Application of Kevlar to Parachute System Design

C. W. Peterson,* W. B. Pepper,† D. W. Johnson,† and I. T. Holt†
Sandia National Laboratories, Albuquerque, New Mexico

Kevlar-29, an aramid fiber manufactured by DuPont, is being used on parachute systems requiring high strength-to-weight ratios or resistance to sustained high temperatures. Tests of parachutes using Kevlar webbing, braided cords, ribbons, and thread have demonstrated that these Kevlar materials can be used successfully in ribbon parachutes with no detrimental effects on performance. A few changes must be made in the design of a ribbon parachute to accommodate Kevlar's high modulus. Examples of parachutes that use Kevlar suspension lines, radials, ribbons, reefing lines, bridles, and skirt bands are presented to show that they are much lighter and more resistant to aerodynamic heating than their all-nylon counterparts.

Introduction

MANY parachutes must satisfy the opposing design objectives of possessing adequate structural strength to accommodate inflation loads without exceeding stringent weight and volume restrictions. Consequently, parachute designers have always sought out materials with high strength-to-weight ratios for use in all structural elements of a parachute system. A major advance in high-tenacity parachute materials took place in the middle of the last decade with the introduction of Kevlar,[1-4] an aramid fiber produced by E. I. DuPont de Nemours & Co. Kevlar-29 woven materials have less than one-half the weight and one-third the bulk of nylon materials with the same ultimate tensile strength. In addition, Kevlar is much more resistant to strength degradation at elevated temperatures; it retains half its strength at 290°C (550°F), the temperature at which nylon fails completely. These characteristics have made Kevlar-29 a very desirable material for use in parachute systems. However, the differences between physical properties of Kevlar and nylon may affect the way Kevlar is integrated into a parachute design. One important difference is the very low ultimate elongation of Kevlar compared to nylon: Kevlar stretches by only 5% of its original length before failing, whereas nylon stretches by approximately 25%. Other physical parameters of Kevlar, including sewability and weave stability, may also have to be taken into account during the parachute design process.

The primary purpose of this review article is to describe when and how to use Kevlar-29 in parachute systems. The advantages and disadvantages of using Kevlar suspension lines, bridles, and canopy elements will be discussed. In some cases, there are preferable alternatives to the use of Kevlar materials. Specific examples of parachutes with Kevlar structural elements are presented, and performance data from these parachutes are discussed. The large number of successful applications of Kevlar to parachute designs is proof that this strong, lightweight fiber will find extensive use in future parachute sytems.

Kevlar Suspension Lines and Radials

Replacement of nylon suspension lines with Kevlar lines on existing parachutes can enable the designer to utilize a proven canopy design while reducing the overall parachute system weight and volume. Kevlar suspension lines can also be for nylon lines so that the original canopy can be strengthened or enlarged without increasing overall system weight or volume. The original nylon lines are removed and the new Kevlar lines are attached near the skirt. The method of attachment depends upon the specific parachute geometry and construction at the skirt along the radial; a variety of standard attachment procedures have been used successfully. Even greater weight savings can be realized by substituting Kevlar materials for radials as well as for suspension lines. Obviously, Kevlar suspension lines and radials can also be used on new parachute designs as original equipment.

Kevlar suspension lines have been used on a wide variety of parachute systems at Sandia National Laboratories. The first-stage parachute for the NASA ARIES recovery system[5] is a 15-ft-diam ribbon parachute with 2000-lb braided Kevlar suspension lines. These lines were spliced onto the canopy at the skirt using 8 in. of zigzag stitching with 3-cord Kevlar thread. During the development of ARIES, the diameter of the original first-stage parachute had to be increased from 12.6 to 15 ft. By replacing the original 1500-lb nylon lines with Kevlar lines, the canopy diameter could be increased without changing the overall parachute pack volume. If the original 12.6-ft canopy had been retained, it would have weighed approximately 21% less with the 2000-lb Kevlar lines than with the 1500-lb nylon lines. No problems have been encountered with the modified 15-ft parachutes, even when one parachute was reused at system overtest deployment conditions.

An all-nylon 12.5-ft-diam ribbon parachute with 9000-lb nylon suspension lines and radials is used on a store shared by the U.S. Air Force and the U.S. Navy. The Navy requested that a few of these parachutes be modified with ram-air flotation bags on the canopy for ocean recovery during training exercises. The standard suspension lines and radials were replaced by 6000-lb Kevlar webbing to make room in the tight pack for the flotation bags. The reduction in parachute weight caused by this change was 34%. If 9500-lb Kevlar webbing had been used to retain the strength of the original suspension lines, the weight reduction would have been 27%. Parachutes with the Kevlar lines and flotation bags were tested with no damage and no significant changes in performance.

In order to save weight on the retardation system for a 2400-lb store, Kevlar suspension lines were used instead of nylon on both the 13-ft-diam first-stage lifting parachute and the 36-ft-diam second-stage ringsail parachute. The 9000-lb nylon webbing used for suspension lines and radials on the lifting parachute was replaced by 13,500-lb Kevlar webbing, and the 2250-lb nylon suspension lines on the ringsail were replaced by 2000-lb braided Kevlar lines. Performance of the

Presented as Paper 84-0810 at the AIAA 8th Aerodynamic Decelerator and Balloon Technology Conference, Hyannis, MA, April 2-4, 1984; received March 17, 1985; revision received Aug. 20, 1985.

*Supervisor, Parachute Systems Division Associate Fellow. AIAA.
†Member, Technical Staff, Parachute Systems Division Member. Associate Fellow. AIAA.

system was improved, while the combined weight of the two parachutes was reduced by approximately 20%. Kevlar was also used extensively in the design of deployment bags, reefing lines, bridles, and skirt reinforcement for an overall weight reduction of 37% with respect to the original all-nylon design. In over 70 flight tests of this system at deployment Mach numbers from 0.5 to 1.5, the Kevlar suspension lines were found to be reliable and predictable.

Sandia uses 4- and 6-ft-diam guide surface parachutes to recover artillery shells launched almost vertically from a cannon. The shells and recovery system experience as much as 18,000-g setback loads in the barrel, and their maximum spin rate is approximately 15,000 rpm. On some flights, the 550-lb nylon suspension lines have been frayed and broken when parts of the spinning shell have rubbed against the lines. To minimize abrasion damage, the 550-lb nylon lines were replaced by 1500-lb braided Kevlar suspension lines, which weigh the same as the original lines. The Kevlar lines withstood a continuous abrasion test for 3.6 times longer before breaking than the nylon lines. Replacement of the nylon lines was straightforward, and packing of the guide surface parachutes with Kevlar lines was easier than packing the original system.

An 8-ft-diam, all-nylon ribbon parachute was modified to fit an existing parachute can for recovery of a 130-lb ballistic reentry vehicle.[6] The diameter was reduced to 6.44 ft and the 1000-lb tubular nylon suspension lines were removed and replaced with 2000-lb braided Kevlar lines. Webbing of 6500-lb tensile strength, 1.75-in. wide, was used for the skirt band. The finished parachute weighed 3.6 lb. This parachute was deployed in free flight successfully at a dynamic pressure of 766 lb/ft^2 with no reefing.

The same 8-ft ribbon parachute was modified for the Sadarm booster rocket recovery of a 266-lb test vehicle up to 1200 ft/s at deployment.[7] The 1000-lb nylon lines were removed and replaced with 3500-lb braided Kevlar. The parachute was reefed for 2 s by a 9-ft-long, 1500-lb braided nylon reefing line. Reefing rings 1/2-in. in diameter were used at each radial and at mid-gore.

Table 1 summarizes these and other Sandia parachute systems that were retrofitted with Kevlar suspension lines in place of the original nylon lines. Typically, the parachute weight can be reduced by 20-25% by this retrofit alone, and by more than 25% if the nylon radials are replaced by Kevlar in addition to the suspension lines. As mentioned earlier, however, comparable weight savings can be realized on new parachute designs as well as on existing configurations. An example of a new parachute that uses Kevlar suspension lines and radials is a 46.3-ft-diam, 60-gore, 20-deg conical ribbon parachute developed at Sandia National Laboratories. The suspension lines continue across the canopy as radials. Four suspension lines are formed from a single length of 6000-lb Kevlar webbing in a figure-eight loop in order to minimize the number of splices and thereby maximize the efficiency of the suspension lines. The canopy is a continuous-ribbon design rather than a cut-gore construction; again, this design maximizes strength and minimizes weight by reducing the number of ribbon splices and eliminating material overlap at each radial. The 46.3-ft parachute weighs approximately 185 lb, yet it has generated deceleration loads of 208,000 lb on a 2200-lb payload during flight tests at $M = 1.4$. This parachute is deployed by a cluster of three 3.8-ft-diam pilot parachutes, which also use Kevlar for suspension lines and radials. Reference 8 describes this parachute system in more detail.

The 1-in., 2400-lb Kevlar webbing used for radial backing on the 46.3-ft parachute was developed specifically for this retardation system. Establishing a new Kevlar weave is not a major development program because there are now several weavers with extensive experience with Kevlar parachute materials. The new 2400-lb Kevlar webbing weighs less than 0.4 oz/yd and has good sewability characteristics. Sandia conducted tests of candidate weaves, including specimens with sewn joints, before selecting the 2400-lb weave used in the 46.3-ft parachute.

Most applications of Kevlar to parachute systems will not require the development of new weaves. A large number of Kevlar parachute materials was developed by the Air Force Flight Dynamics Laboratory in the 1970s. Extensive tests of the strength of Kevlar weaves, the efficiency of sewn joints, and other mechanical properties of Kevlar webbings, tapes, cords, and thread have provided the parachute designer with a wide variety of Kevlar materials that should meet most parachute design requirements. The Air Force has published military specifications of these Kevlar textiles,[9-12] which describe their construction and mechanical properties in detail.

Table 1 Examples of Sandia parachute systems retrofitted with Kevlar suspension lines

Parachute system description	Original nylon suspension lines	Replacement Kevlar suspension lines	Potential weight reduction, %[a]	Kevlar radials	Comments on advantages of Kevlar lines
12.5-ft ribbon, Navy Trainer unit	9000-lb webbing	6000-lb webbing	27	Yes	Kevlar lines allowed flotation bags to be added to canopy without increasing parachute weight
15-ft ribbon, ARIES 1st stage	1500-lb braided	2000-lb braided	21	No	Kevlar lines allowed canopy diameter to be increased from 12.6 to 15 ft without increasing parachute pack volume
13-ft ribbon lifting parachute	9000-lb webbing	13,500-lb webbing	25	Yes	Kevlar parachute weighed less but provided higher performance than original nylon configuration
36-ft ringsail, recovery parachute	2250-lb webbing	2000-lb braided	20	No	Both retrofitted and new ringsails with Kevlar lines were tested successfully
4-ft guide surface, shell recovery parachute	550-lb braided	1500-lb braided	16	Yes	Kevlar lines are much more resistant to abrasion but weigh no more than the nylon lines they replaced
12.5-ft ribbon, SLAP-TV parachute	9000-lb webbing	9000-lb webbing	33	Yes	First attempt at using Kevlar lines with a nylon canopy at Sandia
8-ft ribbon, recovery parachute	1500-lb tubular	1500-lb braided	16	Yes	Kevlar lines were required to pack parachute in limited volume
6.44-ft ribbon, LBRV	1500-lb webbing	2000-lb braided	26	No	Same as above
8-ft ribbon, Sadarm recovery	1500-lb webbing	3500-lb braided	100% increase in line strength for 16% weight increase	No	Twice line strength of original parachute

[a]The potential weight savings refers to the reduction in weight that would occur if the nylon lines were replaced by Kevlar lines of the same strength and no other changes were made to the parachute.

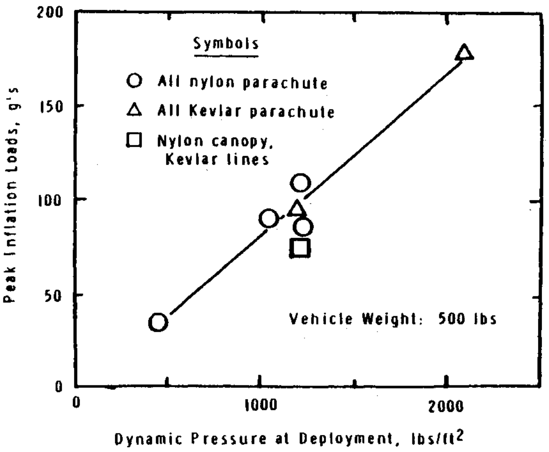

Fig. 1 12.5-ft-diam parachute peak inflation loads.

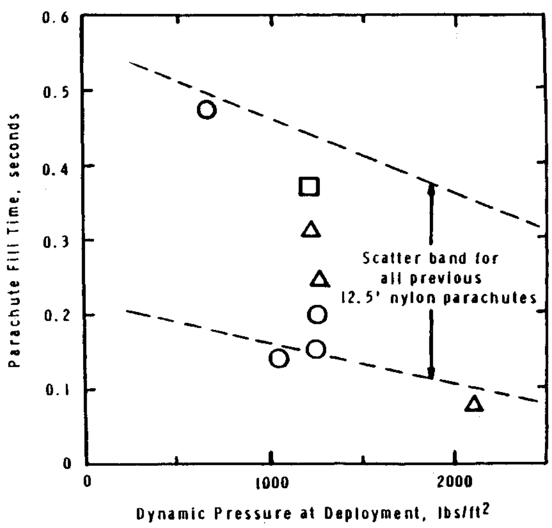

Fig. 2 12.5-ft-diam parachute filling time.

Snatch Loads and Inflation Loads with Kevlar Suspension Lines

Some designers have been reluctant to use Kevlar suspension lines in parachutes for fear that snatch loads might be significantly higher than for nylon suspension lines because Kevlar's ultimate elongation is so much lower than nylon's. Nylon lines are able to store more energy than Kevlar lines of the same strength when equal loads are applied. For this reason, Kevlar suspension lines may not be as desirable as nylon lines for applications in which the limiting loads for the parachute system are imposed by what the payload, rather than what the parachute itself, can withstand. In personnel parachutes, for example, the higher snatch loads associated with Kevlar suspension lines are often unacceptable to the "fragile" payload. For high-performance parachutes decelerating payloads with no sensitivity to load levels, the parachute designer should not rely upon the potential energy capabilities of the suspension line material to withstand snatch loads. If snatch loads are too high (particularly if they are higher than peak inflation loads), the parachute deployment method should be reexamined, not the suspension line material. High snatch loads in high-performance parachutes are invariably created by excessive bag velocities at canopy stretch or by a deployment method or bag design that prevents an orderly "lines-first" deployment of the canopy.

Similarly, we have found that the peak inflation loads depend upon canopy geometric porosity, number of verticals, and ribbon materials, but not suspension line material. This should not be surprising, since the amount of kinetic energy removed from the payload by a high-performance parachute far exceeds the potential energy storage capacity of the suspension lines. The suspension line material should have relatively little effect upon the peak inflation loads because the suspension lines are intended to transmit these deceleration loads to the payload rather than to attenuate these loads. Tests of 12.5-ft-diam parachutes[13] with both Kevlar and nylon suspension lines and radials were conducted to observe any differences in peak inflation loads caused by the suspension line material. Figure 1 shows that the suspension line material had a negligible effect on peak inflation loads. Similar results were reported by Pinnell[4] for 15.3-ft-diam all-Kevlar and all-nylon conical ribbon parachutes.

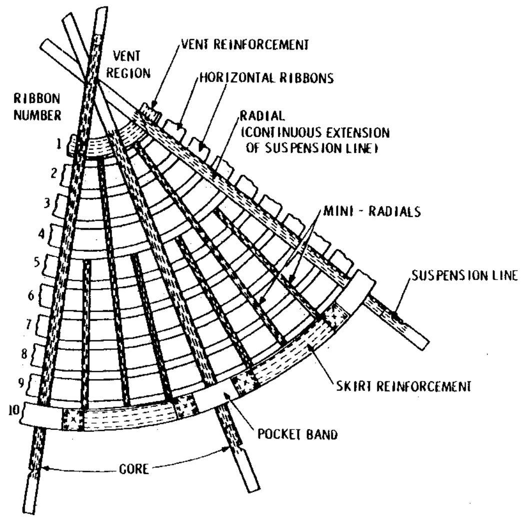

Fig. 3 All-radial parachute design.

Kevlar Ribbons and Verticals

If additional weight savings are desired, Kevlar can be used in place of nylon for parachute ribbons and verticals. Several parachutes have been built at Sandia with Kevlar ribbons and verticals to obtain higher drag area without increasing the weight of the packed parachute. Other all-Kevlar canopies have been designed for applications involving higher temperatures than nylon can withstand. From the following examples, it is evident that Kevlar can be used throughout the canopy as long as its low ultimate elongation is taken into account by the parachute designer.

Sandia's initial research using Kevlar-29 in parachutes was accomplished using a 500-lb sled-launched adaptive parachute test vehicle (SLAP-TV) with 12.5-ft-diam, 15-deg conical ribbon parachutes.[13] This configuration was selected because an all-nylon version of it had successfully completed over 500 tests from aircraft. Several all-Kelvar versions of this parachute were constructed, along with one nylon canopy with Kevlar suspension lines and radials. During ten flight tests of these parachutes, it was discovered that the all-Kevlar parachute would not inflate fully when it was constructed using the same patterns made for the all-nylon parachute. The incomplete inflation was caused by rotation of the Kevlar ribbons about their centerlines (a motion similar to that of a venetian blind); this rotation increased the effective porosity of the canopy and limited the drag area of the all-Kevlar parachute to only 70% of the all-nylon parachute drag area. Three more ribbons (for a total of twenty-seven) and a seventh vertical were added to the all-Kevlar parachute to reduce the geometric porosity of the canopy and to exert more control over the orientation of the Kevlar ribbons. These changes made the inflation characteristics of the all-Kevlar parachute similar to those of the all-nylon parachute. Figures 1 and 2 show that the peak inflation loads and inflation times for the

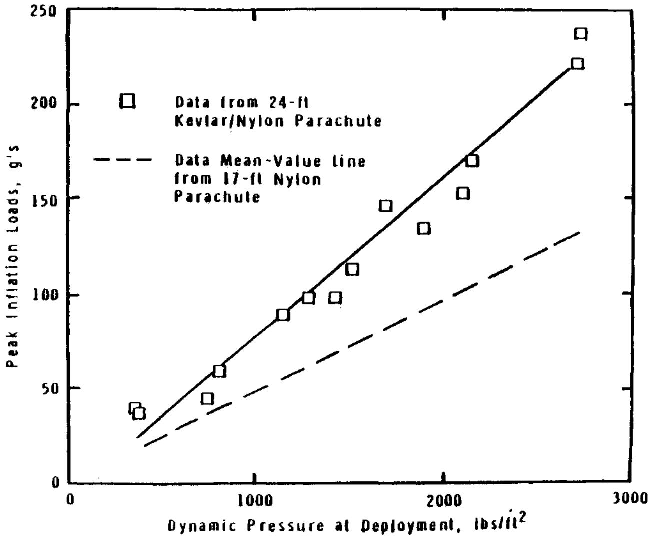

Fig. 4 Peak inflation loads for a 24-ft-diam Kevlar/nylon parachute.

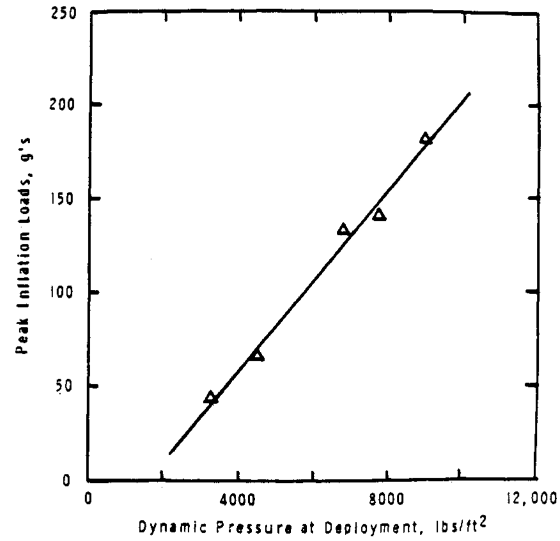

Fig. 6 Peak inflation loads for 19-in.-diam all-Kevlar ribbon parachute.

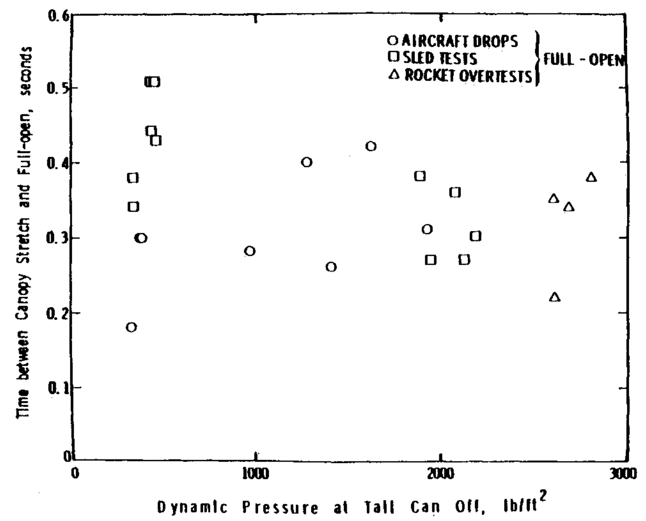

Fig. 5 24-ft-diam Kevlar/nylon parachute fill times.

modified all-Kevlar parachutes are not significantly different from the data obtained for the all-nylon parachutes.

When the first modified all-Kevlar parachute was tested at high dynamic pressure, approximately 20 of the 3000-lb Kevlar ribbons located near the vent of the parachute were half-torn, starting at the outer edge of the ribbon nearer the skirt. The low elongation of the Kevlar material, coupled with the difference in circumference between the inner (nearer the vent) and outer (nearer the skirt) edges of the continuous ribbons (Fig. 3), resulted in excessive loading of the outer edges of these ribbons. The vent band was strengthened, and the seven 2-in.-wide 3000-lb Kevlar ribbons nearest the vent were replaced by fourteen 1-in.-wide 2000-lb Kevlar ribbons to reduce the difference in circumference across the ribbons. Graduated fullness was added to the six 2-in.-wide ribbons next to the 1-in.-wide ribbons to eliminate any stress concentrations. These modifications enabled the parachute to survive a supersonic deployment with no damage to the vent region of the canopy.

An alternative to using narrow Kevlar ribbons in the vent region is to design a "hybrid" canopy with nylon ribbons in the vent region and Kevlar ribbons throughout the rest of the canopy. Nylon's greater elasticity enables it to smooth out the stress concentrations caused by the differences in circumference across the ribbons near the vent. Furthermore, a nylon ribbon will experience lower stresses than a Kevlar ribbon for a given parachute geometry and pressure distribution because the greater elasticity of a nylon ribbon decreases its radius of curvature under load. The hybrid canopy weighs more than the all-Kevlar canopy, but the difference in weight is usually small because the nylon ribbons near the vent are short.

An example of a hybrid Kevlar/nylon parachute canopy is the 24-ft-diam ribbon parachute[14] designed to retard a 760-lb store at deployment velocities as high as 800 knots calibrated airspeed (KCAS). The twenty-one ribbons nearest the vent were 3000-lb reinforced selvage nylon. Ribbons 22-31 were made of 2000-lb Kevlar-29, and ribbons 32-54 were made of 1000-lb Kevlar-29. Ribbons 22-28 were made slightly longer than their normal geometric lengths to prevent the adjacent nylon ribbons from transferring their loads to the Kevlar ribbons as they stretched. The extra ribbon length ("fullness") was reduced linearly from 4% at ribbon 22 to zero for ribbon 29. No ribbon failures have been encountered in the region where this extra fullness was incorporated.

The 24-ft hybrid parachute has twice the drag area of the 17-ft-diam, all-nylon parachute it replaces, yet it weighs the same (84 lb with all rigging and bag) and is packed in the same volume (2.1 ft^3) as the 17-ft parachute. Kevlar suspension lines, radials, verticals, reefing line, and skirt reinforcement were used on this parachute in addition to Kevlar ribbons. There were no unusually high values of peak deceleration caused by the extensive use of Kevlar. Figures 4 and 5 present measured values of peak loads and inflation times over the operational range of deployment dynamic pressures.

The preceding examples show that Kevlar's low ultimate elongation requires modifications to the design practices that were developed for parachutes using all-nylon canopies. Parachutes with only Kevlar ribbons or both nylon and Kevlar ribbons may have to be built with ribbon fullness, lower geometric porosity, and modified Kevlar ribbon widths in the vent region. These modified design techniques can add to the complexity and cost of the parachute. As a result, Sandia parachute designers give preference to all-nylon canopy designs over hybrid or all-Kevlar canopy designs whenever possible. With the development of several new lightweight nylon ribbon weaves, an all-nylon canopy does not have to be much heavier than a hybrid canopy. Efficient nylon ribbons, such as the 2-in.-wide, 550-lb reinforced selvage weave used in the bottom half of the 46.3-ft parachute, are viable alternatives to Kevlar ribbons. The 550-lb nylon ribbon weighs about the same as the 2-in.-wide, 1000-lb Kevlar ribbon used in the 24-ft hybrid parachute; it is 43% lighter than the Class

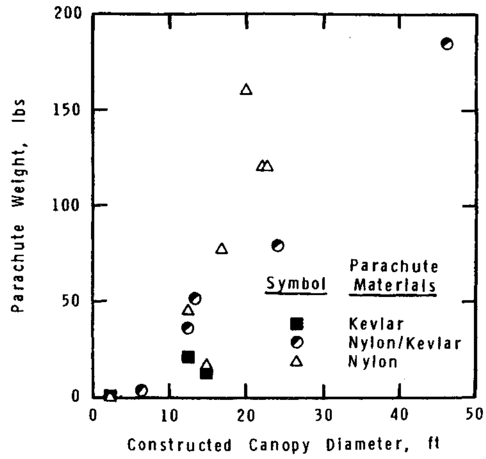

Fig. 7 Weight of ribbon parachutes.

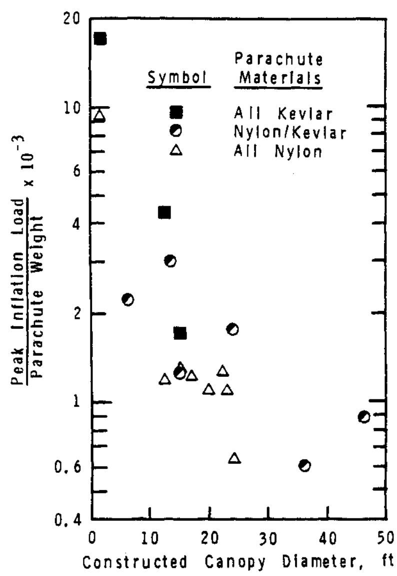

Fig. 8 Tested parachute strength-to-weight ratios.

D, Type II, 460-lb nylon ribbon that it has replaced on Sandia parachute designs. On large, high-performance parachutes, the 550-lb nylon ribbon can be used instead of the 1000-lb Kevlar ribbon in the skirt region because the parachute slows the payload down by the time the ribbons in the skirt region experience any aerodynamic loads. Lighter Kevlar ribbons (rated at 400, 600, and 800 lb) are available in 2-in. widths, but these ribbons have inferior sewability, tear initiation resistance, weave stability, and porosity compared to the 550-lb nylon selvage ribbon. The reason for the poor stability, porosity, and sewing of these lightweight Kevlar ribbons is that the minimum commercially available denier for Kevlar yarn is presently 200. Improved weave characteristics require Kevlar yarns with lower denier. DuPont has recently produced experimental 55-denier Kevlar yarn for evaluation in fabrics for personnel parachutes. Even if ribbons made from 55-denier Kevlar yarn were available today, trade-offs between canopy weight, simplicity of design, performance, and cost should be made before selecting the ribbon material for any parachute system.

All-Kevlar canopies are practically a necessity for parachutes that operate at supersonic speeds and elevated temperatures for extended periods of time. One example is a 19-in.-diam ribbon parachute[15] designed to recover a 57-lb re-entry vehicle nosetip at deployment dynamic pressures up to 9000 lb/ft^2. The canopy has 15 continuous ribbons made of 0.5-in.-wide, 550-lb Kevlar. The skirt and vent bands were formed by doubling the 550-lb Kevlar. The three verticals per gore were made of doubled 400-lb braided Kevlar. Suspension lines are 2000-lb braided Kevlar. The same material was used to build a 48-in.-long overinflation line. The entire canopy, with overinflation line, weighs only 9.4 oz.

No structural failures of this reentry vehicle have occurred up to the maximum deployment dynamic pressure. Nylon ribbon splice wraps in the 19-inch canopy have melted due to stagnation temperatures exceeding 500°F at Mach numbers approaching 3. The Kevlar canopy components took a permanent set because of the combination of aerodynamic heating and high loads, but there was no failure due to aerodynamic heating anywhere in the parachute. The linear relationship between maximum inflation loads and deployment dynamic pressure for the 19-in. all-Kevlar parachute is shown in Fig. 6.

Other Kevlar Parachute System Components

Kevlar has been used in several other Sandia parachute system components, including vent reinforcement bands, vent lines, skirt bands, reefing lines, overinflation lines, bridles, and deployment bags. In general, the design of these Kevlar components is similar to the design of their nylon counterparts, with minor changes required to accommodate Kevlar's low ultimate elongation.

Kevlar vent reinforcement bands have been used on all-Kevlar canopies like the 19-in. reentry vehicle first-stage parachute. On hybrid and all-nylon canopies, however, nylon vent reinforcement is preferred over Kevlar for the same reasons that nylon ribbons are preferred over Kevlar ribbons in the vent. The extra stretch of the nylon vent reinforcement minimizes stresses and distributes loads more evenly than Kevlar reinforcement. Kevlar vent lines are used extensively at Sandia because they are usually extensions of Kevlar suspension lines and radials. Kevlar vent lines are designed to be about 5% shorter than the vent diameter (rather than 10% shorter for nylon vent lines) because of Kevlar's lower ultimate elongation.

Kevlar skirt reinforcement bands, reefing lines, and overinflation lines are used extensively at Sandia because significant weight savings can be realized for these canopy elements. The design of these Kevlar elements is the same as for their nylon counterparts. In some cases, a slightly different reefing line cutter may have to be used to cut a Kevlar reefing line because of its reduced bulk and higher resistance to abrasion compared to nylon. Kevlar skirt reinforcement and reefing lines have been used without problems on the 12.5-ft SLAP-TV parachutes, the 24- and 46.3-ft parachutes, and an 8-ft recovery parachute.

Kevlar bridles can be used in place of both nylon and steel aircraft cable to reduce pack weight and volume. Examples of Kevlar bridles include those used on the first- and second-stage parachutes for the reentry vehicle recovery system described in Ref. 7. Kevlar bridles are more flexible and easier to pack than steel cables, and they have greater strength-to-weight ratios than either nylon or steel bridles. No problems have been caused by Kevlar's low ultimate elongation on any of Sandia's Kevlar bridle designs. We have used steel cables instead of Kevlar bridles only on systems in which the bridle may be exposed to sharp edges or a severe abrasion environment.

Kevlar's high strength-to-weight ratio and low ultimate elongation are particularly desirable in the construction of deployment bags for high density packs. Pack densities of 43 lb/ft^3 for the 24-ft parachute, 40 lb/ft^3 for the 46.3-ft parachute, and over 50 lb/ft^3 for the 19-in. reentry vehicle first-stage parachute have been achieved by using Kevlar cloth, webbing, and even lacing in the deployment bag design. Kevlar's low elongation minimizes stretching of the bag and lacing after the parachute packing process has been completed. A few minor adjustments in deployment bag fabrication are needed to accommodate the differences in take-up between nylon and Kevlar cloths and webbings.

Summary and Conclusions

Kevlar-29 materials have been used successfully in place of nylon for all structural elements of parachute systems. Parachutes with Kevlar components have demonstrated structural integrity and performance comparable to all-nylon parachutes of the same basic configuration. Kevlar parachutes are lighter and more resistant to aerodynamic heating and abrasion than their nylon counterparts. Fabrication experience and flight test data from a wide variety of Kevlar parachutes lead to these conclusions about the use of Kevlar in high-performance parachute systems:

1) Significant weight savings can be expected when Kevlar-29 is used instead of nylon on parachute systems. Weight reductions of approximately 25% are possible if Kevlar is substituted for nylon for suspension lines and radials. A 50% weight reduction has been demonstrated for an all-Kevlar parachute system. Figure 7 summarizes the relative weights of all-nylon, nylon-Kevlar, and all-Kevlar parachutes as a function of constructed diameter. Figure 8 shows that parachutes with Kevlar have a higher strength-to-weight ratio than all-nylon parachutes.

2) All-Kevlar parachutes have been tested successfully in high aerodynamic heating environments that would have melted nylon parachutes.

3) Snatch loads and peak inflation loads do not depend upon the suspension line material as much as upon the deployment system and canopy geometry. Snatch loads can be accommodated by Kevlar suspension lines if an orderly, lines-first deployment of the parachute system is inherent in the deployment system design.

4) Kevlar's low ultimate elongation requires that the design of an all-Kevlar ribbon parachute canopy be somewhat different from the design of an all-nylon canopy. Kevlar ribbons in the vent should have extra fullness and may have to be narrower than the ribbons nearer the skirt. All-Kevlar canopies may have to be designed with extra verticals to control the Kevlar ribbon orientation. A lower geometric porosity may also be required for an all-Kevlar canopy in order to get the same inflation loads as an all-nylon canopy of the same diameter.

5) The use of Kevlar in parachute design should be treated as a design option rather than a design requirement. Kevlar is more expensive than nylon, and nylon may be structurally preferable to Kevlar in certain regions of the parachute. Each parachute system design should be analyzed thoroughly to determine whether Kevlar's unique physical characteristics are required to meet performance objectives and weight/volume constraints.

Acknowledgments

This work was performed at the Sandia National Laboratories, supported by the U.S. Department of Energy under contract number DE-AC04-76DP00789.

References

[1]Williams, D., "Investigation of Fiber B as a Lightweight Parachute Recovery System Material," Goodyear Aerospace Corp., Akron, OH, GER-16012, April 1974.

[2]Coskren, R. J., Abbott, N. J., and Ross, J. H., "Kevlar 29 and 49 in Parachute Fabrics," AIAA Paper 75-1360, Nov. 1975.

[3]Pepper, W. B. Jr., "Some Observations and Uses of Kevlar-29 at Sandia Laboratories," SAND77-0305A, Abstract for Kevlar Workshop, April 1977.

[4]Pinnell, W. R., "Materials and Design Criteria for Kevlar-29 Ribbon Parachutes," Air Force Wright Aeronautical Laboratory, AFWAL-TR-81-3138, April 1982.

[5]Pepper, W. B. and Collins, F., "Development of the ARIES Parachute System," AIAA Paper 81-1949, Oct. 1981.

[6]Pepper, W. B., "Development of the Parachute Recovery System for the LBRV-2 Reentry Vehicle," AIAA Paper 84-0802, April 1984.

[7]Pepper, W. B., "Development of an 8-ft-diam Ribbon Parachute for Recovery of a Test Device at Transonic Speeds," AIAA Paper 84-0793, April 1984.

[8]Johnson, D. W. and Peterson, C. W., "High-Speed, Low-Altitude Payload Delivery Using a Single Large Ribbon Parachute," AIAA Paper 84-0803, April 1984.

[9]*Webbing, Textile, Tubular, Para-Aramid Intermediate Modulus,* Military Specification MIL-W-87127 (USAF), May 17, 1978.

[10]*Thread, Para-Aramid, Intermediate Modulus,* Military Specification MIL-T-87128 (USAF), May 17, 1978.

[11]*Cord, Coreless, Para-Aramid, Intermediate Modulus*, Military Specification MIL-C-87129 (USAF), Aug. 2, 1978.

[12]*Tape and Webbing, Textile, Para-Aramid, Intermediate Modulus,* Military Specification MIL-T-87130, May 17, 1978.

[13]Pepper, W. B. Jr., "Evaluation of Kevlar-29 vs Nylon for 3.81 m (12.5 ft) Diam Ribbon Parachutes," *Journal of Aircraft*, Vol. 17, March 1980, pp. 198-205.

[14]Peppers, W. B. Jr., "Design and Development of the 24-ft Diam Hybrid Kevlar-29/Nylon Ribbon Parachute," *Journal of Aircraft*, Vol. 17, Jan. 1980, pp. 45-52.

[15]Pepper, W. B. Jr., "Preliminary Report on Development of an Interim Parachute Recovery System for a Re-entry Vehicle," *Journal of Aircraft*, Vol. 17, March 1980, pp. 218-224.