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A STUDY TO IDENTIFY DATA VOIDS IN THE APPLICATION OF HI-GLIDE CANOPIES TO REMOTELY PILOTED VEHICLES (RVP)

RECOVERY AND CREW STATION BRANCH
VEHICLE EQUIPMENT DIVISION

JANUARY 1976

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Wright-Patterson Air Force Base, Ohio 45433

This technical report has been reviewed and is approved for publication.

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Substitution of an all-flexible Hi-Glide canopy in a Remotely Piloted Vehicle (RPV) recovery system offers many advantages over the use of a conventional parachute. However, prior to the incorporation of a Hi-Glide canopy system into an RPV, a comparative analysis of the various canopies available (Parawing, Ram-air, Sailwing) should be conducted; this requires a determination be made that sufficient data is available to conduct such an analysis. Potential Hi-Glide canopy applications for RPV's, definition of data voids which prevent a comparative analytical evaluation of the various Hi-Glide canopies for RPV application,

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ABSTRACT (Cont'd)

and program outlines for filling selected data voids are presented. A comprehensive literature search was made which resulted in the tabulation of Hi-Glide canopy characteristics and capabilities. A number of data voids were found to exist which would prevent the accomplishment of a meaningful comparative analysis of the application of Hi-Glide canopies to RPV's. A Hi-Glide canopy bibliography, originally published as AFFDL-TM-73-25-FER, is included. Bibliographies extracted from two NASA Parawing publications are included.

FOREWORD

This Technical Report was prepared by the Recovery and Crew Station Branch, Air Force Flight Dynamics Laboratory (AFFDL/FER), Wright-Patterson Air Force Base, Ohio, under Project 1964, "Advanced Launch and Recovery", within the scope of a Memo of Agreement between AFFDL and the Aeronautical Systems Division's Remotely Piloted Vehicle (RPV) Systems Program Office (SPO). The work covered the period from 23 October 1974 to 30 June 1975.

This report was submitted in October 1975.

TABLE OF CONTENTS

SECTION PAGE

I INTRODUCTION 1

1. Background 1
2. Purpose, Scope, and Approach of the Study 3

II IDENTIFICATION OF DATA REQUIREMENTS 7

1. Potential Applications 7
2. Operational Sequence/Data Requirements 9

III ANALYSIS OF DATA VOIDS 12

1. Identification of Hi-Glide Canopy Characteristics/Capabilities 12
2. Identification/Categorization of RPV Related Data Requirements 22
3. Identification of Data Voids Which Prevent a Hi-Glide Canopy Comparative Analysis 22
    a. Canopy Related Data Voids 24
        (1) Packing 24
        (2) Canopy Wing Area/Payload/Wing Loading 24
            (a) Canopy Wing Area 24
            (b) Canopy Payload 25
            (c) Wing Loading 25
        (3) Reefing 26
        (4) Canopy Control Data 26
        (5) Scaling Techniques 26
        (6) Reliability, Maintainability, and Cost 27

TABLE OF CONTENTS (Cont'd)

SECTION PAGE

(7) Miscellaneous Data Voids 27

(a) Materials 27

(b) Canopy Design 27

b. RPV Related Data Voids 28

(1) Acceptable Impact Condition 28

(2) RPV Operational Requirements 28

IV PROGRAM OUTLINES TO FILL SELECTED DATA VOIDS 29

1. Hi-Glide Canopy Aerodynamic Reefing Program 29

2. Hi-Glide Canopy Wing Loading Program 31

3. Hi-Glide Canopy Hi-Density Packing Program 32

4. Ram-Air Canopy Wing Area/Payload Program 33

5. Ram-Air Canopy Landing Flare Control Program 34

V CONCLUSIONS 36

REFERENCES 38

BIBLIOGRAPHIES

1. AFFDL-TM-73-25-FER 43

2. Flexible Wings For Transportation 66

3. Recent Flexible Wing Research 79

LIST OF ILLUSTRATIONS

FIGURE		PAGE
1	Hi-Glide Canopy Configurations	
	a. Parawing	2
	b. Ram-Air	2
	c. Sailwing	2
2	Hi-Glide Canopy Sketches	4
3	Hi-Glide Canopies as Applied To RPV's	8

LIST OF TABLES

TABLE		
1	Recovery Applications-Phase of Operation and Data Requirements	10
2	Identification of Hi-Glide Canopy Characteristics/Capabilities	13-20
3	Identification/Categorization of RPV Related Data Requirements	23

LIST OF SYMBOLS AND ABBREVIATIONS

AR	Aspect Ratio $(\frac{b^2}{S})$
aero	aerodynamic
b	Span; feet
bal	balance
C_D	Drag Coefficient $(\frac{\text{drag force}}{q\ S})$
C_L	Lift Coefficient $(\frac{\text{lift force}}{q\ S})$
C_M	Pitching Moment Coefficient $(\frac{\text{pitching moment}}{q\ S\ l_{ref}})$
C_R	Resultant Force Coefficient $(\frac{\text{resultant force}}{q\ S})$
C_{T_o}	Opening Force Coefficient $(\frac{\text{opening force}}{q\ S})$
C_{T_R}	Reefed Opening Force Coefficient $(\frac{\text{reefed opening force}}{q\ S})$
cu. ft.	cubic feet
F.F	Free Flight
fps	feet per second
Ft^2 or sq. ft.	Square feet
g or g's	$\frac{\text{applied force}}{\text{body weight}}$
GN&C	Guidance, Navigation, and Control
h	Altitude; feet
KEAS	Knots Equivalent Airspeed
l	Reference Length; feet
L/D	Lift to Drag Ratio

LIST OF SYMBOLS AND ABBREVIATIONS (Cont'd)

l_k	Parawing Keel Length; feet
MH	Manhours
psf	pounds per square foot
q	dynamic pressure ($\frac{1}{2}\rho V^2$); psf
RPV	Remotely Piloted Vehicle
S	Reference Area; sq. ft.
SPO	Systems Program Office
T/O	Take-Off
V	Velocity; feet per second
W or wt.	Weight; pounds
W/S	Wing-Loading $\left(\frac{\text{body weight}}{\text{reference wing area}}\right)$
ρ	air density (0.002378 slug/cu. ft.)
Λ_o	flat planform leading edge sweep; degrees
γ	flight path angle; degrees
#	pounds

SUBSCRIPTS

depl	deployment
FF	Free Flight
L.S.	Line Stretch
max	maximum
min	minimum
Par	Parawing
ref	reference
TOT	Total
V	Vertical

SECTION I

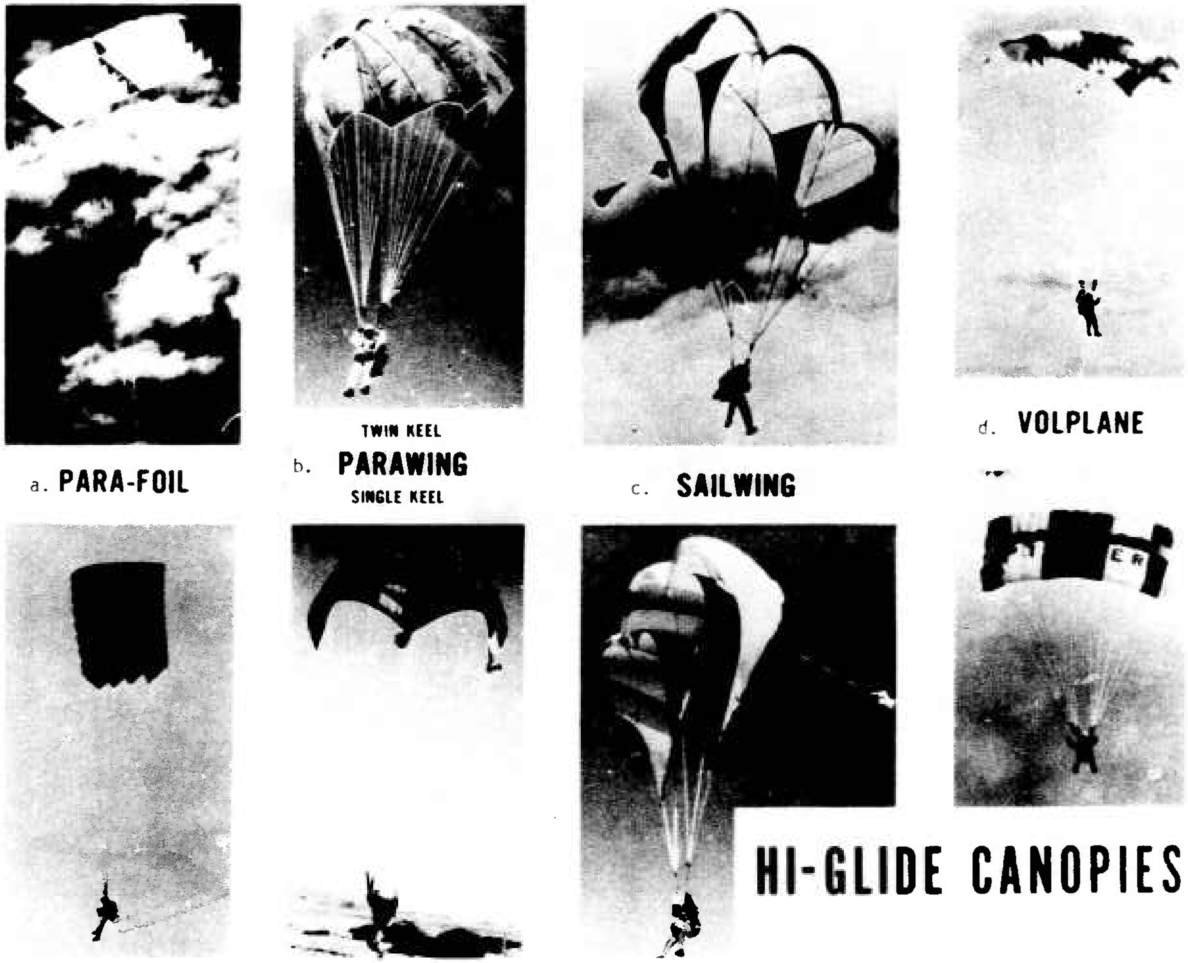
INTRODUCTION

1. BACKGROUND

The current Air Force use of a conventional parachute system for Remotely Piloted Vehicle (RPV) recovery, either midair or surface impact, provides for a minimum descent rate/impact velocity of approximately 13 to 15 feet per second and provides no control over the system's trajectory during descent. The substitution of an all-flexible Hi-Glide ($L/D \geq 2.25$) canopy for the conventional parachute system could provide a reduced descent rate and impact velocity, flight path control, homing to a precise surface impact location (automatic or manual), a wind offset capability, and the possibility of powered flight utilizing the RPV propulsion system during the recovery operation to increase the period of time available for recovery. Hi-Glide canopies could also be used to augment the RPV wing during take-off, thus significantly improving RPV launch performance. However, prior to the incorporation of a Hi-Glide canopy system(s) into RPV's, a comparative analysis of the various canopies available should be conducted to select the optimum configuration for a given application. This requires a determination be made that sufficient data is available to conduct such an analysis.

The candidate Hi-Glide canopies which represent the third generation of advanced lifting decelerators (References 1 and 2) are categorized as:

1. Parawing (Figure 1b)
2. Ram-Air (Figure 1a and d)
3. Sailwing (Figure 1c)



a. PARA-FOIL

b. PARAWING
TWIN KEEL
SINGLE KEEL

c. SAILWING

d. VOLPLANE

Figure 1. Hi-Glide Canopy Configurations

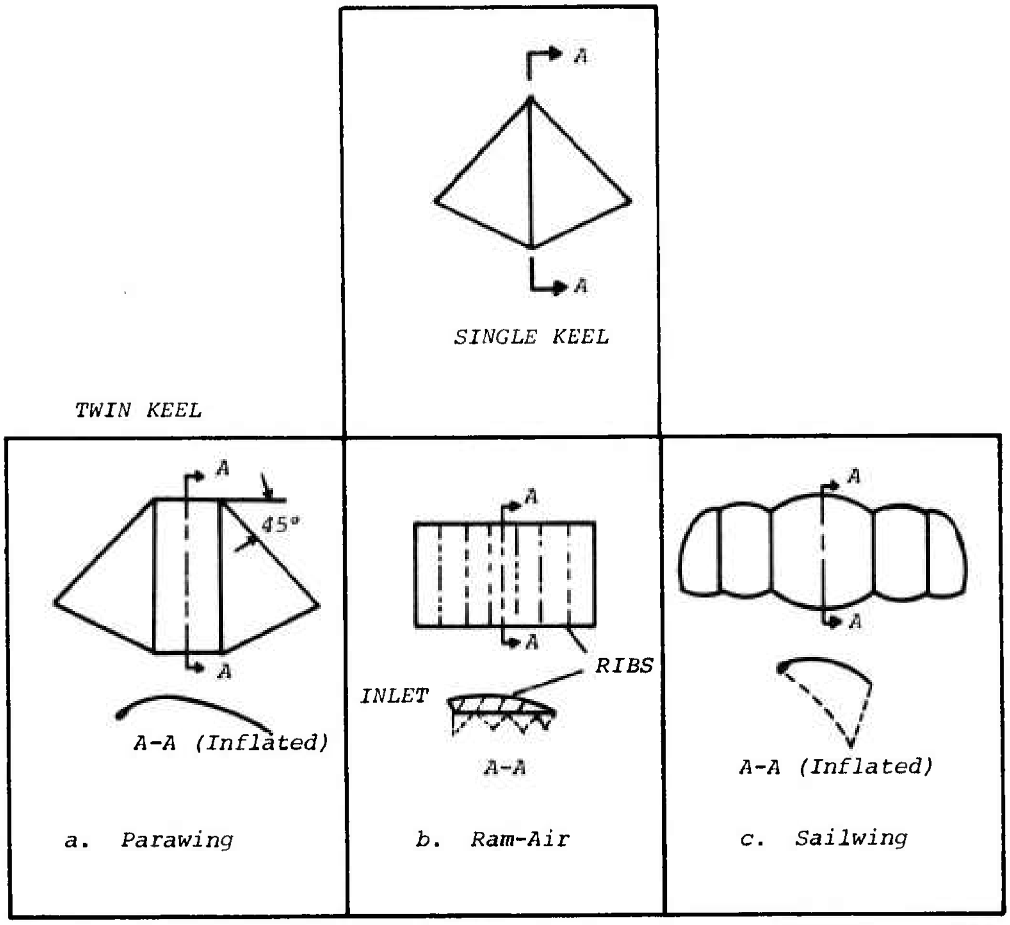
The Parawing Hi-Glide canopy is characterized by a single membrane surface of single or twin keel design (Figure 2a) which inflates to a cambered airfoil section by proper rigging of the suspension lines. Suspension lines are attached along the leading edges and keel(s). Directional control is accomplished by deflection of the outboard tip lines.

The Ram-Air Hi-Glide canopies are characterized, in general, by an upper and lower membrane and internal airfoil shaped fabric ribs, forming cells (Figure 2b). The planform is rectangular and the leading edge is open to allow ram-air to inflate the cells and shape the canopy. Suspension lines are attached to the lower surface. Various methods of directional control have been attempted; among these are trailing edge deflection and leading edge collapse.

The Sailwing Hi-Glide canopy is characterized by a single membrane surface of essentially a rectangular planform with rolled leading edge which is inflated by ram-air (Figure 2c). The planform is divided into lobes by suspension line flares. Directional control is accomplished by deflecting lines which change the shape of the outer lobe.

2. PURPOSE, SCOPE, AND APPROACH OF THE STUDY

The purpose of this study is the identification of potential Hi-Glide canopy applications for RPV's, the definition of data voids which would prevent a comparative analytical evaluation of the various Hi-Glide canopies for application to RPV's, the development of program



a. Parawing

b. Ram-Air

c. Sailwing

Figure 2. Hi-Glide Canopy Sketches

outlines for filling selected data voids, and the documentation of the study results. It should be stressed at this point that the study was not to conduct a Hi-Glide canopy comparative analysis but rather to identify the data voids which would prevent such an analysis.

The RPV chosen by the RPV SPO for this study as representative of the current generation of RPV's was the AQM-34V. This RPV has a maximum gross weight of 4520 lbs. with a maximum allowable g limit established for the study of 3.72 g's at maximum gross weight. A target deployment q value for the Hi-Glide canopy was established at 100 psf. Vertical descent velocity should be less than the 15 fps currently available with the ability to minimize total velocity for surface impact to minimize impact damage. A landing accuracy for surface impact recovery of 1/2 mile diameter circle is desired.

The approach adopted for this study was to first establish the candidate Hi-Glide canopies available and their potential applications for RPV's. An analysis of the various phases (as defined in Table 1) of each application (e.g. midair recovery) led to identification of the system data requirements for the various phases of each application. A literature search was then conducted to identify the capabilities of each candidate canopy. It should be stressed at this point that only data documented in the published literature was considered in this study. A comparison of data requirements and data available resulted in identification of the data voids. Programs were developed which would attempt to fill selected voids.

It should be emphasized here that the programs outlined are those required to fill the selected Hi-Glide canopy data voids; this does not imply that the entire program outline for a given void must be accomplished as a single effort. The outlined programs may be subdivided into smaller efforts.

SECTION II

IDENTIFICATION OF DATA REQUIREMENTS

1. POTENTIAL APPLICATIONS

A review of current RPV operations resulted in the identification of the general categories of recovery and take-off as potential areas for Hi-Glide canopy application. For recovery, Hi-Glide canopies offer the potential of reduced descent rates (including the possibility of zero descent rate under powered flight), increased wind penetration capability, flight path control, homing (manual or automatic) to a specific impact point, and reduced impact velocities. For take-off, a Hi-Glide canopy offers additional wing area to reduce the required take-off speed, thus reducing take-off distance.

The potential applications are depicted in Figure 3 and include midair recovery and surface impact recovery. Midair recovery will utilize an uncontrolled canopy, be powered or unpowered, and be conducted in daytime under visual (good weather) flight conditions. Surface impact recovery will be accomplished through automatic homing or manual guidance of a powered or unpowered vehicle. Under each of these categories of guidance, a possibility of two further subdivisions exists - use of canopy control surfaces or use of RPV control surfaces. Automatic homing will be accomplished in daytime or night and in all weather. Manual guidance will be limited to daytime/good weather only.

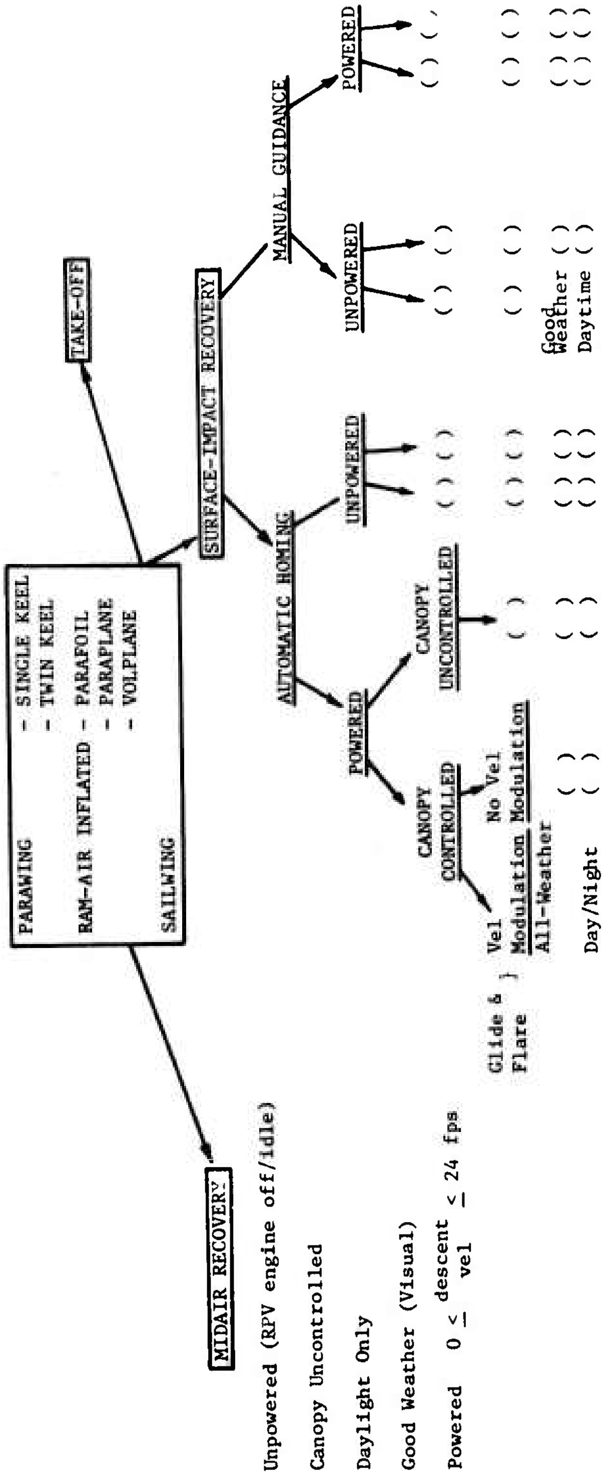


Figure 3. Hi-Glide Canopies as Aoplied to RPV's

2. OPERATIONAL SEQUENCE/DATA REQUIREMENTS

A consideration of the RPV operations during each of the potential applications led to identification of a sequence of events or phases of operation occurring during each application. An analysis of each phase of operation resulted in the identification of the system data requirements necessary to perform a Hi-Glide canopy comparative analysis. Through this analysis it was determined that all data requirements identified for a recovery application encompassed those identified for a take-off application. Therefore, only the recovery application will be addressed in the remaining sections of this study. It should be noted that a program to fill a data void under the recovery applications will, in general, be more extensive than one to fill the same data void under the take-off application due to the additional restrictions imposed on the recovery application (e.g. volume constraint).

The phases of the recovery system utilization and the data required for evaluation of the recovery system within each phase are given in Table 1:

TABLE 1

RECOVERY APPLICATIONS-PHASES OF OPERATION AND DATA REQUIREMENTS

PHASE	DATA REQUIREMENTS
1. Packed and stored in the RPV	a. Achievable packing densities for Hi-Glide materials.
	b. Material types for Hi-Glide application.
	c. RPV weight and balance data.
	d. RPV aerodynamic data.
	e. RPV structural data.
	f. RPV recovery system volume available.
2. Deployed from the RPV	a. RPV "g" limitations for all axes.
	b. RPV recovery envelope.
	c. RPV recovery weight.
	d. Hi-Glide canopy deployment capabilities . Dynamic Pressure . Reefing . Opening Forces . Reliability
3. Steady state flight/descent	a. Hi-Glide canopy aerodynamic data.
	b. Hi-Glide canopy stability data.
	c. Hi-Glide canopy control data . Forces . Travel

TABLE 1 (Concluded)

PHASE	DATA REQUIREMENTS
	d. Hi-Glide canopy turn data.
	e. Desired/allowable descent rate.
	f. Desired wind offset capability.
	g. Ability to design a canopy for a given weight range.
	h. RPV aerodynamic data.
	i. RPV stability data.
	j. RPV control data.
	k. RPV engine data.
	l. RPV guidance, navigation, and control capabilities.
4. Flight Termination	a. All items of Number 3 above.
	b. RPV "g" limits.
	c. Midair recovery constraints.
	d. Acceptable impact conditions.
	e. Impact accuracy requirements.
	f. Surface based control equipment requirements.
5. Turnaround	a. Packing time.
	b. Packing facilities required.
6. Miscellaneous	a. Canopy cost.
	b. Reliability.
	c. Maintainability.

SECTION III

ANALYSIS OF DATA VOIDS

1. IDENTIFICATION OF HI-GLIDE CANOPY CHARACTERISTICS/ CAPABILITIES

Following compilation of the data required for conducting a comparative analysis (Table 1), a literature search was conducted to determine which of these data are available for each of the candidate Hi-Glide canopies. This information is presented in Table 2.

The available data has been divided into several categories in Table 2. Table 2a presents various physical characteristics of the candidate Hi-Glide canopies as they exist today. Free flight wing loading, $(W/S)_{FF}$, is indicated as having a potential lack of data due to its interrelationship with other factors such as wing area, payload weights, and overall system performance requirements. For example, volume constraints might be such that a canopy of sufficient area could be stowed which would carry the payload within the demonstrated $(W/S)_{FF}$ capability. However, the requirement for a smaller recovery system volume or for increased system wind offset capability might easily push the $(W/S)_{FF}$ requirement above the current demonstrated capability. It should be noted at this time that due to the flexible nature of Hi-Glide canopies an increase in wing loading tends to distort the canopy as the increased load is distributed into the canopy, causing a degradation in performance. This shortcoming is partially due to the inability to analytically predict the stress distribution throughout the canopy for a given application. Table 2b presents Hi-Glide canopy deployment

TABLE 2

IDENTIFICATION OF HI-GLIDE CANOPY CHARACTERISTICS/CAPABILITIES*

a. PHYSICAL CHARACTERISTICS

	AGHIEVABLE PACKING DENSITY	MATERIAL TYPES	WING AREAS DEMONSTRATED	ASPECT RATIOS INVESTIGATED	PAYLOAD WEIGHTS	FREE FLIGHT WING LOADING
PARAWING	Hand Packed	(Rip-Stop Nylon, coated)	(3) Up to 4000 Ft^2	(4) Up to 3.0 ($\Lambda_o = 45°$) 4.0 ($\Lambda_o = 0°$)	(3) Up to 6000 #	(3) Up to 1.5 psf**
RAM-AIR	Hand Packed	(Rip-Stop Nylon, coated)	(5) Up to 864 Ft^2	(6) Up to 3 Personnel 1.5→2.0	(5) Up to 2000 # ?	(5) Up to 2.7 psf**
SAILWING	Hand Packed	(Rip-Stop Nylon, coated)	(7) Up to 2700 Ft^2	(8) Up to 4.0	(7) Up to 1000#	(8) Up to .75 psf

* Numbers in parentheses denote a reference.

** Potential data void depending on other factors.

TABLE 2. (Cont'd)

b. CANOPY FREE FLIGHT DEPLOYMENT CAPABILITIES - PARAWING

	MAXIMUM SPEED SUCCESSFUL DEPLOYMENT	ASSOCIATED CANOPY AREA (FT^2)	ASSOCIATED MAXIMUM OPENING FORCES (g's)
REEFED (9)	220 KEAS q_{max}=93 to 20000'	400	4.2 - 6 to 20000'
UNREEFED (10)	160 KEAS q_{max}=87 to 1000'	276.5	24 - 37 (Minimal Data)

ARE METHODS AVAILABLE TO SCALE OPENING FORCES
A method has been demonstrated for unreefed parawings up to l_k = 24', S = 400 Ft^2 (11)

	MAXIMUM CANOPY AREA (FT^2)	ASSOCIATED SPEED SUCCESSFUL DEPLOYMENT	ASSOCIATED MAXIMUM OPENING FORCES (g's)
REEFED (3)	4000	180 KEAS to 22000' $q_{L.S.}$ = 76	2.8 - 4 to 22000'
UNREEFED (3)	4000	NO DATA	NO DATA

TABLE 2. (Cont'd)

b. CANOPY FREE FLIGHT DEPLOYMENT CAPABILITIES - RAM-AIR

	MAXIMUM SPEED SUCCESSFUL DEPLOYMENT	ASSOCIATED CANOPY AREA (FT^2)	ASSOCIATED MAXIMUM OPENING FORCES (g's)
REEFED(12)	200 KEAS to 15000' $q_{max}=100$	230	14 - 18 to 15000' (Higher at 22000')
UNREEFED(12)	100 KEAS to 3000' $q_{max}=32$	230	NO DATA

ARE METHODS AVAILABLE TO SCALE OPENING FORCES
? (5) Possible Scaling of $\frac{C_{To}}{C_{Tr}}$ (Minimal Data)

	MAXIMUM CANOPY AREA (FT^2)	ASSOCIATED SPEED SUCCESSFUL DEPLOYMENT	ASSOCIATED MAXIMUM OPENING FORCES (g's)
REEFED(5)	864	130 KEAS TO 3000'	8 - 10 Low Altitude (Minimal Data)
UNREEFED	(5) 864	NO DATA	NO DATA

TABLE 2. (Cont'd)

b. CANOPY FREE FLIGHT DEPLOYMENT CAPABILITIES - SAILWING

	MAXIMUM SPEED SUCCESSFUL DEPLOYMENT	ASSOCIATED CANOPY AREA (FT^2)	ASSOCIATED MAXIMUM OPENING FORCES (g's)
REEFED (8)	119KEAS to 1500' q = 46	400	UNAVAILABLE*
UNREEFED	NO DATA	NO DATA	NO DATA

ARE METHODS AVAILABLE TO SCALE OPENING FORCES
none

	MAXIMUM CANOPY AREA (FT^2)	ASSOCIATED SPEED SUCCESSFUL DEPLOYMENT	ASSOCIATED MAXIMUM OPENING FORCES (g's)
REEFED (7)	2700	q = 20 psf	2.2
UNREEFED	NO DATA	NO DATA	NO DATA

* Tests at 59KEAS and 1500' (q=12psf) produced $g_{max} = 13.5$

TABLE 2. (Cont'd) c. AERODYNAMIC PERFORMANCE AND CONTROL DATA** - PARAWING

PERFORMANCE		
▨	Wind Tunnel	Free Flight
S	Up to 400 Ft^2	Up to 4000 Ft^2
AR_{Par}	Up to 4	Up to 3
q	Up to 4 psf	Up to 2 psf
C_L	✓	✓
C_D	✓	✓
C_M	✓	▨

CANOPY CONTROL		
S	UP TO 400 FT^2	4000 FT^2
q	UP TO 2 psf	UP TO 2 psf
TURN CONTROL	▨	▨
·Aero Data	✓	✓
·Force	✓	✓
·Stroke	✓	✓
·Response Time	✓	✓
LANDING CONTROL	▨	▨
·Aero Data	✓	✓
·Force	✓	✓
·Stroke	✓	✓
·Δ V	✓	✓

Methods Available to Scale Steady State Performance	Not specifically; but much date on many sizes is available

Are Methods Available to Scale Control Characteristics	SOME

NOTE: (1) A check (✓) indicates that this data is available.

(2) Stability*: W. T. - Stability data shows only trends due to types of testing techniques (constraints) used.

F. F. - Stability data is qualitative in most instances.

* This applies to all three types of Hi-Glide Canopies.

** This information is contained in many sources in the bibliographies

TABLE 2. (Cont'd)

c. AERODYNAMIC PERFORMANCE AND CONTROL DATA-RAM AIR

	PERFORMANCE	
▨	Wind Tunnel	Free Flight
S	Up to 300 Ft^2	Up to 864 Ft^2
AR	Up to 3	Up to 2
q	Up to 4.3 psf	Up to 4.3 psf
C_L	✓	✓
C_D	✓	✓
C_M	✓	▨

CANOPY CONTROL		
S	UP TO 300 FT^2	LARGE (> 300 ft^2)
q	UP TO 4.3 psf	
TURN CONTROL	▨	▨
•Aero Data	✓	NO DATA
•Force	✓	NO DATA
•Stroke	✓	NO DATA
•Response Time	✓	NO DATA
LANDING CONTROL	▨	▨
•Aero Data	NO DATA	NO DATA
•Force	NO DATA	NO DATA
•Stroke	NO DATA	NO DATA
•Δ V	NO DATA	NO DATA

Methods Available to Scale Steady State Performance	No, but much data is available from which methods may be developed

Methods Available to Scale Control Characteristics	NONE

TABLE 2. (Cont'd)

AERODYNAMIC PERFORMANCE AND CONTROL DATA - SAILWING

	PERFORMANCE	
▨	Wind Tunnel	Free Flight
S	Up to 328 Ft^2	Up to 2700 Ft^2
AR	NO DATA	NO DATA
q	Up to 12 psf	Up to 1.5 psf
C_L	LIMITED DATA	NO DATA
C_D	LIMITED DATA	NO DATA
C_M	LIMITED DATA	▨

	CANOPY CONTROL	
S	95.5 FT^2	328 FT^2
q	1 psf	UP TO 6 psf
TURN CONTROL	▨	▨
·Aero Data	LIMITED DATA	LIMITED DATA
·Force	NO DATA	NO DATA
·Stroke	LIMITED DATA	LIMITED DATA
·Response Time	NO DATA	NO DATA
LANDING CONTROL	▨	▨
·Aero Data	NO DATA	NO DATA
·Force	NO DATA	NO DATA
·Stroke	NO DATA	NO DATA
·Δ V	NO DATA	NO DATA
Methods Available to Scale Steady State Performance	NONE	

Are Methods Available to Scale Control Characteristics	NO

TABLE 2 (Concluded)

d. MISCELLANEOUS INFORMATION

	DEMONSTRATED FIELD PACKED CAPABILITY	COST ESTIMATING DATA BASIS	RELIABILITY*	MAINTAINABILITY
PARAWING	Personnel size only	Cost for fabricating personnel sized wings	NO DATA	NO DATA
RAM-AIR	Personnel size only	Cost for fabricating personnel sized wings	NO DATA	NO DATA
SAILWING	NO DATA	NO DATA	NO DATA	NO DATA

*NOTE: Hi-Glide Canopies are inherently reliable in their opening. Efforts to control the opening forces creates problems in reliability.

capabilities. The Sailwing data presented is based on a minimal amount of test information (e.g. only one successful test a $q = 20$ psf for the 2700 ft^2 Sailwing). The 4000 sq. ft. Parawing was developed under a NASA program (Reference 3) and employed a complex five-stage pyrotechnic reefing system which would probably be unacceptable for the RPV application under consideration. Under this and other NASA programs the ability to scale the opening forces for Parawings up to 400 sq. ft. ($l_k = 24$ ft.), Reference 11, from model results has been demonstrated. This scaling technique has not been verified for other Hi-Glide canopies. An attempt to predict the reefed opening forces of the 4000 sq. ft. Parawing from test results of a 400 sq. ft. "model" were largely unsuccessful due in part to a mismatch between desired and actual test conditions of the verification tests, Reference 3. Under an Air Force program, Reference 5, a possible scaling of the ratio of opening force to reefed opening force for a Ram-air canopy was demonstrated; however, this is based on minimal data. Table 2c presents the aerodynamic performance and control data. As indicated in the table, no specific methods are presently available to directly scale the steady state flight performance of Hi-Glide canopies. The limited wind tunnel aerodynamic performance data for the Sailwing is contained in References 13, 14, and 15. However, the range and numbers of variables included are not considered sufficient to adequately predict the aerodynamic performance of other Sailwing configurations. No free flight aerodynamic performance data or canopy control data is available for the Sailwing. Table 2d represents additional miscellaneous information required to round out the complete comparative analysis. Due to the limited investigation of large scale (>300 sq. ft.) Hi-Glide canopies, cost, reliability, and maintainability information is virtually non-existent.

2. IDENTIFICATION/CATEGORIZATION OF RPV RELATED DATA REQUIREMENTS

The information presented in Table 3 represents the RPV related information required to conduct a Hi-Glide canopy comparative analysis. A check mark (✓) indicates that sufficient data is available. The term GN&C stands for guidance, navigation, and control. These terms are defined (Reference 16) as follows:

Navigation - Ability to determine position relative to a given position.

Guidance - Ability to establish a suitable ground track and flight condition in order to reach the given position.

Control - Ability to cause the vehicle to follow the desired flight path.

RPV Operational Requirements include, but are not limited to:

Acceptable system descent velocity.

Acceptable impact conditions.

Acceptable weather conditions.

Acceptable turn capabilities and response.

Acceptable recovery envelope.

3. IDENTIFICATION OF DATA VOIDS WHICH PREVENT A HI-GLIDE CANOPY COMPARATIVE ANALYSIS

Having identified (1) the potential applications and data requirements for evaluation of the RPV recovery system and (2) the

TABLE 3

IDENTIFICATION/CATEGORIZATION OF RPV RELATED DATA REQUIREMENTS

RPV

WT & BAL DATA	AERO DATA	STRUCTURAL DATA	G LIMITS	RECOVERY WT.
✓	✓	✓	✓	✓

ACCEPTABLE IMPACT CONDITIONS	STABILITY DATA	CONTROL DATA	ENGINE DATA
NO DATA	✓	✓	✓

GN&C

ABILITY TO DESIGN NAVIGATION & GUIDANCE SUBSYSTEM	ABILITY TO DESIGN ON-BOARD CONTROL SUBSYSTEM
✓	✓

RPV OPERATIONAL REQUIREMENTS

TAKE-OFF	MID-AIR	GROUND IMPACT
NO DATA	✓	NO DATA

published Hi-Glide canopy characteristics/capabilities, the latter can be balanced against the former to establish the canopy data voids which exist. It is recognized that many areas are interrelated (e.g. the successful flight demonstration of a large Ram-Air canopy will not insure its ability to meet all the requirements of the RPV application under consideration). However, for the sake of simplicity, the data voids will be addressed separately.

a. Canopy Related Data Voids - The following canopy data voids have been identified and, unless specifically stated otherwise, apply to all Hi-Glide canopy configurations. An additional lack of data in the area of aerodynamic performance data and canopy control data also exist for the Sailwing.

(1) Packing - To meet the RPV recovery system volume constraints the Hi-Glide canopy system may have to be pressure packed to densities greater than those currently demonstrated for low-permeability materials. No data is currently available of the effects on material and canopy performance of pressure packing the low-permeability materials currently utilized in Hi-Glide canopy fabrication.

(2) Canopy Wing Area/Payload/Wing Loading

(a) Canopy Wing Area - An estimate of the canopy area required for application of the RPV recovery can be calculated as follows:

given, W_{max} = 4520#

$V_{v_{max}}$ = 24 fps based on midair recovery requirement assume, $L/D = 3.0$

$h = 10{,}000$ ft.

$C_{R_{\text{ram-air}}} = 0.65$

$$V_{TOT} = V_v/\sin\gamma = \frac{24}{\sin\left[\text{arc tan}\left(\frac{1}{3.0}\right)\right]}$$

$$\approx 76 \text{ fps}$$

$$V_{TOT} = \frac{2W}{\rho S C_R}$$

$$S_{min} = \frac{2(4520)}{(0.001756)(0.65)(76)^2} = 1371 \text{ sq. ft.}$$

Parawings have been successfully demonstrated to wing areas of 4000 sq. ft. The demonstration of Ram-Air canopies of areas up to only 864 sq. ft. have been documented, resulting in a data void in this category for Ram-Air canopies. The data available on the 2700 sq. ft. Sailwing is minimal.

(b) Canopy Payload - Ram-Air canopies have successfully flown with payloads up to 2000 lbs. This represents only approximately 1/2 of the payload (4520 lbs) under consideration. Parawing payloads to 6000 lbs have been successfully demonstrated.

(c) Wing Loading - This category represents a possible data void for all Hi-Glide canopies depending upon other factors in the RPV application (e.g. available volume, achievable packing density). Due to the interrelationship among the various factors it cannot definitely be determined that a data void exists in this area for the application under consideration. However, due to the desire for wind offset capability (a function, in part, of wing loading) and minimum volume for recovery system, it is felt that wing loadings above those in Table 2a will be desirable. The inability to predict the effect of increased wing loading on canopy performance is due, in part, to the lack of accurate methods to predict the stress distribution in the all-flexible canopy under a given loading. Thus, wing loading is identified as a potential data void for all Hi-Glide canopies.

(3) Reefing - The Hi-Glide canopy deployment q has been established as 100 psf for the application under consideration with a g limit of 3.72 at maximum gross weight. No reefing system has been demonstrated to date which will meet these conditions. The five stage pyrotechnic system used by NASA on the 4000 sq. ft. Parawing comes closest to meeting them; however, reefing system complexity would probably preclude its use for RPV application.

(4) Canopy Control Data - Ram-Air canopy turn control data is nonexistent for systems larger than approximately 300 sq. ft. and landing flare control data is minimal or nonexistent for systems larger than 300 sq. ft. Data on Parawings up to 4000 sq. ft. is available.

(5) Scaling Techniques - Scaling techniques for unreefed opening forces have been validated for Parawings of areas up to 400 sq. ft. An attempt to extend these techniques to reefed opening forces of a 4000 sq. ft. Parawing system was not completely successful due, in part, to a mismatch between desired and actual test conditions. No scaling techniques for opening forces have been documented for Ram-Air canopies. Specific techniques are not available for accurate scaling of Hi-Glide canopy free-flight performance.

(6) Reliability, Maintainability, and Cost - Hi-Glide canopies are inherently reliable in their opening; efforts to control or reduce the opening forces create problems in reliability. All Hi-Glide canopy types are capable of gliding (with reduced performance) with considerable damage (e.g. holes in the canopy fabric). Production costs are available only for personnel sized canopies. Limited quantity costs are available for larger sized canopies.

(7) Miscellaneous Data Voids

(a) Materials - Materials, per se, may not be a factor preventing a comparative analysis of Hi-Glide canopies unless system constraints (e.g. volume) are such that, for a given material, one canopy could be incorporated and another one not. If this were the case, utilization of a different material might allow for incorporation of both canopies. The predominant material used to date in the construction of Hi-Glide canopy systems has been a coated and/or calendered rip-stop nylon. An evaluation of alternate materials may yield others equally suited for Hi-Glide canopy application but with possible advantages of increased packing efficiency, decreased weight, etc.

(b) Canopy Design - The ability to successfully design a Hi-Glide canopy larger than personnel size, ≈300 sq. ft., for a specific application has not been demonstrated. This inability is a result of many of the data voids previously presented.

b. RPV Related Data Voids

(1) Acceptable Impact Conditions - A definition of acceptable impact conditions is required to allow the establishment of recovery systems parameters such as acceptable impact velocity/acceleration.

(2) RPV Operational Requirements - A definition of the RPV operational requirements is needed for surface impact recovery and take-off applications. These requirements include such items as weather conditions, turn capability and response, recovery envelope, etc.

SECTION IV

PROGRAM OUTLINES TO FILL SELECTED DATA VOIDS

Following identification of existing Hi-Glide canopy data voids, programs were outlined which attempt to fill specific voids or combinations of voids. The general format of the program outlines which follow is: title, background/payoff, and approach. To reiterate a previous statement, it should not be interpreted that an entire program must be accomplished as outlined; most of the programs outlined are capable of being broken into subprograms. If all data voids are not filled before a comparative analysis is conducted, the program outlines are listed below in a prioritized order which attempts to minimize the effect on the analysis of the assumptions required by those voids which are not filled.

All programs generated to fill selected data voids as outlined below also apply to the Sailwing with the exception of the manhour estimates. The estimates given do not include the Sailwing since programs to fill most Sailwing data voids will be much more extensive than those for the Parawing and/or Ram-Air canopies due to the minimal amount of published information currently available.

1. TITLE: HI-GLIDE CANOPY AERODYNAMIC REEFING PROGRAM

OBJECTIVE: To evaluate an aerodynamic reefing system(s) for Hi-Glide canopy systems applicable to RPV recovery.

BACKGROUND/PAYOFF: A pyrotechnic reefing system was developed by NASA for a 4000 ft^2 Parawing Hi-Glide canopy system. This reefing system comes closest to meeting RPV recovery requirements; however, it consists of five stages and is probably unacceptable for RPV recovery application due to its complexity. Other pyrotechnic systems used to date on Parawings and Ram-Air Hi-Glide canopy systems will not limit opening forces to those required throughout the entire RPV recovery envelope encompassed by this study. An aerodynamic reefing system is currently used successfully on personnel sized Ram-Air canopies; however, little data is available to determine its applicability to other Hi-Glide canopy systems or larger Ram-Air systems. This type reefing system offers the potential of a simple reefing system which is dynamic pressure sensitive, an attribute which a pyrotechnic system lacks.

APPROACH: The overall approach to this program involves three phases. Phase 1 involves the review of available data on dynamic pressure sensitive reefing systems and the analysis and testing of model (20-40 ft^2) Hi-Glide canopy systems. An attempt will be made to develop a scaling technique for the deployment loads of unreefed and reefed Hi-Glide canopies. Model canopies will be designed and fabricated for wind tunnel deployment testing and drop testing. The drop testing would be similar to that accomplished by NASA in testing unreefed Parawings inside a large building. These tests will provide input to the deployment force scaling technique to predict deployment forces on a small scale (200 to 300 ft^2) system. Phase 2 involves a program similar to Phase 1 but for a small scale system(s). Free flight drop tests are included in this phase to provide, in conjunction with the "building" drop tests, a data base for comparison and modification, if required, of the predicted deployment forces. Phase 3 represents a follow-on evaluation of aerodynamic reefing applied to a full scale (> 1000 ft^2) system(s) involving the design, fabrication, flight testing and documentation of this system(s).

2. TITLE: HI-GLIDE CANOPY WING LOADING PROGRAM

OBJECTIVE: To evaluate the performance of Hi-Glide canopy systems at high wing loadings (2 to 5 psf) for application to RPV recovery.

BACKGROUND/PAYOFF: To minimize recovery system stowed weight and volume for mid-air recovery applications, it is desirable to utilize the maximum Hi-Glide canopy wing loading consistent with the vertical descent rate constraints of the recovery vehicle. To maximize system wing penetration (offset) capability for RPV ground impact applications it is desirable to utilize the maximum Hi-Glide canopy wing loading consistent with the RPV ground impact velocity requirements and canopy landing flare capabilities.

The current demonstrated wing loading capabilitites for the various Hi-Glide canopy systems are:

Parawing - 1.5 psf
Ram-Air - 2.7 psf

Providing an increased W/S capability could significantly reduce the recovery system stowed volume/weight requirements and increase the system wind offset capabilities.

APPROACH: The overall approach to this program involves four phases. Phase 1 involves the acquisition and analysis of existing data, development of a structural (stress) analysis methodology for both Parawing and Ram-Air Hi-Glide canopy systems, the prediction of steady state glide performance for the higher wing loadings on small scale systems (200 to 300 ft^2), and develop scaling techniques for steady state glide performance for larger canopies. These developments will be applicable to the entire W/S range in question. Phases 2 through 4 involve the design, fabrication, testing, and documentation of these efforts for W/S of 2, 3, and 4, respectively, for both small scale Parawing and Ram-Air Hi-Glide canopy systems. During Phases 2 through 4 the result of the prediction techniques will be compared with test results and modified as required. Testing will include wind tunnel (if applicable), tow, and drop tests. Drop test will be conducted on an instrumented range to acquire the data necessary to evaluate system performance.

3. HI-GLIDE CANOPY HI-DENSITY PACKING PROGRAM

OBJECTIVE: To evaluate the effect of high density packing on the properties of low permeability materials and on the Hi-Glide canopy deployment and free flight performance.

BACKGROUND/PAYOFF: To date, the primary method of packing Hi-Glide canopy systems has been by hand. This method results in relatively low packing densities which may not meet the Hi-Glide canopy volume constraints for application to RPV recovery. The ability to pack a Hi-Glide canopy system to sufficient density to allow it to be used in an RPV recovery system could provide the RPV system with a decreased descent rate, wind offset capability, homing capability (trajectory control), multiple recovery capability, and decreased vertical impact velocity.

APPROACH: The overall approach to the program involves three phases. Phase 1 would evaluate the hi-density packing of Hi-Glide canopy materials. Here the problems associated with the pressure packing of low permeability materials would be identified and resolved. Phase 2 involves the high-density packing of candidate Hi-Glide canopies themselves, addressing the problems of pressure packing system components in addition to the low permeability material. Phase 3 provides for the flight testing of high density packed Hi-Glide canopy systems to evaluate the effect of hi-density packing on canopy deployment and flight performance.

4. TITLE: RAM-AIR CANOPY WING AREA/PAYLOAD PROGRAM

OBJECTIVE: To demonstrate a Ram-Air Hi-Glide canopy applicable to RPV recovery (> 3000 lb payload) and to evaluate this design for application to a 4520 lb vehicle at increased wing loadings.

BACKGROUND/PAYOFF: Ram-Air Hi-Glide canopies are currently being used by sport parachutists at wing loadings of less than 2.0. The largest documented wing loading to date is 2.7 psf on an 864 ft^2 Parafoil. This combination is insufficient for the desired application. An effort is currently underway in the RPV SPO to demonstrate a 3200 ft^2 Parafoil for recovery of an RPV. Successful completion of this effort will substantially fill this data void for Ram-Air canopies if sufficient/ acceptable data is obtained.

APPROACH: It is difficult to break this program into phases since it deals only with the demonstration of one size (large) canopy. The program consists of an analysis of existing data, turn control, landing flare control, and scaling technique for steady state performance; the design and fabrication of a large scale system(s); tow and drop tests of this system; and documentation of all of the above. The drop tests will include steady state glide evaluation, turn control tests, and landing flare tests.

5. TITLE: RAM-AIR CANOPY LANDING FLARE CONTROL PROGRAM

OBJECTIVE: To quantify the landing flare capability of a small scale (300 ft^2) Ram-Air canopy.

BACKGROUND/PAYOFF: A limited landing flare capability for Parawing Hi-Glide canopy systems was established under the NASA 4000 ft^2 system tests. Manned application of Ram-Air canopies indicates, at least qualitatively, better landing flare control capability with Ram-Air canopies than with Parawing canopies. Providing a Hi-Glide system with landing flare capability for RPV recovery offers the potential of increased wind penetration while maintaining a given ground impact velocity, reducing recovery system weight and volume, or reducing impact velocity.

APPROACH: The overall approach to this program involves two phases. Phase I involves the analysis and tow testing of a small scale Hi-Glide Ram-Air canopy system(s). The analysis will consider existing control information and establish possible techniques for accomplishing landing flare. Following design and fabrication of the canopies and control system, tow tests will be conducted on an instrumented range. It is possible that the control system might be eliminated by performing instrumented manned tests on an instrumented test range. Phase 2 involves drop tests on an instrumented test range.

SECTION V

CONCLUSIONS

As a result of this study a number of data voids were found to exist which may prevent the accomplishment of a meaningful comparative analysis of Hi-Glide canopies as applied to RPV's.

Hi-Glide Canopy related data voids include:

	Parawing	Ram-Air	Sailwing
Pressure Packing	X	X	X
Canopy Wing Area		X	X
Canopy Payload		X	X
Canopy Wing Loading	X	X	X
Reefing	X	X	X
Canopy Control Data		X	X
Opening Force Scaling Techniques	X	X	X
Reliability, Maintainability, Cost	X	X	X
Materials	X	X	X
Canopy Design	X	X	X

RPV related data voids include:

Acceptable Impact Conditions

RPV Operational Requirements

The nature of the above data voids is such as to prevent the accomplishments of a meaningful comparative analysis of the application of Hi-Glide canopies to RPV's.

It should be noted that additional information may be available on the various canopies (especially the Sailwing) in unpublished form through manufacturers or other government agencies.

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This bibliography is limited to steerable parachutes/flexible wings intended to operate non-rigidized in the subsonic flight regime.

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FLEXIBLE WINGS FOR TRANSPORTATION

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A SELECTED BIBLIOGRAPHY OF PARAWING PUBLICATIONS

Recent requests for a bibliography of parawing publications have prompted a computer search of literature on flexible wings available from 1962 to the present. This literature search and a working list of references previously compiled have provided the information from which the present bibliography was selected. A comprehensive listing of references on flexible wings has not been attempted because it was believed that a more concise bibliography of basic research information would be more useful. Inasmuch as a large part of the present technology for parawings was developed by the NASA or under its sponsorship, a complete listing of available NASA publications on parawings has been attempted. In like manner, a significant amount of work on applications of parawings and paragliders for military use has been conducted by the U.S. Army Transportation Research Command (TRECOM), Ft. Eustis, Virginia, and basic references reporting this work are included.

Many talks and papers on flexible wings have been sponsored by various technical societies. A few of these papers have been included in this bibliography; however, this type of reference has not been generally included because many of these papers were based on research that was later published in a more complete form in a formal report.

A definitive and complete bibliography can be assembled only when the technology has become static. In this respect, it is hoped that the present compilation represents a status report on information presently available and that it will prove useful to those interested in flexible-wing technology.

TERMINOLOGY

There has always appeared to be some confusion in regard to the terminology used at different times to identify various flexible-wing configurations. It may be helpful, therefore, to provide some definitions of terminology that have evolved over the past decade.

PARAGLIDER — The originators of the flexible-wing concept in the late 1940's created a completely flexible lifting surface with a parachutelike tension structure in which the wing surface shape is maintained by the balance of forces between the airload on the surfaces and the tension in the suspension lines, and flexible wings that could have several types of localized stiffening. The early experimental work was conducted largely by flying the wings as kites; consequently, the first flexible wings tested in NASA wind-tunnel and flight investigations in the late 1950's were known as flexible kites.

Early applications under study by NASA for flexible kites, such as recovery of the Saturn booster and manned spacecraft, appeared to warrant a more suitable name for the recovery system. The term "paraglider" was used, therefore, to identify the gliding, deployable wing being investigated in studies of recovery of the Saturn booster and other space and aeronautics applications underway at about the same time. Inasmuch as the wing configurations being investigated in these studies had rigid-tube or inflated-tube leading edges and keel and a sweptback planform with a flexible fabric canopy, the term "paraglider" was generally accepted as descriptive of this type of wing.

PARAWING — Early potential applications for flexible wings involved their use as a gliding descent system for various space and aeronautical vehicles. Other applications that involved powered or towed vehicles, however, did not use gliding flight over the major portion of their operation, and the gliding connotation did not appear appropriate. It also appeared desirable to use a term that described the lifting surface without regard to the type of use for it, and the name "parawing" was derived to meet this need. The term "parawing" was originally intended to refer to a broad class of aeroflexible lifting surfaces, with both stiffened and unstiffened leading edges and keels. In general practice, however, the names "parawing and paraglider" came to be used interchangeably to describe wings with stiffening members, and the broad-class connotation of parawing was not widely recognized.

ALL-FLEXIBLE PARAWING – A new term was needed to differentiate between parawings that had rigid or inflated stiffening members and parawings that were completely flexible with no structural or stiffening members. The name "all-flexible parawing" was selected to denote a class of flexible wings that had a flexible fabric lifting surface, a pure tension structure, and for which the shape of the surface is determined by the balance of forces between the airloads on the canopy and the tension in the suspension lines, that is, the original concept in its purest form.

GLIDING PARACHUTE – The advantages of being able to steer or change heading on a personnel parachute have long been recognized, and techniques and modifications to standard personnel parachutes to provide steering capability have been explored for many years. In the 1950's and 1960's, parachutes were modified to provide some forward velocity by venting air from the rear portion of the canopy. Many of these gliding parachutes could be steered with relative ease and were capable of providing about half as much lift as drag. Later design refinements increased ratios of lift to drag to near 1.0 for gliding parachutes of roughly hemispherical shape. The term "gliding parachute" can be considered to identify a class of descent devices that produce lift in gliding flight that is equal to, or less than, the drag.

FLEXIBLE WINGS – The term "flexible wings" identifies a broad class of fabric or membrane lifting surfaces that provide more lift than drag in gliding or powered flight. Included in this definition are paragliders, parawings, and several other gliding, fabric wings of various planforms and shapes that have been developed since the introduction of the flexible-wing concept.

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