

Nose cone drag study for the SStS Rocket Rev. 2005/10/07

## Background

The SStS rocket has a design goal of reaching at least 100km altitude, using a low performance sugar-nitrate propellant in a single stage rocket. In order to achieve this goal, it will be important to keep the drag loss at a minimum. Two strategies are being applied in this respect:

1. Dual phase rocket motor
2. Minimum drag airframe

The dual phase motor splits the burn into two parts, divided by a coasting phase. This allows the rocket to save half of its propellant until it has passed through the denser part of the atmosphere.

The minimum drag airframe will improve the rockets altitude performance by keeping the energy loss in form of aerodynamic drag at a minimum. The overall shape of the rocket consists of a nose cone and a cylindrical rocket body and one set of fins. The dimensions of the cylindrical body are determined primarily by motor design restrictions and are as such outside the scope of this report. The dimensions of the fins are to be determined according to stability requirements, and are also outside the scope of this report. The purpose of this report is to investigate the impact of shape and fineness ratio of the nose cone on the performance of the rocket, when it follows a trajectory profile that is reasonably realistic (i.e. as realistic as possible at the current stage of design).

Conditions
This investigation is based on Richard Nakka's DPH47 configuration as detailed below:


| Dual phase configuration |  |
| :---: | :---: |
| Run ID number | dph47 |
| Configuration | dual-phs. |
| SIM code | SOAR |
| Metric or Imperial | M |
| Cd function code | cdo $=0.4$ |
| Phase Delay (sec.) | 16.5 |
| Vehicle OD | 25.5 |
| Motor total impulse | 257850 |
| Motor burn time (each ph.) | 8.7 |
| Motor average thrust | 29638 |
| 1st charge grain mass | 202 |
| 2nd charge grain mass | 202 |
| Vehicle dead mass | 88.0 |
| Vehicle liftoff mass | 492 |
| Propellant mass fraction | 0.822 |
| Meet 14 CFR Ch. 3 crit? | No |
| Max. altitude | 107694 |
| Max. velocity | 1542 |
| Max. mach no. | 5.2 |
| Max. acceleration | 240 |
| Min. Acceleration | -63 |
| Burnout altitude, 1st phase | 1946 |
| Burnout altitude, 2nd phase | 16843 |




| Burnout altitude, 2nd phase | 16843 m |
| :---: | ---: |

## Tools

This investigation is based on the "Aerolab" drag and stability software and the "Launch" trajectory simulation software, both by the author.
"Aerolab" is used to calculate the coefficient of drag in the entire Mach range of relevance for the SStS for the configuration candidates of the airframe. The calculated drag coefficients are fed into the trajectory
calculator, and the output is collected into a spread sheet for comparison. The trajectory simulator is being tricked to handle the dual phase configuration by adding a zero empty weight first stage and a dummy stage separation.

Although the overall purpose of this study is to set up a realistic scenario, some things are not known at this early stage. This affects the drag model in two ways:

1. Base drag reduction during powered flight is ignored as there is (yet) little knowledge of the nozzle dimensions.
2. The dimensions and number of fins are not yet known.

Furthermore, fin canting has been suggested but not (yet) specified, so the drag contribution from the fins has to be guesstimated. All the candidate configurations are being analysed with the same set of dummy fins that are assumed to provide a reasonable first order approximation of the fins impact on the trajectory profile.

The base configuration, featuring a 3:1 conical nose cone is shown below.


All Dimensions are: mm

Number of Fins: 4
Fin Aspect Ratio: 0.000
Fin Taper Ratio: 0.500
Fin Taper Ratio: 0.500
Fin Thickness Ratio: $3.75 \%$
Fin Thickness Ratio: $3.75 \%$
Fin Leading Edge Sweep: 0.00 deg
Fin Trailing Edge Sweep: 0.00 deg Fin midchord Sweep: 26.57 deg Profile: Hexagonal

Candidate configurations are being generated using all the nose shapes currently implemented in Aerolab:

- Conical
- Tangent Ogive
- Parabolic
- Elliptical
- 1⁄2 Power
- $3 / 4$ Power (also known as "hypersonic optimum")

Configurations are being generated with nose fineness ratios of 2:1, 3:1..., 7:1 for all shapes. A trajectory simulation of the DPH47 configuration is being run for all combinations of shape and fineness ratio. The trajectory simulator calculates - among other things - the altitude and drag loss (in Newton seconds) versus time.

Trajectory profile
The main highlights of the trajectory when using the standard drag model from Launch is:

- 1'st phase burnout
- 2'nd phase ignition
- 2'nd phase burnout
- Apogee

| 8.70 s | 2232 m | $558 \mathrm{~m} / \mathrm{s}$ |
| :--- | :--- | :--- |
| 16.50 s | 5882 m | $401 \mathrm{~m} / \mathrm{s}$ |
| 25.20 s | 13664 m | $1638 \mathrm{~m} / \mathrm{s}$ |
| 164.75 s | 107689 m | $257 \mathrm{~m} / \mathrm{s}$ |

The drag varies mostly with the Mach number, so one wants to check out the variation in Mach number:


One notable feature of this chart is that the Mach number stays constant between approximately 60 and 70 km . This is not because the rocket travels at constant speed, but rather that the Mach velocity decreases with altitude

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Page 5
at the same rate as the rocket speed decreases. This is however a curiosity, as the air drag is neglible at that altitude.

Different nose shapes are known to be optimal at different Mach ranges, so in order to select the best nose shape, it would be advisable to look at the velocity distribution:


Again, the Mach 3 peak is clearly visible. Even ignoring this, the rocket will spend approximately $50 \%$ of the travelling time at Mach $1.5+$, where the hypersonic optimum shape has minimum wave drag for any given fineness ratio. For comparison the same rocket spends approximately $35 \%$ of the travelling time at transsonic speeds, where the hypersonic optimum shape is not the optimal choice.

## Simulation results

The simulation results are listed below. The main conclusions are

- For any given finenes ratio, the hypersonic optimum shape has the least drag loss. The difference in drag loss between conical and hypersonic optimum shapes decreases however for increasing fineness ratio, and at 7:1 it has nearly vanished.
- For any given shape, altitude increases with increasing fineness ratio. However, the benefits of increasing fineness ratio beyond 5:1 are small.
- For fineness ratios up to 6:1, the hypersonic optimum shape yields the highest apogee - but for increasing fineness ratios, the conical shape gets increasingly closer in performance, and at 7:1 fineness ratio, the conical shape yields the highest apogee, although only by a very small margin.
Configuration apogee

- Cone
- Cone
\ Tangent Ogive
\ Tangent Ogive
\ Ellipsoid
\ Ellipsoid
- Parabolic
- Parabolic
4 Power 0.5
4 Power 0.5
4 Power 0.75
4 Power 0.75
\square standard model
\square standard model
Configuration drag loss


The wave drag contribution decrease at higher fineness ratios, so skin friction becomes more important, and it becomes less important what shape has the least high Mach number wave drag.

Not surpricingly, the elliptical shape has poorer performance than the other shapes, but except from that, and perhaps the parabolic shape, the difference in apogee between the other shapes is so small for the higher fineness ratios, that other criteria may be taken into account when selecting the shape. A 5:1 fineness ratio may be chosen over 7:1 for practical reasons. The hypersonic optimum shape may be chosen for performance, but the the penalty for choosing a conical shape is neglible, and it would have the advantage of simplicity. Also there are the thermal considerations. In general, the aerodynamic heating increases with the equivalent nose vertex angle, so a conical nose would be expected to have higher temperature at the base than the hypersonic optimum but lower temperture at the tip. However, the temperature rise also depends on the local heat capacity, and the tip of a hypersonic optimum nose can have a larger heat capacity so it may still have the lowest skin temperature overall. A blunted cone could be a reasonable way of approximating the hypersonic optimum shape while keeping the simplicity of a cone.

Appendix: Shapes and values.

| 3/4 Power |  |
| :---: | :---: |
| Cone |  |
| 1/2 Power |  |
| Tangent ogive |  |
| Parabolic |  |
| Ellipsoid |  |

The estimated wave drag coefficient of the different nose shapes can bee seen below for comparison. Fineness ratio is 5:1.

Nose cone drag coefficient


| Shape | fineness ratio | Apogee (m) | Drag loss (NS) |
| :---: | :---: | :---: | :---: |
| Std model |  | 107689.48 | 89845.35 |
| Cone | 2 | 88431.57 | 116252.31 |
| Cone | 3 | 114586.13 | 90229.24 |
| Cone | 4 | 118866.81 | 86218.07 |
| Cone | 5 | 123265.52 | 82182.73 |
| Cone | 6 | 126596.16 | 79189.36 |
| Cone | 7 | 126795.51 | 79042.53 |
| Tangent Ogive | 2 | 97449.44 | 106055.99 |
| Tangent Ogive | 3 | 113617.85 | 90530.79 |
| Tangent Ogive | 4 | 120670.25 | 84114.32 |
| Tangent Ogive | 5 | 123994.64 | 81211.40 |
| Tangent Ogive | 6 | 125702.14 | 79773.05 |
| Tangent Ogive | 7 | 126360.27 | 79273.71 |
| Ellipsoid | 2 | 77462.16 | 124407.31 |
| Ellipsoid | 3 | 102372.61 | 99337.69 |
| Ellipsoid | 4 | 113155.23 | 89821.00 |
| Ellipsoid | 5 | 117091.51 | 86579.03 |
| Ellipsoid | 6 | 118435.59 | 85578.61 |
| Ellipsoid | 7 | 118945.96 | 85285.61 |
| Parabolic | 2 | 91310.21 | 111542.51 |
| Parabolic | 3 | 111337.57 | 92085.08 |
| Parabolic | 4 | 119310.95 | 85013.97 |
| Parabolic | 5 | 122084.03 | 82682.97 |
| Parabolic | 6 | 122961.20 | 82015.86 |
| Parabolic | 7 | 123235.92 | 81871.03 |
| Power 0.5 | 2 | 100525.18 | 102533.45 |
| Power 0.5 | 3 | 116713.05 | 87438.03 |
| Power 0.5 | 4 | 122754.53 | 82156.34 |
| Power 0.5 | 5 | 124719.69 | 80524.67 |
| Power 0.5 | 6 | 125234.74 | 80161.53 |
| Power 0.5 | 7 | 125292.89 | 80195.21 |
| Power 0.75 | 2 | 104437.02 | 99696.99 |
| Power 0.75 | 3 | 118941.77 | 85836.55 |
| Power 0.75 | 4 | 124347.02 | 80964.59 |
| Power 0.75 | 5 | 126121.40 | 79428.98 |
| Power 0.75 | 6 | 126607.69 | 79051.66 |
| Power 0.75 | 7 | 126688.21 | 79036.80 |

