Source of Acquisition
NASA Johnson Space Center

AIAA 2001-2051

SPACE SHUTTLE ORBITER DRAG PARACHUTE DESIGN

Robert E. Meyerson*
Kent, WA

ABSTRACT

The drag parachute system was added to the Space Shuttle Orbiter's landing deceleration subsystem beginning with flight STS-49 in May 1992. The addition of this subsystem to an existing space vehicle required a detailed set of ground tests and analyses. The aerodynamic design and performance testing of the system consisted of wind tunnel tests, numerical simulations, pilot-in-the-loop simulations, and full-scale testing. This analysis and design resulted in a fully qualified system that is deployed on every flight of the Space Shuttle.

INTRODUCTION

The Space Shuttle Orbiter design effort was undertaken during the 1970's with first flight of the vehicle occurring in 1981. The original design parameters for the Orbiter included a landed weight of 188,000 lbs at a speed of 171 knots equivalent airspeed (KEAS). A drag parachute was included in the original Orbiter design but was removed in 1974 in an effort to reduce vehicle weight. Currently, nominal landings are planned at weights up to 210,000 lbs and speeds up to 205 KEAS. An abort landing may be designed to 248,000 lbs at 230 KEAS. The Roger's Commission investigation of the Challenger disaster in 1986 led to the recommendation for the addition of a drag parachute to add margin to all landing and rollout subsystems.

The benefits of a drag parachute on an un-powered vehicle like the Orbiter include reductions in brake energy, landing rollout, tire wear, landing gear strut loads, and sensitivity to wet runways. The drag parachute may also increase the Orbiter's tolerance to brake failures and increase directional control.

The Orbiter drag parachute program was approved in January 1988 and detailed design was conducted at Rockwell International and its subcontractor, Irvin Industries. This paper is a summary of the overall systems design work performed at NASA JSC and Rockwell International between 1988 and 1994. The objective of this paper is to provide an overview of the design of the Orbiter Drag parachute system from a vehicle performance standpoint, not to review the detailed design of the parachute itself.

Orbiter Configuration

The Space Shuttle Orbiter, when first flown in 1981, was the first reusable spacecraft ever flown. The vehicle's unique shape was designed to re-enter the earth's atmosphere, transitioning from hypersonic (primarily decelerating) flight to supersonic/subsonic (primarily maneuvering) flight. Configuration features such as the double delta wing, combination rudder/speedbrake, flared base, and Orbital Maneuvering System (OMS) pods, while required to meet the numerous flight requirements of the Orbiter, add a significant amount of low speed drag to the landing configuration. The flared base and OMS pods combine to give the Orbiter an effective base diameter of 25 feet. These features, as shown in Figure 1, also provide a turbulent wake environment, which poses a challenge for drag parachute deployment.

The typical landing condition for the Space Shuttle Orbiter is 195 KEAS at an angle-of-attack of eight degrees. At main gear touchdown, the speed brake (located on the vertical tail) is commanded to the fully deflected position. The flight crew commands a de-rotation rate of approximately two degrees per second, utilizing the elevator for pitch rate control. Nose gear touchdown typically occurs at 150 KEAS, followed by full application of the brakes.

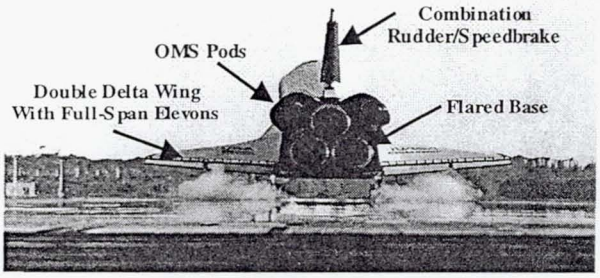

Figure 1. Configuration details which contribute to the Orbiter's wake flowfield

* Formerly Orbiter Aerodynamics Subsystem Manager at NASA JSC. Currently Landing and TPS Manager at Kistler Aerospace, Associate Fellow, AIAA.

Drag Parachute Design Requirements

The drag parachute system was designed to meet the following requirements:

- The stopping distance requirement for drag parachute design shall be 8,000 feet for a 248,000 pound Orbiter landing in a Transatlantic (TAL) abort condition in the following environment: hot day (103° F), 10 knot tailwind, parachute deployed at main gear touchdown, maximum braking applied at 140 knots ground speed or mid-field.
- Total system weight added to the Orbiter shall be less than 422 lb.
- No contact is allowed between the parachute system and the main engine nozzles.
- The Orbiter handling qualities shall not be degraded with the addition of the drag parachute, as verified by simulation.
- The system will be deployed during all landings between 140 and 230 KEAS, and jettisoned between 50 and 80 KEAS.
- The system will operate over the full range of center-of-gravity locations (from 1076.7 to 1109 inches).
- Loading to the vertical tail shall be limited to 125,000 lbs in any condition.

Drag Parachute Description

The drag parachute system was designed and built by a team consisting of NASA JSC, Rockwell International, and Irvin Industries.[1,2,3] The main parachute is a 20° conical continuous ribbon canopy with variable porosity and 40 ft nominal diameter. The suspension lines and radial members are Kevlar while the ribbons are nylon of varying strengths. A mortar deployed ribbon parachute, 9 ft in diameter, is used to extract the main canopy. Addition of the system to the Orbiter also included the modification of the vertical tail to accommodate the drag parachute compartment, design and construction of the attach/jettison mechanism, and the avionics. The drag parachute deployment profile and approximate timeline is shown in Figure 2.

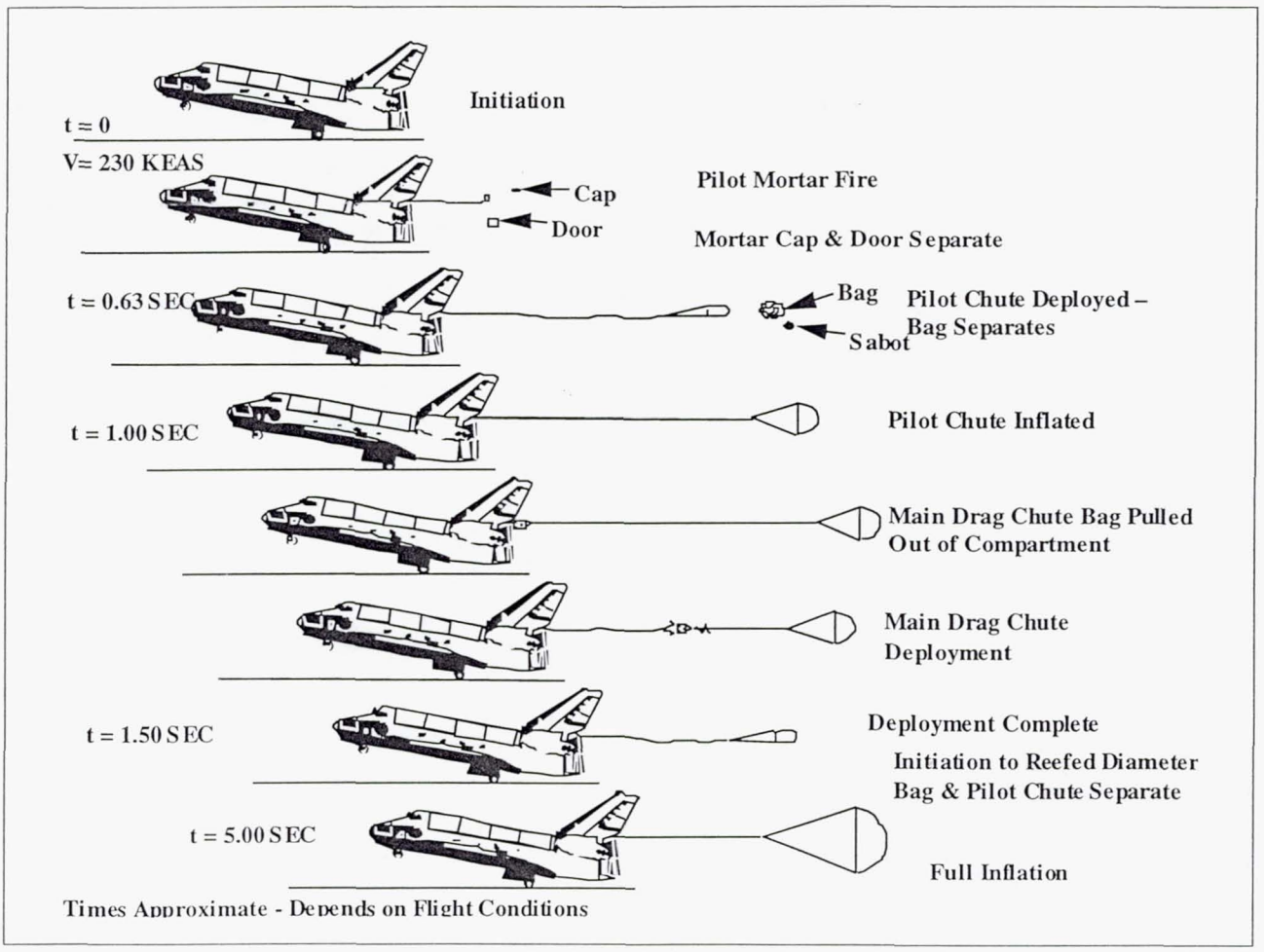

Figure 2. Drag Parachute Deployment Profile

PRE-FLIGHT PERFORMANCE PREDICTION

Wind tunnel testing and empirical data were used to develop a mathematical model of the parachute loads and dynamics. This model was then implemented in both fixed-base and motion-base simulators and tested with the pilot-in-the-loop. Handling qualities ratings generated during these simulator tests were then used as a measure to verify that the system met the defined performance requirements.

Wind Tunnel Testing

A series of wake survey and subscale model tests were conducted to characterize the behavior of the drag parachute in the wake of the Orbiter. The tests utilized a 4.05% scale model of the Space Shuttle Orbiter and were conducted in the Texas A&M University 7 x 10 foot Low Speed Wind Tunnel.[4] Tufts and a smoke wand were used first to obtain a general understanding of the wake flow structure.

These wake survey tests were conducted to characterize the wake flow velocities and directions as a function of vehicle angle of attack, trailing distance, and control surface settings. The wake was measured using both hot wire anemometers and 7-hole pressure probes. The first test series defined the basic drag loss in the wake of the Orbiter and identified a region of reverse flow in the wake from the base to approximately 1.5 body diameters (38 feet) aft. The data also identified large increases in axial turbulence below the parachute attach point and a strong decrease in lateral turbulence component at one-half body diameter to the right or left of the vehicle centerline.

The second test series was used to completely map the wake at the drag parachute design location. Time averaged velocity measurements were taken at approximately 75 y-z locations spaced two inches apart (model scale). The measured velocities were ratioed to free stream velocity and then averaged over the parachute canopy area to provide wake factors. The wake factor is multiplied by the freestream parachute drag coefficient to provide an effective drag coefficient in the wake of the Orbiter. Wake factors were calculated in this manner for each combination of vehicle attitude and control surface deflection. This method ignores the effect of the parachute itself on the wake but has been experimentally verified by Peterson and Johnson.[5]

A series of scale model parachute tests were conducted to provide a visual reference of the parachute in the wake of the Orbiter. These tests were also used to study relative parachute inflation characteristics and stability in an effort to determine the proper canopy trailing distance. While sub-scale testing of parachutes always raises questions because of the difficulty in matching fabric stiffness, the Orbiter tests only attempted to match the parachute forces. Therefore, these results were believed to be adequate for use only in comparing between various vehicle attitudes and control settings. The parachute model itself was scaled geometrically and the geometric porosity of the parachute was scaled by cutting circular holes in the canopy. The model parachute mass, tunnel dynamic pressure, and deployment forces required a scaling parameter known as Froude's number, the ratio of inertial to gravitational forces. The effect of trailing distance on parachute dynamics in the Orbiter wake was evaluated using data from this test. Figure 3 shows the model parachute deployed behind in the wind tunnel.

The wind tunnel program raised concerns regarding canopy inflation and determination of the proper parachute trailing distance. The parameters affected by the choice of canopy trailing distance include parachute weight, packing volume, mortar velocity, system stability, and parachute drag. The data gathered in the wind tunnel program was used along with historical data from the parachute handbook to recommend 3.5 body diameters (87.5 feet aft of the Orbiter base) as the canopy trailing distance.

Orbiter Drag Parachute Force Model

A mathematical model defining forces and dynamics for the Orbiter drag parachute was developed using data from the wind tunnel test program and parachute handbooks.[6,7] This model was used in Orbiter landing

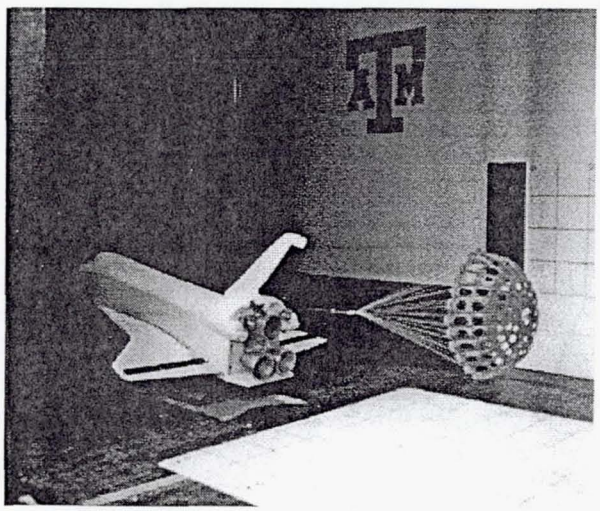

Figure 3. Model parachute deployed behind the Space Shuttle in the Texas A&M Low Speed Wind Tunnel

and rollout simulations as well as structural and mechanical analyses. The parachute force is calculated as a function angle of attack and control surface settings and is applied at the parachute attach point at the base of the vertical tail. The equation for parachute force is shown below:

$$F_c = K_t \left(\frac{C_D}{C_{Do}} \right) C_{Do} S_o \bar{q}_\infty$$

where K_t is a transient factor that models parachute inflation and opening shock and (C_D/C_{Do}) is the wake factor. The transient factor corresponds to eight different events in the deployment process and ranges between 0 and 1.05. The time corresponding to each of these events is computed using kinematics relations, parachute fill time equations[6], and reefing time delays. The wake factor was determined from the wind tunnel test program and ranges between 0.65 and 0.9. The free stream drag coefficient for the parachute was estimated to be 0.575.

The drag parachute force vector angles are referenced to the vehicle waterline and are computed as a function of time to simulate the coning of the parachute in the wake of the Orbiter. The equations for the parachute pitch angle is shown below:

$$\theta_c = \alpha - \left(\frac{W_c}{F_c} \right) \left(\frac{360}{2\pi} \right) + T \sin \omega_c t$$

where W_c is the weight of the canopy, T is the coning angle, and ω_c is the coning frequency. A similar form of this equation, without the weight effect, is used to estimate the parachute heading angle, Ψ_c. The coning parameters were estimated prior to flight based on empirical data.

Flight Simulations

Both NASA and Rockwell International conducted drag parachute system performance and design studies in a number of simulation environments. The key simulators used were the Systems Engineering Simulator (SES) at NASA JSC and the Vertical Motion Simulator (VMS) at NASA's Ames Research Center.[8] The SES is a fixed-base simulator used for performance studies and early procedures development. The VMS was the main facility used for procedures development and crew training. This facility is a 6-degree of freedom, motion-based simulator with visual scenes and Orbiter specific displays and controls. The parachute design parameters that were varied in the simulator included the reefing percentage (drag area ratio), reefing time delay, and deployment technique. Three techniques were evaluated: 1) deploy the drag parachute at main gear touchdown (MGTD), 2) deployment after the initiation of de-rotation, and 3) deployment at a specified time after MGTD. Environmental parameters varied in the simulation matrix include winds, aerodynamic characteristics, weight, center-of-gravity, and runway friction. Failure conditions included blown tires, inadvertent parachute deployment, hardware failures, and control system failures.

Each of the simulator pilots flew the entire test matrix and rated the de-rotation and rollout tasks using the Cooper-Harper handling qualities rating scale.[9] This scale is used to measure pilot workload and assigns a higher (less favorable) rating to a situation that requires improvement. While this technique may be considered subjective, it has proven to be quite useful when a sampling of at least 4 or 5 pilots is used. Pilot ratings were used to evaluate the different configurations (with and without the drag parachute) and to verify that the design requirements were met.

Recommendations made based on the VMS sessions included the incorporation of reefing and the recommended deployment technique. Reefing was desired because it was found that an unreefed parachute caused the Orbiter to "skip off" the runway for the configurations with aft center of gravity and lightweight. This "skip off" was caused by the response of the elevons to the nose up pitching moment induced by drag parachute deployment. With the elevons deflected downward to de-rotate the nose, enough lift was generated to lift the Orbiter off the runway. Reefing the main canopy to 40% drag area ratio for a time delay of 3.45 seconds was recommended. The recommended technique was to deploy the parachute after initiation of de-rotation, having canopy disreef occur at or near nose gear touchdown. This configuration and deployment technique met all system performance requirements.

B-52 Flight Testing

Functional testing of the system was conducted on the B-52 aircraft at NASA's Dryden Flight Research Center (DFRC) during the summer of 1990.[10] Eight deployment tests were conducted to verify the operation of the door release, mortar deployment, parachute operation, and the attach/jettison mechanism. Test conditions were limited to less than 200 KEAS because of aircraft structural limits. Even thought the configuration of the B-52 is significantly different from the Orbiter, an attempt was made to compare measured loads to the force model. These data are shown in

Figure 4. The Force model predictions shown on the figure were calculated using wake factors of 0.93 and 1.0 for the reefed and disreefed canopies, respectively. The results from Tests 1 and 2 (shown as shaded symbols) showed that the reefing line needed to be lengthened to obtain the specified drag area ratio of 40%. The corrected configuration was flown on subsequent tests. Once the reefing line length was corrected, all of the test results were higher than predicted. This was believed to be due to the many configuration differences between the B-52 and the Space Shuttle. These included the base configuration, the ratio of the height of the attachment point to the canopy diameter, and the effects of engine thrust. The effects of these differences was difficult to extract, so the B-52 test results were used to develop a landing placard for the upcoming flight tests on the Orbiter. The placard was presented in the form of a mass-moment (moment arm is the difference between the c.g. and main landing gear rotation point) and is plotted against the nominal flight envelope in Figure 5. Compliance with this placard allowed nominal deployment of the parachute for configurations with combinations of heavy weight and forward c.g.

ORBITER FLIGHT TEST

A multi-phase flight test program was planned on the Space Shuttle to a) clear the drag parachute system for operational use, and b) to expand the envelope for higher speed deployments. Flight instrumentation was installed on Endeavour (OV-105) and flight tests were planned starting with STS-49. A summary of results from the first 14 flights (on all vehicles) is shown in Table 1.

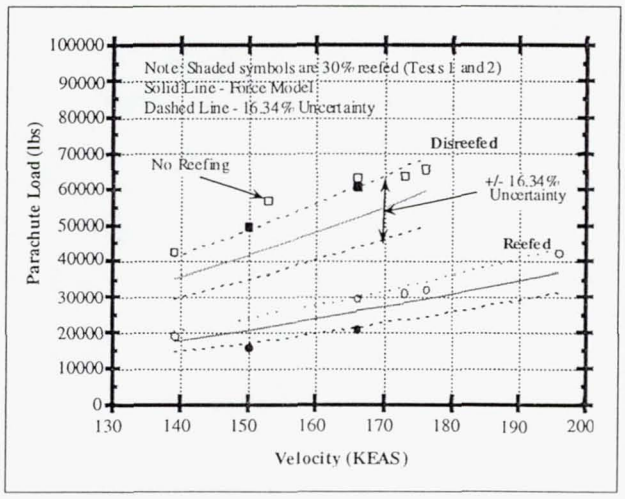

Figure 4. Measured Loads from the B-52 Test Program

Results from STS-47, -49, and –50

Early flight test results indicated higher than predicted loads and unpredicted riser heading angles. The results from STS-49 indicated disreefed parachute loads that were 15% higher than predicted by the force model. The parachute was also observed to be trimming at a yaw angle of about 4 degrees from the centerline. Similar riser heading angles were observed on STS-50, even though parachute loads were not measured on this vehicle. Measured load data from STS-47, as shown in Figure 6, was 20% higher than predicted at disreef and the parachute trimmed at an angle of 8 – 10 degrees. STS-47 was the first flight where the parachute was deployed prior to nose gear touchdown so the resulting crew workload was increased. The commander reported that vehicle drift due to the drag parachute deployment resulted in a significant rudder and aileron inputs during rollout. The flight data from STS-49, -50, and –47 were used to develop an assessment model for STS-52 crew training. Until this issue was resolved, drag parachute deployment conditions were limited such that disreef occurred after nose gear touchdown.

Parachute experts identified two possible reasons for the anomaly. The first hypothesis was that the canopy was inherently unstable, and that increasing the porosity would result in a stable system behind the Orbiter. A full-scale wind tunnel test at NASA's Ames Research Center (ARC) was planned to evaluate the stability of the system. The second possible reason for the anomaly was that the wake effect was causing the instability and increased loads and that increasing the trailing distance would improve the system. A series of CFD analyses, wake survey tests, and water tunnel tests were conducted to investigate this hypothesis. It was

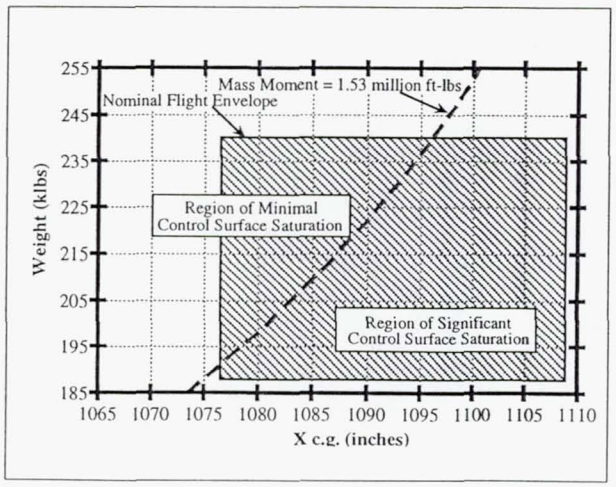

Figure 5. Landing Placard developed in the Vertical Motion Simulator using results from the B-52 tests

Table 1 –Flight Test Results from the first 14 flights of the Drag Parachute

Flight Number	Flight Date	Vehicle (OV-?)	Deployment Attitude	Deployment Velocity (KEAS)	Heading Angle after Disreef (deg)	Disreefed Loads	Configuration
STS-49	5/92	105	NGTD	158	4 ± 2-3, Right	15% higher than predicted	Baseline
STS-50	7/92	102	NGTD	147	0 ± 3-4	Nominal	Baseline
STS-47	9/92	105	Nose Up	177	8 ± 2, Right	20% higher than predicted	Baseline
STS-52	11/92	102	Nose Up	165	7 ± 2, Left	Nominal	Baseline
STS-53	12/92	103	Nose Up	161	9 ± 2, Left	Nominal	Baseline
STS-54	1/93	105	Nose Up	164	5 ± 3, Right	Nominal	Baseline
STS-56	4/93	103	Nose Up	162	2 ± 2, Left	Nominal	90% PR
STS-55	5/93	102	Nose Up	160	N/A	Nominal	Baseline
STS-57	7/93	105	Nose Up	176	2 ± 2, Right	Nominal	90% PR
STS-51	9/93	103	Nose Up	162	4 ± 1, Right	Nominal	5 RR
STS-58	11/93	102	Nose Up	163	3 ± 1	Nominal	5 RR
STS-61	12/93	105	Nose Up	169	3 ± 2, Left	Nominal	5 RR
STS-60	2/94	103	Nose Up	170	5 ± 2, Left	Nominal	5 RR
STS-62	3/94	102	Nose Up	160	1 ± 2, Right	Nominal	5 RR

NOTES: 1) NGTD = Nose Gear Touch Down, PR = Permanently Reefed, RR = Ribbons Removed
2) STS-60 landed in 18 kt headwind with 8 kt gusts, resulting in higher Heading Angles.

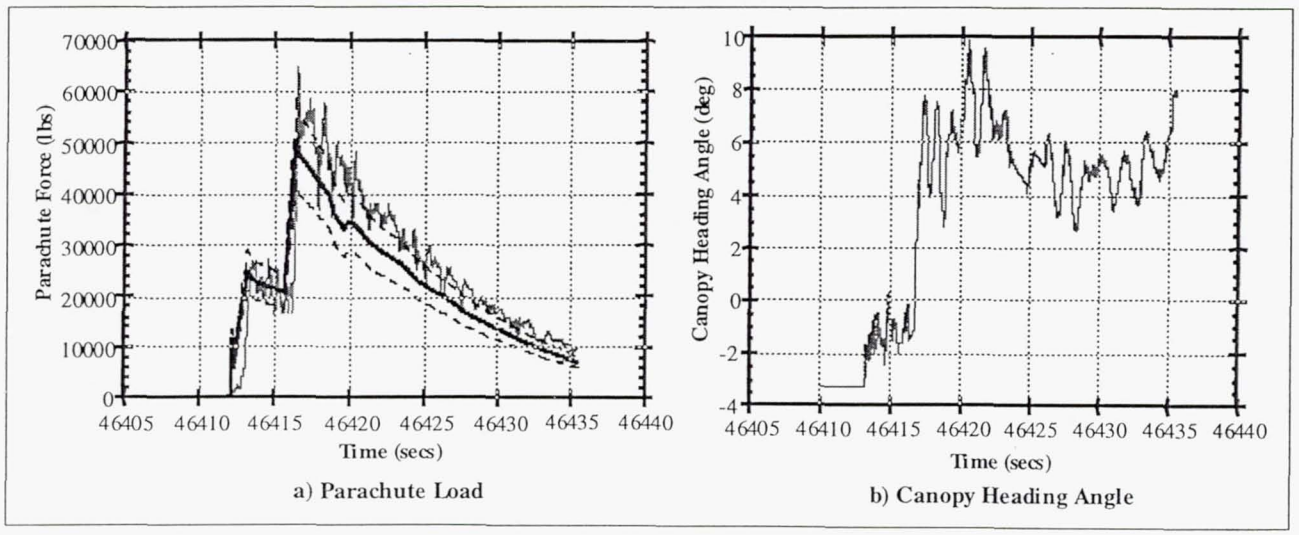

Figure 6. Flight measured data from flight STS-47 using the Baseline Drag Parachute

increase porosity would significantly improve parachute stability. It was also concluded that increasing the trailing distance of the canopy would have minimal effect on parachute stability.

Drag Parachute Stability Test

The drag parachute stability test was conducted in March 1993 at the ARC 80 X 120 ft Wind Tunnel.[11] Personnel from Sandia Labs were hired to develop the test plan and conduct the test. Parachute loads and canopy position versus time were measured.[12] No attempt was made to simulate the Orbiter wake in the wind tunnel. The canopies were first permanently reefed (to 80%, 85%, 90%, and 95%) to determine the effect on stability. Permanent reefing was very successful: improving stability to within two degrees of centerline. This improved stability, however, came at the expense of a 23% reduction in drag. Ribbons were then removed from the canopy, one at a time, to determine the effects of increased porosity on stability. The recommended configuration was one with five ribbons removed, which improved stability to within two degrees of centerline with only an 8% reduction in drag. Results from the test program are shown in Figure 7.

Results from STS-57 and –61

Due to parachute packing and launch preparation constraints, the permanently reefed configuration was packed and flown on STS-56 and –57. This configuration was well understood and could be flown with confidence prior to the completion of the wind tunnel test program at ARC. Instrumented results from STS-57 verified the wind tunnel results as shown in Figure 8. A 23% loss in drag was observed with up to four degrees of heading measured using ground cameras.

The recommended configuration with five ribbons removed was first flown on STS-51 in September 1993, with the first instrumented flight occurring on STS-61. Measured data from STS-61, as shown in Figure 9, validated the wind tunnel results with an 8% reduction in parachute drag and a stable canopy after disreef. With the correction to the parachute stability verified in flight, the flight test program was completed and the drag parachute was certified for operational use.

Figure 10 shows a photograph of the modified parachute deployed behind the Space Shuttle Atlantis.

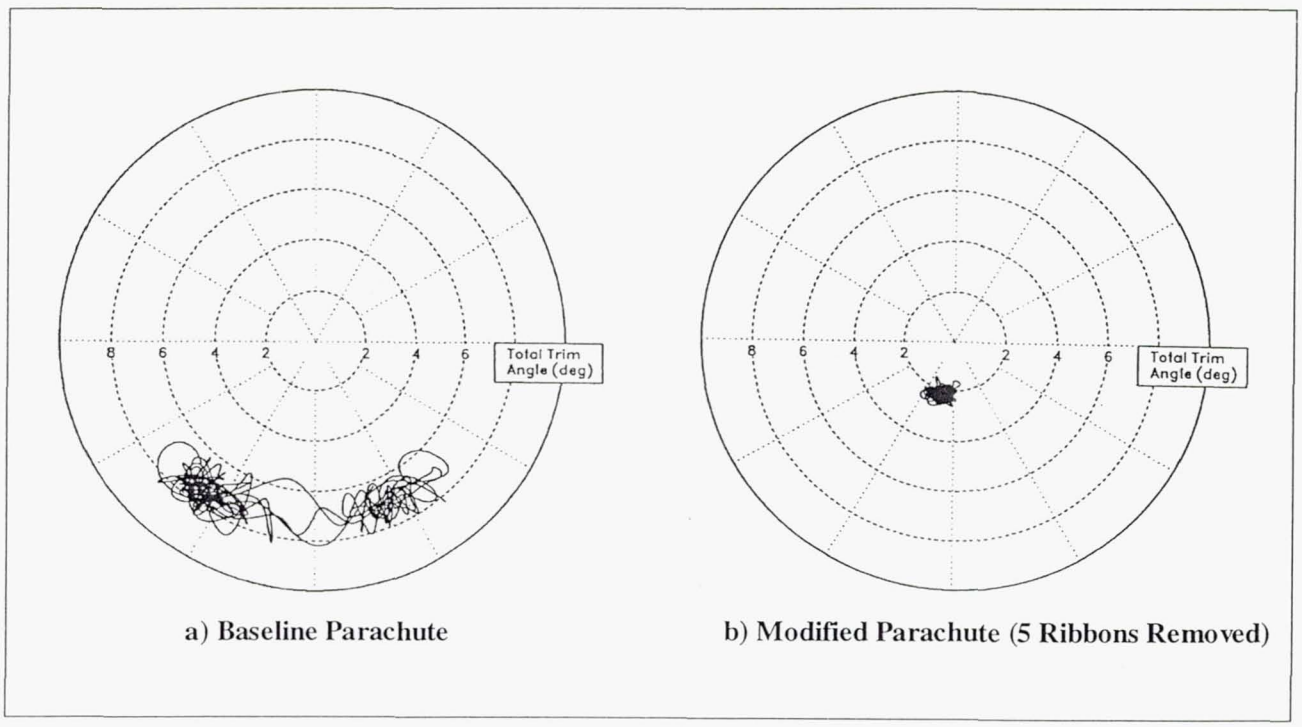

Figure 7. Canopy position measured as a function of time for 2 configurations in the NASA Ames Wind Tunnel

Results from each of the Orbiter flights are included in Table 1. The flight results show that the modifications to the parachute canopy reduced the riser-heading angle from about 5.5 degrees (average from the first nine flights) to less than three degrees (average from the next five flights).

SUMMARY

The drag parachute system has been certified for use on the Space Shuttle Orbiter. Wind tunnel tests, aerodynamic analyses, pilot-in-the-loop simulations, and flight test results were all used to develop the system design parameters and operational procedures. Extensive work went into the development of the mathematical model used to predict parachute forces and resulting impacts on Orbiter flying qualities. Flight test data on the Space Shuttle has verified this model for use in simulations used for crew training and flight procedures development.

ACKNOWLEDGEMENTS

This paper is the result of work performed by the author while working at NASA's Johnson Space Center. While there were many people who contributed, the author would like to specifically mention those who made a significant contribution to the work discussed in this paper. These include John Kiker, Bill Acres, Howard Law, John Kennedy, Tom Bunce, John Casper, and Andy Allen from NASA Johnson Space Center; Charles Lowry, Joe Baumbach, Olman Carvajal, and Mike Zyss from Rockwell International; Don McBride from Sandia Labs, and Jim Sickels and Phil Delurgio from Irvin Aerospace.

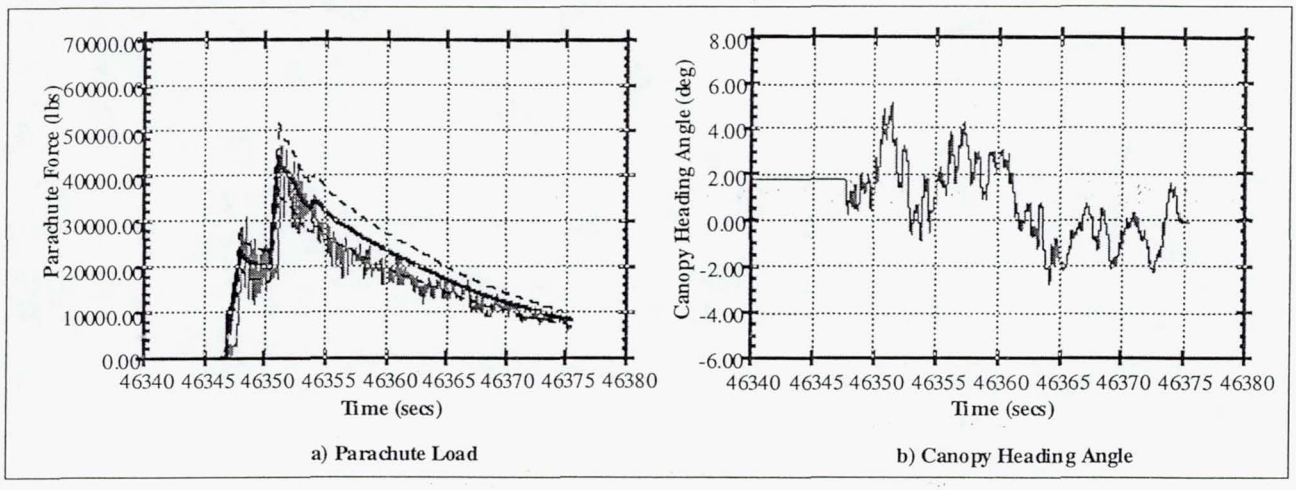

Figure 8. Flight measured data from flight STS-57 using the 90% permanently reefed Drag Parachute.

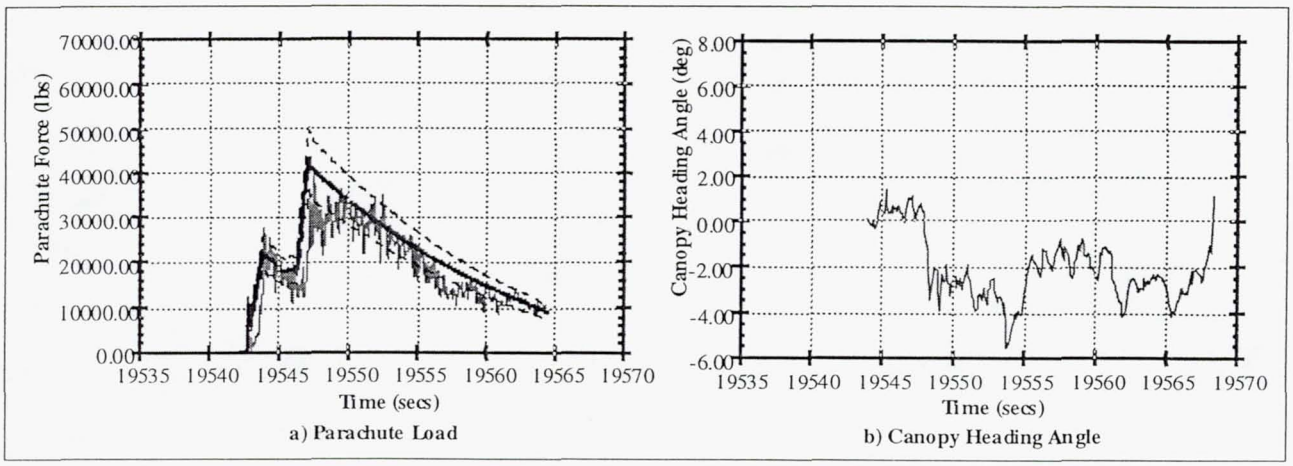

Figure 9. Flight measured data from flight STS-61 using the Drag Parachute with 5 ribbons removed.

REFERENCES

1. Kiker, J.W., "Orbiter Drag Chute Assessment," Lockheed Engineering and Management Services Company Report LEMSCO-24668, 1987.
2. Sickels, J.A. and R.A. Lawrence, "Design and Testing of a 40 ft. Diameter Hybrid Nylon/Kevlar Ribbon Parachute for the NASA Spacecraft Landing Deceleration Subsystem," AIAA-91-0860, 1991.
3. Kennedy, J.J., and C.H. Lowry, "Space Shuttle Orbiter Drag Parachute System," AIAA 95-1595, 1995.
4. Unknown, "Oran W. Nicks Low Speed Wind Tunnel Web Site," http://wind.tamu.edu.
5. Peterson, C.W., and D.W. Johnson, "Reductions in Parachute Drag due to Forebody Wake Effects," AIAA Journal of Aircraft, Vol. 20, No. 1, January 1983, Pp. 42-49.
6. Knacke, T.W., Parachute Recovery Systems Design Manual,: Naval Weapons Center Technical Publication NWC TP-6575, 1990.
7. Bixby, H.W., E.G. Ewing, and T.W. Knacke, Recovery Systems Design Guide, USAF Report AFFDL-TR-78-151, 1978.
8. Unknown, "NASA Ames Vertical Motion Simulator Web Site," http://www.simlabs.arc.nasa.gov/vms/vms.html.
9. Cooper, G.E., and R.P. Harper, Jr., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities," NASA TN D-5153, April 1969.
10. Lowry, C.H., and A. Mandviwala, "Development Test Report for the Orbiter Drag Parachute System Test Program on the B-52B Aircraft," Rockwell International Report SSD91D0140, 1991.
11. Unknown, "NASA Ames Full Scale Aerodynamics Complex - 80 x 120 Foot Test Section," http://windtunnels.arc.nasa.gov/windtunnels/80ft1.html.
12. McBride, D.D., "Orbiter Drag Chute Stability Test in the NASA/Ames 80x 120 Foot Wind Tunnel," Sandia Report SAND93-2544, 1994.

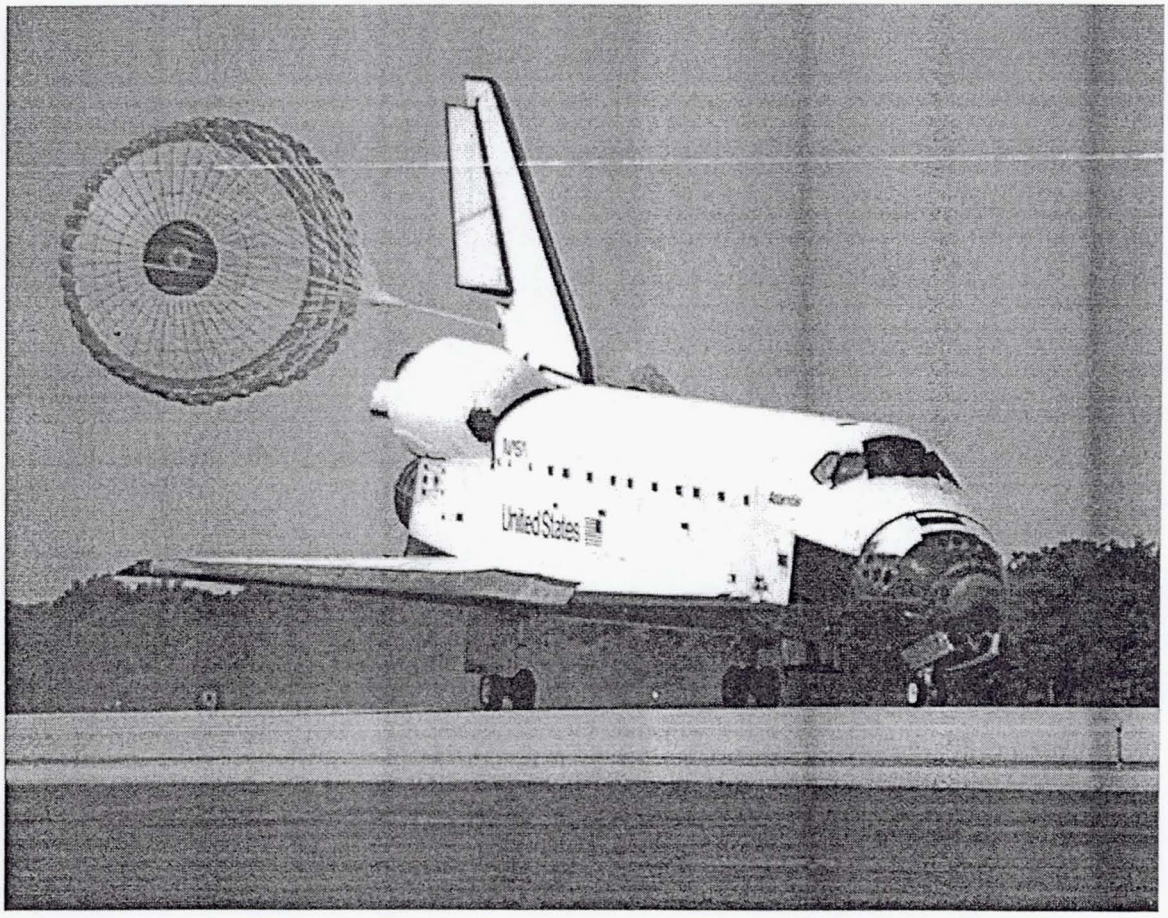

Figure 10. Drag Parachute deployed behind the Space Shuttle Atlantis