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DESIGN AND PERFORMANCE OF A PARACHUTE FOR THE RECOVERY OF A 760-LB PAYLOAD +

Donald E. Waye *
Sandia National Laboratories
Albuquerque, New Mexico

ABSTRACT

A 26-ft-diameter ribbon parachute deployed using a pilot parachute system has been developed at Sandia National Laboratories for the recovery of a 760-lb payload released at subsonic and transonic speeds. The wide range of deployment dynamic pressures led to the design, utilizing wind tunnel testing and computer simulation, of a unique pilot parachute system verified in full-scale flight tests. Performance data from 20 full-scale flight tests were used to evaluate system performance and structural validity.

INTRODUCTION

A parachute system is being developed at Sandia National Laboratories for the recovery of a 760-lb airdropped payload. The requirements for this high performance parachute system include low altitude releases over a wide range of velocities which require the best inflation and initial deceleration characteristics to achieve the most favorable conditions of impact angle and velocity at ground impact.

The conical ribbon parachute design chosen for this development effort follows the practice of previous Sandia National Laboratory parachute development programs for high performance airdropped payloads.[1,2] The design process for this parachute system included a tradeoff study to evaluate and compare the performance between an equivalent drag area 26-foot-diameter single parachute system and a cluster system of three 14-ft-diameter parachutes[3]. The results showed a small advantage for the cluster system in inflation and initial deceleration characteristics. However, the higher cost, higher weight, greater packing complexity and greater risk involved in the development of the cluster system outweighed the performance advantages and led to the choice of the 26-ft-diameter parachute as the baseline design for development. This paper describes the design and performance of the 26-foot-diameter parachute which was chosen for the recovery of a 760-lb payload. The results of 20 full-scale flight tests of this parachute system are summarized.

PARACHUTE SYSTEM REQUIREMENTS

Deployment Conditions

The minimum and maximum dynamic pressure at parachute deployment are determined by the two modes of payload delivery. In the laydown mode the parachute deployment is initiated shortly after release from the aircraft. In this mode the parachute will be deployed at a minimum velocity of 170 KCAS from altitudes between 200 and 3200 ft MSL, which results in a minimum dynamic pressure (q) of 97.6 lbs/ft^2. Also in this mode the payload will be released at velocities between 200 KCAS and the lessor of 635 KCAS or M1.04 from altitudes between 100 ft and 1000 ft AGL up to 11,000 ft MSL, which results in a laydown maximum dynamic pressure of 1365 lbs/ft^2. In the retarded ground mode the parachute deployment is initiated after the payload is allowed to freefall from a high altitude to a low altitude. During the freefall portion of the trajectory the payload is spun up using a spin rocket and canted fins in order to maintain aerodynamic stability. This results in the parachute deployment occurring with payload spin rates between 3 and 5 rev/sec.

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* Senior Member Technical Staff, Parachute Systems Division, Member AIAA.

The maximum dynamic pressure at deployment in the retarded ground mode is 1600 lbs/ft^2 at a Mach number of 1.06.

Functional Requirements

The payload to be recovered by the parachute is an ogive cylinder weighing 760 lbs and having a length of 9.67 ft and a diameter of 13.3 inches. The payload is required to attain a vertical velocity of less than 55 ft/sec and a trajectory angle greater than 30° at impact for pressure altitudes up to 10,000 ft MSL. A minimum of 10 g's deceleration is required for the operation of payload system components. The maximum parachute deceleration loads were originally limited to 80 g's, but due to the need for improved impact conditions this value was increased to 95 g's late in the development program.

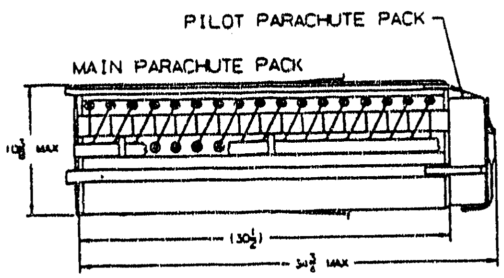

Fig. 1 Packed Parachute System

The maximum dimensions of the packed parachute system are 10.415 inches in diameter and 34.75 inches in length (see figure 1). The maximum weight of the parachute system is 61 lbs.

PARACHUTE DEPLOYMENT METHODS

Due to the large range of deployment dynamic pressures (a factor of over 16) the selection of a parachute deployment system was critical for the optimization of parachute performance. Several deployment methods were examined including tractor rockets, telescoping tubes, a pilot parachute system, and a high drag component. The tractor rocket was chosen because it could provide a uniform deployment velocity for the parachute over the large range of dynamic pressures.

On the first parachute development flight test the tractor rocket was used to deploy the parachute but it began to rotate during extraction of the canopy from the bag. After release from the parachute the tractor rocket continued to demonstrate signs of instability. Due to aircraft safety concerns, concerns about possible canopy damage during deployment at higher velocities, and the high cost of modifications to the tractor rocket to increase its stability, the tractor rocket was discarded as the baseline design for the deployment system.

A pilot parachute system for deployment of the main parachute had been designed on paper in parallel with the development of the tractor rocket. The major design concerns included the two conflicting requirements of having adequate drag to extract the main parachute at minimum dynamic pressure but not having excessive drag, which would damage the canopy during deployment from the deployment bag, at maximum dynamic pressure. Wind tunnel extraction tests of a full scale parachute system, with the main parachute tied shut, were performed in the Lockheed wind tunnel in Marietta, Georgia[4]. The purpose of the tests was to determine the drag area necessary to extract the main parachute at the minimum dynamic pressure (100 psf). It was determined that a 3-ft-diameter guide surface parachute, which has a drag area of approximately 5.5 ft^2, provided the minimum drag necessary to ensure a successful deployment.

A pilot parachute deployment simulation computer code was then used to determine the bag strip velocity at high dynamic pressure[5]. It was desired that bag strip velocities not exceed about 400 ft/sec to reduce the risk of friction burns on the canopy ribbons during deployment. The computer code predicted that the 5.5 ft^2 drag area necessary to ensure successful deployment at minimum dynamic pressure resulted in excessive bag strip velocities at the maximum dynamic pressure. To ensure bag strip velocities below 400 ft/sec at the maximum dynamic pressure the maximum pilot parachute drag area was calculated to be about 4 ft^2.

PARACHUTE SYSTEM DESIGN

Pilot Parachute System

The final pilot parachute design consists of a cluster of two 2.5-ft-diameter guide surface parachutes constructed of 7 oz/yd^2 nylon cloth with six 1-inch x 4000 lb Kevlar suspension lines. Each pilot parachute has a drag area of approximately 3.9 ft^2 and is attached to the main parachute bag by a two legged common bridle. One of the parachutes is attached permanently to the bridle and the other is attached using a unique breakaway linkage, shown in figure 2, with a shear pin designed to break at the load (approximately 2000 lbs) seen at 450 KCAS (dynamic pressure = 500 lb/ft^2). At low velocities the main parachute is deployed using both pilot parachutes, with a combined drag area of approximately 7.8 ft^2, but at higher velocities the main parachute is extracted using only one pilot parachute[7]. The pilot parachutes are packed into an "envelope" deployment bag which is attached via bridles to the payload tail plate. The tail plate is explosively ejected to initiate the deployment process.

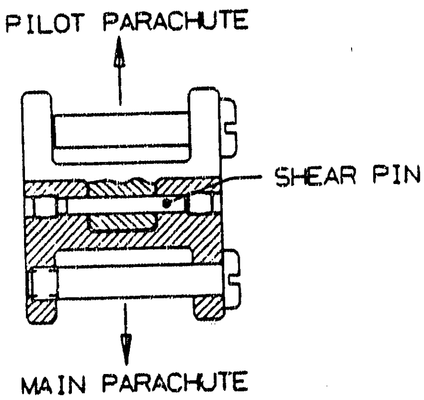

Fig. 2 Breakaway Linkage

Main Parachute

The canopy ribbon design and porosity was determined through use of a canopy design code for conical ribbon parachutes[6]. The main parachute, shown in figure 3, is a 20-degree conical ribbon parachute with 32 gores and 57 ribbons in the canopy. The parachute has a constructed diameter of 26 feet and a geometric porosity of 20.9%. Ribbons 1 through 21 are 1500-lb 2-inch-wide nylon, ribbons 22 through 35 are 1000-lb 2-inch-wide nylon and ribbons 36 through 57 are 550-lb 2-inch-wide nylon. Suspension lines are 28 ft long and are made of 5000-lb 1-inch-wide Kevlar webbing developed specifically for this parachute system. Radials are continuations of the suspension lines with 2400-lb Kevlar tape backing up the ribbons along the radial. The suspension lines and radials are constructed using "figure eight" loops to minimize sewing and loss of material strength. Three mini-radials, made from doubled 550-lb $^{1}/_{2}$-inch-wide Kevlar tape, are used to stabilize the position of the ribbons on this parachute. The center mini-radial extends from the vent reinforcement (6500-lb $1^{23}/_{32}$-inch-wide nylon) to the skirt reinforcement (6500-lb $1^{3}/_{4}$-inch-wide Kevlar). The outboard mini-radials extend from the skirt to ribbon 25 on the parachute.

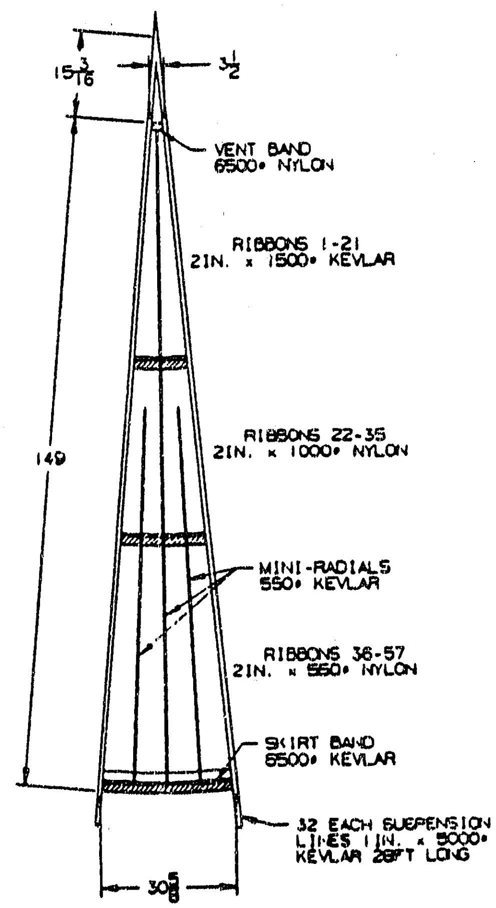

Fig. 3 Schematic of 26-ft-Diameter Parachute

Flight test parachutes were packed in a two-leaf Kevlar deployment bag. The finished main parachute pack diameter was 10.375 inches and the bag length was 30.5 inches (volume = 1.492 ft^3). The average weight of the packed main parachute was 54.8 lbs and the resulting average pack density was 36.72 lbs/ft^3.

Calculations of structural margins for the parachute were made using the CALA finite element structural parachute design code[7]. The maximum parachute inflation load used for the calculations was 72,200 lbs (95 g's). A minimum safety factor (material rated strength divided by predicted stress) of 2.2 was used in the design of all structural elements of the parachute.

Reefing System

A 6500-lb braided Kevlar reefing line and two reefing line cutters, shown in figure 4, were incorporated into the main parachute design to control the inflation loads. The two redundant reefing line cutters are positioned 180° apart at the skirt of the main parachute. The cutters are mechanically actuated at line stretch and provide a 0.4 second delay.

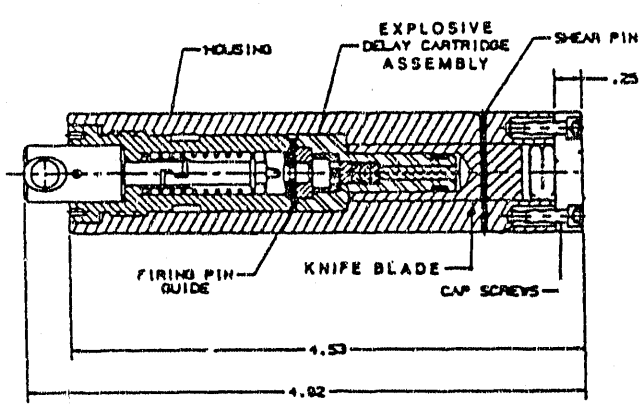

Fig. 4 Reefing Line Cutter

FLIGHT TEST PROGRAM DESCRIPTION

Test Description

A parachute test unit (PTU) was designed and fabricated for the parachute development test program. This vehicle was designed to duplicate the external shape, weight, center of gravity, and pitch and yaw moments of inertia of the system payload. An exception was made to include two external camera pods to house onboard cameras for parachute analysis. The PTU included a telemetry package with onboard accelerometers to aid in the analysis of parachute performance.

Parachute performance was measured by the onboard accelerometers, ground tracking cinetheodolite cameras, and radars. Ground tracking documentary cameras and the onboard cameras aided in the analysis of parachute events.

Prototype Test Program

In order to best meet the functional requirements for this parachute system, a cluster of three 14-ft-diameter parachutes and a single 26-ft-diameter parachute, were proposed for early prototype tests. These two systems were evaluated on the basis of performance (i.e drag coefficient, turnover efficiency, opening characteristics) and physical parameters (i.e. size and weight to drag ratio, packing complexity, cost, risk).

An analysis of the performance of these two systems is contained in ref. 1. The comparison of the two systems showed strong evidence that the performance of the cluster system was superior during the initial 100 to 150 feet after release from the aircraft. In addition there was evidence that the repeatability of the performance was better with the cluster system due to the absence of wake recontact which affected the trajectory of the payload on single parachute system tests.

An analysis of the weight versus drag of the two systems indicated that, for an equivalent drag area, the single parachute system weighed less. The packing complexity of the cluster system was greater than that for a single parachute system with a resulting increase in the system cost. However, the final determining factor in choosing the single 26-ft-diameter parachute over the cluster parachute system revolved around the increased risk, based on the limited experience of Sandia National Laboratories with high performance cluster systems, involved in developing the cluster system in the short development time available.

Development Tests

The purpose of the development test program was to demonstrate the performance of the deployment system over the dynamic pressure envelope, demonstrate adequate structural strength of all parachute system elements, and define payload impact conditions and parachute performance curves for system component design. The development test program consisted of an airdrop test series, a rocket launched test series and a sled test series. The purpose of the airdrop series was to subject the parachute system to aircraft releases between the minimum speed (170 KCAS) and the maximum attainable aircraft speed (approximately 627 KCAS). The purpose of the rocket launched series was to test the parachute system at the maximum dynamic pressure and at 120% maximum dynamic pressure. The sled test series is intended to test the parachute system at the required environmental extremes of temperature and humidity at minimum and maximum dynamic pressure.

Seventeen airdrop tests (Table 1) and three rocket launched tests (Table 2) have been performed to study the performance of the parachute. The parachute has been tested from a minimum dynamic pressure of 98 lb/ft^2 to a maximum dynamic pressure of 1713 lb/ft^2.

FLIGHT TEST RESULTS

Pilot Parachute Performance

The pilot parachute system has been demonstrated over the entire dynamic pressure envelope during the flight test program. This included proof of sufficient drag to deploy the main parachute at low dynamic pressure, demonstration of the breakaway linkage, demonstration of proper performance at high dynamic pressure and demonstration of structural integrity of system elements at maximum dynamic pressure. The graph in figure 5 shows that the time to line stretch is a function of deployment dynamic pressure. This time varies between 0.25 seconds and 0.38 seconds for dynamic pressures between 487 and 1713 lbs/ft^2 but increased to 0.70 seconds at lower dynamic pressures. Bag strip velocities varied from 150 ft/sec at low speeds to just over 400 ft/sec at high speeds. In contrast, the tractor rocket extraction time to line stretch was 0.25 seconds even at the low dynamic pressure of 300 lbs/ft^2.

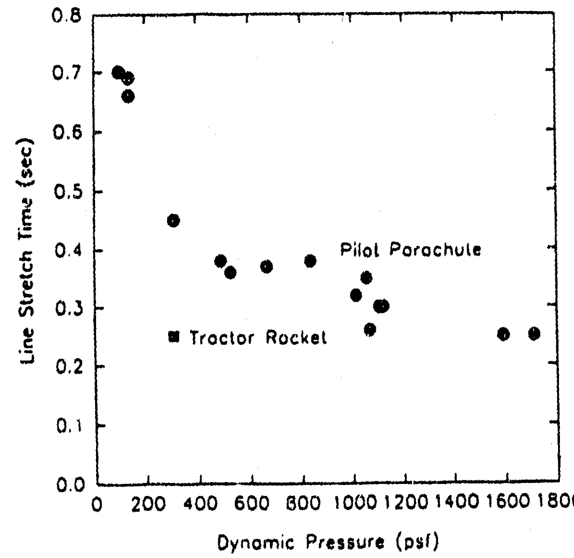

Fig. 5 Time to Line Stretch versus Dynamic Pressure

With the exception of one test (TV224) the breakaway linkage performed as expected. On TV224 the pilot parachute attached to the breakaway linkage opened very late and the resultant dynamic pressure did not provide sufficient load to break the shear pin.

Two changes to the pilot parachute system were made following the first rocket launched test (RTU1). On this test the pilot parachute deployment bag, which was originally a 3.5 inch high right cylinder, was stripped from the pilot parachutes without extracting them from the rear of the vehicle. As indicated in the test results in Table 2 the time to line stretch was very long due to the delay in getting the pilot parachutes into the airstream. After this test the "envelope" deployment bag was designed, lab tested, and used on all subsequent tests. In addition, this test revealed a weakness in the design of the pilot parachute attachment to the load links. This attachment was modified on future tests.

Reefing Line Length

The reefing line length necessary to limit the maximum deceleration loads to 80 g's was determined from graphs in the Recovery System Design Guide[8] and from the results of Sandia wind tunnel tests. Throughout the flight test program maximum deceleration versus dynamic pressure as a function of reefing line length was monitored as shown on the graph in figure 6. The original reefing line length of 21 feet was gradually decreased as the flight test velocities increased until a reefing line length of 15 feet was experimentally determined for the 80 g maximum deceleration requirement. Based on this data a reefing line length of 18 feet was calculated for the 95 g requirement. On RTU3, at a deployment dynamic pressure of 1590 lbs/ft², the maximum deceleration was 102 g's. Based on this data point the final reefing line length for the 95 g requirement should be approximately 17.3 ft.

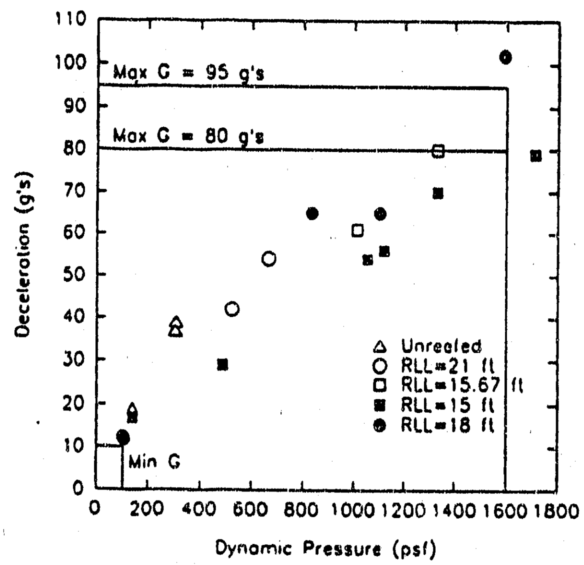

Fig. 6 Maximum Deceleration versus Dynamic Pressure

Parachute Performance Data

The performance of the 26-ft-diameter parachute was measured both optically and by onboard accelerometers. Tables 1 and 2 list the flight tests, the test parameters, and some of the measured test results.

The parachute has been shown to be structurally adequate, following minor modifications, at dynamic pressures up to 1713 lbs/ft² and velocities up to M1.28. The maximum deceleration measured during the flight test program was 102 g's, which corresponds to a load of about 77,500 lbs. Figures 7 and 8 show typical deceleration versus time curves measured by onboard accelerometers for high and low speed flight tests, respectively. Note that the maximum deceleration occurs in the reefed stage on high speed tests and in the full-open stage on low speed tests.

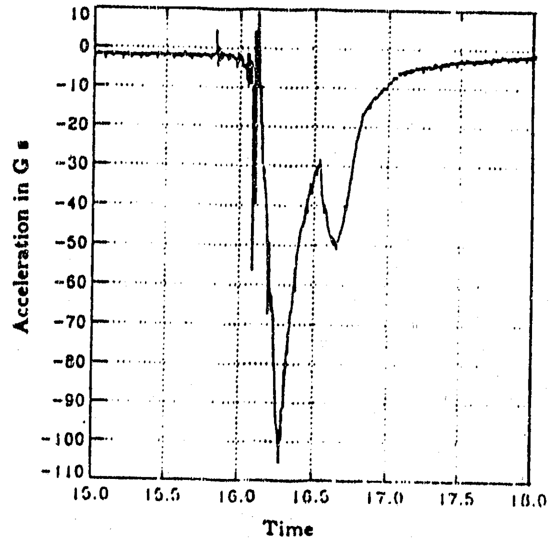

Fig. 7 Deceleration versus Time: Dyn. Pres. = 1713 lbs/ft²

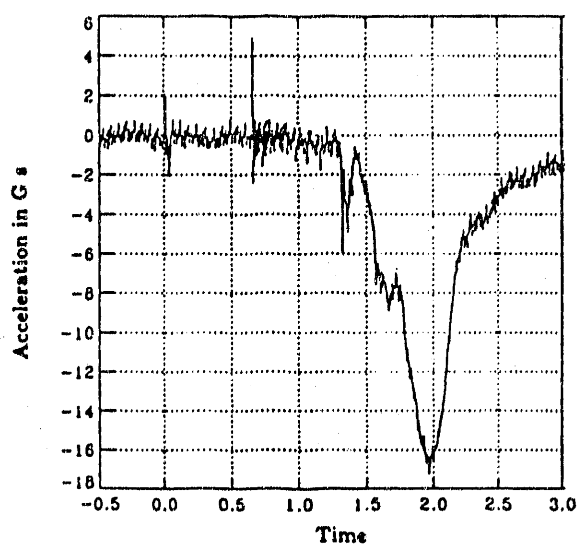

Fig. 8 Deceleration versus Time: Dyn. Pres. = 142 lbs/ft²

As shown in tables 1 and 2 the terminal velocity of the parachute (all measured at the 5334 ft MSL altitude of the test range) averaged about 51 ft/sec. This terminal velocity corresponds to a terminal drag area of about 295 ft² and to a drag coefficient (C_D), based on constructed diameter, for the 26-ft-diameter ribbon parachute of 0.55. Figure 9 shows a plot of effective drag area for one of the flight tests. Effective drag area was calculated by dividing the deceleration forces measured by the onboard accelerometers by the dynamic pressure derived from optical cinetheodolite data.

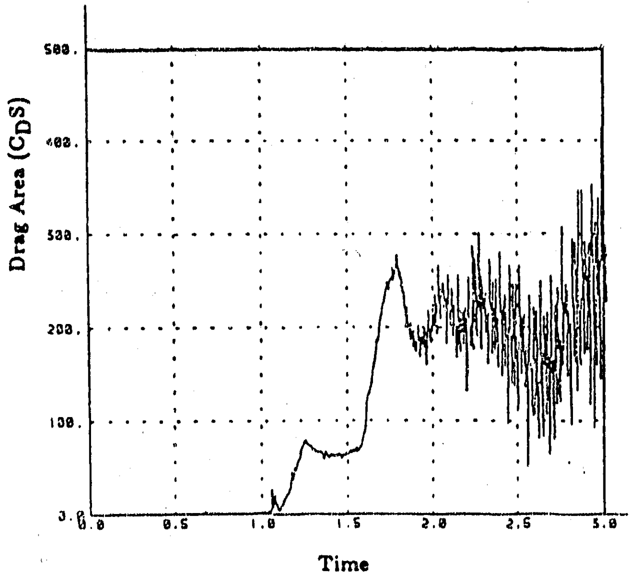

Fig. 9 Effective Drag Area versus Time

The inflation time versus dynamic pressure plot shown in figure 10 shows that the inflation time for reefed parachutes was between .19 and .32 seconds over the entire dynamic pressure range and was not a function of reefing line length. The two exceptions to this range of inflation times occurred on TV235 and ATU1 (data not plotted in figure 10). On these two tests the parachute was deployed with the payload spinning and the parachute suspension lines wrapped up several revolutions. Data indicates that 1)the parachute did not fully open to the reefed stage thereby decreasing the peak deceleration and 2)the parachute could not fully open after disreefing until the suspensions lines unwound. Further study of these results are in progress.

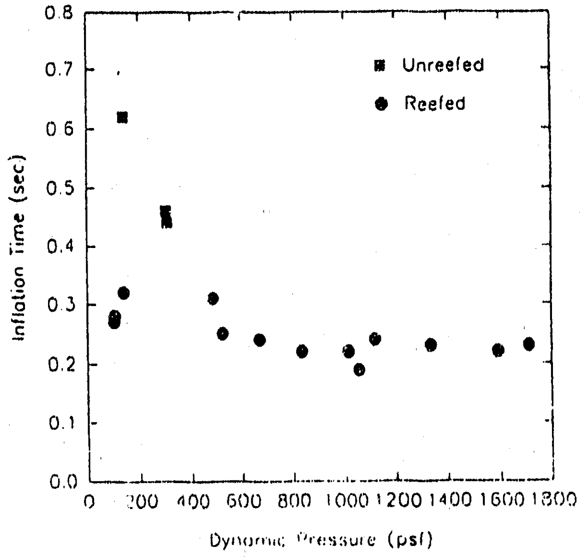

Fig. 10 Inflation Times versus Dynamic Pressure

Typical optical data plots are shown in figures 11 through 13 showing total velocity versus fall distance, vertical velocity versus fall distance, and trajectory angle and attitude versus fall distance. These plots illustrate that the parachute performance meets the requirements for less than 55 ft/sec vertical velocity and greater than 30° trajectory angle at a distance of 100 ft below release from the aircraft.

Optimization of the system lanyards, bridles and pilot parachute/main parachute interface was accomplished during the flight test program. The dynamic pressure buildup of the airdrop and rocket test series revealed that the skirt/radial joints on the main parachute were not structural adequate. These joints were strengthened and, along with all of the system component, were demonstrated to be structurally adequate in subsequent tests.

CONTINUING DEVELOPMENT

At the time of this report the majority of the development test program is complete. The sled test program has not been started and is presently scheduled for the fall of 1991. In addition, the final 120% maximum dynamic pressure overtest of the parachute is not complete and is scheduled for the spring of 1991. As indicated above, further study of the parachute deployed behind a spinning payload is in progress.

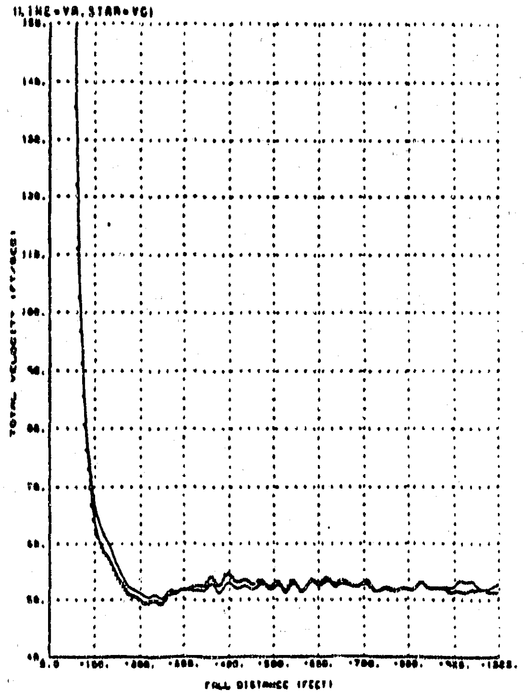

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Fig. 11 Total Velocity versus Fall Distance

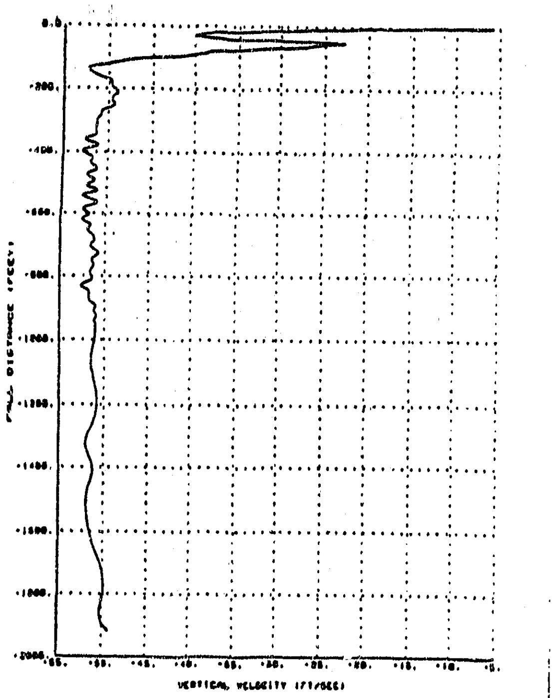

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Fig.12 Vertical Velocity versus Fall Distance

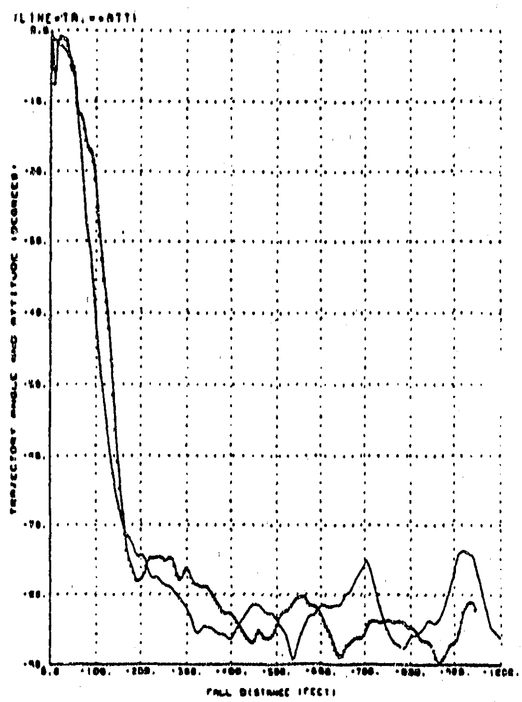

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Fig. 13 Trajectory Angle and Attitude versus Fall Distance

Examination of parachutes similar in design to this parachute that have been stored for many years has shown significant shrinkage of the nylon ribbons in the parachute canopy. This shrinkage changes the porosity of the parachute and may affect the inflation time and deceleration performance of the parachute. Because the low altitude requirements of this system require optimum early time parachute performance a parachute with improved dimensional stability over time is desirable. Present studies indicate that preconditioning of the 2-inch-wide nylon ribbon materials can remove 75-80% of the shrinkage. Efforts are continuing to fabricate, evaluate and test "pre-shrunk" materials for future use on this parachute system.

SUMMARY AND CONCLUSIONS

A 26-ft-diameter parachute deployed by a pilot parachute system has been developed to provide an impact vertical velocity of less than 55 ft/sec and a trajectory angle greater than 30° for a 760 lb payload released 100 ft above the ground at velocities between 200 and 635 KCAS. Computer codes were used to design the parachute canopy geometry, analyze structural stresses in parachute elements, and simulate the pilot parachute deployment process. A unique pilot parachute system, consisting of a cluster of two 2.5-ft-diameter guide surface parachutes, one of which is attached to a breakaway linkage, was developed to tailor the main parachute deployment velocities over the large dynamic pressure range of 97.6 lbs/ft^2 to 1600 lbs/ft^2. Twenty development tests have been performed to demonstrate and validate the parachute system design.

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TABLE 1

AIRCRAFT DROP DEVELOPMENT TESTS

Test	Mach No.	Altitude ft, MSL	Dynamic Pressure psf	Velocity KCAS	Velocity fps	t_{ls} sec	t_{fo} sec	V_{imp} fps	Max G's	R_{LL} ft	t_{rd} sec
	Release or Deployment Condition										
PTU1	.524	8332	304	302	582	.25	.46	52	37	NA	NA
PTU2	.528	8425	308	304	577	.45	.44	51	39	NA	NA
PTU3	.351	8315	137	202	390	.69	.62	50	19	NA	NA
PTU4	.688	8341	524	398	751	.36	.25	53	42	21	.5
PTU5	.307	8402	103	175	335	.70	.28	50	12	21	.5
PTU6	.305	8333	100	172	328	.70	.27	47	12	21	.5
PTU7	.779	8387	665	451	847	.37	.24	47	54	21	.5
PTU8	.870	8325	835	506	970	.38	.22	51	65	18	.5
PTU9	.955	8277	1013	559	1057	.32	.22	53	61	15.7	.5
PTU10	.975	8324	1055	571	1091	.35	.19	51	54	15	.4
TV273	.630	5584	487	382	707	.38	.31	51	29	15	.5
TV224	.987	7254	1120	587	1105	.30	.24	49	56	15	.5
PTU11	.342	6370	138	202	385	.66	.32	52	17	15	.4
TV236	.950	250	1330	627	1061	ND	ND	ND	70	15	.4
PTU12	.288	6360	98	170	313	ND	ND	ND	12.5	18	.4
TV235	.884	1290	1104	627	1074	.30	1.67*	ND	65*	18	.4
ATU1	1.053	11729	1067	583	1127	.26	3.11*	51	ND	15	.5

* Time to full open and deceleration affected by suspension line wrapup resulting from payload spin at deployment.

Table Symbols

t_{ls} = Time from tail plate release to line stretch
t_{fo} = Time from disreef to full open
V_{imp} = Velocity at ground impact
R_{LL} = Reefing line length
t_{rd} = Time of reefing line cutter delay

TABLE 2

ROCKET LAUNCHED DEVELOPMENT TESTS

Test	Release or Deployment Condition: Mach No.	Altitude ft. MSL	Dynamic Pressure psf	Velocity KCAS	Velocity fps	t_{ls} sec	t_f sec	V_{imp} fps	Max G's	R_{LL} ft	t_{rd} sec
RTU1	1.15	10234	1330	652	1260	2.69*	.23	51	80*	15.7	.5
PTU2	1.28	9670	1713	734	1435	.25	.22	53	79	15	.4
PTU3	1.25	10342	1590	710	1366	.25	.22	51	102	18	.4

* Time to line stretch and deceleration affected by pilot parachute system failure to extract the pilot parachutes.

END

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