, because the rocket vehicle's mass is huge (assumed 'infinite') in comparison to the available drag, and therefore the velocity of the system can be assumed to be constant during the opening period.

If this high canopy loading condition, known as 'infinite mass' occurs, then calculating the opening shock of the 'chute is trivial, as empirical values relating the opening-shock force coefficient to the eventual steady-state **drag coefficient** are known for most 'chute types.

Several values are given on the following page, note that the simplest canopy designs give the highest opening shock loads.

Simply multiply the steady-state drag coefficient *Cd* by the (peak) opening load factor $C_X$ given in the diagram here and then plug the resultant coefficient into the **drag equation** as usual.

The opening shock is therefore $C_X$ times the drag force at the opening airspeed.

The table of $C_X$ values is given here is for the types that have constructional details given in part 3 of this paper.

| Type | Drag Coef. $C_{D_o}$ Range | Opening Load Factor $C_X$ (Inf. Mass) |
|---|---|---|
| Flat Circular | .75 to .80 | ~1.8 |
| Conical | .75 to .90 | ~1.8 |
| Cross | .60 to .78 | ~1.2 |
| Flat Ribbon | .45 to .50 | ~1.05 |
| Conical Ribbon | .50 to .55 | ~1.05 |

Main ‘chute opening shock

The canopy loading of drogues are almost always ‘infinite mass’ but main 'chutes must have much lower **canopy loadings** than drogues to keep their vertical descent speed low, and strictly require a ‘finite mass’ analysis.

The store *will* decelerate during the canopy inflation process, which lowers the **dynamic pressure** progressively during the filling.

This *lowers* the peak opening shock force considerably compared to the ‘infinite mass’ case perhaps by more than 50%, therefore a conservative design philosophy is to calculate the infinite-mass value as before, which therefore gives a safety-factor of about two.

This may over-engineer the main ‘chute system, but without the comfort of extensive testing this may be no bad thing.

In Ref. 3, Lingard relates that all parachutes have a unique opening ‘fingerprint’ - a characteristic load versus time graph. Peak opening force scales directly with a dimensionless parameter known as **Froude number** (see glossary).

So if you can measure the peak opening force for one size of parachute (perhaps using an onboard accelerometer) then you can calculate the peak force for other sizes and/or other opening airspeeds provided it’s the same design of ‘chute.

Deployment from a vertical trajectory increases the peak opening load (quite significantly at low Froude numbers) because gravity is trying to re-accelerate the system.

In fact, for a Froude number of 10 and above – corresponding to a **mass ratio** of about 3 - gravity dominates and the system actually *accelerates* during the opening process, which increases the opening shock load to *higher* than the infinite mass case.

Another effect that significantly increases the peak opening load of main ‘chutes is to open them at high altitude.

Generally, aircraft flying at the same **Indicated airspeeds** or **Equivalent airspeeds** will experience the same aerodynamic forces, whatever altitude they’re flying at. But canopy inflation forces depend upon **True airspeed**, therefore at very high altitudes a moderate Equivalent airspeed can have a very large True airspeed, so the opening shock forces get large.

Note that this altitude effect depends upon **canopy loading** - only low canopy loadings (such as main ‘chutes) suffer from this altitude effect whereas drogues are insensitive to altitude.

# Part 2: Recovery system notes and system components

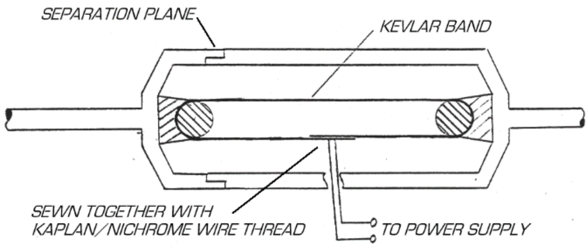
The following are some notes and information that I discovered in my parachute design research.

## Positive deployment

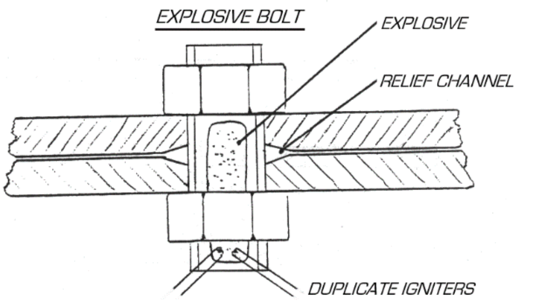
For reliable parachute opening, it is essential to physically pull or throw the ‘chute away from the rocket vehicle at a reasonable initial relative speed, otherwise the ‘chute may flop against the fuselage or snag or rip on the fins before it has a chance to open. Subsequently, it may not open fully or even open at all.

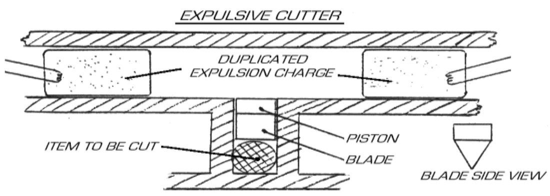
The initiator

The device that initiates the deployment can be of many forms:

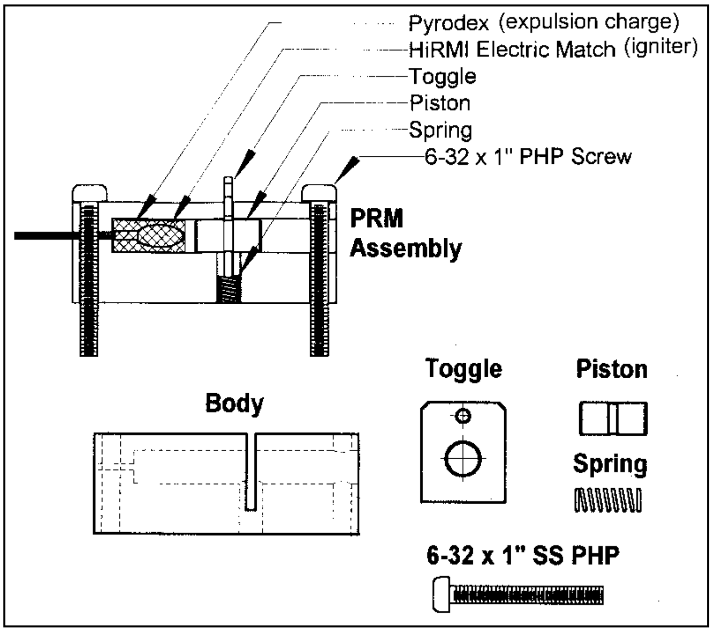



- Electromechanical (solenoid or geared electric motor/servo)
- Thermal (bi-metallic strip or melt-through plastic restraint sewn with nichrome hot-wire as shown here).
- The pyrotechnic variety, such as explosive bolts, or hot-gas-expansion powered devices (piston-driven line-cutters and latches, burst diaphragms) have very low mass for their power – an exceptionally high power-to-weight ratio - so are extensively used.




It’s true that large Launch vehicle manufacturers are shying away from pyrotechnic systems, but this is because of technician litigation worries rather than proper Engineering concerns! Commercial pyrotechnic devices for HPR rocketry can be purchased from the usual online vendors.



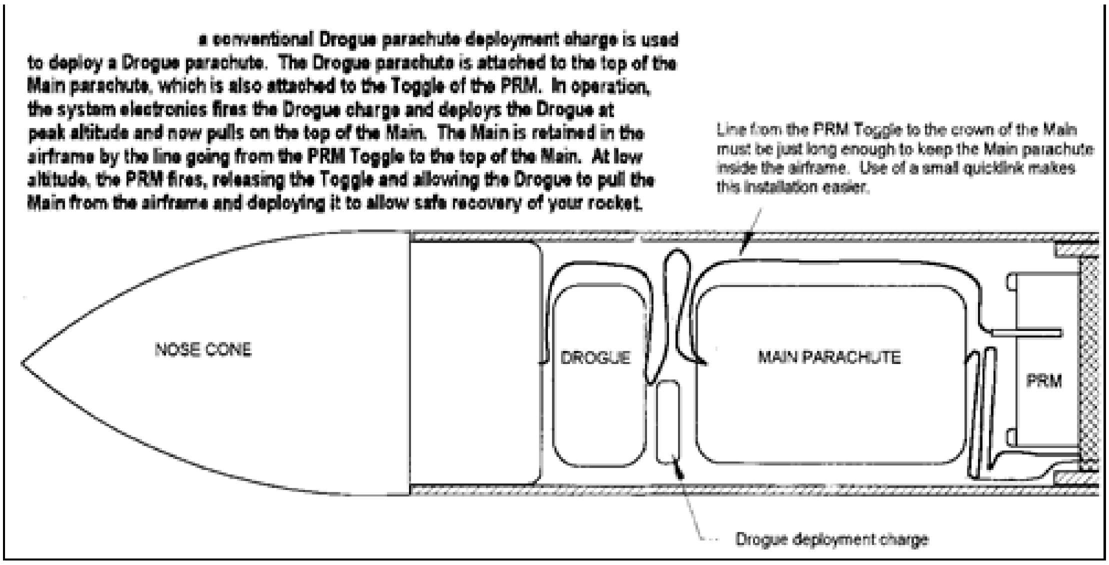

For example, the ‘Pyrotechnic Release mechanism’ from Black Sky Research consists of an expulsion-powder powered piston that releases a metal toggle from a slot in the piston barrel upon actuation.

Although highly reliable, problems have been encountered if too much powder is used, as this can give the piston enough momentum to rebound off of its end-stop back down the barrel, before the toggle has moved clear.

A new, more expensive ‘PRM 2’ has been released, but all that is required to prevent this problem is to absorb the piston’s momentum with ‘blu-tack’ or wet tissue paper placed just ahead of the end-stop.

The tether release system from ‘Defy gravity’ is similar but more versatile, and can restrain much larger loads until separation is required. (www.defyg.com/tether.html)

A typical HPR installation is shown here:




A few pyrotechnic initiators of the hot-gas type can allowably be homemade, but their reliability is only as good as the testing and quality control applied.

Installing identical backup devices (redundancy) in such a way that the failed device will not hinder operation of the backup is advised.

Backup igniters are advised too, wired in parallel, or better yet fired from a completely separate circuit.

Frangible bolts

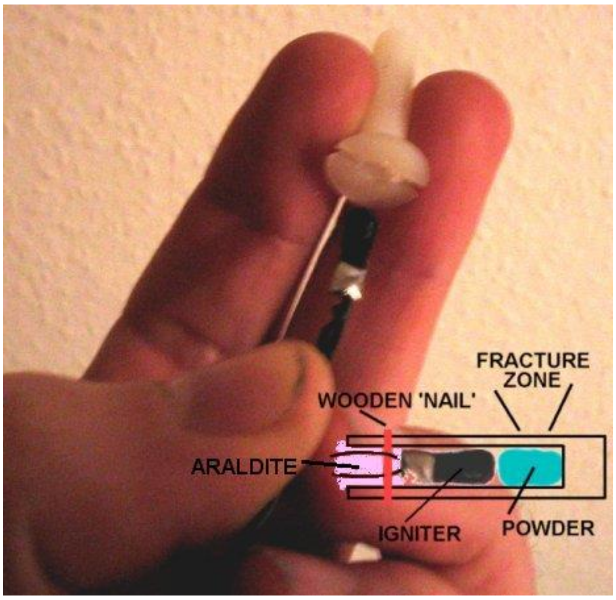
I prefer the name 'frangible bolt' rather than the name 'explosive bolt' because the latter term is too emotive here in the UK!

**N.B.** Homemade explosive bolts are illegal in the UK if manufactured from metal because of the shrapnel hazard. Instead, nylon bolts can be purchased from hardware or electronics shops, then drilled to form a small cavity (3mm long by 3mm diameter) which can be filled with expulsive powder, then blocked at each end.

These can be activated by a hot nichrome wire or an igniter. The benefit of using a nylon bolt instead of a metal one is 1) it's lighter. 2) the shattered fragments are not razor-sharp.

Plastic is viscoelastic: a shock load will shatter it like glass whereas a constant or slowly applied load will be restrained.

Here's one I made earlier: the components are restrained by a plug of epoxy adhesive secured by a wooden dowel. I've made dozens of these, even double-ended ones (twin igniters for redundancy) and every one performed flawlessly. Be warned: the fragments of plastic fly far and fast upon ignition (quite a loud bang too!) so shield your eyes.




The power-source

The stored energy source used to provide the motive power to deploy the 'chute can be of almost any type, even the simple big spring.

In a multiple-stage system, the 'chute from the previous recovery stage is often used to pull the next 'chute out, for simplicity.

In rocketry, pyrotechnic power-sources such as hot-gas expulsion-tubes or rocket motors are used to launch 'chutes, (or their container if used), because pyrotechnics have very low mass for their power (very high power-to-weight ratio), and are simple and compact.

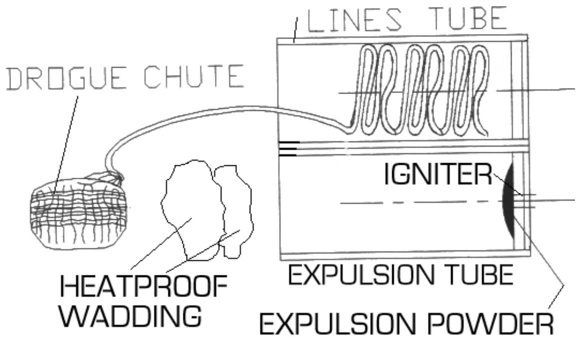
They are surprisingly reliable when properly ignited.

Expulsion tubes

These have the initiator and energy source combined. The humble ‘party popper’ is such a device.

When the small amount of internal expulsion powder is ignited, it burns rapidly, filling the expulsion tube with expanding gas, which launches the ‘chute.

In rocketry, the fuselage body-tube is traditionally used as a large expulsion tube.




**N.B:** The use of metal expulsion-tubes is illegal in the UK because of the shrapnel that can occur if the expulsion tube overpressures and fractures.

Composite tubes are less of a hazard and weigh less: in traditional HPR recovery systems, the composite fuselage tube is used as the expulsion tube.

A 3mm wall-thickness cardboard tube will withstand typical expulsion pressures, and being insulative, rarely chars, as the hot gasses aren’t resident within the tube for long enough for sufficient heat to build up.

Restrict the use of adhesives to the outside of the tube as many adhesives are flammable.

Pros:

- Simplicity.

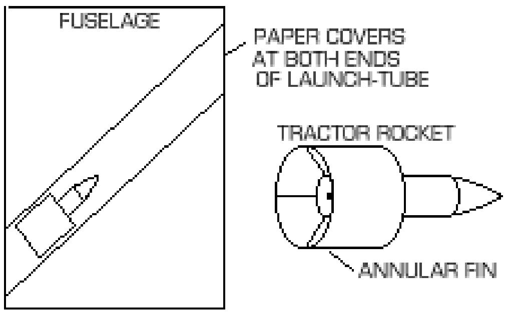
Cons:

- The ‘chute must obviously be heat-protected: Sheets of Estes 'wadding' can be bought from model shops to roll into a ball and place between the expulsion powder and the ‘chute, but this is merely tissue paper soaked in a solution of water and powdered-alum (aluminium sulphide) then allowed to dry. Or use Nomex shields.
- The ‘chute riser and/or bridal lines should be protected too.

The tractor rocket

This is a small auxiliary rocket motor tied to a heatproof **lanyard** so that the rocket exerts a pull. It is currently used on several emergency parachute recovery systems for manned light aircraft. One design is shown here:

There is an obvious fire risk if launched from inside the fuselage, so a tractor rocket would usually be fired from inside an insulated tube.



The exhaust from the rocket - being contained by the rear of the tube - exerts a back-pressure on the rocket's nozzle that can reduce thrust (The 'Krushnik effect') so although there is an expulsion tube effect also, the net thrust is lower.

**N.B:** There is the temptation to try putting a little expulsion-powder inside the tube but don't, as this could crack the rocket's nozzle, or worse its brittle block of solid propellant, which would cause the motor to explode.

Use a tube open at both ends to reduce the back-pressure as shown above.

Any paper end-covers should be glued onto the tube, otherwise they will blow-out during ascent of the main rocket-vehicle.

Pros:

- It has an extremely high power-to-weight ratio.
- There is no recoil on the vehicle as the system deploys.

Cons:

- It will exit the vehicle initially at a much lower speed than a drogue-shell, for example, although it will then continue to accelerate.
- Unless it's launched axially out of the nose, the effect of hitting the airflow side-on while still travelling slowly could - without an extendable launch-rod - deflect it onto an unexpected trajectory. Choose a rocket motor with a high boost thrust/short duration burn for the tractor.

I don't know whether a fin-stabilised tractor-rocket deployed rearwards would fly straight as I haven't tried this.

It's possible to obtain spin-stabilised rocket motors (used for handheld distress flares) that don't need fins so would be better in this application.

Expulsion powder

Commercial rocketry expulsion powder (aka 'ejection charge') is stable, shock insensitive, and (fairly) static insensitive. It burns rapidly, but at a fairly moderate temperature. The main types available to the rocketeer are traditional Black powder (gunpowder) and a Black powder substitute known as 'Pyrodex'.

One cubic centimetre of powder is about five times as much as you'll need to expel a drogue on an HPR-sized rocket: a good rule-of-thumb is that you require 1 gram of powder per 3300 cubic centimetres (200 cubic inches) of expulsion tube to be pressurised.

Expulsion powder is only effective if a reasonably gas-tight seal exists between - for example - the expulsion-tube and the 'chute and/or wadding to allow a sufficient build-up of pressure.

Commercial model rocketry rocket motors use powder sealed-in by a cap of ceramic similar to Plaster-of-Paris, which only finally fractures at high pressure.

**N.B:** If you overdo the 'Plaster-of-Paris' in homemade 'burst-diaphragms' you'll cause a dangerous build-up of internal pressure that could rupture the expulsion tube, or send the expulsion powder past its detonation pressure.

Only ever use thin balsawood sheet for burst-diaphragms.

(In order to get a dangerous pressure build-up between a 'chute (or drogue shell) and an expulsion tube, the seal would have to be ludicrously tight. Just tight enough so that it won't slide out when the expulsion tube is held upside-down will be sufficient.)

Adjust the fit of a drogue shell in its launch tube by wrapping tape around its perimeter.

Glue a strip of paper or thread across the mouth of the expulsion tube as an added restraint if required, or use a **shear pin** (see later).

High altitude problems

It's been reported that several rocket vehicles have suffered ejection charge failures at very high altitude. It's not clear what went wrong, but it's thought that the near-vacuum of very high altitudes is preventing the propagation of heat and flame across the loose pile of expulsion powder; the bulk of the powder doesn't burn.

Black powder - like other propellants - has a 'deflagration limit' which is a minimum pressure at which combustion is barely self-sustaining. If the pressure drops too low, combustion will cease or be erratic at best.

Similarly, below roughly six kilometres (20,000 feet), air contributes significantly to the heat transfer from the igniter to the powder. Above that altitude there is significantly lower assisted convective and conductive heat transfer, so a much more energetic igniter is required to set off the powder than at sea level.

The primary way to correct this problem is used on military and civilian high-altitude rockets: they use sealed canisters to contain the powder, containing sea-level-pressure air with burst diaphragms for motor igniters and deployment devices. The container is designed to burst at a set over-pressure when the powder burns and expands.

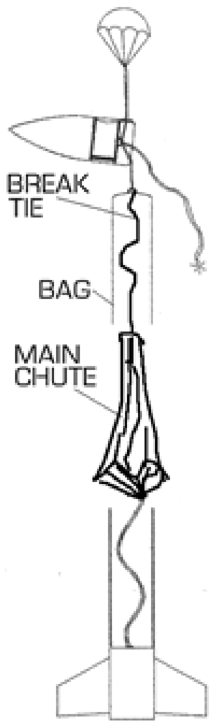
Whatever material is chosen for the burst diaphragm should be tested to make sure it will break at around 1.4 Bar (20 PSI) overpressure to prevent fragment damage to the rocket vehicle, since over-confined Black powder can generate 1,700 Bar pressure or higher.

A second - though heavier - option is to use pressurised gas such as carbon dioxide ($CO_2$) to power the recovery system. The 'Rouse Tech CD3' gas ejection system is such a system that is available commercially.

Rouse Tech say that for every gram of Black Powder you would use in a deployment system, you should substitute 5 grams of $CO_2$. Rocketeer Richard Brown reports that in his experience, the figure is nearer to 10 grams of $CO_2$, and he also says that **shear pins** (see later) are a must for $CO_2$ as it helps build the pressure up before popping off the nose.

Obviously, the mass of the $CO_2$ cartridge/s and actuator adds to the system mass.

## Some ejection options




Forward ejection

The traditional method used in model rocket recovery systems, the ‘chute deploys in the direction of travel.

Pros:

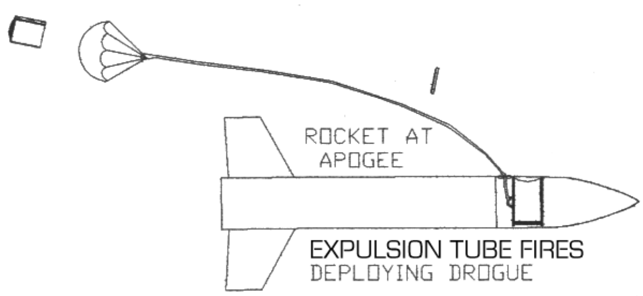
- Simplicity of design: thrust forces keep the ‘chute within its compartment during ascent, therefore little restraint is required.
- The same forces keep the expulsion charge at the bottom of the parachute compartment as required.

Cons:

- When the ‘chute opens, it naturally decelerates much more than the rocket-vehicle and ends up behind the vehicle. The riser, if anchored to a **hardpoint** within the fuselage, therefore gets bent back nearly 180 degrees round the edge of the deployment bay and can ‘zipper’.
- Even if these don’t occur, severe compressive loads are imposed down the fuselage, which being slender is much weaker in compression than in tension.

Sideways ejection

The ‘chutes deploy side-on to the direction of travel.




Pros:

- Ensures that the ‘chute cannot impact with the fins.
- Ensures that the riser has a sufficient moment arm to combat the rocket-vehicle’s aerodynamic stability, to flip the vehicle around into a tail-first attitude.
- If the riser is short to keep the ‘chute upstream of the fins to prevent snagging, the vehicle must be rotated into a tail-first trajectory to prevent the ‘chute lying unopened against the fuselage, as actually happened on some slender HPR vehicles.

Cons:

- A side-hatch or door may be required, which must withstand the pressure differential between the lower pressure of the air moving past the vehicle and the static pressure inside. When we ran the NRC competition, one team’s side-door had a weak catch, and the door was sucked out.
- Limitation on hole size in the side of the fuselage, as a large hole needs extensive edge reinforcement otherwise the fuselage is weakened.

- Holes for main ‘chutes tend to be long and narrow, which makes uniform deployment difficult. We experimented with ‘parabags’. These are Calico (see materials section) or Nomex airbags inflated by a small packet of expulsion-charge or cold gas, and ensure an even deployment pressure along the length of the ‘chute. The bags need coated in liquid rubber or some other sealant to make them gas-tight.
- Zippering is still a potential issue, but avoidable with grommets/radiusing etc.

Rearwards ejection

Expulsion tubes or drogue-shells require modification if they're to be used for ejection from the rear of the vehicle, or they'll simply fall out due to the acceleration during motor thrust. Having a ‘chute open while the motor is thrusting could have a very dangerous effect on the trajectory!

Using an extremely tight-fitting ‘chute or shell could cause an overpressure which fractures the tube and so is ill-advised.

A special latch or suchlike must secure the ‘chute in place during motor firing, and furthermore, the system must be designed fail-safe so that any pyrotechnics used cannot be armed - let alone fired - until this latch is released after motor burnout.

**Shear pins** (see later) will do the job of restraint.

Pros:

- Vehicle is not swung off of its nose-first trajectory at deployment: A large mass-optimised fuselage suddenly flying sideways at high airspeeds may fail due to excessive drag (deceleration), and rotational accelerations.

Cons:

- Limited space available for installation around the motor.
- Safety latch or shear pins required.
- A good expulsion speed is required to avoid the ‘chute getting caught in the recirculating region of dead air that occurs behind the blunt base of the vehicle.
- An expulsion tube installed in the fuselage near a rocket motor (for rearwards expulsion) will need heatproofing both for itself and the ‘chute from the heat radiated from the rocket motor and its exhaust, or it might go off prematurely.

Fuselage separation prior to ejection

In this traditional HPR method, whole sections of the fuselage are separated at a designated point (known as a separation plane) using some kind of joint, in order to provide an open compartment to allow the subsequent release of the ‘chute.

The method popular in both model rocketry and High power rocketry is to use expulsion charge to pressurise the inside of the fuselage, which then pistons apart at a slide-collar joint.

Traditionally, this collar is at the base of the nose, which is thrown off as the ‘chute below it cannons into it, as a form of forwards ejection.

In an HPR system known as ‘anti-zippering’, ‘chutes are rearwards-deployed from the upstream section. The expulsion charge used for separation also blows the ‘chute out.

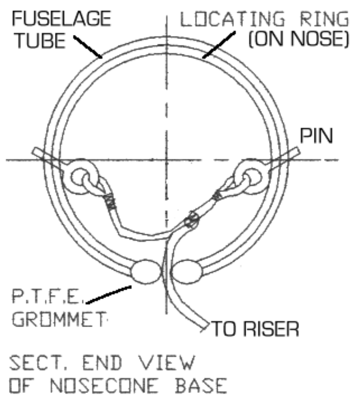
Points to consider when choosing the location of a 'separation plane' are:

- In a multistage recovery system, at which recovery stage should separation occur?
- Will the difference in drag-to-mass ratios of the two separated parts of the structure cause them to drift apart under aerodynamic forces after separation, or collide? Recently, two separating parts of a 'K' powered-rocket collided near apogee, embedding the fins of one half through the composite fuselage of the other half.
- Are the separated parts aerodynamically stable or unstable? As well as causing fouling problems, a tumbling section has a much higher drag than if not tumbling.
- What Normal, Axial, and Bending mechanical forces will the separation joint have to withstand at your chosen separation plane location prior to separation?
- If both sections are joined by a long length of riser, there is a risk of collision.
- Each completely separated part will need its own recovery system, and the required reliability of each part's recovery system will increase if any expensive payloads, rocket motors, or equipment, are housed within it.
- The chances of the ground crew successfully recovering all completely separated parts increase if they all land fairly close together, which depends upon how late in the recovery sequence they separate.

Separation joint design

A separation joint needs forethought in its design:

Creating a separation joint that is lightweight but can withstand the forces acting on it is tricky in itself, but the biggest technical challenge is to design a mechanism that won't jam if actuated while the joint is suffering any sideways or bending forces, and in fact will work every time.




As used in model and HPR rocketry, The 'locating ring' or 'socket' simply consists of a 'coupler' tube or ring that acts as an internal collar linking the two fuselage sections together.

Fixed rigidly to one section, it is a simple slide-fit into the other.

A particularly heavy forward section might decelerate less than the rearward section after burnout, causing premature separation. If this could be a problem, the sliding parts can be secured prior to deployment via release pins, which are pulled out by a common lanyard. Alternatively, secure the joint with **shear pins**.

Pros:

- Simple.
- Reliable.
- Well-tested.

Cons:

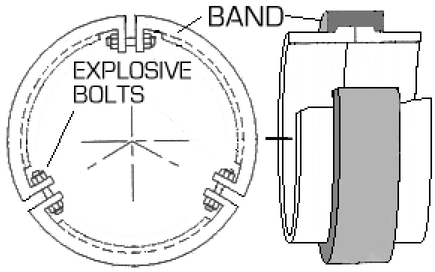
- Fuselage tube often needs local reinforcement at the 'coupler' to withstand high bending moments.
- Reinforced cloth/card composite tubes are notorious for absorbing moisture on damp days and swelling up: this increased diameter can cause the socket joint to jam. Always test the joint just prior to flight.

From Ref. 2, here are two popular joint designs that are used on large commercial sounding rockets and spacecraft: The Separation band and the Bearing lock:

The ‘separation band’ consists of a tight strap holding the two halves of the fuselage together. The band has a 'C' shaped channel section to grip protrusions from the lip of both halves.

The band is made from equal segments, which are usually joined by several explosive bolts for redundancy.

If only one explosive bolt is used, with a hinge diametrically opposite it, this is known as a ‘Manacle clamp’, and resembles a handcuff.




The highly successful Skylark sounding rocket used wire-tensioned separation bands, whereas the Black Arrow satellite launcher used a manacle clamp to hold the 3rd stage on.

Pros:

- Moderately simple construction (lends itself to 3D printing).
- Very reliable if multiple explosive bolts are used, as the firing of any one bolt will free the band (with the help of separation springs).
- Can withstand very high mechanical loads and bending moments.

Cons:

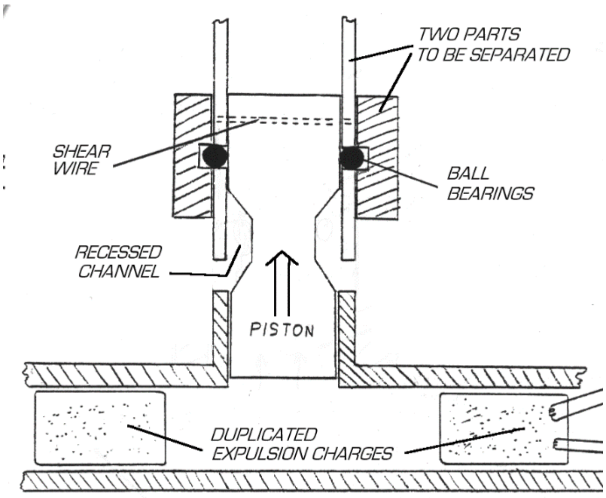
- The original design needs explosive bolts.
- Careful design is needed to allow access to the bolts for assembly.
- Needs an aerodynamic shroud or causes high drag.

Hydraulic quick-release couplings often incorporate a ‘bearing lock’.

When the inner piston is fired upwards pyrotechnically, the ball bearings can roll inwards into the now exposed recessed channel in the piston, freeing the outer tube.

Pros:

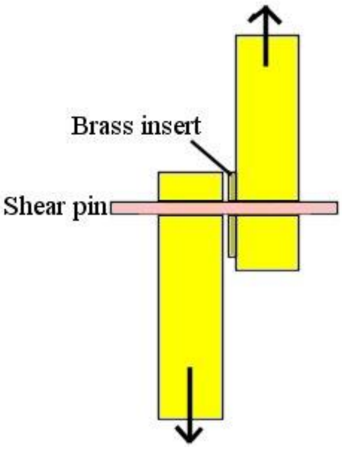
- Reliable, especially if multiple expulsion charges are used.
- Very little force is required to move the piston, whereas the lock can successfully restrain very heavy loadings prior to separation.
- The ball-bearings can be used to give a low-friction release if more than one set is used.




Cons:

- Has to be manufactured to a reasonable tolerance to work.
- Unacceptable debris hazard from flying ball bearings unless they’re captured after leaving the recessed channel.

<u>Shear pins</u>
It has become standard practice in the HPR world to use shear pins to hold sections of fuselage together prior to recovery system deployment.




These are small rods/pins of plastic that shear when the expulsion charge fires, due to the visco-elastic properties of plastics which means that they can absorb heavy static loads, but only small shock-loads.

The pins are inserted snugly into holes drilled through the coupler joint to be restrained, and glued in place. Often a small insert of very thin brass plate or tube is mounted within the hole to provide a sharp cutting edge.

Suitable sizes of plastic rod shear pins per diameter of airframe are (courtesy of UKRA):

| Fuselage diameter | Recommended shear pins |
|---|---|
| 38mm (1.5") diameter | 2 x 1.6mm shear pins |
| 54mm (2") diameter | 2 x 1.6mm shear pins |
| 68mm (2.6") diameter | 3 x 1.6mm shear pins |
| 75mm (3") diameter | 3 x 2.5mm shear pins |
| 100mm (4") diameter | 3 x 2.5mm shear pins |
| 137mm (5.5") diameter | 4 x 2.5mm shear pins |
| 150mm (6") diameter | 4 x 2.5mm shear pins |
| 187mm (7.5") diameter | 4 x 2.5mm shear pins |
| 290mm (11.4") diameter | 4 x 3.2mm shear pins |

The most common plastic used is Styrene rod from online model shops.

When using shear pins, more expulsion charge is needed.

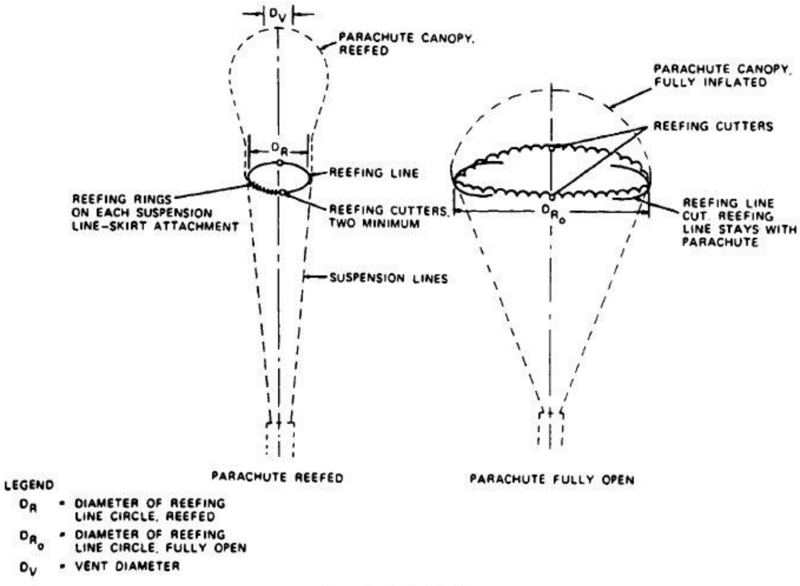
**<u>Reefing</u>**

A reefed ‘chute is one whose canopy mouth has been restricted so that the canopy cannot open fully. This reduces the ‘chute drag so in effect gives a staged recovery: at some later time ‘reefing line cutters’ or other ‘dis-reefing devices’ release to allow the ‘chute to fully open.

‘Skirt reefing’ is the most common reefing method.

Reefing rings are attached to the canopy skirt on the inside of the canopy at the connection point of each suspension line.

The reefing line - a continuous line that restricts the opening of the canopy - is guided through the reefing rings and several reefing line cutters.

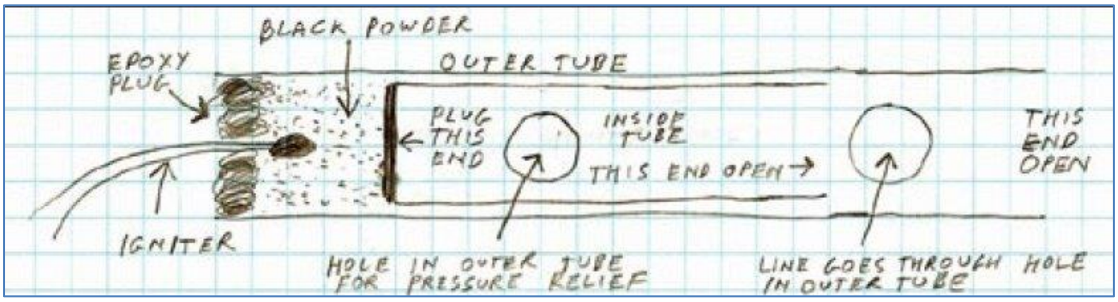


Parachute Skirt Reefing.

Each cutter contains a pyro-timer ‘train’ fuse and a cutter knife, and is initiated at canopy stretch by pull-cords attached to the suspension lines or to the canopy. At a preselected time, the cutter fires and the knife severs the reefing line, allowing the parachute canopy to open fully.

Reefing line cutters can be bought or home-made.

Ref. 4 describes a small reefing cutter made from two concentric metal tubes: the inner tube is fired along the inside of the outer tube and its sharp edge cuts the reefing line:



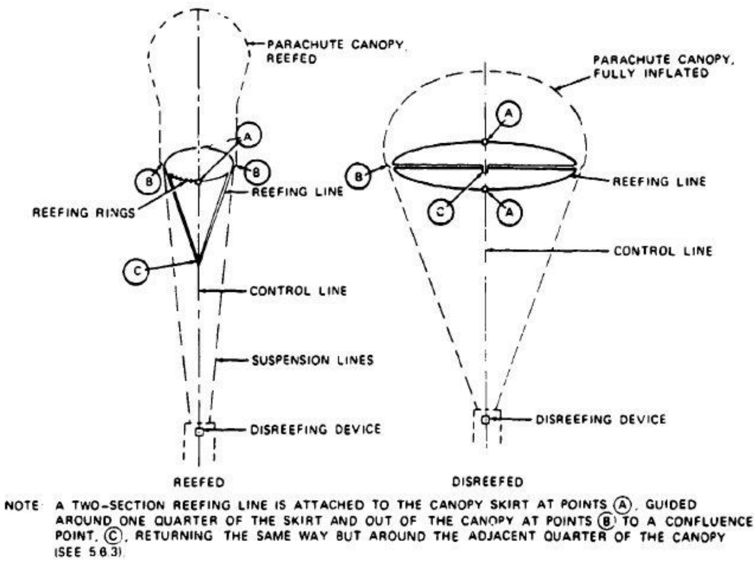

(The inner tube must be a snug fit within the outer tube.)

Control line reefing

A reefing method that is simpler for HPR rocketeers to implement is skirt reefing with a control line.

A two-section reefing line is attached to the canopy skirt at points A, guided around one-quarter of the skirt and out of the canopy at points B to a confluence point C, returning the same way but around the adjacent quarter of the canopy.

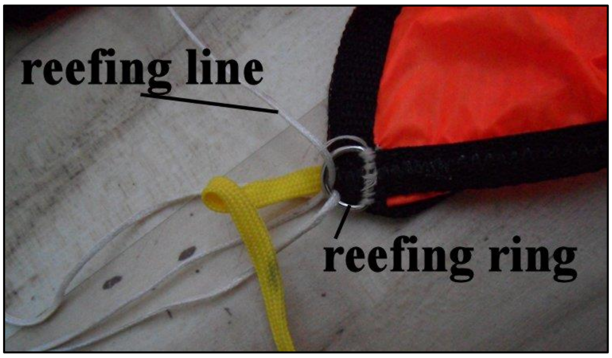
A second reefing line is run similarly around the second half of the canopy, and is connected with the first line at point C.




Parachute Skirt Reefing With Control Line.

The reefing system must allow full opening of the canopy. Pulling the control line toward the confluence point of the suspension lines reefs the canopy; paying out the control line dis-reefs it.

Here's a skirt-reefing system I added to a commercial HPR parachute, using metal 'D' rings I bought from a sewing supplies website:



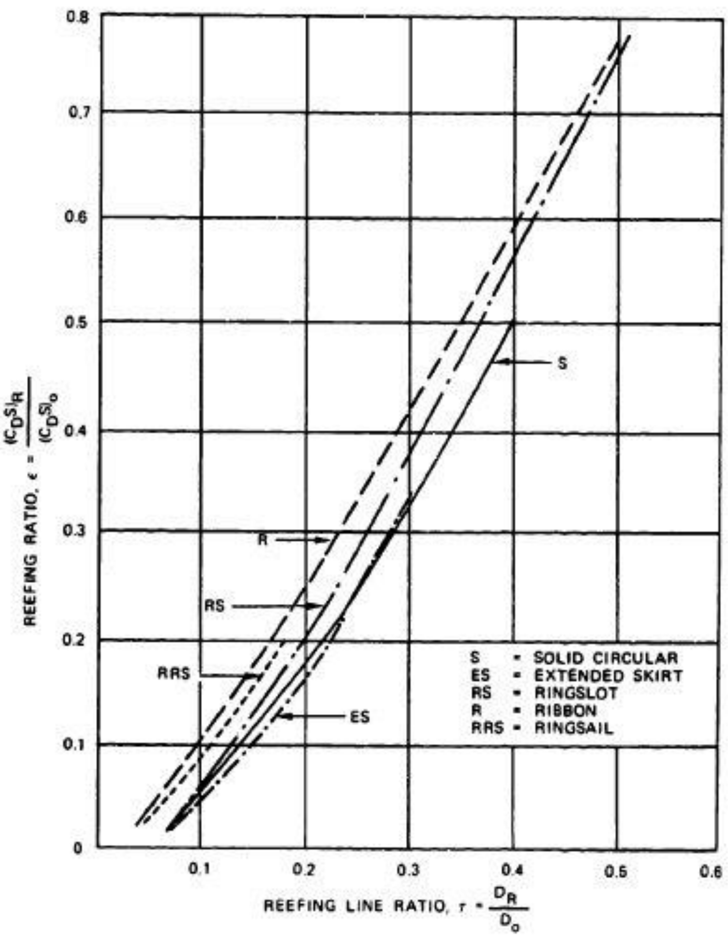

I used a 'Defy gravity' tether for the dis-reefing device for this 'chute.


Note that small HPR-sized 'chutes can't be reefed below about 10% (reefed canopy mouth area compared to the unreefed mouth area) otherwise they won't open properly.

Reefing ratio
To calculate the effect of skirt reefing, first calculate the drag reduction you require (reefing ratio).

The required reefing *line* ratio can then be calculated from this graph:

where the reefing *line* ratio is the diameter (actually circumference) of the reefed chute mouth compared to the un-reefed diameter, and describes how much reefing line needs to be pulled-in to reef the 'chute. The relationship isn't quite linear:




Reefing Ratio Versus Reefing-Line Ratio for Various Parachutes.

Reefing line forces
The shock load on the reefing line during reefed canopy inflation is surprisingly low, around 5% of the opening shock load of the reefed 'chute.

## Vehicle landing speeds

The landing speed of a store suspended under a parachute can simply be calculated by assuming that the system has reached terminal velocity.

This landing vertical velocity should be around 5 metres per second, and no more than 8.

A velocity much higher than this could be dangerous to persons underneath the store, and might break the fuselage.

The drag of the store is negligible in comparison to the drag of a 'chute large enough to attain this terminal velocity, and can be ignored in the **terminal velocity** equation (see glossary), so the vertical landing velocity is:

$$V_V = \sqrt{\frac{2mg}{\rho S C_D}}$$ (see glossary)

## Squidding

If opened at too high an airspeed, simple main 'chute type canopies simply fail to open, and streamer behind the rocket vehicle. The canopy and lines then look remarkably like a squid.

Squidding seems only to affect very large 'chutes, I haven't heard of an HPR-sized 'chute that went squid.

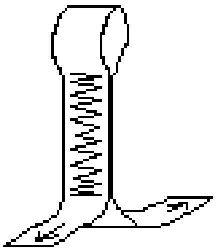
## Load dissipation

A device that can dissipate some of the high loads occurring within parachute risers during opening are often incorporated into recovery systems.

Note that nylon rope stretches permanently above a certain load, dissipating this load. Kevlar does not, and simply snaps without prior stretch at too high a load.

Several long bungee cords or elastic straps connected in parallel with the riser are often used. (These are known in rocketeering circles as 'shockcord'.)

The 'frangible tie' is shown here, which is a strip of webbing folded lengthways and sewn together. On opening, both ends of the webbing get pulled apart and the graduated stitching tears smoothly and progressively, dissipating shock-loads.



Raptor Aerospace uses a variation on this idea: they make loops in their risers, and wind adhesive tape across the neck of the loop. The tape tears upon recovery deployment, dissipating some of the load.

## Testing

This is vital for ironing out the inevitable bugs in the recovery system.

For reasons that aren't terribly understood, windtunnel testing never yields overly useful drag or opening shock results, so other novel methods have to be used:

Method 1: Dropped from a manned aircraft or hot-air balloon.

Pros:

- Controlled experiment.
- High snatch velocity.

Cons:

- Expensive if large or manned aircraft are used.
- Civil Aviation Authority waivers have to be acquired to allow dropping of anything from a manned aircraft or balloon.
- Possibly hazardous to pilots and ground personnel.

Method 2: Dropped from a radio-controlled aeroplane/helicopter/drone, HPR rocket, or large kite.

Pros:

- Cheaper.
- No Aviation Authority waiver required.
- Horizontal deployments can be obtained using rocketry: lowering the launch-angle allows the same apogee airspeeds to be reached using lower-power rocket motors.

Cons:

- Complexity of remote release systems.
- Snatch velocity, altitude, attitude information etc., must be remotely obtained.
- Possible construction and launch of another, though simpler, rocket vehicle.

Method 3: Dropped from a tall building (an airship hanger is traditional), or off a cliff.

Pros:

- Simple.
- Cheap.

Cons:

- Vertical trajectory only: gravitational effects have to be removed when extrapolating to deployments from horizontal trajectories.
- Safety of those below.
- Building or cliff might not be tall enough to obtain required deployment airspeed.

Method 4: Deployment from road vehicles.

Pros:

- Cheap.
- Controlled experiment: in-situ recording.

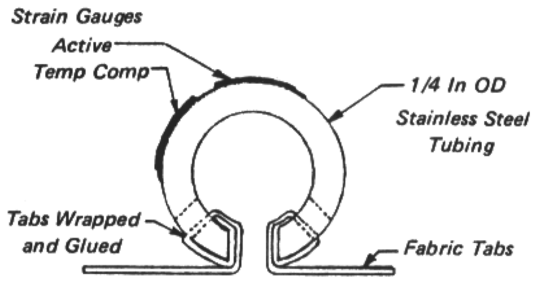
Cons:

- Even allegedly aerodynamic cars affect the airflow around them to quite a distance away from the vehicle, so the airflow around the ‘chute may well be travelling at an airspeed and direction quite different to what is expected, especially in the vehicle's wake. A pyramidal framework of poles bolted to a roof-rack or suchlike should raise the test-parachute at least two metres above the roof of the car.
- Definitely finite-mass deployment unless a representative store mass is released with the ‘chute.
- Best done on private roads or runways for legal reasons.

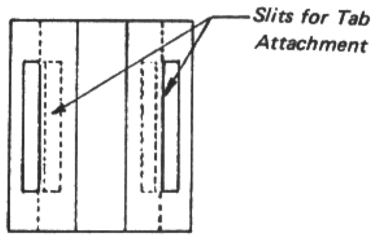
Measuring the load versus time curve during the deployment of a recovery system requires fixing strain gauges to a recording device such as an Arduino microcontroller, and letting the whole system fall free.

The recording device needs to have a fast scan rate.

A force-transducer known as an 'omega sensor' is shown opposite. These can be made extremely small:




The variation of tube-strain with force is a simple engineering formula, and is easily calibrated.




Bottom View of Omega Sensor Without Tabs

Testing of expulsion tubes or drogue shells or whatever is required: too much powder and the snatch load will be excessive.

A video-camera/web-cam and a freeze-frame player can be used to discern the exit velocity, provided you know the frame rate (number of pictures taken per second) of the camera.

**Recovery pyrotechnics electronics safety**

Any recovery pyrotechnics used must only be armed at launch - preferably during lift-off - for the safety of ground personnel.

A pull-out metal pin tied to the pad, or simple break-wire, will tell the onboard electronics when the rocket is leaving the launchpad, and can be used to arm the system and/or initiate timers. The RDAS flight computer can be armed with such a break-wire.

With ever more electronics being fitted into HPR rockets, the potential for inadvertent recovery device actuation by stray electrical currents from other systems becomes a concern.

Here are a list of recommendations from ref. 5 for pyrotechnic electronics for spacecraft:

- The electrical wiring and power source must be completely independent and isolated from all other systems. They must not share common cables, terminals, power sources, tie points, or connectors with any other system.
- The system initiator must be isolated electrically by switches in both the power and return legs.
- All electrical circuit wiring must be twisted, shielded, and independent of all other systems. The use of single wire firing lines having their shield as the return is prohibited.
- Shielding must provide a minimum 20 decibel safety margin below the minimum rated function current of the system initiator - the maximum no-fire current for electrically-actuated pyrotechnic devices.
- Shielding must be continuous, and terminated to the shell of connectors and components. The shield must be joined electrically to the shell of the connector or component around the full 360 degrees of the shield. The shell of connectors or components must provide attenuation at least equal to that of the shield.

- The electrical circuit to which the system electrically-actuated pyrotechnic device is connected must be isolated from vehicle ground by no less than 10K ohm of resistance.
- All circuits must be designed with a minimum of two independent safety devices. Any time personnel are exposed to a hazardous system, a minimum of two independent safety devices are required to be in place.
- The system electrically-actuated pyrotechnic device must be protected by an electrical short until its programmed actuation. This requirement does not negate the use of solid-state switches.
- Any electrical relay or switch electrically adjacent to the system initiator, either in the power or return leg of the electrical circuit, must not have voltage applied to the switching coil or the enable or disable circuit for solid state relays and switches until the programmed initiation event.

# Part 3: parachute design

## Parachute types

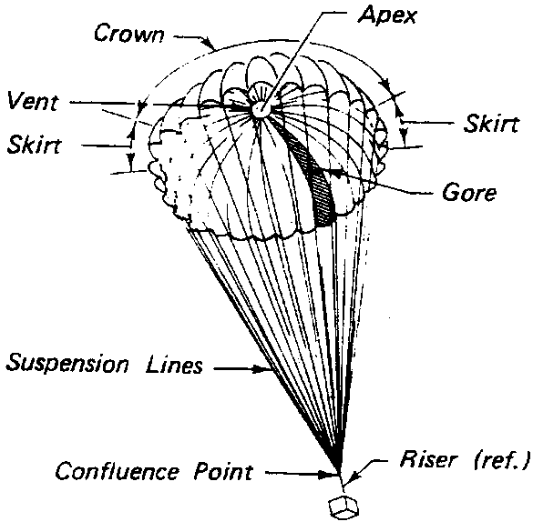
| Type | Constructed Shape: Plan | Constructed Shape: Profile | $\frac{D_c}{D_o}$ | Inflated Shape $\frac{D_p}{D_o}$ | Drag Coef. $C_{D_o}$ Range | Opening Load Factor $C_X$ (Inf. Mass) | Average Angle of Oscillation | General Application |
|---|---|---|---|---|---|---|---|---|
| Flat Circular | | | 1.00 | .67 to .70 | .75 to .80 | ~1.8 | ±10° to ±40° | Descent |
| Conical | | | .93 to .95 | .70 | .75 to .90 | ~1.8 | ±10° to ±30° | Descent |
| Cross | | | 1.15 to 1.19 | .66 to .72 | .60 to .78 | ~1.2 | 0° to ±3° | Descent, Deceleration |
| Flat Ribbon | | | 1.00 | .67 | .45 to .50 | ~1.05 | 0° to ±3° | Drogue, Descent, Deceleration |
| Conical Ribbon | | | .95 to .97 | .70 | .50 to .55 | ~1.05 | 0° to ±3° | Descent, Deceleration |

Parachute Types and Characteristics

| Characteristics | Parachute System: Conical Ribbon | Disk-Gap-Band | Modified Ringsail | Cross | Ribless Guide Surface |
|---|---|---|---|---|---|
| Drag coefficient | 0.5 to 0.55 | 0.52 to 0.58 | 0.52 to 0.8 | 0.6 to 0.78 | 0.3 to 0.34 |
| Opening load factor | ~1.05 to ~1.3 | ~1.3 | ~0.1 | ~1.2 | ~1.4 |
| Average angle of oscillation | 0 to ±3° | ±3 to 6° (WT tests) | ~±7° | 0 to ±3° | 0 to ±3° |
| Canopy stability | Beginning of severe pulsation and ribbon flutter at M > 1.5 | These parachutes were characterized by partial collapse and fluctuations of the canopy immediately after the first inflation peak at Mach numbers M > 1.4. The partial collapse was most severe for the disk-gap-band configuration and least severe for the modified ringsail system | | | No data available |
| Mach range | 0.1 < M < 2.0 | | Stable for M < 1.4 | Never stable in 1.1 < M < 1.64 | |

The drag figures quoted for large 'chutes are often higher than they actually are in reality, due mainly to a poor measuring method. Expect small replicas of big 'chutes to have lower drag coefficients (Cd's); perhaps by around 20 percent.

## Materials and construction




Canopy
The best material for strong, lightweight 'chutes is ripstop nylon, as sold in kite shops.

For extra strength for drogues, use a double-thickness of material, or use hot-air-balloon-grade ripstop which is a thicker material.

Remember to make a vent hole at the apex of circular canopies, of roughly one percent of the canopy area. (This will need reinforcing.)

Good practice is to continue the bridal lines right across the canopy, across the vent-hole, and down the other side, as this adds strength.

Construction plans for several common types are given below.

'Chutes can be bought off the shelf: consult rocketry suppliers, magazines, and websites.

Streamers
These are strips of material about 10 times as long as they are wide, that are popular in the model rocketry world as subsonic drogues. They create drag by fluttering like a flag.

We don't have any drag data for streamers. They appear to be size-limited - may work at larger sizes.

Deployment bags

Deployment bags should not be made of synthetic fabrics such as nylon, as frictional heating between the parachute bay walls and the bag during a vicious extraction can melt synthetic fabric.

Heavy cotton, sack-cloth, or linen is typically used instead, such as heavy-duty curtain lining, Calico, or Nomex.

The bag may require axial strengthening with webbing or tapes.

Ropes and Lines
Heavy-duty webbing (e.g. Dacron tape) and strong lines can be bought either from kite-shops, or from shops supplying materials to make horse-rugs and bridals. Alternatively, purchase these from rocketry vendors.

Other lines and fastenings can be bought from Yacht Chandlers or mountaineering supply shops.

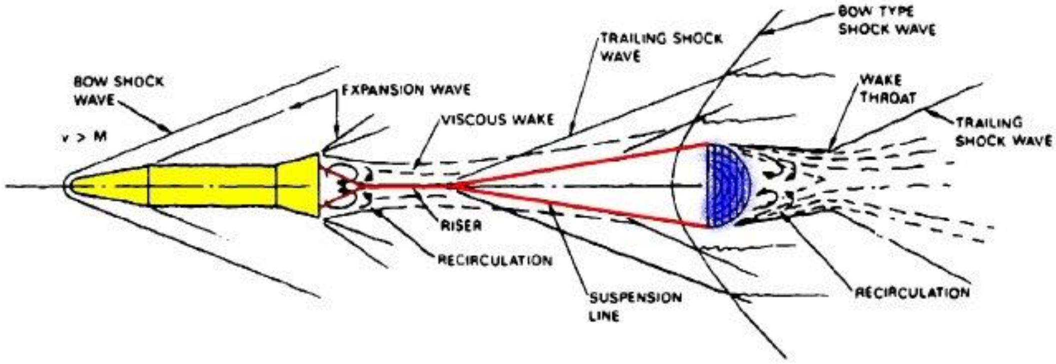
Ropes and lines are weakened considerably if forced to turn sharply through a large angle, especially if they kink: some sort of guide with a large radius - such as a pulley-wheel or grommet - is advised.

**Supersonic parachutes**

Most HPR drogue ‘chutes are deployed at low to moderate subsonic airspeeds. But the time will come when amateur vehicles will rise above then re-enter the sensible atmosphere at supersonic airspeeds.

Subsonic ‘chute designs forced to open at supersonic airspeeds will experience a shockwave across the canopy mouth which destabilises them: they can flutter inside-out and/or tear apart. Supersonic ‘chutes therefore have to be designed differently.

This figure shows the supersonic flow-field around a streamlined body with an attached aerodynamic decelerator at a velocity of approximately Mach 3. The distance between the body and the leading edge of the parachute canopy is equal to six to nine times the maximum body diameter to get the ‘chute well behind the stagnant rocket vehicle wake, and the suspension line length is equal to two times the nominal parachute diameter, *Do*.

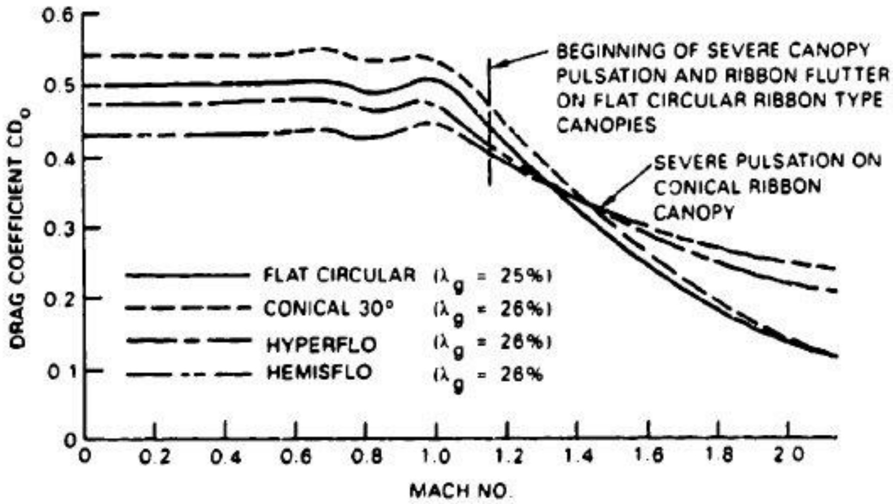



Supersonic Flow Around a Vehicle-Parachute System.

Conical ribbon parachutes are suitable up to around Mach 2.5. Several new canopy designs have been developed, including the ‘Hemisflo’ ribbon, ‘Equiflo’ ribbon, and ‘Hyperflo’ parachutes. The ‘Hemisflo’ ribbon parachute proves to be the most practical design for velocities up to Mach 3.

Low-altitude, high **dynamic pressure** application of nylon parachutes is limited to about Mach 2.2, because at higher airspeeds aerodynamic heating starts to melt the leading edge of the canopy, and lightweight canopy parts such as ribbons and tapes.

Whatever the ‘chute type, its drag coefficient reduces with Mach number:




Drag Coefficient of Several Ribbon Parachutes as Function of Mach Number (1962 Data)

Supersonic 'chutes suitable for airspeeds up to about Mach 1.5 can be bought from Ky Michalson's website: [www.the-rocketman.com/chutes.html](http://www.the-rocketman.com/chutes.html)

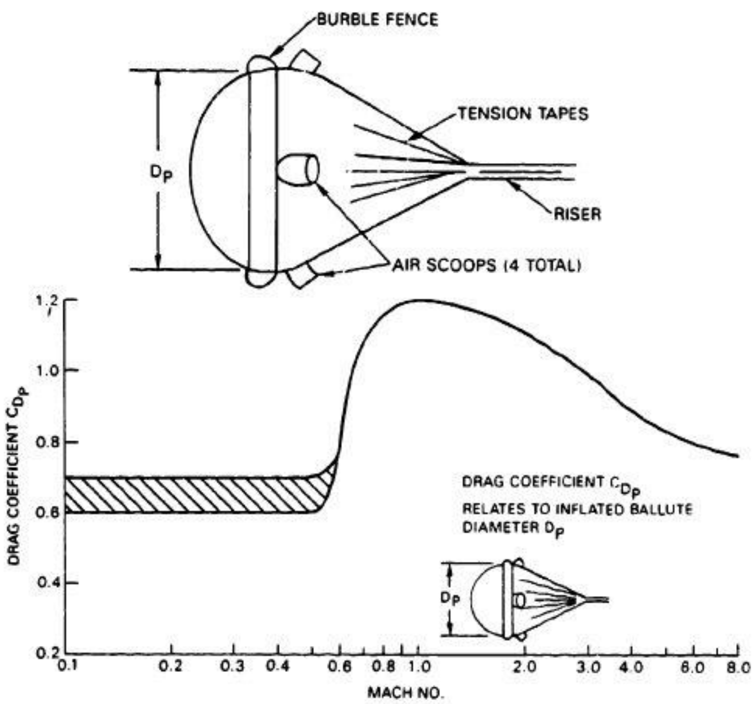
<u>Ballutes</u>

At even higher Mach numbers, a more radical design is required.

The ballute (or 'attached inflatable decelerator - AID), is an inflatable device similar in shape to the 'space hopper' children's toy.

Structurally, the balloon-shaped rear and centre part is a tension shell. The conical forward part carries the loads to a junction point for connection to the **store**.

A 'burble fence' around the equator of the ballute creates a uniform flow separation, thereby eliminating destabilizing side forces.

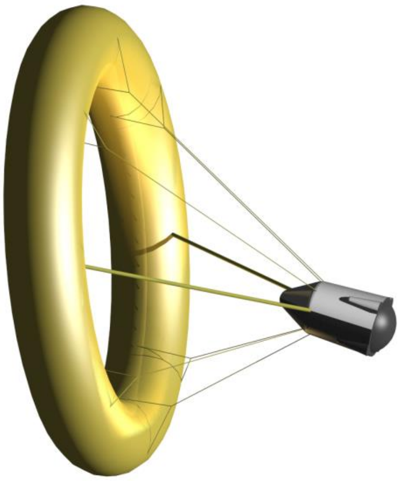



Drag Coefficient Versus Mach Number for Goodyear Ballute.

The burble fence and the inverted conical front-part together provide good stability. Air scoops in front of the burble fence ram-air inflate the ballute. Inflation with stored gas or gas generators has been investigated but is generally replaced with the simpler ram-air inflation method where possible.

The above figure shows the ballute drag coefficient *Cdp*, as a function of Mach number. (The drag coefficient relates to the inflated area of the ballute, *Sp*, and not to the total surface area *So* as is customary on parachutes.)

Another more modern ballute design is an inflatable ring; this is easier to fabricate, and avoids the wake of dead air behind the base of the body:

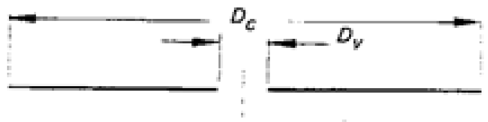


www.gaerospace.com/projects/Hypersonics/aerodecelerators.html

## Parachute canopy design templates

**Solid Cloth Parachutes**

**Flat Circular.** The canopy is a regular polygon of $N$ sides, constructed as a flat surface with a central vent. It's design is the basis for most circular parachutes, other types being variations in gore pattern and general geometry. Flat circular parachutes are simple and economical to construct, handle and inspect, and are often used in clusters. They are in wide use for personnel and airdrop applications. This parachute is very reliable. Data for several specific flat circular parachute and load configurations are listed below for drag coefficient increase and improved inflation characteristics.




CONSTRUCTION SCHEMATIC

$$h_s = \left[\frac{S_o}{N \tan(180^\circ/N)}\right]^{1/2}$$

$$e_s = 2h_s \tan(180^\circ/N)$$

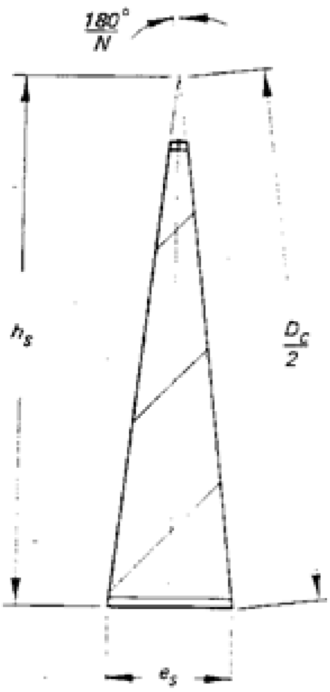
*Generally :*

$$S_v < 0.01\ S_o$$

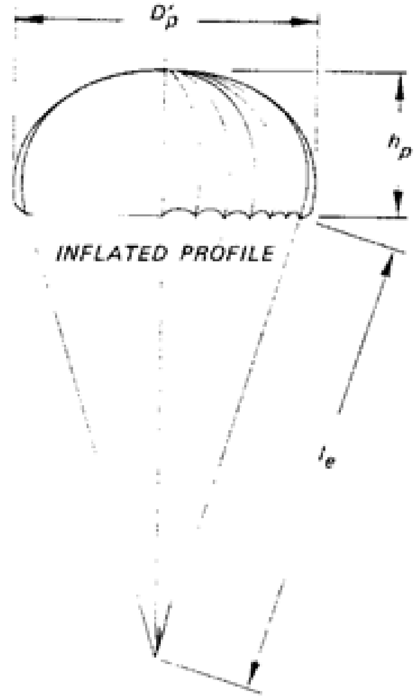
$$\frac{l_e}{D_o} \approx 0.80 \text{ to } 1.25$$

$$\frac{D_p'}{D_o} \approx 0.67$$

$$\frac{h_p}{D_p'} \approx 0.41$$

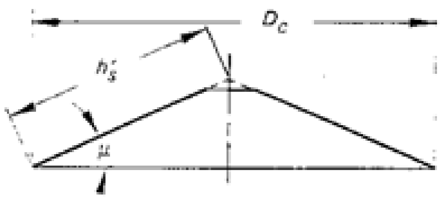



GORE LAYOUT

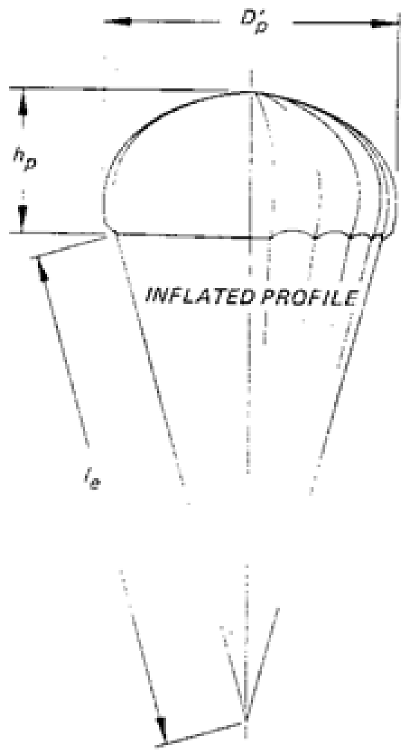



| Designation and Size $D_o$, ft | Canopy (nylon) oz/yd² | No. of Gores $N$ | Line Str. (nylon) lbs | Line Length $l_e/D_o$ | Parachute Weight lbs | Payload | Payload Weight lbs | Max. Deploy. Velocity | Rate of Descent fps | Special Conditions | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| C-9 28 | 1.1 | 28 | 550 | .82 | 11.3 | Personnel | 200 | 275 kts | 20.0 | | |
| G-12 64 | 2.25 | 64 | 1000 | .80 | 130 | Cargo | 2,200 | 200 kts | 28.0 | | 204 |
| G-11A 100 | 1.6 | 120 | 550 | .80 | 215 | Cargo | 3,500 | 150 kts | 25.0 | Reefed | 204 |
| 135 | 1.6 | 160 | 550 | 1.25 | 460 | Cargo | 50,000 | 150 kts | 22.0 | Cluster of 6 | 194 |

**Conical.** The canopy is constructed as the surface of a regular pyramid of $N$ sides and base angle, $\mu$, by joining gores having a vertex angle, $\beta$, less than $360°/N$. It's design is a minor variation of the flat circular canopy. The conical parachute is as simple and economical to construct, handle and inspect as the flat circular and serves similar applications. As a result of drop tests with models conducted in 1949, conical parachutes with up to 30° cone angles showed approximately ten percent higher drag than solid flat parachutes of the same surface area. Subsequent full scale tests using 28 ft and 32 ft diameter parachutes confirmed these results. Data for specific conical parachute and load configurations are listed below.




CONSTRUCTION SCHEMATIC




$$\beta = 2 \sin^{-1}\left[\left(\sin \frac{180°}{N}\right) \cos \mu\right]$$

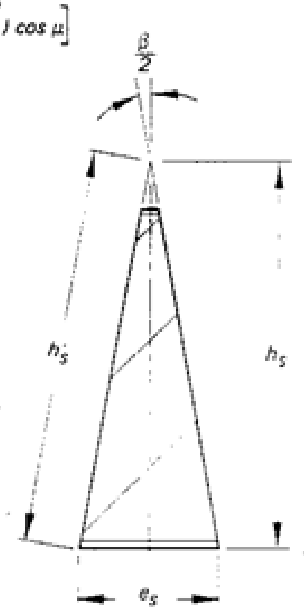
$$h_s = \left[\frac{S_o}{N \tan \beta/2}\right]^{1/2}$$

$$e_s = 2\, h_s \tan \beta/2$$

*Generally :*

$$S_v < 0.01\, S_o$$

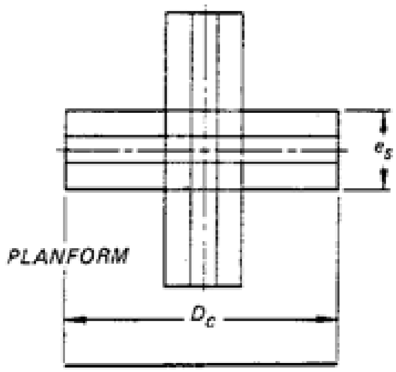
$$\frac{l_e}{D_o} = 0.80 \text{ to } 1.2$$




GORE LAYOUT

| Size $D_o$, ft | Cone Angle $\mu$ | Canopy (nylon) oz/yd$^2$ | No. of Gores $N$ | Line Str. (nylon) lbs | Line Length $l_e/D_o$ | Parachute Weight lbs | Payload | Payload Weight lbs | Max. Deploy. Velocity | Rate of Descent fps | Special Conditions | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 26 | 25° | 1.1 | 24 | 550 | .8 | 8.1 | Personnel | 200 | 275 kts | 19.5 | | 49 |
| 67 | 25° | 1.1<br>2.25 | 60 | 750 | 1.2 | 66 | Missile | 1800 | 200 kts | 20.0 | Reefed | 205 |
| 95 | 25° | 1.6<br>2.25 | 108 | 550 | 1.0 | 163 | Missile | 3500 | 275 kts | 22.0 | Reefed | 206 |

**Cross.** The cross parachute, a French development, is finding increased use for deceleration in applications that require good stability and low cost. The design is simple. The canopy consists of two identical cloth rectangles, crossed and joined to each other at the square intersection to form a flat surface having four equal arms. Suspension lines are attached to the outer edges of four arms. Some versions employ tie cords between corners of adjacent arms. The Cross parachute is similar in stability performance and drag efficiency to the ringslot parachute, but it has a tendency to rotate. It is popular as a deceleration parachute for ground vehicles (dragsters). Recent applications include stabilization and deceleration of air dropped naval weapons [53,211] and low rate of descent high altitude probe experiments.



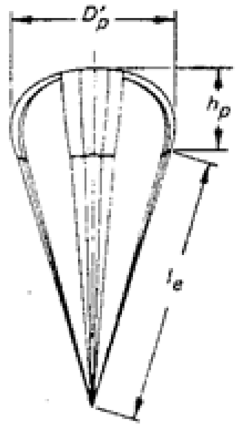

CONSTRUCTION SCHEMATIC

$$S_o = 2 D_c e_s - e_s^2$$

*Generally:*

$$\frac{l_e}{D_o} = 1 \text{ to } 2$$

$$\frac{e_s}{D_c} = 0.263 \text{ to } 0.333$$

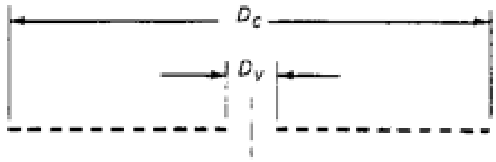



INFLATED PROFILE

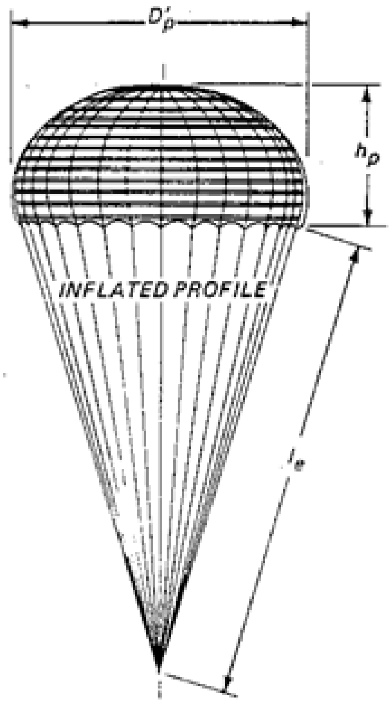
| Size $D_o$, ft | Canopy (nylon) oz/yd² | Dimension $D_c$ ft | $e_s$ ft | Line Str. (nylon) lbs | No. of Lines $Z$ | Line Length $l_e/D_o$ | Parachute Weight lbs | Payload | Vehicle Weight lbs | Max Deploy. Velocity | Rate of Descent fps | Application | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 54.3 | 0.3 silk | 63 | 16 | 100 | 28 | 1.16 | 17.5 | Inst. Package | 120 | 564 kts | 8.0 | Hi Alt Probe | 210 |
| 9.8 | 7.0 nylon | 14 | 3 | 4000 | 16 | 1.78 | 7.0 | (Dragster) | 3000 | 300 mph | N/A | Ground Deceleration | |

### Slotted Canopy Parachutes

**Flat Circular Ribbon.** The canopy is a flat circular design and consists of concentric ribbons, usually two inches in width, supported by smaller horizontally spaced tapes and radial ribbons at gore edges. Ribbons and tapes are accurately spaced to provide the desired ratio of open space to solid fabric over the entire canopy. Gores are triangular and dimensions are determined in the same manner as for the solid cloth flat circular parachute. The flat circular ribbon parachute has a lower drag efficiency than the solid cloth parachutes. However, its stability is excellent and the maximum opening force is low in comparison. The canopy is relatively slow in opening and its performance reliability depends on specific design parameters. Compared to solid cloth parachute canopies, the flat circular ribbon canopy is more difficult to manufacture. Data for specific flat circular ribbon parachute and load configurations are given below.




CONSTRUCTION SCHEMATIC




*(A regular polygon of N sides)*

$$h_s = \left[\frac{S_o}{N \tan(180^\circ/N)}\right]^{1/2}$$

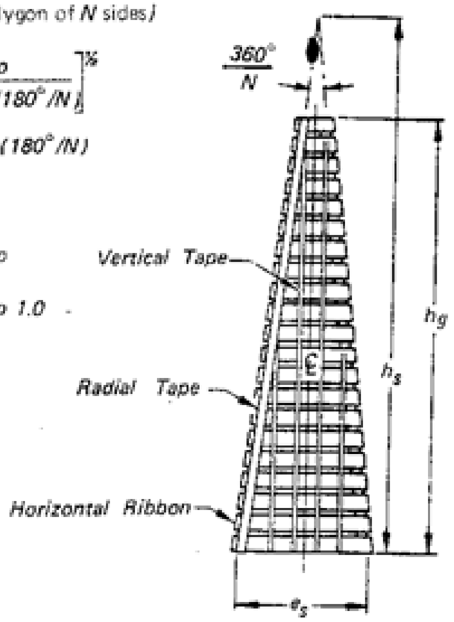
$$e_s = 2h_s \tan(180^\circ/N)$$

*Generally:*

$$S_v < 0.01\, S_o$$

$$\frac{l_e}{D_o} \approx 0.85 \text{ to } 1.0$$

$$\frac{D'_p}{D_o} \approx 0.67$$

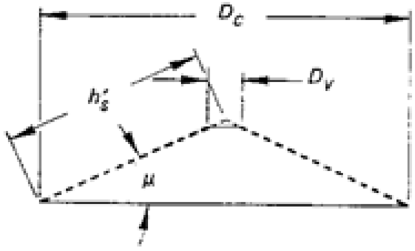



GORE LAYOUT

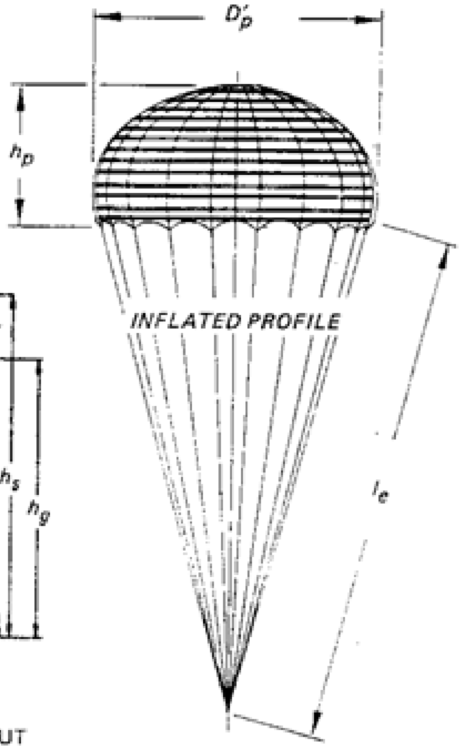
| Size $D_o$, ft | Ribbon (nylon) lbs | No. of Gores $N$ | Line Str. (nylon) lbs | Line Length $l_e/D_o$ | Parachute Weight lbs | Vehicle Weight lbs | Max. Deploy. Velocity | Application | Remarks | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| 32 | 300 | 36 | 2250 | 1.0 | 60 | 160,000 | 160 kts | B-47 Brake | (obsolete) | |
| 44 | 300 | 48 | 4000 | 1.0 | 108 | 320,000 | 180 kts | B-52 Brake | Reused | |

**Conical Ribbon.** The constructed shape of this canopy is obtained in the same manner as that described for solid cloth conical parachutes. Gores, like the flat circular ribbon design, are composed of a grid of horizontal ribbons spaced and retained at close intervals by narrow vertical tapes. Radial tapes which extend from the vent to the skirt are sewn together in the joining of adjacent gores.

The conical ribbon parachute shows higher drag than the flat circular ribbon just as the solid cloth conical parachute does over the solid flat parachute of equal area. Data for several specific conical ribbon parachute and load configurations are listed below.



CONSTRUCTION SCHEMATIC



INFLATED PROFILE

Varied Porosity. Unlike other parachutes of the conical ribbon classification, the gore of the 14.2 ft diameter drogue parachute in the table below is constructed with geometric porosity varied in three levels, increasing from vent to skirt, e.g., the upper one-third of the gore uses closer spacing and the lower one-third, a wider ribbon spacing than the center section. With this parachute, a drag coefficient, $C_{D_o} = 0.64$, was obtained in wind tunnel tests without loss of stability. However, the opening load factor increased (see Table 2.2).

$$h_s = \left[\frac{S_o}{N \tan \beta/2}\right]^{1/2}$$

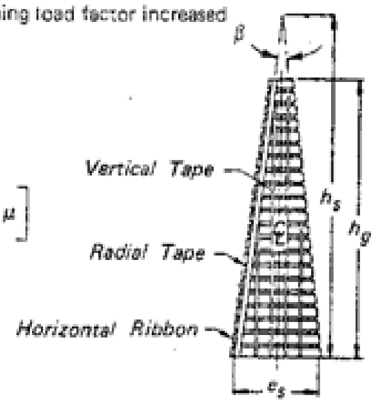
$$e_s = 2 h_s \tan \beta/2$$

$$\beta = 2 \sin^{-1}\left[\left(\sin \frac{180^\circ}{N}\right) \cos \mu\right]$$

*Generally:*

$$S_v < 0.01\ S_o$$

$$\frac{l_e}{D_o} = 1.00 \text{ to } 2.0$$



GORE LAYOUT

| Size $D_o$, ft | Cone Angle $\mu$ | Ribbon (nylon) lbs | No. of Gores $N$ | Geom. Porosity $\lambda_g$, % | Line Str. (nylon) lbs | Line Length $l_e/D_o$ | Parachute Weight lbs | Payload | Payload Weight lbs | Max. Deploy. Cond. | Rate of Descent fps | Special Cond. | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 16.5 | 25° | 300 | 20 | 26.5 | 2000 | 2.0 | 25.2 | Apollo | 13,000 | 204 psf | 310 | Drogue | 27 |
| 115 | 20° | 1000<br>400 | 96 | 16 | 6000 | 1.7 | 1400 | Booster | 164,000 | 200 psf | 85 | Cluster of 3 | |
| 17.0 | 20° | 3000<br>2000 | 24 | 25 | 10000 | 1.0 | 76 | Ordnance | 715 | 800 kts | 71 | | |
| 14.2 | 20° | 2000<br>1500<br>1000 | 32 | 10/14/17 | 6000 | 2.0 | 75 | B-1 Capsule | 8700 | 1.6 M<br>1600 psf | | Drogue | 213 |

Hemisflo Ribbon Parachute

‘Hemisflo’ ribbon parachutes have been used at velocities up to Mach 3, primarily as drogue and stabilization devices and for applications where the parachute must operate for longer periods of time in the supersonic region and often in the wake of a large forebody.

Typical applications are as stabilization and retardation parachutes for several types of ejection seats, for the encapsulated seats of the B-58 and B-70 bombers, and as first-stage drogue chutes for the F-111 and the B-1 crew modules.

The canopy of the ‘Hemisflo’ parachute forms part of a perfect sphere with the suspension lines connected tangentially to the sphere (see figure below), where:

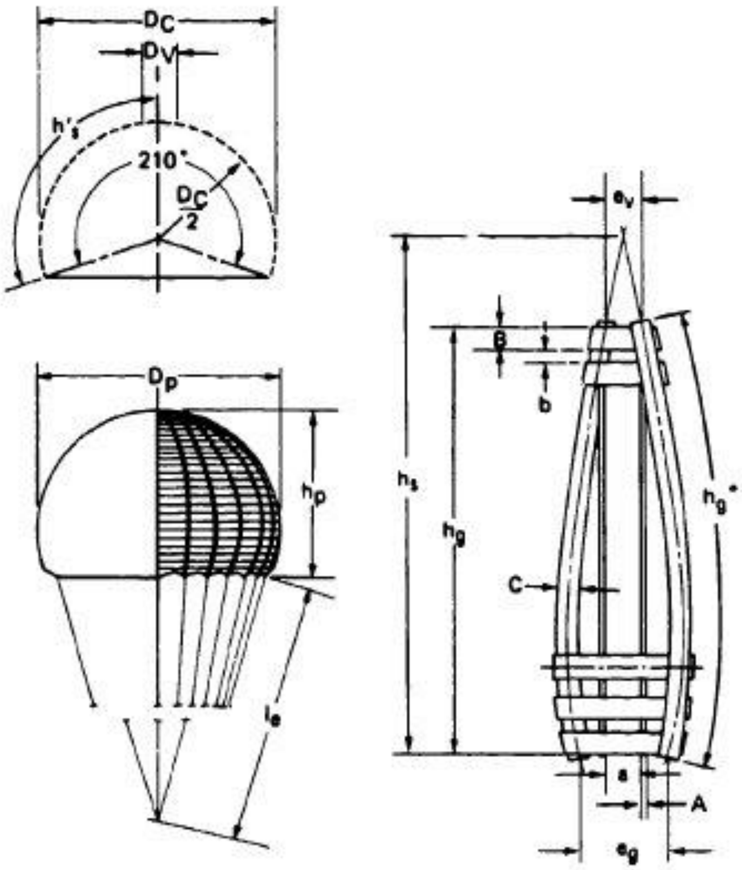
$$L_r/D_o = 2.0$$

$$D_o = 1.1284\sqrt{S_o}$$

$$D_p = D_C = \frac{\sqrt{360 S_o}}{210\pi}$$

$$h_s = 0.916\ D_o$$

$$L_e = 2.0\ D_o$$




Typical Design of a Hemisflo Parachute.

The point where the lines contact the canopy becomes the canopy skirt, resulting in a 210-degree canopy (see above figure).

The hemispherical shape avoids the use of gores that can flutter in and out, as on flat or conical canopies, and eliminates the length difference in the leading and trailing edges of the horizontal ribbons. This greatly reduces canopy breathing and high-frequency ribbon flutter, both sources of canopy damage and drag decrease on conical ribbon parachutes operating at supersonic velocities.

All detail design recommendations of conical ribbon parachutes also apply to ‘Hemisflo’ canopies. The figure above shows horizontal ribbons on alternate gore sides. As previously explained, this arrangement may cause a venetian-blind effect and can lead to canopy rotation. Having both radials on the same side will decrease rotational tendencies.

# Glossary

Items in **bold** are cross-referenced with other glossary entries to save repetition.

Apex

The geometric centre of a **canopy** where the **bridal lines** converge, which requires reinforcing around the **vent hole**.

Apogee

The highest altitude reached by a body on a trajectory launched from, or passing close to, or orbiting, the Earth. (Latin: apo-geos.)

The corresponding lowest point is the perigee, but this term isn't usually used if the perigee would be within the thicker, lower atmosphere, or worse, underground.

**Bridal lines** (or Suspension lines.)

The many individual lines running from the canopy to the **confluence point**.

Canopy

The fabric drag-producing area of the 'chute.

Canopy loading

The ratio $\frac{Cd\ S_O}{mg}$ where *Cd* is the drag coefficient of the canopy and $S_0$ its **Nominal Area.**

'*m*' is the total system mass (parachute plus **store**) and '*g*' is gravity.

Confluence point

Where the **bridal lines** converge at the **riser** (sometimes at a large knot or 'keeper').

Constructed area *Sc*

The cross-sectional area of the mouth of the canopy when constructed, based on the **Constructed diameter *Dc*.**

Constructed diameter *Dc*

The diameter of the mouth of the canopy when constructed.

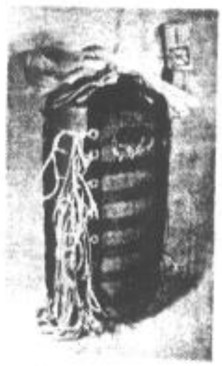
For a flat, circular canopy, this is the same as **Nominal diameter $D_0$**, whereas for a conical canopy, *Dc* will be less than $D_0$, depending on how steep the cone is.

Deployment bag (see main section)

A rucksack-like or sausage-like bag used to contain the packed ‘chute during deployment, to reduce snatch loads by reducing cross-sectional area.

The bag is usually pulled out by the previous stage's **riser**.

When the current stage's riser goes taut, a release-pin is pulled out or laces are cut, opening the bag and allowing the ‘chute to deploy.



Drag coefficient *Cd*

A numerical constant in the drag equation whose value depends primarily on the shape of the object in question. The aim of parachute design is to maximise *Cd*. Note that this so-called ‘constant’ actually varies with Mach number, particularly in the **Transonic** zone.

Drag (equation)

Is simply the **drag coefficient** *Cd* multiplied by **dynamic pressure** multiplied by some reference area.

For the rocket vehicle, this reference area is typically the maximum cross-sectional area of the fuselage (ignoring the fins or small local structures), whereas for aircraft, it's the total wing planform area.

For ‘chutes, the reference area is the **nominal area** $S_0$ which is why the drag coefficients of ‘chutes are quoted as $Cd_0$

Drogue

A small-area ‘chute used as the first stage of a recovery system (sometimes called a pilot ‘chute).

Dynamic pressure (*Q or q*)

All aerodynamic forces scale directly with the kinetic energy term $^1/_2\, \rho\, V^2$

$\rho$ being volume-specific mass i.e. the air density at the current rocket vehicle altitude, and *V* is the vehicle’s airspeed.

This kinetic energy term is known as Dynamic pressure (*q or Q*), to distinguish it from its Potential energy counterpart of Static pressure (*P*).

Equivalent Airspeed

The density of the atmosphere decreases with altitude, which means that an aircraft must fly faster (at the same angle of attack) to achieve the same Lift force 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 the pilot flies at 100 Knots Equivalent airspeed, then the aircraft will perform and ‘feel’ 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, ‘hull’ pressure) will be the same.

The conversion factor from True airspeed (TAS) to Equivalent airspeed (EAS) comes directly from the aerodynamic force equation:

$$\tfrac{1}{2}\rho_{Sea\_level} V_{EAS}^2 S\,Cf = \tfrac{1}{2}\rho_{at\_altitude} V_{TAS}^2 S\,Cf$$ ($\rho$ = atmospheric density)

Rearranging and canceling:

$$V_{EAS} = V_{TAS}\sqrt{\frac{\rho_{at\_altitude}}{\rho_{sea\_level}}}$$ where sea-level atmospheric density $\rho$ is 1.225 kg/m$^3$

It would be convenient for the pilot if the 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 displayed airspeed is then called **Indicated airspeed** (IAS).

Expulsion charge

An amount of pyrotechnic material designed to generate hot expanding gas in order to expel a parachute in a cannon-like manner.

Filling time

The time taken for the canopy to fully inflate.

Froude number

An aerodynamic scaling factor equal to:

$F_r = \frac{V_s^2}{g\,D_o}$ where $V_s$ is the **snatch velocity**, $g$ is gravity, and $D_0$ is the **Nominal diameter** of the **canopy**. The higher the **snatch velocity**, the higher the Froude number.

Gore

One of the fabric panels sewn together to make the **canopy.**

The number of gores used to make a ‘chute tends to vary linearly with increasing canopy diameter, and is equal to the number of **bridal lines** minus one.

Hardpoint

The strengthened attachment point on the **store** that the **riser** is attached to.

High powered Rockets/Rocketry (HPR)

Non-commercial/hobbyist rocket vehicles powered by motors of ‘H’ class or above Total impulse. I strongly suggest that large HPR vehicles require non-HPR recovery system designs.

The governing body for HPR in the UK is the United Kingdom Rocketry Association. (www.ukra.org.uk) I believe that the techniques and devices described in this document comply with UKRA rules and legislation, though ask their Safety and Technical Committee for advice.

Indicated airspeed

See: Equivalent airspeed.

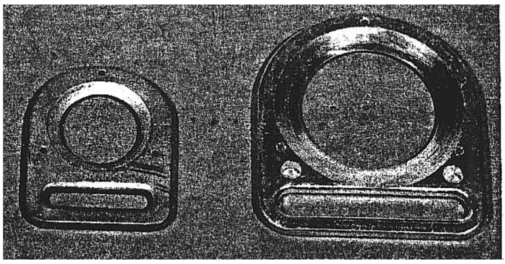
Lanyard

An auxiliary pull-line used to haul or actuate something.

Line Cutters (or knife cutters)

Used for general line-cutting, such as cutting through the laces of a lace-packed **deployment bag** as an alternative to the release wire.

They’re in essence small washers whose inner edge has been sharpened to a knife-edge, perhaps by careful countersinking:

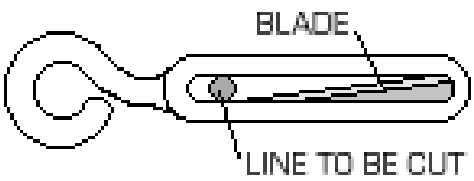


Two small holes drilled in the rim of the cutter allow you to *weakly* sew the cutter - as if it were a button - to some part of the **recovery system** to temporarily restrain it.

The diameter of the cutter’s inner hole should be slightly bigger than the line that’s to be threaded through it for clearance, and for safety if the cutter vibrates or moves a little during flight before deployment.

The cutters have a slot to allow connection to a **lanyard** so that a strong pull on this lanyard breaks the cutters free, and further, pulls the cutters through the line, cutting it.

Another shape of cutter which is easy to manufacture out of disposable razorblades:



Mass ratio $M_r$

The ratio of the **store mass** to the mass of air trapped within the ‘chute (which varies with the cube of the **Nominal diameter $D_0$**) $M_r = \frac{m_{store}}{\rho \, D_0^2}$ where $\rho$ is atmospheric density.

Main ‘chute

The large final-stage ‘chute, also called the **landing ‘chute.**

Model rocketry

Rocket vehicles powered by motors of ‘G’ class Total Impulse or less.

Nominal area $S_0$

The actual area of fabric of the ‘chute.

Nominal diameter $D_0$

This is defined from the **Nominal area $S_0$** as: $S_0 = \pi D_0^2$ for all canopy types, though this is only actually the case in reality for flat circular canopies.

Opening shock load

Some milliseconds after the **snatch load** peak is past, the canopy opens. (If a drogue-shell was used, the drogue has just been pulled free of the shell as the shell’s inertia kept it going.)

The ‘chute rapidly fills and inflates, creating a momentary peak drag load known as the opening shock load: this peak can be two or three times the steady drag of the ‘chute and is caused by the mouth of the canopy swallowing a mass of air which it then decelerates.

Projected area *Sp*

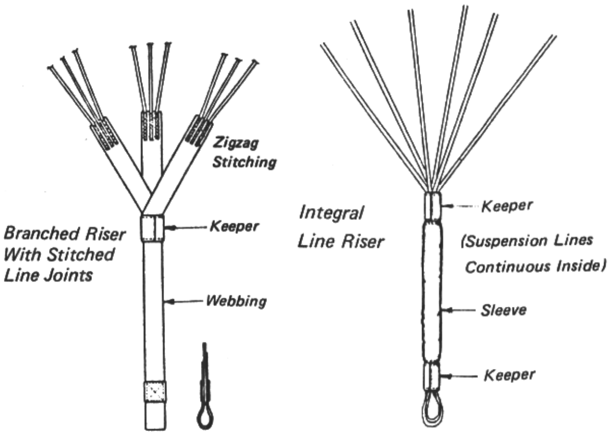
The actual cross-sectional area of the 'mouth' of the canopy when inflated.

For (originally) flat circular canopies, this is considerably less than their **Nominal area.**

Recovery system

All components of the system designed to allow safe recovery of some **store**.

Riser




The main line attaching the ‘chute to the **store**.

This runs from the **confluence point** to the store **hardpoint**, and is sometimes formed from extended **bridal lines** which are sewn together at the confluence point (and bound further by a hoop of tough fabric or metal at that point known as a 'keeper').

Extended (bridal line) risers are usually protected by a fabric sleeve as shown above.

Separation plane

The sectional plane across a joint that separates during part of the recovery sequence, to allow the ‘chute/s to exit.

Shear pin

A pin of metal or plastic that holds some recovery component in place until the pin is shattered by a shock shearing force.

Snatch load

Whether forcibly expelled (pyrotechnically) or not, by the time a ‘chute has travelled to the full extension of the riser, the ‘chute has built up a sizable difference in velocity relative to the rocket vehicle it deployed from.

In consequence, when the **riser** connecting the ‘chute to the rocket vehicle finally goes taut, there will be a sudden whip-load down the riser caused by the deceleration of this momentum. This dynamic ‘twang’ is known as the snatch load.

Snatch time

The time when the **Snatch velocity** occurred:

Snatch velocity $V_S$ (actually a scalar quantity - airspeed)

What point in the **canopy** opening process should be defined as the start of opening?

One could use the airspeed the rocket vehicle was doing when the recovery sequence was initiated. But if the physics of the actual **canopy** inflation process are to be investigated, the effects of varying **riser** lengths, or varying expulsion velocities, would preferably be removed from the equation, so a more useful reference point is the airspeed of the system just prior to inflating, during the **snatch load**.

The snatch velocity is defined as the airspeed the system was doing at the peak (maximum) of the snatch load, at whatever time that peak occurred.

This peak is used because it's easily spotted in recorded load/time data on a graph, but if this isn't known, the rocket vehicle's airspeed at deployment often isn't greatly different.

Store

'Store' is the preferred (originally military) recovery system term for the payload suspended under the 'chute, i.e. everything else that isn't part of the recovery system itself.

In rocketry, avoid using the term 'payload' when referring to the store, as payload also means the cargo carried by the rocket-vehicle, which causes confusion.

Strain

Percentage stretch of a line per unit length:

$$\varepsilon = \left( \frac{StretchedLength}{UnstretchedLength} \right) - 1$$

Or, if *d* is the difference between stretched and unstretched length:

$$\varepsilon = \frac{d}{UnstretchedLength}$$

System

The system is the 'chute *and* the **store**; (different from the **recovery system**).

Terminal velocity

As a falling object accelerates under gravity in an atmosphere, its drag will increase until a point is reached where the drag force equals the object's weight, and the net acceleration is zero, resulting thereafter in a constant vertical velocity known as terminal velocity. (The drag reduces any initial horizontal velocity component of the trajectory to zero fairly quickly.)

Depending upon the **Nominal area $S_0$** of the 'chute in relation to the total **system** mass '*m*', this terminal velocity could be higher or lower than the parachute deployment airspeed.

The terminal velocity is simply calculated by rearranging the **drag equation** as:

$V_{terminal} = \sqrt{\dfrac{2mg}{\rho\,(S0_p Cd_p + S_s Cd_s)}}$ where subscripts *p* = parachute and *s* = store.

Standard sea-level atmospheric density $\rho$ is 1.225 kg/m$^3$, and gravity *g* is 9.81

Transonic

A region roughly defined from about Mach 0.7 to Mach 1.2 where the aerodynamics become difficult to predict due to shockwaves successively forming around different parts of the vehicle. This is also the region where the **drag coefficient** peaks (it can double) leading to a **drag** peak known as ‘max Q’ (see: **Dynamic pressure**).

True airspeed

The actual speed through/relative to the atmosphere. (See **Equivalent airspeed.**)

Vent hole

A small hole at the apex of the **canopy** that’s designed to allow some of the air trapped in the inflated canopy to leak out.

This tends to prevent air spilling over the edges of the canopy, which would otherwise cause the canopy to oscillate sideways quite dramatically.

# References

Ref. 1 has a different title for each re-issue:

- 'U.S.A.F. Parachute handbook', March 1951
- 'Performance and Design Criteria for Deployable Aerodynamic Decelerators'. Jun 1963
- 'Recovery Systems Design Guide', Irvin Industries Inc, AFFDL-TR-78-151, Dec 1978 (downloadable on the internet)

Ref. 2: 'Notes on the design of spacecraft deployment and separation systems', Guy Gratton, Vladimir M Shakhmistov, with Marina A Kulinik, © Guy Gratton/UKSEDS

Ref. 3: 'A semi-empirical theory to predict the load-time history of an inflating parachute', RAE TR 79141, by J.S. Lingard

Ref. 4: 'Sport Parachuting Technology Applied to Rocketry' Apogee newsletter 279

www.apogeerockets.com

Ref. 5: 'Safety design for space systems', Musgrave, Larsen, Sgobba, International Association for the advancement of space safety, ISBN 978-0-7506-8580-1, Elsevier publishing

Other References:

- Help and advice from Irvin Parachutes U.K, Rocket Services Dorset, the United Kingdom Rocketry Association, and friends from the Black Arrow launch-vehicle programme, and the High Power Rocketry community.