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REEFING OF PARACHUTES
FORCES IN REEFING LINES

DIRECTORATE OF EQUIPMENT ENGINEERING

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This report presents data on the forces in reefing lines. The force data were obtained from wind tunnel tests, from aerial free-flight tests and through the analysis of known reefing line failures.

It was found that forces in reefing lines vary with the type of parachute used, with the reefing ratio, with the length of the suspension lines and with single or multiple stage reefing.

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The report discusses the difference in the reefing line forces of first stage drogue chutes, ordnance type retardation parachutes and large final descent main parachutes. Recommendations are made for stressing the reeefing lines for various types of application.

FOREWORD

This report was prepared by T.W. Knacke as a consultant to the Crew Equipment and Human Factors Division of the Directorate of Equipment Engineering of the USAF Aeronautical Systems Division (ASD) at Wright-Patterson AFB, Ohio. Management supervision was provided by Mr. Herman Engel, Technical Advisor to the Crew Equipment and Human Factors Division.

The report is a continuation of work previously published in report ASD-TR-76-2, "Reefing of Parachutes, Drag Area Ratios vs Reefing Ratios."

The author wishes to acknowledge the excellent cooperation of numerous government agencies and recovery systems companies. He is especially grateful to the Flight Dynamics Laboratory at Wright-Patterson AFB, the Sandia Laboratories in Albuquerque, New Mexico, the Pioneer Parachute Company in Manchester, Connecticut, Irvin Industries in Gardena, California and to the Douglas Aircraft Company in Long Beach, California.

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LIST OF SYMBOLS

The symbols of report AFFDL-TR-78-151 "Recovery System Design Guide" have been used in preference to symbols used in Reference 1.

Symbol	Unit	Concept
C_D	-	Drag Coefficient
C_{D_o}	-	Drag Coefficient related to S_o
D_o	ft	Nominal parachute diameter, $D_o = (4S_o/\pi)\frac{1}{2}$
D_r	ft	Diameter of circle formed by installed reefing line
DFFT	-	Dynamic Free-Flight Test (Aerial drop test)
ELS	-	Earth Landing System (Apollo Parachute System)
F_o	lb	Parachute Opening Force
F_r	lb	Force (drag) of reefed parachute
F_{RL}	lb	Force in reefing line
H	ft	Altitude
l_s	ft	Length of suspension line
q	psf	Dynamic pressure
R	lb	Radial force acting on canopy skirt
S_o	ft^2	Nominal surface area of parachute canopy
$(C_dS)_o$	ft^2	Drag area of full inflated parachute
$(C_DS)_R$	ft^2	Drag area of reefed parachute
t_r	sec	Reefing time
V_o	knots	Velocity
$\frac{W}{(\overline{C}_DS)_o}$	psf	Canopy loading

LIST OF SYMBOLS (Concluded)

WTT	-	Wind Tunnel Test
z	-	Number of suspension lines
δ	degree	Angle between canopy radials and suspension lines at canopy skirt
λ_g	%	Geometric porosity of parachute canopy

SECTION I

INTRODUCTION

This report provides data, discussion and recommendations on forces in the reefing lines of reefed parachutes. The report supplements a prior publication of the author: "Reefing of Parachutes, Drag Area Ratios vs Reefing Ratios," USAF Aeronautical Systems Division report ASD-TR-76-2 (Reference 1).

Data on the design and working of reefing systems used in operational parachutes are seldom published individually. Such information is generally combined with other parachute development and test data contained in company or government internal reports that are not published for general distribution to the technical community. The author has collected data on the design and performance of parachute reefing systems using published reports, industry and government internal reports, data from his files, and published data obtained from discussion with companies and government agencies. However, no claim is made for an all-inclusive coverage.

All collected data were forwarded to the USAF Parachute Data Bank at the Flight Dynamics Laboratory at Wright-Patterson AFB, Ohio, 45433, for permanent storage.

SECTION II

FORCES IN REEFING LINES

1. GENERAL

The first use of reefed parachutes in the early forties immediately raised the question of how to stress the reefing line and its related components. Early failures led to a test program where reefed ribbon parachutes, 10 feet in diameter were towed behind an aircraft. A short jumper break link of tested strength was installed in the reefing line and the speed of the aircraft increased until the break link ruptured. The force in the reefing line was found to be 2.5 to 3.5 percent of the steady state drag force of the reefed ribbon parachute.

In 1948, the author conducted tests with 3 foot D_o reefed ribbon parachutes in the 20 by 40 foot Massie Memorial Wind Tunnel at Wright-Patterson AFB. The tests were to determine the size and performance of a drogue/stabilization parachute for the ejectable nose capsule of the X-2 research aircraft. The tests included measurements of reefing line forces with strain gage links. The nature of the parachute application prevented publication of the test results at that time.

The USAF 6511th Test Group (Parachutes) in El Centro, California, in the early fifties collected data on reefing line failures. An analysis of these data led to a rule-of-thumb that the ultimate strength of the reefing line should not be less than 10 percent of the maximum reefed parachute force. No reefing line failures were experienced after this rule was applied. The Sandia Laboratories in the early sixties conducted wind tunnel tests on ribbon parachutes and analyzed reefing line failures encountered in free-flight tests in order to determine go and no-go reefing line load conditions.

The Ventura Division of the Northrop Corporation in 1962, 1964, and 1967 performed wind tunnel and free-flight tests on large reefed ringsail parachutes used for landing the Mercury and Apollo spacecraft. These tests included measurements of reefing line forces. In these tests it was found that reefing line forces measured in free-flight tests were considerably lower than reefing line forces measured on the same parachutes in constant velocity wind tunnel tests. This difference was traced to the time-dependency of the reefed parachute inflation and its effect on canopy radial and associated reefing line forces.

Reefing line force problems were encountered as recently as 1977 with the high force drogue parachute of the NASA Space Shuttle solid booster recovery system. The Sandia Laboratories in 1978 conducted extensive wind tunnel tests with reefed ribbon parachutes in support of the NASA Space Shuttle program. These tests included measurements of reefing line forces.

2. DESIGN PARAMETERS AFFECTING REEFING LINE FORCES

In the forties and early fifties, reefing was used primarily for first stage drogue chutes, generally small ribbon parachutes, deployed at speeds in excess of 300 knots. Filling times of these parachutes were short and the parachutes reached full reefed inflation long before disreefing occurred. Applying the earlier mentioned 10 percent rule for the strength of the reefing line served its purpose to prevent reefing line failures.

When reefing started to be used on large final descent parachutes for the recovery of missiles, drones and military supplies, it became apparent that lower reefing line forces were encountered in free-flight drops of large solid flat, extended skirt, and ringsail parachutes than on reefed ribbon drogue chutes.

Large final descent parachutes, opened at 250 knots or below, have long inflation times and may not reach full reefed inflation prior to disreef; this naturally affects the force in the reefing line. Figure 1 illustrates the relationship between canopy shape angle δ_1, suspension line angle δ_2 and the influence of the suspension line length L_s/D_o. The force in the reefing line expressed as a percentage of the reefed parachute force will be a maximum when the angle δ is a maximum; that means after full reefed inflation. However, on large parachutes the maximum reefed parachute force may occur prior to full reefed inflation. For example, during the second reefing stage of the Apollo main parachutes the maximum parachute force occurred at a canopy inflation stage close to shape A in Figure 1, with practically no force in the reefing line.

3. DISCUSSION OF VARIOUS TEST PROGRAMS

This is a review of reefing line force data obtained in various wind tunnel and free-flight tests programs on ribbon, ringsail, and solid material parachutes.

a. Early Tests

As previously mentioned, the author in 1940 conducted measurements of reefing line forces on ribbon parachutes 10 feet in diameter. Both skirt reefing and skirt reefing with control lines were investigated on parachutes towed behind aircraft (Reference 2). The parachute force was measured with hydraulic load cells and the force in the reefing lines with jumper break links. The speed of the aircraft was increased until the calibrated break link ruptured. The recorded parachute force, the known strength of the break link, and the known reefing ratio permitted a good estimate of the reefing line force. These tests may be compared to steady state velocity wind tunnel tests with the forces recorded after the parachutes had reached full reefed inflation. The measured

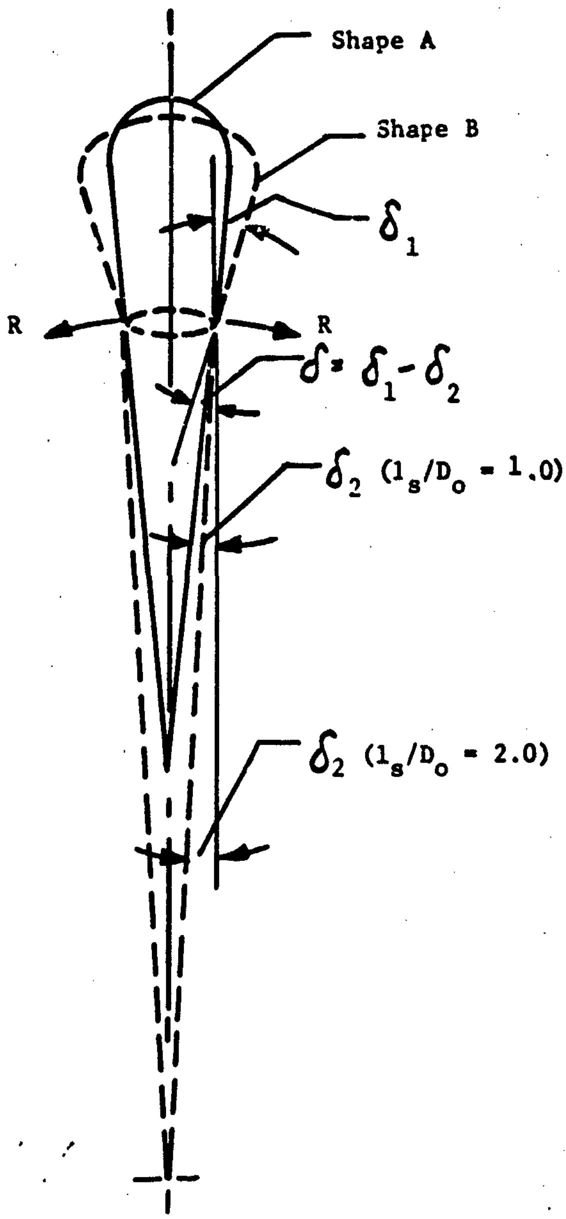


Figure 1 Reefed Parachute Geometry

ratio of reefing line force to reefed parachute force was from 2.5 to 3.5 percent for the tested reefing ratio range D_r/D_o of 0.2 to 0.5 and aircraft speeds from 80 to 120 knots. The data are plotted in Figure 2, item 1 and tabulated in Table 1.

b. XS-2 Nose Section Retardation

The author in 1947 was project engineer on the parachute retardation system for the ejectable nose section (crew module of the Bell Aerospace XS-2 research aircraft. The program included tests with 3/8 scale models of the nose section and the ribbon retardation parachute in the Wright Field Massie Memorial Wind Tunnel (dismantled in the early fifties). The test section of the closed circuit wind tunnel had a diameter of 20 feet and permitted speeds up to 400 mph. Three-foot diameter ribbon parachutes were tested fully open and in various reefed stages in free-stream and behind the arrested and free-oscillating section. Forces in the reefing lines were measured for reefing ratios D_r/D_o of 0.435, 0.354 and 0.3. Special U-Shaped strain gage links were designed to accommodate the relatively small forces which were measured after the parachute had reached full inflation (Reference 3). The force records are not available anymore, however, all forces were in the 2.75 to 3.75 percent range of the measured parachute force (see Figure 2, item 2).

A 8.13-foot D_o ribbon parachute for the full scale XS-2 nose section was subsequently sled-teated at dynamic pressures up to 2250 psf at a reefing ratio of 0.354. The reefing line was designed in accordance with the 3.75 percent load ratio; no reefing line ruptures occurred. The tests included a 1.25 dynamic pressure overload test.

c. El Centro Investigations

The USAF 6511th Test Group in El Centro in the early fifties experienced several reefing line failures on first stage drogue chutes for projects SMART, Q-4 Drone, Bomarc and others. All failures occurred on reefed ribbon parchutes in the diameter range of 4 to 16 feet. A failure analysis was conducted and documented in 1954 (see memo Lt Rosenlof/446/agp, Reference 4). It was concluded that reefing lines started to break as soon as the ultimate strength of the installed line was in the 3 to 4 percent range of the measured parachute opening force (see Figure 2, item 3 and Table 1). It was recommended that a reefing line be selected with an installed ultimate strength equivalent to 10 to 15 percent of the actual maximum reefed parachute force. Using the 10 percent rule of reefing line strength eliminated reefing line ruptures on subsequent projects. Random failures could be traced to sharp edges on reefing line cutters, misaligned instal'ation of cutters and reefing lines, poor attachment of reefing rings, faulty sewing connections of reefing lines and similar installation problems.

TABLE I LIST OF PARACHUTES ANALYZED

TEST ITEM	D. FT	REEF RATIO D_r/D_O	PARACHUTE TYPE	POROS	L_S/D_o	TYPE OF TEST	DYN PRESS PSF	AGENCY	REF
1	10	.2-.5	Flat Ribbon	26	1.0	A/C Tow	25-50	FIST INSTIT	2
2	3	.3-.44	Flat Ribbon	34	1.0	WTT	20-200	USAF/ASD	3
3	4-16	.25-.5	Flat Ribbon	20-30	1.0	DFFT	2250	USAF/AFFTC	4
4	3	.13-.55	Flat Ribbon	-30	1.0	WTT	20	Sand Lab	5
5	3	.24-.59	Con Ribbon	25	1.0	WTT	50	Sand Lab	6
6	3	.24-.59	Con Ribbon	25	1.5	WTT	50	Sand Lab	6
7	3	.24-.59	Con Ribbon	25	2.0	WTT	50	Sand Lab	6
8	3	.24-.59	Con Ribbon	15	1.0	WTT	50	Sand Lab	6
9	3	.24-.59	Con Ribbon	15	1.5	WTT	50	Sand Lab	6
10	3	.24-.59	Con Ribbon	15	2.0	WTT	50	Sand Lab	6
11	88	.08-.18	RingSail	8	1.38	WTT	5-20	Northrop	7
12	44	.08-.18	Ringsail	8	1.38	WTT	5-20	Northrop	7
13	28	.08-.18	Ringsail	8	1.38	WTT	5-20	Northrop	7
14	29.6	.08-.18	Skysail	9	1.0	WTT	5-20	Northrop	7
15	23.9	.08-.18	Solid Conical	-	0.8	WTT	5-20	Northrop	7
16	28	.08-.18	Solid Flat	-	0.82	WTT	5-20	Northrop	7
17	32	.08-.18	Solid Hemisph	-	2	WTT	5-20	Northrop	7
18	88	.08-.18	Ringsail	9	1.4	WTT	5-20	Northrop	8
19	88	.08-.13	Ringsail	9	1.4	WTT	10-14	Northrop	8
20	23	.23	Flat Ribbon	20-25	1.0	DFFT	100	Sand Lab	5
21	18.8	.24	Flat Ribbon	20-25	1.0	DFFT	600	Sand Lab	5
22	64	.1-.12	Ringsail	9	0.92	DFFT	95-135	Northrop	9
23	85.5	.084-.27	Ringsail	9	1.4	DFFT	85-120	Northrop	11,12
REEFING LINE TO REEFED PARACHUTE STRENGTH DATA ARE QUOTED IN SECTION IV ON FOLLOWING PARACHUTES									
	22.2	.28	Con Ribbon	-	-	DFFT	-	Sand Lab	13
	24	.37	Con Ribbon	-	-	DFFT		Sand Lab	14
	54	.43.57	Con Ribbon	16	-	DFFT		Pioneer	15
	115	.19.43	Con Ribbon	16	-	DFFT		Pioneer	15
	78	.066	Con Ext Skirt	-	-	DFFT		SRS	16
	34	.078	10% Ext Skirt	-	-	DFFT		SRS	16
	28		Solid Flat	-	-	DFFT		MDAC	17

TEST ITEM *	D_o ft	λ_g %	l_s/D_o	SYMBOL
1	10	26	1.0	▽
2	3	34	1.0	▷
3	4-16	20-30	1.0	◁
4	3	~ 30	1.0	△

* Refers to Table 1

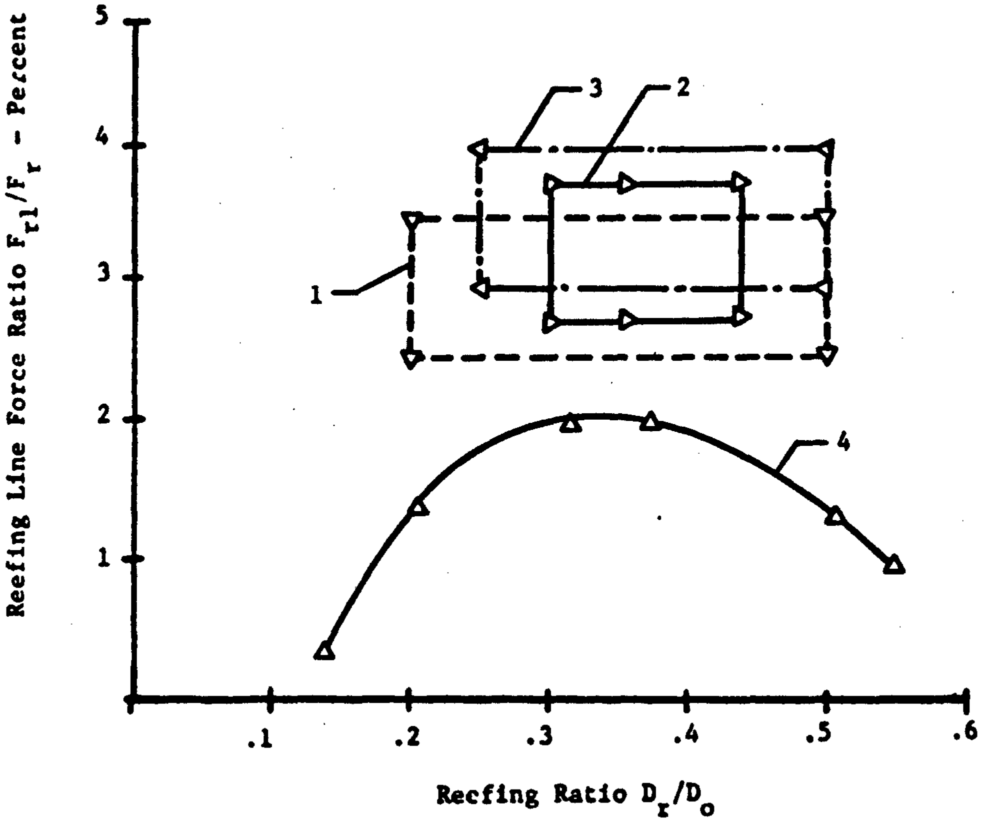


Figure 2 Ratio of Reefing Line Force F_{RL} to Reefed Parachute Force F_R vs Reefing Ratio D_r/D_o (Data Prior to 1962)

d. Sandia Laboratory Test, Series I

In 1961, Sandia Laboratories, Albuquerque, New Mexico at the University of Minnesota course on Aerodynamic Deceleration, presented reefing line force data measured in wind tunnel tests on 34.4 inch diameter ribbon parachutes (Reference 5). Data were recorded after the model parachute had reached full reefed inflation covering a reefing ratio D_r/D_o of approximately 0.14 to 0.55. The results are shown as item 4 in Figure 2. The maximum force ratio of 2 percent is low compared with most other measurements. This may be due to a high porosity parachute canopy and due to the problem of accurately measuring very low forces; this difficulty has been a problem in all reefing line measurements with small wind tunnel models tested at low speeds.

e. Sandia Laboratories Test, Series No. II

In 1977, NASA experienced problems with the 56 foot D_o ribbon drogue parachute of the recovery system for the Space Shuttle 170,000 pound solid booster. A failure, occurring during an overload test, was traced to the two-stage reefing system. Sandia Laboratories, a consultant to NASA on this program, conducted wind tunnel tests with 3 foot D_o ribbon parachutes for determining reefing parameters including forces in the reefing line (Reference 6). Tests included parachutes with 10, 15, 20, and 25 percent geometric porosity, λg, line length ratios of 1.0, 1.5, and 2.0, and reefing ratios D_r/D_o from 0.24 to 0.59. These very comprehensive tests for the first time established the effect of porosity and suspension line length on reefing line forces. The data are summarized in Figure 3 and Table 1, items 5 to 10. For reasons of clarity only, the data for the 15 and 25 percent geometric porosity λg parchutes are plotted in Figure 3 as most representative data. The increase in reefing line force due to longer suspension lines was unexpected since the shape and inflated diameter of the parachute canopy, the drag producing surface, is principally determined by the length of the reefing line, the canopy design and the canopy porosity. However, a review of Figure 1 shows that the angle δ between the canopy radials and the suspension lines increases with longer suspension lines and, in turn, increases the radial force R and concomitant force in the reefing line.

The effect of porosity that Wolf and Crill found in these tests, has to be used judiciously. First stage drogue chutes used in the high subsonic and low supersonic range generally have porosities in excess of 20 percent as used on Mercury, Apollo, and reentry nose cone drogue chutes; therefore, the data for the parachute with a porosity , λg, of 25 percent are most applicable. The ratio of reefing line force to reefed parachute load for a L_s/D_o ratio of 1.0 is again in the 3 to 4 percent range and increases to 5 percent for parachutes with suspension line ratios, L_s/D_o, approaching 2.0. Parachutes deployed in the Mach 2 and above range (hemisflo and varied porosity conical ribbon) use porosities closer to 15 percent and long suspension lines. The appropriate data of the Sandia report should be utilized for these parachutes.

TEST ITEM *	D_o ft	λ_g %	l_s/D_o	SYMBOL
5	3	25	1.0	●
6	"	"	1.5	×
7	"	"	2.0	+
8	"	15	1.0	○
9	"	"	1.5	□
10	"	"	2.0	△

* Refers to Table 1

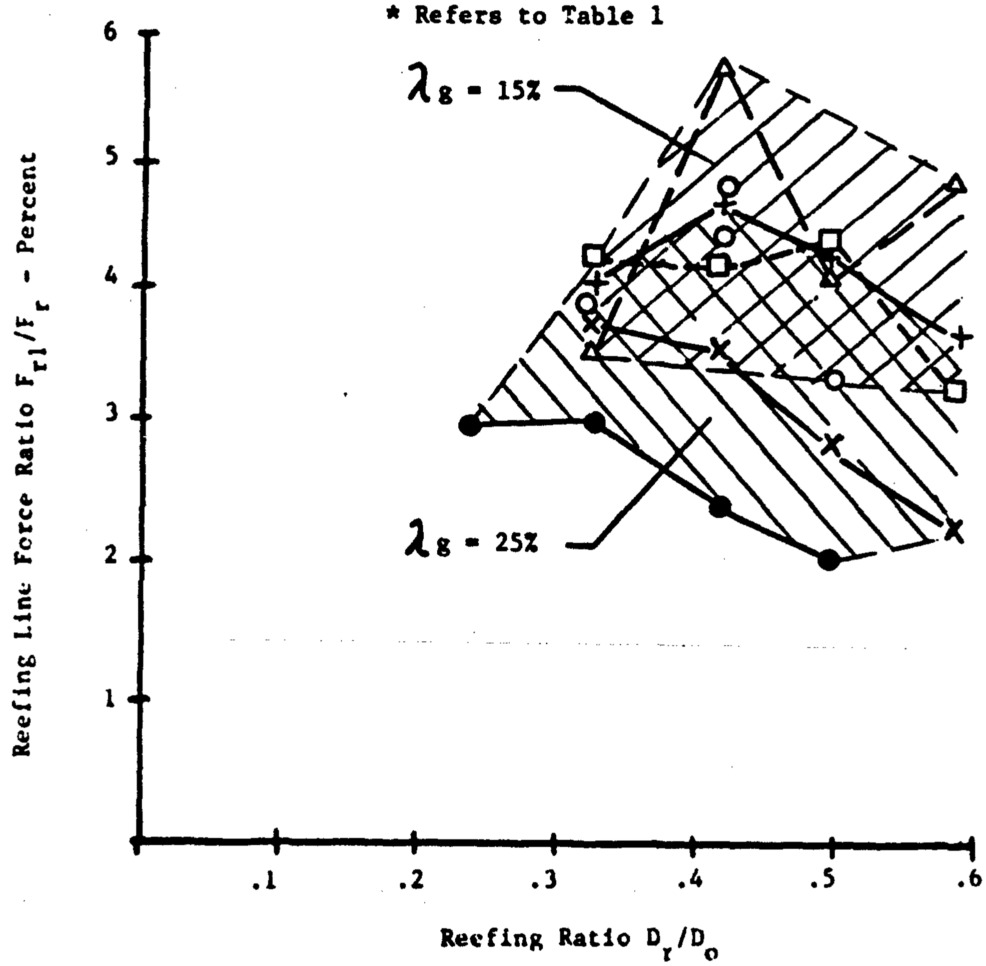
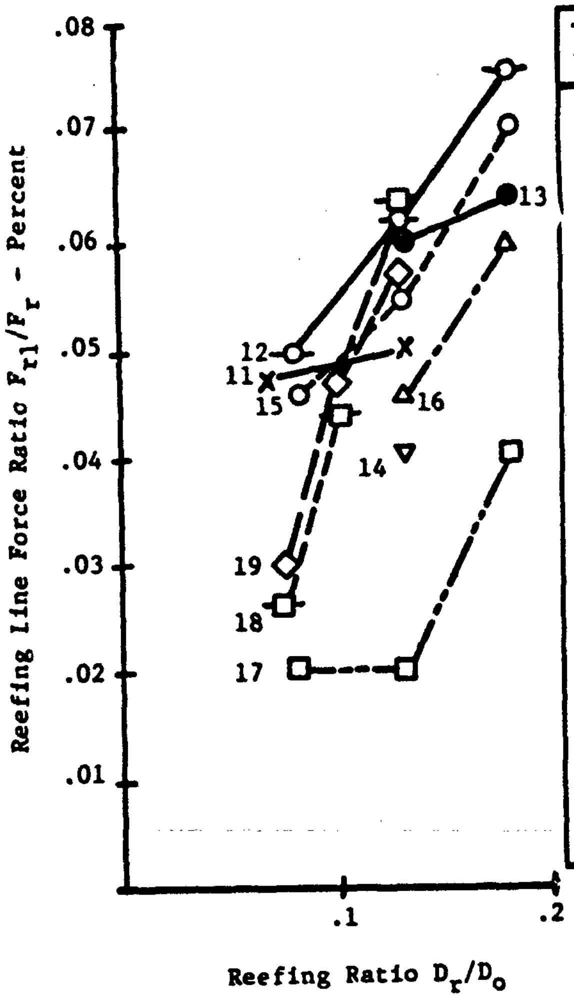


Figure 3 Ratio of Reefing Line Force F_{RL} to Reefed Parachute Force F_R vs Reefing Ratio D_r/D

(1978 Sandia Laboratory Wind Tunnel Test)



TEST* ITEM	SYM.	D_o ft	PARACHUTE TYPE
11	✕	88	Ringsail
12	-○-	44	"
13	●	28	"
14	▽	29.6	Skysail
15	○	23.9	Con. Solid Mat.
16	△	28	Solid Flat
17	□	32	Solid Hemisph.
18	-□-	88	Ringsail
19	◇	88	" (MGR)
20		23	Not Plotted
21		18.8	" "
22		64	" "
23		85.5	" "

* refers to Table 1

Figure 4 Ratio of Reefing Line Force F_{RL} to Reefed Parachute Force F_R vs Reefing Ratio D_r/D_o (Apollo Wind Tunnel Test)

f. Apollo Main Parachute Wind Tunnel Tests

During the early development of the Apollo Earth Landing System (ELS) problems were encountered with nonuniform inflation of the three 88 feet D_o ringsail main parachutes.

Tests were conducted in the NASA Ames 40 by 80 foot wind tunnel at Moffet Field, California to investigate parachute modifications for obtaining more uniform cluster parachute inflation. The primary test items were 88 foot D_o ringsail parachutes which could be inflated reefed, and 44 foot and 29 foot ringsail models of the 88 foot parachute which could be inflated fully. For comparison purposes the tests included a 28 foot D_o solid flat parachute, a 23.6 foot D_o solid conical parachute, a 32 foot D_o hemispherical parachute and a 29.8 foot D_o Skysail parachute; the latter being a man-carrying version of the ringsail parachute. Reefing line forces were measured on all parachutes. The first test series conducted in 1964 included all the above parachutes with the 88 foot ringsail parachutes tested at reefing ratios (D_r/D_o) of 8, 13 and 18 percent (Reference 7). The second test series conducted in 1964 included only modified versions of the 88 foot D_o main parchute tested at reefing ratios of 8, 10 and 13 percent (Reference 8). The results of these tests are plotted in Figure 4. For all parachutes the reefing line force ratio (F_{RL}/F_r) increased with an increase in reefing ratio in the tested 8 to 18 percent reefing range.

The low porosity ringsail and the solid conical parachutes, known for short canopy filling times, have strong radial opening forces and resultant high reefing line forces. The slow opening hemispherical parachute has the lowest force ratio. All reefing line forces were measured with strain gage links installed in the skirt of the parachute canopy with care being taken to minimize friction between the reefing line and other parts of the canopy. Force data were recorded on wind tunnel instrumentation, together with parachute drag and stability.

Reference 7 includes data on reefed opening times of various versions of the 88 feet diameter ringsail parachute modified to achieve a more uniform inflation (see Figure 5). The reefed filling time for a reefing ratio of 13 percent at a dynamic pressure of 10 psf ranges from 5 to 8 seconds. This indicates that full reefed inflation may not occur prior to disreefing and the maximum parachute force as well as maximum reefing line force on these parachutes can occur before full reefed inflation is reached. A careful analysis is required in using reefing line force data obtained in wind tunnel tests of large, slow opening, main parachutes.

g. Early Free-Flight Tests

The El Centro evaluation of reefing line failures, discussed in paragraph 3c, and shown in Figure 2, item 3, was actually based on a failure/no-failure analysis of free-flight tests. A similar analysis

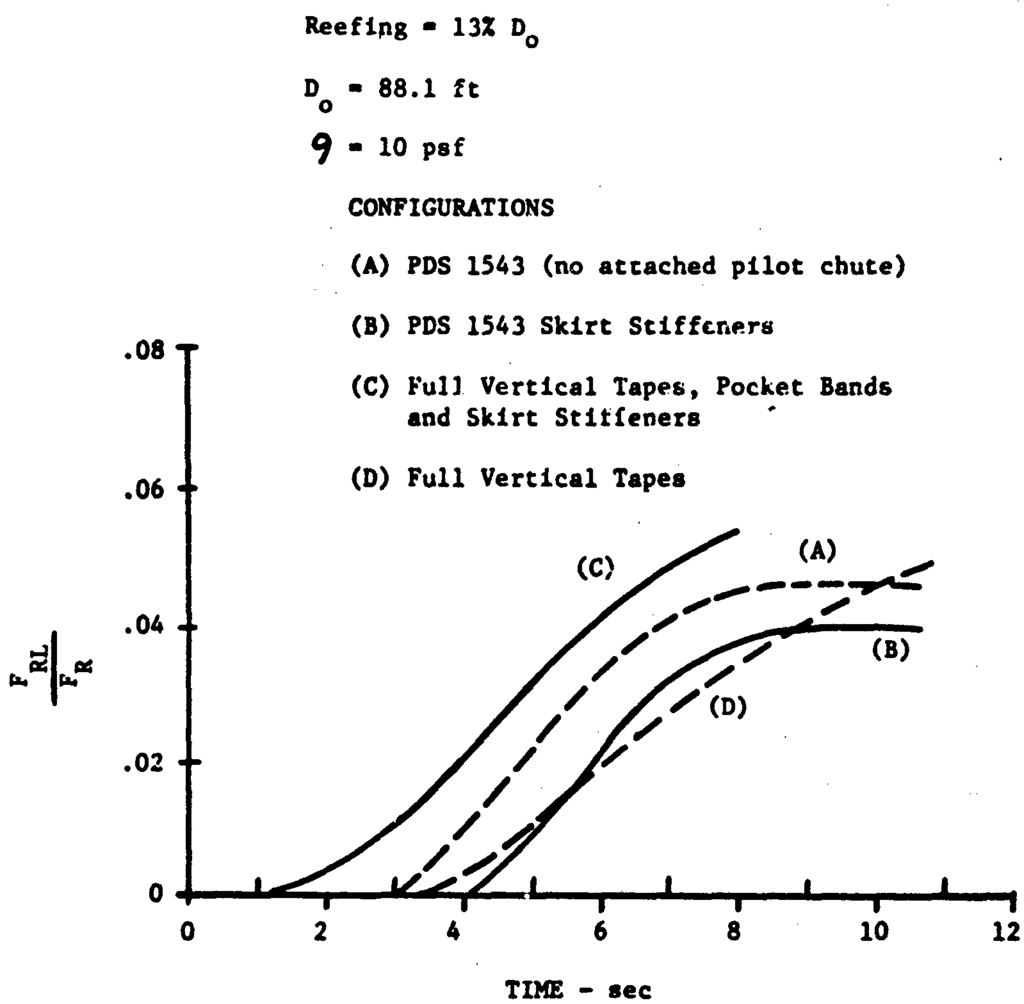


Figure 5 Reefed Parachute Inflation Time vs Force Ratio (F_{RL}/F_R) for Various Versions of an 88-Ft D_o Ringsail Parachute (Taken from Figure 47, Reference 7)

TEST ITEM *	D_o ft	λ_g %	l_s/D_o	SYMBOL
3	4-16	20-30	1.0	◁
20	23	20-25	1.0	●
21	18.8	20-25	1.0	○
22	64	~8	1.0	◇

* Refers to Table 1

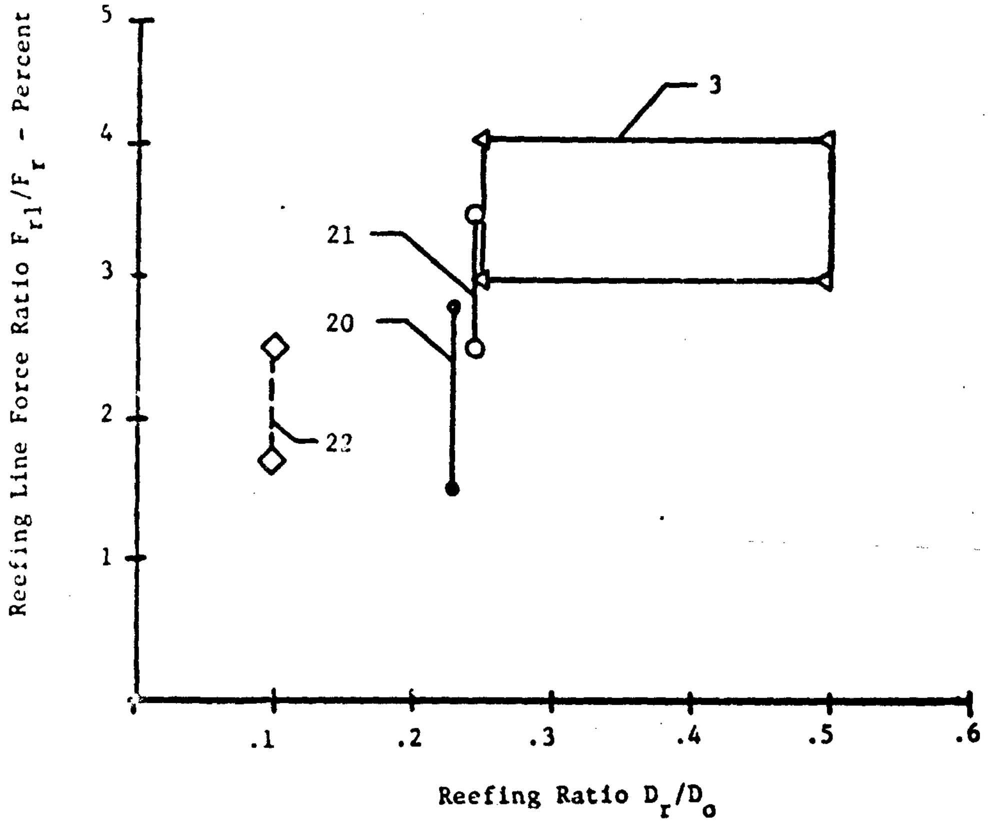


Figure 6 Ratio of Reefing Line Force F_{RL} to Reefed Parachute Force F_R vs Reefing Ratio D_r/D_o

(Free-Flight Test)

was conducted by the Sandia Corporation and the results presented at the previously mentioned University of Minnesota lecture in 1961. The Sandia data plotted as items 20 and 21 in Figure 6 and Table 1 show an upper and lower value. Failures occurred on reefing lines with ultimate strength of the lower value and no failures with reefing lines sized to the upper value.

h. Project Reef (Mercury)

In 1962 the Ventura Division of the Northrop Corporation conducted tests for requalifying the ringsail main parachute of the Mercury spacecraft for the so-called "18-Orbit Mercury" missions (Reference 9). The required increase in flight time from the original 6-orbit configuration to the 18-orbit configuration increased the landing weight of the Mercury spacecraft from 2400 pounds to 3000 pounds due to the larger weight of the on-board consumables.

The Mercury ringsail main parachute had a diameter, D_o, of 64 feet, 48 suspension lines, each 62 feet long. One-step reefing was used with a reefing ratio (D_r/D_o) of 10 percent and a 4 second reefing time. The parachute design load for both reefed and full open was 10,000 pounds. In addition to qualifying the parachute for the higher crew module weight, the ultimate strength of the parachute was to be determined in overload drop tests.

Thirty tests were conducted at a test vehicle weight of 3000 pounds, altitudes of 10,000 to 26,000 feet and dynamic pressures at main parachute deployment of 95 psf (design q) to 135 psf (overload test).

In early tests, two reefing line failures occurred. Both were traced to degradation of the reefing line due to sharp edges of the reefing line cutters at the point of line penetration and to misaligned (V-Type) routing deficiencies in the early days of reefing application. Subsequently, the cutter hole edges were rounded and the reefing line was aligned with the reefing cutter holes. Reefing line forces were measured in 11 tests including the overload tests. Two reefing conditions were tested: 10.65 percent reefing with 6 seconds reefing time, and 12 percent reefing with 4 seconds reefing time. The load links used were stress coated metal tension links. Cracks occurring in the resin coating indicated the stress in the material. The links were calibrated in pounds of force applied to the tension link (Reference 9). Cracks in the coating of the links did not occur below 250 pounds, the measurable minimum force in the reefing line. Any load above 250 pounds was a direct measurement of the reefing line force experienced. The reefed parachute forces varied between 8000 and 15,500 pounds. In 10 tests, no cracks occurred in the load links; e.g., the reefing line load was below 250 pounds or less than 2.5 percent of the measured reefed parachute force. In one test, a reefing line force of 260 pounds was measured for a reefed parachute force of 15,500 pounds, this indicates a reefing line force ratio (F_{RL}/F_r) of 1.67 percent (see Figure 6, item 22).

As a result of these measurements, the 750 pound reefing line was replaced with a line of 1000 pounds specified strength for a new maximum parchute design load of 11,000 pounds and a 12 percent reefing ratio. This new reefing line strength comes close to the rule-of-thumb that the ultimate strength of the reefing line should not be less than 10 percent of the maximum reefed parahute force.

i. Apollo Aerial Drop Tests

Reefing line forces were measured in aerial drop tests of the main parachutes for the final Block II, Increased Capability, Apollo configuration. This parachute system consisted of three each 83.5 foot D_o (85.5 foot D_o based on the Recovery System Design Guide (Reference 18) ringsail parachutes with 120 foot long suspenion lines (l_s/D_o = 1.4), reefed by midgore reefing in two steps of D_r/D_o = 8.4 and 26.9 percent. These parachutes differed from the 88.1 feet diameter parachutes tested in the 1963/64 wind tunnel program (see paragraph 3f) in size and canopy configuration. The diameter was reduced to 85.5 feet and 75 percent of the fifth ring, counting from the vent, was removed thereby forming a wide slot between the fourth and sixth ring. Dual reefing lines were installed in the first reefing stage for reliability reasons. This minimized the possibility of a catastrophic failure due to premature cutting or inadvertent rupture of the reefing line. Reefing line forces were measured in tests series 80 and 81 which finalized the reefing system in single and cluster parachute tests. It should be remembered that a single drogue chute and a cluster of two main parachutes were the primary Apollo landing system. The second drogue chute and the third main parachute constituted the back-up system. They were simultaneously deployed with the primary system to eliminate a complex failure sensing system, to lower individual parachute forces, and to provide a lower rate of descent at water impact. During testing, two small strain gages each were placed in series in one of the reefing lines. Woven conductive leads were attached to individual suspension lines connecting the strain gages to the on-board telemetry (TM) system in the airdrop test vehicle. The suspension lines were loaded to 50 percent of their ultimate tensile strength and the leads attached with slack to the lines in multiple places.

Of the 11 single and two-parachute cluster tests in test series 80 and 81, nine tests were instrumented for measuring reefing line forces. On seven tests good force records were obtained. Three of these were single parachute tests (80-3, 80-3R and 80-3R1), and four were cluster tests 81-1 through 81-4. Test 81-4 measured the reefing line force in the first reefing stage, since no force data or any kind were available for second stage reefing. References 11 and 12 describe the Apollo parachute system and the -80 and -81 test series. All pertinent test data are listed in Table 2. Four of the test records are shown in Figures 7 through 10.

TABLE 2

APOLLO ELS TEST SERIES 80 &

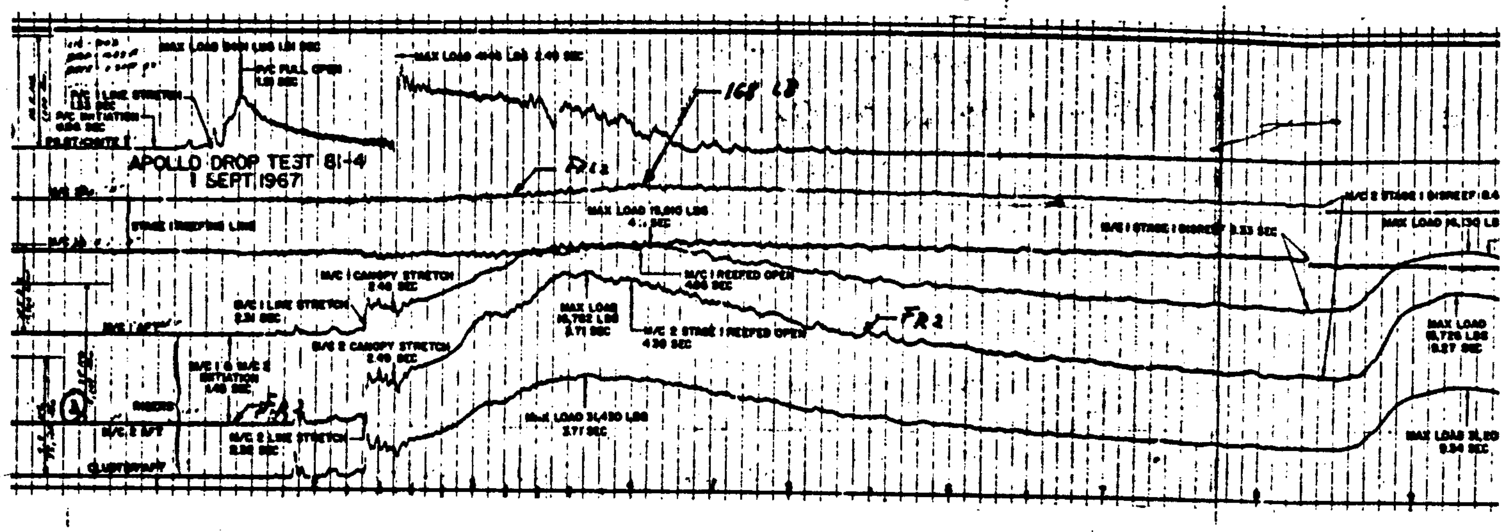
TEST NO.		80-3R	80-3R1	81-1 Para 1	81-1 Para 2
DATE		8-10-67	8-25-67	7-27-67	
TEST VEHICLE WEIGHT	LB	7490 (1)	7498	12,989	
A/C DROP SPEED	KNOTS	163	180	165	
DROP ALTITUDE	K FT	10	10	10	
NO OF MAIN PARACHUTES		1	1	2	
REEFING RATIOS D_r/D_o	%	8.4/26.7	8.4/26.7	8.2/24.0	8.2/24.0
REEFING TIMES t_r	SEC	5/8	5/8	5/8	5/8
MAX REEF PARA FORCE, STAGE 1	F_{r_1}, LB	15,167	19,885	16,200	12,696
MAX REEF PARA FORCE, STAGE 2	F_{r_2}, LB	21,184	19,491	19,052	13,696
MAX REEF LINE FORCE, FULL OPEN	F_o, LB	23, 252	21,185	14,212	15,120
MAX REEF LINE FORCE, STAGE 1	F_{RL_1}, LB	-	-	-	-
MAX REEF LINE FORCE, STAGE 2	F_{RL_2}, LB	307	268	229	132
RATIO $F_{RL_{max}}/F_{r_{max}}$		0.145	0.138	0.12	0.096
TIME OF $F_{RL_{max}}$ = TIME OF $F_{r_{max}}$ + Sec	$F_{r_{max}}$ + Sec	F_{r_2} +0.6 (2)	F_{r_2} + 2.6 (3)	F_{r_2} + 1.0	F_{r_2} + 1.7
RATIO (F_{RL}/F_r) max		0.0225	0.03	0.024	0.018
TIME OF (F_{RL}/F_r) max		Disreef	Disreef	F_{r_2} + 2.4	F_{r_2} + 1.8

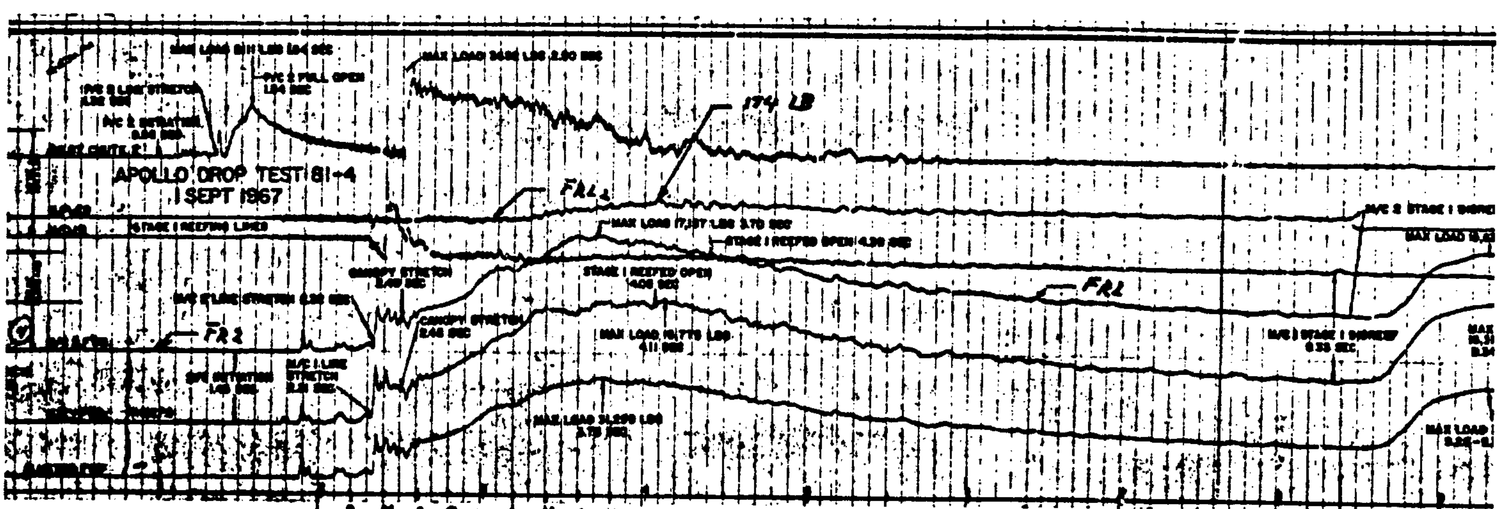
(1) High load test for second reefing stage = 0.58 of total system weight of 13,000 lb.
(2) Slow opening second stage.
(3) At disreef.
(4) Effect of variation in reefing cutter time and reefing line length.
(5) No force link.
(6) Poor recording.

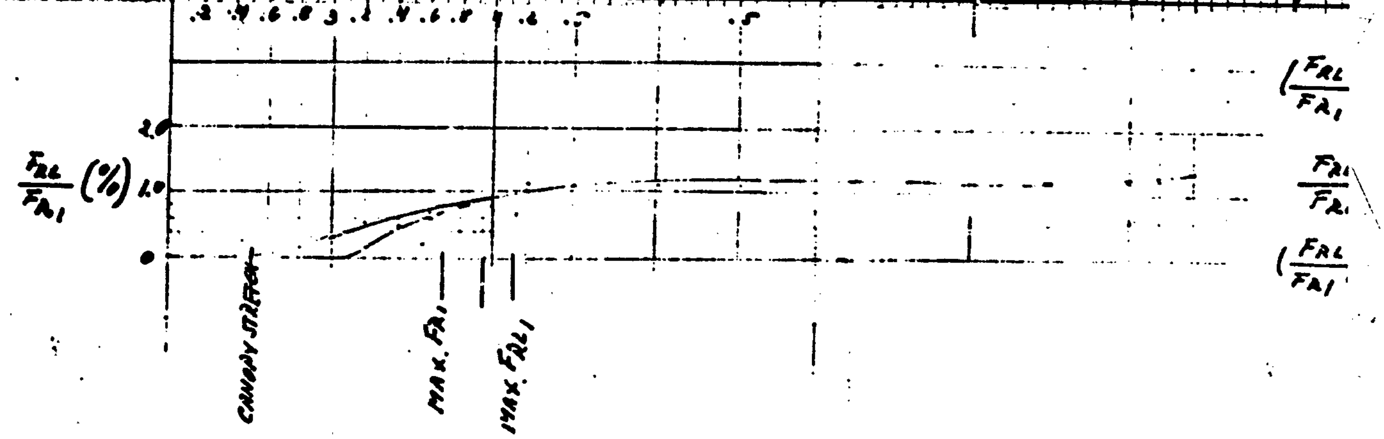
1

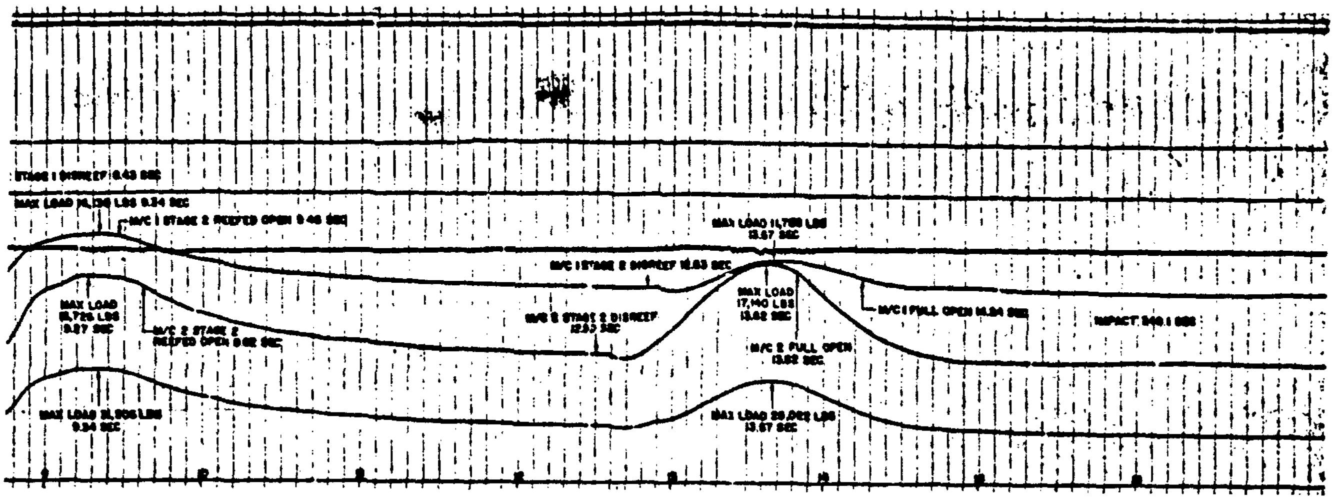
81-2		81-3		81-4	
Ch 1	Ch 2	Ch 1	Ch 2	Ch 1	Ch 2
9-8-76		8-26-76		9-1-67	
12,992		13,054		12,990	
165		180		182	
10		10		10	
2		2		2	
8.4/26.7	7.8(4)/26.7	8.4/26.7	8.4/26.7	8.4/26.7	8.4/26.7
5/10	6/12 (4)	5/8	5/8	6/10	6/10
13,434	13,634	16,445	18,438	15,775	17,157
18,597	13,391	14,710	19,925	16,318	15,834
17,581	7,103	14,185	16,060	17,161	17,162
-	-	-	-	-	174
259	(5)	225	257	(6)	-
0.139	-	0.0153	0.0129	-	0.0101
F_{r_2} + 2.4	-	F_{r_2} + 1.35	F_{r_2} +2.8 (3)	-	F_{r_2} + 0.45
0.026	-	0.031	0.022	-	0.013
Disreef	-	Disreef	F_{r_2} + 2.3	-	Disreef

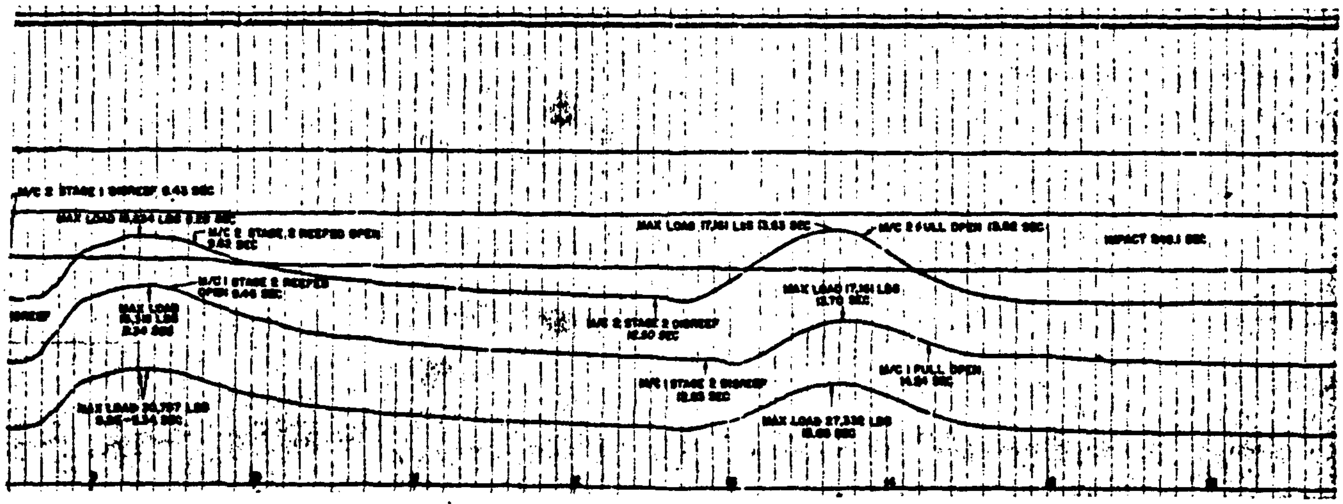
2


APOLLO DROP TEST 81-4
1 SEPT 1967
168 LB
F_{RL}
F_{R2}


APOLLO DROP TEST 81-4
1 SEPT 1967
174 LB
F_{RL}
F_{R2}


$\frac{F_{RL}}{F_{R1}}$ (%)
2.0
1.0
0
CANOPY STRETCH
MAX. F_{R1}
MAX. F_{RL1}





$\left(\frac{F_{RL}}{F_{R_1}}\right)_{max} = 1.3\%$

$\frac{F_{RL\,max}}{F_{R1\,max}} = 1.0\%$

$\left(\frac{F_{RL}}{F_{R1}}\right)$ at $F_{R1\,max} \sim 0.8\%$

Figure 7 - APOLLO ELS, Drop Test 81-4
Reefing Line Load Measurements
ICTV Weight - 3,000 lbs.
Conf: 2 Main Parachutes (D_o - 83.5')
Reefing: 8.4, 16.7%, t_r = 8 & 10 sec
Drop Alt/Speed: 10,000 Ft/182 KEAS
Reefing Line Load Links: 1st Stage

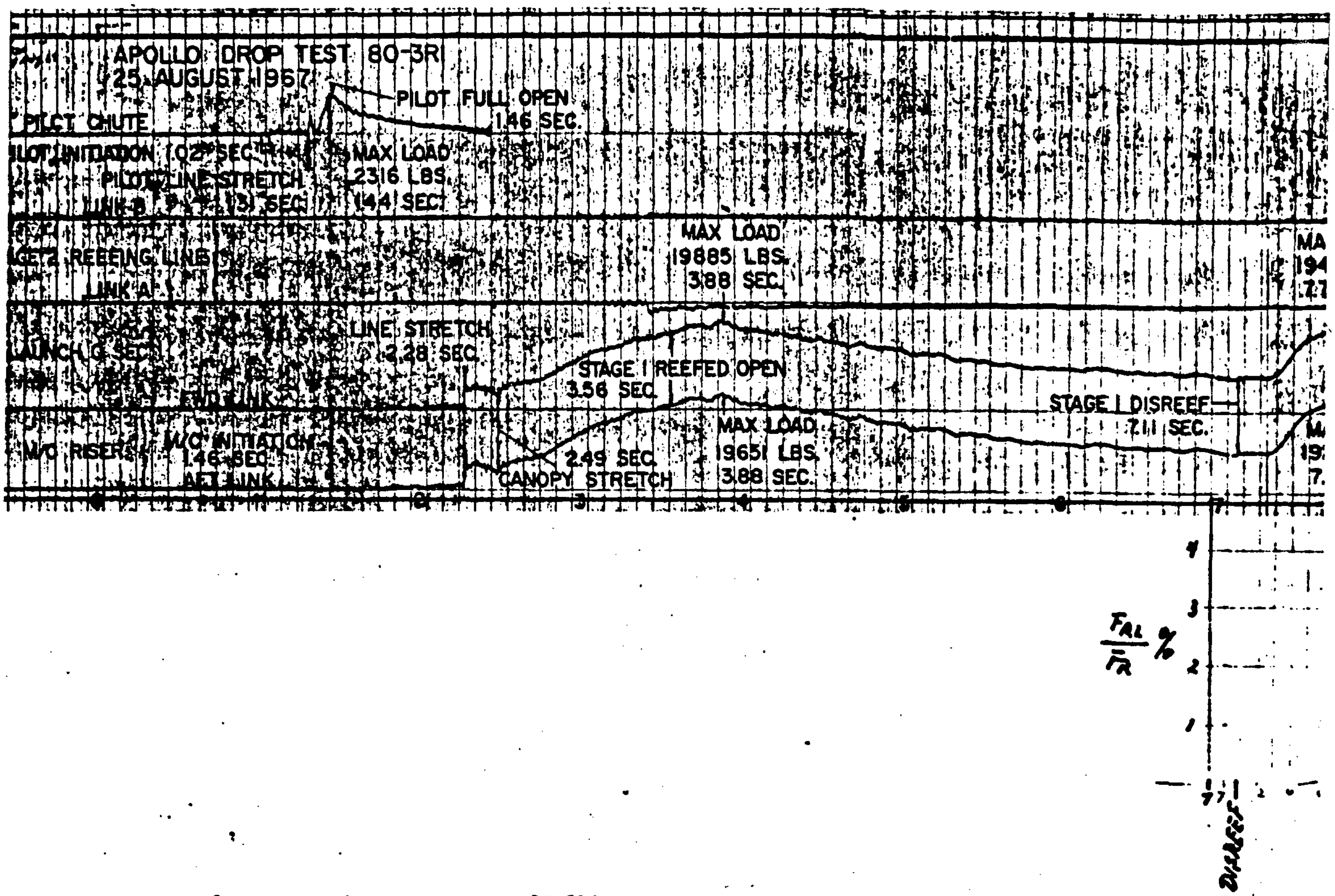
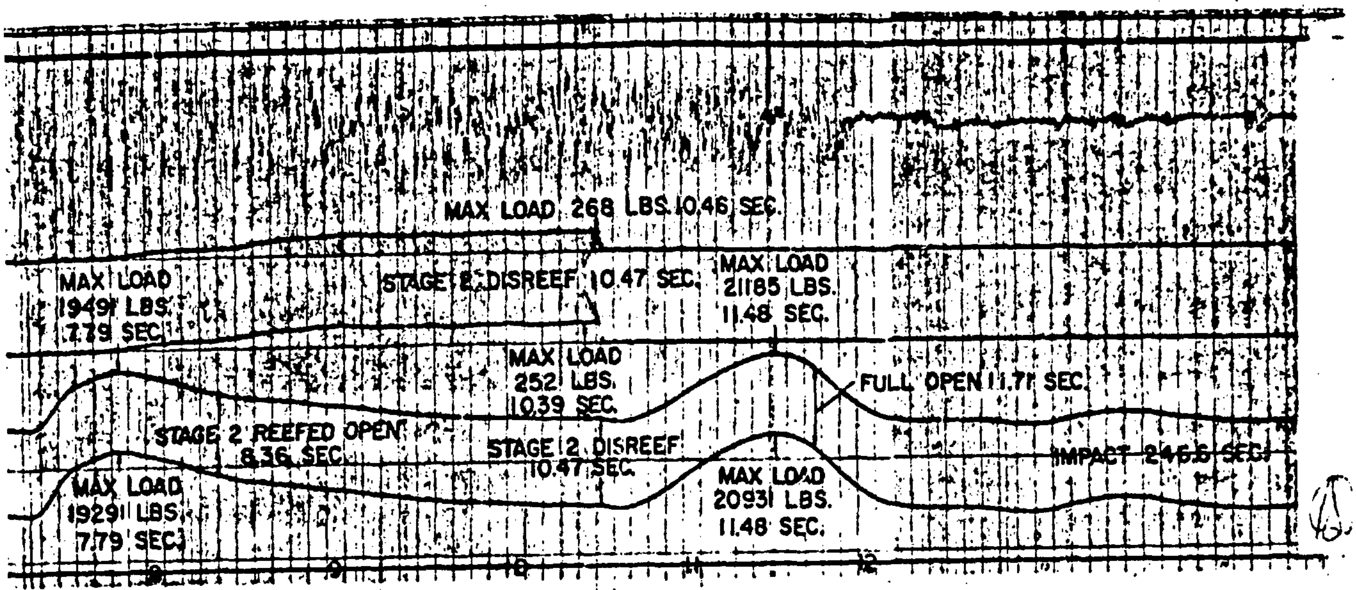
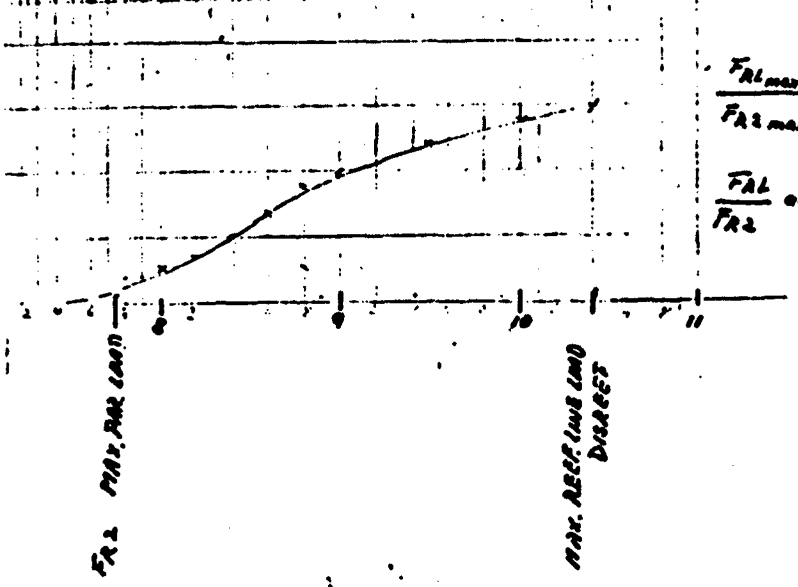


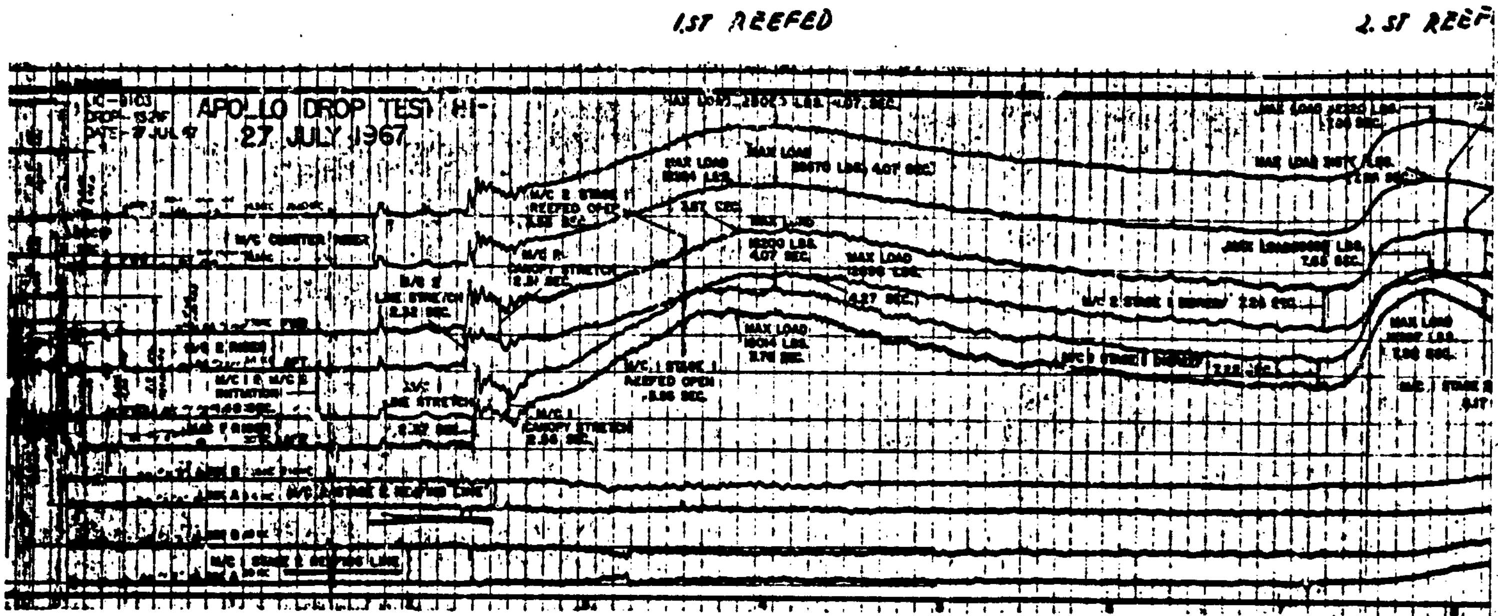
Figure 8 - APOLLO ELS, Drop Test 80-3R1
Reefing Line Load Measurements
ICTV Weight - 7,490 lbs
Conf: 1 Main Parachute (D_o = 83.5')
Reefing: 8.4, 26.7%, t_r = 5 & 8 sec.
Drop Alt/Speed: 10,000 Ft/180 KEAS
Reefing Line Load Links: 2nd Stage





$\frac{F_{RL_{max}}}{F_{R2_{max}}} = 1.3\%$ $\left(\frac{F_{RL}}{F_{R2}}\right)_{max} = 3.0\%$

$\frac{F_{RL}}{F_{R2}}$ at $F_{R_{max}} = 0.2\%$



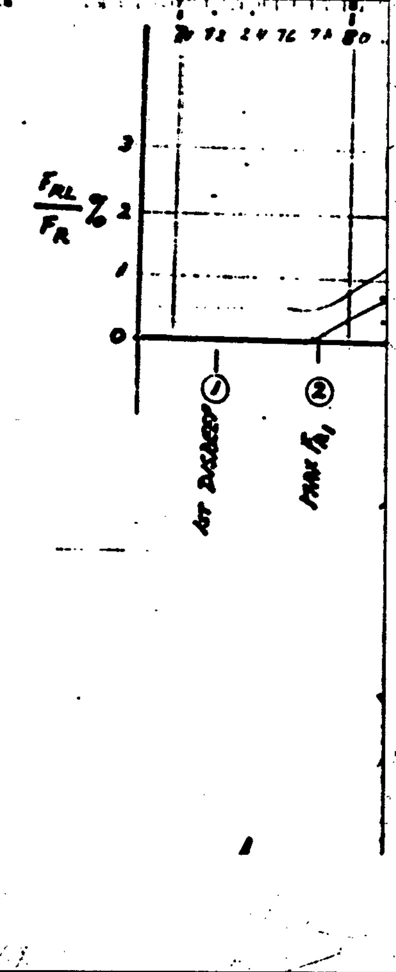
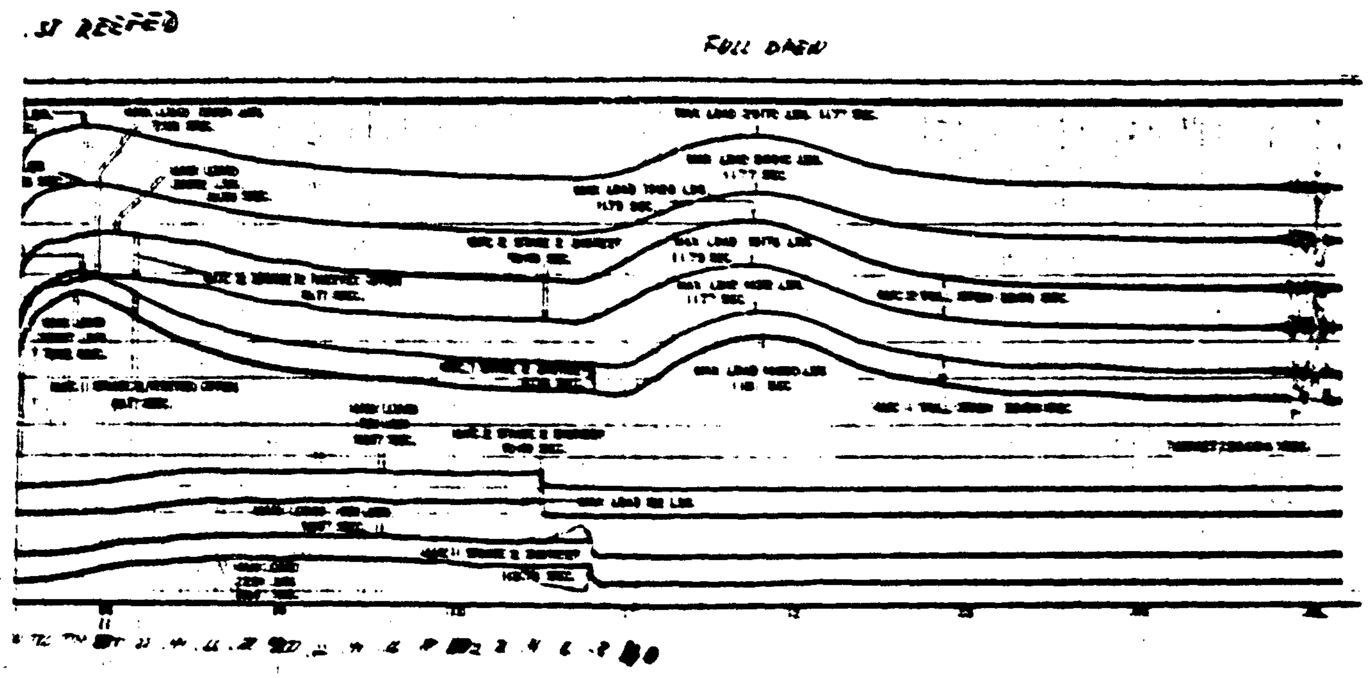
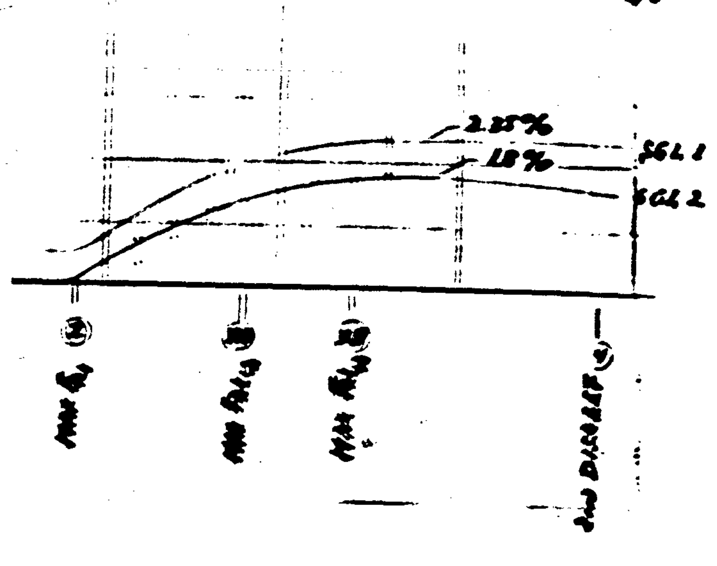


Figure 5 APOLLO ELS, Drpp Test 81-1
Reefing Line Load Measurements
ICTV Weight - 13,000 lbs.
Conf: 2 Main Parachutes (D_O= 83.5')
Reefing: 8.2, 24.8%, t_r= 5 & 8 sec.
Drop Alt/Speed: 10,000 Ft/160 KEAS
Reefing Line Load Links: 2nd Stage

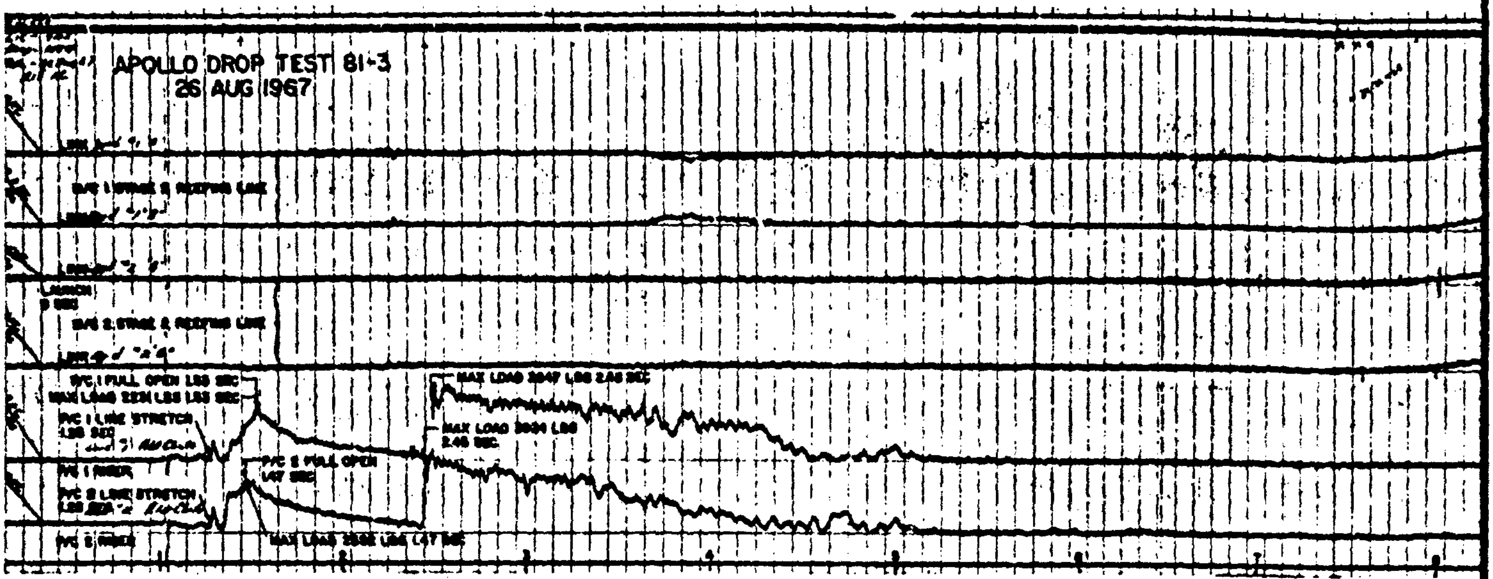


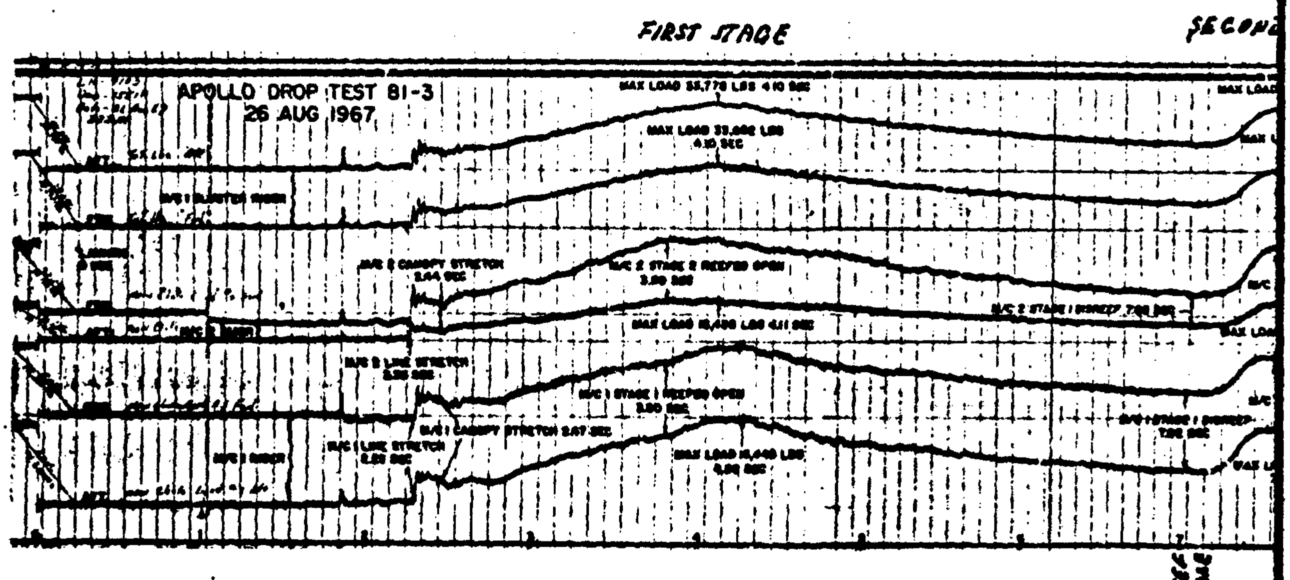


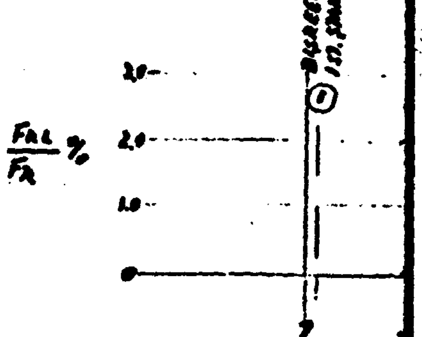
$$\frac{F_{R1max}}{F_{R2max}} = \frac{???}{????} = 12\%$$

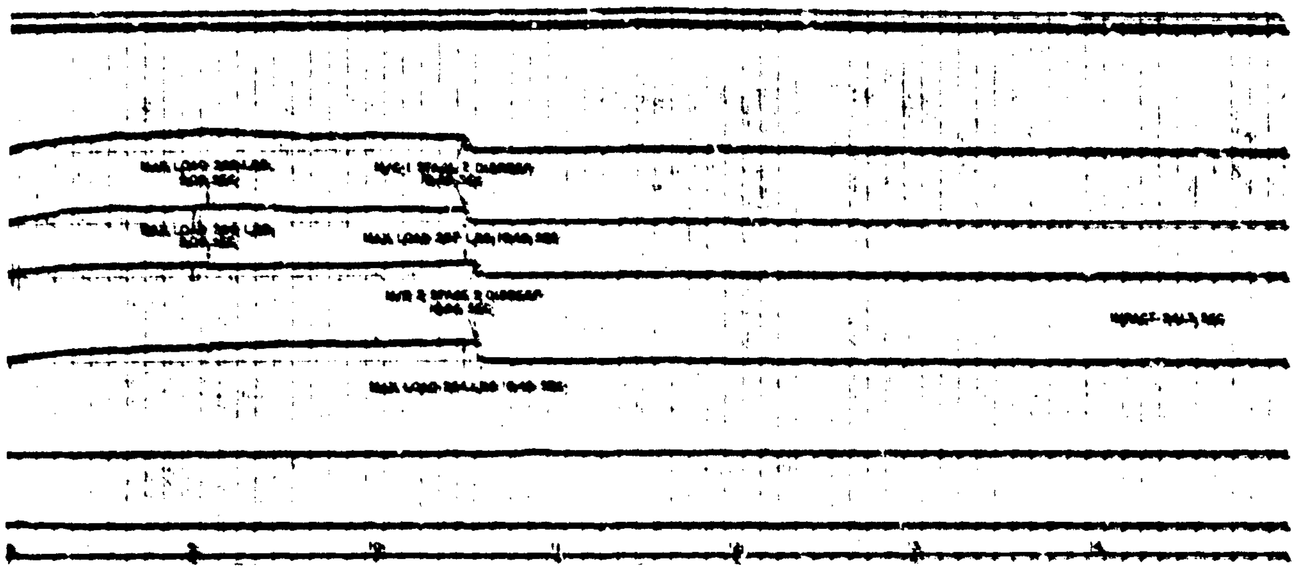
$$\left(\frac{F_{R1}}{F_{R2}}\right)_{max} = 2.35\%$$

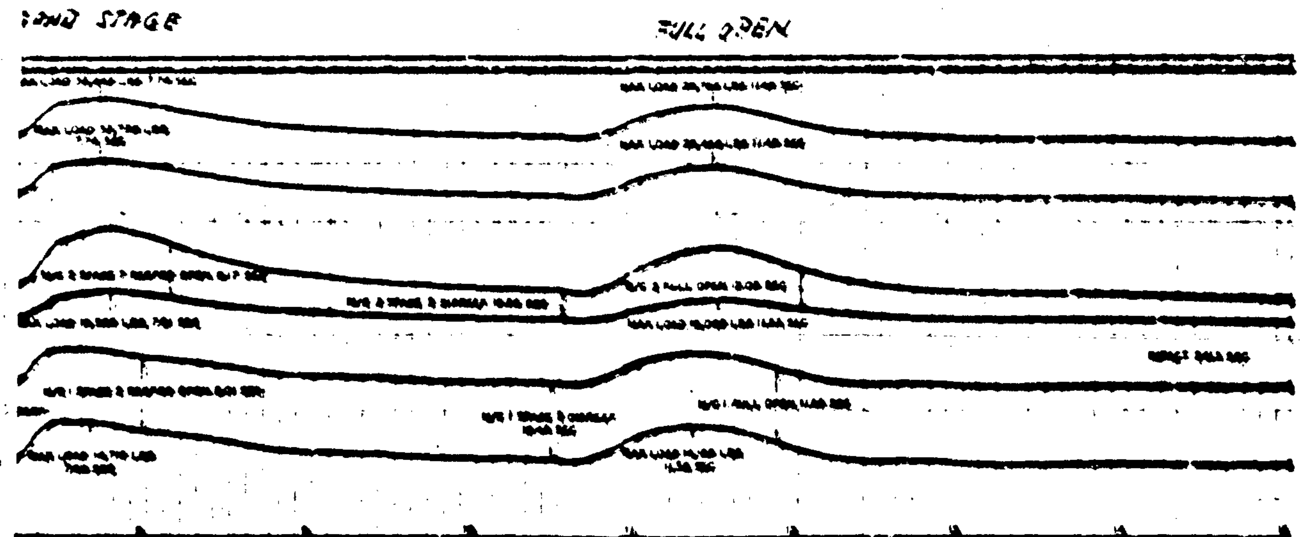
SGL = Strain Gage Link


APOLLO DROP TEST 81-3
26 AUG 1967


FIRST STAGE
SECOND
APOLLO DROP TEST 81-3
26 AUG 1967


DISREEF
1ST STAGE





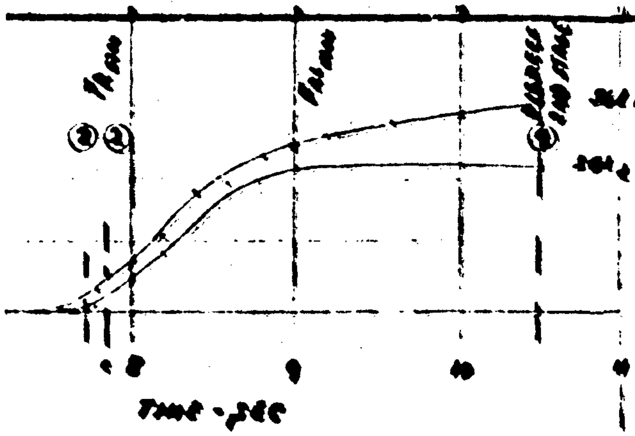


Figure 10 APOLLO ELS, Drop Test 81-1
Reefing Line Load Measurements
ICTV Weight = 13,000 lbs,
Conf: 2 Main Parachutes (D_0 = 83.5')
Reefing: 8.4, 26.7%, t_r = 5&8 sec,
Drop Alt/Speed: 10,000 Ft/165 KEAS
Reefing Line Load Links: 2nd Stage

First Stages Reefing Line Forces, Test No. 81-4. Only parachute No. 2, was instrumented for measuring the forces in one of the first stage reefing lines. Figure 7, a copy of the actual TM record of test 81-4 shows the recorded force for each paraachute, the combined parachute cluster force and the force in one of the two first stage reefing lines of parachute No. 2 using two strain gage links in series. The forces measured were 174 and 168 pounds, respectively. This good force agreement is also obvious in the individual parachute and the combined cluster force records. On the bottom of Figure 7 the author has evaluated the ratio of reefing line force to parachute force for both strain gage recordings. The subscript 1 defines the forces in the first reefing stage. The maximum reefed parachute force F_{RL} occurs at time 3.72 seconds after parachute deployment and the maximum reefing line force F_{RL} at time 4.1 seconds, e.g., later than the maximum parachute force. The ratio of maximum reefing line force to maximum parachute force (F_{RLmax}/F_{L1max}), generally the criterion for the required reefing line strength is one percent. However, this is only half the total reefing line force since two reefing lines were used and only one line was instrumented. The actual force for a single reefing line installation would be close to two percent, a value which is in general agreement with the 1.7 percent force ratio measured on the Mercury parachute in project Reef (see paragraph 3f). The ratio of reefing line force to parachute force at the time of maximum parachute force is 0.8 (1.6) percent. The maximum ratio of reefing line force to reefed parachute force (F_{RL}/F_{r}) max at any time is 1.3 (2.6 percent and occurs at disreefing. At disreef the parachute approaches a steady state velocity condition which permits a limited comparison to wind tunnel test results of parachute No. 18, the modified ringsail parachute with midgore reefing (see paragraph 3f and Figure 13 in Reference 12). However, parachute No. 18 did not have the wide slot in ring No. 5 of the final 83.5 feet diameter Apollo main parachute. This slot had a considerable effect on the shape of the reefed canopy and thereby on the force in the reefing line. Parachute No. 18 without the wide slot in wind tunnel tests inflated reefed to ring No. 6. Insertion of the wide slot limited the opening to inflation of the fourth ring. This means that the parachute in wind tunnel tests for the same length reefing line had a larger inflated diameter than the parachute used in the -80 and -81 aerial tests and therefore a larger angle δ between the suspension lines and canopy radials and associated reefing line forces. The desire to have the wind tunnel tests repeated with the final wide-slot version of the Apollo main parachutes was judged to be too costly and time consuming even for the Apollo program.

Forces in Second Stage Reefing Lines, Tests 80-3R1, 81-1, 81-2 and 81-3. The second reefing stage of the final Apollo main parachutes had a reefing ratio (D_r/D_o) of 26.7 percent and used only one reefing line. Again two strain gage links in series were used for measuring the reefing line forces. Table 2 which lists specifics of all tests shows that in cluster tests 81-1, 81-3, and 81-4 both parachutes were instrumented for reefing line force measurements. Detailed TM force records for tests 80-3R1, 81-1, and 81-3 are shown in Figures 8 through 10. All force records are reasonably similar. The force, in the second stage reefing line at the time of the maximum parachute force, is close to zero, increases with time, and reaches its maximum force value at or close to disreef.

The ratio of maximum reefing line force (F_{RL}) to maximum reefed parachute force (F_{r2}) varies betgween 1 percent for test 81-1, parachute No. 2 to 2.0 percent for test No. 81-4, parachute No. 2. This is the force ratio that determines the sizing of the reefing line. The maximum ratio of reefing line force to parachute force at any given time (F_{RL}/F_{r2}) max is 1.8 to 3.1 percent. This value approaches data measured in wind tunnel tests. The surprisingly large difference in the ratio of measured maximum reefing line force to maximum reefed parachute force (F_{RL}/F_{r1}) on the large parachutes measured in wind tunnel tests, from 3 to 7 percent, and measured in free-flight drop tests from 1 to 2 percent, is partially caused by the change in canopy design of the large ringsail parachute, and also by the time dependent reefed inflation process and the resulting lower radial and reefing line forces.

SECTION III

SUMMARY AND ANALYSIS OF TEST RESULTS

1. TEST SUMMARY

Data presented in pararaphs 3a through 3i show that the maximum reefing line force, measured during reefed inflation, varies from 1.5 to 7.5 percent of the maximum reefed parachute force, depends on the type of parachute used and the parachute application such as small first stage drogue chute, medium sized ordnance retardation parachute or large diameter final descent parachute. In addition, the reefing line force is affected by parachute size, canopy porosity, length of suspension lnes, first or second stage reefing and reefing time.

The following general test results can be stated:

(1) Good reefing line force data have been measured in wind tunnel tests on ribbon and ringsail parachutes and to a lesser degree on solid material parachutes. Reefing line forces range from about 2.5 percent to 7.5 percent of maximum reefed parachute force. All wind tunnel measurements were obtained on parachutes that had reached full reefed inflation and were tested at a constant tunnel velocity, neither of these conditions may exist in free-flight applications of reefed parachutes.

(2) Reefing line forces have been measured in free-flight tests on large diameter ringsail parachutes used for the Mercury and Apollo spacecraft landing. These measurements showed reefing line forces from about 1 to 2 percent of the maximum reefed parachute force.

(3) Evaluation of in-flight reefing line failures and no-failures of small first stage drogue chutes indicates maximum reefing line forces from 3 to 4 percent of the maximum reefed parachute force. The same analysis conducted on ordnance retardation parchutes by Sandia Laboratories indicates a maximum reefing line force in the 2.5 to 3.5 percent range.

(4) Data obtained in recent Sandia Laboratories wind tunnel tests show an increase in reefing line force with increase in suspension line length, a fact not previously recognized.

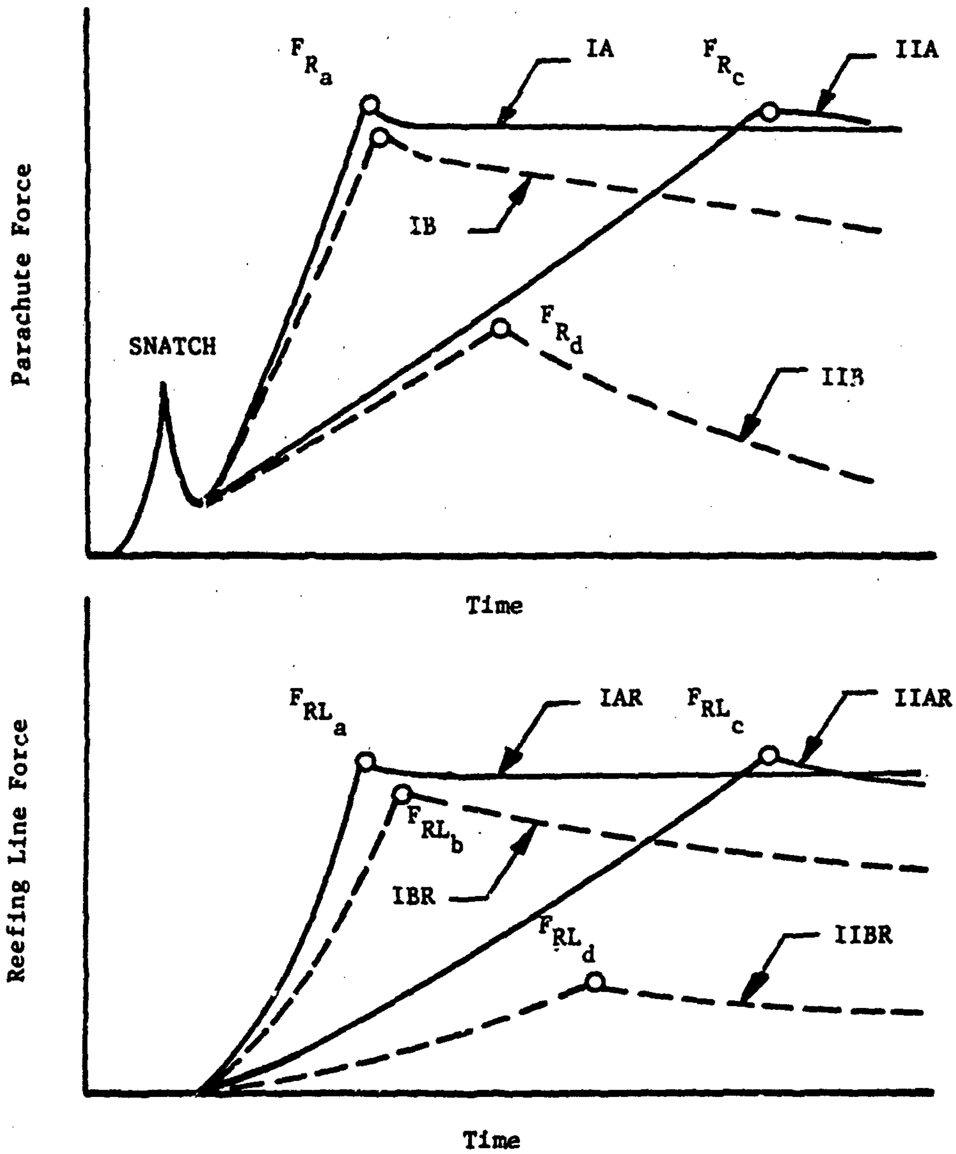
(5) Evaluation of numerous reefing system application points to the recurring problem of reefing line failures due to sharp edges on reefing line cutters, misalignment of reefing lines through reefing cutters and poor installation of reefing rings and reefing cutters inside the parachute canopy. Proper stress installation of the reefing system to meet existing load requirements has to be emphasized.

(6) The application of the "10-percent-rule" ultimate strength of the reefing line equal to 10 percent of the maximum reefed parachute force has always resulted in a no-failure reefing line installation, provided that the installation avoided the problems outlined in (5) above.

2. ANALYSIS OF TEST RESULTS

The wide variation in reefing line forces measured in wind tunnel tests and free-flight tests is primarily due to time, dependent reefed inflation process of the various parachute types and the associated velocity decay during reefed inflation. This is schematically shown in Figure 11. Curve IA shows a typical parachute force vs time curve for a first stage drogue parachute deployed in wind tunnel tests, and curve IB is for the same parachute deployed in free-flight tests with the related reefed parachute peak forces being F_{ra} and F_{rb}. The related reefing line force curves are IAR and IBR. There is little difference in the peak reefing line force (F_{rLa} and F_{rLb}) between both types of tests due to the relatively small difference in velocity decay during reefed parachute inflation.

This relationship is distinctly different for reefing line forces measured in wind tunnel tests and free-flight tests for large diameter final descent parachutes (see curves IIAS and IIB in Figure 11 and the associated reefing line force curves IIAR and IIBR). In wind tunnel tests, reefed parachutes forces and reefing line forces remain constant due to the constant tunnel velocity. In free-flight applications a rapid velocity decay occurs during reefed inflation due to the low canopy loading (W/C_DS). In addition, full reefed inflation may not occur prior to disreefing due to the relatively long inflation time. This appears to be the main reason for the low measured reefing line force ratios of 1 to 2 percent obtained in the Mercury and Apollo tests with large diameter ringsail parachutes.



IA	Drogue Parachute Force	WTT	$\frac{W}{(C_D \cdot S)_P}$ High
IB	" " "	DFFT,	
IIA	Main Parachute Force	WTT	$\frac{W}{(C_D \cdot S)_P}$ Low
IIB	" " "	DFFT,	
IAR	Drogue Par. Reef Line Force	WTT	
IBR	" " " " "	DFFT	
IIAR	Main Par. Reef Line Force	WTT	
IIBR	" " " "	DFFT	

Figure 11 Schematic Diagram of Parachute and Reefing Line Forces

SECTION IV

REEFING SYSTEMS OF OPERATIONAL PARACHUTES

Table 3 lists data on reefing installations of several operational parachute systems. It includes first stage drogue parachutes, ordnance retardation parachutes, and large diameter final descent parachutes. The data listed do not establish a clear-cut rule for determining the strength of reefing lines, especially a rule that fully agrees with the test results discussed in paragraph 3. However, all reefing line strength data listed in column F_{RL} ult/F_r, defining the ratio ultimate reefing line strength to maximum reefed parachute force, are, with few exceptions, in the 8 to 10 percent range, a range that agrees with the higher force values obtained in wind tunnel and free-flight tests. Not even the Apollo program dared to utilize the low measured values for the strength of the reefing lines. There are several reasons for this. It is highly recommended to use a factor of safety for reefing lines of 2.5 since a reefing line failure generally results in a catastrophic failure of the system. The reefing line force tests in the Apollo and the Mercury programs were made at the end of the development cycle. Changes in the system would have resulted in additional tests and costs. Stronger reefing lines as a safety means add little weight and volume. Last but not least, the free-flight test data presented in paragaphs 3h and 3i of this report were not available prior to the design of the Mercury and Apollo parachute systems and were not available to the general technical community prior to the publication of this report.

The following discussion may help in determining the strength of reefing systems for first stage drogue chutes, ordnance retardation parchutes, and large diameter final descent parachutes.

First Stage Drogue Chutes: These parachutes are generally small and are deployed at high speeds. The velocity decay during reefed inflation is small and full reefed inflation is reached long before disreef occurs. These parachutes are, therefore, quite similar in their reefed characteristics to parachutes tested in constant speed wind tunnel tests; wind tunnel tests data, therefore, are applicable. However, attention must be payed to the drag reduction of the reefed parachute due to the frequently large forebody wake and the effect of suspension line ratios (L_s/D_o) larger than 1.0 (Reference 11).

Ordnance Retardation Parachutes: These parachutes generally in the 8 to 30 fot D_o range show a slight decrease in velocity during reefed inflation if compared with wind tunnel tests due to the lower canopy loading, W/C_DS. This is reflected in Table 3 in the ordnance parachutes developed by Sandia Laboratories and the Solid Booster final descent parachutes. The latter, with a rate of descent at water entry of 85 ft/sec, is more related to ordnance retardation parachute than to final descent parachutes

TABLE 3

REEFING DATA OF OPERATIONAL PARA(

PROGRAM	YEAR	APPLICATION	Parachute Type	D_o / Z FT/	H/V_o KFT/KN	Vehicle Weight LB	Re(Ra(D_r
APOLLO (1)	1967	Drogue Chute	Con Rib	16.5/20	40K/245	13,000	0 (
APOLLO	1967	Main Parachute	Ringsail	83.5/68	18K/165	13,000	0.(0.2
MERCURY (6-Orbit)	1958	Main Parachute	Ringsail	64/48	10K/165	2,300	0.1
MERCURY (18-Orbit)	1959	Main Parachute	Ringsail	64/48	10K/165	3,000	0.1
USD-5	1960	Main Parachute	Ext Skirt	78/68	10K/250	4,800	0.0
B-70	1961	Encapsul Seat	Ext Skirt	34.5/36	15K/350	750	0.0
ACES II	1978	Ejection Seat	Solid Flat	28/28	15K/300	215	0.1
SPACE SHUTTLE SOLID BOOSTER	1978	Drogue Chute	Con Rib	54/60	16K/250	170,000	0.4 0.5
SPACE SHUTTLE SOLID BOOSTER	1978	Main Parachute	Con Rib	115/96	6.6K/195	170,000	0.1 0.4
SANDIA LABORATORY	1972	Ordnance	Con Rib	22.2/32	7K/1.5M	2,000	0.2
SANDIA LABORATORY	1978	Retardation	Con Rib	24/24	7K/1.7M	760	0.3
AGM-34	1972	Midair Retrieval	Tri-Con	101/88	15K/200	2,700	0.06

(1) All Apollo parachutes were tested at 1.35 design load.
(2) Two reefing lines were used for reliability reasons.
(3) Unless specifically tested $F_{RL_{ult}}$ was assumed to be specification strength X 0.9.
(4) Two-step reefing.
(5) Overload test.
(6) Test data.
(7) Information supplied by Pioneer Parchute Company.

HUTE SYSTEMS

fing io /D_o	t_r Sec	$F_{r_{Design}}$ LB	Reefing Line Mat/Str	$F_{RL_{ult}}$ (3) LB	$F_{RL_{ult}}$ / F_r	Ref	Comments
28	6	23,000	Nyl/2000 (2)	2055 (6)	0.089	11	Cluster of 3
84 (4)	6	12,000	Nyl/2000 (2)	2055 (6)	0.089	11,12	Cluster of 2
67	10		Nyl/2600	2340 (3)	0.114		
0	4	10,000	Nyl/750	810 (6)	0.081	9	
2	4	11,000	Nyl/1000	990 (6)	0.09	9	
66	4	8,000	Nyl/750	675	0.085	16	Cluster of 2
78	2	6,100	Nyl/750	675	0.105	16	
4	1.15	4,300	Nyl/750	675	0.16	17	
3 (4)	7	270,000	Nyl/36,000	27,675	0.1025	15	(7)
7	12	270,000					
9 (4)	10	174,000	Nyl/18,000	16,547	0.095	15	Cluster of 3
5	17	174,000					
8	0.5	150,000 (5)	Nyl/9000	8,100	0.054	13	
7		182,000 (5)	Kev/13,500	12,150	0.064	14	
		150,000			0.081		
53	10	12,000	Nyl/1000	1,280	0.107	10	

in the 20 to 30 ft/sec descent range. An utimate strength of the reefing line of 8 percent of the maximum reefed parachute force seems to satisfy the requirements for this type of parachute application. However, it may be prudent to use this lower ultimate strength ratio only for configurations where sufficient tests can verify the proper strength of the reefing line (Reference 13 and 14).

Final Descent Parachutes: In determining the strength of the reefing line for large final descent parachutes, the following should be considered. The data presented in paragraphs 3h and 3i on the measurements of reefing line forces on large final descent parachutes were obtained on ringsail parachutes only. These parachutes have a very pronounced tendency to grow in the reefed stage (see the discussion of this phenomenon in paragraphs 3i). This may not be true for large diameter solid material parachutes or large diameter ribbon and ringslot parachute (Reference 15).

Fully extended-skirt parachutes of 78 foot D_o (see item 4, Table 3) reached full reefed inflation, as indicated by the measured C_DS vs time curve, prior to the 4 second disreefing time (see Figure 46, Reference 16). Figure 12 of Reference 1 shows that extended skirt parachutes in the normally used reefing range of 5 to 20 percent have only half the drag area of ringsail parachutes with equal reefing ratios. This indicates that for the same length reefing line the extended skirt parachute has about half the inflated area of a ringsail parchute. As Figure 1 shows, this results in a smaller angle δ and a concomitant smaller force in the reefing line. However, this consideration is strictly hypothetical due to lack of measured reefing line forces on extended skirt parachutes. It appears that an ultimate reefing line strength of about 6 to 7 percent of reefed opening force would meet all safety requirements on large final descent parachutes. However, these values should be used with caution and only for cases where the installation meets all good design requirements and where sufficient tests can be conducted to verify the selection of the reefing line.

Tests conducted with the reefed 28 foot D_o solid flat parachute for the ACES II ejection seat (Reference 17) show full reefed inflation and a constant C_DS prior to disreefing after 1.15 seconds. The relatively strong reefing line was based on the qualified ACES I system which had a considerably higher reefed parachute force. Also it should be recognized that a smaller parachute for the same canopy loading, W/C_DS, has less velocity decay during reefed opening than a larger parachute and probably will cause a slighty higher reefing line force.

SECTION V

RECOMMENDATIONS

1. Use a reefing line force to maximum reefed parachute force ratio of 3 to 4 percent in the design of first stage drogue chutes used in the medium to high subsonic range. Consider the effect of suspension line ratios (l_s/D_o) greater than 1.0 and the effect of lower porosity for supersonic drogue chuges in determining the reefing line forces.

2. Use a reefing line to maximum reefed parchute force ratio of 3 percent in the design of ordnance retardation parachutes and parchutes with similar canopy loadings (W/C_DS).

3. Use a reefing line force to maximum parachute force ratio of 2.5 percent minimum in the design of large final descent parachutes. This ratio should be increased for parachutes with unknown reefing characteristics, for small parachutes, and for parachutes with large reefing ratios.

4. A factor of safety of not less than 2.5 is considered mandatory in the design of all components of the reefing system.

5. Pay particular attention to reefing cutter finishes (smooth holes), straight-through routing of reefing lines, reefing ring attachments and proper actuation of the reefing cutter.

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