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# An Introduction to Testing Parachutes in Wind Tunnels

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# AN INTRODUCTION TO TESTING PARACHUTES IN WIND TUNNELS*

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## Abstract

This paper reviews some of the technical considerations and current practices for testing parachutes in conventional wind tunnels. Special challenges to the experimentalist caused by the fabric construction, flexible geometry, and bluff shape of parachutes are discussed. In particular, the topics of measurement technique, similarity considerations, and wall interference are addressed in a summary manner. Many references are cited which provide detailed coverage of the state of the art in testing methods.

## Introduction

Because a parachute's performance is governed by a complicated coupling of fluid- and solid-mechanics principles, physical experimentation remains a necessary complement to theoretical modeling and prediction capabilities. In many situations, a conventional wind tunnel is an appropriate, cost-effective alternative to flight testing. The wind tunnel may be used to quickly evaluate the performance of new, innovative parachute designs, or to establish extensive data bases for the development and validation of analytic models. But compared to other aerodynamic devices, the bluff shape and fabric construction of parachutes cause unique difficulties in designing and carrying out a successful wind tunnel test. Because parachutes represent only a small fraction of wind tunnel activity, the standard references on testing methods do not address these difficulties. The objective of this paper is to collect and discuss some of the more common issues peculiar to parachutes. The material presented has been gleaned from the author's own testing and research experience and from published reports by others in the testing community.

## Wind Tunnels and Model Support

General information on testing in low-speed and high-speed wind tunnels can be found in Refs. 1 and 2, respectively. Although parachutes are not specifically mentioned, these sources cover the basics of tunnel design and operation and testing procedure. Reference 1 also contains a comprehensive listing of subsonic wind tunnels worldwide, including test-section type, size and maximum wind speed. More detailed descriptions of both high-speed and low-speed tunnels in the U. S. can be found in Ref. 3. As an illustration of the variety of tunnels available, Table 1 lists some of the facilities known to the author to have been used previously to test parachutes. The list is only a sampling of possible test sites.

In designing the model support system, consideration must be given to whether the intent is to determine the aerodynamic properties of the parachute alone, or the properties of the parachute behind, but in proximity to, a forebody of particular shape. The subsonic experiments reported in Ref. 4 demonstrated that the wake of even a streamlined forebody can cause a significant reduction in the parachute's drag, depending on the length of the suspension lines. In transonic and supersonic airstreams, forebody influence on the drag and/or inflated shape of the parachute is further complicated by the interaction of the forebody and canopy shock waves with the forebody wake. In Ref. 5, the drag coefficient of a disk-gap-band parachute behind a bluff forebody was reduced by up to 60% at Mach 1.0, for a suspension line length approximately equal to the canopy constructed diameter. Therefore, it is good testing practice to make a forebody as small and as streamlined

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**Table 1. Some Wind Tunnels Used Previously to Test Parachutes**

| Facility | Max. Speed |
|---|---|
| CALSPAN 8-by-8-ft | Mach 1.3 |
| General Dynamics (San Diego) 8-by-10-ft | 300 mph |
| Lockheed-Ga. 16-by-23-ft/26-by-30-ft | 250/125 mph |
| LTV 7-by-10-ft/15-by-20-ft | 240/50 mph |
| NASA Ames 40-by-80-ft/80-by-120-ft | 300/100 mph |
| NASA Ames 9-by-7-ft | Mach 2.6 |
| NASA Langley 14-by-22-ft | 230 mph |
| NASA Lewis 9-by-15-ft | 150 mph |
| NASA Lewis 10-by-10-ft | Mach 3.5 |
| Univ. of Maryland 8-by-11-ft | 220 mph |
| Univ. of Minnesota 4.8-by-4.8-ft | 80 mph |

as possible when parachute-only measurements are required. If, on the other hand, the aerodynamic properties of a parachute/payload system are required, the model forebody should be in the proper scale and should incorporate enough geometric detail that its wake is realistically simulated.

If the forebody is supported in the test section by a conventional strut arrangement, the wake of the strut will also influence the aerodynamics of the parachute. The effect may be small if the strut has a streamlined cross section, but should still be estimated in terms of the reduction in dynamic pressure over the frontal area of the inflated canopy. Whenever a single, floor-mounted, streamlined strut is used, care should be taken that the strut is at zero angle of incidence with respect to the tunnel flow. Otherwise, even a slight angle of attack may produce a vortex on the centerline of the tunnel of sufficient strength to cause the parachute to rotate.

A usually convenient and economical alternative to a strut support, particularly in subsonic applications, is to hold the forebody in place with three or more wires or thin cables anchored in the tunnel walls. An example of this type of installation for parachute-alone measurements is described in Ref. 6. Another cable-support arrangement, which permitted the forebody to be placed at an angle of attack, was used in the tests reported in Refs. 4 and 7. With a cable system, an internal balance (described in the next section) is required to measure the aerodynamic forces on the parachute.

Other specialized model support systems for "lifting" parachutes, or for conventional parachutes at angle of attack have been described in Ref. 8. Reference 9 details a tunnel setup used recently to test a ram-air inflated wing.

By their nature, conventional, steady-flow wind tunnels have been limited, almost exclusively, to testing parachutes under infinite-mass (i.e., no deceleration of the model relative to the airstream) conditions. The one exception known to the author is the moving-model support system discussed in Ref. 10, which was used to simulate the inflation of a model parachute attached to a finite-mass payload.

## Measurement Techniques

Much of parachute testing in wind tunnels involves time-averaged data for a model of fixed configuration under steady airflow conditions. The usual measurement for this kind of test is parachute drag, or in the case of nonsymmetric canopies, drag plus a normal force (i.e., lift). To determine the forces, two types of balances are in general use: external balances which carry the model loads outside the test section before they are measured, and internal balances, which fit into the forebody and send data out through electrical wires. Either type may be used if the forebody is strut supported; as stated earlier, an internal balance is required if the forebody is supported by cables. Chapter four of Ref. 1 contains an excellent discussion of balance types and their operation.

Wind tunnel tests are frequently also used to determine force versus time during the inflation of a parachute. In this situation, a check should be made to insure that the dynamic characteristics of the model-support/balance system do not distort the force measurement in either phase or amplitude. Such an analysis will usually dictate the use of an internal balance. The external balances in place at most tunnels have such low natural frequencies and high mechanical damping that the peak inflation force will probably be significantly attenuated.

Other measurements that are sometimes made include canopy surface pressure and canopy fabric stress. The distribution of normal pressure over a canopy can be used to calculate canopy shape and fabric stresses[11], and is needed to formulate input to numerical models of the inflation process.[12] Unfortunately, the desired spatial resolution and measurement accuracy for pressure distributions have not yet been achieved on a regular basis. Techniques used for steady-state testing include somehow mounting orifices to the canopy fabric, more or less normal to and flush with either the inner or outer surface, or attaching notched lengths of plastic tubing to the canopy surface along a radial.[7] The main problem with these methods is a disruption of the airflow (and the local static pressure) caused by the protruding orifices and/or the tubing. Acceptable results can be obtained in regions of separated flow, but spurious pressures are often measured upstream from the point of maximum inflated diameter. In addition, the bulkiness of the tubing may prevent the incorporation of an adequate number of measurement locations for smaller models.

For dynamic surface-pressure measurements during inflation, miniature, strain gage-type transducers have been used.[7,13] The small electrical wires leading from the sensors disturb the flow much less than plastic tubing, but even very thin units cemented or sewn to the canopy still present much more of a flow distortion than is tolerated with other types of rigid wind tunnel models (e.g., airfoils). The cost of these transducers may limit the number of measurement locations during a single test.

The measurement of stresses in parachute fabric has a long and troublesome history. The requirement to experimentally verify predicted structural margins of safety for high-performance parachutes is compelling, but the technical difficulties are great. A recent review paper critically examined the state of the art in fabric-stress measurement.[14]

## Similarity Considerations

References 15-18 address the problem of extrapolating the results of flight tests of reduced-scale model parachutes to full-scale systems. The similarity requirements discussed in those studies are equally applicable to the wind tunnel environment. For steady-state tests of fixed geometries, four parameters demand consideration: model geometry, model elasticity, Reynolds number, and Mach number. If the parachute is allowed to inflate in the tunnel, two additional parameters—mass ratio and model stiffness—are involved.

The foremost requirement for a valid wind tunnel test is that the model be geometrically similar to the flight article, both as constructed (i.e., linear dimensions, number of gores, geometric porosity, etc.) and in its inflated shape as influenced by its elastic properties. If the relative sizes of the parachute and the available wind tunnel make it necessary to test a reduced-scale model, achieving an acceptable degree of geometric similarity may be difficult. The nature of the fabrication process for model parachutes may result in dimensional tolerances as high as 1/8-inch, which can significantly affect geometric characteristics such as vent area and geometric porosity if the model is very small. The inflated shape of the model is further influenced by the amount of strain in the various fabric members. Drawing on the analysis presented in Ref. 18, it can be shown that the strain of an element of the model is directly proportional to the dynamic pressure of the airstream and inversely proportional to the product of the element elastic modulus and the ratio of element thickness to a model reference length (constructed diameter, e. g.). That is,

$$\varepsilon \sim \frac{\rho V^2}{E \frac{\delta}{L}} . \qquad (1)$$

Assuming that the model and full-scale prototype have the same modulus, E, (e.g., both made of nylon) and that fabric thickness, $\delta$, is properly scaled (not likely, owing to the limited selection of woven materials), then attaining the correct strain in the model dictates that the tunnel dynamic pressure match the flight condition.

If the test includes dynamic measurements during inflation of the model, the mass ratio and stiffness of the model must also be properly scaled. The mass ratio is defined as the parachute mass divided by the air density and the cube of the reference length. This ratio should have the same value in the wind tunnel as in the flight environment. Here again, a limited selection of woven materials makes it difficult to duplicate the mass distribution of a full-scale parachute, as well as its planar geometry, at a greatly reduced size.

Parachute stiffness was first investigated as a model performance parameter in Ref. 19. The effective bending stiffness of an element of a parachute depends not only on basic material properties and element cross section, but also on factors related to the method of construction (e.g., type and amount of stitching, strength reinforcement using multiple plys, seams and joint contruction, etc.). In Ref. 19, a quantitative stiffness index was defined and used to show that conventional, reduced-scale model parachutes were much stiffer than the full-scale prototypes on which they were based. Different methods of model construction were developed that led to major reductions in the stiffness index. Supporting wind tunnel experiments showed that models that are too stiff tend to open too rapidly, resulting in peak inflation forces that are 30-40% higher than corresponding forces for the more flexible models and full-scale prototypes. It should be mentioned that an alternate stiffness index was defined for fabric models other than parachutes in Ref. 20.

Reynolds number as a testing parameter for *streamlined* types of models has received a great deal of attention (see, e.g., Chap. 7 of Ref. 1). The magnitude of surface friction and the location of flow separation, both of which are strongly dependent on the Reynolds number, dominate the aerodynamics of streamlined bodies. For conventional round and cruciform parachutes, flow separation is fixed by the bluff geometry (more or less), and the shearing stress on the small portion of the model where the flow follows the surface is a negligible contribution to the total force. (This result is certainly not the case for ram air-inflated wings or, to some degree, for conventional, solid canopies that are highly reefed.)

There is, however, a more subtle effect of Reynolds number for conventional parachutes that deserves attention. Typical parachute fabrics are not impermeable, and the flow through the weave depends on both porosity and Reynolds number. More specifically, this flow is laminar and the coefficient of pressure drop across the fabric increases as the Reynolds number based on approach velocity and yarn diameter decreases.[21] A decrease in the local pressure drop coefficient will be accompanied by a decrease in the overall drag coefficient for the parachute. Thus, if a full-scale model is tested, the ratio of airspeed to kinematic viscosity should match that of the flight environment. If a reduced-scale model made of the same fabric as the prototype is tested, the ratio should still match that of the flight environment. If a different fabric is used for the reduced-scale model to improve the elasticity, mass and stiffness scaling discussed earlier, the porosity has probably changed and there is little hope of closely matching the pressure drop coefficient.

For reduced-scale models with geometric porosity (e.g., ribbon parachutes), it may be asked if the flow between narrow, closely spaced ribbons is sensitive to Reynolds number. As a rule, the product of airstream velocity and width of a ribbon should be greater than approximately 0.10 $ft^2/s$ to ensure that the local flow is turbulent and independent of Reynolds number. This criterion is easily satisfied for typical models as small as one foot in diameter.

Mach number is a measure of the importance of changes in density in a high-speed flow, as the air is brought to rest and then re-accelerated by a model. There is little unambiguous experimental data on the effects of Mach number on parachute performance, primarily because of the collateral influence of the forebody wake discussed earlier in the section on model supports. There is, however, ample data for rigid, bluff bodies (disks and spheres, e.g.) which when compared to available parachute data lead to reasonable speculations. The observable effect of the compressibility of air on the aerodynamics of a rigid, axisymmetric bluff shape is a small (less than 10%), gradual increase in drag coefficient between Mach numbers of 0.4 and 0.9.[22] This behavior is similar to that found for a disk-gap-band parachute well behind a small, streamlined forebody, as reported in Ref. 5. For rigid models, flow-visualization shows that shock waves first appear as Mach number increases above 0.9. Between Mach numbers of 0.9 and 2.0, the drag coefficient rapidly increases to a value approximately 50% greater than the low-speed value. Above Mach 2.0, the drag coefficient remains constant. The available parachute data in the transonic and supersonic ranges deviate from this rigid-body data. Referring again to the results reported in Ref. 5, the increase in drag coefficient for the disk-gap-band parachute at Mach numbers as high as 1.4 was only about 10%. In another experimental study[23] at Mach numbers between 1.5 and 2.5, decreases in drag coefficient of up to 20% appeared to be correlated with a reduction in inflated diameter. Apparently, the strong axial pressure gradients associated with the shock waves were responsible for the changes in canopy shape.

Drawing from this very limited amount of data, it seems acceptable to ignore Mach number effects for parachutes behind small, streamlined forebodies through the subsonic, compressible range (i.e., M < 0.9). In fact, by testing in a subsonic rather than a transonic or supersonic wind tunnel, it is likely that a much larger model can be used, thereby reducing the uncertainty caused by all of the other similarity parameters discussed above. At Mach numbers above 0.9, the shock waves probably influence the shape of the canopy to such an extent that subsonic test results would be unrealistic. If the test configuration includes a relatively large-diameter or bluff forebody, the data from Ref. 5 show that the test Mach number should equal that of the flight condition to duplicate the strong interactions among the forebody wake, the shock waves and the canopy flow field.

## Tunnel Boundary Interference

In the few instances of transonic and supersonic testing of parachutes to date, test-section boundary interference has not been a serious problem because other considerations (i.e., starting the tunnel and avoiding impingement on the model of reflected shock waves) kept the models sufficiently small. On the other hand, published data from a number of previous subsonic tests contain significant errors because the effect of boundary interference was underestimated. Figure 1 illustrates the large influence that the size of a parachute relative to the size of the test section has in solid-wall wind tunnels. The data is for a 10-ft-constructed-diameter, solid-canopy parachute that was tested in three different-size wind tunnels to obtain geometric blockage ratios ranging from 0.01 to 0.13, approximately. (Geometric blockage ratio is defined as the projected area of the inflated model, $S_m$, divided by the cross sectional area of the test section, $S_t$.) Extrapolation of the measurements to zero blockage suggests that the true drag coefficient of the parachute is between 0.75 and 0.80. Even for a relatively low blockage ratio of 0.05, the measured drag coefficient was approximately 17% too high.

Chapter 6 of Ref. 1 may be consulted for an introduction to the theory of tunnel boundary interference. In essence, solid test-section walls constrain the displacement of streamlines around a model and its trailing wake, causing the average velocity in the vicinity of the model to be greater than the calibrated tunnel airspeed. If model force coefficients are based on the calibrated airspeed, they will be too large. To obtain accurate coefficients, the airspeed that is used in data reduction is adjusted to a higher value; this adjustment is referred to as the "blockage correction." With conventional, drag-producing parachutes, this is the only boundary-interference correction to the data that is required. In the case of models that produce significant lift, there is an additional correction to the angle of attack that accounts for the fact that the walls increase the curvature of flow streamlines.

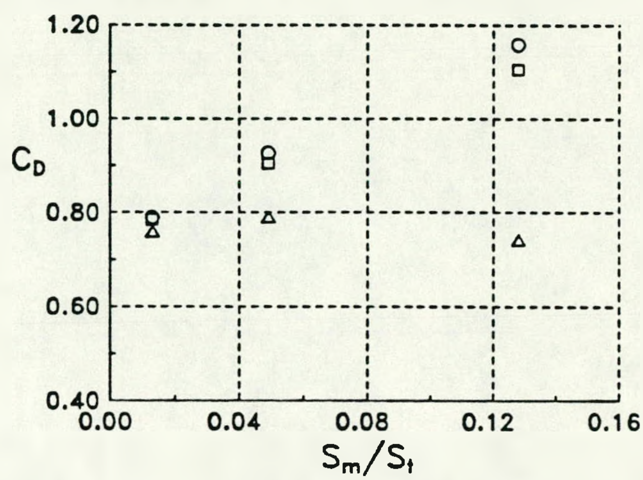


**Fig. 1. Parachute drag coefficient as a function of geometric blockage ratio. ○-uncorrected, □-corrected using Eq. (2), △-corrected using Eq. (3).**

Wind tunnel operators are well aware of the need to correct data for these boundary effects. But because parachutes are often a novelty in wind tunnels, general knowledge of an appropriate correction method has been lacking. Without specific direction from the customer, the tunnel engineer will usually apply a "standard" correction algorithm such as the one suggested in Ref. 1:

$$\frac{q}{q_u} = 1 + .5\,\frac{S_m}{S_t}\ . \qquad (2)$$

Here, q is the corrected airstream dynamic pressure, and $q_u$ the as-measured, uncorrected dynamic pressure. In fact, corrections based solely on geometric blockage are valid for streamlined models only. As shown in Fig. 1, Eq. (2) severely underestimates the correction required for the solid-canopy parachute at blockages greater than a few percent.

An accurate blockage correction for parachutes, based on a general method for bluff models developed by Maskell[24], is described in Ref. 6. Repeated here,

$$\frac{q}{q_u} = 1 + 1.85\,\frac{(C_D S)_u}{S_t} \qquad (3)$$

where

$$(C_D S)_u = \frac{\mathrm{Drag}}{q_u} \qquad (4)$$

is the uncorrected drag area of the parachute. It is notable that for bluff models the correction is proportional to an "aerodynamic" blockage ratio rather than the geometric blockage ratio. Reference 6 states that Eq. (3) is valid for moderately reefed to full-open round canopies of standard construction (i.e., solid, ring-slot, ribbon, etc). Its application to the parachute considered in Fig. 1 attests to its accuracy at geometric blockages as high as 0.13.

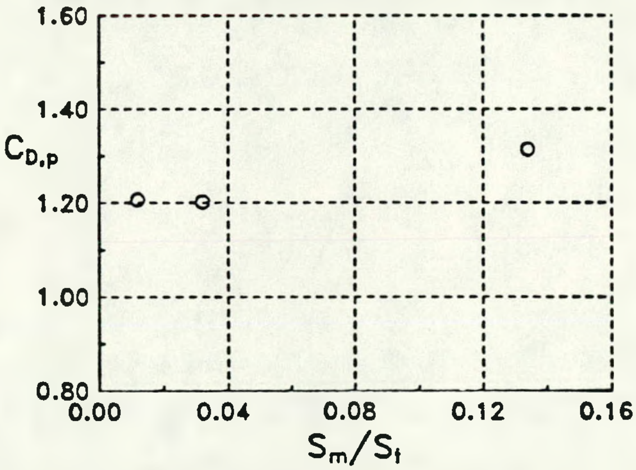


**Fig. 2. Peak inflation drag coefficient as a function of full-open geometric blockage ratio.**

A wind tunnel test in which a parachute inflates presents a unique boundary interference problem. During inflation, the geometric blockage increases rapidly and the instantaneous drag reaches a peak that may be twice the fully inflated, steady-flow value because of the effect of the added mass of air. If Eqn. (3) were applied at each instant during the inflation, the correction would become very large, indeed. However, limited experimental data exist that suggest boundary interference during this dynamic process cannot be treated in a quasi-steady manner. Figure 2 presents previously unpublished data showing how the peak inflation drag coefficient was observed to vary as a function of the fully inflated geometric blockage ratio. The model used in these low-speed tests was a 5-ft-diameter, flat, circular ring-slot canopy with a geometric porosity of 10%. Each of the symbols in Fig. 2 represents the average of a number of repeated, infinite-mass inflations; the scatter among individual inflations was approximately ±5%. At the relatively high blockage ratio of approximately 13%, the peak drag coefficient was only 10% greater than the extrapolated, zero-blockage value. Yet, the boundary interference with this model under steady-state, full-open conditions followed Eqn. (3).

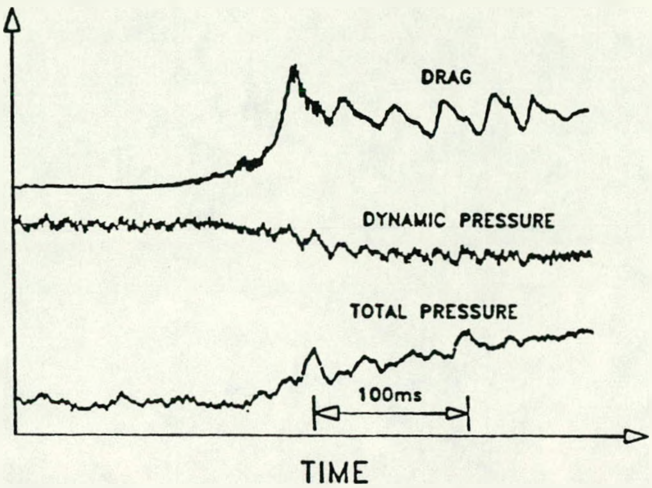


**Fig. 3. Drag and airflow properties during inflation in a test section with solid walls. From Ref. 25. Used with permission.**

The study reported in Ref. 25 helped reconcile this striking difference in observed boundary interference between the constant-geometry and inflation situations. In that study, steady-state and dynamic interference was experimentally investigated for parachutes in the presence of both porous and solid tunnel walls. Besides model drag, the total and dynamic pressures of the airstream were recorded during the inflation using fast-response instrumentation. Figure 3, which is taken from Ref. 25, shows that the dynamic pressure in the solid-wall test section decreased simultaneously with the increase in parachute drag. The decrease in flow velocity is, of course, in response to the higher energy loss associated with the expanding model. At the instant when the peak drag occurred, the dynamic pressure was approximately 3% lower than the pre-inflation value. It was concluded in Ref. 25 that the measured peak drag was the combined result of three independent factors: 1) the decrease in dynamic pressure; 2) a simultaneous, transient, streamwise static-pressure gradient; and 3) a time-lagged manifestation of conventional, steady-state boundary interference.

Almost all of the subsonic wind tunnels in regular use in the U. S. have test sections with solid walls. There are a few tunnels with open-jet test sections. As a rule, the blockage correction in an open-jet tunnel is opposite in sign to and only a fraction of the magnitude of the correction in a solid-wall tunnel. The available literature on boundary interference in open-jet tunnels, as far as the author knows, has dealt only with streamlined models. There are even fewer partly-open/partly-closed (e.g., slotted-wall), subsonic test sections in use.

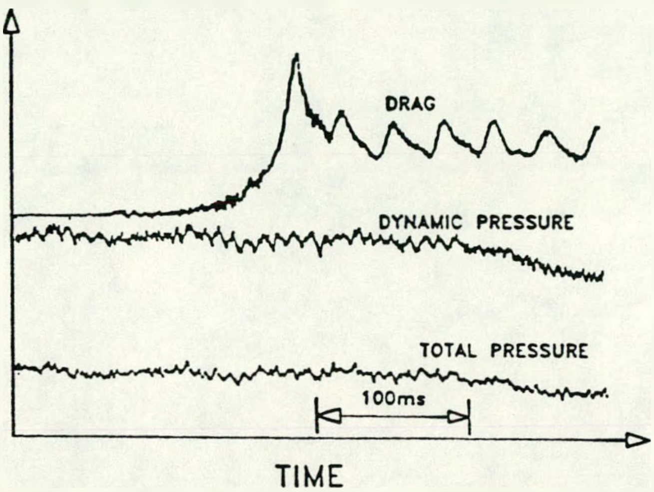


**Fig. 4. Drag and airflow properties during inflation in a 20%-open, slotted-wall test section. From Ref. 25. Used with permission.**

There may be, however, significant advantages to testing parachutes in partly or totally open test sections. Figure 4 is also taken from Ref. 25. The data shown are similar to those in Fig. 3, except the test section is slotted with 20% of the wall area open. Notice that the dynamic pressure eventually decreased by approximately the same amount as with the solid walls, but the decrease did not begin until *after* the parachute was fully inflated. Consequently, drag measurement during the inflation was not confused by the changing dynamic pressure or the postulated, transient static-pressure gradient that occurred with the solid walls. On the other hand, Ref. 25 goes on to show that proximity of the model to the upstream and downstream boundaries of a slotted test section can significantly influence drag measurements. It is expected that there are similar bluff-body boundary effects in open-jet tunnels, though they have not been discussed in the literature.

## Recent Testing Examples

This section describes the use of wind tunnels to great advantage in the development of two complicated parachute systems. For the first system discussed, it simply was not feasible to obtain the required data from flight tests. For the second system, wind tunnel testing was chosen as a timely, less-expensive alternative to a series of flight tests.

The first example involves the pilot parachute and deployment method used with the aircraft crew escape module (CEM) recovery system described in Ref. 26. This particular deployment system uses a catapult to eject the packed main parachute from its compartment in the CEM. As the pack begins to clear the CEM, the pilot parachute is deployed with the aid of a slug fired from a drogue gun mounted on the pack. In actual operation, the angle of attack of the CEM can vary over a wide range. It was necessary to demonstrate that the pilot parachute could be successfully deployed and rapidly inflated in all possible directions, including across the airstream and directly downstream through the large wake of the CEM.

The prototype deployment system was tested over the complete range of angles of attack, using a full-scale CEM in the NASA Ames 40-by-80-ft subsonic wind tunnel. The deployments fully duplicated the operational use of the system, up to the point where the 80 feet of risers and main-parachute suspension lines had been extracted from the pack.

One of the greatest challenges in designing the test was finding a way to arrest the motion of the still-packed main parachute after the suspension lines were played out. At that point, the kinetic energy of the 110-lb pack was more than 30,000 ft-lb, and the force that would be required to abruptly stop the pack was much greater than the breaking strength of the suspension lines. This problem was solved by installing a tear-ply energy dissipater between the pack and the suspension lines. This device

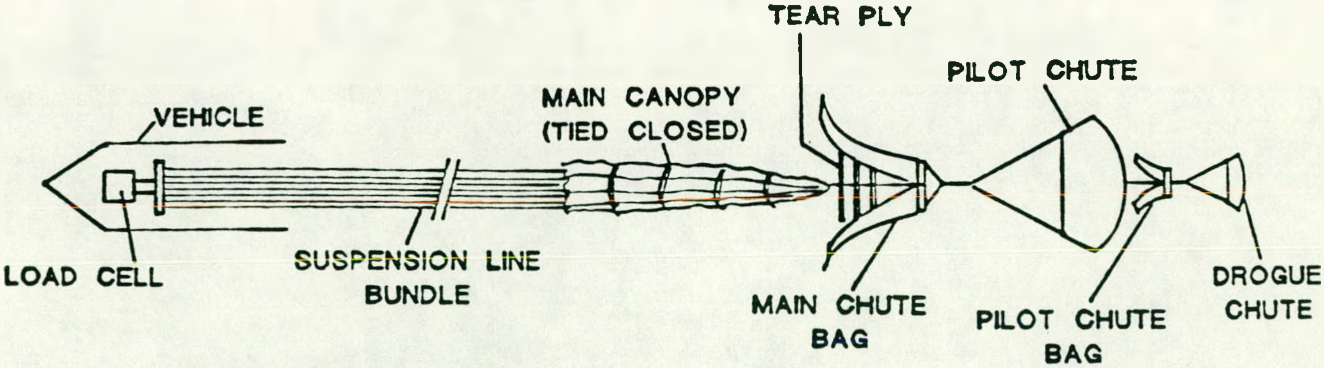


**Fig. 5. Schematic of the test setup used in the Lockheed-Ga. wind tunnel.**

consisted of a length of 20,000-lb, 1.75-in.-wide Kevlar webbing sewn back on itself with six rows of single-throw, ziz-zag stitching. The thread used was 5-cord Kevlar. In a static pull test, the tearing strength of the dissipater was found to be approximately 1,200 lb. Additional, dynamic ground tests were performed to measure the tearing strength at the high loading rate that would occur in the wind tunnel. That study showed that the tearing strength was independent of loading rate. Each of the 10 deployments performed in the wind tunnel at dynamic pressures as high as 100 lb/ft$^2$ used approximately 30 ft of tear ply.

The second wind tunnel program to be discussed also involved the deployment of a prototype parachute. In this case, the objective was to qualify the pilot parachute used in a bomb-retardation system at the low dynamic-pressure edge of the operational envelope. Successful deployments had been demonstrated at higher dynamic pressures with flight tests, but there was concern that the pilot chute might provide too little drag at low speeds to quickly extract the main parachute from its pack. To answer this concern, a series of deployments were performed in the Lockheed-Georgia 16-by-23-ft wind tunnel using a full-scale parachute system, at the operational dynamic pressure of 100 lb/ft$^2$.

The components of the system that was tested in the wind tunnel are shown schematically in Fig. 5. The aft portion of the bomb body was supported by cables at the upstream end of the test section. When fully deployed, the system extended over the total length of the test section. The load cell in the body measured force versus time for various combinations of pilot-parachute size and suspension-line retainer strengths. Notice that a short length of tear-ply energy dissipater was used to insure that the inertia of the main-chute deployment bag did not overload the support cables as the system was brought to rest.

## Concluding Remarks

This paper is an introduction to the technology of testing parachutes in wind tunnels. From the discussions presented, it is obvious that there are some serious problems with state of the art methods, especially in the area of canopy instrumentation and when working with reduced-scale models. Often, there are competing similarity issues that must be dealt with. But if the experimentalist is informed about the relative importance of the various factors for a specific test objective, it is usually possible to design a test that will yield meaningful results. The lower cost and the more favorable measurement environment of wind tunnels make their use an attractive alternative to flight testing whenever possible.

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