Aerodynamic Decelerators—An Engineering Review

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Nomenclature

C_D = drag coefficient based on S
C_DS = drag area of fully inflated parachute, ft²
$(C_DS)_r$ = drag area of reefed parachute, ft²
d = constructed parachute diameter across base of conical parachute, ft
D_i = inflated diameter, $\frac{2}{3}$ d, ft
h_r = release altitude, msl, ft
K_1 = outflow coefficient (approximately 0.6)
K_2 = inflow coefficient (a value of 0.7 is used for a first approximation, and adjusted as determined by experimental data)
L_r = circumferential length of reefing line, ft
ΔP = pressure across canopy, lb/ft²
q = dynamic pressure $\frac{1}{2}\rho V^2$, lb/ft²
R = radius of canopy during inflation normal to mean local canopy contour, ft
R_m = maximum inflated radius of canopy, ft (approximately $\frac{2}{3}$ of constructed radius)
R_0 = initial radius of canopy at start of inflation, ft (radius of suspension lugs or pack radius)
s = tensile stress, lb/ft²
S = area of base of conical chute, $\pi d^2/4$, ft²
t = thickness of ribbon, ft
t_f = filling time, sec
T = ribbon tensile load, lb
V = vehicle velocity, fps
V_0 = vehicle velocity at start of parachute filling, fps
w = ribbon width, ft
W = vehicle weight, lb
λ_G = geometric porosity of canopy
ρ = air density, slugs/ft³

1 Introduction

AERODYNAMIC decelerators are assuming an important role in aerospace technology, as exemplified by the Apollo Program, where an efficient, reliable, parachute-landing system was essential for the successful return by man from his first voyage into deep space. The F-111 crew module recovery system has been utilized to save the lives of crew members in several operational ejections. The first use of a parachute on another planet occurred in Oct. 1967, when the USSR parachuted a capsule toward the surface of Venus. Undoubtedly, aerodynamic decelerators will be used with increased frequency to assist in the landing of men and equipment on other planets and in assuring their safe return to earth.

The first known aerodynamic decelerator (of which parachutes are one type) was designed by Leonardo da Vinci in 1514. The first[1] reputed parachute jump was made from a balloon over Paris in October 1797. Parachutes of flat, circular design were used in the early 1800's in Europe and USA for exhibition jumps from balloons. During World War I, many pilots' lives were saved by the simple circular, flat solid canopy parachutes of that time. Gold[1] discusses the history of the development of personnel parachutes up through 1919. Since then, parachutes have grown in diversity of design to meet special requirements, such as the ribbon parachute for deployment at high dynamic pressures at supersonic speeds, the guide surface parachute for exceptional stability and inflation reliability, and the ring-sail parachute for large drag area at moderate subsonic-speed deployment. Shepardson[2] summarizes some of the major milestones in U.S. parachute R&D up through 1963. A large technical effort was required to develop the ribbon/ring-sail parachute systems used on Mercury, Gemini, and Apollo, the latter being described by Knacke[3] and Kiker.[4] Many recent applications of parachute technology by the DOD and NASA laboratories and their contractors are discussed by Burnham.[5]

Heavy duty ribbon parachutes have been recently developed for supersonic[6] deployment and for recovering large loads. A 76-ft-diam ribbon parachute[7] has been utilized to recover a 45,000-lb vehicle; parachute systems of this type could be the forerunner of recovery systems for large spacecraft. A high-altitude, sounding rocket payload recovery[8] system (which provides flotation and a locator beacon for over-water recovery for payloads up to 500 lb) has been

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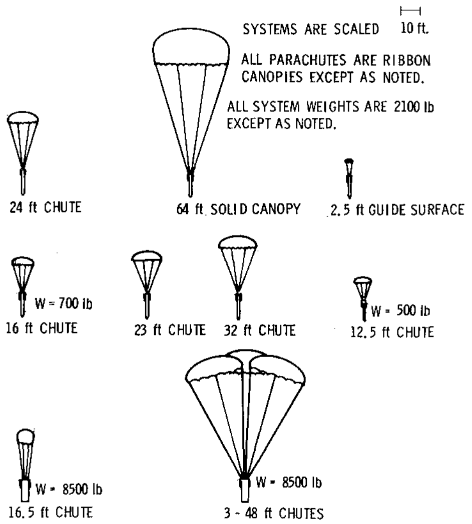

Fig. 1 Typical parachute/payload systems.

developed. Over 30 successful instrumentation payload recoveries, for payload apogees of up to 200-miles altitude, have been made with this system over water. Sandia Laboratories has conducted approximately 3000 aircraft drop tests (from bomb bay and external pylon carriage) and rocket-boosted tests of parachutes at instrumented ballistic ranges in the last 15 years to develop retardation systems for nuclear and other ordnance, instrumentation rocket payloads, and special applications.

One of the newest fields covered briefly in this paper is flexible wings (sometimes called lifting aerodynamic decelerators). In general, parachutes are designed to achieve minimum lift-to-drag ratios whereas flexible wings are designed to achieve maximum lift-to-drag ratios. Flexible wings add the possibility of maneuverability and controllability to the otherwise uncontrolled ballistic path of a descending payload system. Rogallo[9] conducted the pioneering studies on flexible wings in the late 1940's and 1950's; he discusses current applications in a recent article[10] in Astronautics and Aeronautics. The status of flexible wing development was covered by several survey papers and a panel discussion at the Sept. 1968 2nd Aerodynamic Decelerations Systems Conference.[11]

This survey will attempt to define the present state of aerodynamic decelerator technology available to the design

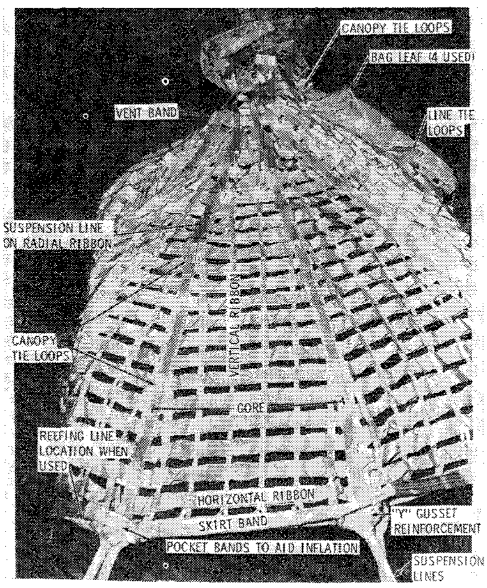

Fig. 2 The 12.5-ft-diam ribbon parachute illustrating construction.

engineer with emphasis on the heavy duty ribbon parachute development work at Sandia Laboratory. Many papers and reports were reviewed during the preparation of this survey. Numerous references of applicable, significant and timely work have been included to aid the reader in obtaining more detailed information on the various categories of aerodynamic decelerators. Brown[12] has written the only book (known to the authors) on parachute technology. The U.S. Air Force Parachute Handbook[13] is the most widely used reference for general parachute engineering. Other sources of current engineering data are the AIAA 1st[14] and 2nd[11] Aerodynamic Deceleration Systems Conference papers, papers published in the AIAA Journals, and reports from aerospace companies, government agencies, and universities.

2. Typical Utilization of Decelerators

Some of the many uses for decelerators are load recovery after drop test, instrumentation rocket payload recovery, aircraft landing deceleration, aircraft spin recovery, aircraft pilot or capsule escape, payload trajectory control, racing car deceleration, sport jumping, maneuvering descent, deceleration from planetary orbit, vehicle stabilization, cargo delivery, antenna line stabilization, bomb trajectory control, and airborne troop delivery. Typical types and sizes of parachutes used by Sandia Laboratories, varying from a 2.5-ft-diam guide-surface canopy to a 64-ft-diam solid canopy, are shown in Fig. 1.

The same technology used for parachutes is now being used for the fabrication of less familiar textile components, such as umbilical control leads, suspension of delicate instruments during deceleration, trailing antennas, flotation bags, balloons, erectable surfaces and containers for use in space, and solar sails.

Table 1 Characteristics of frequently used parachutes

Parachute type (inventor)	Characteristics	Maximum dynamic pressure	Mach No. range	C_D	Typical applications
Ribbon (Knacke)	Suitable for high q and supersonic Mach number deployment; heavy loads; very stable.	6,000	0–3	0.5	Payload recovery weights to 45,000 lb; aircraft landing deceleration; aircraft ejection capsule and spin recovery; nuclear and other bombs.
Guide surface (Heinrich)	Most stable; reliable inflation; high C_D; small chutes only.	6,000	0–3	0.8	Initial pilot chute; vehicle stabilization.
Solid canopy	Suitable for large chutes at low-speed deployment; cones about ±30°.	300	0–0.5	0.7	Final stage recovery.
Ring-sail (Radioplane Co.—Ed Ewing)	Suitable for large chutes up to moderate subsonic speed deployment; cones about ±10°.	600	0–0.7	0.6	Final stage recovery (Apollo, Gemini, Mercury).
Hyperflo (Sims)	Suitable for hypersonic speed deployment; small chutes only.	10,000	1–5	0.5	First stage of hypersonic recovery.
Ring-slot (Knacke)	Cheap to manufacture; suitable for large chutes.	1,000	0–1	0.55	Aircraft deceleration and cargo recovery.

3. Frequently Used Parachutes

Characteristics and typical applications of commonly used parachutes are listed in Table 1. There is extensive aerodynamic information available for these parachutes.

Drag coefficient data as a function of angle of attack and porosity for these frequently-used canopies is given in the Parachute Handbook[13] and by Heinrich and Haak.[15] Heinrich[16] presents drag data for a guide surface parachute at Mach numbers up to 3.0. The effect of clustering chutes on the drag coefficient is given by Heinrich and Noreen.[17] Niederer[18] presents drag data for decelerators at high altitude, i.e., for Reynolds numbers range down to near free molecule flow.

Normal force coefficient and pitching moment data as a function of angle of attack and parachute porosity for several canopies is given by Heinrich and Haak[15] and in the Parachute Handbook.[13] Additional references on aerodynamics (drag, flowfield, aerodynamic heating, etc.) are given in Sec. 10 (General) and in the following sections where each of the frequently-used parachutes are discussed in more detail.

Ribbon Parachute

The versatile ribbon parachute was invented by Theodore Knacke (now with Northrop Ventura) and G. Madelung in Germany in the late 1930's. It is used for aircraft landing deceleration, vehicle trajectory control, and vehicle recovery over an operational deployment Mach number range from low subsonic to Mach 2 or 3[19] at dynamic pressures up to 5700 lb/ft^2.

Parachute design

The canopy usually consists of 2-in. wide horizontal ribbons spaced 0.5–1.5 in. apart as shown in Fig. 2. The primary aerodynamic loading on the canopy is taken by the horizontal ribbons and then transferred to the payload via the radial/shroud lines. The vertical ribbons control the local porosity and camber or effective airfoil shape of the horizontal ribbons. The geometric porosity is usually between 15 and 30%; the higher values are suitable for high Mach number deployment, and the lower values are for very large canopies at subsonic deployment speeds. The optimum porosity is usually a tradeoff between a higher drag coefficient (lower porosity) and increased chute stability (higher porosity). Filling time and thereby opening shock load are influenced by porosity. A reinforced selvage ribbon[19] (Sec. 7) prevents complete gore failure resulting from progressive ribbon tearing. Sandia Laboratories[6] over the last ten years has perfected several methods of improving ribbon parachute performance, such as, continuous ribbon (one splice for each horizontal ribbon), figure eight suspension line construction (one splice for four suspension lines), graded ribbon strength over the canopy (strongest ribbons in the vent region to maximize strength during initial filling and minimize weight and volume), increased ribbon strengths up to 4,000 lb, increased line strength up to 12,000 lb and reinforced selvage ribbon. Other design information is presented in the Parachute Handbook.[13]

Table 2 Ribbon parachute characteristics

Parachute diam, ft	Total system weight, lb	Maximum deployment conditions: Dynamic Pressure, lb/ft^2	Mach number	Altitude, ft, msl
12.5	500	4200	1.94	7,000
17	700	2828	1.6	9,500
20^a	1,100	5700	2.43	12,000
48^a	45,800	321	0.61	15,000
76^a	45,000	280	0.81	45,000

Parachute diam, ft	Parachute system: Weight, lb	Bag diam, ft	Bag length, ft	Volume, ft^3	C_DS, ft^2	Deployment method
12.5	50	0.79	3.5	1.25	63	Ejection tube
17	90	0.75	4.83	2.5	118	Ejection tube
20^a	180	1.5	4.16	8.8	130	Drogue gun
48^a	266	4.0	1.6	20	1150	Static line
76^a	700–900	5.7	1.75	23	2800	Static line

^{a} Reefed during deployment and first-stage inflation.

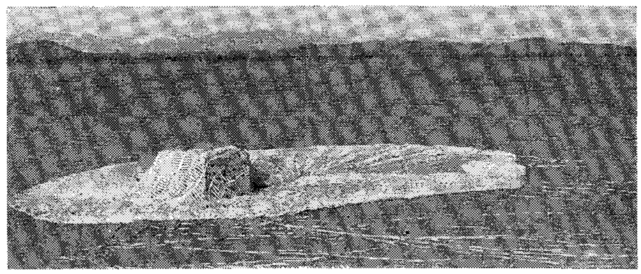

Fig. 3 The 76-ft ribbon parachute.

Weight and volume

Ribbon parachutes[6,7,19] from 1- to 130-ft diam, used to decelerate vehicles weighing 5–45,000 lb, have been designed and tested. Test parameters for representative sizes are listed in Table 2. Figure 3 shows a 76-ft-diam parachute[7] after impact; this parachute was used to retard an 8,000-lb test vehicle. The weight of this parachute system is 700–900 lb (depending on application) and is shown plotted in Fig. 4 along with weights for other parachutes as a function of constructed diameter. The pack volume was approximately 23 ft^3 as shown in Fig. 5. Note that both weight and volume of heavy duty ribbon parachutes may be an order of magnitude larger (depending on the application) than a solid canopy parachute.

Testing methods

In addition to aircraft drop tests (such as a B52 release from 45,000-ft altitude or an F-4 release at 500 knots at 1000-ft altitude), extensive use has been made of rocket boosting parachute test vehicles to obtain high dynamic pressure deployment conditions. Utilization of two Nike boosters to test a 20-ft chute at high dynamic pressure is discussed by Pepper.[19] A photograph of a rocket-boosted test vehicle used in deploying a 12.5-ft-diam ribbon chute at $M = 1.94$ (see Table 2) is shown in Fig. 6. Figure 7 is a photograph of the Genie rocket and the parachute test vehicle on a

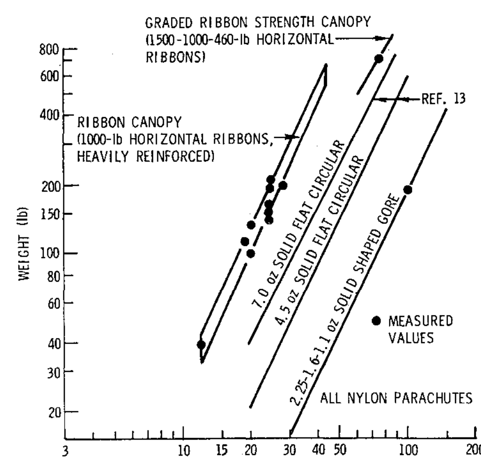

Fig. 4 Parachute pack weight as a function of constructed diameter.

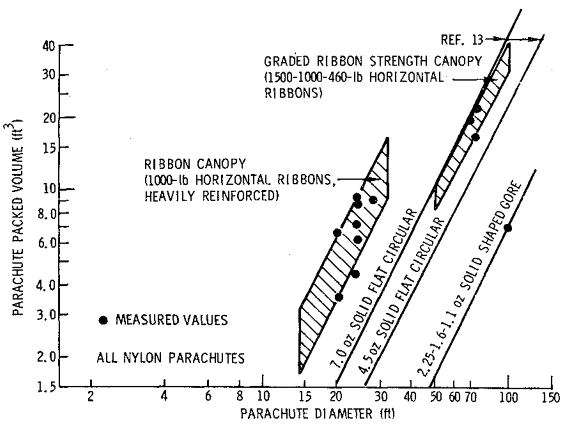

Fig. 5 Parachute packed volume as a function of constructed diameter.

launcher at the AEC Tonopah Test Range, Nevada.[20]* A sketch of the 500-lb test vehicle and the 500-lb Genie booster (which has a total impulse of 74,500 lb-sec is shown in Fig. 8. A timer-actuated gas generator is used to deploy the chute (Sec. 8).

Filling time and inflation dynamics

Extensive studies on parachute filling time and inflation dynamics have been made by Heinrich,[21,22] Melzig,[23] French,[24,25] and others,[26-32] primarily to investigate the effect of filling time on the opening shock load. However, these methods developed are primarily applicable to solid canopies at low subsonic deployment speeds. A recent paper by Greene[33] develops a theory (corroborated by experimental data up to $M = 3.31$) for predicting the opening distance for cross, disk-gap-band, and ring-sail parachutes. The following equation (as used by Pepper[6]) is quite useful for estimating filling time of heavy duty ribbon parachutes during high-speed deployment:

$$t_f = 1/V_0(K_2 - 2\lambda_g K_1)[2(R_m - R_0) - (3\pi/2)(R_m - R_0) + 3R_m \ln(R_m/R_0)] \quad (1)$$

This equation is obtained by relating the inflow of air at the skirt and the outflow of air through the ribbon slots. Filling time estimates using this equation are compared with experimental data in Figs. 9 and 10 for the first- and second-stage filling of a reefed 24-ft-diam ribbon parachute. Deployment altitudes were between 5000- and 15,000-ft msl. Experience indicates that the filling time can vary ±50% from a mean value.

Fig. 6 The 12.5-ft-diam parachute after rocket boost test.

* The DOD Joint Parachute Test Facility, El Centro, Calif., is the primary drop testing area for parachute systems in the U.S.

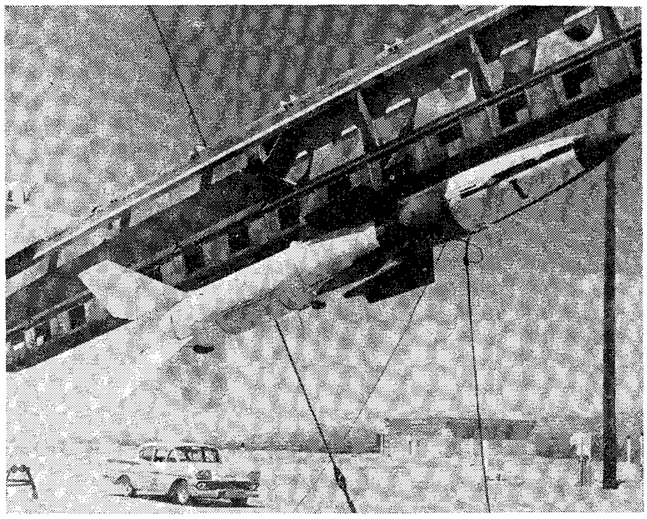

Fig. 7 Genie rocket-boosted parachute test vehicle.

The filling-time variation with dynamic pressure at deployment for a 12.5-ft-diam ribbon parachute and 12-ft-diam ring-slot parachute is shown in Fig. 11. The average deployment time from start of deployment to line stretch is 0.15 sec. The average filling time for the 12.5-ft-diam ribbon parachute is 0.33 sec, with a scatter of ±0.15 sec. Representative filling times for a 76-ft-diam ribbon parachute are shown in Fig. 12.

Parachute loads

The maximum parachute opening shock load can be approximated by

$$D = C_D S q \text{"}X\text{"} \quad (2)$$

where the amplification "X" factor varies from approximately 0.3 to 3.0 as a function of type of canopy, deployment velocity, payload mass, etc. The low and high values of amplification factor refer to extremely low and high values of canopy loading and filling time, respectively; a value of unity is normally used. Total rated suspension line strength should be twice the estimated load at maximum design dynamic pressure. If this design factor becomes less than 1.8, suspension line failure may occur. To prove structural integrity, the parachute should be successfully deployed several times at 25% greater than the design maximum dynamic pressure.

The horizontal ribbon stress during the dynamic process of inflation, can be estimated by several step calculations using the hoop tension formula $s = \Delta P \cdot R/t = T/wt$ and $\Delta P \approx q$. Several approximate side profile shapes of the canopy during the progressive inflation are used to determine the average radius of the canopy surface R from the parachute centerline. The ribbon tension is then, $T = qR/6$, (Eq. 3) for 2-in. wide ribbons. The ribbon ultimate rated strength should be twice the maximum calculated load during the inflation process.

The opening shock loads for an 8-ft-diam ribbon parachute are shown in Fig. 13. One horizontal ribbon in the skirt

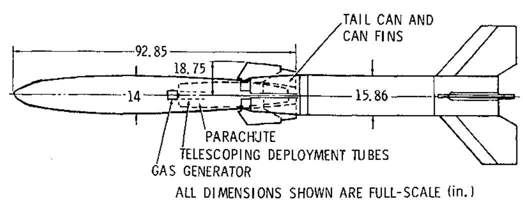

Fig. 8 Parachute test vehicle and Genie booster.

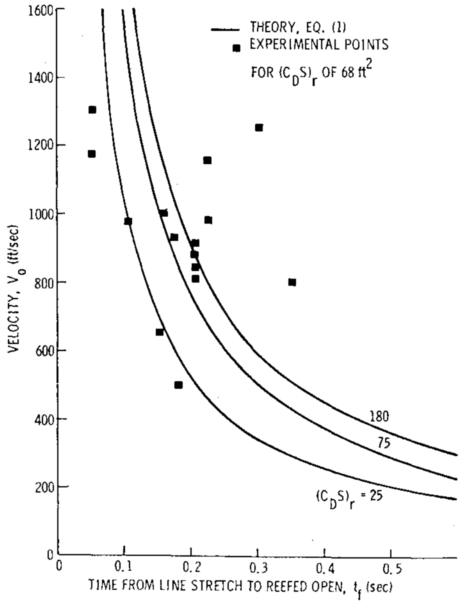

Fig. 9 First-stage filling time for reefed 24-ft-diam ribbon parachute.

region of the 8-ft-diam parachute was removed to decrease the opening shock loads to within the safe design limits. The loads were decreased as shown by the lower curve in Fig. 13; however, the decreased loads were obtained at the cost of slightly increased filling time.

Peak loads measured, by accelerometers through the use of telemetry, for 12.5-, 16-, 17-, 20-, 30-, 32- and 76-ft-diam ribbon parachutes[6,7,19] are presented in Figs. 14–18. The peak opening load varies approximately linearly with dynamic pressure up to about 2000 lb/ft^2 for the unreefed 12.5-ft ribbon parachute shown in Fig. 14 and then decreases up to a "q" of 4000 lb/ft^2 because of the supersonic squidding. This produces the desirable effect of automatic reefing to lower the peak loads.

Figure 15 shows the peak loads developed by unreefed 16- and 17-ft ribbon parachutes.[6] The use of selvage ribbon is very successful in preventing the canopy failures shown for the flat ribbon parachutes. Figure 16 shows maximum deceleration of 30- and 32-ft-diam unreefed ribbon parachutes

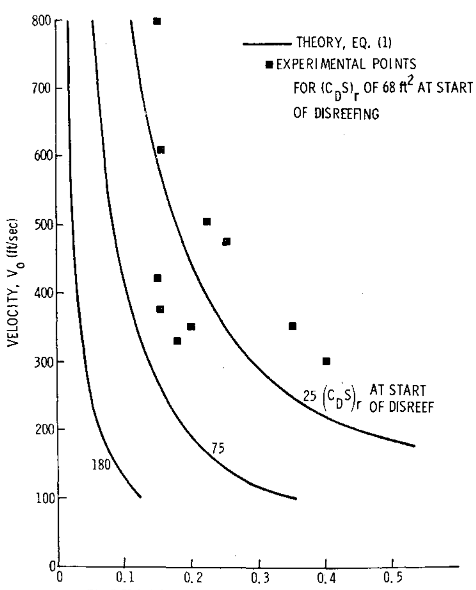

Fig. 10 Second-stage filling time for reefed 24-ft-diam ribbon parachute.

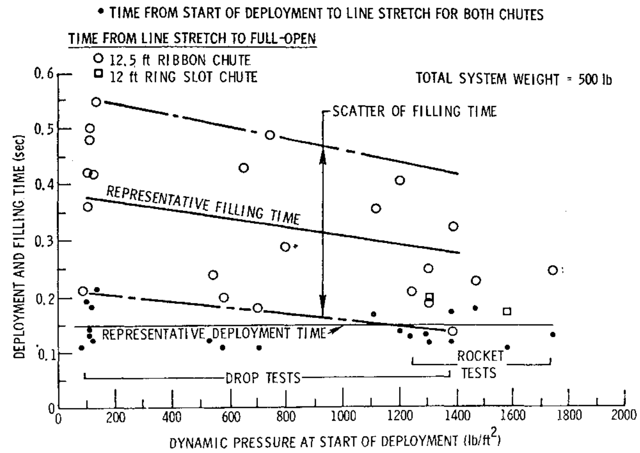

Fig. 11 Variation of parachute function times with dynamic pressure at start of deployment for 12.5-ft-diam ribbon and 12-ft diam ring-slot parachutes.

using a 2100-lb vehicle. For the data symbol noted as a 30° toss, the unit was released in a 30° climb and the unit decelerated more prior to and during inflation thereby producing a smaller peak load (opening shock). The use of an apex line (a separate line from chute apex to payload to flatten the canopy) resulted in higher deceleration because of the flattening effect on the canopy. The maximum deceleration of reefed 20-ft ribbon parachutes[19] over the range of deployment dynamic pressures from 1700 to 5700 lb/ft^2 are shown in Fig. 17. There is a leveling of the opening shock between dynamic pressures of 3000 and 4300 lb/ft^2, with a sharp rise at higher dynamic pressures.

Some representative opening shock loads from drop tests[7] of reefed 76-ft-diam ribbon parachutes are shown in Fig. 18. The heavier payload weights of up to 45,230 lb result in the highest opening loads since the first stage inflation time is shorter.

Drag area

Drag areas of ribbon parachutes (in terminal descent) from 12.5- to 76-ft diam are presented in Table 2. A ribbon parachute[13] is generally considered to have a drag coefficient of 0.5 based on constructed area. The drag area variation with time for supersonic deployment of 20-ft reefed ribbon

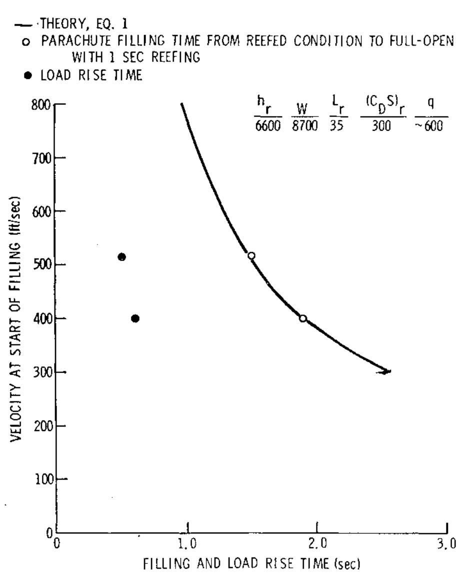

Fig. 12 Variation of filling time and load rise time with velocity at start of filling for 76-ft-diam ribbon parachute.

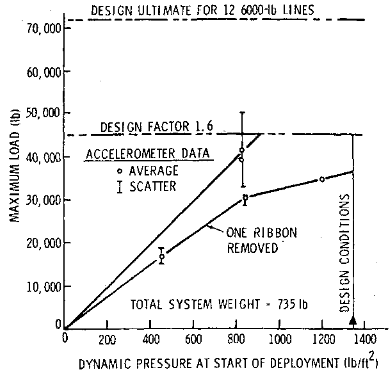

Fig. 13 Maximum opening shock loads for an 8-ft-diam ribbon parachute.

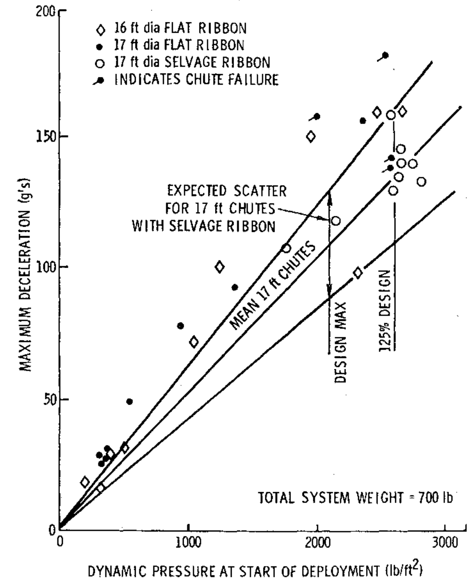

Fig. 15 Variation of maximum deceleration with dynamic pressure at start of deployment for 16-ft- and 17-ft-diam ribbon parachutes.

parachutes using reefing of 2-sec time delay is shown in Fig. 19. The drag area was calculated from on-broad vehicle-telemetered accelerometer data (with dynamic pressure determined from ballistic range tracking and meteorological measurements) and from accelerations derived from the trajectories measured from the tracking camera data.[20] The agreement between the accelerometer data and the camera tracking data is good for the three tests when the chute is reefed. The data scatter increases for the full open chute because of the small decelerations (see upper curve).

The drag area of a reefed chute can be determined from Fig. 20 as a function of reefing line length ratio. The scale model parachute data (obtained from wind tunnels) agrees fairly well with the full-scale test data.

Stability

The stability specifications of the vehicle system will usually influence the type of canopy (ribbon, ring-slot, solid, etc.) selected during the design. Solid canopies possess low static stability (they oscillate approximately $\pm 30°$) while canopies such as the ribbon type are quite stable as discussed by Heinrich and Haak.[15] Ludwig[34] has conducted stability studies using digital and analog computer techniques. Other papers[35–42] have analyzed several special systems. Recent work by White and Wolf,[43–45] and Heinrich and Rust[46,47] have provided valuable insight into the dynamic stability of parachute/payload systems.

The use of a slight amount of permanent reefing or lengthening the suspension lines are standard methods of improving the stability, especially when the parachute has to function behind a large bluff body.

Wake characteristics

The body wake characteristics (i.e., the local dynamic pressure, unsteady flow, and lateral velocities) are not of great significance when the parachute diameter is ten or more times the vehicle diameter; however, for diameter ratios of less than five and/or at supersonic speeds, the wake becomes very important to understand. Heinrich[48] and others[17,49–58] have studied the wake characteristics of various payloads and related these data to parachute performance.

Guide Surface Canopy

The guide surface canopy[13,16,59–61] invented by H. G. Heinrich, Professor at University of Minnesota, is probably the most frequently used design for a pilot or extraction parachute due to its high-opening reliability. This canopy is one of the most stable, having oscillations of less than $\pm 1°$. The guide surface canopy can be used over a wide range of Mach numbers from near 0 to 3.0. The senior author has observed successful deployment and stable inflation of an 18-in.-diam guide surface at approximately Mach 3 and at a dynamic pressure of 8000 lb/ft^2, indicating its usefulness at high Mach numbers.

The senior author[62] has also used a 6-ft-diam guide surface parachute to recover a 155-mm shell after the shell has been subjected to 20,000 g's acceleration and 250 RPS spin rate in the gun barrel. Guide surface chutes have been deployed at altitudes of over 130,000 ft[63] at supersonic speeds using a water vapor filled torus in the skirt to insure inflation at dynamic pressures less than 1 lb/ft^2.

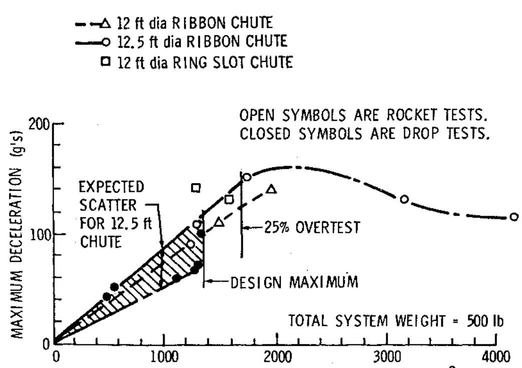

Fig. 14 Variation of maximum deceleration with dynamic pressure at start of deployment for 12-ft-diam ribbon and ring-slot parachutes.

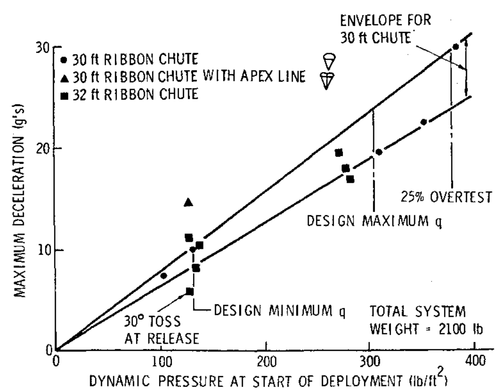

Fig. 16 Maximum deceleration as a function of dynamic pressure at start of deployment for 30-ft- and 32-ft-diam ribbon parachutes.

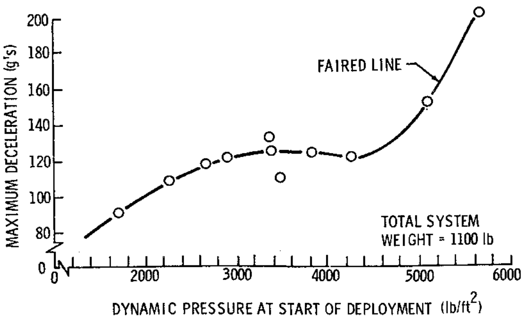

Fig. 17 Variation of maximum deceleration with dynamic pressure at start of deployment for the 20-ft-diam ribbon parachute.

Solid Canopy

The circular, solid, flat canopy[13,64–67] is probably the most widely used parachute for personnel and cargo recovery because of its geometry, low cost, and light weight. The solid canopy is suited for deployment at low subsonic velocities, but becomes overly bulky for deployment at high dynamic pressures. The gores are usually fabricated individually from standard 36-in. wide nylon of 1.1–1.6 oz/yd² cloth spliced on a bias for strength. Large solid canopies, such as a 100-ft-diam parachute, are made with three weights of cloth, the heaviest being located at the top one-third of the canopy (see Figs. 4 and 5). Considerable weight and volume savings are realized by the use of graded cloth weights.

Solid parachutes have the inherent disadvantage of being unstable with a coning oscillation of 20°–30°, which may be detrimental to successful shock attenuation by impact cushioning devices. Large 64- to 100-ft solid canopies are often used clustered[68,69] 3–10/load, which eliminates the oscillation difficulty, but may result in partial or no inflation of several canopies due to interference during inflation.

The pack weight and volume for solid canopies are shown in Figs. 4 and 5 as a function of constructed flat diameter. Filling time as a function of deployment velocity is treated by Berndt and DeWeese.[70]

Ring-Sail Parachute

The ring sail[71–74] has been used exclusively as the final recovery parachute for all U.S. manned orbital and space flights because of its light weight, slower inflation rate (thus lower opening load), and more desirable stability than a solid canopy. The side profile resembles a Christmas tree, with the notches ejecting air upstream, resulting in much more porosity than a solid canopy. The top third of the canopy is designed much like a ring slot to permit through-air-

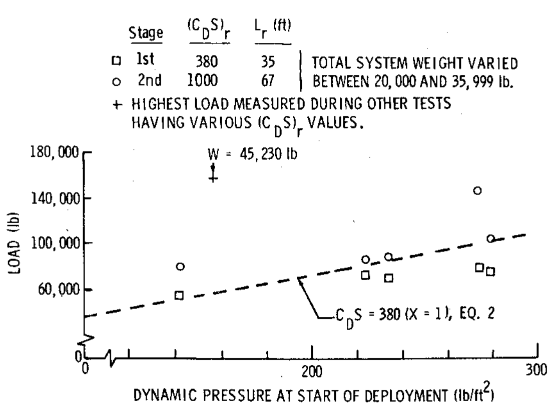

Fig. 18 Variation of maximum opening load with dynamic pressure at start of deployment for the 76-ft-diam ribbon parachutes.

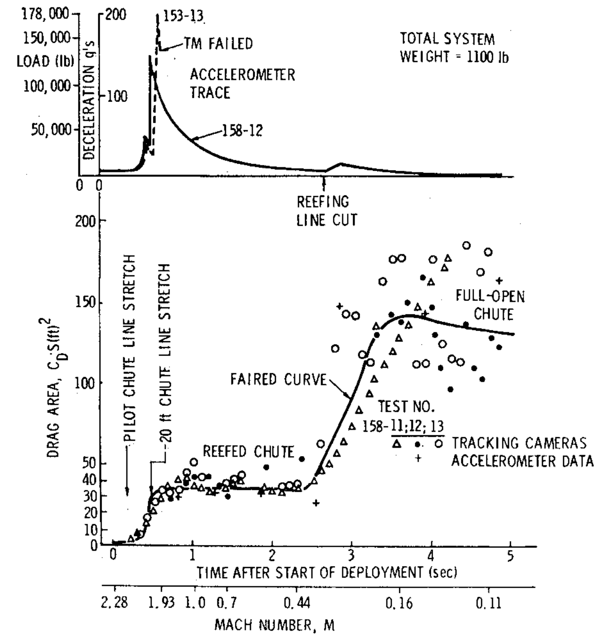

Fig. 19 Parachute deceleration and drag area variation with time for 20-ft-diam ribbon parachutes.

flow during initial inflation. Knacke[3] describes the cluster of three ring-sail canopies used for Apollo recovery. A ring-sail canopy is also used as the final recovery stage of the F-111 crew capsule.

Ring-Slot Canopy

The ring-slot canopy,[13] developed by T. W. Knacke at WADC in the 1946–1951 period, is similar to the ribbon canopy in that it is composed of horizontal bands and open slots. The bands are much wider, generally 1 ft, with selvaged- or tape-reinforced edges. The ring slot has the advantage of being more stable (±5–15°) than a solid canopy and cheaper to construct than a ribbon parachute. The ring slot is frequently used[13] for cargo delivery and aircraft landing deceleration, and is suitable for deployment at moderate subsonic speeds, higher than a solid canopy could withstand.

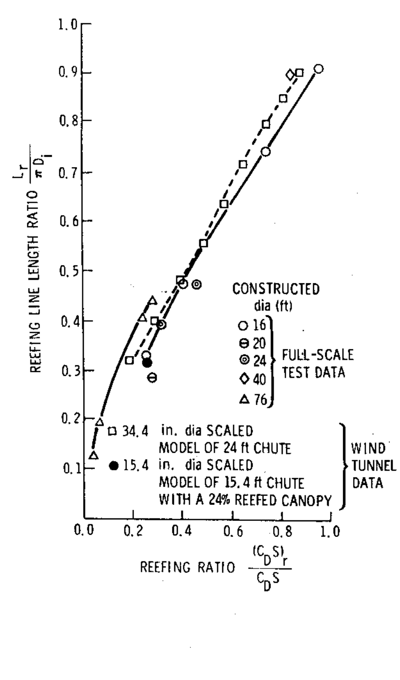

Fig. 20 Variation of reefing ratio with reefing line length ratio for ribbon parachutes.

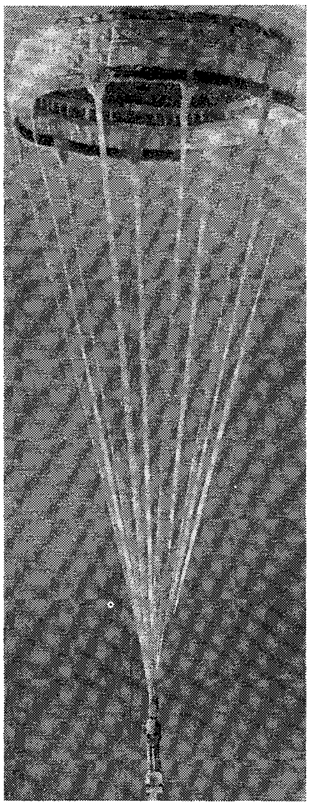

Fig. 21 The 2-ft-diam hyperflo composite construction for Mach 4 deployment.

Hyperflo Parachute

The hyperflo parachute was invented by L. Sims,† for operation at Mach numbers above 2. The canopy consists of a flat ribbon grid roof and a conical frustrum solid cloth skirt. Extensive wind tunnel and rocket-boosted free-flight tests of this design have been conducted.[75–83] The senior author[84] has deployed and recovered a 2-ft hyperflo, shown in Fig. 21, at a Mach number of 4.0 at an altitude of 114,000 ft. Aerodynamic heating is, of course, a primary concern at such speeds. The parachute can be made of Nomex, which will withstand 600°F instead of the 300°F to which nylon is limited; however, Nomex is quite expensive, and the stagnation temperature at Mach 4 is approximately 1000°F. Therefore, a new composite construction was used. The suspension lines and canopy structure were made of nylon for strength and elasticity; the forward face of the canopy was covered with silicone-coated glass fiber cloth and then treated, along with the suspension lines, with four coats of RTV silicone rubber which acted as an ablator.

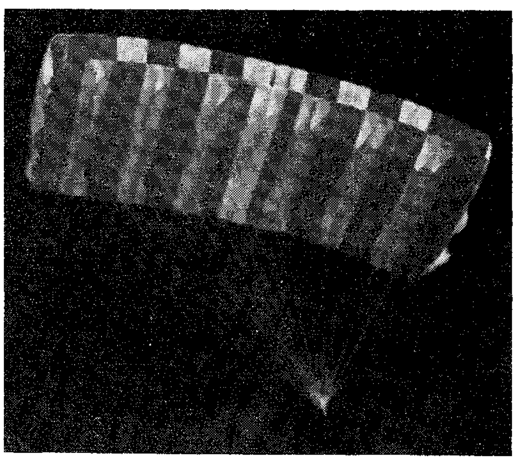

Fig. 22 The 44-ft-span (704 ft^2) para-foil in tether flight.

† Currently with General Electric Company, Valley Forge, Pa.

Table 3 Lifting aerodynamic decelerators (flexible wings)

Type	Characteristics	Source	Approximate, lift/drag
Sailwing	Has been tested for Apollo landing	Barish	2–4
Parawing	Being developed for Apollo landing	Rogallo	2–4
Para-foil	Reliable, stable, proven for jumping	Jalbert	2–4
Para commander	Used extensively for sport jumping	Pioneer	1
Volplane	Newest design, undergoing testing	Pioneer	2–4

4. Flexible Wings—Lifting Aerodynamic Decelerators

The flexible wing concept, as evolved by Rogallo,[10] was a marriage of the advantages of conventional parachutes (low volume and weight and deployable) and rigid wings (high L/D). Attempts to achieve gliding ability by modifying conventional, circular parachute design has generally resulted in lift-to-drag ratios of less than one. For example, Kane[85] tested a solid canopy with one gore removed and obtained an L/D of about $\frac{1}{2}$. Most of the flexible wings developed to date have lift-to-drag ratios of 2–4. Several contemporary and novel designs are listed in Table 3 and discussed in more detail below. Flexible wings have received considerable interest[86] (for personnel, cargo, bombs, spacecraft, rocket payloads, etc.) because they offer the possibility of a controlled orientation of the descent path and landing within a smaller restricted zone than would otherwise be possible without a lifting configuration.

Parawing or Paraglider

Rogallo[87] began development of flexible wings in 1945 and was granted a patent[88] on such a device in 1951. Rogallo[89,90] and coworkers[91–93] at NASA Langley Research Center have conducted extensive aerodynamic research on parawings (including static aerodynamics and lateral and longitudinal dynamic stability and control) through analysis, wind tunnel, and flight tests. A comprehensive bibliography of flexible wing publications is given by Naeseth[94] in a recent paper.

The parawing planform generally consists of a triangular single layer of low porosity cloth with two rigid leading edges and a keel spar forming two lobes to the canopy. Naeseth[94] illustrates the planform of some 25 single keel, twelve double keel and three triple keel configurations that have been investigated. A twin-keel parawing has been tested by Northrop Ventura as an Apollo landing configuration.

Para-Foil

The para-foil,[95–97] invented by Domina Jalbert, Boca Raton, Fla., is like a rectangular planform, ram-air inflated wing. The lower and upper surfaces are connected by vertical webs forming chordwise channels open at the leading edge. The para-foil has the advantage of high lift-to-drag ratios of 2–4 because of the greater aspect ratio allowable with ram air inflation. Opening reliability is good, and the parachute is very stable in glide. A 44-ft span para-foil constructed at Sandia is shown in Fig. 22.

Sailwing

The sailwing[98] was invented by D. Barish of Barish Associates, New York. The canopy is similar to three joined spinnaker sails, having an irregular planform composed of one layer of low-permeability cloth. Fabrication and deployment are somewhat complicated.

Para-Commander

The Pioneer para-commander[99] is probably the highest performance flexible lifting aerodynamic decelerator that is in use extensively by jumpers. It has a lift-to-drag ratio greater than one, and is of circular planform resembling a ring-sail canopy with controllable slots directed aft. Inflation reliability is very good.

Volplane

The Pioneer volplane is a relatively new flexible wing, similar in appearance to the para-foil and having a multichannel leading edge open to ram air. The upper surface is a single-ply, low-porosity cloth, and the lower surface extends from the leading edge inlet to approximately the one-third chord where it is joined to the top surface. Performance is similar to a para-foil with the additional advantage of having one-third less cloth. Other studies[100–105] discuss various aspects of lifting parachutes.

5. Other Parachutes and Drogue Devices

Ballute Parachute

The Goodyear ballute[106–113] resembles a boxer's punching bag. The ballute has been wind tunnel tested [107] up to Mach 10. A burble fence or torus at the meridian is used to insure stability. Four ram air scoops located ahead of the burble fence provide positive inflation. Weight and volume of such a decelerator may be less than optimum, for operational Mach numbers of 3–6, where a hyperflo design may be more economical in weight and volume.

Disk-Gap-Band Parachute

The Schjeldahl disk-gap-band parachute described by Murrow and Eckstrom[114,115] and Lemke[116] was designed to have better stability than a solid flat canopy without loss of the desirable features of drag efficiency and ease of construction. The disk portion is much like a solid flat canopy. The band is a cylindrical cloth skirt separated from the disk by an air gap. The stability of this parachute is ± 5–$\pm 10°$, being similar to a ring sail but probably easier and cheaper to manufacture. Eckstrom and Preisser[117] conducted several supersonic deployments of this canopy as an evaluation for a planetary landing parachute.

Rotochute

The rotochute discussed by Barzda.[118] Levin and Smith,[119] and others[120,121] is generally thought of as being a series of one to eight rigid blades operating similar to those of an autogyro. Probably the most experienced company in analysis and application of rotochutes is Kaman Aircraft Co. Sandia Laboratories conducted considerable research on rotochutes during the late 1950's and concluded that nylon parachutes offered a 50% saving in weight and $\frac{1}{3}$ the stowed volume of a rotochute as shown in Fig. 23 for deceleration from transonic speeds down to approximately 150 fps.

Establishing a stable rotor-vehicle system was found to be rather difficult, and rotor speed governing becomes necessary for high subsonic release speeds.

Vortex-Ring Parachute

The vortex-ring parachute,[13] invented by D. Barish of Barish Associates, is a four-bladed all-fabric rotating decelerator. The drag coefficient is about the same as a ribbon parachute, being 0.5 based on the flat laid-out disk area. One advantage of the vortex ring is its stability, which is less than $\pm 1°$ of oscillation. Small sizes (up to 10-ft diam) have been inflated reliably up to dynamic pressures of 200 lb/ft^2. Sandia Laboratories successfully tested a 48-ft-diam vortex-ring parachute on a 2400-lb test vehicle. The layout and construction of this canopy is complicated.

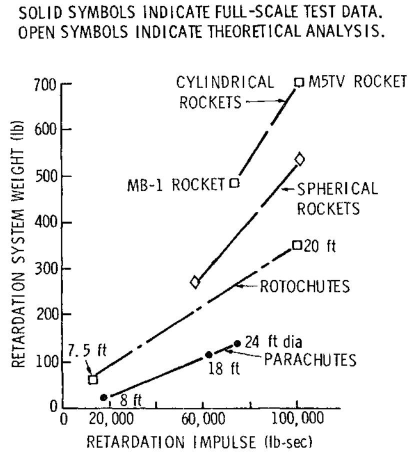

Fig. 23 Variation of retardation system weight with retardation impulse.

Paravulcoon Parachute

The Raven Industries paravulcoon[122] is a hot-air-inflated balloon. A burner is suspended beneath the open lower skirt of a balloon so that hot air enters and fills the balloon. During deployment of the balloon, it acts much as a parachute in decelerating the payload. This system has been used on the Raven Brighteye night-illuminating flare.

Cross Parachute

The cross parachute design[123] was originated in France and resembles the Red Cross symbol in planform. This design is easy and cheap to construct and is more stable than a solid parachute.

Square Parachute

A square canopy layout, as used by the U.S.S.R., is even simpler and cheaper to build than the cross, but is relatively unstable like a solid parachute and has nonideal stress distribution relative to design for efficient load distribution. The square parachute could be cheap and useful for low-speed aerial supply drop.

Flexirotor Parachute

The Barish flexirotor consists of four flexible fabric blades, much like an aircraft propeller, extending from a vortex-ring hub. Sandia Laboratories successfully deployed a four-bladed, 12-ft-diam flexirotor several years ago, but found that deployment was not too reliable.

6. Trailing Systems

Nylon lines trailing behind various test vehicles have been used by the senior author[124] as antennas and as a means of supporting a trailing camera.[125,126] A double, 4000-lb tensile strength trailing line, up to 150 ft long, has been deployed successfully at velocities up to 1000 fps.[127] A permanently-reefed, $2\text{-}\frac{1}{16}$-ft-diam, ribbon parachute was used to stabilize the trailing line, which would otherwise whip back and forth 45° without the parachute. The trailing line can be used as

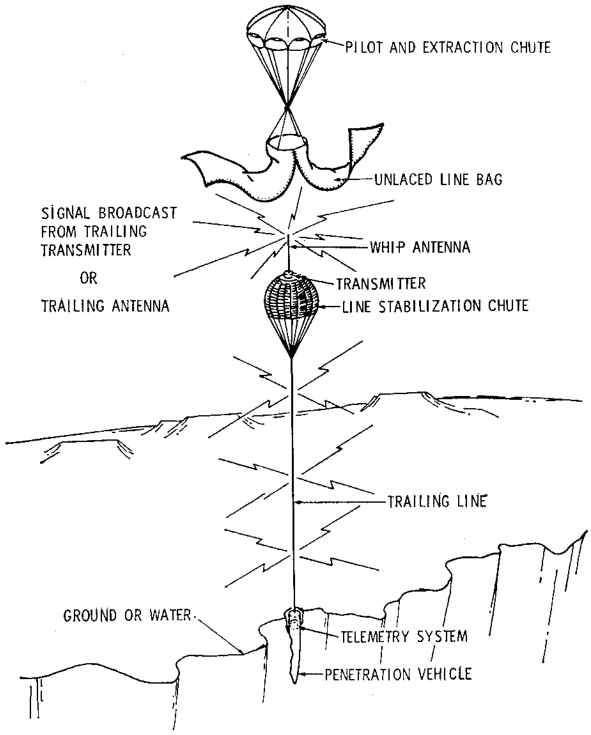

Fig. 24 Nylon trailing antenna line concept.

an antenna to transmit telemetry signals from the vehicle while it penetrates ground or water, thus, relaying deceleration data (Fig. 24).

7. Materials

The most frequently used material for parachutes is nylon because of its high strength-to-weight ratio and elasticity. Nylon is not affected by most chemicals except acids. The one factor which must be considered is loss of strength because of the sunlight, which can be 50% after a month of exposure to the sun. The service life of nylon parachutes is 15 years or more. Parachute materials, such as cloth, webbing, and thread, are ordered and described by Air Force Military Specifications.[13]

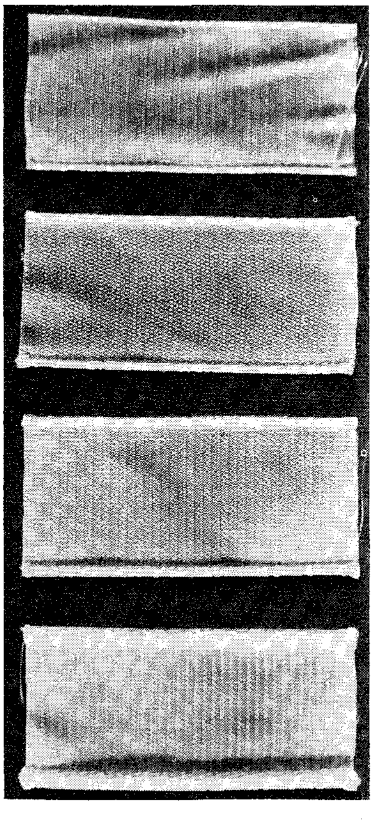

Fig. 25 Reinforced selvage parachute ribbon (top to bottom 1000-, 2000-, 3000- and 4000-lb tensile strength).

Table 4 Sandia Laboratories specifications for reinforced selvage ribbon[a]

Bally Ribbon Mills pattern no.	Minimum breaking strength, lb	Width, in.	Ground Ends	Ground Denier	Ground TPI[b]
8823-2	1000	2±1/16	302/1	210	3
8878	1500	2±1/16	448/1	210	3
8824-2	2000	2±1/16	152/1	840	3
8825-2	3000	2±1/16	208/1	840	3
9139-2	4000	2±1/16	264/1	840	3

Bally Ribbon Mills pattern no.	Preshrink edge yarn Ends	Preshrink edge yarn Denier	Preshrink edge yarn TPI[b]	Filling PPI	Filling Denier	Filling TPI[b]
8823-2	38/2	210	3	38	420	3
8878	56/2	210	3	36	420	3
8824-2	18/2	840	3	38	420	3
8825-2	28/2	840	3	36	420	3
9139-2	38/2	840	3	36	420	3

[a] Note: All samples must be tested for minimum breaking strength prior to production.
[b] TPI = twists/in.

Specifications for parachute fabrics can be found in the Air Force parachute handbook. Nylon can be used at temperatures up to 200°F, and is still usable after short exposures at 300°F. The melting point is approximately 460°F. Where higher temperatures are to be expected, Nomex has been used successfully up to 600°F. Glass fiber cloth is suitable up to 2000°F, but has the undesirable characteristic of low elongation (3%), and sewing with glass thread is difficult because of its brittleness.

A new 2-in. wide reinforced selvage ribbon,[6] shown in Fig. 25, is now used almost exclusively by Sandia Laboratories and the Air Force for construction of heavy-duty ribbon parachutes. The specifications of this ribbon are listed in Table 4.

The characteristics of fibrous materials at elevated temperatures are discussed by Ross,[128] Schulman and Johnstone,[129] Freeston et al.,[130] Opt,[131] and others.[132–139]

8. Deployment Systems

Bag Design and Packing

The bags which are described in a patent by Widdows[140] (a typical one is shown in Fig. 26) are made with two, three, or four leaves, which are first laced by hand through the grommets. Canopy and line ties are made to loops on the bag leaves. These ties, which may be 100–1500 lb tensile strength, depending on the dynamic pressure at deployment, are used to insure orderly deployment. After the ties and the canopy locking flap are installed, the lacing is drawn tight in successive steps by use of a 20-ton press, heavy rubber mallets, and a long lever-arm bar to pull on the lacing. Other relevant reports consider pressure packing,[141,142] rigging,[143] and the use of line ties.[144]

Deployment

The most conventional method for initiating deployment of a parachute is a static line permanently affixed to the carrier aircraft. Static lines and attachment fixtures should be designed with a safety factor of 3–6, since the function is crucial. Laboratory drop tests to verify static line loads

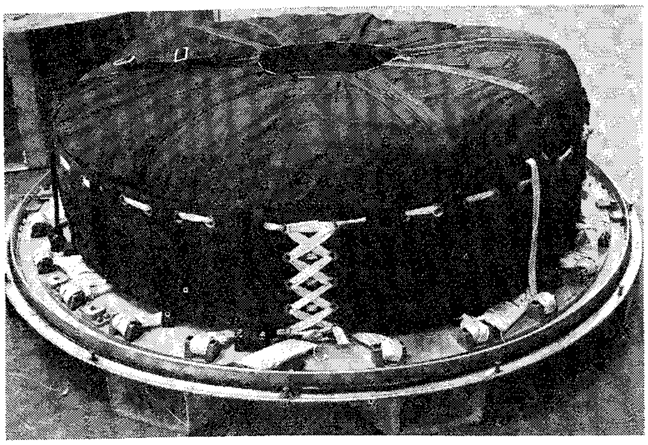

Fig. 26 Packed 76-ft parachute.

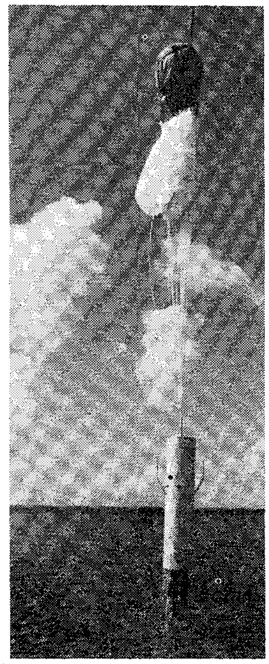

Fig. 28 Recovery of rocket payload in the Pacific Ocean by 8-ft-diam guide surface parachute and dual ram-air/ CO_2 gas flotation bags with radio beacon.

during pilot parachute deployment and overtesting of the system are recommended.

Another deployment method commonly used is a drogue gun. An electrically initiated squib[145] is fired to force the drogue gun projectile aft, pulling out the pilot parachute.

The tail cover or tail can, can be fired aft by the use of a linear shaped-charge; the pilot parachute is then deployed by the tail can. Where deployment conditions are transonic or supersonic, this method may result in collision of the tail can with the inflating main parachute and cause canopy damage. Therefore, the tail can and bag may have to be attached to the vent region of the main canopy.

For low-altitude delivery of ordnance at transonic speeds, where the total down time is 2–5 sec, the entire parachute pack is ejected by a telescoping tube located along the parachute pack centerline as shown in Fig. 8. An electrically initiated gas generator is fired to eject the pack at 100–150 fps.

Still another method is mortar deployment of the entire parachute. This method is sometimes used at high supersonic speeds to overcome the strong dead air wake region behind a bluff body. The canopy must be enclosed in a blast resistant bag to prevent damage from the explosive.

9. Ancillary Apparatus

Reefing Cutters

Two or four reefing cutters are used to sever a reefing line installed through rings in the parachute skirt (see Fig. 2). Reefing is used as a means of controlling load peaks by staging the drag area. Figure 27 shows three types of cutters which are mechanically actuated at deployment by lanyards attached to the canopy. Sandia Laboratories uses the "Half-Moon" cutter housing design[146] exclusively, since it is light (0.67 lb), rugged, and reliable. Actuators and pyrotechnic time-delay elements of 0.5–10-sec delay are procured commercially.

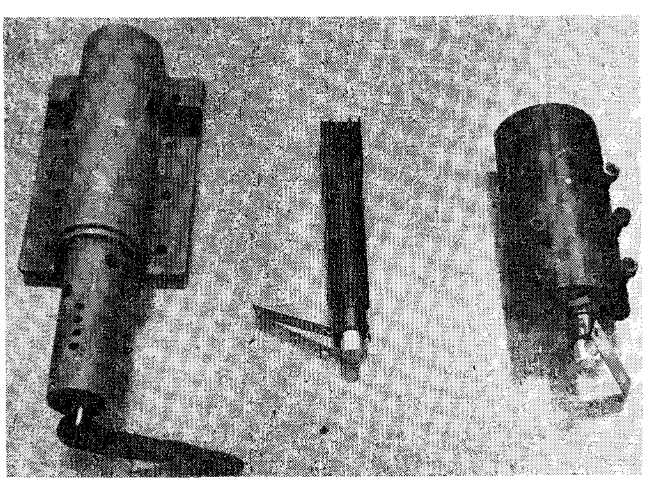

Fig. 27 Reefing-line cutters: MC-1 cutter (left); ordnance Associates cutter (center); Sandia Half-Moon cutter (right).

Flotation Bags

Rocket-launched diagnostic payloads, which achieve apogees of 50–400 miles altitude, are quite often flown over the ocean, necessitating a flotation system as shown in Fig. 28. Johnson,[147,148] has developed a dual redundant flotation bag, consisting of a ram-air filled[149,150] and gas-bottle filled bag, either of which can sustain the payload.

The location system[147,148] used for ocean recovery consists of a flexible steel tape antenna and transmitter on top of the flotation bag and 14-v power supply with two insulated copper bars, which act as a salt-water actuation switch. A progressive reduction in size (Fig. 29) resulted from development and miniaturization over the past seven years.

10. General

Other papers of interest on specialized subjects relating to decelerator technology are wind-tunnel testing,[151–157] drag,[13,158–165] environmental effects on materials,[166–169] scaling laws,[170–172] apparent mass effects,[173–174] parachute flowfield,[58,78,175–178] aerodynamic and fireball heating,[179–183] struc-

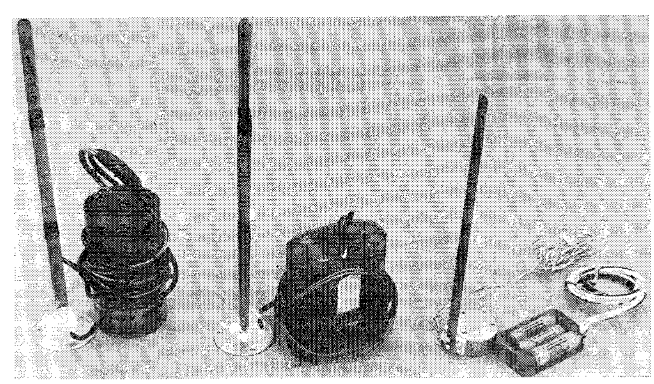

Fig. 29 Size decrease of beacon used in payload recovery.

tural,[13,184–186] parachute hydrodynamics,[187] cloth porosity,[188–190] low-altitude delivery,[191–194] parachute/rocket hybrid systems,[195–196] high-altitude and space vehicle recovery,[197–205] and planetary entry.[206–214] An excellent discussion of the technical voids in aerodynamic deceleration R&D is presented in a recent AIAA position paper.[215]

II. Concluding Remarks

The ribbon parachute is a versatile, reliable, and efficient decelerator; a 20-ft-diam parachute has been deployed at a dynamic pressure of 5700 lb/ft at a Mach number of 2.43. A 76-ft-diam ribbon parachute was used to recover a 45,000-lb test vehicle.

The guide surface parachute is extremely reliable and useful as a pilot or first-stage parachute and is very stable as a drogue device.

Special composite construction methods of a hyperflo parachute are available, permitting the use of this parachute as an economical decelerator at Mach numbers of 4 and greater where aerodynamic heating creates a severe thermal environment.

The ring-sail canopy is light, efficient, and reasonably stable as a large final descent stage, and has been used successfully on all U. S. space missions.

The technology of flexible wings is considered the newest phase in decelerators. Interest in flexible wings will probably increase over the next decade because of the additional maneuverability offered during descent.

Parachute design and development is still largely empirical. Cut-and-try methods of design and field test are still currently used to advance the state-of-the-art. Mathematical models (utilizing recently developed numerical techniques with high-speed computers) need to be developed to predict the unsteady fluid flowfields, the ribbon and shroud line aeroelastic effects, canopy-payload (2-body) stability, and the transient snatch load, opening shock and the bag-chute interaction during deployment at test velocities up through supersonic. More highly trained scientists with practical experience in decelerator technology are and will be needed in the future to design systems required to function reliably in more severe environments such as hypersonic speeds and planetary atmospheres.

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Perspective of SST Aircraft Noise Problem. I: Acoustic Design Considerations

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The current state of research concerning noise suppression for SST jet engines is presented. The noise of unsuppressed, augmented power engines is defined and compared with several engine types that have been used on subsonic aircraft. Results of an extensive research program of both model and large scale levels which has investigated many different noise suppressor concepts are described. Test results show several fundamental means to reduce jet noise at different frequency regions. Acoustic design charts have been developed for several suppressor types. Part II of this paper (to be published in the *Journal of Aircraft*) will cover thrust losses and some installation factors.

Introduction

During takeoffs and landings, the engines of the supersonic transport will produce community and airport noise. The control of this noise is of very great interest to all people involved in the design of the SST, and those involved in the problems of noise around airports. Most supersonic aircraft designs make use of jet engines, usually with afterburning, as contrasted to the turbofan engines now used in all recently produced subsonic jet aircraft. Low airport and community noise from the SST may require the application of complex jet exhaust and inlet noise suppression devices as well as the use of noise abatement operating procedures. The successful development of a very effective jet exhaust noise suppressor integrated into the propulsion system would be of great value in achieving low noise during SST takeoff, climbout, and landing.

In the absence of a jet noise suppression theory, The Boeing Company is conducting a suppressor research test program. This program is based on pioneering work in the 1950's. Recent investigations are identifying key variables, and the

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