EVOLUTION OF THE RINGSAIL PARACHUTE

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The Ringsail parachute was first designed in February 1955. Ed Ewing, a gifted parachute designer and system engineer, conceived it as a modification of the Ringslot canopy. Since its initial development, and early failure to qualify as an escape system parachute, the canopy reached acclaim on all of the U. S. manned spacecraft recovery applications including Mercury, Gemini and Apollo. Its opening reliability, damage tolerance and low opening shock characteristics have since made it the canopy of choice when man rated reliability level was included in the design requirements. Other applications used the Ringsail with great success as discussed in Section 2.0 where a review of the Ringsail is presented.

Nomenclature

C_{D0} = drag coefficient
D_o = nominal diameter, ft.
g_0,F_0 = parachute opening load: gee’s, lb.
h, h_g = height(variable), gore height
K_A = shape stress factor
K_B = leading edge fullness factor
l_S = parachute line length, ft.
$l_{S/}$ D_o = line length ratio
Q_s = line stretch dynamic pressure, lb./ft^2
S_0 = nominal cloth area, ft.^{2}
Ve_0 = nominal rate of descent, ft/sec
V_0 = deployment velocity, ft/sec TAS or KEAS
W_c = canopy weight, lb.
W_V/ S_0 = canopy loading, lb./ft^2
W_V = air vehicle suspended weight, lb.
η_D = drag efficiency, drag area per/lb.

1.0 INTRODUCTION

This paper provides the designer detailed information on the evolution of the Ringsail canopy design. Areas discussed are crown region fullness, the characteristic leading edge fullness and planform alternatives, some of which were found less than meritorious. Ewing[1] documented the Ringsail in his comprehensive report written after the Apollo development. An important Ringsail application, in service prior to the 1972 Reference 1 publication date, namely the F-111 Crew Escape Module recovery parachute is documented.

Numerous Ringsail designs have emerged after the publication date using performance enhancing techniques, construction methods and current materials. A substantial increase in drag performance and drag efficiency has served to continue the use of this canopy type into the next century. Technical areas presented include planform enhancements, opening phase control techniques and performance improvement details.

Open variation of both slot and section width and number was considered early in the development of the Ringslot gore geometry. Adding section fullness and increasing the average angle of attack in the rings in the lower gore was proposed by Ewing to have technical merit in three areas. These were: 1) a drag coefficient increase, 2) better opening characteristics and 3) reduced transverse crown area fabric stress by reducing the local radius of curvature. The first and second premises proved the major advancement of the Ringsail. The third premise merely reinforced the concept of adding crown fullness for stress relief, a practice warranting considerable reevaluation when less than ideal opening process intermediate shapes unfurl.

2.0 BACKGROUND OF THE RINGSAIL SPACECRAFT APPLICATIONS

The three manned spacecraft applications of the 1960’s and 1970’s brought the Ringsail into national prominence. Its opening reliability was the major consideration for selection on the Mercury program. When the Paraglider development stalled on the Gemini program, the 84.2 ft. Ringsail was ready for timely qualification. Then the Apollo earth landing system was qualified as the first manned application to use a three-chute cluster as the recovery parachute. The various reentry modes and command module attitudes coupled with a difficult multi-bay installation dictated individual mortar deployed pilot chutes as the deployment approach. This led to severe lead-lag opening load problems between the three main parachutes. In part, the tendency of the Ringsail to overinflate, or continue a drag area increase during the reefing interval, aggravated the problem. The solution was to add a major slot width in panel 5 of the 14 panel sections. This change, coupled with a gore count decrease from 72 to 68 reduced the nominal diameter of the canopy from 88.1 to 85.6 ft., but allowed a load balanced design with assurance that all three canopies would reach and maintain full inflation.

There were several other important spacecraft recovery applications, both manned and military satellite recovery completed by Northrop Ventura as listed on Table 1.

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PARAMETER	ASSET	E-6	MERCURY	E-5 SAMOS	GEMINI	APOLLO	CENTURY	EELV	K-1 OrbiterV	K-1 LaunchP	20 K	20 K
$W_{v,}$ lb.	1,085	1,300	2,340	1,700	4,400	14,250	9,762	20,000	27,000	45,000	20,000	20,000
W_v/S_o, lb/ft^2	1.577	0.985	0.751	0.393	0.790	0.825	0.749	0.459	0.471	0.392	0.754	0.708
Q_s, lb/ft^2	250	76	76	66	120	122	64	45	40	40	80	80
Ve_0, ft/sec	55.0	35.0	24.0	20.6	29.6	29.5	27.9	20.0	19.6	18.3	27.5	25.5
C_{D0}	.67	.68	.91	.78	.76	.85	.90	1.03	1.10	1.10	.84	.92
No.of Chutes	1	1	1	1	1	3	1	3	3	6	1	1
D_o, ft	29.6	41.0	63.0	74.2	84.2	85.6	128.8	136.0	156.0	156.0	183.8	189.6
W_c, lb.	14.0	24.0	55.4	73.0	41.9	105.4	206.0	135.0	230.0	230.0	544	557.0
No.of Gores	24	32	48	60	72	72	112	96	112	112	156	156
No.of Rings	9	9	10	12	13	14	21	15	15	15	27	27
l_S/ D_o	.93	.93	.97	.94	.94	1.40	1.15	1.15	1.15	1.15	1.18	1.23

Table 1 Spacecraft Applications of the Ringsail

Several Table 1. Ringsails were developed outside of Northrop Ventura. In 1964 the 20 K Program, a development to recover a 20,000 lb. Apollo Exploration Series (AES) Command Module was initiated. The canopy was intended for use in the backup mode, including the pad abort mode, where the Cloverleaf Steerable main recovery parachute could not meet the 3g opening shock or timeline to full inflation. The contract was placed by NASA with Irvin and was only the second application of the Ringsail developed outside of Northrop Ventura at the time. The 189.6 ft. Phase 1 design was resized based on the high Phase 1 drag achieved. The Phase 2 183.8 ft. Ringsail met all NASA descent and opening time requirements.

Recently the Ringsail was applied to recover the propulsion module on the Boeing Evolved Expendable Launch Vehicle. Figure 1. shows the EELV main system at splashdown. The 136.0 ft. Ringsail offered Apollo heritage three chute cluster reliability and applied advanced inflation control techniques to allow elimination of the Apollo type lead-lag control slot. Deployment by the drogue stage of all main canopies eliminated the main source of the timing variance that plagued the Apollo main development. The canopy was proposed as the recovery parachute on a commercial satellite launcher, the K-1 Launch Vehicle. As weight growth occurred, the main parachute evolved from the EELV all nylon 136.0 ft. to 156.0 ft. Ringsails with a Kevlar structural grid. The K-1 system has been deployed in single, 3-chute cluster and 6-chute cluster. Figure 2 shows the size of the K-1 cluster representing a world record in total cloth area and drag area deployed at one time scaled against the Eiffel Tower.

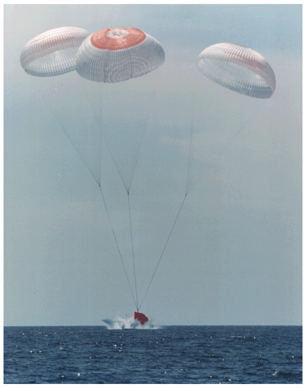


Fig. 1 EELV Splashdown

Fig. 2 K-1 6-Chute Cluster vs. Eiffel Tower

On Table 2. are listed a few large Ringsail features.

Application	Size, ft.	No. of Rings	No. of Panels	Feet of Suspension Line
Century Series	128.8	21	2,352	16,589
EELV	136.0	15	1,440	15,014
K-1	156.0	15	1,680	20,093
20 K	189.6	26	4,056	34,842

Table 2 Large Ringsail Salient Features

Large parachutes have been deployed. Both a 150 ft. and a 200 ft. Flat Circular cargo chute prototypes have been deployed in the early 1950's. Opening characteristics of these parachutes was poor with prolonged fill time and infolding present. Thus the 189.6 ft. 20K Ringsail stands as the second largest nominal diameter parachute ever built

ESCAPE SYSTEM APPLICATIONS

The initial Ringsail candidate as an escape system parachute was the Skysail. The canopy had to meet a 400 knot deployment speed and not produce greater than 25g opening loads at less than 22 fps rate of descent and be installed at minimum pack weight and bulk. It was found that Ringsails in lower size could not develop the high drag coefficient that larger, high ring count designs produce. While opening loads could be met, the stability of the Skysail was also marginal and the canopy could not be qualified.

Crew modules, such as used on the B-58, F-111 and B-1A aircraft surfaced as applications where the Ringsail was prime. The B-58 used a 41.0 ft canopy, while the F-111 applied a 70.0 ft. parachute and the B-1A a three-chute cluster of 69.8 ft. Slotted Ringsails[2]. A F-111 Crew Escape Module recovery parachute replacement program whose objective was to lower CEM rate of descent to acceptable level using advanced material and design concepts was initiated in the late 1980's. Use of a Kevlar structural grid and intermediate permeability fabric in the mid gore allowed an 85.6 ft. canopy to replace the original 70.0 ft. Ringsail in the same compartment volume. A secondary requirement to inflate as rapidly as the original parachute demanded that special attention be paid to inflation time reduction techniques.

UNMANNED AERIAL VEHICLE RECOVERY

Ringsails have been applied as recovery parachutes starting with the RP-76, Q-4A and Q-4B series. The Ringsails were 24.1, 63.0 and 84.2 ft. respectively. The parachute was later applied as a mid-air recovery parachute on the Beech / USAF High Altitude Supersonic Target (HAST) program. A 45.5 ft. Ringsail, the largest size a direct helicopter engagement would allow was applied. The same parachute was then used on the Firebolt program with refinement in compartmentation and drogue deployment system. Because of its positive inflation characteristics, the Ringsail was then studied on the Universal Aerial Retrieval Program for the USAF. It was applied by Northrop as the engagement parachute above an Annular main parachute. Irvin took this concept into qualification status in the late 1970's on the Air Launched Cruise Missile (ALCM) program. Here a 23.6 ft. Ringsail / 70.6 ft Annular with a Kevlar structural grid produced the highest drag efficiency mid-air retrieval system yet developed. The recovery parachute is operational to this date on the C-ALCM program. The concept was successfully applied on two black programs, one a parachute-airbag landing system where the < 5° off vertical stability and drag efficiency prevailed. The other program was a mid-air retrieval system using the ALCM baseline design concept.

SOUNDING ROCKET

Use of the Ringsail as a sounding rocket main recovery parachute was successfully done in the 1970's and 1980's. The Black Brant VC and Nike-Tomahawk Nike-Hydac class payloads were operationally recovered. While limited in scope the payload value was extremely high demanding Ringsail reliability.

SPECIAL WEAPON AND CAPSULE

The Ringsail was combined with the Automatic Inflation Modulation (AIM) style center parachute rigging concept in 1982 on a advanced development program with Sandia National Laboratory Albuquerque. Used in conjunction with the lifting ribbon class drogue, the concept offered faster inflation, coupled with the avoidance of post-inflation collapse. Various sizes of center chutes were tested to optimize the concept. Figure 3 shows the performance achieved in drag area (diameter) versus time. Both time to first full open and the time to steady drag area were improved.

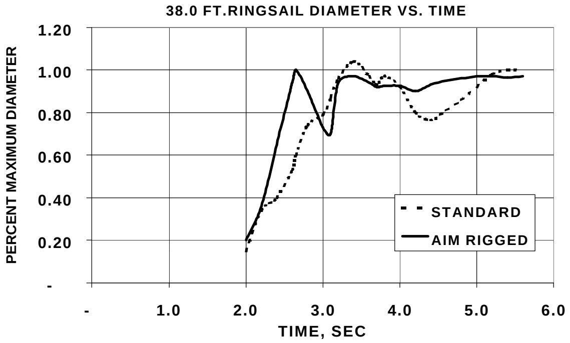


Fig. 3 Ringsail-AIM Performance

Certain programs used the Ringsail as the main parachute in a tandem system mid-air retrieval concept. A 53.0 ft. Ringsail was incorporated in both operational and trainer version. Its reliability was outstanding in this application where data of priceless value was returned and aircraft mission time optimized.

3.0 BASIC CONCEPT

Several planform variations have been applied to the basic Ringsail concept. Some were considered aimed at evaluation of known high performance planforms as enhanced by panel leading edge fullness. Others evolved in development as problem rectification solutions.

PLANFORM

Several planform options were applied by Ewing at Northrop Ventura. Starting with the quarter spherical, the near optimum planform, alternate planforms utilized are shown on Figure 4 by program application

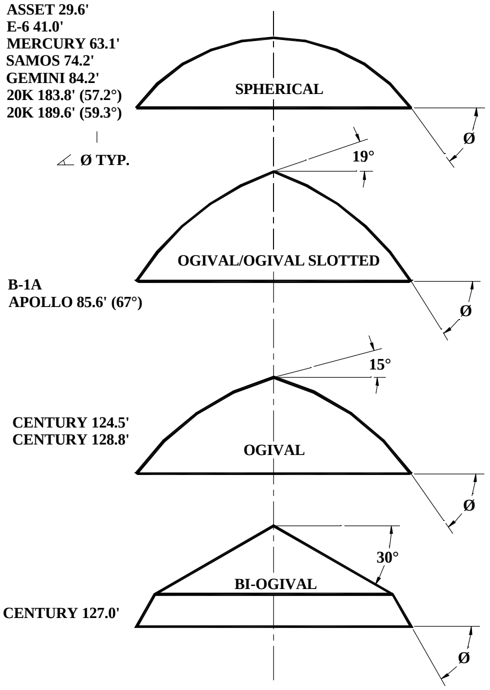


Fig. 4 Planform Constructed Profiles

The gore developed by Ewing has the characteristic leading edge fullness of varied percentage and profile. When displayed as a flat pattern, the planform is shown by Fig. 5. Note that the trailing edge of each panel section conforms to the quarter spherical coordinate plus applied fullness, the K_A term. Early designs considered fullness a must have to reduce crown region stress. While a limited amount of fullness may be applied to preclude undersizing of the final inflated profile, too much fullness can lead to the "infolding" problems encountered as larger Ringsails were produced. The leading edge, or crescent fullness, starts at zero level in the Ringslot crown panels, and then is applied in varying amount as the K_B term per Fig. 5 and Table 3. Not that in some designs K_B overlaps K_A.

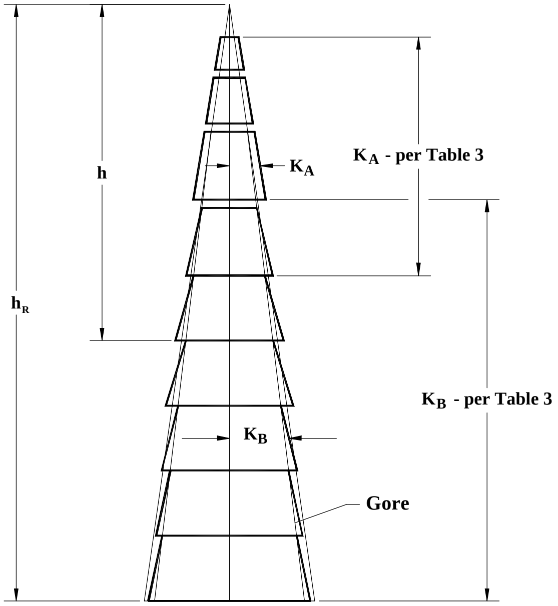


Figure 5 Ringsail Gore Layout View

Note that the Pure Quarter Spherical planform has a 60° angle at the skirt intercept. This opened up the concept of maintaining high drag while increasing the size of the F-111 recovery parachute canopy. The upper gore was of proven structural integrity at 300 knots. Irvin applied the added cloth at the constant 60° angle as shown on Figure 6. as the QUARTER SPHERICAL CONICAL EXTENSION. For original designs, Irvin applied the pure quarter spherical planform. We also apply very limited fullness to the quarter spherical coordinates with the expectation that good cutting and manufacturing will maintain the planform intention.

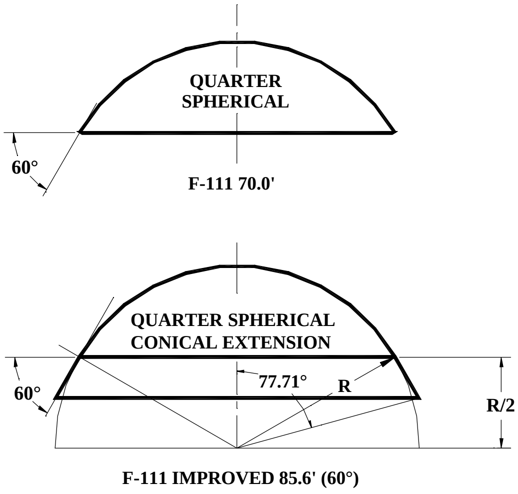


Fig. 6 Planform Constructed Profiles

TRIP SELVAGE FABRIC

A benefit to early Ringsail designs was the use of trip selvage fabric. The woven form was characterized by added strength woven into the half inch selvage area by adding warp yarns. This fabric effectively eliminates cross seams, eliminating considerable manufacturing labor. Textile manufacturers cooperated in the Skysail development and with the Navy on mine parachute fabric by producing fabrics of double and triple strength in the warp direction versus the basic cloth from lightweight 1.1 to 3.5 oz./yd^2 fabrics.

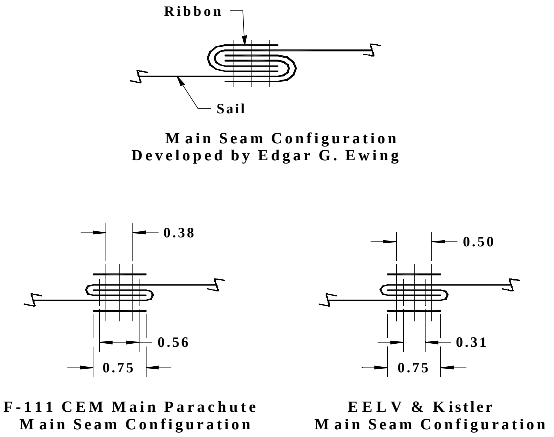
Presently this fabric is not readily available or cost effective. As air looms emerged and the parachute fabric market diminished, the cost of trip selvage fabric rose. Today, it is unlikely the shuttle looms which could produce Type 1a even exist. Thus the construction of a true lock-selvage fabric is not possible.

A work-around to non-availability of trip selvage cloth has been made. Conventional air loom fabric (non-woven selvage) in hemmed configuration is now used on the Ringsail. The work-around involves hemming the trailing edge using high speed (2800 RPM) two needle machines.

Ironically, hemming has been found better in both hoop structural strength and flutter separation than trip selvage fabric. The flutter avoidance and hoop direction strength of the alternate hemmed construction was proven by sled and lab tests on the F-111 CEM Program. Edge-on full scale panel samples of both alternatives, Trip Selvage and Hemmed Selvage, were concurrently driven down the NAWC China Lake SNORT Track leading edge forward. The Hemmed Selvage samples showed 45-60% less flutter separation at the trailing edge and no leading edge separation. Hem strength was found in lab tests comparable to trip selvage material which permitted continued production of the 70.0 ft. Ringsail to this date for the Australian F-111 fleet. The added panel hemming labor takes away, however, one of the major Ringsail advantages.

MAIN SEAM

The most interesting aspect of the early Ringsail implementation was found in the main seam. As seen on Fig. 7, radial tapes were applied much like a ribbon chute implementation. The upper and lower tapes were, however, rolled into the classic fell seam. This technique, in combination with the use of trip selvage fabric in block construction, offered much shop labor avoidance or produceability to the Ringsail. Parachutes as large as the Mercury 63.0 ft. canopy were produced with this main seam. Sufficient concern existed over the increase in seam height that both Irvin and Steinthal in the F-111 flyoff used a double tape main seam.



Main Seam Configuration
Developed by Edgar G. Ewing

F-111 CEM Main Parachute
Main Seam Configuration

EELV & Kistler
Main Seam Configuration

Fig. 7 Main Seam Options

LEADING EDGE FULLNESS IMPACT

In the early inflation phase, a benefit is seen attributed to the leading edge fullness. Inflow from not only the mouth inlet, but also the leading edge of each panel acting as a scoop, takes place. With flow energy higher on the outer surface of the canopy than the inner, flop-in/flop-out fluttering action of the scoop readily establishes fullness as a contributor to faster inflation.

Figure 8. shows the outflow from the crescent slots acting as aerodynamic strakes in limiting the shed vortices and leading to good stability. The slotted version as flow on Apollo offers even greater stability enhancement in that no reattachment of a vortex shed in the skirt region could occur.

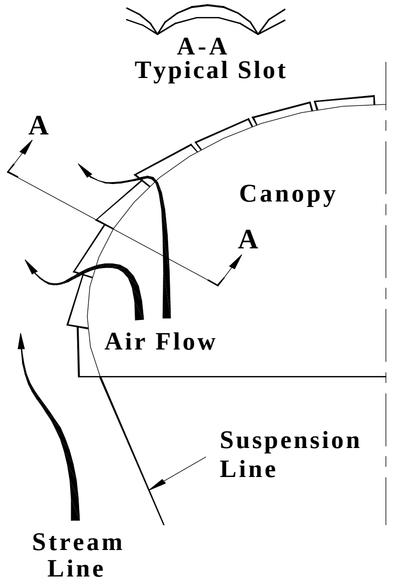


Fig. 8 Ringsail Flow Field in Steady Descent

In steady state the benefit of panel section fullness K_B is readily seen. The internal pressure coefficient is positive throughout the canopy. Thus, any meridian direction rotation of the panel rays toward the local horizon results in rotation of the total panel area vector toward drag increase. As leading edge fullness increases, however, the leading edge to trailing edge load sharing potential decreases. Thus, a practical limit on leading edge fullness is reached at around 10-12%. Lower fullness is required in the upper, high stress region giving credence to the dependence on Ringslot construction with its structural advantages. In steady state, the ratio of mouth inlet area compared to total outflow area (vent, slot, crescent slots and material permeability) is in the range of 1.15:1. The designer cannot, however, open up crescent fullness beyond this ratio or a risk of pressure coefficient loss would occur.

4.0 ADVANCED DESIGN VARIATIONS

The Ringsails developed well after publication of Reference 1 broke rank. The planform for the 136.0 and 156.0 ft. canopies was pure quarter spherical. The myth of crown fullness was dispensed with when it was recognized that hoop loading is not benefited by inter-radial radius of curvature. A point of inflection occurs at each panel to radial intercept so that the material stress is primarily the gross canopy mean radius times pressure differential. The anticlastic curvature in the meridian direction, however, is ever present in reducing the stress as a p*r / 2 type expression.

REVISED FULLNESS ALLOCATION

What is important to recognize, is that inflation instability in the form of infolding is precluded by low crown fullness design. Perhaps the practice of removing gores that never inflated anyway to form the Ogival planform could have been revisited had the premise that inflation starts at the vent and carries on throughout the gore. If infolding is precipitated by excess fullness in the crown panel, it will not be counteracted in the lower gore height since pressure coefficients are too low in the lower gore to prevail.

Some liberty is taken in the fullness distribution in the lead panels. These are described as the panels below the equator of the inflated Ringsail. In this region, the fullness is ramped downward, but held to a positive level. Thus panel pressure-area vector is still pro-drag. Ewing’s original concept took the lead panel to zero leading edge fullness. The design could best be described as having an Extended Skirt effect. This design would give the best possible stability with the ideal tangent flow at the skirt plane an objective. This concept has been retained on the most recent designs. A design trade, stability level versus drag contribution, must be made as larger canopies are employed. Increased size and included mass, varying with D_o^3, allows some relaxation of static stability margin.

Table 3 documents the fullness distribution of the latest Ringsails to be developed over the gore height.

RINGSAIL	h/h_g	K_A	K_B
Apollo	Vent	1.7(5.5)	-
	.357	1.7	-
	.625	0.0	-
	.560	(above)	7.0
	1.000	-	11.5
Century (128.8 ft.)	Vent	6.0(6.0)	-
	.600	0.0	-
	.45	(above)	8.0
	1.000	-	8.0
EELV	Vent	0.0(0.0)	-
	.384	0.0	-
	.450	-	6.0
	.918	-	12.0
	1.000	-	0.0
K-1	Vent	0.0(0.0)	-
	.348	0.0	-
	.406	-	5.0
	.928	-	12.0
	1.000	-	0.0
20K	Vent	3.0(6.0)	-
	.675	0.0	-
	.445	(above)	3.4
	.482	-	5.5
	1.000	-	5.5

Table 3 Ringsail Fullness Distribution

Figure 9. shows the descending single main 156.0 ft. K-1 Ringsail. Post-landing the weight tub wound up standing on end at Yuma Proving Ground confirming the outstanding descent stability achieved. Stability was recorded at less than 4° off vertical.

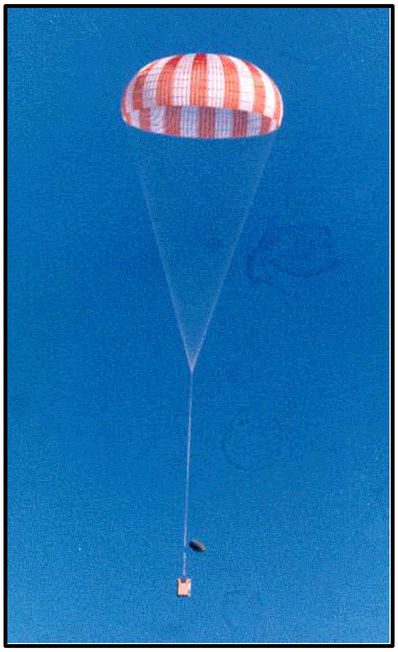


Fig. 9 Single 156.0 ft. K-1Ringsail in Stable Descent

MULTI-PERMEABILITY FABRIC DISTRIBUTION

Certain broadcloth materials exist today as applied on the Parafoil that augment Ringsail performance. The premise that slotted crown could handle initial crown pressurization and opening load while fabric permeability shift contributed less of the needed outflow resulted in a major potential for drag increase. Using low permeability upper rings first appeared on the hybrid Ringslot-Solid cluster developed for the F-111 Crew Escape Module[3].

The concentric ring, block construction of the Ringsail allows the designer to readily select both material strength and permeability over the gore height. Irvin proposed a solution to the USAF on the F-111 CEM Recovery based on an enhanced single recovery canopy. The design featured standard– intermediate– standard- permeability distribution in the crown-,mid- and lower gore height, respectively. The result was a rapid opening, high drag and acceptable opening load design capable of 300 KEAS deployment at 17,000 ft. altitude. The stability level was also found compliant in the < 12° off-vertical range in calm air.

Multi-permeability design carried over past the 85.6 ft. F-111 CEM into the 136.0 ft. EELV and 156.0 ft. K-1and and was used in part on the earlier 20K 189.6 ft. Ringsails. On the EELV and K-1 designs optimum drogue-to-main recovery parachute changeover was possible. The designs could therefore be biased for maximum drag and drag efficiency. The resulting designs were triple and quad strength level, multi-permeability level designs. The stability level of either the EELV or K-1 main was measured at < 4°-8° off vertical based on limited test data in stable, calm air. This level is considered ideal for cluster operation wherein the interference flow drives each canopy past its trim point with respect to the local vertical subtended by the payload center of gravity.

All early Ringsails, as documented in Reference 1, were essentially mono-permeability designs. They used MIL-Spec fabric and applied MIL-C-7020 triple strength selvage ripstop broadcloth.

5.0 OPENING PHASE CONTROL TECHNIQUES

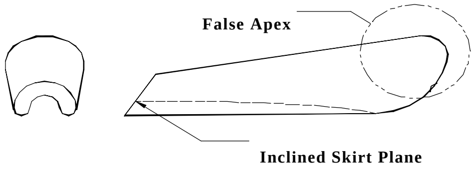
A parachute is as good as its deployment. This adage has been heard through the years, and tears, of those in the design community. Deployment control is comparatively easy compared with the pre-inflation phase control. The pre-opening phase begins at pack open, or line stretch in certain types of deployments, and ends at crown pressurization. It includes subphases including a) canopy stretchout, b) unfurling, and c) air ingestion. Control ***accessories components***, such as pocket bands, sacrifice panels and vent control bridles, all interact with the ***packing technique*** to control the destiny of the initial inflation and ultimately the success of the first stage or full inflation process.

In this section the various support components, design features and techniques believed essential to Ringsail canopy application are discussed. The accessories and techniques apply in varying importance over the speed range and may be, and in fact, have been, applied to other types of recovery parachutes. Seven phases of opening are listed below. The following discussion is limited to details of and the interrelationships between **technique** and **support components** that lead to a controlled Pre-Opening Phase 2.

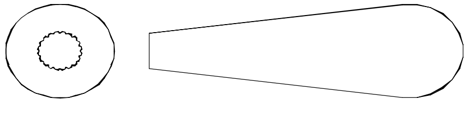
1. **Deployment…**
2. **Pre-Opening…**
3. **Opening…**
    - **Reefed**
        - **a) inflation to reefing line 1 taut…**
        - **b) reefed overinflation…**
    - **Disreef**
        - **a) snap-open to tangent condition,**
        - **b) inflation to reefing line 2 taut…**
4. **First Full Open…**
5. **Overinflation…**
6. **Wake Recontact…**
7. **Steady State Inflation**

PROBLEM DEFINITION

A proper pre-opening phase is considered key to **all** subsequent inflation events. Where does all of the flaccid material gathered in by a reefing line go before and after the reefing line is taut? Figure 10. shows the uncontrolled skirt area following formation of a false apex with the characteristic inclined skirt plane and kidney shaped inlet. Conversely, a well deployed parachute has memory even after the shape achieved on the lower picture of Figure 10. After the flaccid material adjusts randomly around the reefing circle, if initial symmetry has been set, it will re-establish itself.



Poorly Controlled Deployment
False Apex Formation



Correctly Controlled Deployment
Symmetrical Inflation

Fig. 10 Initial Inflation - Pre-Inflation Controlled

A circular inlet may transition to kidney shape late in the first stage without the inclined skirt plane. If false apex has being been avoided, however, the second stage will reform symmetrically with the excess material adjusting to its controlled state with symmetry of inlet plane.

VENT CONTROL BRIDLE

Control of the vent of a cluster of parachutes is mandatory, especially when the deployment speed is high. The B-1A CEM program traded various deployment techniques including independent pilot chutes bridled to the main canopies. The last fourteen (14) tests were, however, configured with the dual pilot chutes controlling the vent of each main by a permanent bridle. This was adequate to achieve a 40/40/20 load sharing ratio. Each bridle, as described in Reference 2. was long enough to permit full inflation without mutual interference yet produced simultaneous line stretch and low crown damage. This is a good example of a permanent vent control bridle.

A permanent bridle loses crown control in the interval from crown stripout to bridle extension and the snatch forces associated with accelerating the pilot chute(s) or drogue(s) to the velocity of the pre-inflation main canopy. The rapid reorientation of the crown could also induce burn damage. Collapse of the pilot chute "stack" raises reliability issues of entanglement and restriction of the cluster trim angle. Release of the deployment bag after concurrent bridling is typical, but leaves the crown region vulnerable to false apex type loading and unfurling burn damage.

An incremental bridle controls the vent and then releases. It is applied immediately on crown motion toward the bag mouth and ends its power stroke at crown pressurization. Fig.11 shows the stowed and active configuration of a typical incremental vent control bridle.

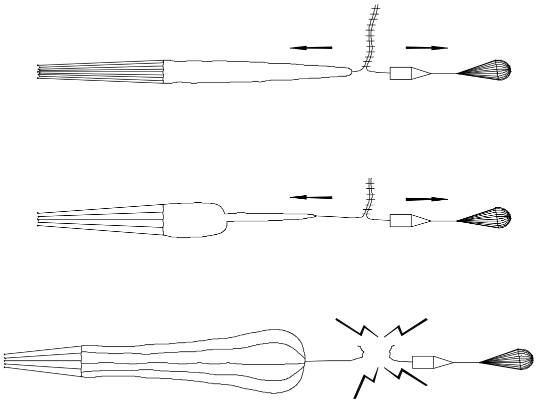


Fig. 11 Active Vent Control Bridle

As shown, the initial free length immediately picks up a vent ring and applies constant, or increasing force during pre-inflation. This period is considered critical to successful inflation since excessive flaccid skirt region material is uncontrollable and vulnerable to inversion tendencies as mass flow related force from the emerging canopy drop off and airflow reaches the skirt region. By applying force through the vent lines and radials, the canopy is tensioned in an ideal linear stretchout as the pre-inflation pressure front progresses toward the crown. When the "ball of air" reaches the crown thus controlled, false apexes are avoided. At this point, the vent bridle power stroke is completed and the open section of the bridle releases.

POCKET BANDS

Pocket bands were not used on recovery parachutes, especially on a main parachute with as positive inflation as the Ringsail. Early Ringsails did not feature these early inflation aids. Ed Ewing saw the benefit when he worked at Irvin following the shutdown of the recovery system group at Northrop Ventura.

Pocket bands have been applied on all large scale Ringsails for their positive influence on inlet area and repeatability of mouth formation. Pocket bands that are aerodynamic in that they provide outward lift to the flaccid lead panel versus mechanical pocket bands which merely control the extent of "flop-in" on the flaccid lead panel are characteristic of contemporary Ringsail design.

SACRIFICE PANEL

A sacrifice panel as shown on Figure 12 is a non-structural lightweight fabric member sewn along the outer surface of one or more radials over the full gore height. During the final phases of the long folding of the parachute the panel is tensioned and wrapped around the drag producing surface. It is held in place by continuous spiral stitching as a dual purpose accessory.

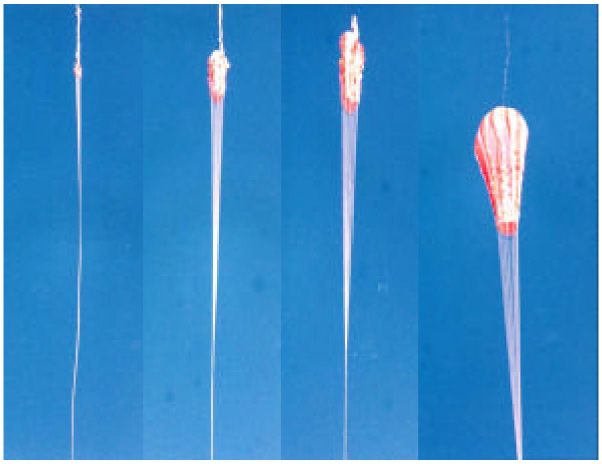


Fig. 12 Sacrifice Panel Concept in Operation

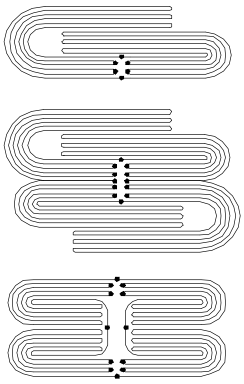
The primary sacrifice panel purpose is deployment damage avoidance. At higher deployment speeds, main recovery parachutes are particularly vulnerable to deployment burn damage. EELV or K-1 class mains may break out of their bags from a high pack density condition at 300 fps or higher. The sacrifice panel takes the hit versus the drag producing structure.

Equally important is the inflation control aspect of the sacrifice panel. As the lead panel unfurls and the pocket bands start lifting outward, the sacrifice panel momentary resistance creates a “moving crown” effect. In other words, radial outward inlet formation is artificially increased on a moving front progressing toward the vent as the restraint tacks and mechanical wrap of the sacrifice panel release. This action serves to create an even higher radial and suspension line tension state than afforded by the Vent Control Incremental Bridle. The unfurling progresses until crown pressurization occurs.

FOLDING TECHNIQUE

The traditional long fold is applied extensively over all parachute applications. Speed of is a rigging major consideration in many applications. The application may in many cases not warrant special treatment of the folding technique. Special techniques apply in high-speed applications and for ultra large canopies that must be applied for reliable, repeatable and reusable results.

Figure 13a shows the Standard Long Fold while Fig.13b the Double S Fold configuration. There are variations around each but the difference in understanding each technique is key. The techniques apply to both reefed and unreefed parachutes. Proper folding technique is key when the pre-inflation process is important to the mission. In a static line jump with its characteristic cross-flow deployment, special folding techniques are not important, as the random roll attitude and jumper weight has major impact on the line stretch condition of the canopy.



a) Standard Long Fold

b) Double S Fold

c) Quarter Fold

Fig. 13 Long Fold Alternatives

The main advantage in the Double S Fold and Quarter Fold per Figure 14 is unfurling uniformity. For minimum opening time objectives, such as in escape system parachutes, the technique results in the fastest formation of the inlet. Where opening symmetry is important, such as on large canopies and clusters, with a reuse level goal set, the folding technique drives both unfurling damage and lead-lag opening load factors to minimum levels.

6.0 PERFORMANCE

The main performance advantage of the Ringsail is its higher opening speed allowable. Both the geometric porosity in the crown region and the lateral reinforcement of intercostal ring construction favor opening load reduction and structural accommodation, respectively. There is no apparent drag or drag efficiency advantage of the Ringsail over other advanced design main recovery parachutes such as the Polyconical, and Tri-Conical. The opening reliability and development risk avoidance afforded by the Ringsail’s positive opening characteristics and damage tolerance make it the canopy of choice.

OPENING CHARACTERISTICS

Several important findings have occurred in application of the ultra-large Ringsail. These pertain to reefing ratio and airspeed sensitivity to airspeed at line stretch.

The reefing ratio of large Ringsails may be set well below the traditional lower limit of smaller canopies. Reference 1. contains data supporting this point. Fig. 14. updates the lower first stage initial reefing ratios achievable on large scale Ringsails. Values applied and achieved on the EELV and K-1 Ringsails are included. Note that the trend does not originate, but starts at a point representing the minimum possible reefing circle and flaccid cloth, pre-inflated shape flag drag on the drag area axis.

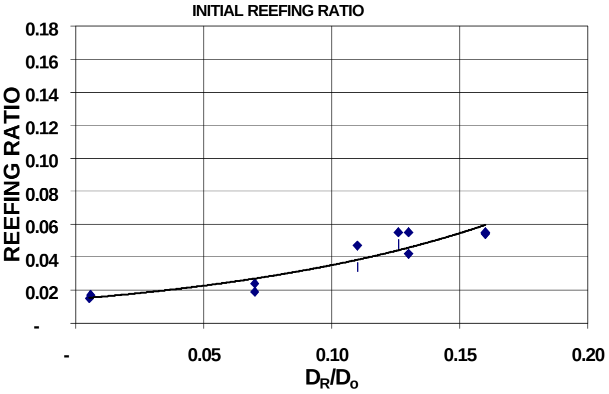


Fig. 14 Ringsail Initial Reefing Ratio

Fig. 15 then shows the Ringsail's reefed overinflation percentage derived from test data. This is a very important characteristic of the Ringsail.

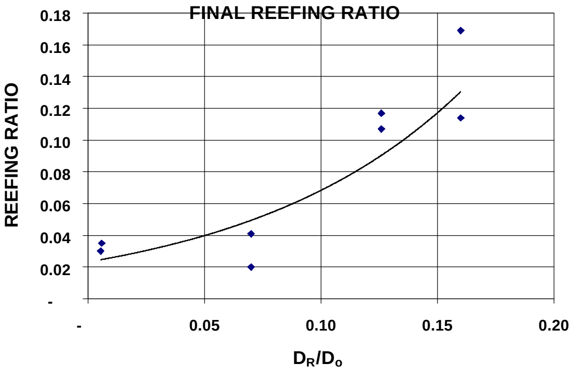


Fig. 15 Final Ringsail Reefing Ratio

On the F-111 CEM Improved Recovery Parachute Program the variation in reefing ratio with airspeed was revealed. At a fixed reefing line length, the initial reefed drag area, defined as the drag area at initial reefed opening peak load, was found to be far from a fixed value. Figure 16 shows the empirical data trend as a function of airspeed. While the literature alludes to "squidding" and sophisticated opening load models will predict this effect, an empirical quantification of this effect is shared since today's limited research funding precludes dedicated pursuit of such effects.

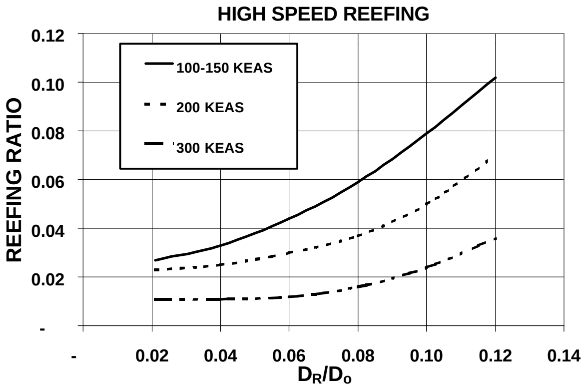


Fig.16 High Speed Reefing Ratio

DRAG PERFORMANCE

Drag coefficient trends are presented on Fig. 17 at Table 1 line length ratios. The data covers both earlier conventional fabric permeability distribution and the current improved planform fabric permeability profile. The increase in drag coefficient with size is somewhat countered by the low elongation of Kevlar, Vectran and Spectra lines and radials as these materials do not contribute the secondary benefit of longer effective meridian member length set at the peak load opening. Current designs must compensate for this effect by introducing radial takeup allowances at the permanent set level that a nylon radial would reach.

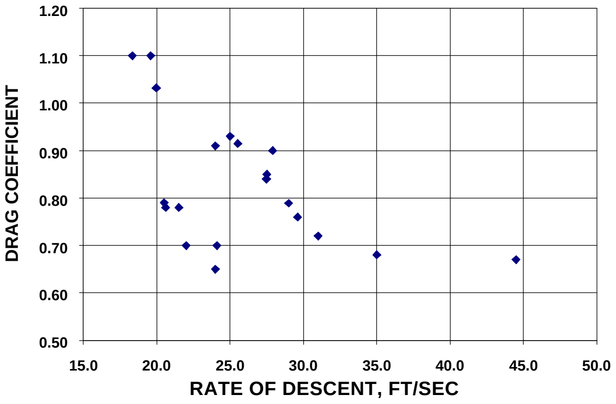


Fig. 17 Ringsail Steady State Performance

STABILITY

Stability level has been addressed from a single plane viewpoint on the recent data as range stability data was not affordable. The best engineering estimates show that a stability in terms of peak angle off-vertical is typically less than 7° for the EELV and K-1 Ringsails. These are calm, low turbulence factor air mass values. The damping characteristic on single canopy drops has similarly been outstanding. Moderate breathing of the canopy in steady descent has been noted, but corrective action not pursued as the effect vanishes, or reaches negligible level, in cluster operation.

7.0 SUMMARY

An update to show recent performance and design advancements for the Ringsail canopy has been established. A comparison of experimental data with prior design shows that improvement in steady state drag may be achieved without stability degradation. Methods to control the pre-inflation phase have been demonstrated to have major benefit in cluster simultaneity, lead-lag fraction and infolding tendency avoidance. High speed recovery class Ringsail performance shows a significant trend for lower initial reefing ratio as deployment speed increases.

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