



Recovery system design for large rockets

Introduction:

Any engineer who's seen a video taken from a camera onboard a 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 'clonk' of one piece of airframe bouncing off another.

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.

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.



Part 1: recovery system design

The traditional design:

The problem is that rocketeers are very conservative when it comes to recovery system design. They want to be sure the recovery system works to save their expensive accelerometers, so they almost never experiment with a new design: they're still using designs only suitable for small Estes-powered 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. When I was tasked, in the early days of Aspirespace, for devising recovery systems, the world of HPR rocketry was still very new, there was nothing really to draw on, so I researched how the 'big boys' do it, and my research is detailed below.

12 years on, and I'm appalled to find that still almost no progress has been made in HPR recovery!

Traditionally, the recovery system comprises splitting the fuselage at a coupled 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; maybe 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, 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 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.

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 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.

Better design for larger vehicles

How are large, commercial sounding rocket vehicles recovered? Certainly not like the above! For start off, hurling large bits of airframe around is clearly not acceptable. For this reason, 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 base 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.



Design philosophies:

Having listed the problems with traditional HPR designs, it's time for me to suggest improvements, 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:

- **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:** 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 design is *too* simple.

As there is only finite internal space and mass to allocate to the recovery system, you have to hypothesize 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.

These 'opening loads', like all aerodynamic forces, vary directly with dynamic pressure, which will obviously be a minimum at apogee.

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

The recovery envelope is the range of speeds 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 dependance 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).

To minimise airspeed, the drogue 'chute must be opened at apogee.

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.

Multiple-stage recovery systems

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

When opened, even if at 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 is 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 *Pilot/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 rocketry as Close Proximity Recovery (CPR) as the rocket vehicle hopefully lands not far from where it was launched.

The 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.

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!

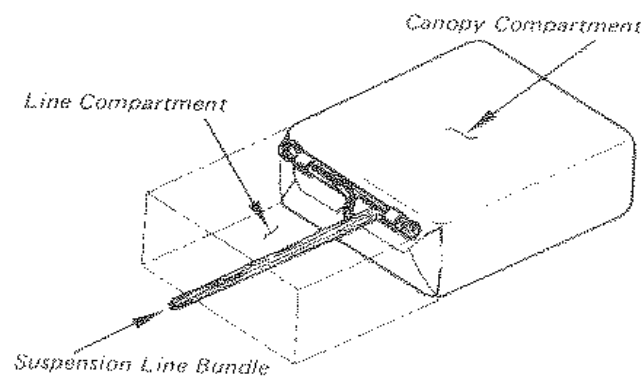
Reducing the snatch load

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 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 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.

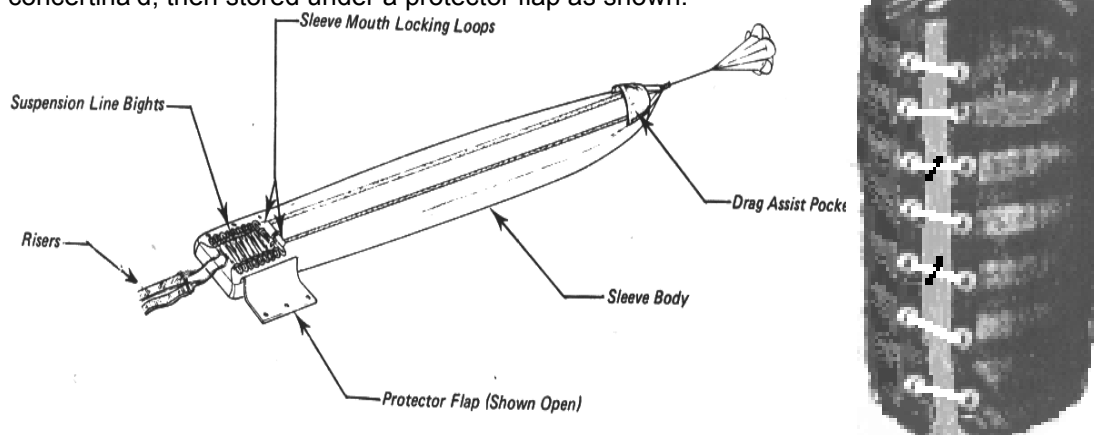


This figure shows line lengths inside such a deployment bag, held tidily in place by loops of elastic until pulled out.

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 being a 'canopy first' deployment.

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.



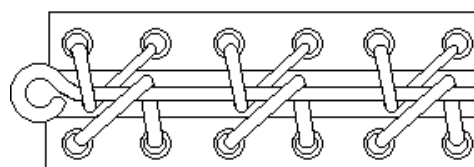
You can buy rather simple deployment bags from rocketry vendors, though they tend to be too loose a fit on the 'chute so sew them tighter. These bags are often nomex, to shield the 'chute from the heat of the expulsion charge.

Compression

Compression packing, by whatever method, is often used for aerospace parachutes: The Apollo 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 as shown:



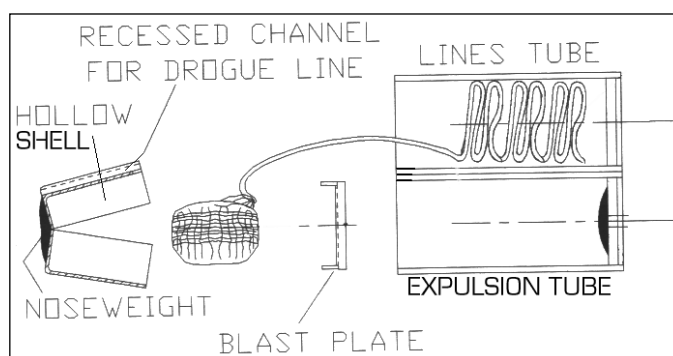
The lacing is laced around a release-pin in such a way that pulling the wire out opens the bag:

The drogue-shell

The drogue-shell system tends to be a more reliable system for drogue deployment from a vehicle 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 noseweight, to give it enough momentum and aerodynamic stability to clear the fins, or the vehicle's base wake region if deployed 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.

Cons:

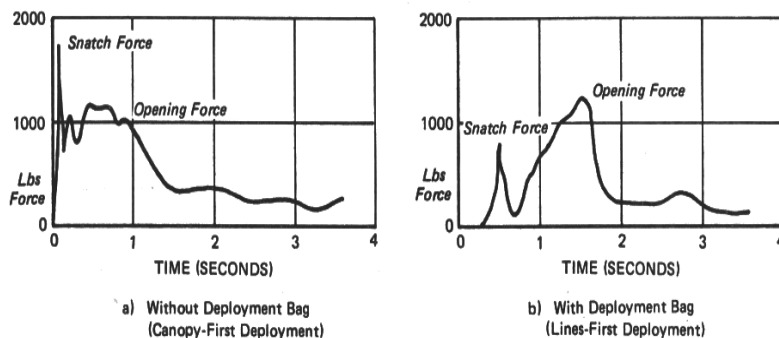
- Slightly higher complexity.
- The shell is jettisoned completely, so it **must** be designed to have a low terminal velocity for the safety of people on the ground below: fit it with its own streamer.

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.

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:

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 it's mass, and the mass of air captured within it) will seriously increase the snatch load if it stays attached permanently. 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.

One important factor in determining the snatch load is the energy-absorbing properties of the riser and 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, and so 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 done on a spreadsheet, but it's easier if programmed. I advise using a better method of integration than the Euler method to get 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.

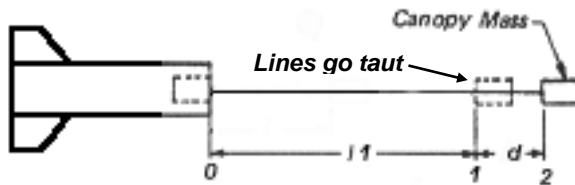
Subject to the following restrictions, a 1-dimensional analysis can be used:

- 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 below) 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, an energy analysis is the usual preferred method, as it can capture the dynamics of the stretch and rebound:



The Snatch load F_s 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, i.e.:

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

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

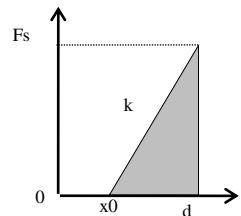
where m =mass, V =velocity, subscript r = rocket-vehicle and subscript c = chute canopy.

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:

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

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

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, r.h.s. = 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_s , this gives the snatch load:

$$F_s = \Delta V_{\max} \sqrt{k \frac{m_r m_c}{m_r + m_c}} \quad \text{where } \Delta V_{\max} \text{ is the maximum velocity reached by the chute canopy}$$

relative to the rocket vehicle, at point 1 and is equal to: $V_b - V_c$. This can be simmed 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. ($m_c \ll m_r$)

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.

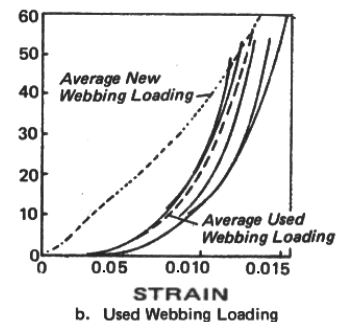
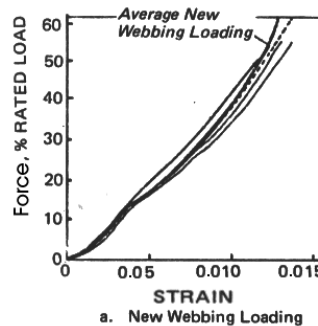
From geometry, this centre of mass is therefore travelling at $\frac{1}{2}(V_b - V_c) = \frac{1}{2}\Delta V_{max}$ when the lines go taut, and so has a momentum of $\frac{1}{2}\Delta V_{max}(m_{riser} + m_{lines})$ so in the above equation, substitute

$$\left[m_c + \frac{m_{riser} + m_{lines}}{2} \right] \text{ for } m_c.$$

Ropes analyses

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

$(k = \frac{dF}{dx} = l_1 \frac{dF}{d\epsilon})$ so multiply the gradient of these graphs by l_1 , the unstretched line length.)



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 Shock load less, therefore those loads will affect the store more.*

To select 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.

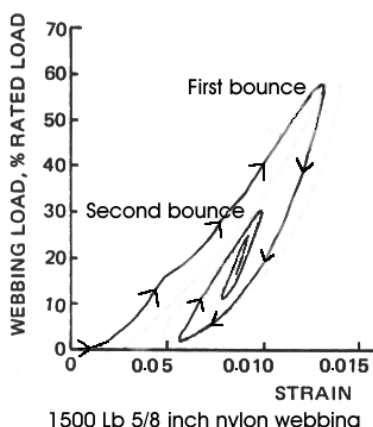
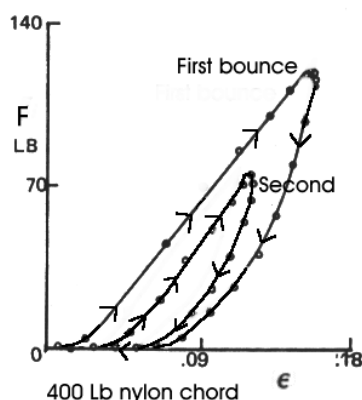
(In the above graphs, the 50% and 100% gradients are probably similar, but if you were using a safety-factor of 5, the gradient at the 20% load is lower.)

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: $1/k_{total} = 1/k_1 + 1/k_2 + \dots$

Impact loads:

The above graphs were plotted by gently hanging successively heavy weights off of a rope, *however* materials behave differently under sudden impact-loadings such as will occur with snatch loadings (and also *Opening Shock* loads, see below).



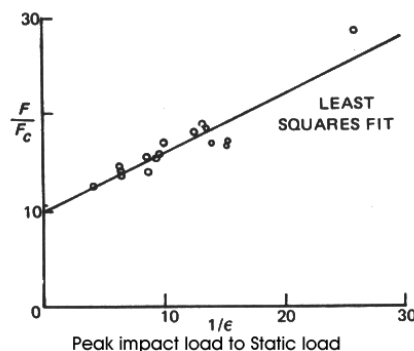
The following graphs were obtained by dropping a heavy mass on the end of a new riser: (ϵ varies with vertical distance)

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 RDAS as an acceleration recording device.

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 2 or 3 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.

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 1436 N/m^2 (30 lb/ft^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.



Type	Constructed Shape		$\frac{D_C}{D_O}$	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
	Plan	Profile						
Flat Circular			1.00	.67 to .70	.75 to .80	~1.8	$\pm 10^\circ$ to $\pm 40^\circ$	Descent
Conical			.93 to .95	.70	.75 to .90	~1.8	$\pm 10^\circ$ to $\pm 30^\circ$	Descent
Cross			1.15 to 1.19	.66 to .72	.60 to .78	~1.2	0° to $\pm 3^\circ$	Descent, Deceleration
Flat Ribbon			1.00	.67	.45 to .50	~1.05	0° to $\pm 3^\circ$	Drogue, Descent, Deceleration
Conical Ribbon			.95 to .97	.70	.50 to .55	~1.05	0° to $\pm 3^\circ$	Descent, Deceleration

Simply multiply the steady-state drag coefficient C_d by the (peak) opening load factor C_x given in the diagram above 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.

A table of C_x values is given here for the types whose constructional details are given at the end of this paper.

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, 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 2

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 how all parachutes have a unique opening signature, 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.

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 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.

Part 2: recovery system notes and components

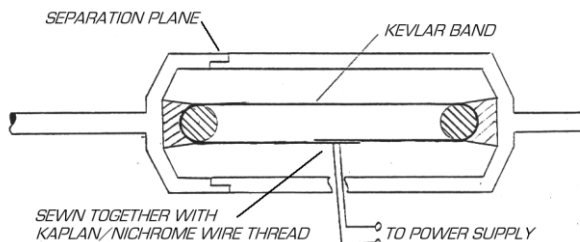
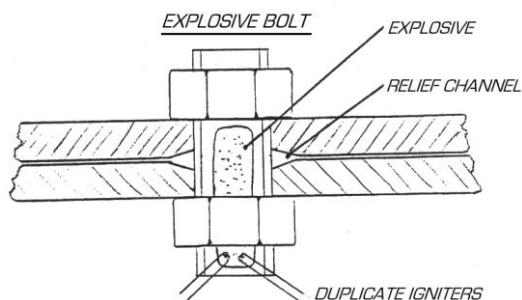
The following are some notes and information that I discovered in my parachute design research.

Positive deployment:

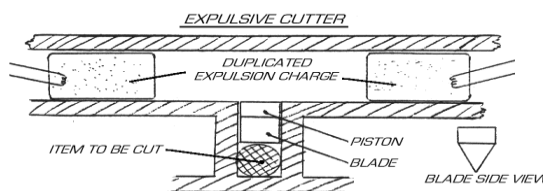
For reliable parachute opening, it is essential to physically pull or throw the 'chute away from the rocket vehicle at a reasonable initial relative speed, otherwise the 'chute may flop against the fuselage or snag or rip on the fins before it has a chance to open, and may subsequently not open fully,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

The initiator

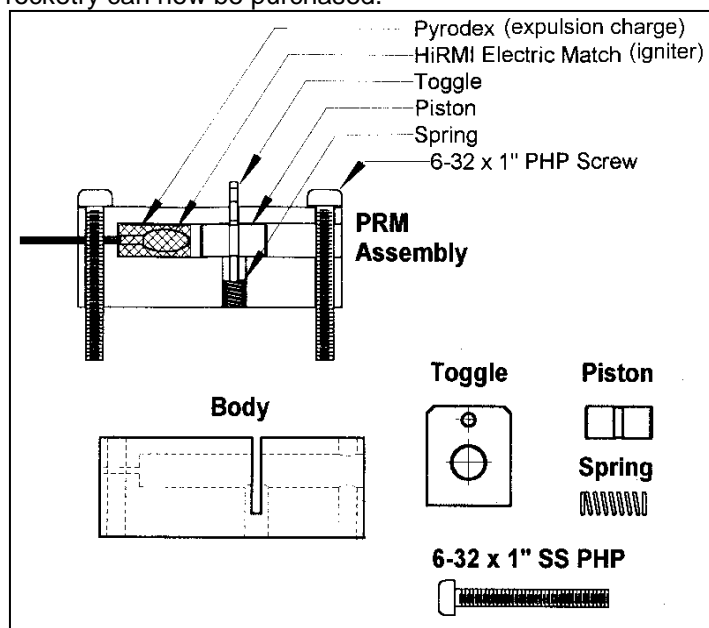
The device that initiates the deployment can be of many forms: electromechanical (solenoid or geared electric motor), thermal (bi-metallic strip or melt-through plastic restraint sewn with nichrome hot-wire as shown here:) or whatever.



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, so are extensively used.



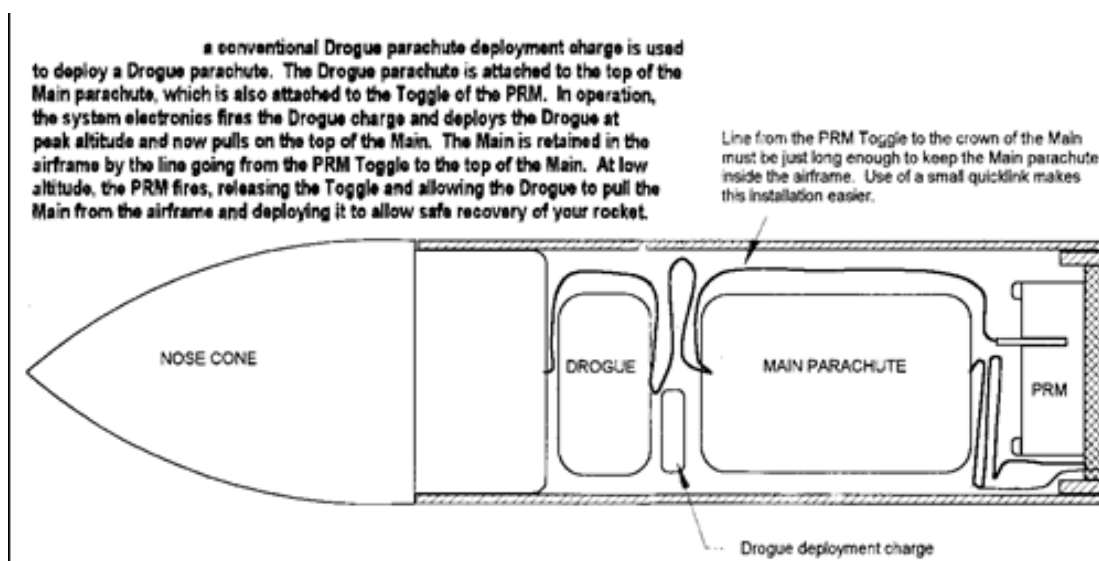
Commercial pyrotechnic devices for HPR rocketry can now be purchased.



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 blue-

tack or wet tissue paper placed just ahead of the end-stop. A typical HPR installation is shown on the next page:



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.

N.B. Homemade explosive bolts are illegal in the UK if manufactured from metal. Instead, nylon bolts can be purchased, then drilled to form a small cavity (say 3mm long by 3mm diameter) which can be filled with explosive powder, then blocked at each end. These can be activated by a hot nichrome wire or an igniter.

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, and are simple and compact.

They are surprisingly reliable when properly ignited.

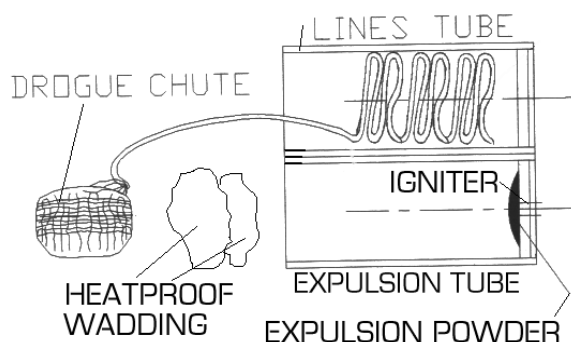
Expulsion tubes:

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.

NB: 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 (or aluminium sulphide) then allowed to dry.
- The 'chute riser and/or bridal lines should be protected too.

The tractor rocket:

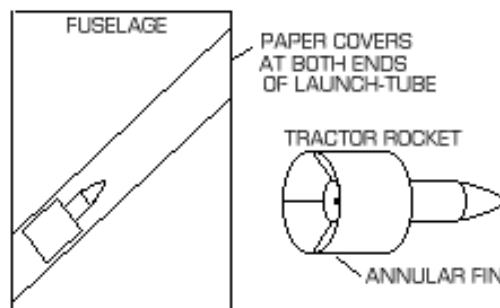
This is a small auxiliary rocket tied to a heatproof lanyard so that the rocket exerts a pull. One design is shown here:

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, 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 here:

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 its 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-thrust, short duration burn for the tractor.

I don't know whether a fin-stabilised tractor-rocket deployed rearwards would fly straight at all. It is possible to obtain spin-stabilised rocket motors.



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 black powder (gunpowder) and 'pyrodex'.

One cubic centimeter of powder is about five times as much as you'll need to expel a drogue. 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 buildup of pressure.

Estes commercial rocketmotors use powder sealed-in by a cap of plaster-of-paris which only finally fractures at high pressure.

NB: 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 buildup 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 adhesive tape around its perimeter.

Glue a strip of paper or thread across the mouth of the expulsion tube as an added restraint if required.

High altitude problems

It's been reported that several rocket vehicles have suffered ejection charge failures at very high altitude. It's not clear why but it's thought that the near-vacuum of very high altitudes is preventing the propagation of heat/flame across the loose pile of expulsion powder; the bulk of the powder doesn't burn. Black powder, like other propellants, has what is called a "deflagration limit" which is a minimum pressure at which combustion is barely self-sustaining. If the pressure drops too low, combustion will cease or be erratic at best. Also, at sea-level to ~20,000ft (more or less), air contributes significantly to the heat transfer from the igniter to the powder. Above that 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 first way to correct this problem is used on military and civilian high altitude rockets: they use sealed canisters containing ground-level pressure air with burst diaphragms, for motor igniters and deployment devices. The container is designed to burst at a set pressure when the powder burns and expands.

Whatever material is chosen for the burst diaphragm should be tested to make sure it will break at a 20 psi overpressure to prevent fragment damage to the rocket, since confined black powder can generate 25,000 psi pressure or higher.

A second, though heavier, option is to use pressurised carbon dioxide (CO₂) to power the recovery system. The Rouse Tech CD3 gas ejection system is such a system that is available commercially. Read the user's manual at: http://www.rouse-tech.com/pdfs/CD3_Manual06.pdf and curse the Americans for using imperial measures!

The Rouse Tech calculation method says that for every gram of Black Powder you would use in a rocket you should use 5 grams of CO₂, obviously then you should round up to the nearest cartridge: 12 gram, 16 gram, 25 gram or 38 gram. Richard Brown reports that in his experiments, the figure is nearer 10 gram of CO₂, and he also says that shear pins (see later) are a must for CO₂ as it helps build the pressure up before popping off the nose.

Obviously, the mass of the CO₂ cartridge/s and actuator adds to the system mass.

Some ejection options:

Forward ejection:

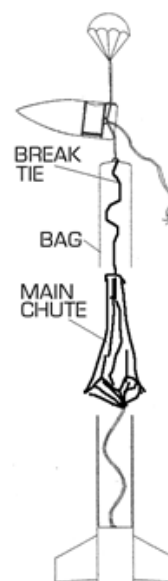
The traditional method used in model rocket recovery systems, the 'chutes deploy in the direction of travel.

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 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.

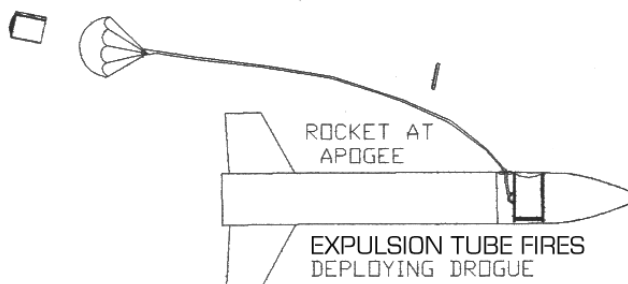


Sideways ejection:

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've been experimenting with 'parabags'. These calico (see materials section) airbags inflated by a small packet of expulsion-charge, 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 an 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 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 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 of itself and the chute from the heat radiated from the rocket and its exhaust or it might go off prematurely.

Fuselage separation prior to ejection

In this 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 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 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, rocketmotors, 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:

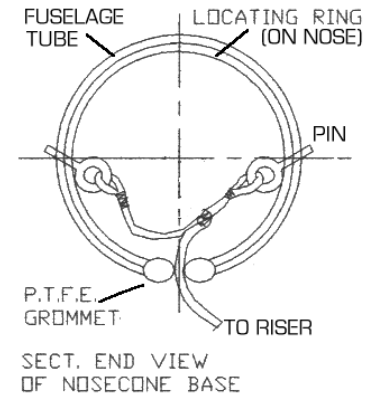
Creating a separation joint that is lightweight, but can withstand the forces acting on it is tricky in itself, but the biggest technical challenge is to design a mechanism that won't jam if actuated while the joint is suffering any sideways or bending forces, and infact will work every time.

The locating ring or socket:

As used in model and HPR rocketry, this 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 to withstand high bending moments.

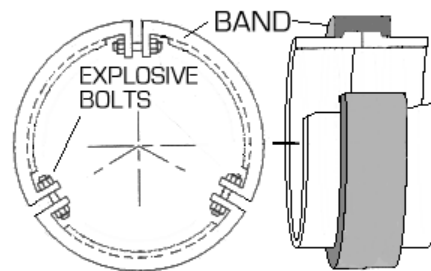
From Ref. 2, here are two popular joint designs that are used on large commercial sounding rockets and spacecraft: The Separation band and the Bearing Lock:

Separation band:

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

**Pros:**

- Moderately simple construction.
- Very reliable if multiple bolts are used, as the firing of any one bolt will free the band (with the help of springs).
- Can withstand high loads and bending moments.

Cons:

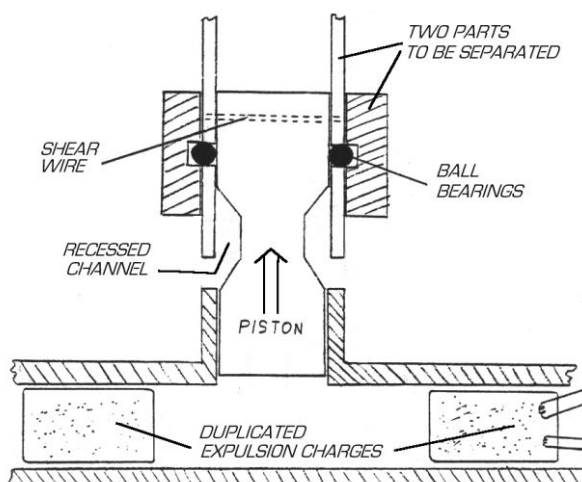
- The original design needs explosive bolts.
- Careful design is needed to allow access to the bolts for assembly.
- Needs an aerodynamic shroud or causes high drag.

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. Hydraulic quick-release couplings incorporate a bearing lock so can be used.

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.



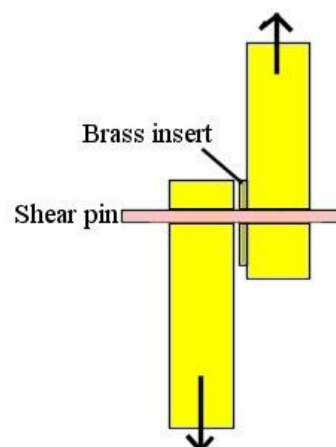
Cons:

- 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.

Shear pins

It has become standard practice in the UK HPR world to use shear pins to hold sections of fuselage together. These are small pieces of plastic that shear when the expulsion charge fires, due to the visco-elastic properties of plastics, which means that they can absorb heavy 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 brass plate or tube is mounted within the hole to provide a cutting edge.



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

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 seems to be the Evergreen styrene rod. Packs are about £2 ish for 4 or 5 12" rods from any model shop. When using shear pins, more expulsion charge is needed.

Chute design:

The drag figures quoted for large 'chutes are often higher than they actually are, due mainly to a poor measuring method, and also expect small replicas of big 'chutes to have lower drag coefficients (C_d 's), say lower by about 20%

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.

Materials and construction:

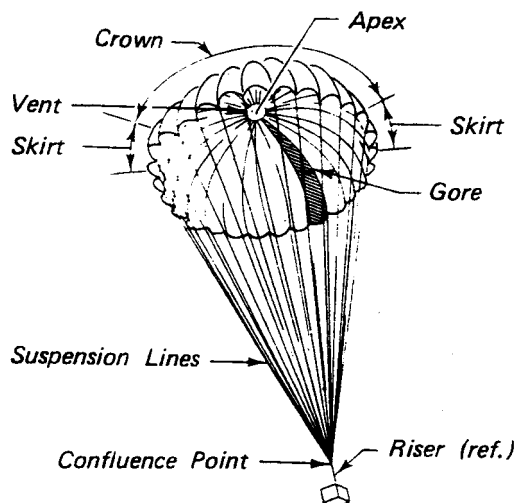
Parachutes are best made from ripstop nylon, as sold in kite shops. For extra strength for drogues, use a double-thickness of material, or use hot-air balloon grade ripstop which is thicker.

Remember to make a Vent hole at the apex of circular canopies, of roughly 1 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.

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

Construction plans for several common types are given at the end of this document, though as yet we don't have any data for streamers: strips of material about 10 times as long as they are wide, that are popular in the HPR world as subsonic drogues.



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, or Calico.

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 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.

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 about 5 metres per second.

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:

$$V_v = \sqrt{\frac{2mg}{\rho SC_D}} \text{ (see glossary)}$$

Load dissipation:

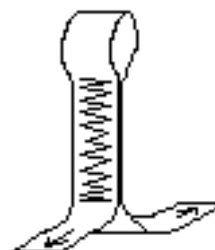
A device that can dissipate some of the high loads occurring within parachute risers during opening are often incorporated into recovery systems.

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

Several long bungee chords, 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 opposite, 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 shockloads.

The MARS rocket society use 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.



Recovery pyrotechnics safety:

Any recovery pyrotechnics used must only be armed at launch, preferably during liftoff, 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 breakwire.

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:

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

Pros:

- Controlled experiment.
- High Snatch velocity.

Cons:

- Expensive.
- Civil Aviation Authority waivers have to be acquired to allow dropping of anything.



- Possibly hazardous to pilots and ground personnel.
2. Dropped from radio-controlled aircraft, rocket, or large kite:

Pros:

- Cheaper.
- No CAA waiver required.
- Horizontal deployments can be obtained by rocketry: lowering the launch-angle allows the same apogee velocities to be reached using lower-power motors.

Cons:

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

3. Dropped from tall building or 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 velocity.

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.

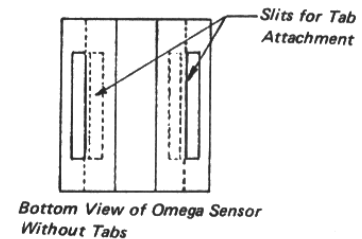
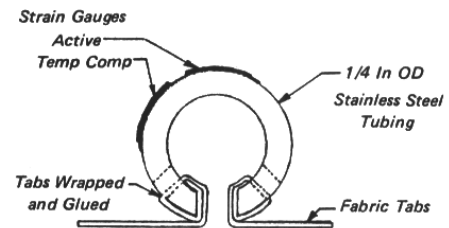
Measuring the load versus time curve during the deployment of a recovery system requires fixing strain gauges to a recording device, and letting the whole system fall free.

The recording device has 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.

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

A videocamera and a freeze-frame player can be used to discern the exit velocity, as videos record exactly 50 frames per second. (60 in the 'States.)





Glossary:

Items in **bold** are cross-referenced with other entries.

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.

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 $\frac{Cd \cdot S0}{mg}$ where Cd is the drag coefficient of the canopy and $S0$ its **Nominal Area**.

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

Confluence point:

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

Constructed area: S_c

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

Constructed diameter: D_c

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, D_c 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 equation:

Is simply the drag coefficient, C_d , times **dynamic pressure**, times some reference area.

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

For 'chutes, the reference area is the **nominal area S_0** : this is why the drag coefficients of 'chutes are quoted as C_{d_0}

Dynamic pressure: (q)

All aerodynamic forces scale directly with the kinetic energy term $\frac{1}{2} \rho \cdot V^2$



ρ 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), to distinguish it from its Potential energy counterpart of Static pressure (P).

Filling time:

The time taken for the canopy to fully inflate.

Froude number:

An aerodynamic scaling factor equal to:

$$Fr = \frac{V_s^2}{g D0} \text{ where } V_s \text{ is the } \mathbf{Snatch\ velocity}, g \text{ is gravity, and } D0 \text{ is the } \mathbf{Nominal\ diameter}$$

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.

The governing body for HPR in the UK is the United Kingdom Rocketry Association. (UKRA)

I believe that the techniques and devices described in this document comply with UKRA rules and legislation, though ask their safety committee for advice.

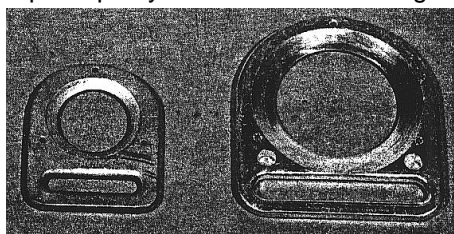
Lanyard:

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 who's inner edge has been sharpened to a knife-edge, perhaps by careful countersinking:



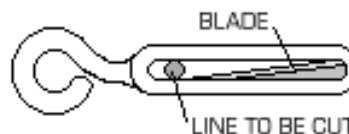
Two small holes drilled in the rim of the cutter allow you to *weakly* sew the cutter, as if it were a button, to some part of the **recovery system** to temporarily restrain it.

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 easier to manufacture out of disposable razorblades, is:



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** $D0$):

$$M_r = \frac{m_s}{\rho \cdot D0^3} \text{ where } \rho \text{ is atmospheric density.}$$

Main 'Chute:

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

Model rocketry:

Rocket vehicles powered by motors of 'G' class 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 the real world for flat, circular canopies.

Projected area: S_p

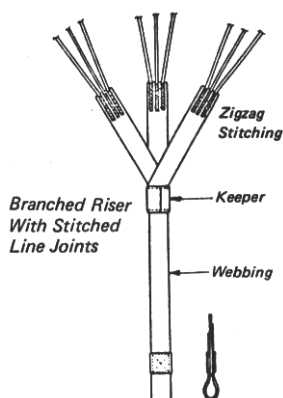
The actual cross-sectional area of the 'mouth' of the canopy when inflated.

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**.

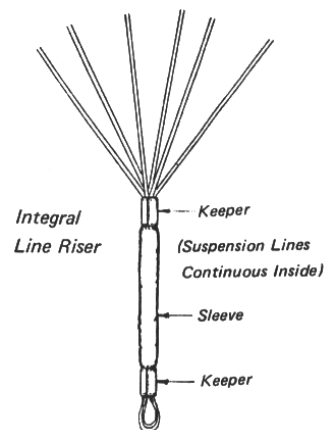
Riser:



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:



Separation plane:

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

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 speed the rocket-vehicle was doing when the recovery sequence was activated, 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 velocity of the system just prior to inflating, during the *Snatch load*. (see Snatch load in main text)

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 such as a graph, but if this isn't known, the rocket vehicle's velocity 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:

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

Or, if d is the difference between stretched and unstretched length, $\varepsilon = \frac{d}{\text{UnstretchedLength}}$

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 S0** 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:

$$V_{\text{terminal}} = \sqrt{\frac{2mg}{\rho(S0_p Cd_p + S_s Cd_s)}} \quad \text{where subscripts } p=\text{parachute and } s=\text{store. Standard}$$

sea-level atmospheric density ρ is 1.225 kg/m^3 , and gravity g is 9.81

Vent hole:

A small hole at the apex 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

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

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.

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.

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

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

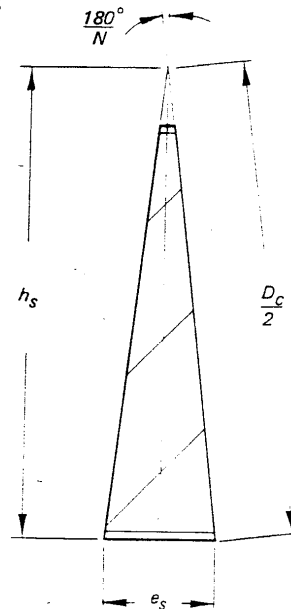
Generally :

$$S_v < 0.01 S_o$$

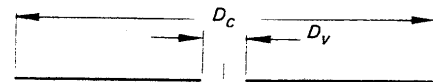
$$\frac{l_e}{D_o} \approx 0.80 \text{ to } 1.25$$

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

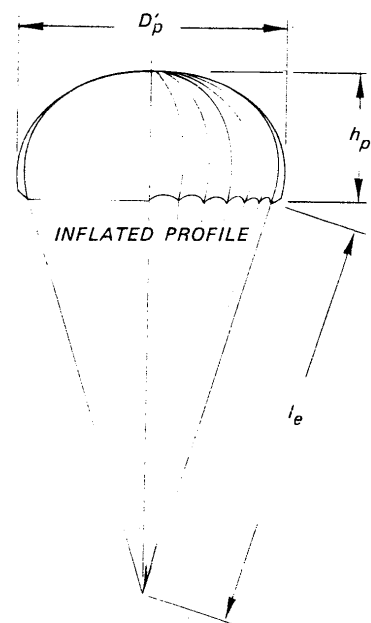
$$\frac{h_p}{D_p} \approx 0.41$$



GORE LAYOUT



CONSTRUCTION SCHEMATIC



Designation and Size	Canopy (nylon)	No. of Gores	Line Str. (nylon)	Line Length	Parachute Weight	Payload	Payload Weight	Max. Deploy. Velocity	Rate of Descent	Special Conditions	Ref.
D_o , ft	oz/yd ²	N	lbs	l_e/D_o	lbs		lbs		fps		
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, μ , by joining gores having a vertex angle, β , less than $360^\circ/N$. Its 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.

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

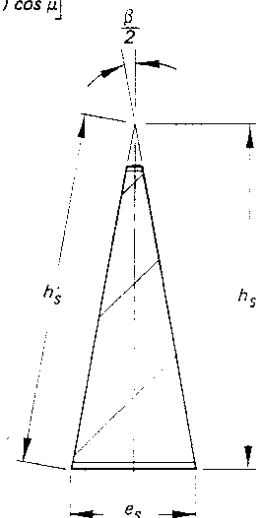
$$h_s = \left[\frac{S_o}{N \tan \beta/2} \right]^{1/2}$$

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

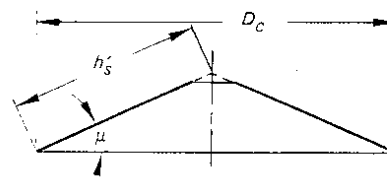
Generally :

$$S_v < 0.01 S_o$$

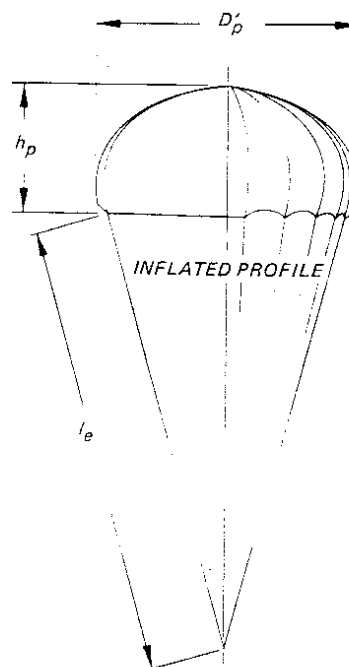
$$\frac{l_e}{D_o} = 0.80 \text{ to } 1.2$$



GORE LAYOUT



CONSTRUCTION SCHEMATIC



Size D_o , ft	Cone Angle μ	Canopy (nylon) oz/ft 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 2.25	60	750	1.2	86	Missile	1800	200 kts	20.0	Reefed	205
95	25°	1.6 2.25	108	550	1.0	163	Missile	3500	275 kts	22.0	Reefed	206

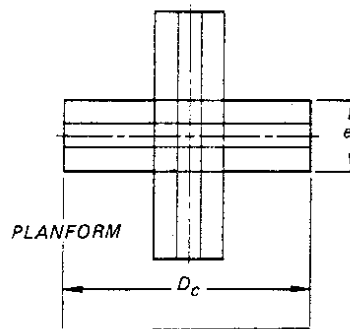
Cross. The cross parachute, a French development, is finding increased use for deceleration in applications that require good stability and low cost. The design is simple. The canopy consists of two identical cloth rectangles, crossed and joined to each other at the square intersection to form a flat 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.

$$S_D = 2 D_C e_s - e_s^2$$

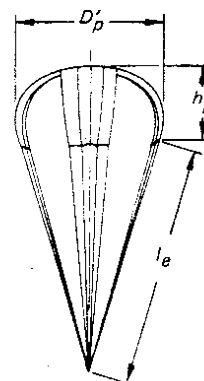
Generally:

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

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



CONSTRUCTION SCHEMATIC



INFLATED PROFILE

Size D_C , ft	Canopy (nylon) oz/yd ²	Dimension D_C ft	e_s ft	Line Str. (nylon) lbs	No. of Lines Z	Line Length l_e/D_C	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.

(A regular polygon of N sides)

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

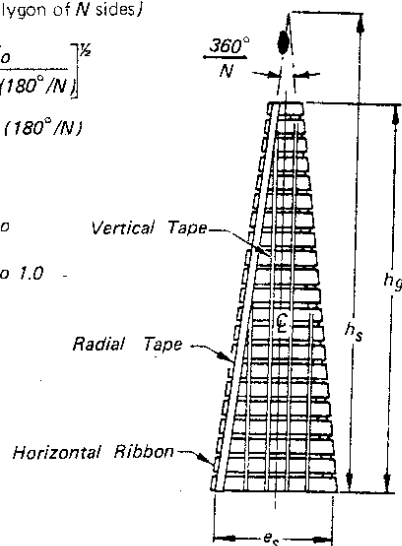
$$e_s = 2h_s \tan(180^\circ/N)$$

Generally:

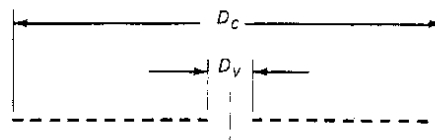
$$S_v < 0.01 S_o$$

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

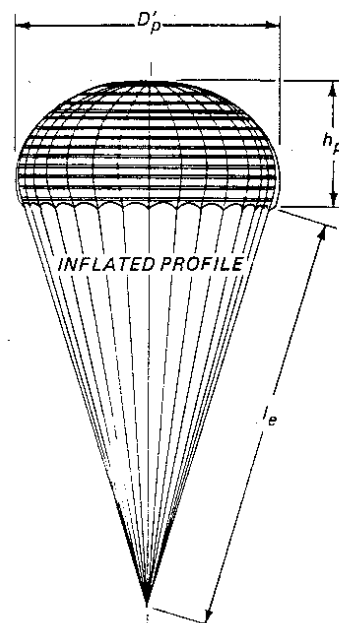
$$\frac{D'_p}{D_o} \approx 0.67$$



GORE LAYOUT



CONSTRUCTION SCHEMATIC



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.

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, $C_{D_0} = 0.64$, was obtained in wind tunnel tests without loss of stability. However, the opening load factor increased (see Table 2.2).

$$h_s = \left[\frac{S_0}{N \tan \beta/2} \right]^{1/2}$$

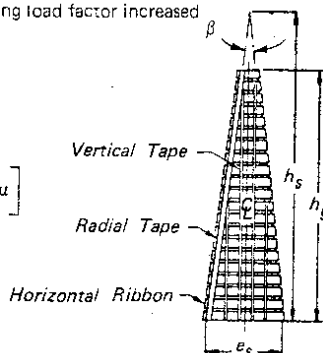
$$e_s = 2 h_s \tan \beta/2$$

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

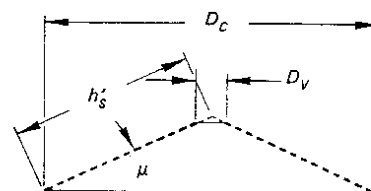
Generally:

$$S_v < 0.01 S_0$$

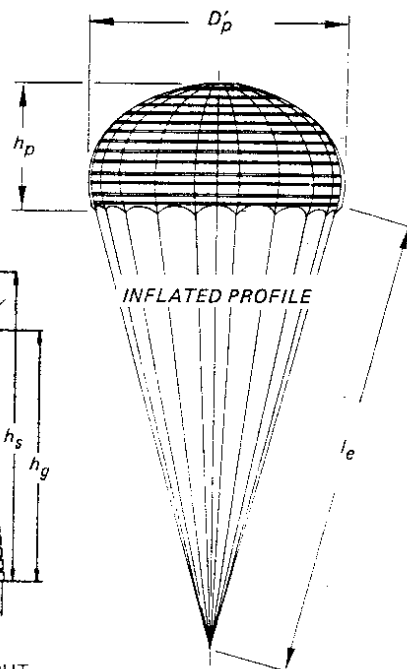
$$\frac{l_e}{D_0} = 1.00 \text{ to } 2.0$$



GORE LAYOUT



CONSTRUCTION SCHEMATIC



INFLATED PROFILE

Size D_0 , ft	Cone Angle μ	Ribbon (nylon) lbs	No. of Gores N	Geom. Porosity λ_g , %	Line Str. (nylon) lbs	Line Length l_e/D_0	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 400	98	16	6000	1.7	1400	Booster	164,000	200 psf	85	Cluster of 3	
17.0	20°	3000 2000	24	25	10000	1.0	76	Ordnance	715	800 kts	71		
14.2	20°	2000 1500 1000	32	10/14/17	6000	2.0	75	B-1 Capsule	8700	1.6 M 1600 psf		Drogue	213