AN EXPERIMENTAL INVESTIGATION OF NINE FACTORS AFFECTING THE BOOST-PHASE PEFORMANCE OF MODEL ROCKET BOOST-GLIDERS AT REYNOLDS NUMBERS NEAR 100,000

A NARAM-32 R&D REPORT

by Trip Barber
NAR #4322 SR

R&D Report from http://nar.org National Association of Rocketry

ABSTRACT

AN EXPERIMENTAL INVESTIGATION
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This project has investigated the effects of nine different design and operating characteristics on the boost-phase performance of model rocket boost gliders in the range of 30 square inches of wing area (tapered rectangular planform) and a boost Reynolds Number of 100,000. The experimental work involved measuring the altitude achieved by the gliders with A and B engines, and then calculating drag coefficients by comparing the measured altitude with altitude predicted by a sophisticated ballistic simulation computer program.

For gliders of the types and sizes used by this project, the following conclusions have been determined:

-- Increasing airfoil camber from 1% to 2% reduces altitude performance by 8%.
-- Typical values of boost-glider boost-phase drag coefficient (referenced to the wing/stabilizer combined area and additive to the 18mm pod drag form factor of 0.24 sq in) are:
  - 0.018 for A engines
  - 0.012 for B engines
-- These drag coefficients are not changed by tissuing the wing, by mounting the pod with up to 2 degrees of pitch-up angle, or by changing the wing aspect ratio over the range of 4.7 to 6.4.
-- Adding a tape-strip turbulator to a wing increases the wing's drag coefficient by 25 percent and decreases the glider's altitude performance by 8 percent.
-- Adding 3 degrees of negative incidence to a stabilizer with an area of 23 percent of the wing area decreases altitude performance by 9 percent; this much incidence on a 17 percent stabilizer does not reduce altitude.

The conclusions developed by this project represent new knowledge in the field of model rocketry. They can be combined with existing or future calculations and measurements of glide-phase characteristics to permit for the first time a comprehensive analysis of the total performance of boost-gliders.

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INTRODUCTION

The overall duration of a model rocket boost-glider's flight depends on two glider performance factors: boost altitude and glide sink rate. While substantial work has been done on glide-phase performance over the past 20 years, the only published boost-phase performance work is an investigation of altitude vs wing area done by Micci and Gressman for NARAM-15 (Reference A).

Many techniques for improving glide-phase performance change the drag and achieved boost altitude of a glider. These techniques may in fact reduce overall performance if this altitude reduction more than offsets the reduction in glide-phase sink rate that the techniques provide. This project provides a start point for examining such tradeoffs; follow-on work is planned in measurement of glide sink rates for the gliders whose altitude performance was measured in this initial work.

The objective of this project was to investigate in a controlled manner as many as possible of the design factors other than wing area which could possibly affect model rocket boost glider boost-phase performance. Approximately 70 flight tests were eventually conducted. A few of these investigated uncommon design variations which were unsuccessful; 61 were used to investigate the following nine common design or flight configuration variations which are discussed in the remainder of this report:

-- airfoil camber
-- boost-phase Reynolds number
-- pitch angle of pod with respect to wing
-- wing turbulators
-- wing covering material
-- average engine thrust
-- engine pod diameter
-- stabilizer incidence angle
-- wing aspect ratio

EXPENDITURES AND ASSISTANCE

This project used the tracking equipment of the Northern Virginia Association of Rocketry--a pair of Triple Track tracking scopes on Sky-Trak tripods, plus three CB walkie talkies. The assistance of fellow NOVAAR members Jon Rains, Greg Bock, Greg McCain, Steve Okay, John Lahey, Adam Nowotarski, and Robert Edmonds in tracking and recovering the many flights is gratefully acknowledged, as is the technical advice from old MIT Rocket Society colleagues Bernard Biales and Bob Parks. Computer analysis of altitudes was done on the author's Tandy 1000.

Approximately $15. was spent for body tubes, balsa, nose cones, and other parts for the gliders used in this project, and $50. was spent on the rocket engines.

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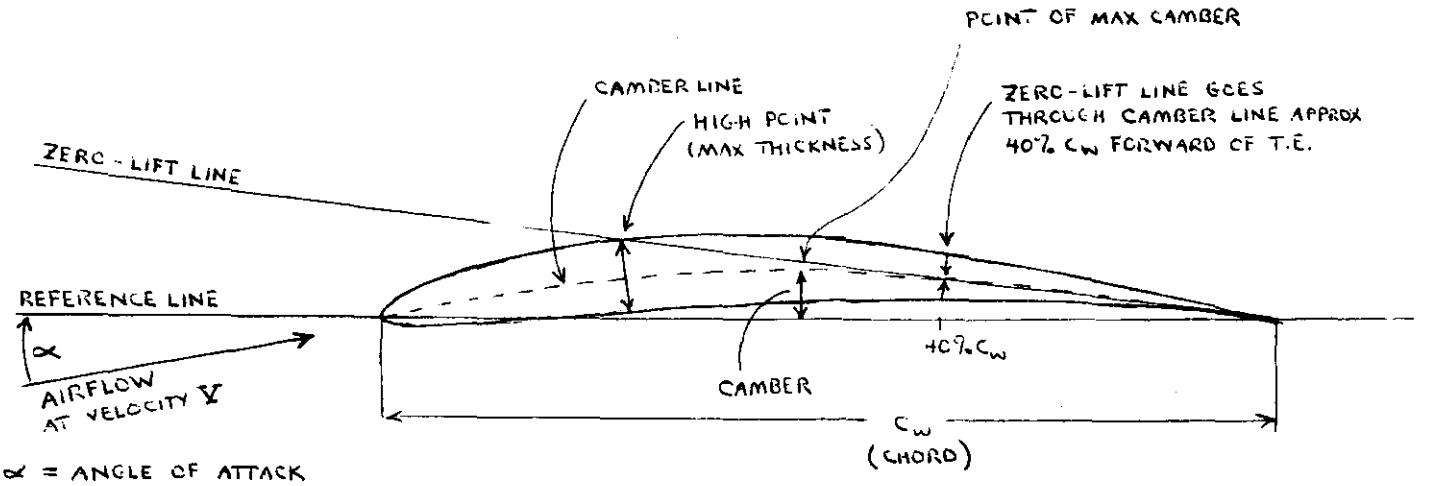
BACKGROUND

The explanations of glider performance in this report presume familiarity with the terminology of wing aerodynamics and glider dynamics. This section provides a qualitative summary of the terminology and principles applicable to those factors tested in the experimental work. Reference B provided some of the source material for this discussion.

An airfoil can be characterized in general terms by its chord, camber, thickness, and high point location. Chord is measured in units of length, while the other three terms are generally expressed as a percentage of the airfoil's chord. The angle of attack at which the airfoil operates determines such key performance parameters as lift and drag, and is by convention the angle between the airfoil's flight velocity vector and a reference line passing from the center of the airfoil's leading edge to the center of its trailing edge. The figure below illustrates these terms:



The flow of air over the surface of an airfoil splits into an upper surface region and a lower surface region at the leading edge. The upper surface, being more curved than the lower, provides a longer path for the air to follow, and the higher air velocity which results leads to a lower static pressure than is found on the underside of the airfoil. This pressure imbalance is the source of lift. If the flow on the upper surface is slowed, pressure increases and there is a loss of airfoil lift.

The flow of air over most airfoils starts as a very smooth, low-energy type called laminar with a thin, low-velocity boundary layer that adheres closely to the airfoil surface. At some point as the flow moves along the surface--either at the distance where the flow has traveled far enough to have reached a particular "critical" Reynolds Number or when the flow hits an area of surface

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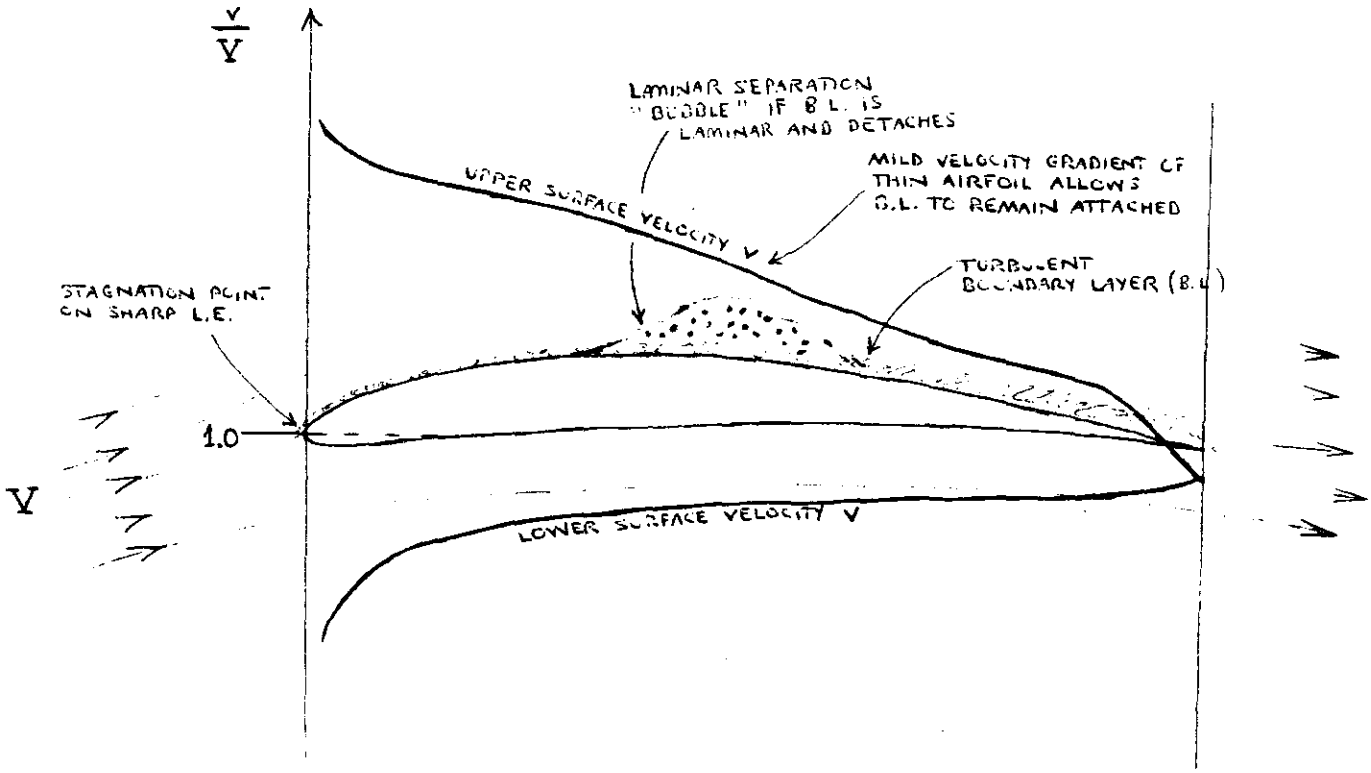
roughness--it develops sufficient instability to become a higher-energy type of flow called turbulent.

Turbulent flow causes more energy loss from skin friction drag and leads to a thicker boundary layer than laminar, but it has a superior ability to remain attached to the wing surface in the face of the negative pressure gradient found on the "downhill" portion of the airfoil top surface that is behind the high point. The flow over airfoils operating at the low Reynolds Numbers (below 150,000) characteristic of model rocket boost-gliders tends to be still laminar--below the critical Reynolds Number--by the time it reaches this negative pressure gradient. The laminar flow's boundary layer has a tendency to separate from the airfoil surface at this point, leading to a region of stagnant, low-velocity/high-pressure flow called a "laminar separation bubble" on the upper surface that greatly reduces lift. If the flow becomes turbulent before reaching the negative gradient (as the result of a sharp leading edge, a turbulator, or surface roughness) it has a superior ability to resist formation of this "bubble". Thinner airfoils have less extreme pressure gradients, and as a result are more resistant to "bubble" formation and often perform better at low Reynolds Number than the thicker airfoils preferred for large air vehicles.

The flow over a typical airfoil is depicted below:



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The performance characteristics of an airfoil are typically expressed in two forms of graphs: lift coefficient vs angle of attack; and drag coefficient--either vs lift coefficient or vs angle of attack. These may either reflect wind tunnel test results or theoretical fluid dynamic calculated performance. At high Reynolds Number the two are generally quite close; at low RN the theory does not predict actual performance very accurately. A set of theoretical graphs for RN = 100,000 (plotted from computer program data provided by Bob Parks) is presented on the following page for the NACA 1305 and 2305 airfoils used in this project. While the absolute values of lift and drag coefficients are probably not accurate, the graphs illustrate several important points:

-- Lift increases with increased angle of attack
-- Increasing camber increases the maximum achievable lift
-- The angle of attack at which an airfoil produces zero lift becomes more negative as camber is increased
-- There is a narrow range of angle of attack across which drag is minimized and is nearly constant (referred to as the "drag bucket" region)
-- Drag increases rapidly at higher and lower angles of attack outside the "bucket" region

The final relevant aspect of glider theory is boost-phase stability and force balance. During vertical flight, a boost glider is acted on by four forces that tend to produce pitching moments around its center of gravity: engine thrust, pod drag, stabilizer lift, and wing lift. This is illustrated on the second following page. Assuming that the engine pod is heavy enough to put the overall boost center of gravity ahead of the wing, these forces do the following:

-- Engine thrust (until burnout): pitches nose down
-- Pod drag: pitches nose up
-- Stabilizer lift: pitches nose up as long as the stab is mounted at zero or negative angle of attack
-- Wing lift: pitches nose down when operating at an angle of attack greater than its zero-lift angle

When a boost-glider boosts straight (as all did in this project except the gliders with high wing airfoil camber or large negative stabilizer angle of attack), these forces must be in balance. During engine thrusting, therefore, the glider probably is in equilibrium with the wing operating at a near-zero or slightly negative angle of attack to produce minimal lift. After engine burnout, the glider is probably at equilibrium with the wing at a slightly higher angle of attack where its lift offsets the nose-up moment of pod drag and stabilizer lift. If the wing is operating outside the "drag bucket" angle of attack region in either one of these states (as the graphs indicate that NACA 2305 does at its zero-lift angle of attack), it experiences high drag.

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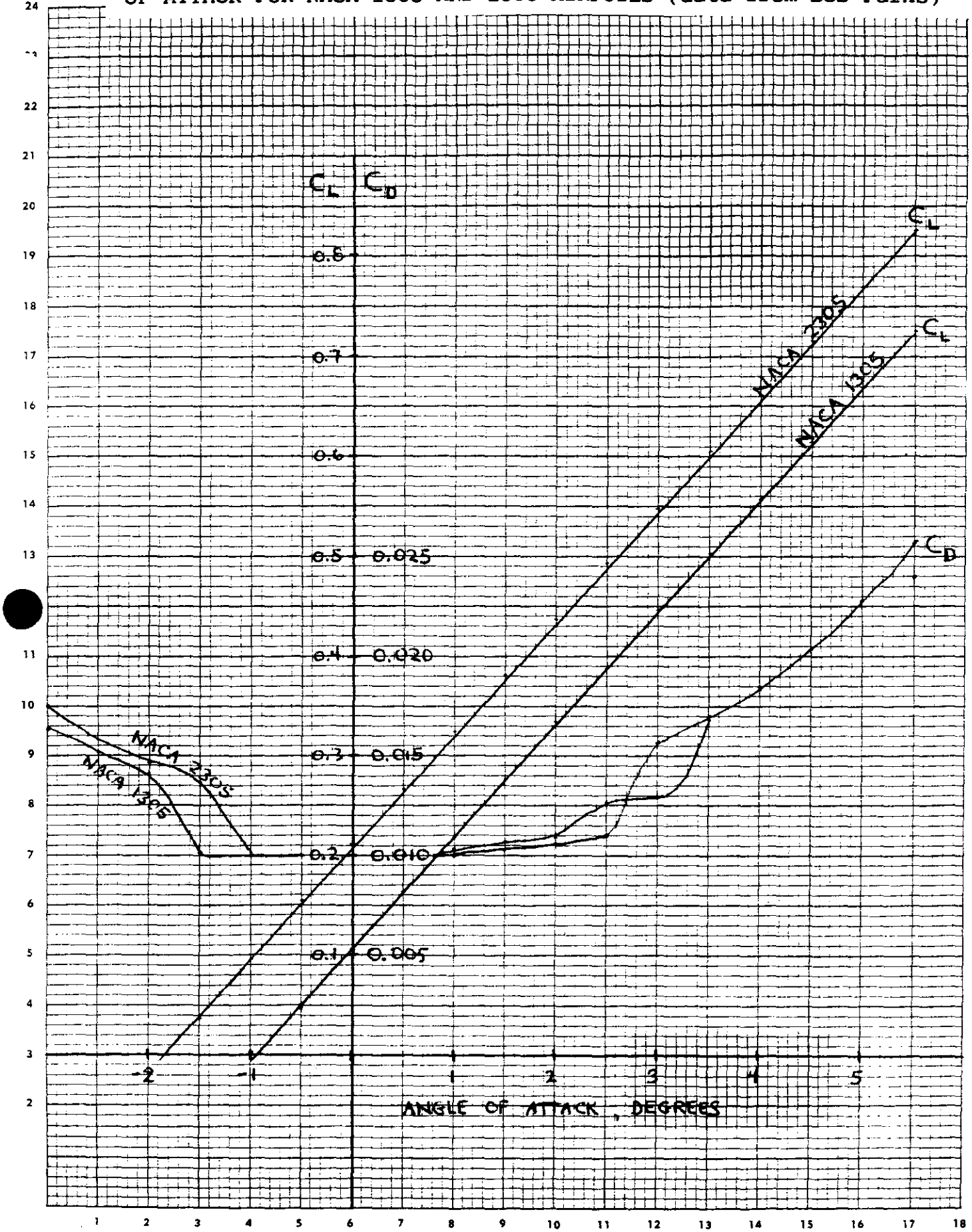
GRAPH OF THEORETICAL LIFT COEFFICIENT AND DRAG COEFFICIENT VS ANGLE OF ATTACK FOR NACA 1305 AND 2305 AIRFOILS (data from Bob Parks)



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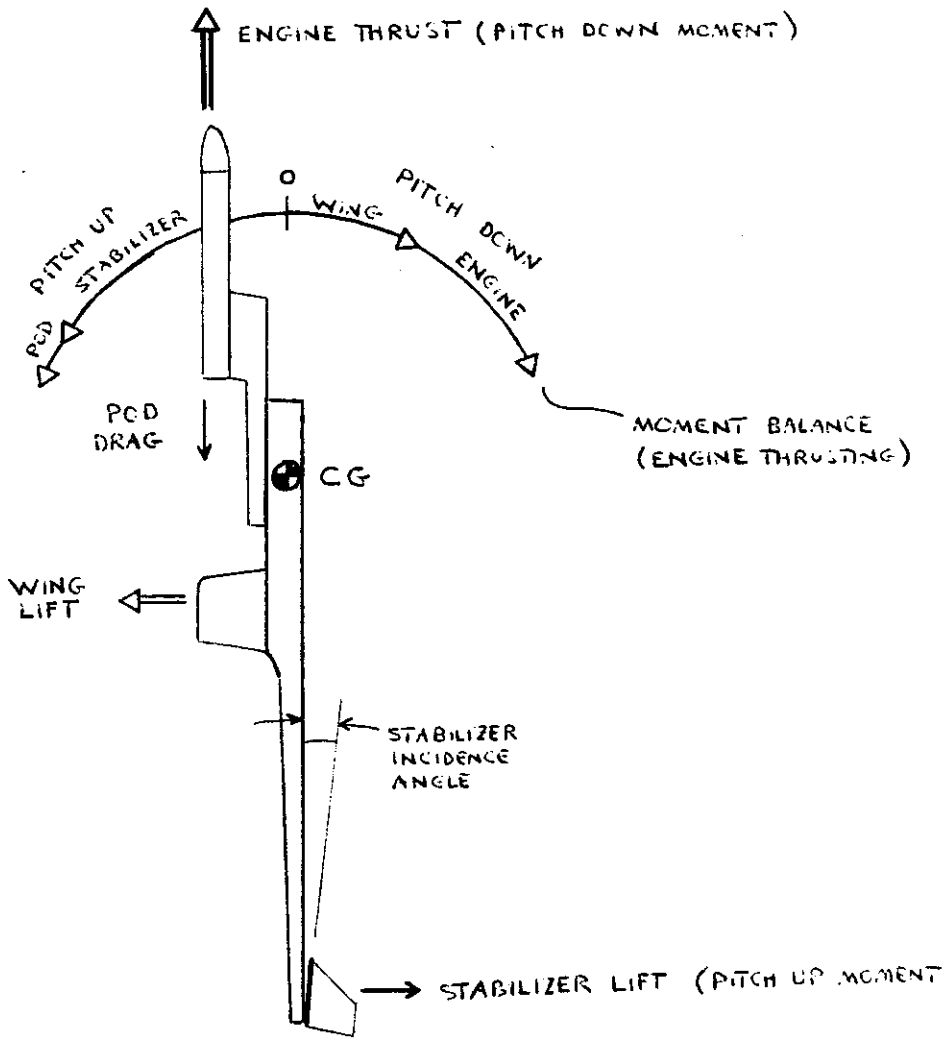

BOOST PHASE FORCES AND MOMENTS ACTING ON A BOOST-GLIDER

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EXPERIMENTAL PROCEDURE

GENERAL COMMENTS

This project used three different boost-glider designs, with wing areas varying from 27.4 to 29.7 square inches. These are referred to as Type I, Type II, and Type III designs, and they are illustrated in Appendix I. All used the same pod design, weighing 11.5 grams with chute and wadding but minus engine.

Ideally an investigation of this type would use a single family of gliders, all identical except for a single characteristic (the experimental variable), so that the effect of each characteristic could be compared to that of every other on an otherwise identical baseline. Unfortunately, each balsa glider is different in some detail from every other as a result of the hand craftsmanship, so this project's experimental procedure generally relied as much as possible on two-point comparisons: a glider in one configuration vs that same glider in a different configuration.

GLIDER CONSTRUCTION

Every glider used the same fuselage and rudder design, and the same engine pod design. The variations were in wing and stabilizer planform shape, area, incidence, and airfoil. All the wings had simple-V dihedral with a 16-degree half-angle. All stabilizers had a symmetrical airfoil and were mounted with a shim to provide 1 degree negative incidence with respect to the fuselage unless otherwise noted.

TYPE I. The Type I glider family was designed as the gliders to be used for measuring the effects of airfoil camber. These used an exactly rectangular wing planform (29.7 square inches, aspect ratio 4.1) as a convenience to ensure accurate shaping of the airfoils. All weighed 8.5 grams. The airfoils were shaped from precisely-plotted templates of a single NACA airfoil family: the 1305 (1% camber, high point at 30% chord, thickness 5% of chord--used on glider #1), the 2305 (2% camber, same other characteristics--used on glider #2), and the 3305 (3% camber--used on glider #3). Each template was Xerox-reduced to 2.7" chord, glued to 1/32" plywood, and cut out of the plywood. One of these plywood templates was then glued to each end of an 11" sheet of 3/16" balsa, and a foot-long sanding block was used to sand the airfoil into the balsa between the templates.

TYPE II. The Type II glider family used a tapered rectangular wing planform made from 3/32" balsa (4% thickness) with 27.6 square inches of area and an aspect ratio of 4.7. The airfoils were not precision-sanded, but were approximately 1% camber with a high point at 30% of chord. There were two gliders in this family: glider #4 with a tissue-covered wing (7.2 grams), and glider #5 with a plain balsa wing finished with clear dope (6.5 grams).

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TYPE III. The Type III glider family used a tapered rectangular wing planform made from tissue-covered 3/32" balsa (4.5% thickness) with 27.4 square inches of area and an aspect ratio of 6.4. The airfoils were not precision-sanded, but were approximately 1% camber with a high point at 30% of chord. There were two generally identical 8.5-gram gliders in this family: glider #8 and glider #9.

ROCKET ENGINES

Three types of Estes rocket engines were used in this project, all purchased at local hobby stores. The entire quantity of each type of engine had the same manufacturing date code, to minimize the experimental error from inter-batch engine variations.

A3-4T (date code 8U1): intitial mass 8.6 grams
A8-3 (date code 11T9): initial mass 15.9 grams
B4-4 (date code 18T12): initial mass 19.8 grams

LAUNCHING PROCEDURE

The gliders were launched on five different days in May, June, and July 1990. In each case, the temperature was 70 to 80 degrees with a wind of 10 to 15 miles per hour. Five "power tower" launch pads were used, each a wooden stake to which was taped a launch rod that gave the glider nearly a full 36 inches of travel. All pads were aligned to true vertical and to each other. The engine pods were taped onto the gliders to minimize recovery problems, and 2 grams of tracking powder were put in the pods (included in their stated no-engine weight of 11.5 grams) to support ejection tracking.

TRACKING PROCEDURE

Two-station two-axis tracking was used at every launch session. The trackers were the standard "Triple Track" design (Appendix II) with an estimated accuracy of 1 degree. The tracking crew was experienced and proficient: no tracks were lost, and none failed to close. Ejection tracking was used on all A8-3 and B4-4 powered flights; apogee tracking was used on those powered by the A3-4T. Except where noted in the data tables, however, nearly every flight appeared to eject at apogee so this difference did not prove to be significant. On the first launch session (27 May), a 300-meter baseline was used; on the remaining 4 sessions, the baseline was 700 feet (213 meters). NAR standard basic (non-geodesic) data reduction formulas were used to compute altitudes. The estimated systematic error in tracking data between tracking sessions on different days is 2% from baseline measurement variations plus 2% from scope zeroing errors of one degree.

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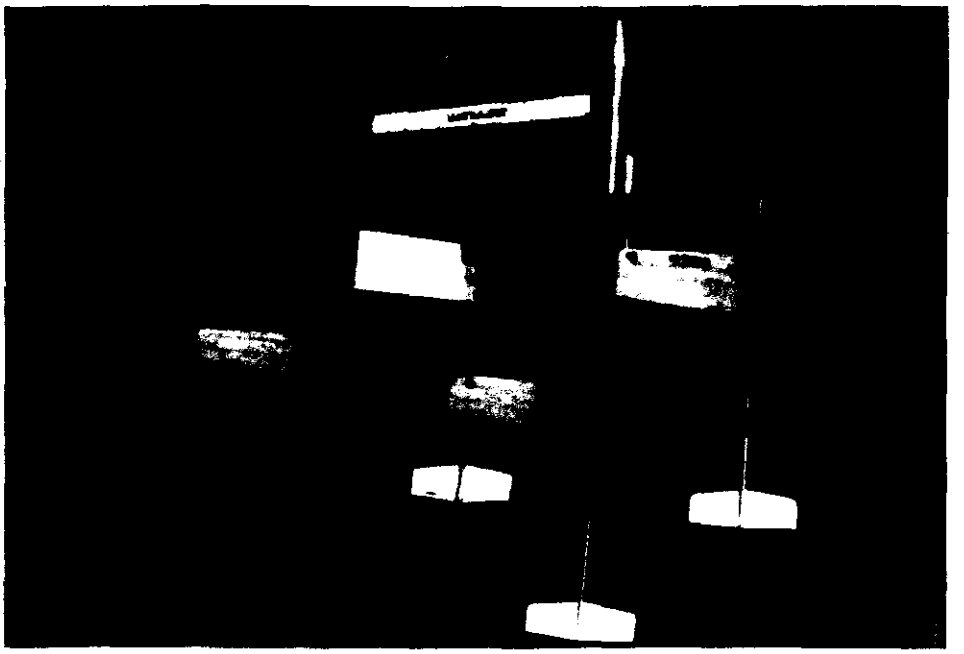

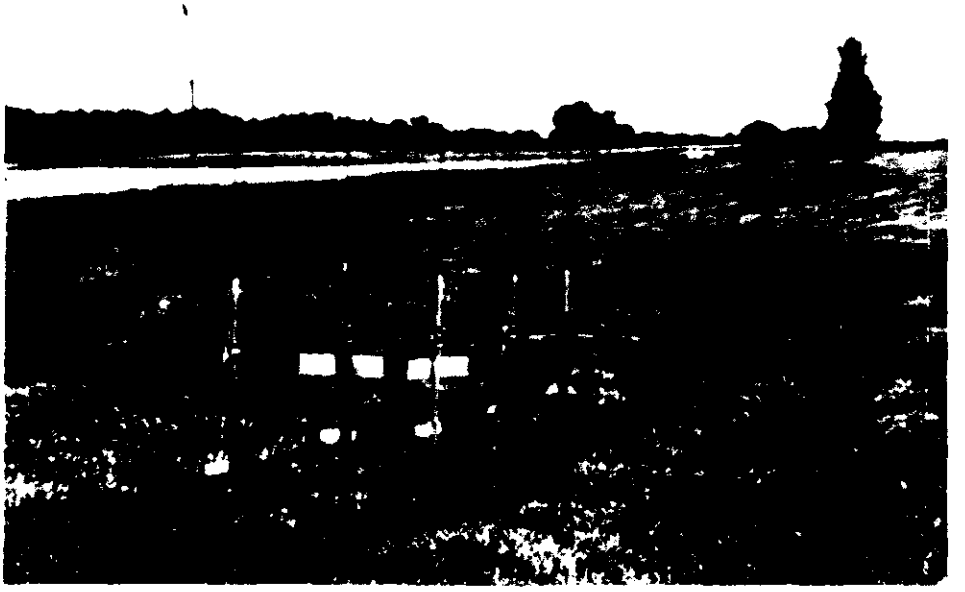

PHOTOGRAPHS OF TYPICAL TEST GLIDERS AND LAUNCH PAD SETUP

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DATA

TEST A.

GLIDER TYPE: I, #1 — WING COVERING: NONE
LIFTOFF MASS: 36 gm — WING AREA: 29.7 sq in
SPECIAL FEATURES: NACA 1305 (1% CAMBER) AIRFOIL
ENGINE TYPE: A8-3 — STAB AREA: 6.7 sq in

DATE	ALTITUDE AVERAGE	ALTITUDE ERROR	COMMENTS
27 May 90	85.8	0.7	
27 May 90	87.2	1.0	
27 May 90	71.9	1.8	Early ejection (not used)
2 Jun 90	85.2	7.2	
AVERAGE	86.1m	3.3m	

POPULATION VARIANCE: 1.0m — 90% CONFIDENCE INTERVAL: 84.7-87.5m

DATA ANALYSIS

ALTITUDE (meters)	TOTAL DRAG FORM FACTOR (sq in)	-	BODY DRAG FORM FACTOR (sq in)	=	WING/STAB DRAG FORM FACTOR (sq in)	WING+ STAB AREA (sq in)	WING/STAB DRAG COEFF.
84.7	.837		.243		.594	36.4	.0163
86.1	.806		.243		.563	36.4	.0155
87.5	.775		.243		.532	36.4	.0146

WING/STAB DRAG COEFFICIENT = .0155 ± .0008

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TEST B.

GLIDER TYPE: I, #2 — WING COVERING: NONE
LIFTOFF MASS: 36 gm — WING AREA: 29.7 sq in
SPECIAL FEATURES: NACA 2305 (2% CAMBER) AIRFOIL
ENGINE TYPE: A8-3 — STAB AREA: 6.7 sq in

DATE	ALTITUDE		COMMENTS
	AVERAGE	ERROR	
27 May 90	79.2	0.4	
27 May 90	77.6	1.9	
27 May 90	80.9	3.2	
10 Jun 90	81.9	2.2	
AVERAGE	79.9m	1.9m	

POPULATION VARIANCE: 1.9m — 90% CONFIDENCE INTERVAL: 77.9-81.9m

DATA ANALYSIS

ALTITUDE (meters)	TOTAL DRAG FORM FACTOR (sq in)	-	BODY DRAG FORM FACTOR (sq in)	=	WING/STAB DRAG FORM FACTOR (sq in)	WING+ STAB AREA (sq in)	WING/STAB DRAG COEFF.
77.9	.977		.243		.734	36.4	.0202
79.9	.930		.243		.687	36.4	.0189
81.9	.884		.243		.641	36.4	.0176

WING/STAB DRAG COEFFICIENT = .0189 ± .0013

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TEST C.

GLIDER TYPE: I, #3 — WING COVERING: NONE
LIFTOFF MASS: 36 gm — WING AREA: 29.7 sq in
SPECIAL FEATURES: NACA 3305 (3% CAMBER) AIRFOIL
ENGINE TYPE: A8-3 — STAB AREA: 6.7 sq in

DATE	ALTITUDE AVERAGE	ALTITUDE ERROR	COMMENTS
27 May 90	72.6	1.7	
27 May 90	81.8	0.5	
27 May 90	76.8	2.6	
2 Jun 90	80.2	5.6	
15 Jul 90	69.5	3.9	Non-vertical boost (not used)
AVERAGE	77.9m	2.6m	

POPULATION VARIANCE: 4.1m — 90% CONFIDENCE INTERVAL: 73.5-82.3m

DATA ANALYSIS

ALTITUDE (meters)	TOTAL DRAG FORM FACTOR (sq in)	-	BODY DRAG FORM FACTOR (sq in)	=	WING/STAB DRAG FORM FACTOR (sq in)	WING+ STAB AREA (sq in)	WING/STAB DRAG COEFF.
73.5	1.101		.243		.858	36.4	.0236
77.9	.977		.243		.734	36.4	.0202
82.3	.884		.243		.641	36.4	.0176

WING/STAB DRAG COEFFICIENT = .0202 ± .0035

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TEST D.

GLIDER TYPE: I, #1 WING COVERING: NONE
LIFTOFF MASS: 36 gm WING AREA: 29.7 sq in
SPECIAL FEATURES: 2-DEGREE PITCH-UP ON POD
ENGINE TYPE: A8-3 STAB AREA: 6.7 sq in

DATE	ALTITUDE		COMMENTS
	AVERAGE	ERROR	
10 Jun 90	74.4	2.2	
10 Jun 90	87.1	0.5	
10 Jun 90	80.3	2.6	
10 Jun 90	94.0	5.5	
15 Jul 90	81.2	5.0	
8 Jul 90	72.3	1.4	
AVERAGE	81.6m	2.9m	

POPULATION VARIANCE: 8.1m 90% CONFIDENCE INTERVAL: 75.0-88.2m

DATA ANALYSIS

ALTITUDE (meters)	TOTAL DRAG FORM FACTOR (sq in)	-	BODY DRAG FORM FACTOR (sq in)	=	WING/STAB DRAG FORM FACTOR (sq in)	WING+ STAB AREA (sq in)	WING/STAB DRAG COEFF.
75.0	1.054		.243		.811	36.4	.0223
81.6	.899		.243		.656	36.4	.0180
88.2	.760		.243		.517	36.4	.0142

WING/STAB DRAG COEFFICIENT = .0180 $\pm$ .0040

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TEST E.

GLIDER TYPE: I, #1 WING COVERING: NONE
LIFTOFF MASS: 40 gm WING AREA: 29.7 sq in
SPECIAL FEATURES: LARGER ENGINE
ENGINE TYPE: B4-4 STAB AREA: 6.7 sq in

DATE	ALTITUDE		COMMENTS
	AVERAGE	ERROR	
8 Jul 90	183.4	9.7	
8 Jul 90	165.7	3.8	
8 Jul 90	168.4	2.3	
AVERAGE	172.5m	5.3m	

POPULATION VARIANCE: 9.5m 90% CONFIDENCE INTERVAL: 159.6-185.4m

DATA ANALYSIS

ALTITUDE (meters)	TOTAL DRAG FORM FACTOR (sq in)	-	BODY DRAG FORM FACTOR (sq in)	=	WING/STAB DRAG FORM FACTOR (sq in)	WING+ STAB AREA (sq in)	WING/STAB DRAG COEFF.
159.6	.744		.243		.501	36.4	.0138
172.5	.651		.243		.408	36.4	.0112
185.4	.574		.243		.331	36.4	.0091

WING/STAB DRAG COEFFICIENT = .0112 ± .0024

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TEST F.

GLIDER TYPE: I, #2 — WING COVERING: NONE
LIFTOFF MASS: 36 gm — WING AREA: 29.7 sq in
SPECIAL FEATURES: 0.25" MASKING TAPE TURBULATOR AT 20% CHORD
ENGINE TYPE: A8-3 — STAB AREA: 6.7 sq in

DATE	ALTITUDE AVERAGE	ALTITUDE ERROR	COMMENTS
10 Jun 90	72.9	0.3	
10 Jun 90	78.8	1.0	
10 Jun 90	72.1	2.0	
8 Jul 90	79.2	3.3	
8 Jul 90	67.1	4.2	
AVERAGE	74.0m	2.2m	

POPULATION VARIANCE: 5.0m — 90% CONFIDENCE INTERVAL: 69.2-78.8m

DATA ANALYSIS

ALTITUDE (meters)	TOTAL DRAG FORM FACTOR (sq in)	-	BODY DRAG FORM FACTOR (sq in)	=	WING/STAB DRAG FORM FACTOR (sq in)	WING+ STAB AREA (sq in)	WING/STAB DRAG COEFF.
69.2	1.240		.243		.997	36.4	.0274
74.0	1.085		.243		.842	36.4	.0231
78.8	.961		.243		.718	36.4	.0197

WING/STAB DRAG COEFFICIENT = .0231 ± .0038

IF STAB IS ASSUMED TO MAINTAIN SAME DRAG COEFFICIENT AS IN TEST B (SAME MODEL WITHOUT WING TURBULATOR), THEN INSTEAD:

WING DRAG COEFFICIENT = .0241 ± .0047
STAB DRAG COEFFICIENT = .0189 ± .0013

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TEST G.

GLIDER TYPE: II, #4 WING COVERING: TISSUE
LIFTOFF MASS: 35 gm WING AREA: 27.6 sq in
SPECIAL FEATURES: IDENTICAL TO GLIDER #5 EXCEPT TISSUED

ENGINE TYPE: A8-3 STAB AREA: 5.8 sq in

DATE	ALTITUDE		COMMENTS
	AVERAGE	ERROR	
10 Jun 90	84.4	4.0	
8 Jul 90	79.9	2.8	
8 Jul 90	86.8	2.0	
AVERAGE	83.7m	2.9m	

POPULATION VARIANCE: 3.5m 90% CONFIDENCE INTERVAL: 79.0-88.4m

DATA ANALYSIS

ALTITUDE (meters)	TOTAL DRAG FORM FACTOR (sq in)	-	BODY DRAG FORM FACTOR (sq in)	=	WING/STAB DRAG FORM FACTOR (sq in)	WING+ STAB AREA (sq in)	WING/STAB DRAG COEFF.
79.0	.977		.243		.734	33.4	.0220
83.7	.884		.243		.641	33.4	.0192
88.4	.791		.243		.548	33.4	.0164

WING/STAB DRAG COEFFICIENT = .0192 ± .0028

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TEST H.

GLIDER TYPE: II, #4 — WING COVERING: TISSUE
LIFTOFF MASS: 39 gm — WING AREA: 27.6 sq in
SPECIAL FEATURES: LARGER ENGINE
ENGINE TYPE: B4-4 — STAB AREA: 5.8 sq in

DATE	ALTITUDE		COMMENTS
	AVERAGE	ERROR	
8 Jul 90	171.0	5.3	
8 Jul 90	165.5	1.4	
AVERAGE	168.3m	3.4m	

POPULATION VARIANCE: N/A

DATA ANALYSIS

ALTITUDE (meters)	TOTAL DRAG FORM FACTOR (sq in)	-	BODY DRAG FORM FACTOR (sq in)	=	WING/STAB DRAG FORM FACTOR (sq in)	WING+ STAB AREA (sq in)	WING/STAB DRAG COEFF.
168.3	.682		.243		.439	33.4	.0131

WING/STAB DRAG COEFFICIENT = .0131

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TEST I.

GLIDER TYPE: II, #5 WING COVERING: NONE
LIFTOFF MASS: 34 gm WING AREA: 27.6 sq in
SPECIAL FEATURES: IDENTICAL TO GLIDER #4 EXCEPT NOT TISSUED

ENGINE TYPE: A8-3 STAB AREA: 5.8 sq in

DATE	ALTITUDE		COMMENTS
	AVERAGE	ERROR	
10 Jun 90	89.2	1.2	
10 Jun 90	83.2	2.8	
8 Jul 90	95.2	1.4	
8 Jul 90	89.3	4.9	
AVERAGE	89.3m	2.6m	

POPULATION VARIANCE: 4.9m 90% CONFIDENCE INTERVAL: 84.1-94.5m

DATA ANALYSIS

ALTITUDE (meters)	TOTAL DRAG FORM FACTOR (sq in)	-	BODY DRAG FORM FACTOR (sq in)	=	WING/STAB DRAG FORM FACTOR (sq in)	WING+ STAB AREA (sq in)	WING/STAB DRAG COEFF.
84.1	.899		.243		.656	33.4	.0196
89.3	.791		.243		.548	33.4	.0164
94.5	.713		.243		.470	33.4	.0141

WING/STAB DRAG COEFFICIENT = .0164 ± .0027

R&D Report from http://nar.org National Association of Rocketry

TEST J.

GLIDER TYPE: II, #5
LIFTOFF MASS: 38 gm
SPECIAL FEATURES: LARGER ENGINE
ENGINE TYPE: B4-4

WING COVERING: NONE
WING AREA: 27.6 sq in
STAB AREA: 5.8 sq in

DATE	ALTITUDE AVERAGE	ALTITUDE ERROR	COMMENTS
8 Jul 90	192.9	7.1	
8 Jul 90	178.3	4.8	
8 Jul 90	168.3	4.6	
AVERAGE	179.8m	5.5m	

POPULATION VARIANCE: 12.4m 90% CONF. INTERVAL: 163.0-196.6m

DATA ANALYSIS

ALTITUDE (meters)	TOTAL DRAG FORM FACTOR (sq in)	-	BODY DRAG FORM FACTOR (sq in)	=	WING/STAB DRAG FORM FACTOR (sq in)	WING+ STAB AREA (sq in)	WING/STAB DRAG COEFF.
163.0	.729		.243		.486	33.4	.0145
179.8	.620		.243		.377	33.4	.0113
196.6	.527		.243		.284	33.4	.0085

WING/STAB DRAG COEFFICIENT = .0113 ± .0030

R&D Report from http://nar.org National Association of Rocketry

TEST K.

GLIDER TYPE: II, #5
LIFTOFF MASS: 28 gm
SPECIAL FEATURES: 13mm ENGINE IN 18mm POD
ENGINE TYPE: A3-4T

WING COVERING: NONE
WING AREA: 27.6 sq in
STAB AREA: 5.8 sq in

DATE	ALTITUDE AVERAGE	ALTITUDE ERROR	COMMENTS
15 Jul 90	88.8	1.0	
AVERAGE	88.8m	1.0m	

POPULATION VARIANCE: N/A

DATA ANALYSIS

ALTITUDE (meters)	TOTAL DRAG FORM FACTOR (sq in)	-	BODY DRAG FORM FACTOR (sq in)	=	WING/STAB DRAG FORM FACTOR (sq in)	WING+ STAB AREA (sq in)	WING/STAB DRAG COEFF.
88.8	.853		.243		.610	33.4	.0182

WING/STAB DRAG COEFFICIENT = .0182

R&D Report from http://nar.org National Association of Rocketry

TEST L.

GLIDER TYPE: III, #8
LIFTOFF MASS: 36 gm
SPECIAL FEATURES: ZERO DEGREE STAB INCIDENCE
ENGINE TYPE: A8-3

WING COVERING: TISSUE
WING AREA: 27.4 sq in
STAB AREA: 6.3 sq in

DATE	ALTITUDE AVERAGE	ALTITUDE ERROR	COMMENTS
10 Jun 90	90.2	0.5	
10 Jun 90	84.4	0.1	
8 Jul 90	78.5	6.5	
8 Jul 90	85.4	5.2	
AVERAGE	84.6m	3.1m	

POPULATION VARIANCE: 4.8m 90% CONFIDENCE INTERVAL: 79.5-89.7m

DATA ANALYSIS

ALTITUDE (meters)	TOTAL DRAG FORM FACTOR (sq in)	-	BODY DRAG FORM FACTOR (sq in)	=	WING/STAB DRAG FORM FACTOR (sq in)	WING+ STAB AREA (sq in)	WING/STAB DRAG COEFF.
79.5	.946		.243		.703	33.7	.0209
84.6	.837		.243		.594	33.7	.0176
89.7	.744		.243		.501	33.7	.0149

WING/STAB DRAG COEFFICIENT = .0176 ± .0030

R&D Report from http://nar.org National Association of Rocketry

TEST M.

GLIDER TYPE: III, #8 — WING COVERING: TISSUE
LIFTOFF MASS: 36 gm — WING AREA: 27.4 sq in
SPECIAL FEATURES: THREE DEGREE STAB INCIDENCE
ENGINE TYPE: A8-3 — STAB AREA: 6.3 sq in

DATE	ALTITUDE AVERAGE	ALTITUDE ERROR	COMMENTS
27 May 90	73.5	1.8	Arc-over on boost
2 Jun 90	78.5	0.1	Past apogee
10 Jun 90	78.2	0.2	Arc-over on boost
AVERAGE	76.7m	0.7m	

POPULATION VARIANCE: 2.8m — 90% CONFIDENCE INTERVAL: 72.9-80.5m

DATA ANALYSIS

ALTITUDE (meters)	TOTAL DRAG FORM FACTOR (sq in)	-	BODY DRAG FORM FACTOR (sq in)	=	WING/STAB DRAG FORM FACTOR (sq in)	WING+ STAB AREA (sq in)	WING/STAB DRAG COEFF.
72.9	1.116		.243		.873	33.7	.0259
76.7	1.008		.243		.765	33.7	.0227
80.5	.915		.243		.672	33.7	.0199

WING/STAB DRAG COEFFICIENT = .0227 ± .0030

R&D Report from http://nar.org National Association of Rocketry

TEST N.

GLIDER TYPE: III, #8 — WING COVERING: TISSUE
LIFTOFF MASS: 36 gm — WING AREA: 27.4 sq in
SPECIAL FEATURES: THREE DEGREE STAB INCIDENCE, SMALLER STAB
ENGINE TYPE: A8-3 — STAB AREA: 4.7 sq in

DATE	ALTITUDE AVERAGE	ALTITUDE ERROR	COMMENTS
15 Jul 90	88.6	2.0	
15 Jul 90	86.2	2.2	
15 Jul 90	74.6	1.3	
AVERAGE	83.1m	1.8m	

POPULATION VARIANCE: 7.5m — 90% CONFIDENCE INTERVAL: 72.9-93.3m

DATA ANALYSIS

ALTITUDE (meters)	TOTAL DRAG FORM FACTOR (sq in)	-	BODY DRAG FORM FACTOR (sq in)	=	WING/STAB DRAG FORM FACTOR (sq in)	WING+ STAB AREA (sq in)	WING/STAB DRAG COEFF.
72.9	1.116		.243		.873	32.1	.0272
83.1	.868		.243		.625	32.1	.0195
93.3	.682		.243		.439	32.1	.0137

WING/STAB DRAG COEFFICIENT = .0195 ± .0068

R&D Report from http://nar.org National Association of Rocketry

TEST O.

GLIDER TYPE: III, #9
LIFTOFF MASS: 36 gm
SPECIAL FEATURES: 18mm ENGINE, 18mm POD
ENGINE TYPE: A8-3

WING COVERING: TISSUE
WING AREA: 27.4 sq in
STAB AREA: 6.3 sq in

DATE	ALTITUDE AVERAGE	ALTITUDE ERROR	COMMENTS
10 Jun 90	82.9	0.2	
15 Jul 90	81.2	1.7	
AVERAGE	82.1m	0.9m	

POPULATION VARIANCE: N/A

DATA ANALYSIS

ALTITUDE (meters)	TOTAL DRAG FORM FACTOR (sq in)	-	BODY DRAG FORM FACTOR (sq in)	=	WING/STAB DRAG FORM FACTOR (sq in)	WING+ STAB AREA (sq in)	WING/STAB DRAG COEFF.
82.1	.884		.243		.641	33.7	.0190

WING/STAB DRAG COEFFICIENT = .0190

R&D Report from http://nar.org National Association of Rocketry

TEST P.

GLIDER TYPE: III, #9 — WING COVERING: TISSUE
LIFTOFF MASS: 28 gm — WING AREA: 27.4 sq in
SPECIAL FEATURES: 13mm POD AND ENGINE
ENGINE TYPE: A3-4T — STAB AREA: 6.3 sq in

DATE	ALTITUDE		COMMENTS
	AVERAGE	ERROR	
27 May 90	86.3	2.0	
27 May 90	81.4	0.5	
2 Jun 90	93.5	7.8	
10 Jun 90	106.0	4.7	
10 Jun 90	100.3	3.4	
8 Jul 90	91.2	2.8	
8 Jul 90	113.2	1.2	
AVERAGE	96.0m	3.2m	

POPULATION VARIANCE: 11.2m 90% CONFIDENCE INTERVAL: 88.0-104.0m

DATA ANALYSIS

ALTITUDE (meters)	TOTAL DRAG FORM FACTOR (sq in)	-	BODY DRAG FORM FACTOR (sq in)	=	WING/STAB DRAG FORM FACTOR (sq in)	WING+ STAB AREA (sq in)	WING/STAB DRAG COEFF.
88.0	.868		.203		.665	33.7	.0197
96.0	.729		.203		.526	33.7	.0156
104.0	.636		.203		.433	33.7	.0128

WING/STAB DRAG COEFFICIENT = .0156 ± .003

R&D Report from http://nar.org National Association of Rocketry

TEST Q.

GLIDER TYPE: III, #9
LIFTOFF MASS: 28 gm
SPECIAL FEATURES: 13mm ENGINE IN 18mm POD
ENGINE TYPE: A3-4T

WING COVERING: TISSUE
WING AREA: 27.4 sq in
STAB AREA: 6.3 sq in

DATE	ALTITUDE		DRAG COEFF	COMMENTS
	AVERAGE	ERROR		
15 Jul 90	84.5	4.9		
15 Jul 90	83.4	0.9		
AVERAGE	84.0m	2.9m		

POPULATION VARIANCE: N/A

DATA ANALYSIS

ALTITUDE (meters)	TOTAL DRAG FORM FACTOR (sq in)	-	BODY DRAG FORM FACTOR (sq in)	=	WING/STAB DRAG FORM FACTOR (sq in)	WING+ STAB AREA (sq in)	WING/STAB DRAG COEFF.
84.0	.946		.243		.703	33.7	.0208

WING/STAB DRAG COEFFICIENT = .0208

R&D Report from http://nar.org National Association of Rocketry

DATA ANALYSIS

OVERALL APPROACH

The direct data measured by this project was the maximum altitude achieved on each of 61 glider flights. Each of nine design or operating characteristics was evaluated by comparing whether a glider with this characteristic could be proved with statistical significance to have gone higher than the same or a comparable glider without the characteristic. In addition to these statistical comparisons (which were developed from Reference [B]), an estimate of the drag coefficient of the wing/stabilizer combination was derived for each glider configuration. This drag coefficient was considered to be the best "normalized" (independent of wing area, glider weight, or engine) expression of the configuration's aerodynamic performance.

STATISTICAL TECHNIQUES

For each glider configuration, "n" tests were conducted, each of which resulted in a measurement of maximum altitude "y". An average value of altitude $\bar{y}$ was computed for each configuration. The sample size (number of tests per configuration) was small, so the true variance (standard deviation) "s" of the scatter in an infinitely large population of measurements of altitude performance was estimated from:

$$s = \sqrt{\frac{\sum_i (y_i - \bar{y})^2}{n-1}}$$

The average altitudes resulting from these tests are only estimates of the true performance of each glider configuration. Assuming that the measurements were snapshots of a field of data with a normal distribution around the true performance, the true performance can be said to a 90% level of confidence to lie within an interval around this average whose size depends on the variance of the data and--through a tabulated factor called the Student's "t"--on the number of tests that were conducted. This 90% confidence interval was computed as:

$$\bar{y} \pm \frac{t_{.05}\, s}{\sqrt{n}}$$

The performance of two different configurations was compared by applying the Student's t test to the common variance "s_c". A change in configuration was considered to have resulted in a true difference if its performance was demonstrably different from the pre-change performance at the .05 level of significance.

$$s_c = \sqrt{\frac{\sum_i (y_i - \bar{y}_1)^2 + \sum_j (y_j - y_2)^2}{n_1 + n_2 - 2}}$$

$$\Delta y = |y_1 - y_2| \geq \frac{t_{.05}\, s_c}{\sqrt{\frac{n_1 n_2}{n_1 + n_2}}}$$

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DRAG ANALYSIS

The measured variable in this project's work was maximum altitude. For a rocket with known liftoff mass and known engine performance, this altitude depends entirely on drag form factor, the product of drag coefficient and a reference area that is characteristic of the design. The relationship between achieved altitude and drag form factor can be established easily with any accurate altitude computation computer program.

DERIVING TOTAL DRAG FORM FACTOR.

This project used an iterative-type computer program (Appendix III) developed by the author several years ago for general altitude computation. The program uses linearized engine time-thrust curves based on NAR Standards & Testing actual test data, with the engine data constrained to exactly deliver the tested average total impulse. Rocket liftoff mass and drag form factor are the inputs. The program updates engine thrust and lost propellant mass every .01 seconds during powered flight. There is no guarantee that the performance of particular engines used in this project exactly matched the total impulse used in this program, and to the extent that they did not, some error (up to 5% based on variance data on total impulse) is introduced in the overall drag analysis.

To derive a total drag form factor for each rocket configuration, the computer program was run repeatedly for each combination of engine type and rocket liftoff mass used in the project. Drag form factor was progressively varied across the range necessary to give predicted altitudes that encompassed the range of measured altitudes, and the results were plotted (following page). Entering the graph with the achieved altitude of the rocket (vertical scale) and using the curve applicable to the engine type and liftoff mass, the estimated total drag form factor can be read on the horizontal scale.

ESTIMATING NON-VARIABLE POD AND FUSELAGE DRAG FORM FACTOR.

Every glider in this project used the same fuselage and rudder design, and all tests (except one) were conducted with the same engine pod exterior design. The experimental variations in design affected the area or the drag coefficient of the wing and/or stabilizer of each glider, but were assumed to not make the kind of radical changes in velocity, pod angle of attack, or yaw angle that would lead to changes in the drag form factor of the fuselage, rudder, or pod. This estimated constant drag form factor was then deducted from the overall drag form factors derived from comparing altitude data to altitude predictions.

Most types of drag coefficient change as a function of Reynolds Number, a dimensionless factor which expresses the balance between viscous and inertial effects in fluid flow. Reynolds Number (RN) increases with the speed of a model and the airframe distance (such as wing chord) across which air must flow. For a model of length L (inches) moving at velocity V (ft/sec) at 70 degrees and sea level altitude:

$$RN = 500\ L\ V$$

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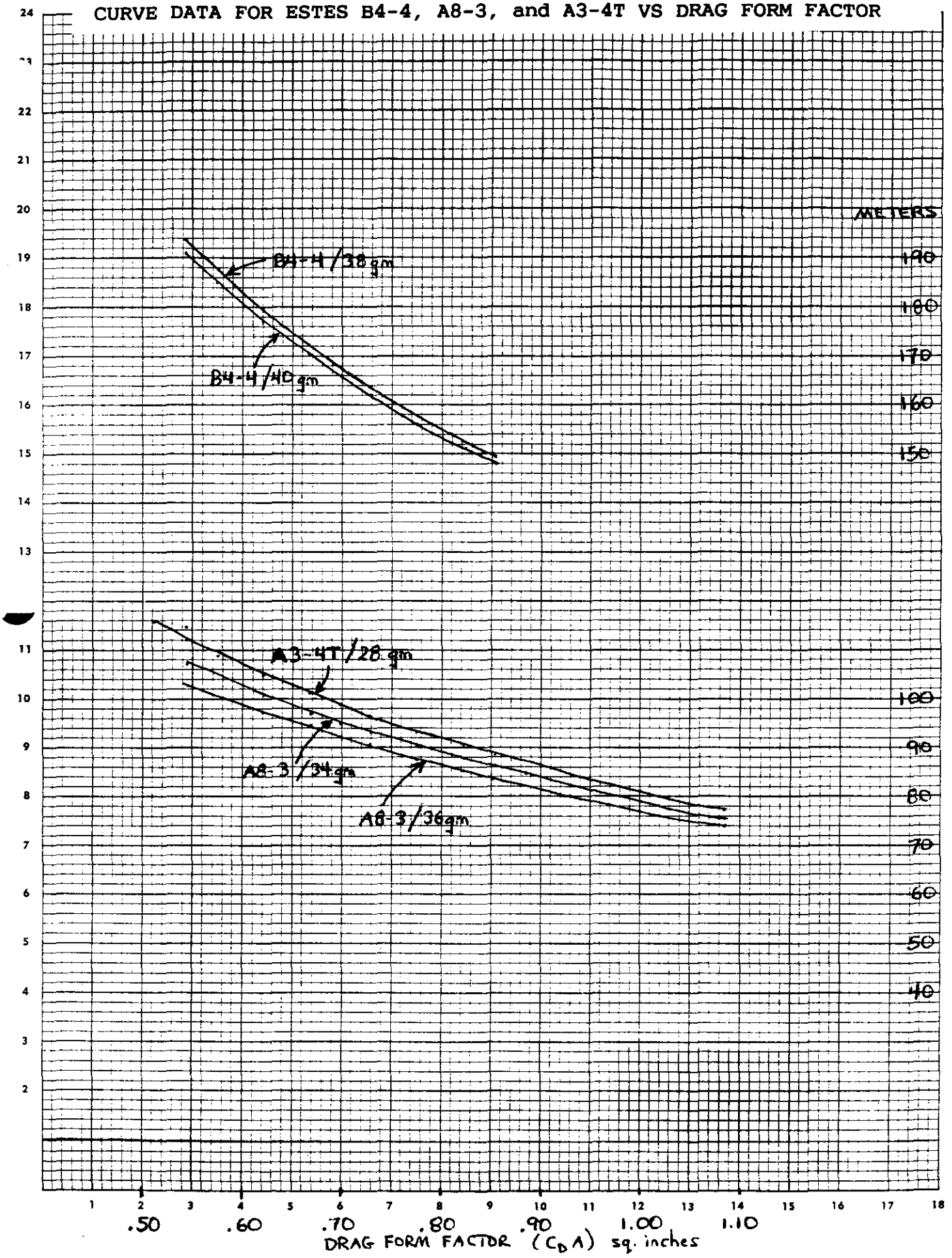
GRAPH OF PREDICTED ALTITUDE PEFORMANCE WITH REAL ENGINE THRUST-CURVE DATA FOR ESTES B4-4, A8-3, and A3-4T VS DRAG FORM FACTOR



R&D Report from http://nar.org National Association of Rocketry

In order to estimate the range of boost-phase Reynolds Numbers at which gliders in this project operated (assuming 2.5-inch wing chord as the applicable dimension), an average boost-phase flight velocity was calculated by dividing the average peak altitude achieved by the average time of flight to that altitude (engine burn time plus delay time).

ENGINE	AVG PEAK ALT	BURN TIME (sec)	DELAY TIME (sec)	AVG VELOC (ft/sec)	RN
A3-4T	90 m = 295 ft	0.70	4.0	63	79,000
A8-3	85 m = 278 ft	0.40	3.0	82	102,000
B4-4	175 m = 574 ft	1.00	4.0	115	144,000

Gregorek's analysis in Reference D was used as the basis for estimating pod and fuselage drag. The pod drag coefficient (referenced to the frontal area of the pod body tube, 0.425 sq in for 18mm and 0.230 sq in for 13mm) is made up of the coefficients of the nose and the body tube ($C_{D_N}+C_{D_{BT}}$ from Figure 28 in the reference), the launch lug ($C_{D_{LL}}$ = .03, Figure 54), and base drag (C_{D_B} = .06, Figure 30). For the 18mm pods used on all but one test, the length-to-diameter ratio was 10 ($C_{D_N}+C_{D_{BT}}$= .20); for the 13mm pod it was 14 ($C_{D_N}+C_{D_{BT}}$= .27). Multiplying the summed drag coefficients by the applicable reference area, the overall drag form factor of the pod was 0.123 sq in for the 18mm pods and 0.083 sq in for the 13mm pods.

The fuselage/rudder drag was estimated by multiplying the overall both-side surface area of pod pylon, glider fuselage, and glider rudder (20 sq in) by the turbulent-flow skin friction coefficient of .006 for a Reynolds Number of 100,000 (C_f , Figure A-1), giving an overall fuselage/rudder drag form factor of 0.12 sq in.. Adding this to the pod values gives the following rough estimates of the fixed drag form factors--independent of wing and stabilizer drag:

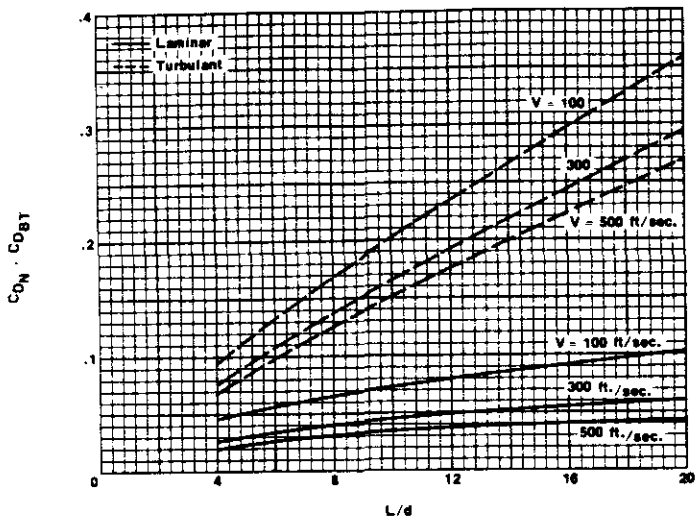
18mm pod gliders: 0.243 sq in
13mm pod gliders: 0.203 sq in

ESTIMATING THE WING/STABILIZER DRAG COEFFICIENT.

The estimated overall rocket drag form factor was derived from comparing computer altitude predictions with measured altitudes. The contribution of the non-varying pod and fuselage/rudder to this overall factor were estimated above. The difference between overall drag form factor and pod/fuselage drag form factor is the drag form factor of the remainder of the glider, the wing and stabilizer. Dividing this by the planform area of the wing plus stabilizer gives a dimensionless boost-phase drag coefficient that represents an estimate of the aerodynamic efficiency of each glider configuration. For each configuration, a separate value of this coefficient was calculated for the altitudes corresponding to the mean measured altitude and to the upper and lower 90%-confidence-interval altitudes. These were taken to define the configuration's 90%-confidence-interval range of wing/stabilizer drag coefficients.

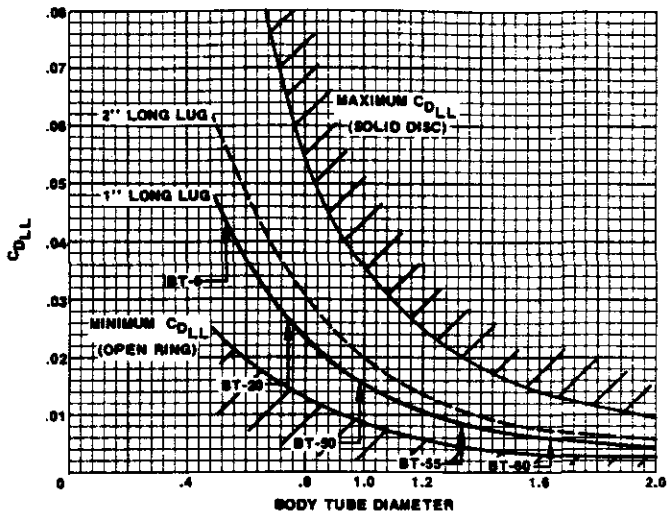
R&D Report from http://nar.org National Association of Rocketry

FIG. 28
NOSE CONE AND BODY TUBE DRAG COEFFICIENT FOR DIFFERENT LENGTH TO DIAMETER RATIO



MODELS WITH 3:1 OGIVE NOSE CONES

FIG. 54
ESTIMATE OF DRAG COEFFICIENT OF A LAUNCH LUG



GRAPHS FROM REFERENCE D USED IN ESTIMATING BOOST-GLIDER POD DRAG

FIG. 30
BASE PRESSURE COEFFICIENT DEPENDENCE UPON NOSE CONE AND BODY TUBE

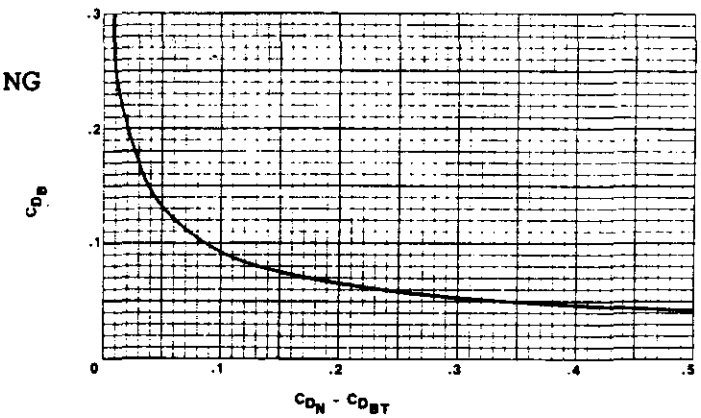
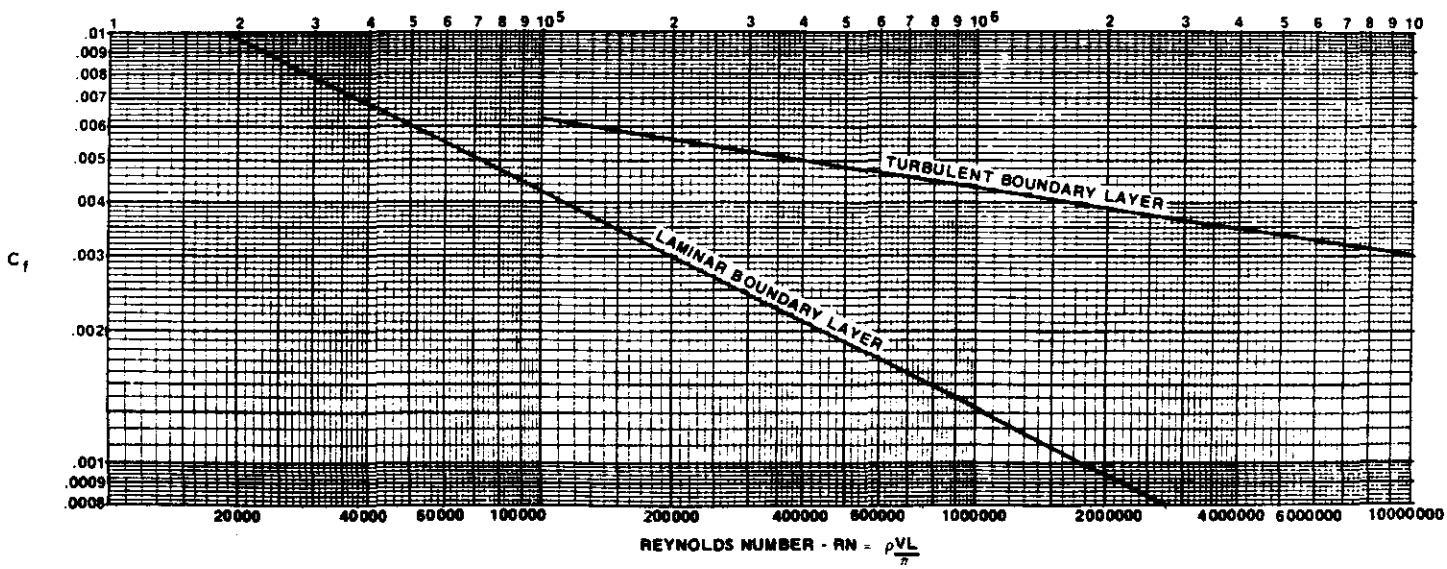


FIG. A-1
SKIN FRICTION COEFFICIENT C_f vs REYNOLDS NUMBER RN FOR LAMINAR AND TURBULENT BOUNDARY LAYERS



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Note: **The following pages analyze the test data presented elsewhere in this report. Each letter designator for a test refers to a unique combination of glider configuration, pod, and engine that is explained with the test data.**

EFFECTS OF WING AIRFOIL CAMBER

TEST	CHARACTERISTIC	ALTITUDE	SAMPLES	WING/STAB DRAG COEFFICIENT
A	1% CAMBER (NACA 1305)	86.1 ± 1.4	3	.0155 ± .0008
B	2% CAMBER (NACA 2305)	79.9 ± 2.0	4	.0189 ± .0013
C	3% CAMBER (NACA 3305)	77.9 ± 4.4	5	.0202 ± .0035

By inspection, the 2% and 3% camber cases cannot be differentiated because of the large scatter in the 3% camber data--these gliders boosted non-vertically because of the post-burnout nose-down pitching moment produced by the lift of the wing. For 1% vs 2% camber, the difference in altitude performance is greater than the t-test acceptance threshold, so at a better than .05 level of significance (90% probability), the 1% camber model went higher.

Increasing wing camber increases the maximum lift coefficient for glide, but cambered wings must fly at a substantial negative angle of attack to reach the zero-lift condition needed for stable boost, and at this negative angle of attack they are outside the drag "bucket" and operate at a higher drag coefficient than less-cambered wings. The higher-camber wings in this series of tests were mounted to the fuselage with shims so that each had the same mounting angle relative to its estimated zero-lift line as the 1% camber wing.

COMPARISON	ALT DIFF	COMMON VARIANCE	t-TEST ACCEPT THRESHOLD
A vs B	6.2 m	1.6 m	1.9 m

CONCLUSION: The model with 1% camber went higher than the model with 2% camber by 6.2 ± 1.9 meters (8 ± 2 percent).

R&D Report from http://nar.org National Association of Rocketry

EFFECTS OF BOOST-PHASE REYNOLDS NUMBER

TEST	CHARACTERISTIC	ALTITUDE	SAMPLES	WING/STAB DRAG COEFFICIENT
A	A8-POWERED (RN = 102K)	86.1 ± 1.4	3	.0155 ± .0008
E	B4-POWERED (RN = 144K)	172.5 ± 12.9	3	.0112 ± .0024
	Ratio of drag coefficients: 1.4			
	Ratio of altitudes: 2.0			
G	A8-POWERED (RN = 102K)	83.7 ± 4.7	3	.0192 ± .0028
H	B4-POWERED (RN = 144K)	168.3	2	.0131
	Ratio of drag coefficients: 1.5			
	Ratio of altitudes: 2.0			
I	A8-POWERED (RN = 102K)	89.3 ± 5.2	4	.0164 ± .0030
J	B4-POWERED (RN = 144K)	179.8 ± 16.8	3	.0113 ± .0030
	Ratio of drag coefficients: 1.5			
	Ratio of altitudes: 2.0			

Typically, doubling the power of a model rocket does not double the altitude: higher-powered models spend a greater proportion of their time at higher velocities, and lose a greater proportion of their energy to drag (which is proportional to the square of velocity). In this set of experiments, doubling the power exactly doubled altitude--apparently because the average wing/stabilizer drag coefficient was lower for the higher-powered rockets as a result of their spending more time at a higher Reynolds Number.

CONCLUSION: Boost-phase drag of all three glider types tested decreased with increasing average boost-phase Reynolds Number (velocity).

R&D Report from http://nar.org National Association of Rocketry

EFFECTS OF ENGINE POD PITCH ANGLE

TEST	CHARACTERISTIC	ALTITUDE	SAMPLES	WING/STAB DRAG COEFFICIENT
A	ZERO PITCH ANGLE	86.1 ± 1.4	3	.0155 ± .0008
D	TWO DEGREES PITCH-UP	81.6 ± 6.6	6	.0180 ± .0040

Numerous flights were conducted using glider #1 with a shim between the front tip of the fuselage and the pod pylon. This moved the thrust line of the engine from its normal position parallel with the fuselage axis to an orientation two degrees above this axis (thrusting more into the wing). This reduced the nose-down pitching moment of engine thrust. It was hypothesized that this reduction would allow the wing to operate at a lower lift value (i.e., angle of attack) to maintain boost-phase rotational balance in the pitch axis. At a lower angle of attack the wing should have had a lower drag coefficient, thereby permitting the rocket to boost higher.

In this case, the altitude difference between the two configurations was less than the threshold needed to prove that there was a statistically significant difference in performance. If anything, the pod pitch-up angle may have actually decreased performance. The glider wing in both cases was probably operating at angles of attack "in the drag bucket" where drag coefficient does not vary strongly with angle of attack.

COMPARISON	ALT DIFF	COMMON VARIANCE	t-TEST ACCEPT THRESHOLD
A vs D	4.5 m	6.8 m	6.4 m

CONCLUSION: Placing the engine pod at pitch-up angles as high as two degrees did not reduce the boost-phase drag coefficient or increase the altitude performance of these gliders.

R&D Report from http://nar.org National Association of Rocketry

EFFECTS OF WING COVERING MATERIAL

TEST	CHARACTERISTIC	ALTITUDE	SAMPLES	WING/STAB DRAG COEFFICIENT
G	TISSUE-COVERED WING	83.7 ± 4.7	3	.0192 ± .0028
I	DOPE-FINISH ONLY	89.3 ± 5.2	4	.0164 ± .0027

There is debate among glider enthusiasts about the effect of wing covering materials on glider performance. There is little doubt that they add strength--perhaps sufficient to allow a thinner wing with its associated advantages in glide performance at low Reynolds Number. The other question is their effect on surface finish and the effect of this on drag coefficient--in both boost and glide. This test series compared otherwise very similar gliders, one with a Japanese tissue wing covering and one with a wing having no covering but with a reasonable surface finish from 600-grit sandpaper and clear dope. The tissue-covered glider was 1 gram heavier; no corrections were made for the effect of this on altitude performance (a reduction of 1.5 meters in altitude according to the computer program).

The data showed that although the non-covered glider appeared to go higher from its average tracking results, this increased performance was not statistically significant.

COMPARISON	ALT DIFF	COMMON VARIANCE	t-TEST ACCEPT THRESHOLD
G vs I	5.6 m	4.0 m	6.1 m

CONCLUSION: The glider with a tissue-covered wing did not have a different altitude performance than the glider with an uncovered wing.

R&D Report from http://nar.org National Association of Rocketry

EFFECTS OF ENGINE AVERAGE THRUST

TEST	CHARACTERISTIC	ALTITUDE	SAMPLES	WING/STAB DRAG COEFFICIENT
I	A8-3 ENGINE	89.3 ± 5.2	4	.0164 ± .0027
K	A3-4T ENGINE, 18mm POD	88.8	1	.0182
O	A8-3 ENGINE	82.1	2	.0190
Q	A3-4T ENGINE, 18mm POD	84.1	2	.0208

The performance produced by the lower average thrust (but almost identical total impulse) of the A3-4T engine was compared to that produced by the A8-3 engine on the same glider in two series of tests. The gliders all used 18mm pods to minimize differences in airframe drag effects. As previously estimated, the A3-4T gliders operated at an average velocity of 63 ft/sec (RN = 79,000) while the A8-3 gliders operated at 82 ft/sec and RN = 102,000. Because of the 7.3-gram difference in engine casing mass between the engines and the fact that the A3-4T provides a lower average flight velocity (with less energy lost to drag), the A3-4T models should have gone 6-7 meters higher than the A8-3 models if the drag coefficients were identical.

There was insufficient data to do a statistical analysis of the results of this set of experiments, but it is obvious from inspection that changing engines (within the same pod) did not significantly change altitude performance. The models powered by the smaller engines probably operated at a higher drag coefficient, either because of the lower average Reynolds Number or beacuse of higher engine pod exhaust plume drag as a result of the longer engine-on time.

CONCLUSION: Changing engines from A8-3 to A3-4T with the same 18mm pod did not change the altitude performance of the gliders tested.

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EFFECTS OF ADDING A TURBULATOR TO THE WING AIRFOIL

TEST	CHARACTERISTIC	ALTITUDE	SAMPLES	WING/STAB DRAG COEFFICIENT
B	2% CAMBER (NACA 2305)	79.9 ± 2.0	4	.0189 ± .0013
F	TURBULATOR ADDED	74.0 ± 4.8	5	.0231 ± .0038

Turbulators are designed to force the laminar boundary layer on the front portion of an airfoil operating at low Reynolds Number to trip to turbulent flow prior to reaching the negative pressure gradient region aft of the airfoil high point. This turbulent boundary layer is more likely to remain attached to the wing upper surface across the negative pressure gradient; a layer that remains laminar often separates in the face of such a gradient, creating a "laminar separation bubble" region of high pressure on the aft portion of the top surface of the wing that greatly degrades the lift (hence glide performance) of the wing.

This turbulator was two thicknesses of 0.25" width masking tape, placed across the entire span of the wing just before the airfoil high point at 20% of the chord. The model with this turbulator went lower than the model without, to a greater than 90% level of confidence. The reduction in performance was 5.9 ± 5.1 meters, or 8 ± 7 percent. This reduction was expected--a turbulator is designed to increase the amount of wing surface area across which the air stream has higher-drag turbulent rather than laminar flow. This is clearly harmful during boost, but as explained above often beneficial in glide at low Reynolds Number.

COMPARISON	ALT DIFF	COMMON VARIANCE	t-TEST ACCEPT THRESHOLD
B vs F	5.9 m	4.0 m	5.1 m

CONCLUSION: The model without a turbulator went higher than the model with a turbulator, by 5.9 ± 5.1 meters, or 8 ± 7 percent.

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EFFECTS OF ENGINE POD DIAMETER

TEST	CHARACTERISTIC	ALTITUDE	SAMPLES	WING/STAB DRAG COEFFICIENT
P	A3-4T in 13mm POD	96.0 ± 8.0	7	.0156 ± .003
Q	A3-4T in 18mm POD	84.0	2	.0208

The pod drag analysis at the beginning of this report indicated that the drag form factor (drag coefficient times pod body tube frontal area) of an 18mm pod should be approximately 0.243, while that of a 13mm pod of the same length (but with a smaller wetted surface as a result of the reduced diameter) should be 0.203. As a result, a glider with a small-diameter pod should go higher than a glider with a larger-diameter pod. In this test series, the two pods were identical in length and (as the result of adding nose weight to the smaller pod) identical in mass.

The small number of flight tests of the 18mm pod configuration and the large scatter in the data from the 13mm pod configuration meant that despite the apparent difference of 12 meters in altitude performance, there was not a statistically significant difference in the performance of the two configurations. Nevertheless, the lower derived wing/stab drag coefficient of the glider with the 13mm pod indicates that either the drag coefficient of the glider is affected by some kind of flow interaction with the pod (larger pods increasing the drag of the glider) or that reduced-diameter pods have a drag form factor 35% less than larger pods rather than the 17% lower drag form factor that this project's drag analysis estimated.

COMPARISON	ALT DIFF	COMMON VARIANCE	t-TEST ACCEPT THRESHOLD
P vs Q	12.0 m	10.4 m	15.8 m

CONCLUSION: Using a 13mm pod rather than an 18mm pod for the glider tested may have resulted in a noticeable increase in altitude performance, but this increase could not be proved to be statistically significant.

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EFFECTS OF STABILIZER INCIDENCE ANGLE

TEST	CHARACTERISTIC	ALTITUDE	SAMPLES	WING/STAB DRAG COEFFICIENT
L	ZERO INCIDENCE/6.3 SQ IN	84.6 ± 5.1	4	.0176 ± .003
M	3 deg INCIDENCE/6.3 SQ IN	76.7 ± 3.8	3	.0227 ± .003
N	3 deg INCIDENCE/4.7 SQ IN	83.1 ± 10.2	3	.0195 ± .0068

Incidence angle on a glider's stabilizer drives the glider to a glide-phase trim condition with the wing operating at a high angle of attack--within limits, a beneficial characteristic. It also gives the glider the ability to pull out of a dive in its transition out of powered flight. During the boost phase, this tail incidence drives the wing to a greater equilibrium angle of attack, potentially forcing it out of the low-drag-coefficient "bucket" region of lift coefficient and forcing it to a condition where its greater lift gives the glider a nose-down pitching moment that reinforces the pitch-down effect of the engine thrust. Thus, excessive stabilizer incidence can make a glider operate at a high drag condition and tend to loop nose-down during boost. This effect can be reduced by reducing the area of the stabilizer--with a smaller (lighter) stabilizer area operating at the higher lift coefficient of a more negative angle of attack replacing a larger (heavier) stabilizer.

The pair of tests comparing the same glider with its stabilizer at zero and at three degrees negative incidence showed that the negative incidence reduced altitude performance by a statistically significant amount--largely the result of the non-vertical flight characteristics of the negative-incidence glider. Reducing the area of the stabilizer from 6.3 square inches (23% of wing area) to 4.7 square inches (17% of wing area) on a second series of tests eliminated this effect.

COMPARISON	ALT DIFF	COMMON VARIANCE	t-TEST ACCEPT THRESHOLD
L vs M	7.9 m	4.1m	6.3 m

CONCLUSION: The glider with its stabilizer at three degrees negative incidence went 7.9 ± 6.3 meters, or 9 ± 7 percent lower than the same glider with a zero-incidence stabilizer. This effect was eliminated by reducing the area of the negative-incidence stabilizer from 23% of wing area to 17% of wing area.

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EFFECTS OF WING ASPECT RATIO

TEST	CHARACTERISTIC	ALTITUDE	SAMPLES	WING/STAB DRAG COEFFICIENT
G	ASPECT RATIO 4.7	83.7 ± 4.7	3	.0192 ± .0028
L	ASPECT RATIO 6.4	84.6 ± 5.1	4	.0176 ± .003
O	ASPECT RATIO 6.4	82.1	2	.0190

Higher aspect ratio wings are desirable in many cases for the improvements that they offer in glide performance--increased lift coefficient and reduced induced drag. For a given wing area, increasing aspect ratio means decreasing the wing chord, and hence decreasing the Reynolds Number at which the wing operates at a given boost or glide speed. At the low RN characteristic of model rocket boost gliders, the loss of performance (increase in skin friction drag) from viscous effects as a result of decreasing RN may more than offset any increase in glide performance.

The set of tests above--on gliders with virtually identical wing areas--indicate no statistically significant change in altitude performance as a result of varying wing aspect ratio from 4.7 to 6.4.

COMPARISON	ALT DIFF	COMMON VARIANCE	t-TEST ACCEPT THRESHOLD
G vs L	0.9 m	4.0 m	6.2 m

CONCLUSION: Varying wing aspect ratio from 4.7 to 6.4 while maintaining constant wing area did not change the altitude performance of the gliders tested.

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CONCLUSIONS

This project has investigated the effects of nine different design and operating characteristics on the boost-phase performance of model rocket boost gliders in the range of 30 square inches of wing area and a boost Reynolds Number of 100,000. For gliders of this type it has determined the following:

-- Increasing airfoil camber from 1% to 2% reduces altitude performance by 8%.
-- Typical values of boost-glider boost-phase drag coefficient (referenced to the wing/stabilizer combined area and additive to the 18mm pod drag form factor of 0.24 sq in) are:
  - 0.018 for A engines
  - 0.012 for B engines
-- These drag coefficients are not changed by tissuing the wing, by mounting the pod with up to 2 degrees of pitch-up angle, or by changing the wing aspect ratio over the range of 4.7 to 6.4.
-- Adding a tape-strip turbulator to a wing increases the wing's drag coefficient by 25 percent and decreases the glider's altitude performance by 8 percent.
-- Adding 3 degrees of negative incidence to a stabilizer with an area of 23 percent of the wing area decreases altitude performance by 9 percent; this much incidence on a 17 percent stabilizer does not reduce altitude.

The conclusions developed by this project represent new knowledge in the field of model rocketry. They can be combined with existing or future calculations and measurements of glide-phase characteristics to permit for the first time a comprehensive analysis of the total performance of boost-gliders.

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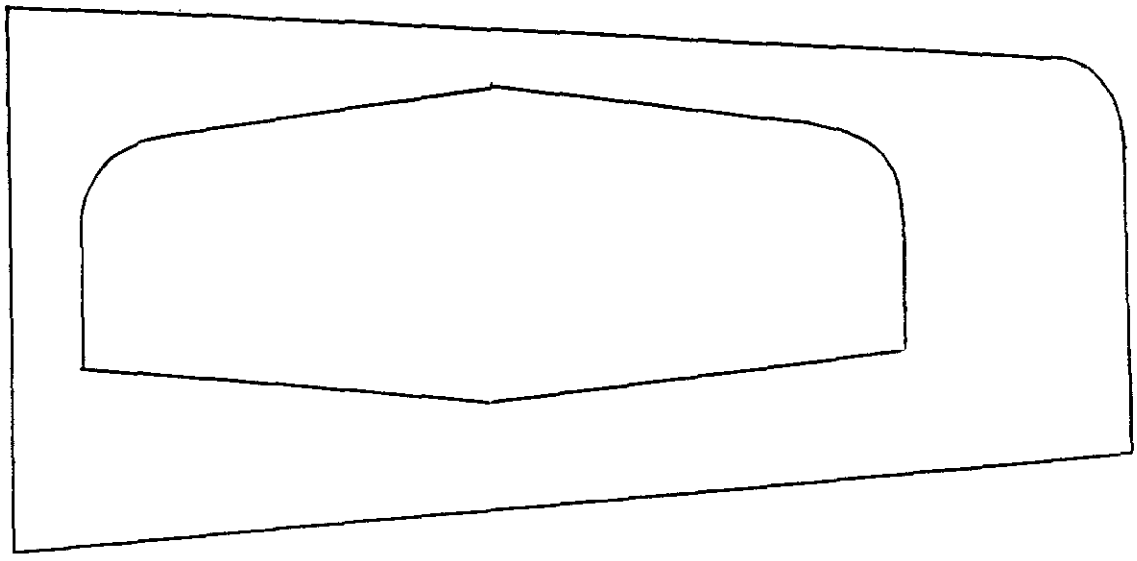
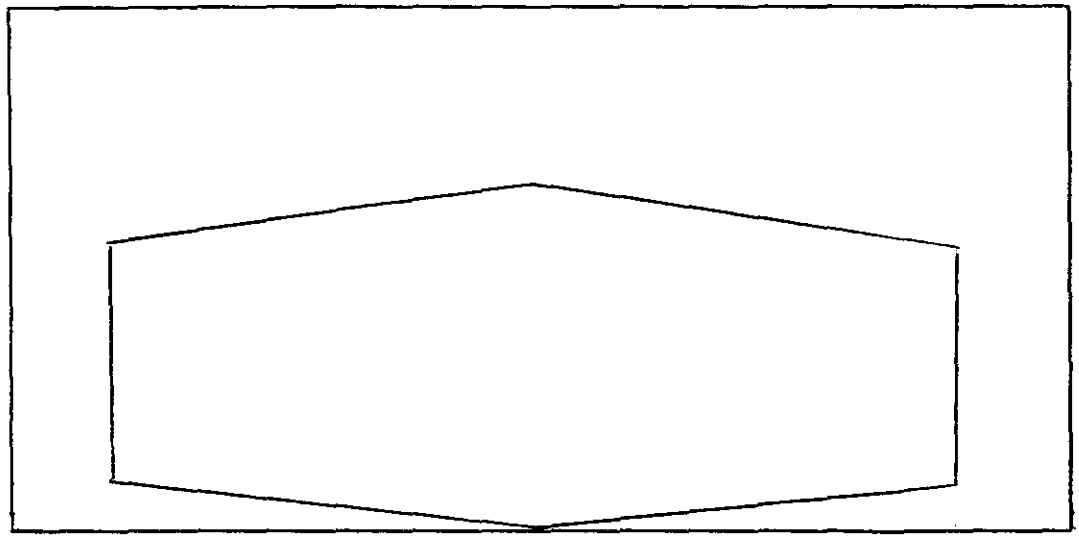
APPENDIX I: GLIDER TEST VEHICLES

ALL GLIDERS USE THE SAME FUSELAGE, RUDDER AND POD DESIGN AS THE TYPE III GLIDER ON THE FOLLOWING PAGE.



TYPE II GLIDER WING AND STABILIZER



TYPE I GLIDER WING AND STABILIZER

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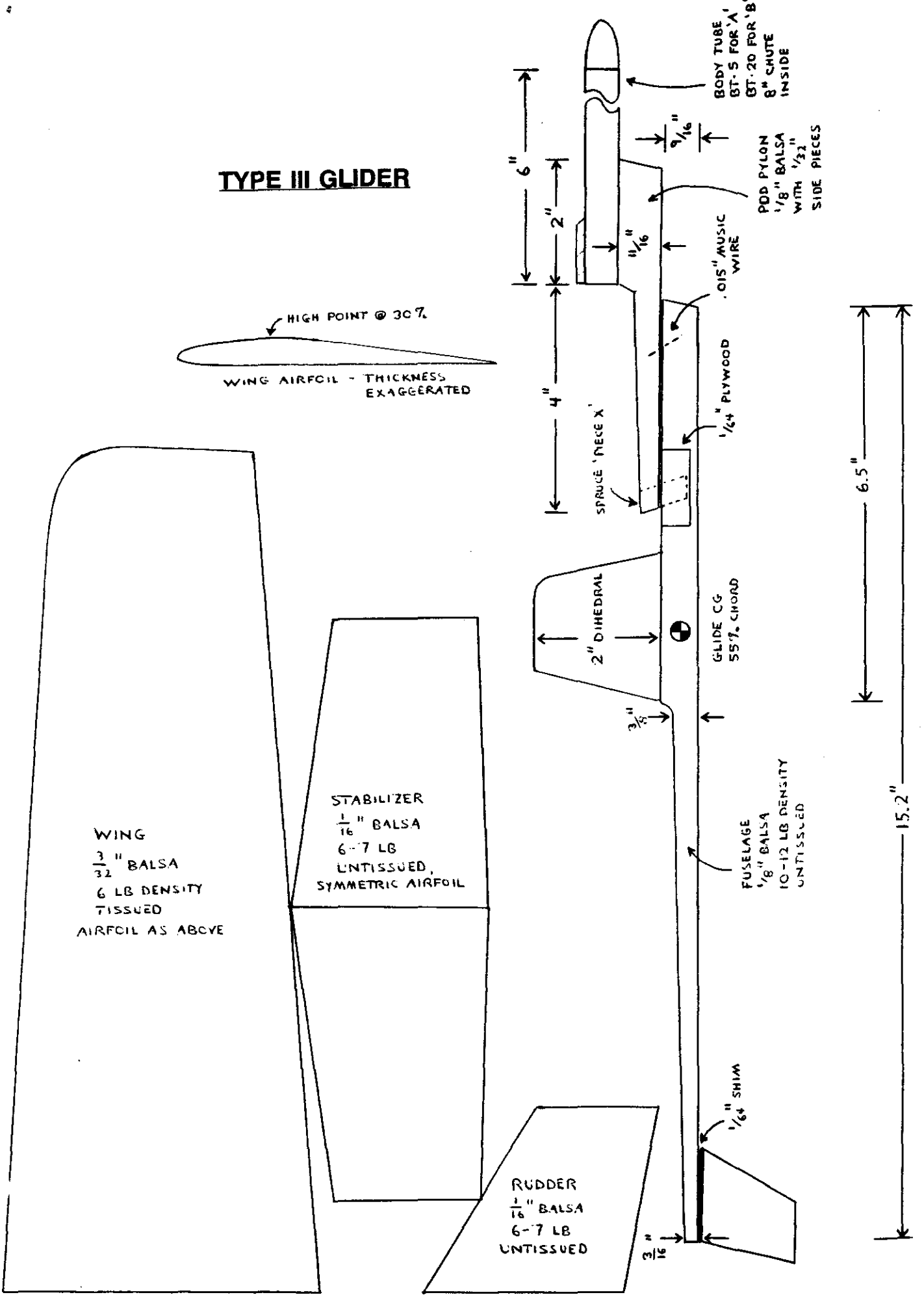
TYPE III GLIDER



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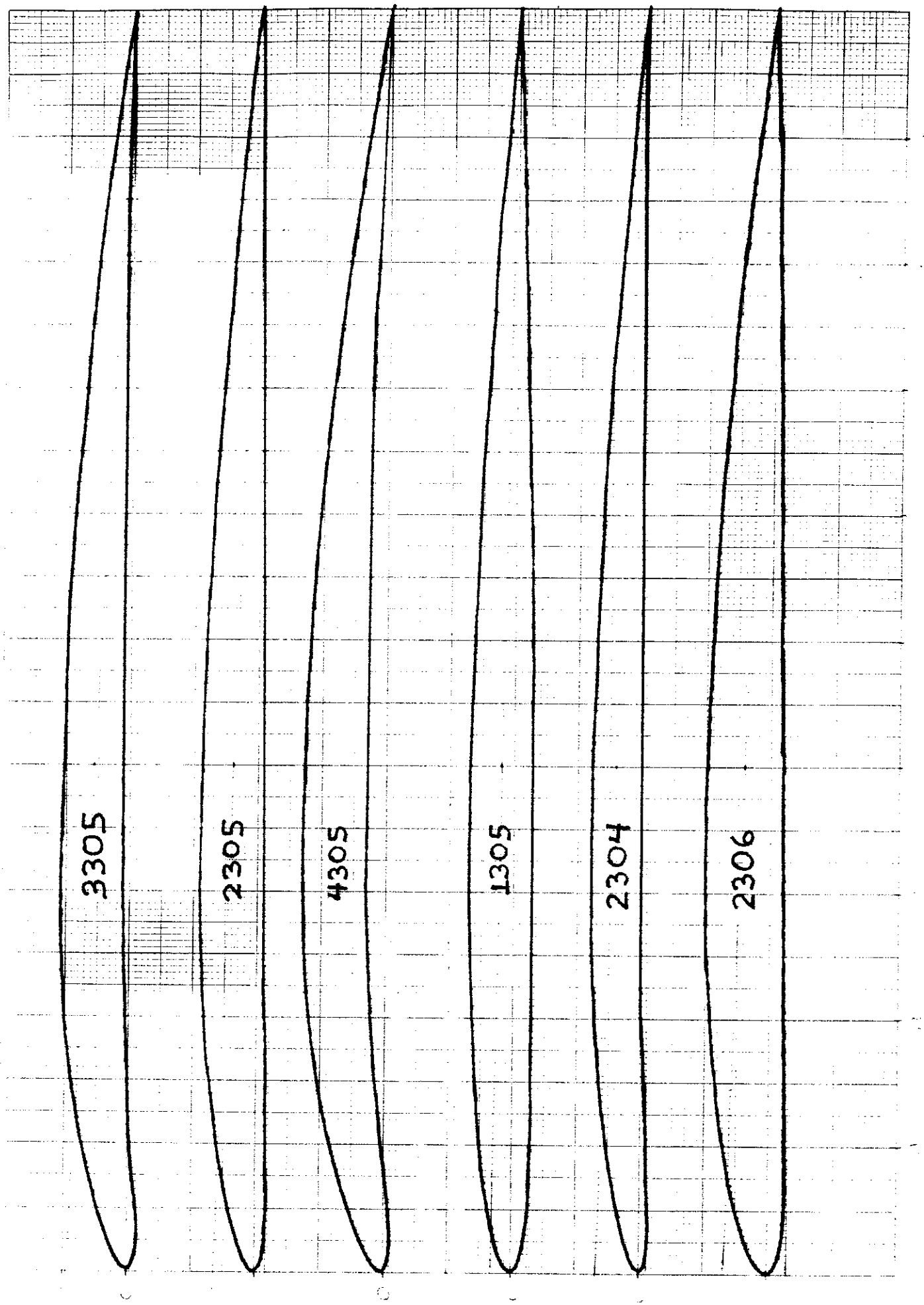
WING AIRFOILS

2.25, 2.75



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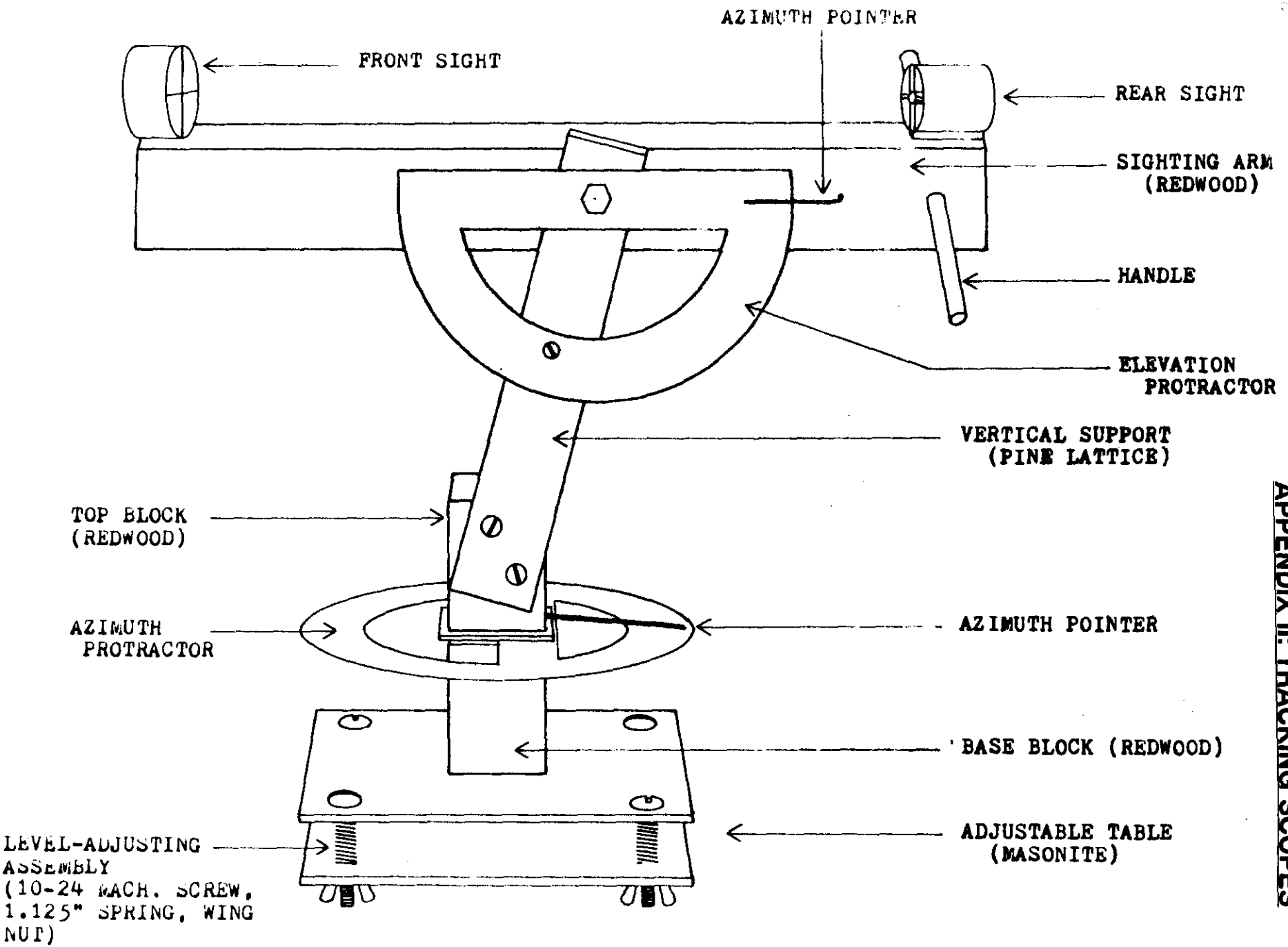

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