Comparison of Theoretical and Experimental Performance of a 6.44-ft-diam Parachute

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A single-stage, 6.44-ft-diam ribbon parachute with no reefing has been developed for deceleration and recovery of the 130-lb Large Ballistic Re-entry Vehicle-2 nose cone. The parachute design makes use of both nylon for horizontal ribbons and Kevlar-29 for suspension lines and skirt band to save weight and volume. The results of five sled-launched, free-flight tests and an operational recovery at velocities of 600-875 ft/s, with corresponding dynamic pressures of 340-766 psf, are reported. Good agreement between experimental values and theoretical modeling is shown. Recovery procedures begin by jettisoning part of the initial re-entry mass before parachute deployment. An operational re-entry vehicle flight resulted in recovery of the payload (in two pieces) and the undamaged parachute.

Nomenclature

C_D = drag coefficient based upon S
D_0 = constructed parachute diameter, ft
q = dynamic air pressure $\frac{1}{2}\rho V^2$, psf
S = parachute constructed area
t = time, s
Δt = delay from upward ejection to can fire
V = vehicle total velocity, ft/s
V_d = vehicle velocity at deployment
V_0 = sled velocity at upward ejection
W = weight, lb
W_p = parachute pack weight
W_T = total vehicle weight
γ = angle between tangent to trajectory and horizontal
Δ = increment
ρ = air density, slugs/ft^3

Subscripts

d = parachute deployment time and time from lid fire to canopy stretch
f = parachute filling time from canopy stretch to full-open
p = parachute pack and hardware
T = total vehicle
0 = upward ejection from sled

Introduction

A SECOND-generation recovery system for the Large Ballistic Re-entry Vehicle (LBRV) was required by Sandia National Laboratories Advanced Systems Division I(1651). For economy of time and money, the same parachute can and lid used on LBRV-1 were to be used.[1] The need for a flotation bag was eliminated, and the volume gained was used for a single, unreefed ribbon parachute. The operational deployment range was a dynamic pressure of 340-760 psf. The deceleration phase was initiated by jettison of a mass similar to the technique described in Refs. 1-3. The single-stage ribbon parachute was deployed by a timer set about 8.6 s after mass jettison at a nominal altitude of 3500 ft mean sea level.

This paper describes the parachute system design and presents results from development of sled-launched, free-flight tests and an operational recovery.

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Recovery System Concept

Deployment of the parachute recovery system is illustrated in Fig. 1. The upper view shows the lid moving aft, deploying the pilot parachute. The center view shows the pilot parachute deployed and ready to extract the main parachute bag from the parachute can. The lower view shows the main 6.44-ft-diam ribbon parachute deployed.

The parachute has 9-ft-long suspension lines so that the parachute skirt is located 5 cone base diameters aft of the vehicle to ensure proper performance. The attachment point noted by "load plate" in the top sketch is ahead of the vehicle center of gravity, which causes undesirable oscillation of the vehicle. This instability was tolerated in order to use the proven mass-jettison system. A swivel attachment was located at the vehicle base to handle the potential 4-rps roll rate and prevent parachute roll-up or bridle damage from the sharp cone edge.

Impact velocity at sea level is calculated at 83 ft/s. The vehicle will decelerate very quickly after entering water, allowing the parachute to remain attached to the vehicle, as discussed in Ref. 1 for LBRV-1.

Parachute System Design

The starting point for the LBRV-2 recovery system design was the 8-ft-diam ribbon parachute weighing 5.4 lb used on the Mod VII high-altitude diagnostic rocket to recover a 1000-lb payload using 50% reefing and initial deployment at a dynamic pressure of 400 psf. To decrease parachute weight

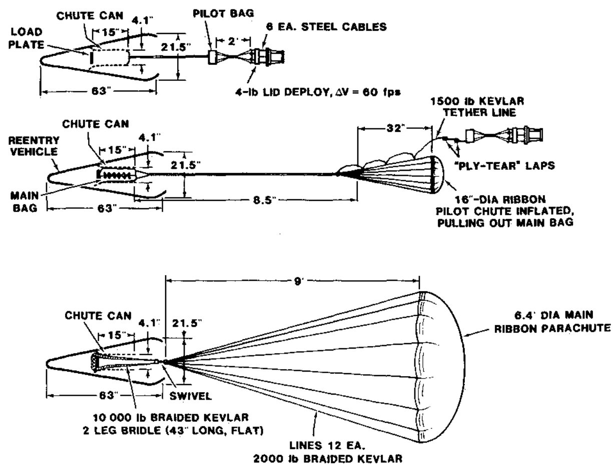


Fig. 1 LBRV-2 parachute recovery system.

Table 1 Parachute specifications for the LBRV-2 recovery system

Item	Main chute	Pilot chute
Drawing No.	—	T22375-000/P16
Type	Ribbon	Ribbon
Constructed diameter	6.44 ft	16 in.
Cone angle, deg	20	0
No. of gores	12	8
Suspension line		
Strength, lb	2000	400
Length	9 ft	32 in.
Material	Braided Kevlar-29, over canopy	Braided nylon
Specification	MIL-C-87129, Type IX	MIL-C-7515 Type I
No. of horizontal ribbons	13	9 in. (1/8-in. spacing)
Nos. 1-8, lb	1000	90 lb, 5/8-in. wide
Nos. 9-13, lb (¾-in. spacing)	460	—
No. of verticals per gore	2	2
Verticals strength, lb	550 (5/16-in. wide)	39 (¼-in. wide)
Gore base width, in.	20¼	5⅞
Gore length, in.	36	7½
Gore width at vent, in.	2¼	1
Pocket bands, lb	1000 (1 in.)	250 (½ in.)
Swivel, Fellerhoff SNLA Dwg size D, R03916		
Main bridle, 43 in. flat length 2 × 10,000 lb braided Kevlar-29[a]		
Cut knife (4 ea) SNLA Dwg size B, S42836		

[a]Freeman Frame Co., Providence, RI, Pattern 10142.

and volume, the 1500-lb tubular nylon lines were removed and 1500-lb braided Kevlar was substituted, but the parachute could not be packed into the LBRV can. Two lower ribbons were removed, along with the reefing rings, and a Kevlar skirt band was installed, creating a 7.16-ft-diam ribbon parachute weighing 3.7 lb. This was packed and used on the first three sled tests. After the lines failed on test 4, the line strength was increased to 2000-lb braided Kevlar. One additional ribbon was removed to permit the parachute to be packed. This final design was 6.44 ft in diameter and weighed 3.6 lb. Specifications for the system are given in Table 1. Figure 2 shows parachute line, canopy, and total weights as a function of parachute diameter. Component weights are detailed in Table 2.

Rigging and Packing

The 6.44-ft-diam ribbon parachute was attached to the specially designed load plate (Fig. 3) by a line of 10,000-lb braided Kevlar-29† made into a continuous loop by an 8-in.-long "Chinese finger" splice centered at the swivel.‡ The swivel and bridle were wrapped with leather (Fig. 4) as a buffer to eliminate abrasion from the can edge or the mass-ejection rails.

A 6-ft tether line made of 1500-lb, 9/16-in.-wide, tubular Kevlar-29 linked the pilot parachute bridle to the lid by way of the pilot bag (Fig. 1, center view). This arrangement permitted the pilot parachute to drag the lid downstream, avoiding deceleration of the main parachute. The tether line, two 6-in.-long accordion-folded "ply-tear" segments sewed with three rows of FF nylon to rip out and absorb energy as the pilot parachute pulled the lid away, was tacked every foot with E-thread nylon to one of the pilot parachute suspension lines and radial to prevent entanglement. Both the pilot and main parachutes were positioned behind the cone base at 5 base diameters (9 ft) to provide good parachute performance; later verified by laser tracker movies and tracking data. Rigging and packing detail strengths are listed in Table 3.

†Made by Freeman Frame Inc., Providence, RI, to FWF Pattern 10-142.

‡The swivel was designed by R. D. Fellerhoff and is described in Sandia Dwg. D/R03916.

Table 2 Component weights

Item	Weight, lb
16-in. ribbon pilot chute	0.15
Pilot chute bag and bridle	0.12
6.44-ft ribbon main chute	3.6
Main bag and riser to pilot chute	0.6
Swivel	0.62
Main chute bridle	0.5
Two lanyards with 2-ea cut knives	0.16
Total pack weight	5.75

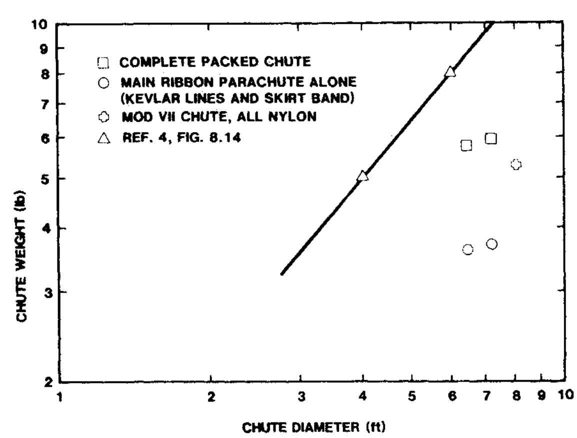


Fig. 2 Parachute weight as a function of diameter.

Deployment Sequence

About 8.6 s after the mass is jettisoned, the lid is fired off the parachute can by the PC-105-2 gas generator. The lid extracts the reaction plate by means of six steel aircraft cables which couple the two pieces of the lid. The pilot parachute bag is attached to the reaction lid by a four-leg bridle (Fig. 1, upper view). When the 16-in.-diam ribbon pilot parachute first deploys (center view) at 5 base diameters behind the cone, it pulls out the main bag and deploys the 6.44-ft-diam ribbon parachute (lower view). The swivel is located so that the sharp aft edge of the heatshield will hit it when the nose cone pitches. The swivel is wrapped with heavy leather to prevent damaging the heatshield's aft lip. Attachment of the bridle forward of the center of gravity causes the system to be unstable and the nose cone to pitch at about 30 deg.

Sled Tests

Pertinent parameters from the five sled tests conducted at the 1-mile-long sled track in area III, Sandia National Laboratories, Albuquerque, (SNLA), and from the operational flight are listed in Table 4. On the first three tests, 7.16-ft-diam ribbon parachutes were used. The first test was made at a dynamic pressure of 680 psf at lid deployment, near the maximum for the operational vehicle. Some stitching failure was observed at the skirt, where the 1500-lb Kevlar lines were sewed on with E-thread nylon. The second test was conducted at minimum deployment dynamic pressure (340 psf). The third test, which was an overtest at a dynamic pressure of 700 psf, resulted in failure of all of the 1500-lb Kevlar suspension lines. All future tests used stronger 2000-lb braided Kevlar lines, and the canopy had one less ribbon to make room for the greater line bulk. The fourth test was a successful overtest at a deployment dynamic pressure of 766 psf; the fifth test was a repeat overtest at 706 psf.

Results of Development Testing

Typical velocity decay with time, as recorded by the laser tracker, is shown in Fig. 5. Altitude vs range is shown in Fig. 6. The data are for the last sled launch overtest on November 3, 1982. Peak velocity at rocket burnout is 1330 ft/s. A piston driven by compressed gas ejects the nose cone up from the sled at a horizontal velocity of 1300 ft/s and a vertical velocity of 120 ft/s. A pullout wire starts an electric timer in the test vehicle that fires the PC-105 gas generator, deploying the

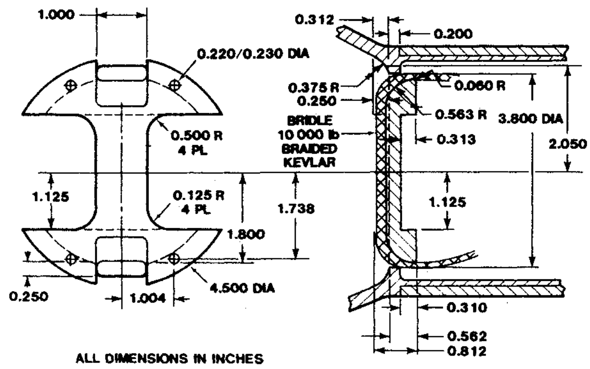
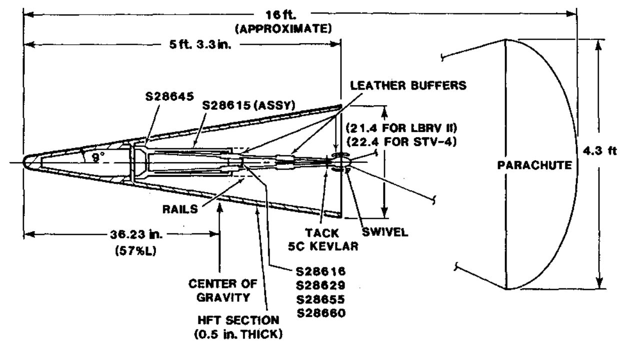


Fig. 3 Load plate.



CARTRIDGE	PURPOSE	QUANTITY	BRIDGEWIRES (DUAL) ALL-FIRE	NO-FIRE	RESISTANCE	PROPELLANTS
PC 105-2 PRESSURE CARTRIDGE (HI-SHEAR)	DEPLOYS PARACHUTE LID & PILOT CHUTE	1 EA	5 AMP	1 AMP-1 WATT 5 MINUTES	1.0 OHM	90 mg. ZIRCONIUM POTASSIUM PERCHLORATE, 350 mg. TITANIUM HYDRYDE AND POTASSIUM PERCHLORATE

Fig. 4 Parachute test vehicle used for sled tests.

Table 3 Rigging specifications for LBRV-2 recovery system

Chutes	Breaking strength, lb
16-in. pilot chute:	
Vent break cord, 12-in. long, 3-cord thread, nylon	24
Bag closing cord	100
Miniature cut knife safety tack, 2-ea places with 3-cord nylon	2×24
Riser, 8.5-ft-long, tubular Kevlar, accordion-folded, and tacked to main bag with E-thread nylon	2×1500
Lid tether line,[a] 6-ft-long, 1500-lb Kevlar tape	1500
6.44-ft ribbon main chute:	
Vent break cord, 12-in.-long, 3-cord thread, nylon	24
Lacing,[b] 375-lb nylon cord	
Swivel retainer:	
At end of swivel nearest vehicle, one turn FF nylon	2×11
At end of swivel farthest from vehicle, one turn 3-cord nylon	2×24
Tack 10,000-lb braided Kevlar bridle to main bag with FF-nylon thread, accordion-folded	2×11

[a]Fold and stitch "ply tear" two places 6 in. long with three rows of FF-nylon thread.
[b]Pull lacing to bag circumference of 13 in.

Table 4 LBRV-2 parachute recovery system sled test and operational flight parameters

Test date	Test No.	W_T, lb	D_0, ft	Serial No./ line strength, lb	W_p lb	V_0, ft/s	Δt, s	V_d, ft/s	q_d, psf	Δt_d, s	Δt_f, s	ρ, slug/ft^3	Results
8-23-82	R802720-1	130	7.16	575304/1500	5.81	1340	1.7	855	680	0.37	0.04	0.001855	Successful
9-9-82	R802720-2	139[a]	7.16	575304/1500	5.94	770	1.7	600	340	0.33	0.25	0.00187	Successful
9-24-82	R802720-3	139[a]	7.16	600870/1500	5.75	1320	1.5	865	700	0.39	0.14	0.00187	Lines Failed
10-8-82	R802720-4	138.5[a]	6.44	581308/2000	5.75	1340	1.5	875	766	0.59	0.27	0.00200	Successful
11-3-82	R802720-5	138.5[a]	6.44	581308/2000	5.75	1340	1.5	840	706	0.37	0.30	0.00198	Successful
1-7-83	Operational	~130[a]	6.44	575300/2000	5.75	NA	NA	700	576	—	—	—	Successful

[a]Mass-jettison rails added.

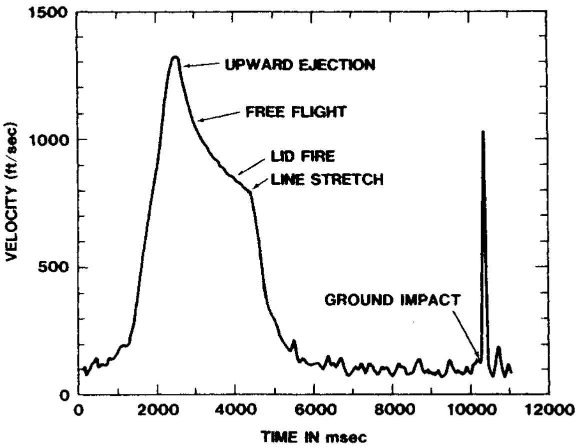


Fig. 5 Velocity vs time from the laser tracker.

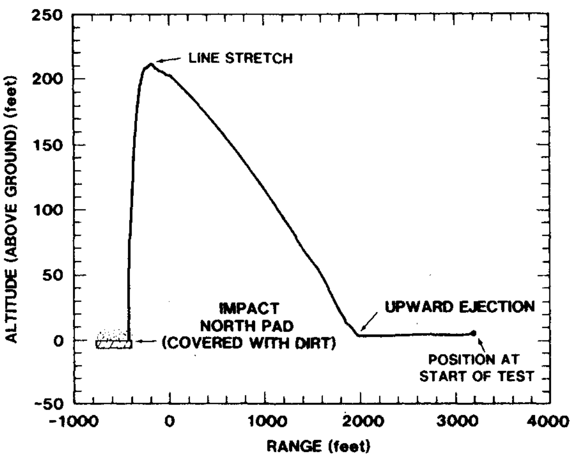


Fig. 6 Altitude vs range from the laser tracker.

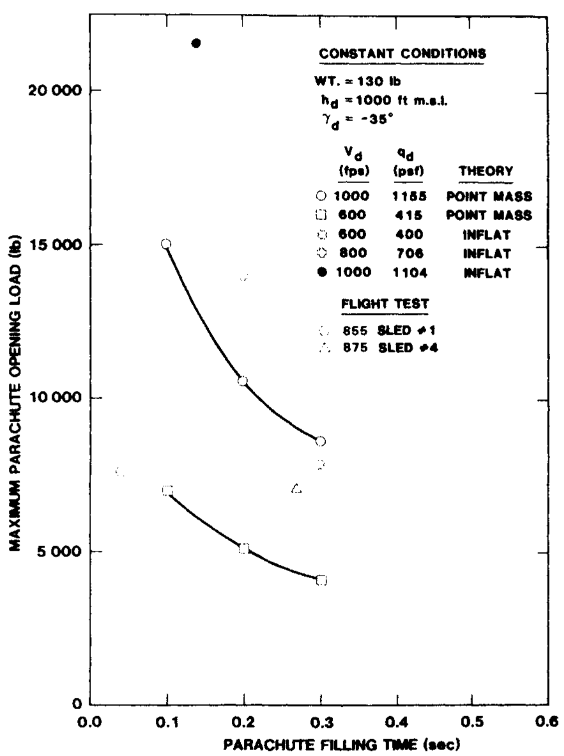


Fig. 7 Maximum parachute opening load vs filling time.

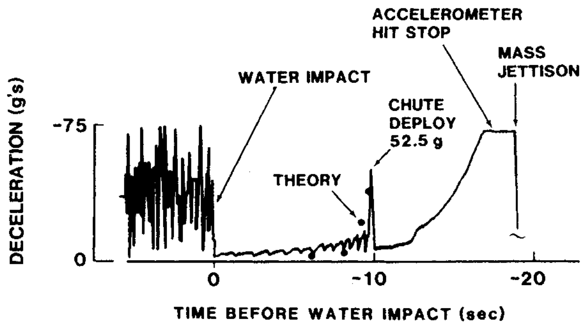


Fig. 8 Telemetered longitudinal deceleration from operational flight.

parachute can lid 1.5 s after upward ejection. The deployment sequence occurs as shown in Fig. 1.

Maximum parachute opening load vs parachute filling time is shown in Fig. 7. Theoretical values from point-mass trajectory calculations are shown as solid curves for the 1000-ft altitude above sea level. Values calculated with the INFLAT code for inflating parachutes are also shown. From Table 4, the nominal filling time is approximately 0.25 s, which would give a maximum load between 5000 and 10,000 lb, depending upon the velocity at the time of deployment.

Operational Flight

The operational flight was launched on January 7, 1983, from Vandenberg AFB, CA, by a Minuteman rocket. After traveling about 5000 miles, the re-entry vehicle and parachute were recovered at Kwajalein Atoll in the South Pacific. Pertinent flight parameters are listed in Table 4. Mass jettison occurred at an altitude of 14,500 ft mean sea level. The longitudinal accelerometer record from onboard telemetry is shown in Fig. 8. Theoretical deceleration values (circles) are shown for comparison. The parachute lid was fired about 8.6 s after mass jettison at an altitude of 2100 ft mean sea level. The fact that the vehicle was rolling may have caused the pulsating deceleration trace.

The re-entry vehicle and parachute were recovered from the lagoon at a depth of about 120 ft. The parachute and swivel were undamaged. The 10,000-lb braided Kevlar loop connecting the swivel to the parachute can load plate was not found. The vehicle had broken into two pieces because of large coning angles at water impact. The bolts holding the parachute can to the re-entry vehicle had failed at water impact and the can remained attached only by the electrical leads. It is believed that the oscillatory deceleration trace (Fig. 8) after parachute deployment is due to the bridle catching on the mass-jettison rails as the vehicle rolled and coned because of the parachute attachment necessarily being ahead of the center of gravity.

Conclusions

A parachute recovery system consisting of a 16-in.-diam ribbon pilot parachute and a 6.44-ft-diam ribbon main parachute has been developed to provide a soft landing of a large, 130-lb re-entry nose cone. The system, weighing 5.75 lb, was packed in a 4.1-in.-diam by 15-in.-long can with a volume of 198 in^3. Five sled tests were performed to qualify the system for a dynamic pressure range at parachute lid fire of 340-766 psf.

The recovery method started by jettisoning a portion of the initial mass, leaving a recovered weight of 130 lb. After an ICBM-type operational flight, the broken nose cone and the undamaged parachute/swivel were recovered.

Additional similar sled tests should be conducted with the parachute attached at least 2 in. aft of the vehicle center of gravity at time of operational deployment. This will ensure a stable parachute/vehicle combination and much higher confidence of intact recovery.

Acknowledgments

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