Model Rocket Drag Analysis

using a

Computerized Wind Tunnel

National Association of Rocketry
Research & Development Report

by

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Introduction

This NAR Research & Development report describes a series of experiments using a computerized wind tunnel to determine the drag coefficients of typical model rocket designs. The main goal of this report is to derive a practical list of drag coefficients to improve the usefulness of existing altitude prediction software. To verify the accuracy of the data, the predicted altitudes are compared to actual tracked altitudes for a sample of the models tested (TBD).

The drag measurements were made using a commercially available wind tunnel intended for experimentation at the high school and undergraduate college level. The design of this equipment is less sophisticated than a wind tunnel found at a research facility, but is more accurate than the typical home-made device. As shown in this report, the wind tunnel is tested for accuracy and is found to be sufficient for the purposes of this report.

Several model rockets were built for each of six series of tests to isolate the major effects on drag: frontal area, finish, nose shape, body shape, fin cross-section, and launch lug. The resulting table of drag coefficients represents most of the typical configurations, making it very useful in many areas of model rocketry. Some applications are: optimizing parameters for maximum altitude in a competition design; selecting an appropriate motor for the model and field size; and verifying compliance within the limit of an FAA waiver.

The methods used in this report may prove useful in studying other research topics in the future. Some of these ideas are discussed further in the last section.

1.0 Project Description

1.1 Background

Most serious rocket hobbyists are interested in predicting the apogee of their model, either for design optimization, motor selection, FAA waiver compliance, or just plain curiosity. In the past few years, the use of altitude prediction software has become common place due to the reduced prices of high performance personal computers. Many programs are available commercially and in the public domain (through the on-line services and the Internet).

An altitude prediction program requires the user to input physical information about their rocket and motor selection. Most of the values are easily measured (mass, frontal area) and the motor thrust curves are based on NAR S&T data. But the drag coefficient (Cd) is more elusive. Most programs require the user to give their 'best guess' for the Cd, and only the most expensive commercial package will calculate the Cd based on specific parameters and some general assumptions [Rogers, 1994].

For practical purposes, it is difficult or impossible to find measured drag coefficient values for model rockets. In the Handbook of Model Rocketry [Stine, 1984] some values are given for a simple model and there is a beginner's level discussion on the causes of drag. Many 'old rocketeers' have their own guidelines based on years of experience with various rocket designs. However, even these values vary greatly from person to person. Another generally accepted method is to track several flights of the same model and work 'backwards' to determine the Cd by successive guesses in the software simulation. This method works well but is not practical for most people.

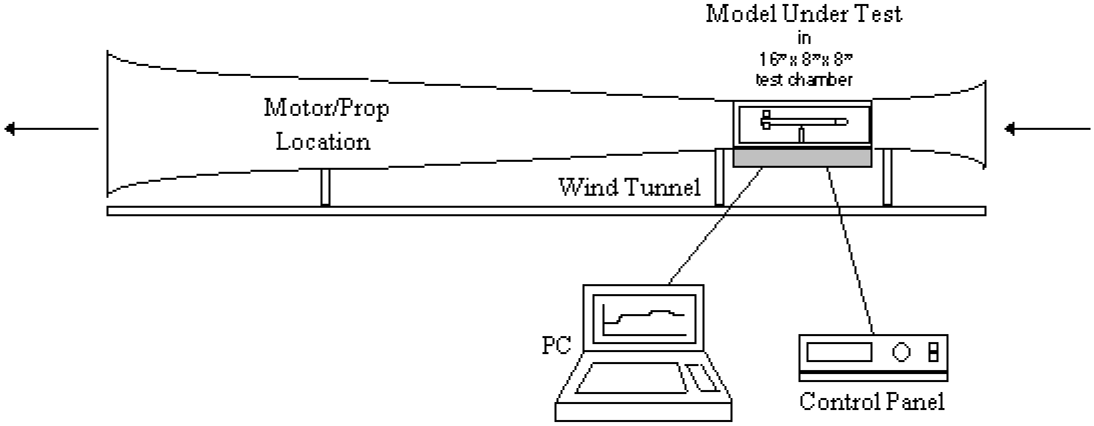
An error in the drag coefficient will cause a considerable error in the predicted altitude, especially for low-drag models (shown by varying Cd in an altitude prediction program). Therefore, it would be a great improvement to have a list of measured Cd's which represent many of the designs, materials, and finishes used in model rocketry.

To measure the coefficient of drag, a model rocket (or plane or car) is placed in a wind tunnel with a controlled air flow. Normally, this would require access to a commercial or university research facility. Another option would be to build a home-made wind tunnel -- useful for showing general concepts but do not have the accuracy in air flow or instrumentation needed for actual measurements.

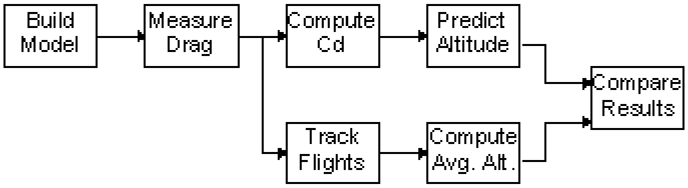
For this report, the author was fortunate enough to borrow a Jetstream 500 'portable' wind tunnel (six feet long) from the manufacturer Interactive Instruments, Inc. (www.interactiveinstruments.com), in Scotia, NY. This device is intended for educational purposes at the high-school and undergraduate level, and is calibrated for drag and lift measurements of wing sections and model cars.

1.2 Test System

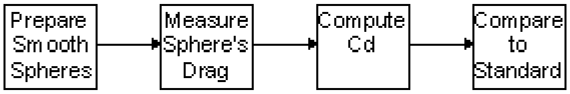
The following diagram shows the system used to measure the drag force for each model tested. The Jetstream wind tunnel is described in more detail in Appendix A. The wind tunnel is computer controlled by both an internal microprocessor and an external personal computer. The wind speed may be controlled from a front panel and the drag may be measured on an LCD display, or a PC may be used to communicate with the system using interactive software. Both methods were used in this experiment with equal results.



Each of the models in the test series were analyzed using the following procedure:



Before the models were measured, the wind tunnel was tested for accuracy and low-turbulence using the following method [Parks, 1995]:



The results of these validation tests proved to be within 10% of the expected results for the Reynolds number of the test (~100,000) using a 3/4" polished steel sphere. For larger spheres, the results were much higher than expected; this would indicate turbulent flow [Pope, 1966]. The tests of the actual models will have a Reynolds number of about 800,000, which should be high enough for laminar flow (above 500,000) [Pope, 1966]. However, a somewhat higher Reynolds number of 1,500,000 is recommended for serious research [Pope, 1966]. For practical purposes in model rocketry, the flow will be turbulent before it passes the nosecone for most designs [Stine, 1986] and, therefore, a less-than-perfect air stream should prove adequate.

These calibration tests were much better when the intake of the wind tunnel was isolated from the exhaust [per Pope, 1966]. The intake was position inside the door of a large closed room, and the output was placed in another room (the measurements were made in the hallway between them!).

1.3 Basis of Calculations

The drag force of an object in a non-turbulent air stream at sub-sonic velocity is computed from the following formula [Puckett, 1959] [Pope, 1966]:

fd = (0.5)ρ_{air} v^2 Cd Ax
where:
fd is the drag force (newtons or kg-m/sec^2).
ρ_{air} is the density of air (kg/m^3).
v is the air velocity (m/sec).
Cd is the drag coefficient (no units).
Ax is the cross-sectional area (m^2).
Solving for Cd and substituting standard air density gives:
Cd = [2 fd] / [(1.29) v^2 Ax]
where:
ρ_{air}= 1.29 kg/m^3 at 25C at sea level.
For practical values in our measurements, converting units gives:
Cd = [2 (9.8) (10^-3) Fd] / [(1/3.6)^2 V^2 (10^-4)Ax]
where:
1kg = 9.8N, and 1kg = 1000gms.
1m/sec = 3.6km/hr, and 1m2 = 104 sq.cm.
Simplifying, gives:
Cd = [(1969) Fd] / [V^2 Ax]
where: Fd is the drag force in grams,
V is the air velocity in km/hr,
Ax is the cross-sectional area in sq.cm. (ie: frontal area of body and fins).

The drag measurements (Fd) were taken three times and averaged. This was recommended by the wind tunnel designer due the way the load cell operates. The average values for the drag force were entered into the data tables in Section 2, and used to compute the Cd using the formula shown above.

1.4 Limitations & Assumptions

1.4.1 Wind Tunnel Velocity Limit

The main limitation of the experiment is due to the maximum velocity of the wind tunnel (~120 km/hr). The average velocity of most model rockets (mid- and high- impulse, too) is in the range of 200 to 600 km/hr. As long as the velocity stays well below the speed sound (~1190 km/hr) the drag coefficient remains relatively constant above a minimum airspeed. For bodies the size of model rockets, the minimum airspeed for laminar flow is about 80 km/hr. Therefore, these experiments were run near the maximum velocity of the wind tunnel, which is about 50% above the airspeed needed for laminar flow.

1.4.2 Instrumentation Resolution

The instrumentation in the wind tunnel reads the drag force with a resolution of about 0.5 gm (the analog to digital converter has 10-bits of resolution[1] with 500gm full scale). For small diameter models and very low drag models (where drag forces are <10gm) these limitations will cause a significant error (>5%). To minimize this problem, a moderate body diameter was chosen for the tests. However, too large of a diameter would cause airflow interference with the chamber walls, and the model would be too long to fit in the 16" long test area. A BT-20 (~0.75" dia.) tube, 8.5" long, was used as the standard body to meet these criteria.

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[1] The newer Jet Stream 500 has a higher resolution 12 bit A/D converter with 400% more resolution than the original 10 bit measurement system

1.4.3 Verification Error

The prediction software and verification flights assume a straight boost with little or no wind. Other factors, such as variations in actual motor performance, will add to the error between predicted and actual altitudes. The tracked flights will be acceptable if below 10% closure error using the Geodesic method. Considering all of the practical variations in the model, motor, launch angle, atmospheric conditions, etc., the derived Cd's will be considered verified if the percent error between predicted and actual altitude is less than 10%.

1.4.4 Subsonic Limit

This report is not concerned with trans-sonic or super-sonic effects on drag. The derived table of drag coefficients should not be used for velocities above 80% the speed of sound (950 km/hr or 260 m/sec).

1.4.5 Secondary Factors

The analysis of other dynamic factors are beyond the scope of this report. For instance, the effects of dynamic stability can change the Cd of a rocket as its angle of attack oscillates due to corrective forces. Also, the base drag of the rocket is known to change when the motor is operating. These two topics would be interesting research areas for future R&D reports.

2.0 Measurement Series

The following six series of measurements were designed to isolate the various effects on a model rocket's drag. Each section shows the design of the model and the results of the tests.
Each model was tested at three airspeeds: 80, 100, and 120 km/hr. The measurements are repeated with the model removed in order to subtract the drag of the mounting apparatus. The resulting Cd's at the upper two airspeeds should be lower to indicate laminar flow. If not, the flow is significantly turbulent; this is not necessarily an error, but reveals the nature of the air flow.
All models are designated by a model number; some models were retested as part of another series if they have the desired characteristics. See Appendix B for drawings of each model.

2.1 Calibration Sphere

The goal of this series is to verify that the airflow is predictable for purpose of this experiment. Also, the derived Cd for the sphere is easily compared to the standard value of ~0.5 at low Reynolds numbers and ~0.15 at Reynolds numbers above where laminar flow begins [Pope, 1966].

Test Item	Fd(80)	Fd(100)	Fd(120)	Cd(80)	Cd(100)	Cd(120)
1.5" Smooth Sphere	20.6	34.7	48	0.56	0.60	0.58

Reynolds number is not high enough for laminar flow. However, this is close to standard for sphere, which validates the instrumentation.

2.2 Scalability

The goal of this series is to show that the Cd is not dependent on the size of the model. Other factors were kept constant across the three sizes (such as shape and finish).

Model# - description	Fd(80)	Fd(100)	Fd(120)	Cd(80)	Cd(100)	Cd(120)
1 - BT-5, 7.3" long	1	3.3	4	0.19	0.41	0.35
2 - BT-20, 10" long	3.3	7.7	10	0.50	0.75	0.68
3 - BT-50, 13.3" long	13.3	19.3	21.3	0.84	0.78	0.73

The BT-5 model is too small to read accurate forces. The BT-20 and BT-50 are within 10%.

2.3 Surface Effects

The goal of this series is to show the effect on Cd due to the quality of the model's finish. The first model has unfinished kraft tubing and balsa fins; the second model has one coat of primer and one coat of Krylon paint; and the third model has a filled, polished, and waxed lacquer finish.

Model# - description	Fd(80)	Fd(100)	Fd(120)	Cd(80)	Cd(100)	Cd(120)
4 - unfinished	6	9.7	11.3	0.92	0.95	0.77
2 - krylon	3.3	7.7	10	0.50	0.75	0..68
5 - polished lacquer	3.7	7.3	9	0.57	0.71	0.61

The surface finish shows a measureable effect.

2.4 Fin Effects

The goal of this series is two show the effect of fin shaping on a model's Cd. The first model has square edged fins, the second has rounded edges, and the third has tapered "airfoil" fins.

Model# - description	Fd(80)	Fd(100)	Fd(120)	Cd(80)	Cd(100)	Cd(120)
6 - square edged fins						

2 - rounded edged fins						
7 - airfoiled fins						

The differences in forces were not measurable. A different test method would need to be developed to test the fin shape effects.

2.5 Launch Lug Effects

The goal of this series is to test the effect of launch lugs on a model's Cd. The first model has no lug (for tower launching), the second has a 1/8th inch inside diameter lug (2 inches long), and the third has two wire loop lugs (one forward and one rear).

Model# - description	Fd(80)	Fd(100)	Fd(120)	Cd(80)	Cd(100)	Cd(120)
2 - no launch lug	3.3	7.7	10	0.50	0.75	0..68
8 - 1/8" x 2" lug	6.3	9.7	13	0.96	0.95	0.88
9 - two wire loops	5.3	9.3	11.7	0.81	0.91	0.80

The addition of a launch lug added 29% to the Cd and the wire loops added 18%.

2.6 Nose Shape Series

The goal of this series is to compare the Cd's of the same model with various nose cone shapes.

Model# - description	Fd(80)	Fd(100)	Fd(120)	Cd(80)	Cd(100)	Cd(120)
2A - w/ elliptical 2:1 cone	3.3	7.7	10	0.50	0.75	0..68
2B - w/ straight 3:1 cone	5	10	11.7	0.77	0.98	0.80
2C - w/ parabolic 3:1 cone	4.3	8.3	11	0.66	0.81	0.75
2D - w/ half sphere cone	3.7	8	10	0.57	0.78	0.68
2E - w/ flat nose	9.7	16.3	21.3	1.48	1.60	1.49

The flat nose was predictably the most draggy. The sphere and elliptical had similar effects, and the straight conical nose was 18% higher. The parabolic (Apogee PNC) was higher than expected.

2.7 Body Shape Series

The goal of this series is to show the effect of the shape of the model on the Cd. Five typical rocket designs are measured and compared.

Model# - description	Fd(80)	Fd(100)	Fd(120)	Cd(80)	Cd(100)	Cd(120)
2 - straight body	3.3	7.7	10	0.50	0.75	0..68
10 - 2:1 5% boattail	2.3	5.7	7.7	0.35	0.58	0.52
11 - 20:1 40% (payloader)	4	6.3	8.3	0.61	0.62	0.56
12 - 20:1 90 % (egglofter)	10	14	18.3	0.43	0.38	0.35
12x - 6:1 30 % (egglofter)	10	16.3	22.3	0.43	0.45	0.63
13 - 1:1.5 +transition	6.3	9.7	11.3	0.96	0.95	0.77

The boattail reduces the Cd over 20%. A full tapered egglofter gives the lowest drag. As expected, a positive transition increases the Cd.

3.0 Flight Prediction and Tracking

3.1 Verification Method

To complete the experiment, the derived Cd's were used to compute the expected altitude using an altitude prediction program and compared to actual tracked altitudes of the same models. The resulting errors are used to determine the validity of the test system and the test methods.

3.2 Altitude Prediction Software

Three software programs were used to predict the maximum altitude of each test model based on the Cd's derived from the wind tunnel measurements. The three programs are: (1) Rogers Aerosciences ALT4 ($65), (2) Stephen Roberson's Alticalc ($20), and (3) the author's software (not yet available).

Each of these programs use numerical integration methods to calculate acceleration during discrete time steps and graph the altitude, velocity, and acceleration for the whole flight period.

The predicted altitude was chosen at the point where ejection would occur.

3.3 Motor Selection

The flight tests were done using Estes 1/2A3-2T's and 1/2A3-4T's, depending on the estimated delay required for maximum apogee. When possible, multiple flights were tracked using motors from the same pack and the altitudes were averaged. All flights were tracked to ejection. [TBD]

A future improvement to the verification method would be to save one motor from each pack and test it on a thrust stand. Then, take the resulting thrust-time curve and use it in the simulation for predicted altitude.

3.4 Results

The Cd's for the 120 km/hr condition (highest velocity) were used for the predicted altitudes. The altitudes were predicted with three different programs: I) Rogers, II) Alticalc, and III) author's.
A few representative flights will be tracked at NARAM-37. *(DID NOT HAPPEN!)*

NOTES:

Mass is in grams, area is in square centimeters, and altitude is in meters.
2gms were added to the mass to allow for tracking powder and streamer.

Model	Cd	Mass	Area	Est. I	Est. II	Est.III	Est Avg	Flight 1	Flight 2	Flight 3	Flt Avg	%error
1	xxx		1.58	----	----	----						
2A	0.68	9	2.0		154	131						
2B	0.80	9.3	2.0		141	121						
2C	0.75	9.9	2.0		142	122						
2D	0.68	8.4	2.0		158	134						
2E	1.49	7.9	2.0		108	90						
3	0.73	21.8	4.87		93	51						
4	0.77	8.3	2.0		150	127						
5	0.61	8.3	2.0		166	141						
6	xxx	9	2.0	----	----	----						
7	xxx	9	2.0	----	----	----						
8	0.88	9.3	2.0		135	115						
9	0.80	9.3	2.0		141	121						
10	0.52	11.5	2.0		149	130						
11	0.56	9	2.0		166	142						
12	0.35	18	7.2		246	275						
12x	0.63	24	7.2		178	210						
13	0.77	8.9	2.0		146	124						

4.0 Conclusions

Using a small wind tunnel to measure model rocket drag has produced significant information to help improve altitude prediction. Most of the predicted altitudes (based on the derived Cd's) were within ___% of the tracked flights. (TBD)

The experimental methods could be improved by increasing the airspeed and reducing the turbulence of the wind tunnel. However, for most model rocket designs, the current system appears to be adequate.

Future experiments with this system would be interesting and may produce other useful results. Some areas of study would be:

- Investigating dynamic stability of a model rocket using a wind tunnel. Gordon Mandell published both theoretical and experimental work on this topic in the early 1970's using much less sophisticated technology. New computer techniques and automated instrumentation would allow a wider range of tests.

- Investigated the base drag of a model rocket using a wind tunnel. A rocket is known to have drag effects from the jet exhaust while the motor is burning propellant. However, little is known about this factor and it is usually ignored in simulations. A high-pressure air jet could be routed through the mounting strut and to the back of the model to simulate the mass flow of a rocket motor [Parks, 1995].

Appendix A: Jetstream Wind Tunnel

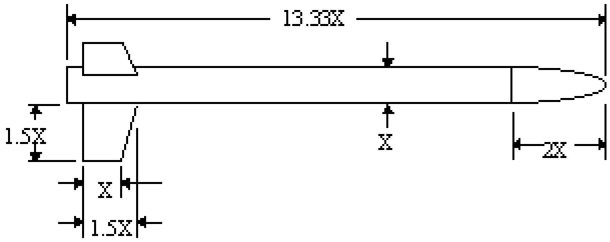
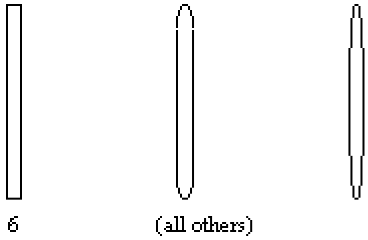
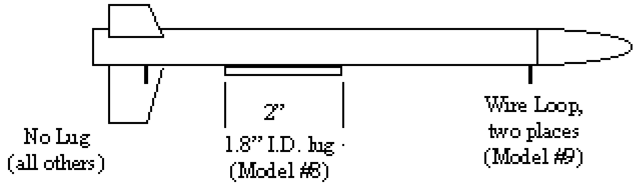
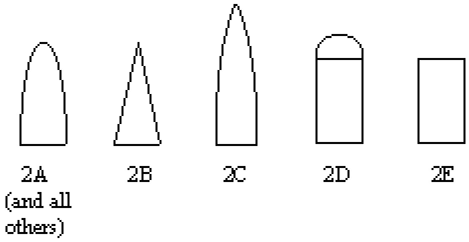
Jet Stream 500 Specification

Tunnel:	Rugged ABS Plastic construction for superior flow
	Total tunnel length of 6' 2"
	Dimensions derived from professional tunnel designs
	Computer generated design
	Maximum wind velocity of 80 MPH
	Safety guards before and after the propeller
Test Area:	Measures 5.25" - h, 5.25" - w, 16.0" - d
	Precision flow straightener before and after the test area for linear wind flow
	Clear unobstructed 3 sided viewing area with reflective bottom
	Measures both lift (+/-) and drag up to 1.8 lb. (0.001 lbs. resolution)
	Airfoil angle adjustment +/- 30° (5° resolution), without removing model
	Optional Test bed supports CO_2 project cars
Motor:	Industrial 1 HP, 110 volt ball bearing AC motor for long life
	10.5" - 3 blade high speed nylon propeller
	Microprocessor controlled for constant wind speed
Instrumentation:	Lift and drag forces measured via precision strain gages
	Wind speed measured and controlled via pitot tube (0.1 MPH resolution)
	Data is collected by a microprocessor with a 12 bit A/D converter
	Displays values in Metric or English units
Controls:	Control panel plugs into the tunnel for remote manual control
	Simple 16 key keypad controls wind speed and selects options
	Programmable Maximum wind speed limits
	Manually enter wind speed or ramp speed up or down
	Display constantly displays lift, drag, and wind speed in real time
	Lift/Drag (L/D) is also calculated and displayed in real time
	Security key limits the tunnel to supervised access
Electronics:	12 MHz, 80C32 Microcontroller with 64k of ROM
	11 channel, 12 bit A/D converter
	RS 232 interface @ 4800 baud
	4 line by 20 character LCD panel
	0 - 1 PSI differential pressure transducer to measure and control the wind speed
	0 - 1.8 lb. strain gages to measure the model's lift and drag
	Computer controlled Solid state motor speed controller
Optional Software:	Easy to use Windows graphical interface with built-in help
	Graphically displays lift, drag, L/D, and C(x) with respect to wind speed
	Overlay graphical test results for quick comparison
	Displays graphical results in Metric or English units
	Data can be imported to most spreadsheets for further analysis
	High resolution graphs can be printed on color printers

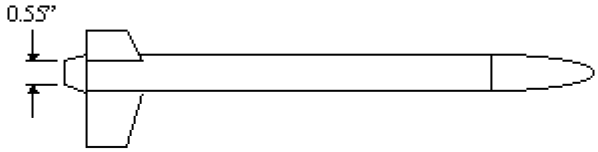
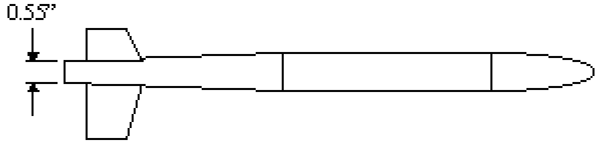
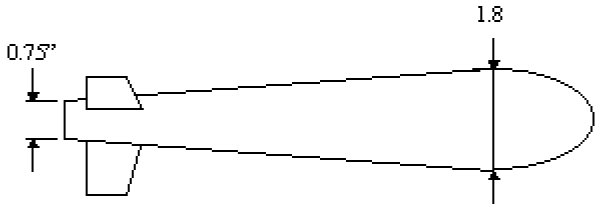
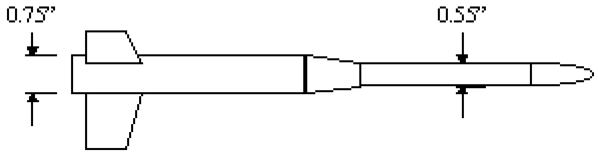
Appendix B: Test Model Drawings and Measured Drag Coefficients

NOTES:

1) All models are finished with average smoothness, primed and sprayed with Krylon, unless noted.
2) All models have no launch lug unless noted.
3) All dimensions are in inches. Dimension X is 0.75 unless noted.

	Model#	C_d
Standard Model Design 	1 (X=0.55)	n/a
	2	0.68
	3 (X=1.0)	0.73
	4 (unfinished)	0.77
	5 (polished)	0.61
Fin Cross-section (exagerated) 	6	n/a
	7	n/a
Launch Lug Locations 	8	0.88
	9	0.80
Nose Cone Shapes 	2A	0.68
	2B	0.80
	2C	0.75
	2D	0.68
	2E	1.49

Test Model Drawings (con't)

	Model #	C_d
	10	0.52
	11	0.56
	12	0.35
	13	0.77

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Standard text describing theory, design, construction, calibration, and measurement for professional sub-sonic wind tunnels.

Parks, Robert, June/July 1995, personal correspondences..

Described how to test the wind tunnel for accuracy for the purposes of this experiment. Suggested using smooth spheres of various sizes over a range of air speeds to test for laminar flow or turbulence in the test area.

Puckett, Allen E., 1959, *Guided Missile Engineering*, McGraw-Hill, New York, NY..

Section 2: Aerodynamics of Guided Missiles. Used for drag computation at subsonic air speeds and its limitations.

Stine, G. Harry, 1983, *Handbook of Model Rocketry*, Prentice Hall, New York, NY..

Reference for typical range of drag coefficient values for a model rocket.

Tilley, Donald E., 1976, *University Physics*, Cummings Publishing, Menlo Park, CA..

Used as general reference for units conversions and constants.
