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Numerical Optimization of Low-Perigee Spacecraft

program review

March 23, 2001

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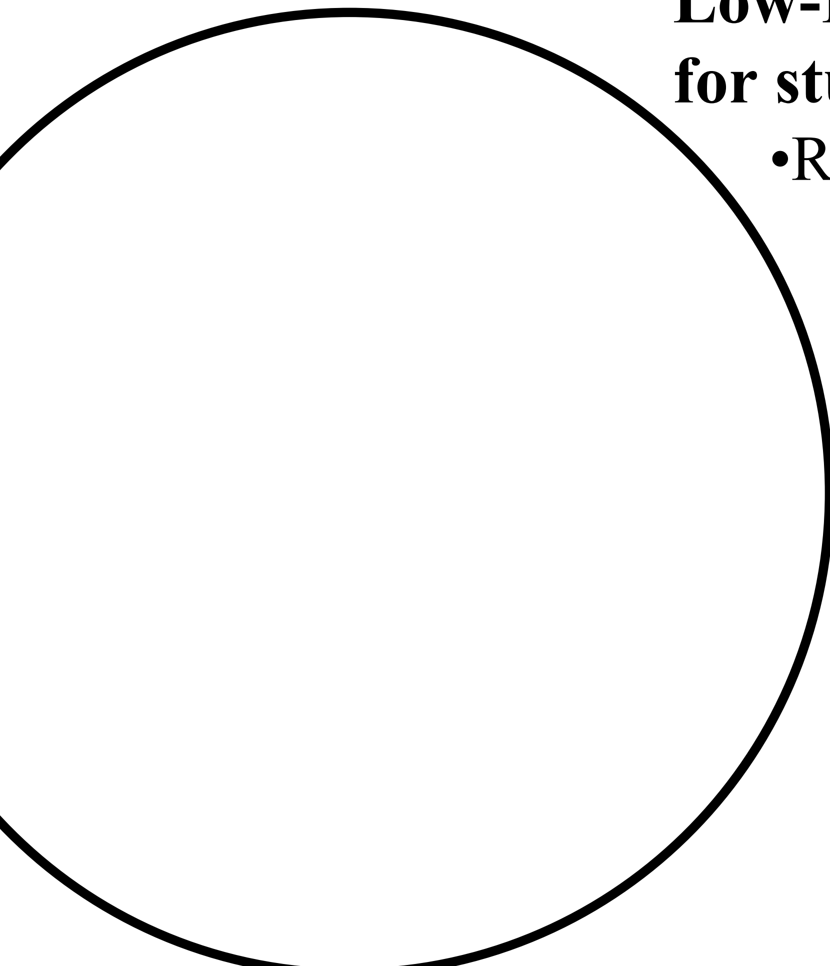
Low-Perigee Orbits



Low-Perigee orbits provide advantages for studying the upper atmosphere

- Regular, repeatable atmosphere passes
- Increased maneuverability due to force generation

These orbits also have disadvantages

- Drag changes speed thereby changing the orbit
- Aerodynamic moments may destabilize spacecraft

Geospace Electrodynamics Connections (GEC) Mission

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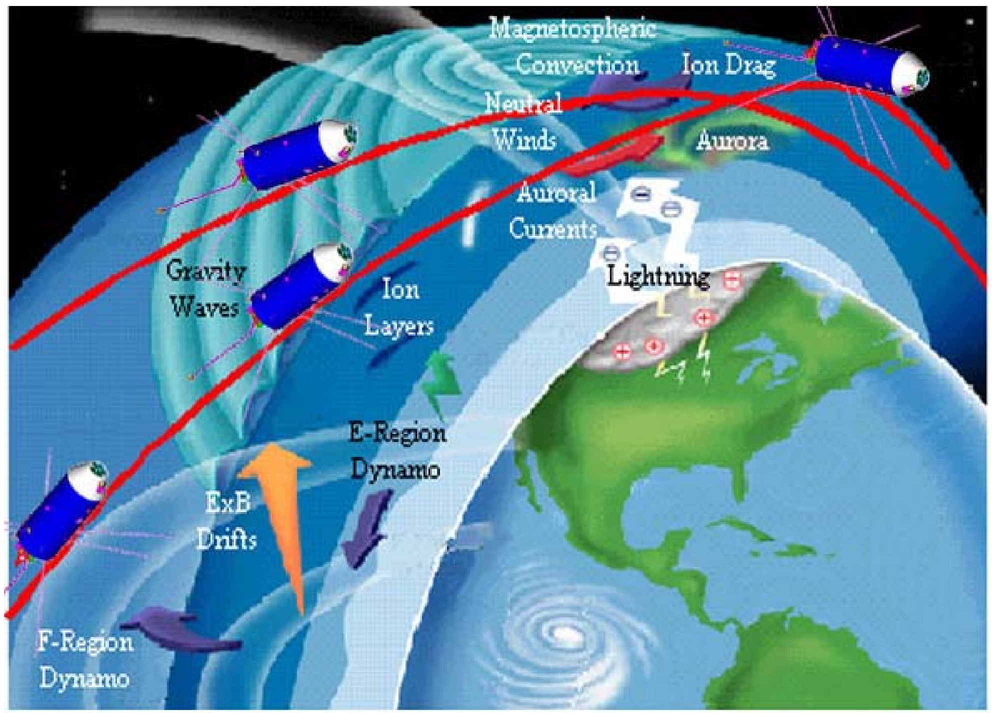

- 4 “dipping” spacecraft reach perigee around 130 km
- Minimal disturbance of electromagnetic field
- Many Earth passes

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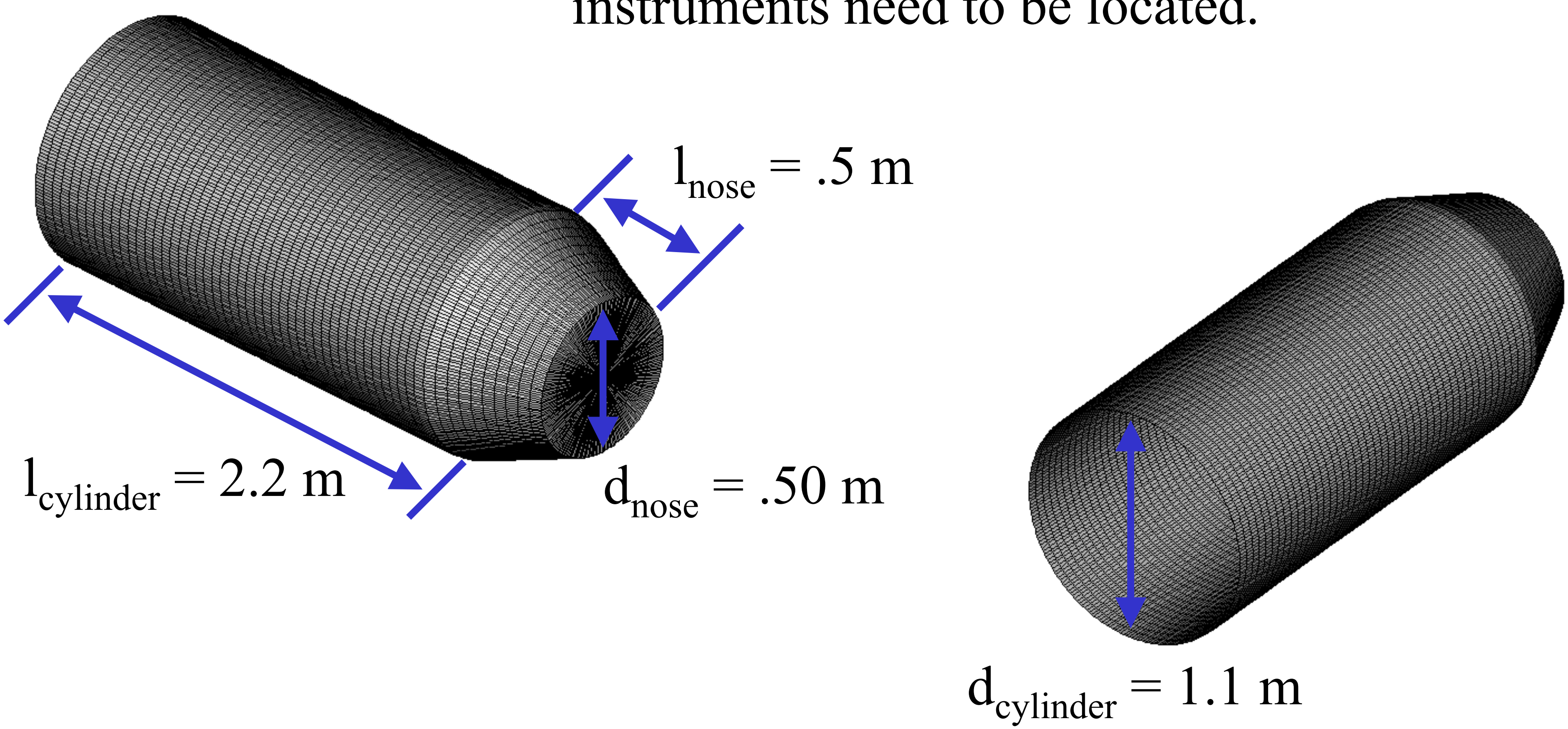
GEC Geometry

The current geometry is based upon a functional approach -- what instruments need to be on the probe and where those instruments need to be located.



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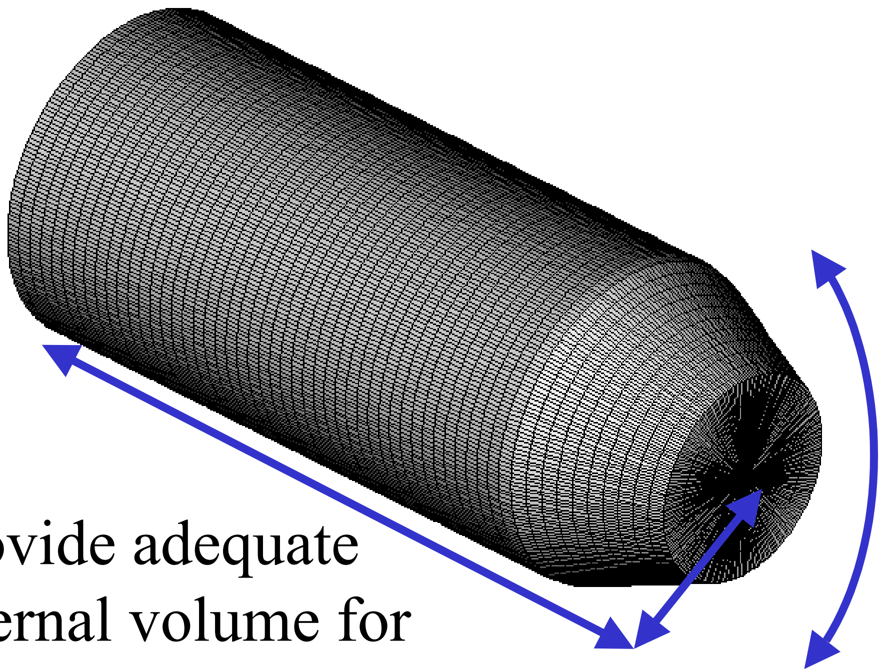
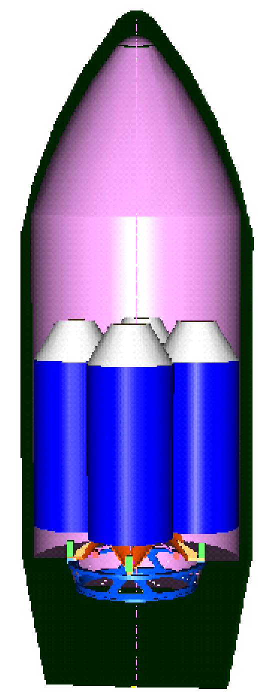
GEC Design Objectives



Provide aerodynamic stability

Provide adequate internal volume for major components **(fuel tank)**

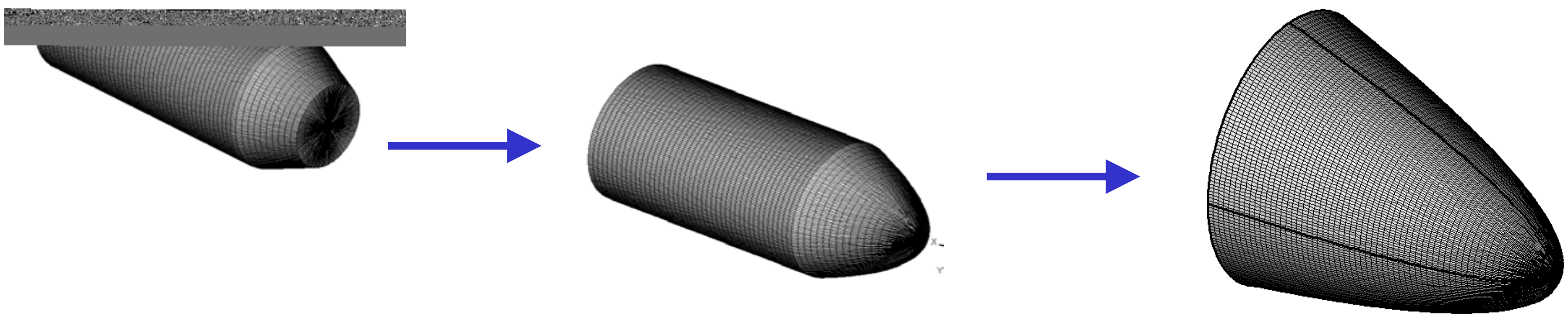


Fit four probes into the launch vehicle (Delta 7920)

Changing the Geometry

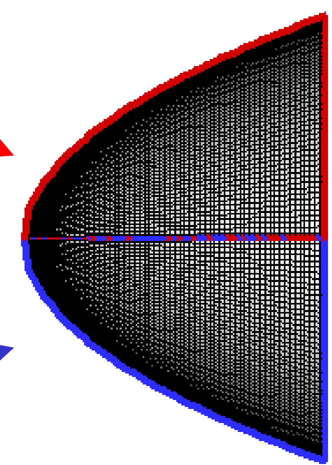
Change the nose to a power law shape.

Next, change the body to a power law shape.



Previous work has shown that **continuum** minimum drag, high speed bodies are approximated by power law shapes.

$$z_u = C_1 x^k$$



$$z_l = C_5 x^l$$

Drag + Stability Profile

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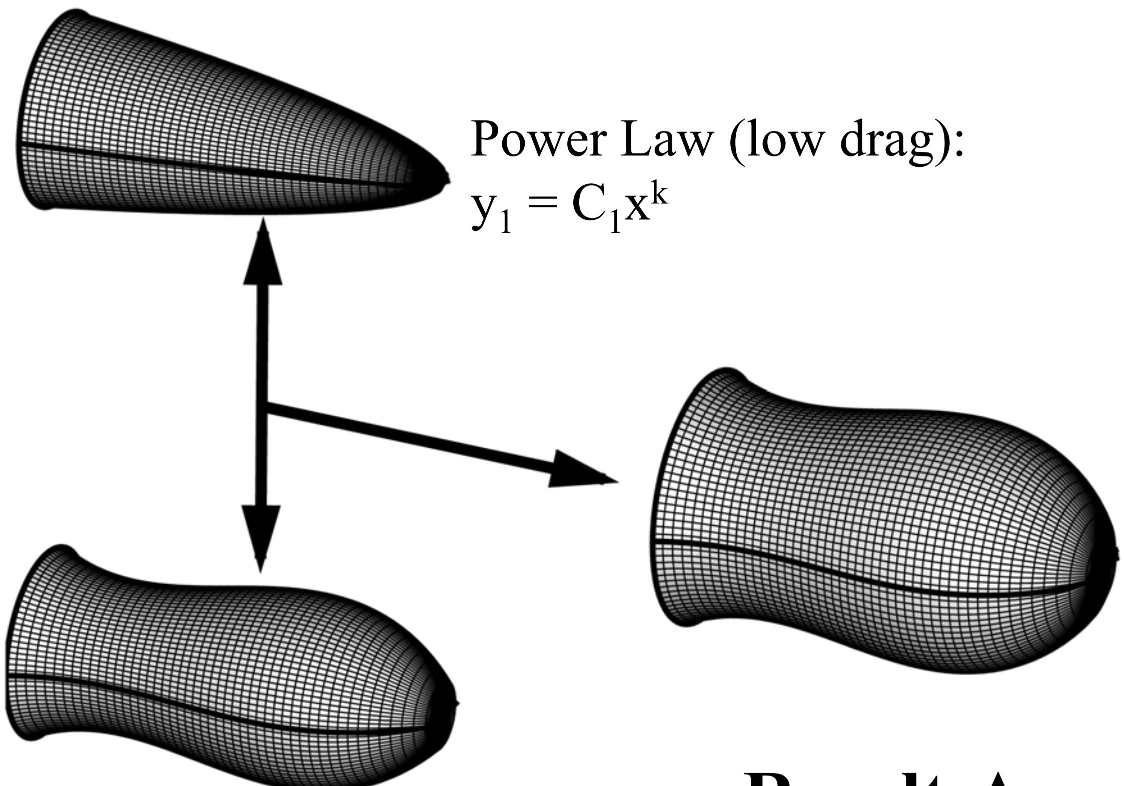

Power Law (low drag):
$y_1 = C_1 x^k$

3rd Order Polynomial (stability):
$y_2 = C_2 x^3 + C_3 x^2 + C_4 x + C_0$

Combined: $y_3 = y_1 + y_2$
5 upper surface variables
5 lower surface variables

Result: An axisymmetric geometry which has both drag and stability concerns incorporated.

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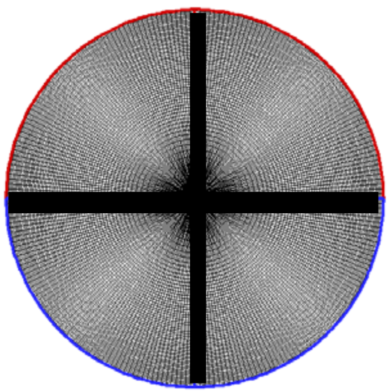
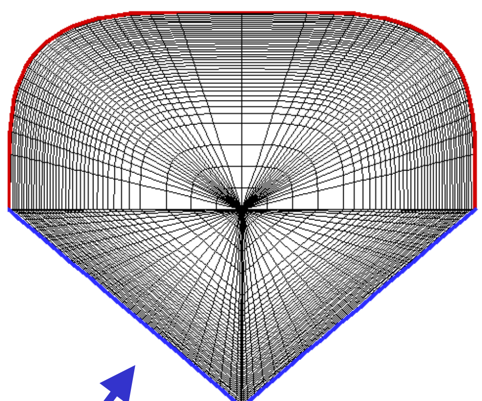
Expanded Geometry

A super-ellipse is used on the upper and lower surfaces to allow a variety of cross-section shapes.





$$z_u = r_{z,u}\left[1-\left(\frac{y_u}{r_y}\right)^{\frac{2}{m}}\right]^{\frac{m}{2}}$$

$$e = \frac{r_{z,u}}{r_y}$$

3 design variables (m, n, e) govern the cross-section shape

$$z_l = r_{z,l}\left[1-\left(\frac{yl}{r_y}\right)^{\frac{2}{n}}\right]^{2}$$

Result: Axisymmetric and non-axisymmetric cross-sections available.

Complete Geometry Model

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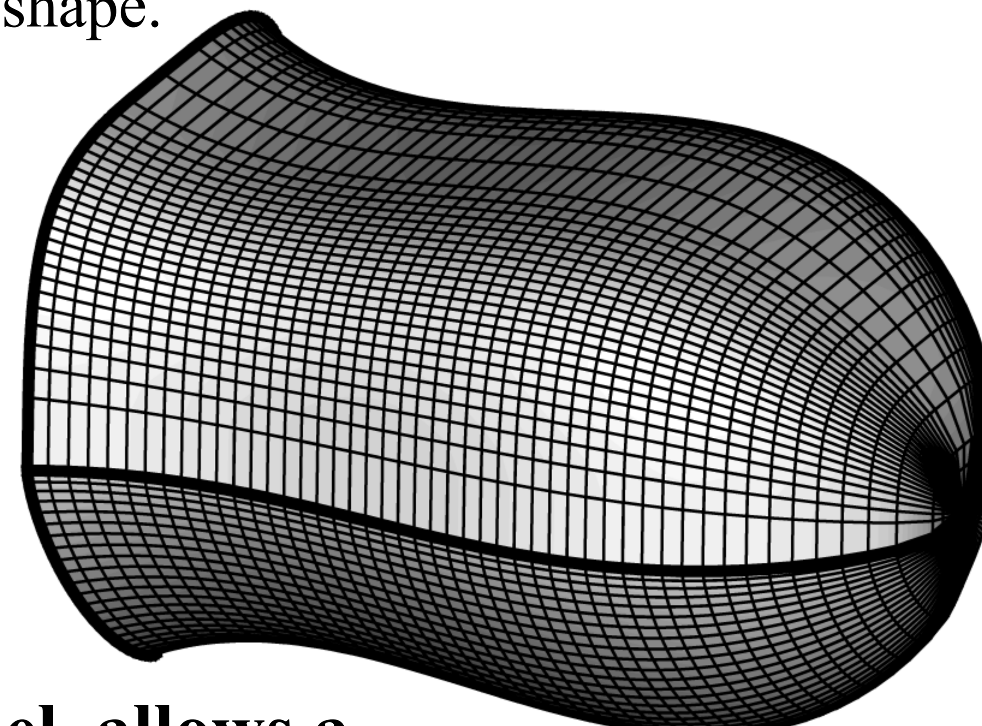
The complete geometry model uses 13 variables to generate a single shape.



5 upper surface variables

5 lower surface variables

+ 3 cross-section variables

13 total geometry variables

Result: A geometry model allows a large variance in shape possibilities.

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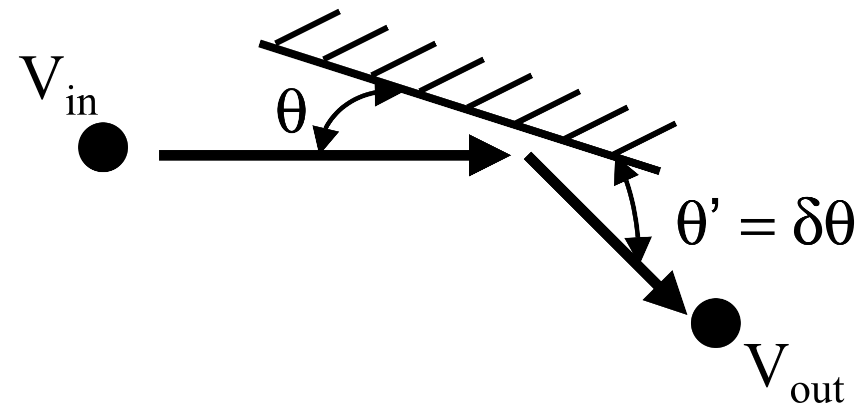
Aerodynamic Model

The aerodynamic model is based upon momentum transfer. Coefficients of rebound-to-impact velocity (ε) and angle (δ) are formulated where specular reflection occurs for $\varepsilon = \delta = 1$.

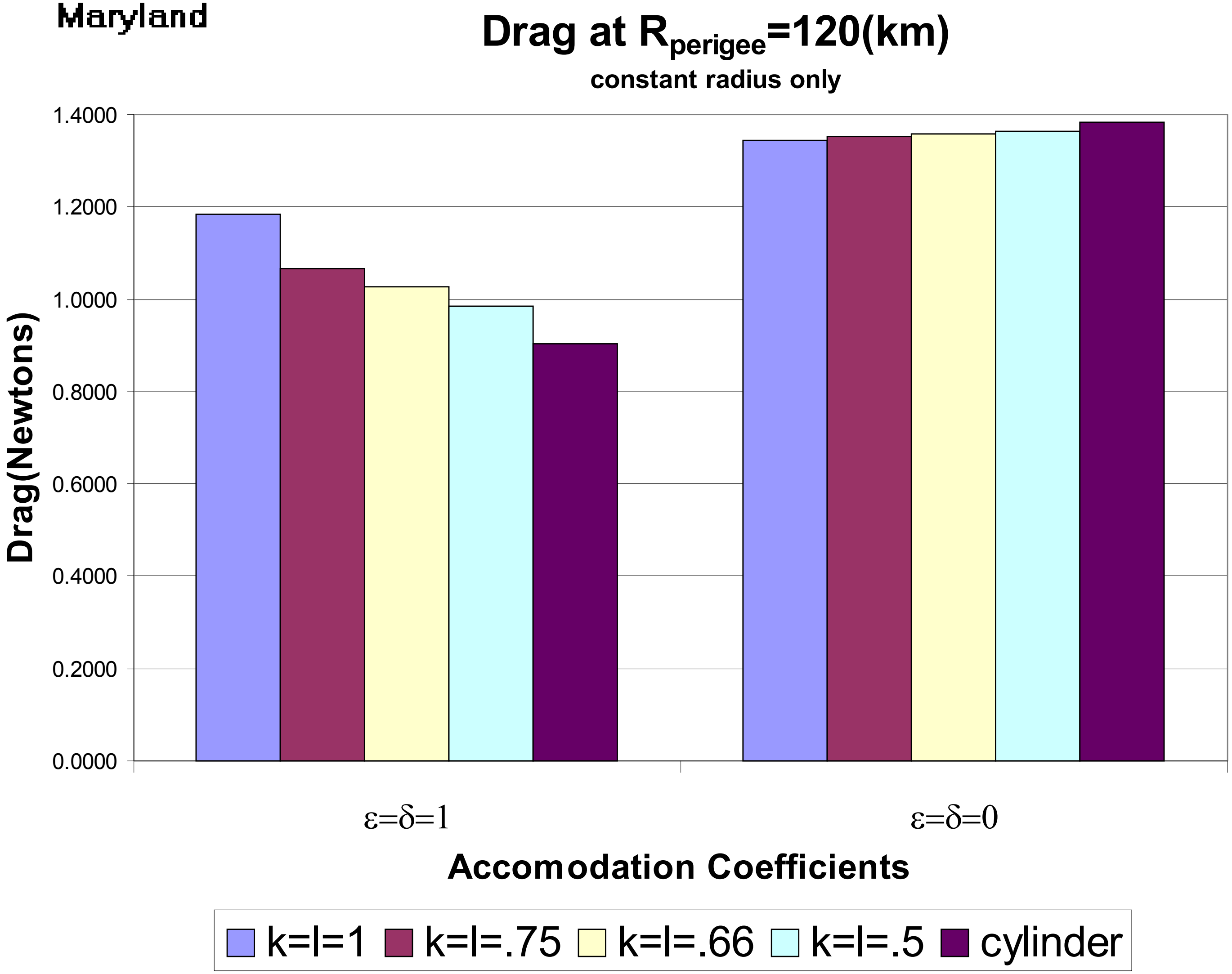


$$\frac{D}{A} = \rho\left(V\sin\theta + \frac{\bar{c}}{4}\right)V\left(1 - \varepsilon\cos\left[(1+\delta)\theta\right]\right)$$

$$\frac{L}{A} = \rho\left(V\sin\theta + \frac{\bar{c}}{4}\right)V\varepsilon\sin\left[(1+\delta)\theta\right]$$

Result: A fast, analytical model for rarefied flow which brackets complete accommodation and specular reflection.

Length-matched Power-Law Nose



The original GEC nose is replaced with same-length power law values of .5, .66, .75, and 1.

Volume-matched Power-Law Nose

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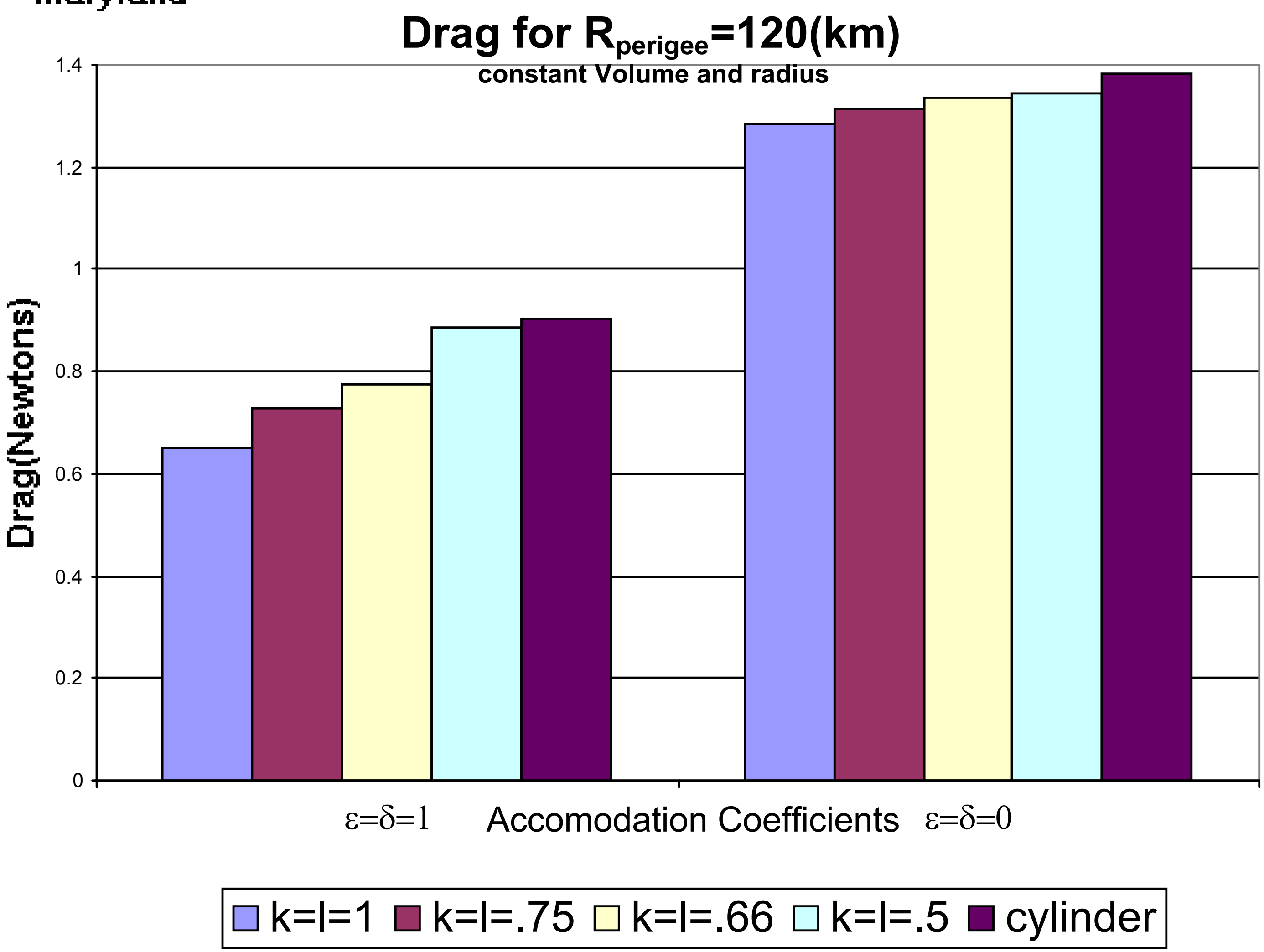

The original truncated nose is replaced with power law values of .5, .66, .75, and 1.

Result: The reflection assumption does influence the optimum.

Improved Gas-Surface Model: Diffuse Effects

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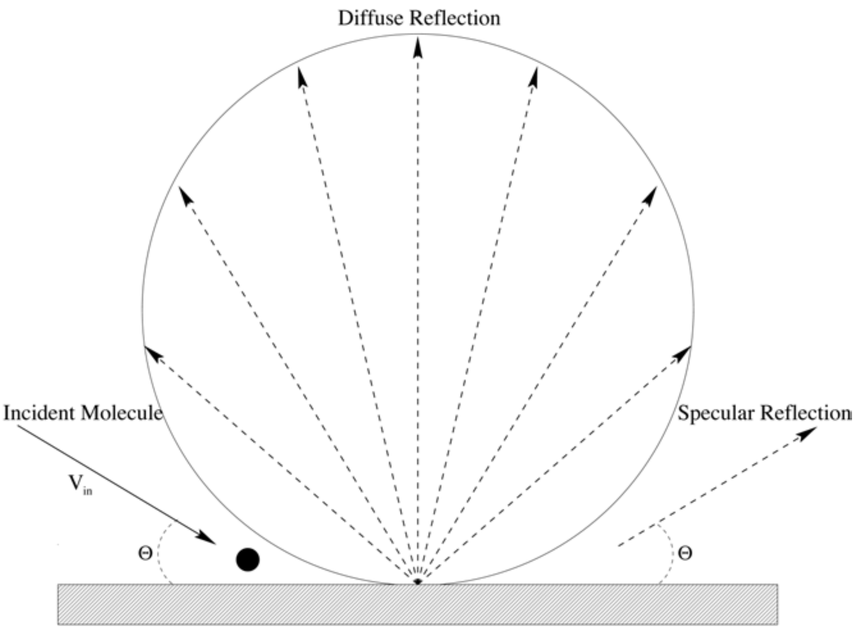

From Woronowicz and Rault

$$\left.\frac{D}{A}\right|_{complete} = \xi \left.\frac{D}{A}\right|_{spec} + (1-\xi)\left.\frac{D}{A}\right|_{diff}$$

$$\left.\frac{L}{A}\right|_{complete} = \xi \left.\frac{L}{A}\right|_{spec} + (1-\xi)\left.\frac{L}{A}\right|_{diff}$$

Result: An analytical model which incorporates specular and diffuse reflection.

Optimization

•Coupled rarefied flow model and geometry model to DOT (commercial numerical optimizer).

•All 13 geometry variables are being used.

•Method of feasible directions is used.

•Complete optimization on the order of 30 CPU seconds on a standard workstation.

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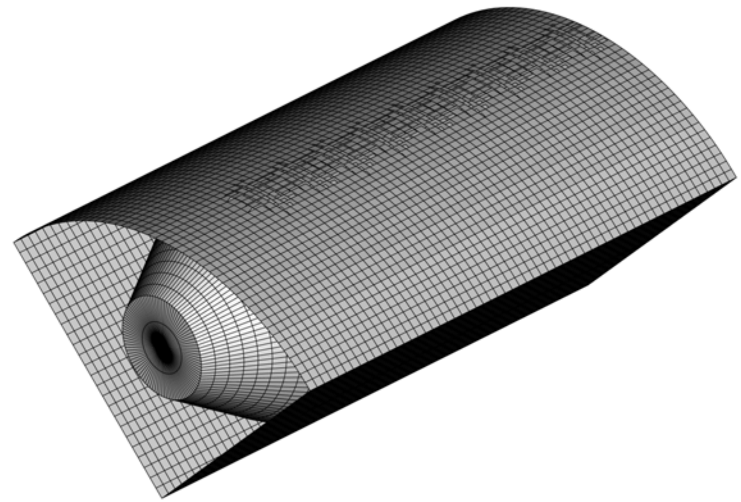
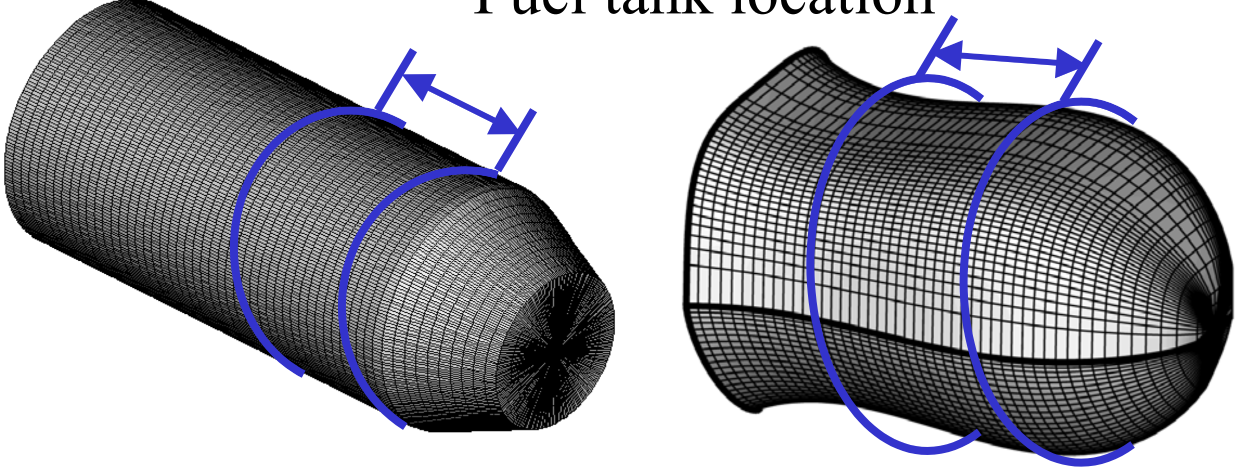
Geometry Constraints

Two geometry constraints:

1. Four spacecraft within one launch shroud



Fuel tank location



2. Adequate volume must exist for the fuel tank

Objective Functions Explored

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Three objective functions have been used thus far:

•Maximum Volume/Drag (specular, diffuse)

•Maximum Volume*$\text{Moment}_{\text{Restoring}}$ (specular, diffuse)

•Maximum Volume * $\text{Moment}_{\text{Restoring}}$ /Drag

$\text{Moment}_{\text{Restoring}}$ is at 5 degree pitch only.

Minimum Drag Results

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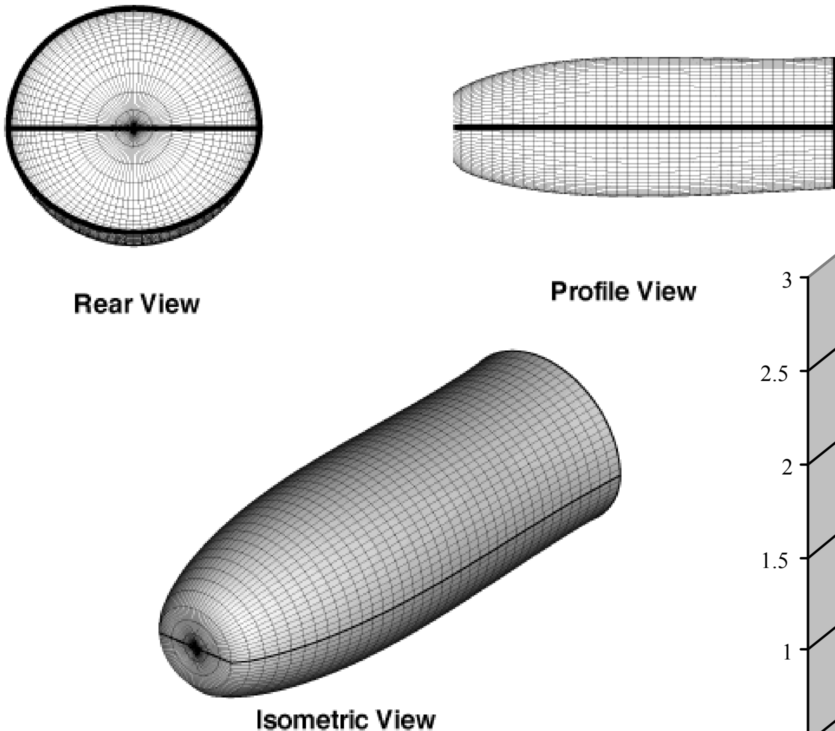

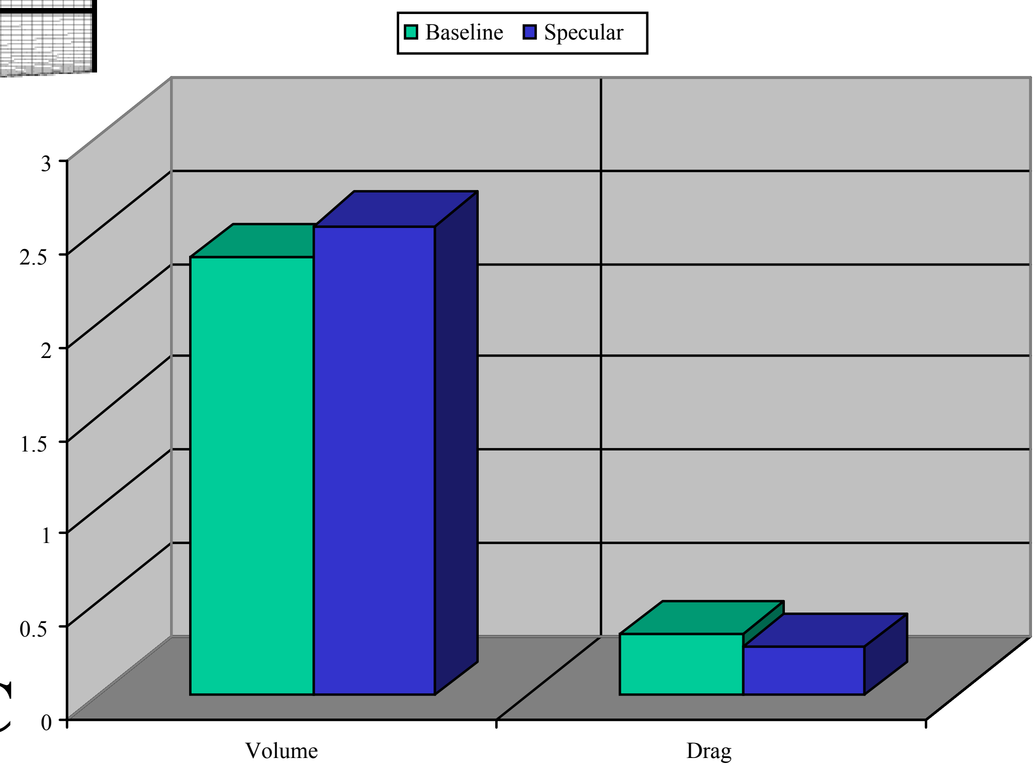

Result: Similar to GEC cylinder BUT increased volume and decreased drag

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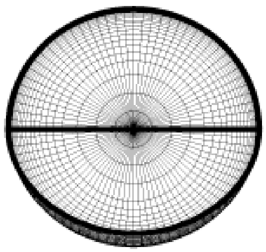
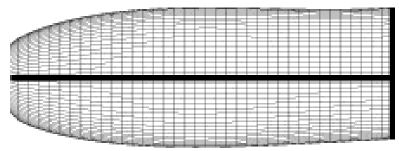
Diffuse Optimization Result

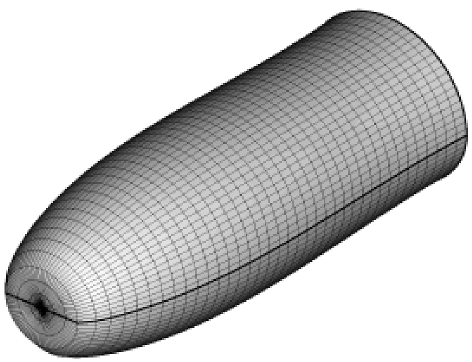


Rear View



Profile View

Nearly the same shape as specular optimization!



Isometric View

Result: For this constrained problem, the optimum is a weak function of reflection assumption.

Maximum Moment Results

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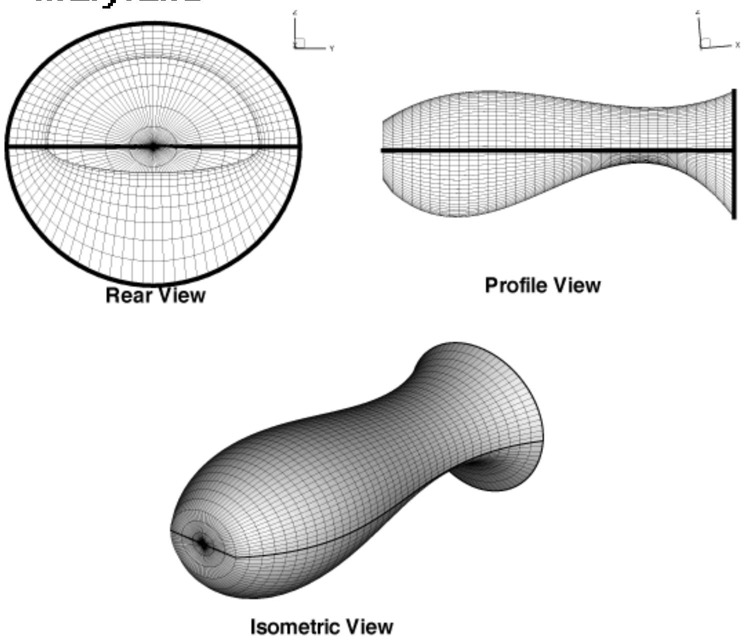
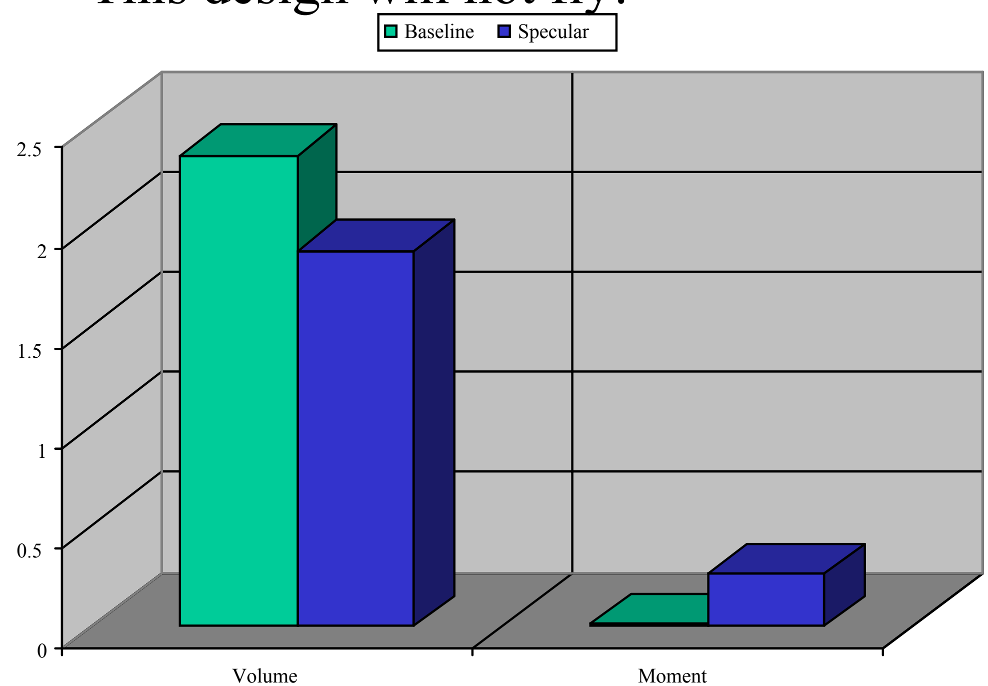


•For this non-realistic solution, volume decreased, moment increased significantly, drag increased significantly

•Diffuse solution very similar

•This design will not fly!



Result: Significant Moment$_{Restoring}$ can be produced through optimization, but there are tradeoffs.

Max Moment/Min Drag Results

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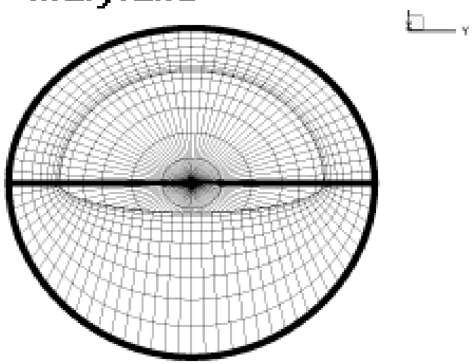
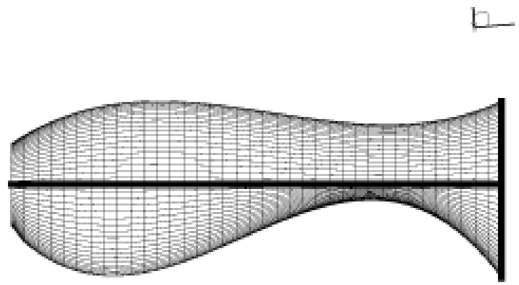
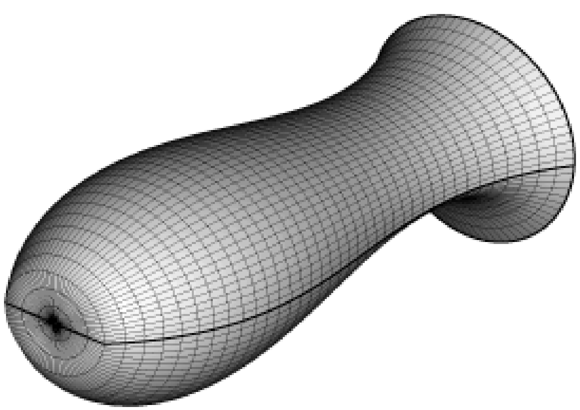


Rear View



Profile View



Isometric View

Result: Due to geometric constraints, this optimum is very close to the maximum moment optimum.

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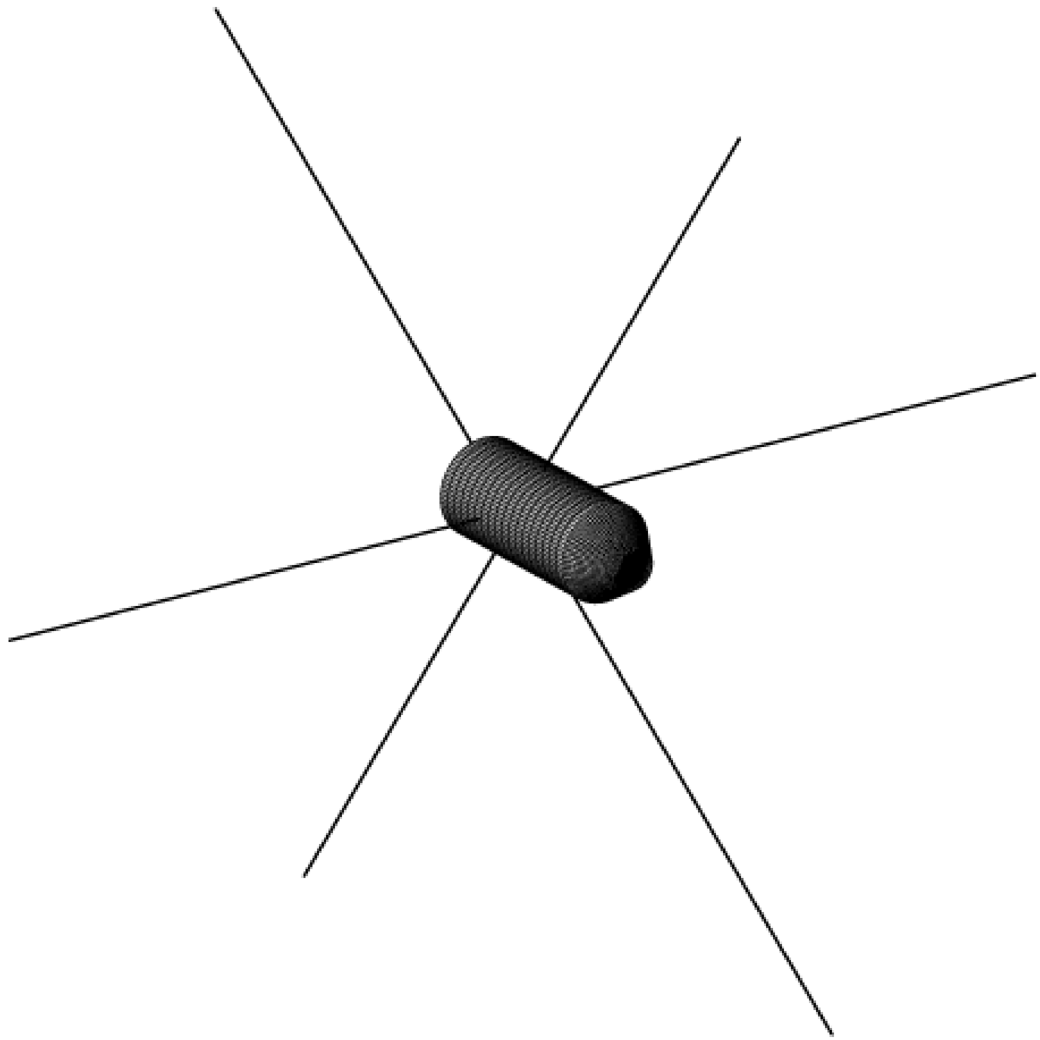
Summary

- A thirteen design variable geometry has been developed
- An analytical model for approximating rarefied forces has been introduced
- The aerodynamic and geometric models have been integrated with a numerical optimizer
- Three objective functions have been presented

GEC with its Booms



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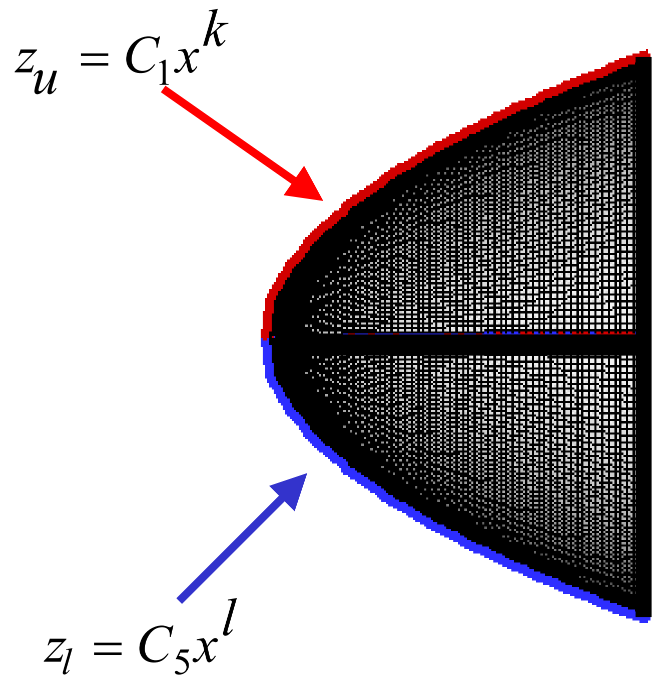
Original Nose Model

Previous work has shown that **continuum** minimum drag, high speed bodies are approximated power law shapes. Thus, power laws are used here to govern the shape in the axial direction.



4 design variables (C_1, C_5, k, l)

Original Geometry Model

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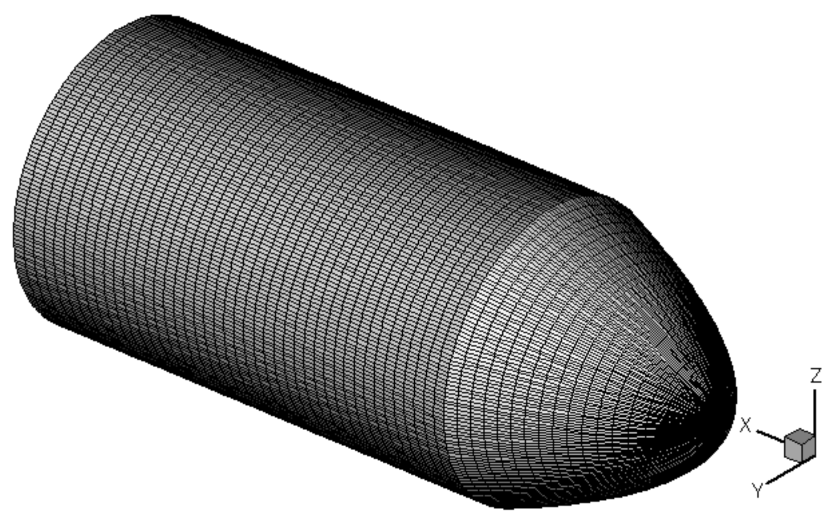
This geometry generator uses 9 variables to describe a single shape. These shapes range from blunt-to-sharp noses and concave-to-circular-to-convex cross-sections.

4 nose variables

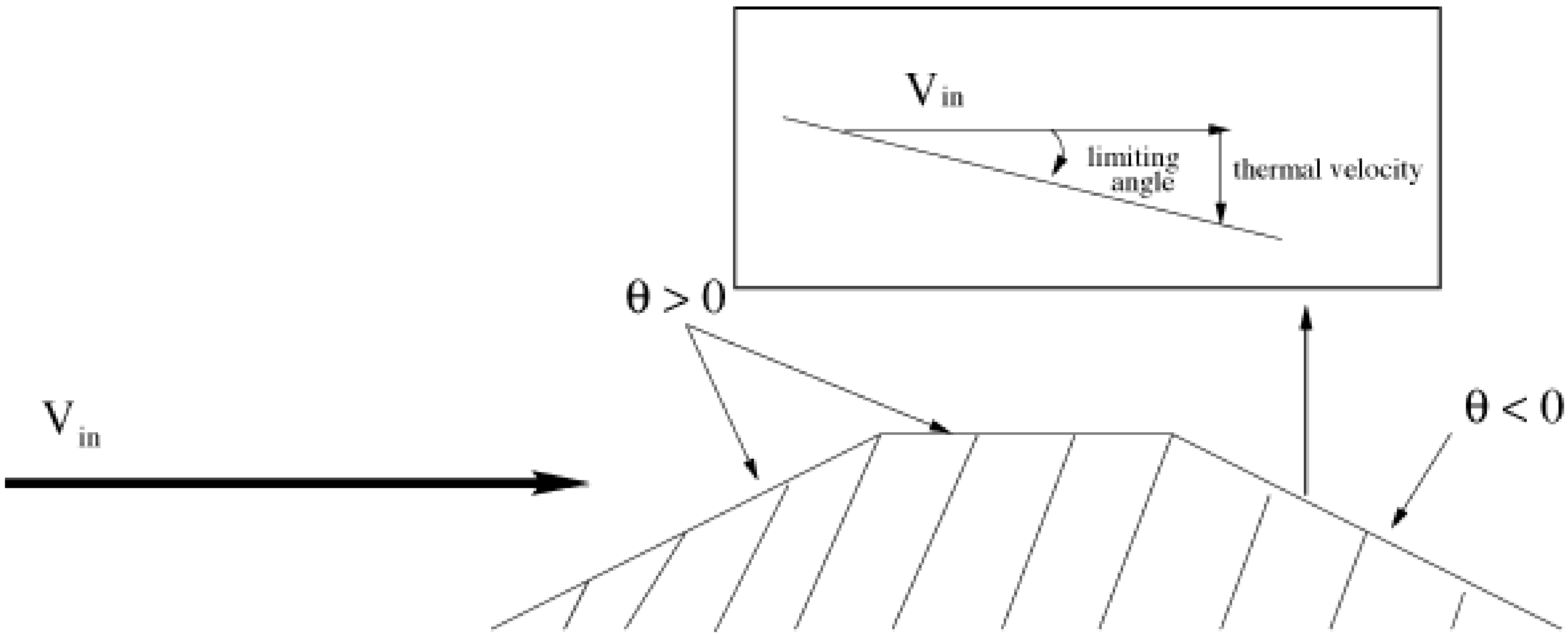
3 cross-section variables

+ 2 length variables

9 geometry variables



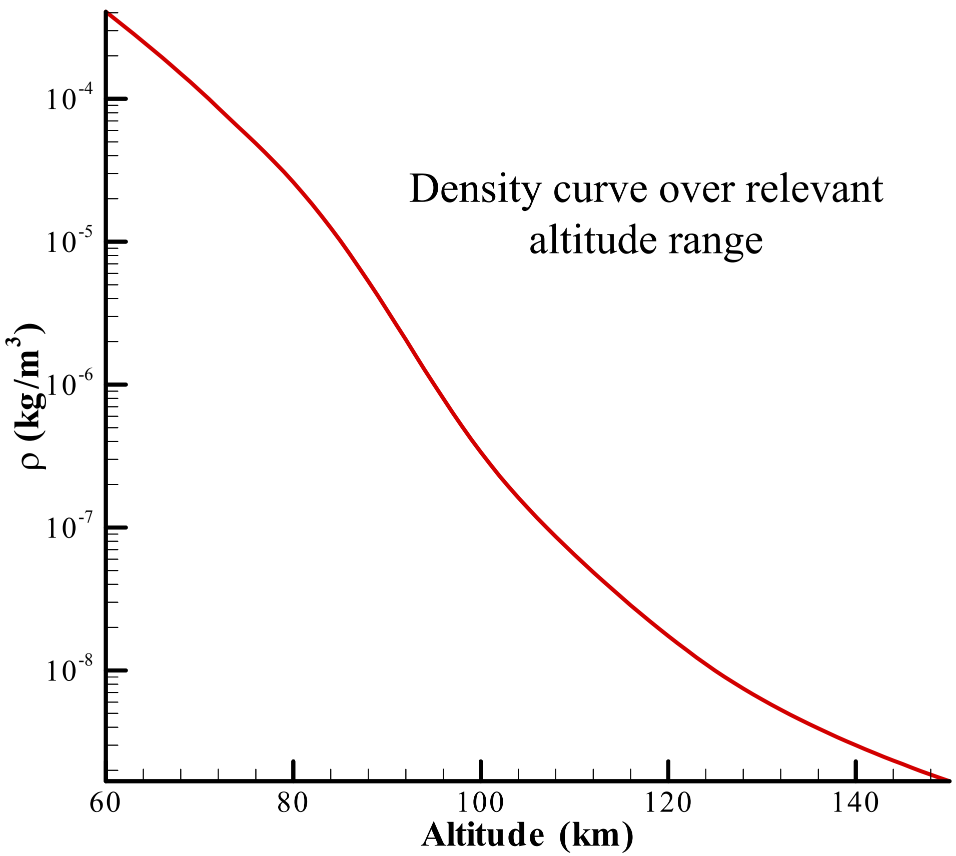
Negative Angle Surfaces



Atmosphere Model

The atmosphere model used is the MSISE-90 model which is valid from sea-level to 1000 km. This model takes into account many factors, some of which are:

- Altitude (130 km)
- Geodetic latitude (83 deg.)
- Geodetic longitude (0 deg.)



ΔV_{loss} Results -- Mission Impact

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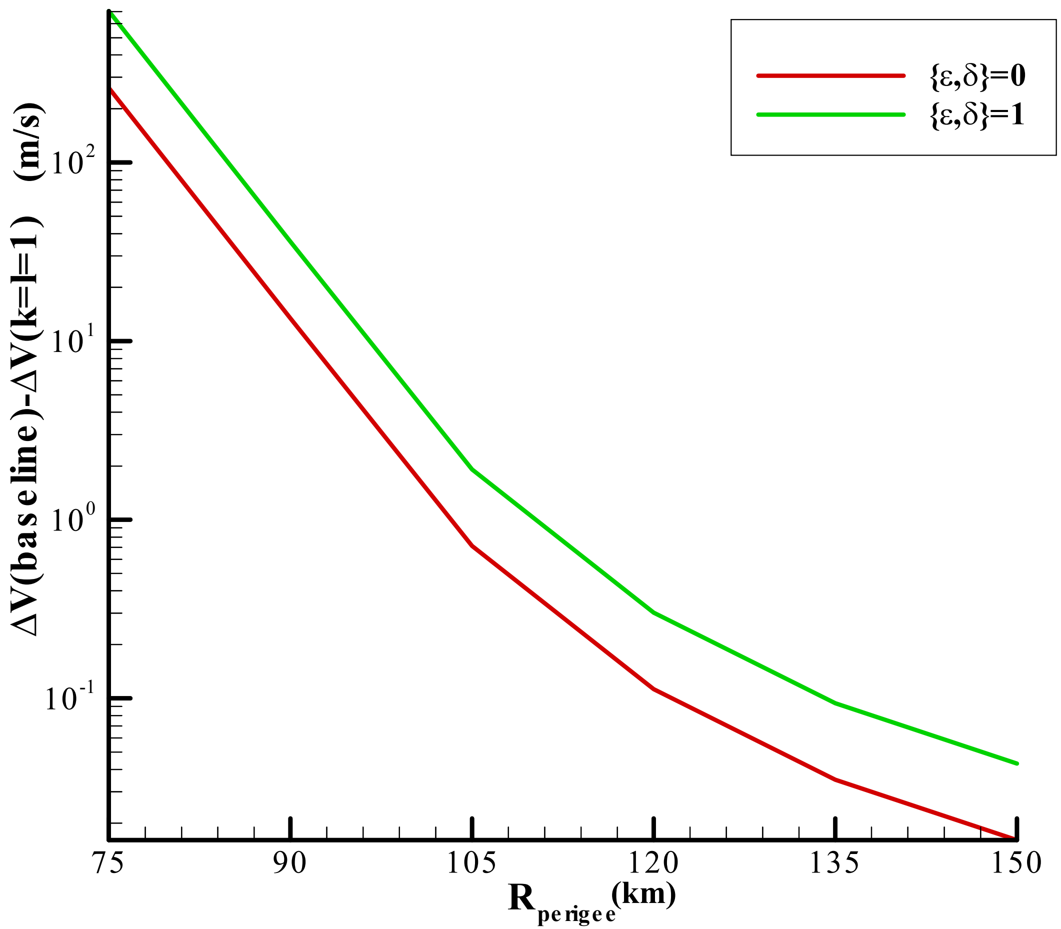

In order to bound the ΔV_{loss} results, the difference in ΔV_{loss} between the original configuration and our lowest drag configuration (volume-matched nose with power of 1) is plotted for conditions of total accommodation and specular reflection. It is seen here that the performance is better as the accommodation approaches specular.

Nose Change Conclusions

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- Gas accommodation conditions are very important for drag calculations.
- For minimum drag, a length-matched power-law nose may work if the accommodation is close to total.
- The volume-matched power-law noses will produce lower drag especially for specular accommodation conditions, but there seems to be no optimum since the drag decreased consistently as the power-law values approached 1.
- The ΔV_{loss} comparison confirmed that the performance of the volume-matched power-law is best as accommodation approaches specular. It also seemed to place tight bounds on the total possible ΔV savings available from lower drag geometries. However, it is expected that a full optimization of all the design variables will make the ΔV bounds much less rigid.

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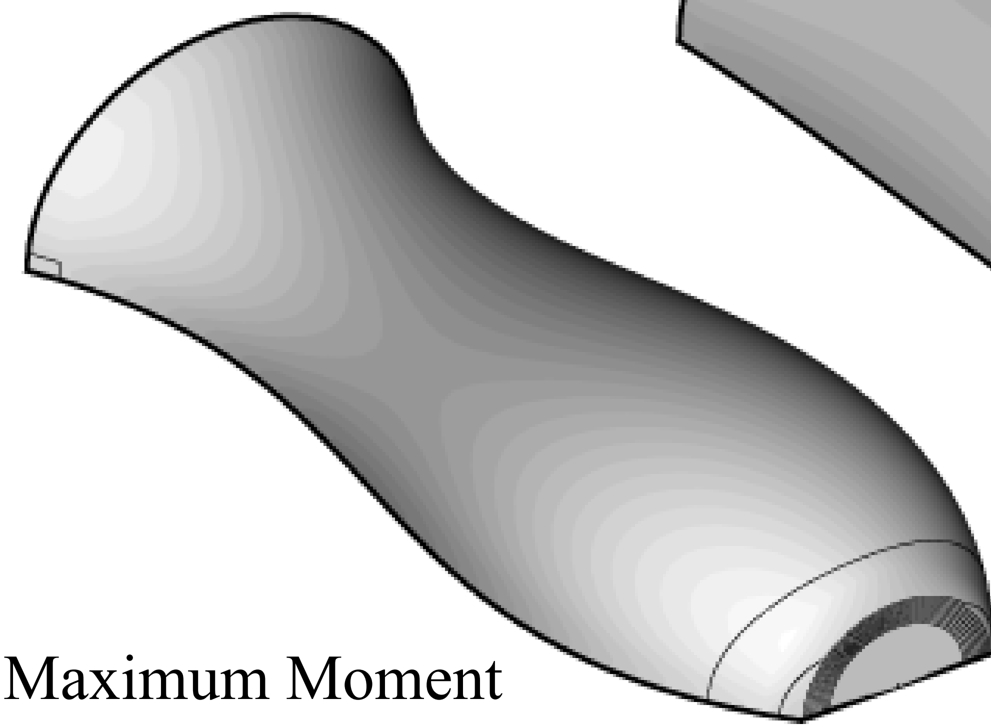
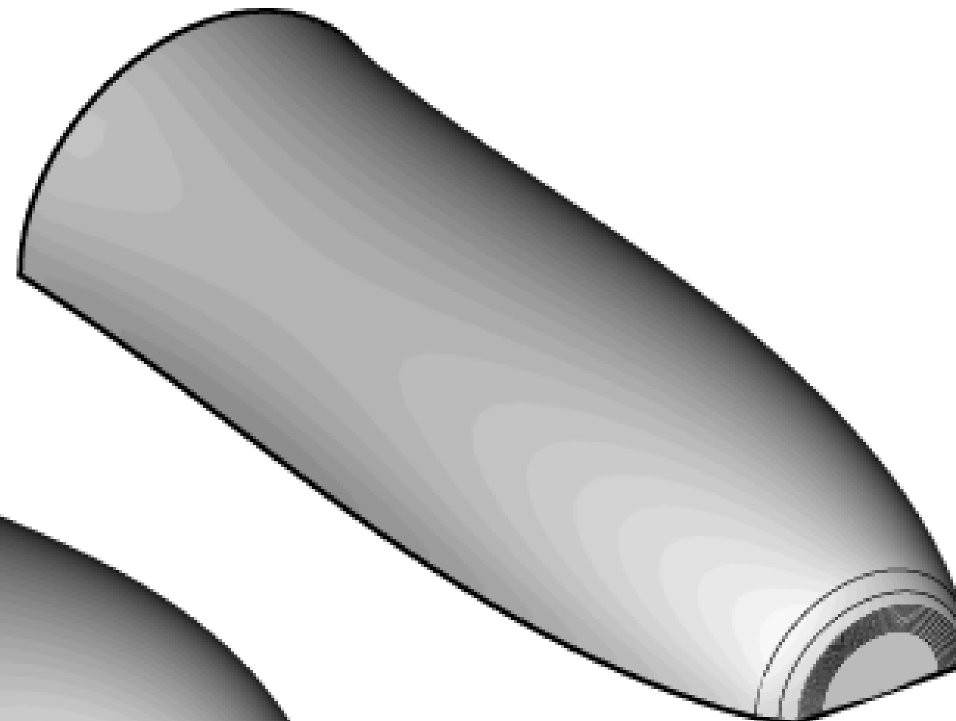
Upper Surface Comparison



Maximum Moment



Minimum Drag

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GEC Mission

The theme of the mission is to establish the role of the ionosphere/thermosphere in the electrodynamic environment of near-Earth space. Within this context the GEC science objectives are:

1. To observe the magnetospheric energy transfer to the ionosphere and thermosphere by making space-time resolved observations in the transfer region.
2. To determine the key processes and their space-time scales for coupling between the ionosphere-thermosphere as magnetospheric energy is dissipated.

Length-matched Power-Law Nose

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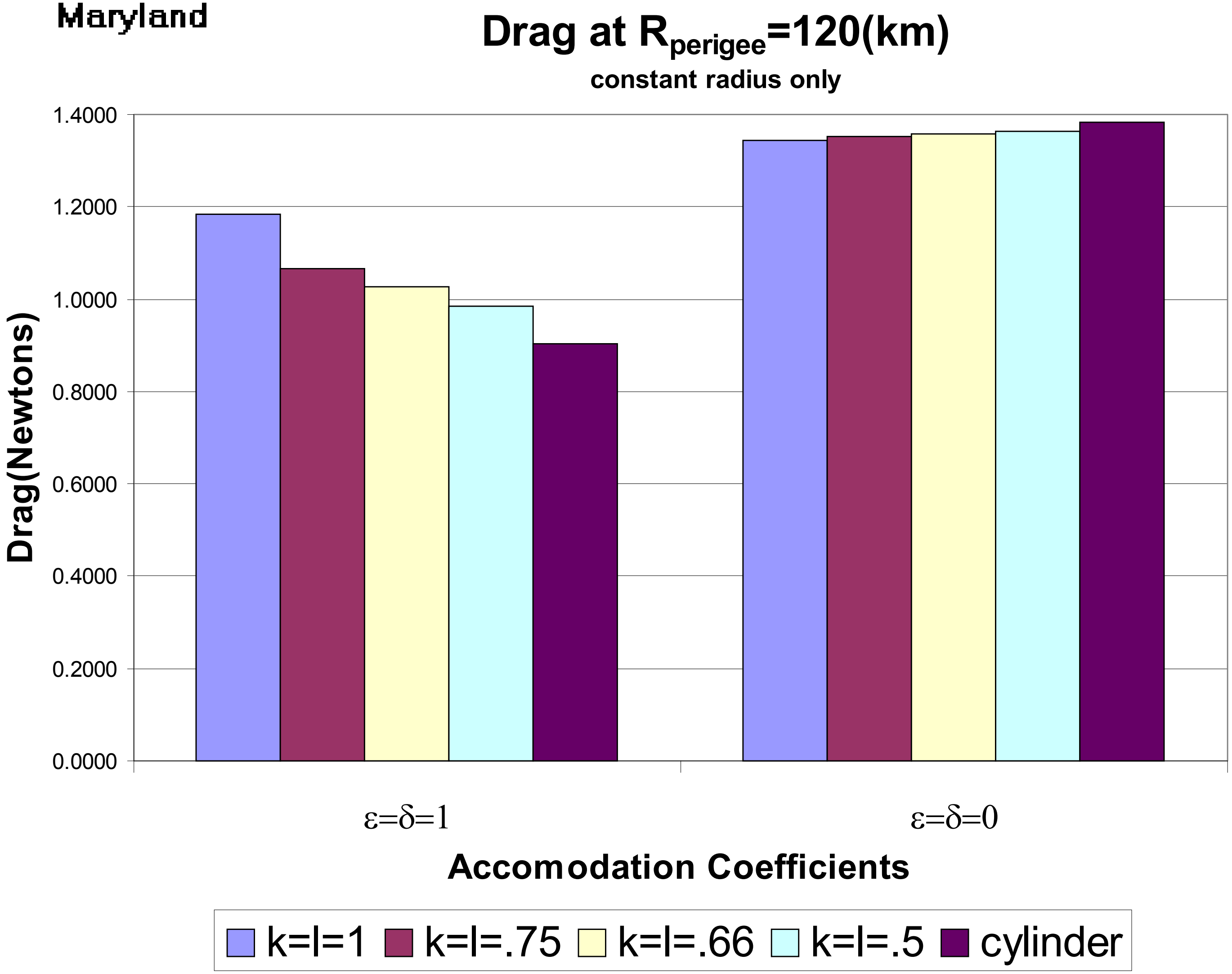

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Volume-matched Power-Law Nose

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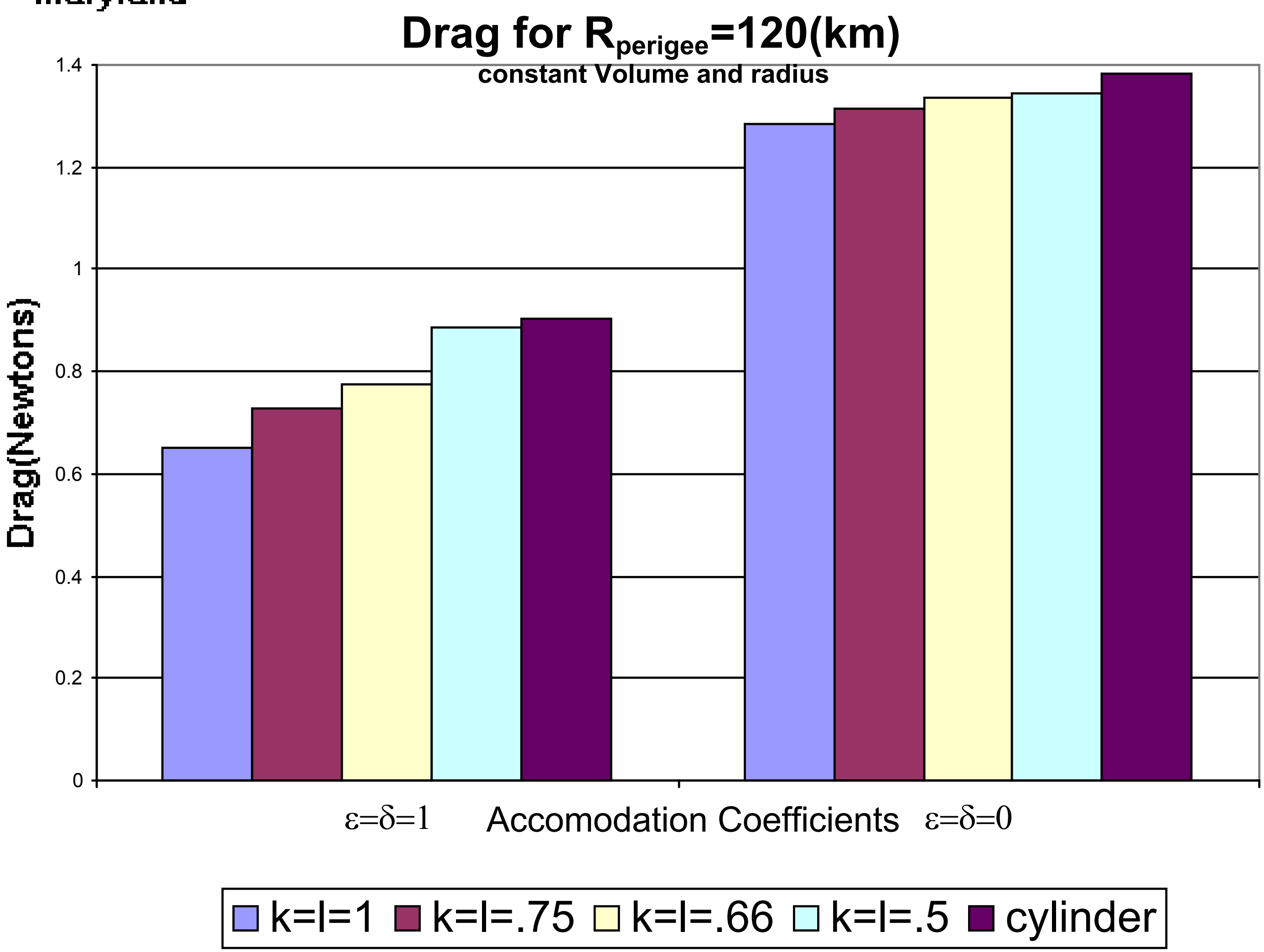

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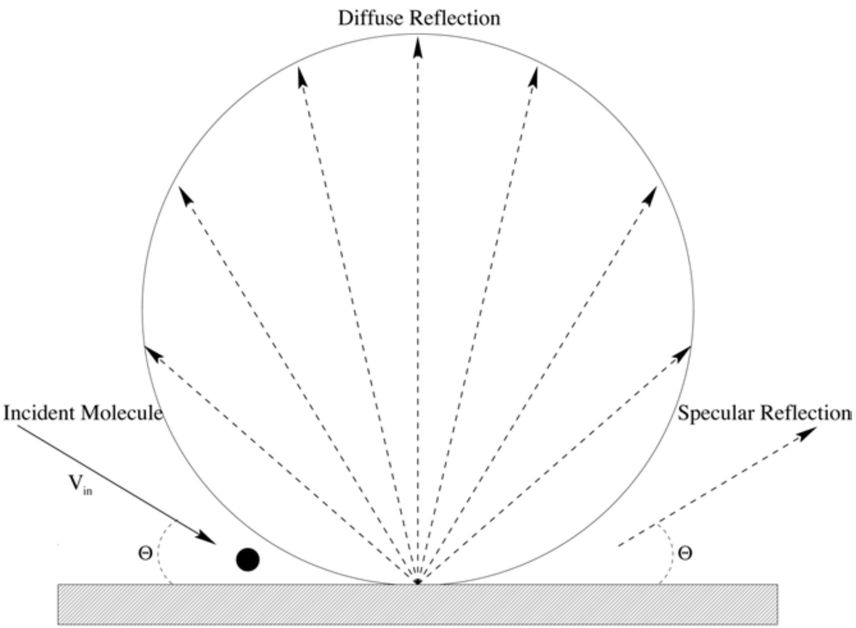

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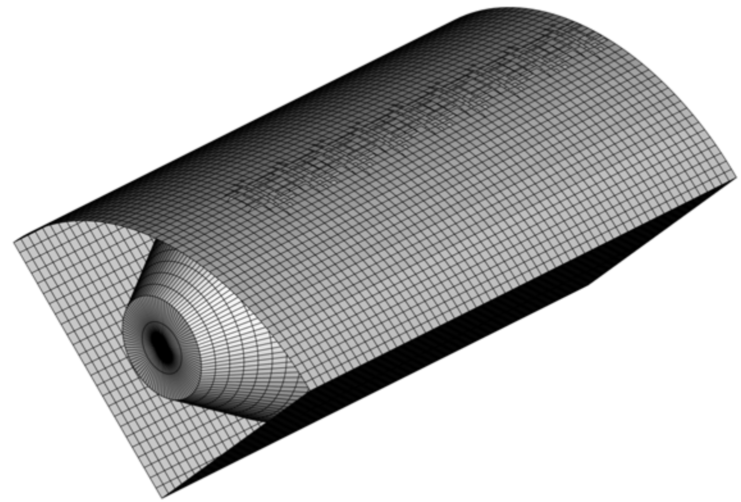
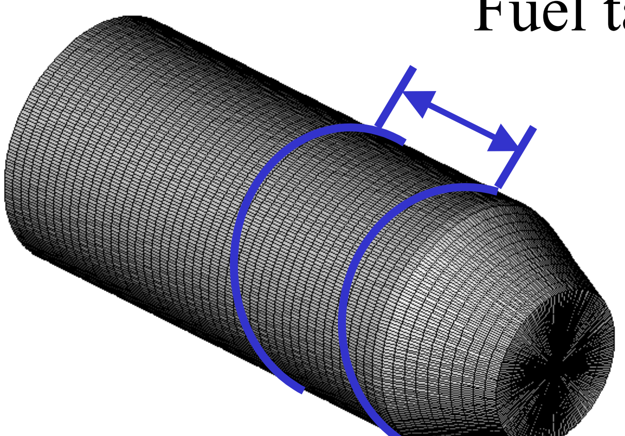
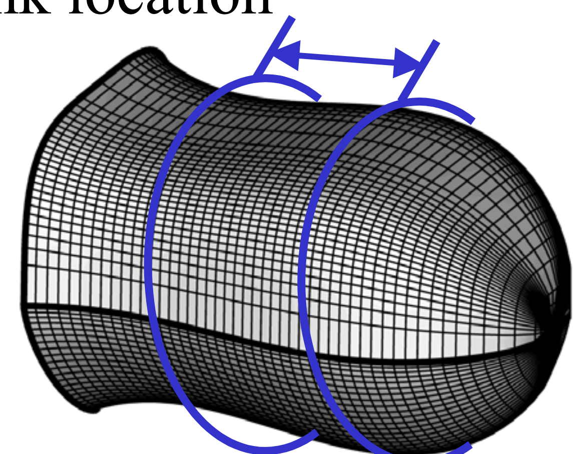




Fuel tank location



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Minimum Drag Results

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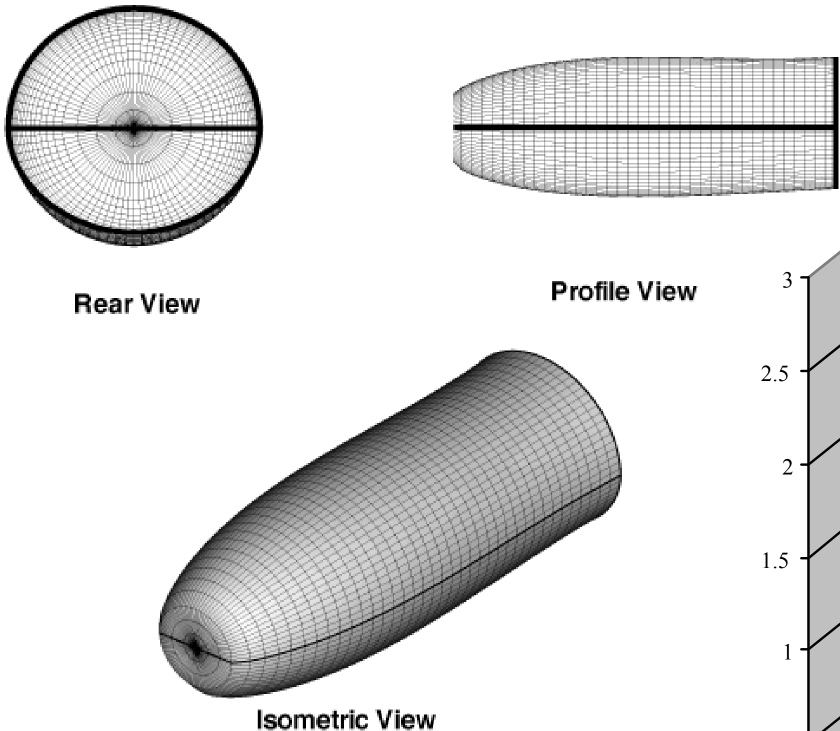

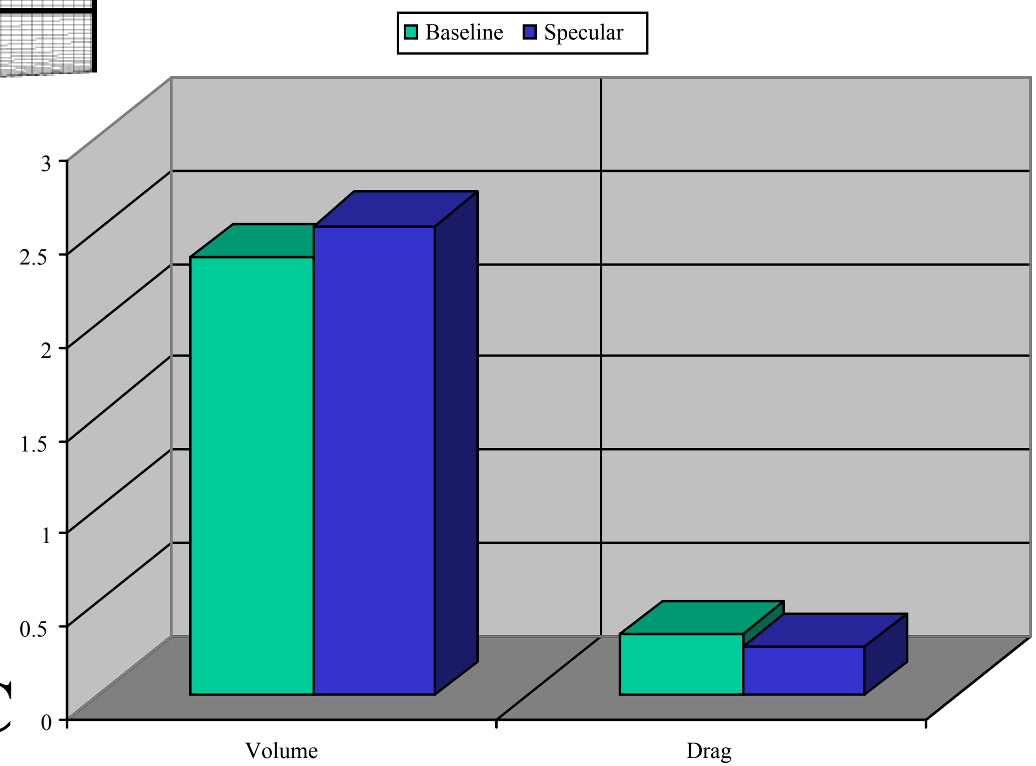

Result: Similar to GEC cylinder BUT increased volume and decreased drag

Diffuse Optimization Result

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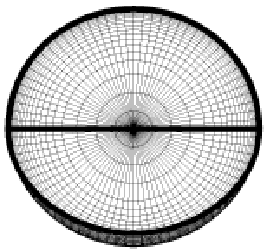
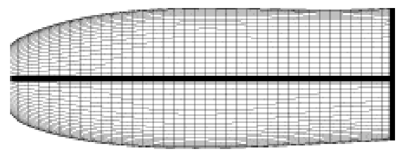


Rear View



Profile View

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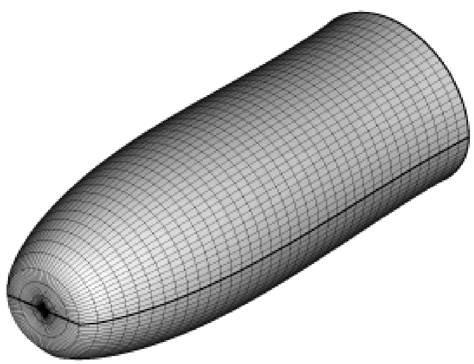

Isometric View

Result: For this constrained problem, the optimum is a weak function of reflection assumption.

Maximum Moment Results

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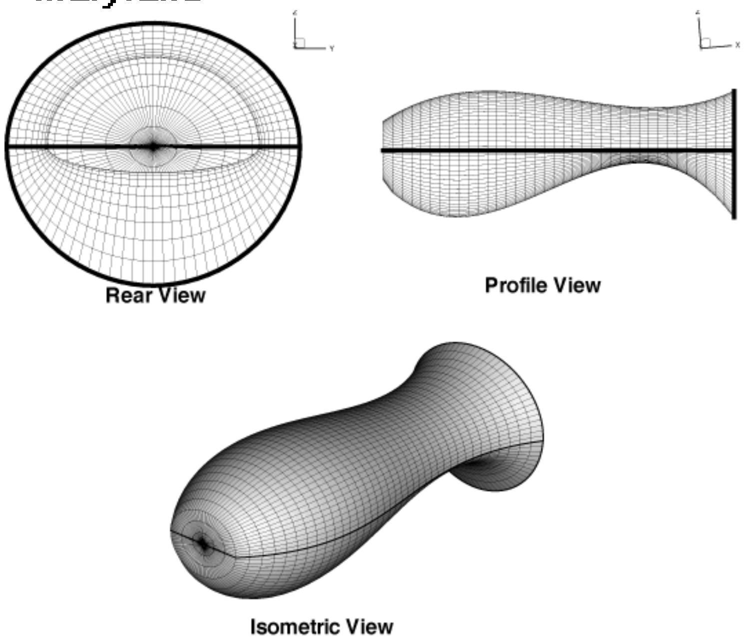
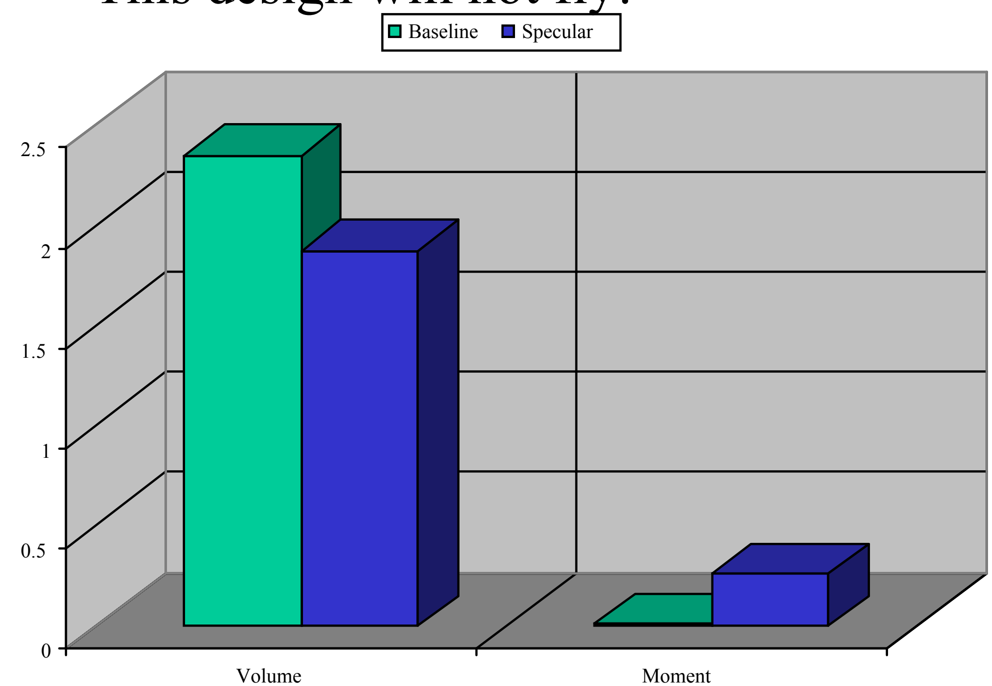


Result: Significant Moment$_{\text{Restoring}}$ can be produced through optimization, but there are tradeoffs.

- For this non-realistic solution, volume decreased, moment increased significantly, drag increased significantly
- Diffuse solution very similar
- This design will not fly!



Max Moment/Min Drag Results

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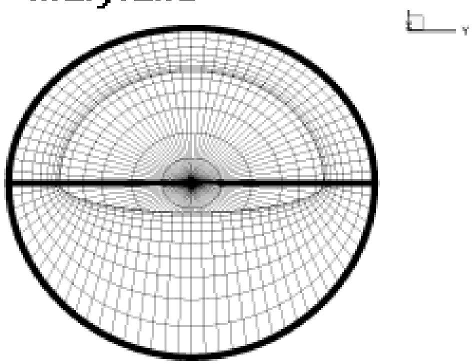
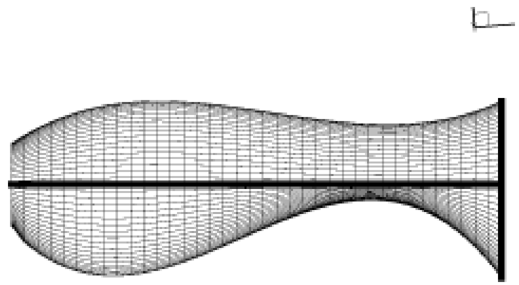
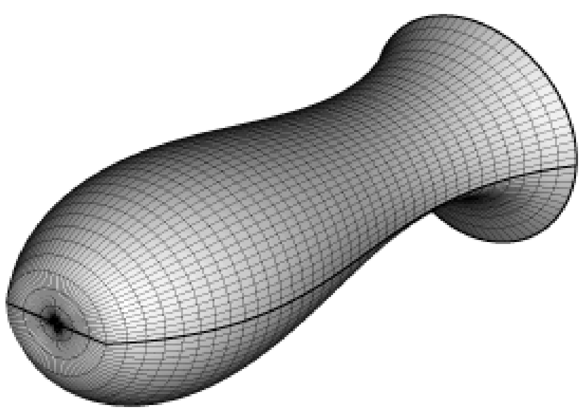


Rear View



Profile View



Isometric View

Result: Due to geometric constraints, this optimum is very close to the maximum moment optimum.

Conclusion

- Minimum drag can be achieved while still increasing volume
- Minimum drag body seems to be close to a cylinder
- For these constrained designs, the reflection assumption is a weak function of the optimum -- this is different from when just the nose was changed!
- Significant $Moment_{Restoring}$ can be produced, but there are volume and drag penalties for one axis stability
- The geometric constraints are tight, forcing the third objective function to behave as the second did

Future Work

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Two future thrusts:

•Explore multiple axis stability

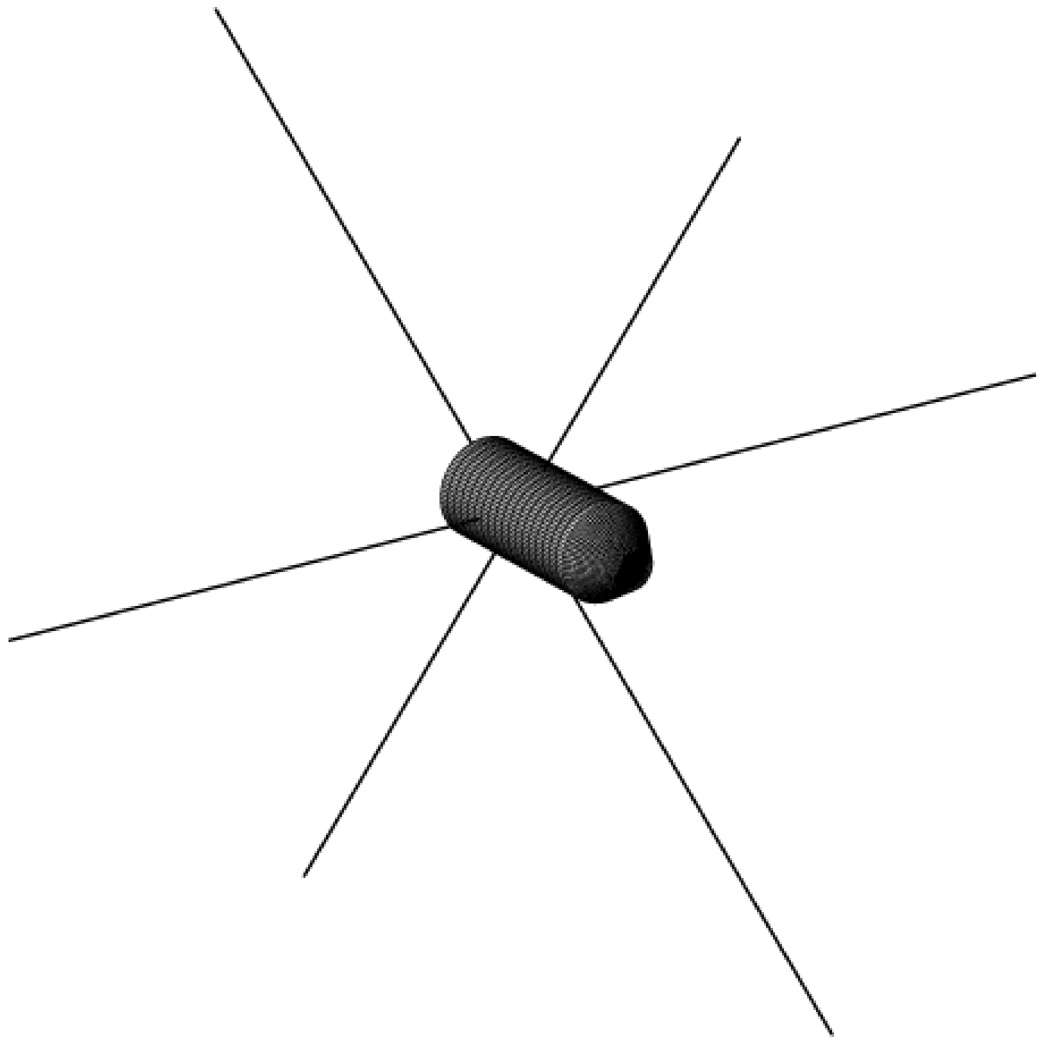
•Consider center-of-pressure vs. center-of-gravity margin

•Explore the design space for lifting body configurations

•Consider influences of booms

•Validate the aerodynamic model using numerical methods

GEC with its Booms



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Previous Work: Experimental

•Early work by Stalder, et al. (1950) focused on drag prediction for simple shapes (cylinders). Theory used Maxwellian velocity distribution and cosine-law scattering and produced good agreement.

•Later work by Boring and Humphris (1970) and Cook, et al. (1997) has focused on the interdependancy of incident velocity, gas species, and surface type. Results have shown that scatter angle is not always normal to surface and is species dependent.

Result: Momentum conservation and cosine-law scattering are reliable approximations for rarefied flow.

Previous Work: Analytical

•Cook (1965) has focused mostly on drag determination for satellite applications. Tried energy accommodation and cosine-law scattering to determine overall C_d change with altitude.

•Blanchard, et al. (1993) have published results of curve-fits based upon experiment for Orbiter aerodynamics. They have reported good correlation in rarefied and transitional flow.

Result: Analytical approximations have been proven to be useful.

Previous Work: Optimization

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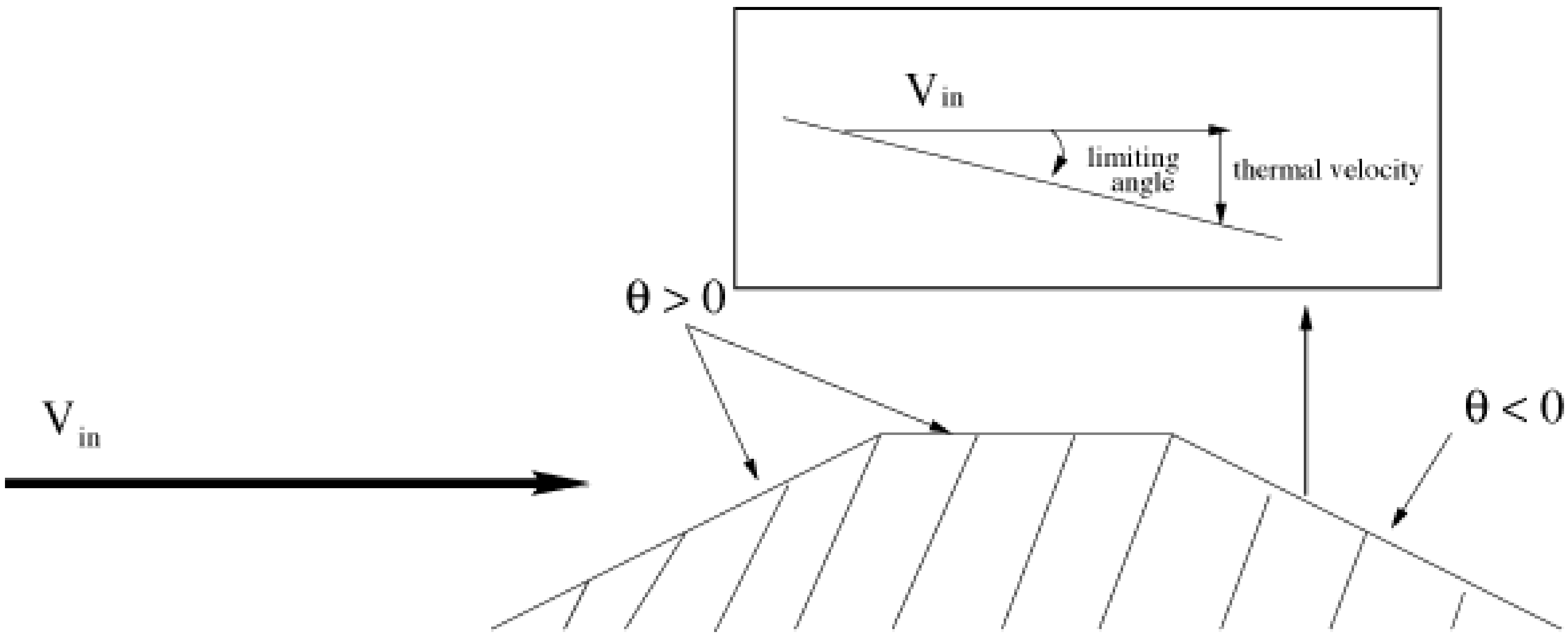
•Carter (1957) has used kinetic theory to develop minimum drag, axisymmetric missile nose shapes. Resulted in differential equation which was then solved by Tan (1958). For high length-to-diameter nose in specular flow, shape approximates $y=Ax^{3/4}$.

•Shidlovskiy (1967) used homogenous flow and specular reflection and derived a Mach dependent solution to minimum drag noses.

•Potter (1992) has optimized waveriders for maximum L/D in 7.6 km/s rarefied flow. Momentum conservation used. Reflection assumption important as altitude increases.

Result: Optimum shapes exist and that shape is a function of the reflection assumption.

Negative Angle Surfaces



Result: Quick approximation for small impingment on negative angles occurs due to thermal velocity.

Improved Gas-Surface Model: Diffuse Effects

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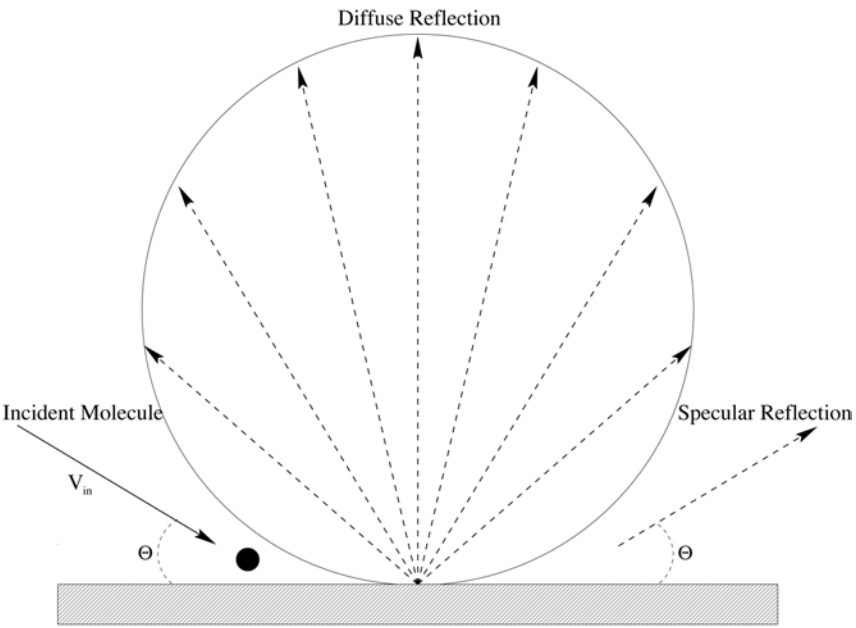


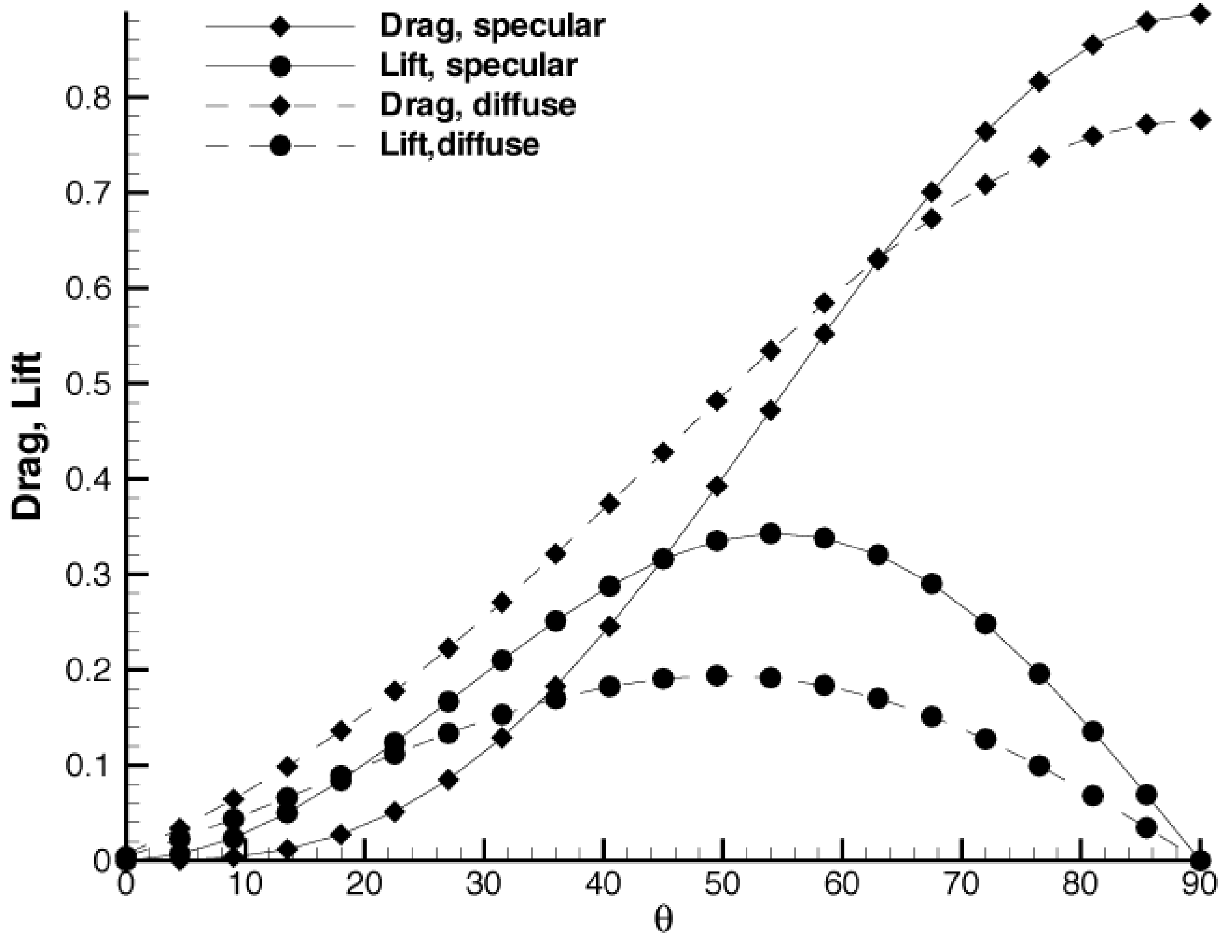
From Woronowicz and Rault

$$\left.\frac{D}{A}\right|_{complete} = \xi \left.\frac{D}{A}\right|_{spec} + (1-\xi)\left.\frac{D}{A}\right|_{diff}$$

$$\left.\frac{L}{A}\right|_{complete} = \xi \left.\frac{L}{A}\right|_{spec} + (1-\xi)\left.\frac{L}{A}\right|_{diff}$$

Result: An analytical model which incorporates specular and diffuse reflection.

Specular vs. Diffuse



Volume & C_g Calculations

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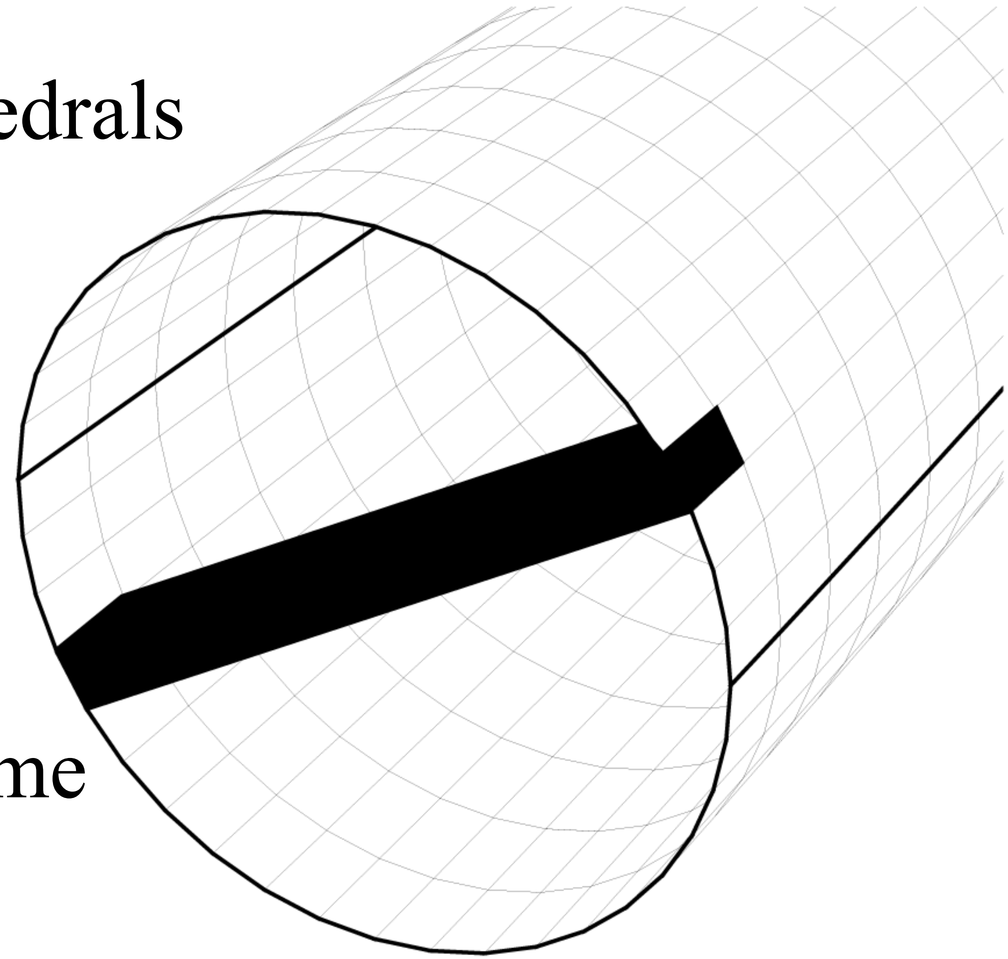
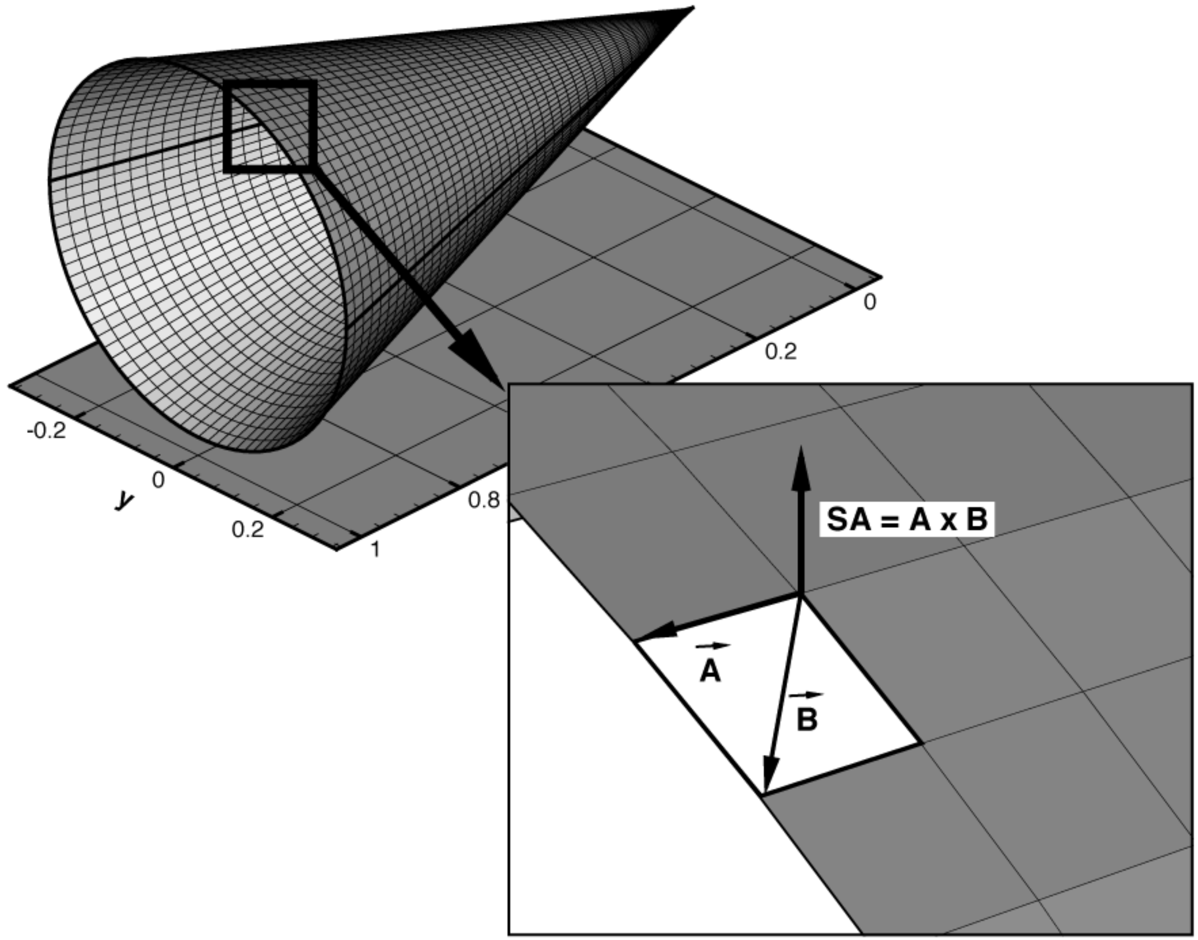
1 column = 6 tetrahedrals



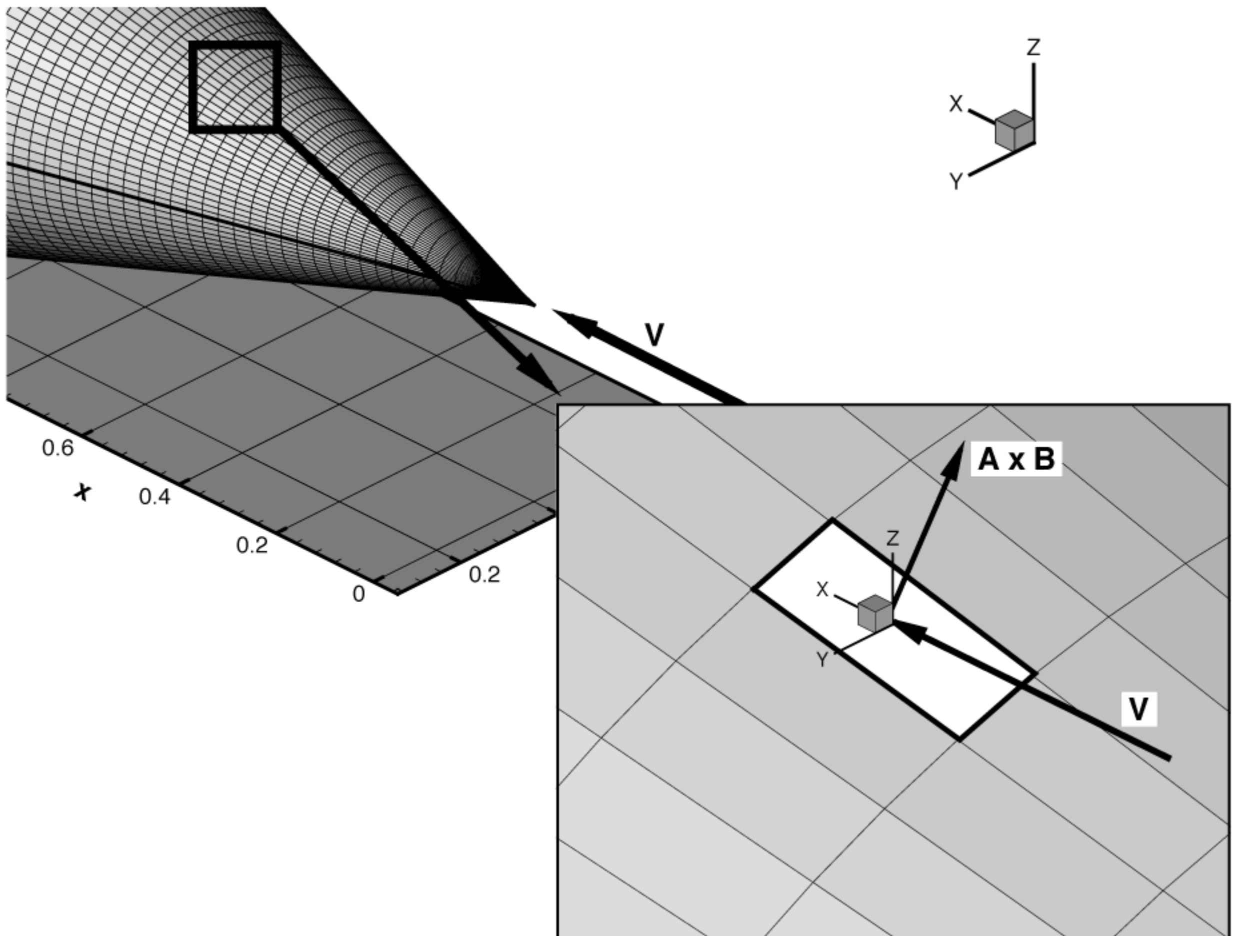
Advantage:

- Analytical volume
- Analytical C_g

Surface Area Calculations



Surface Angle Calculations



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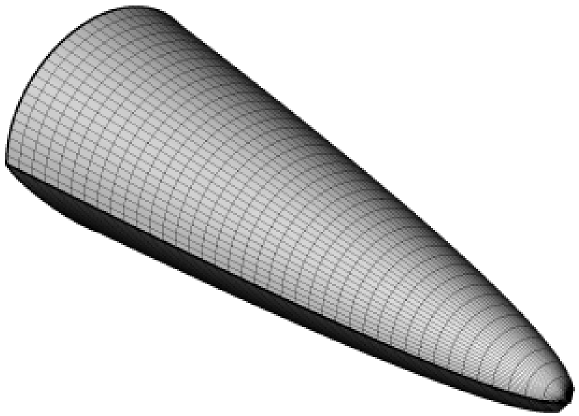
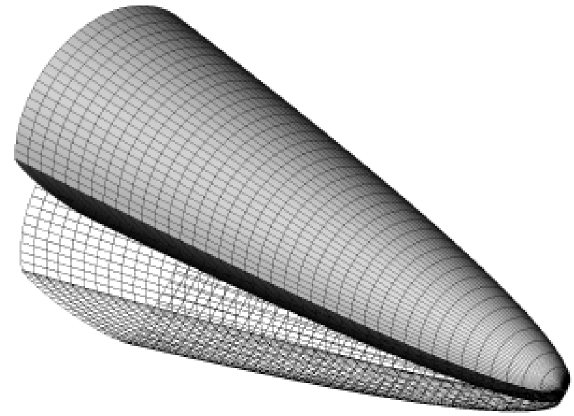
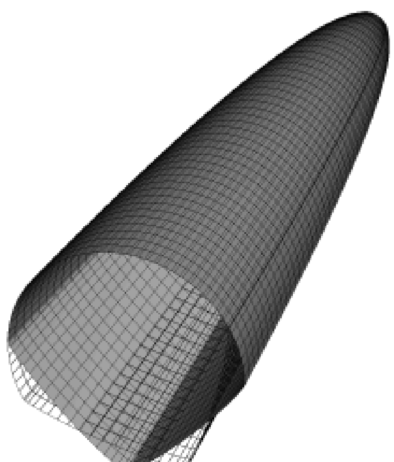
Off-Design Orientation



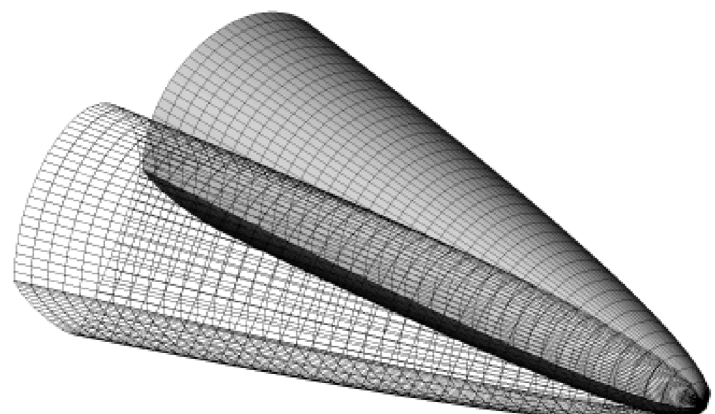
On-design Orientation



Pitch Orientation



Roll Orientation



Yaw Orientation

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Grid Resolution Study

Needed to determine fastest, most accurate grid

- Optimization problem

Use Power-Law Body

- Analytical Solutions

Three Parameters

- Volume Percent Error
- Surface Area Percent Error
- Run-time

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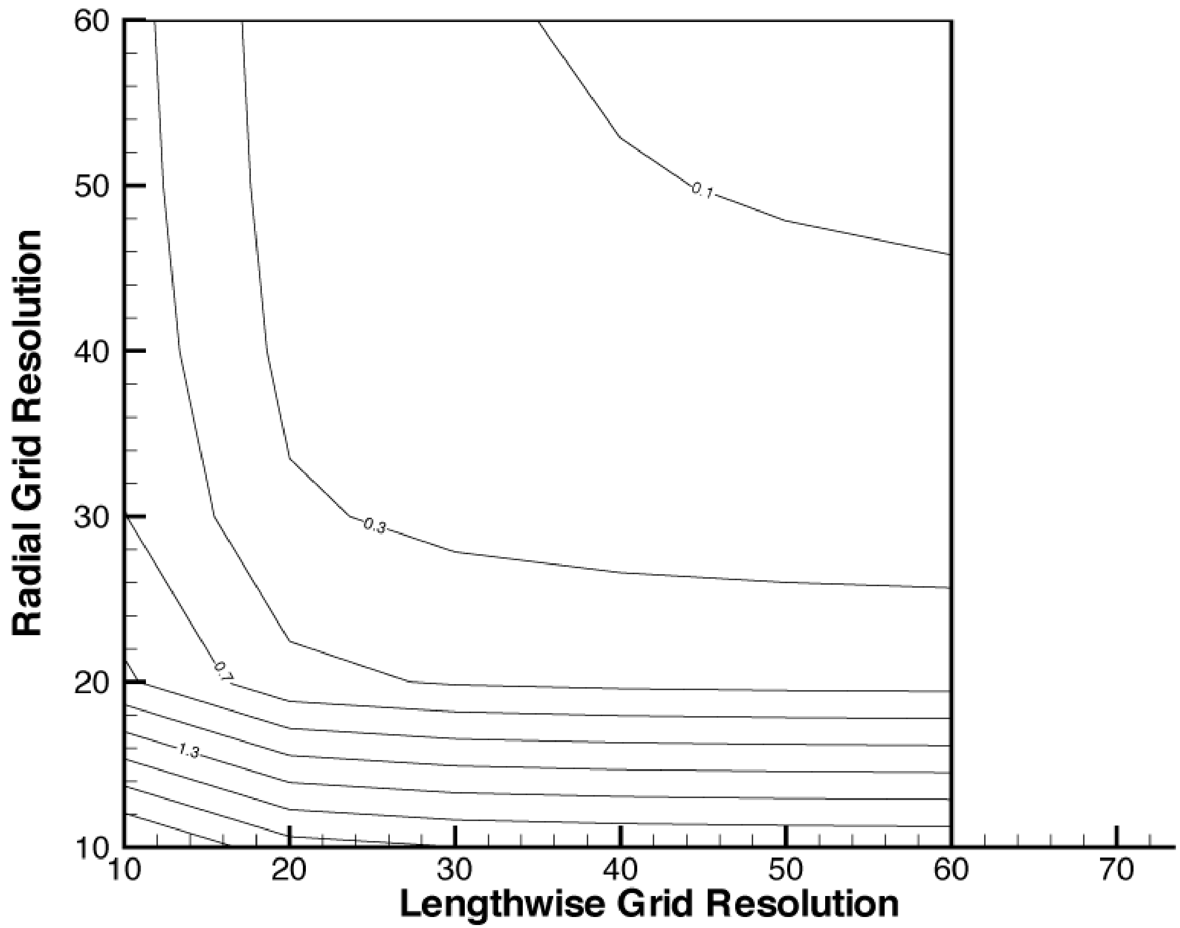
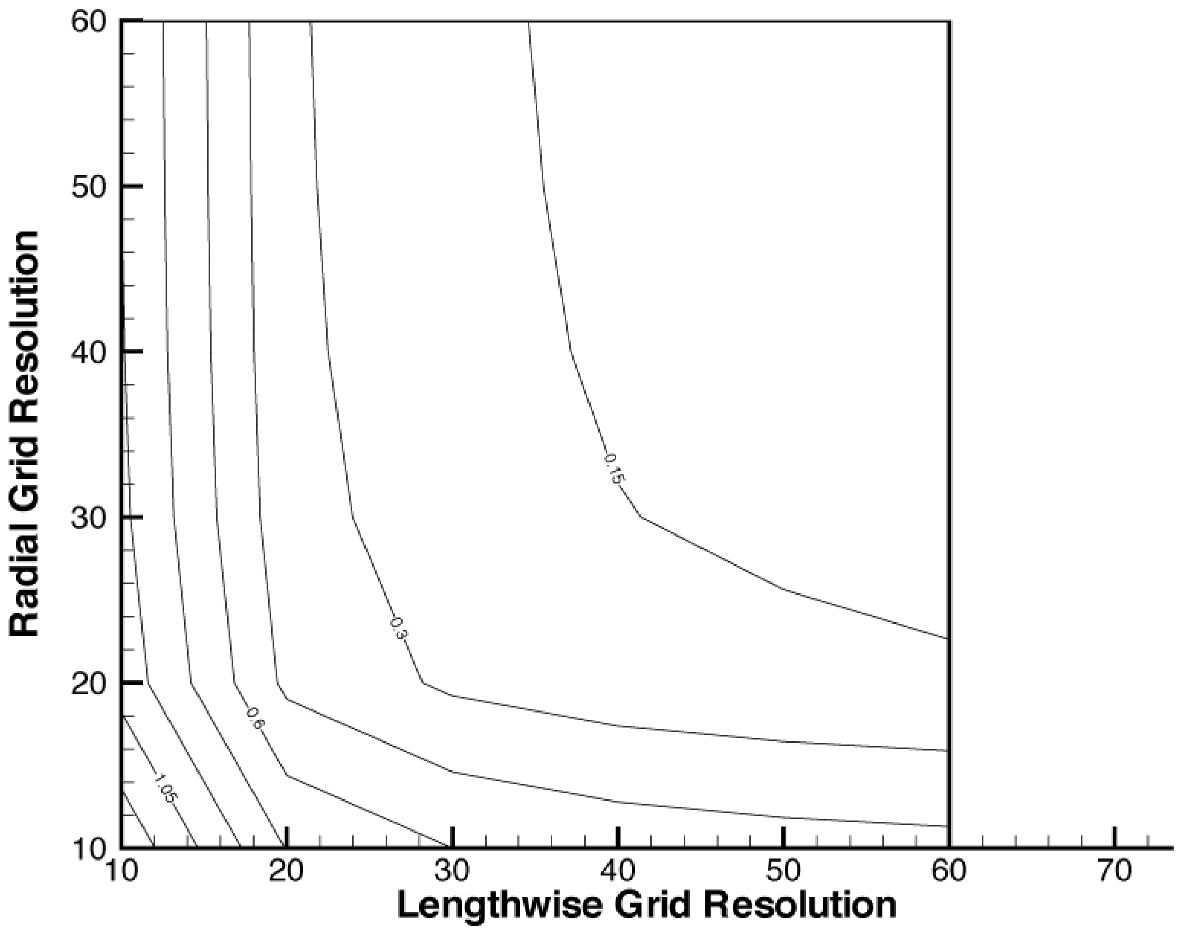
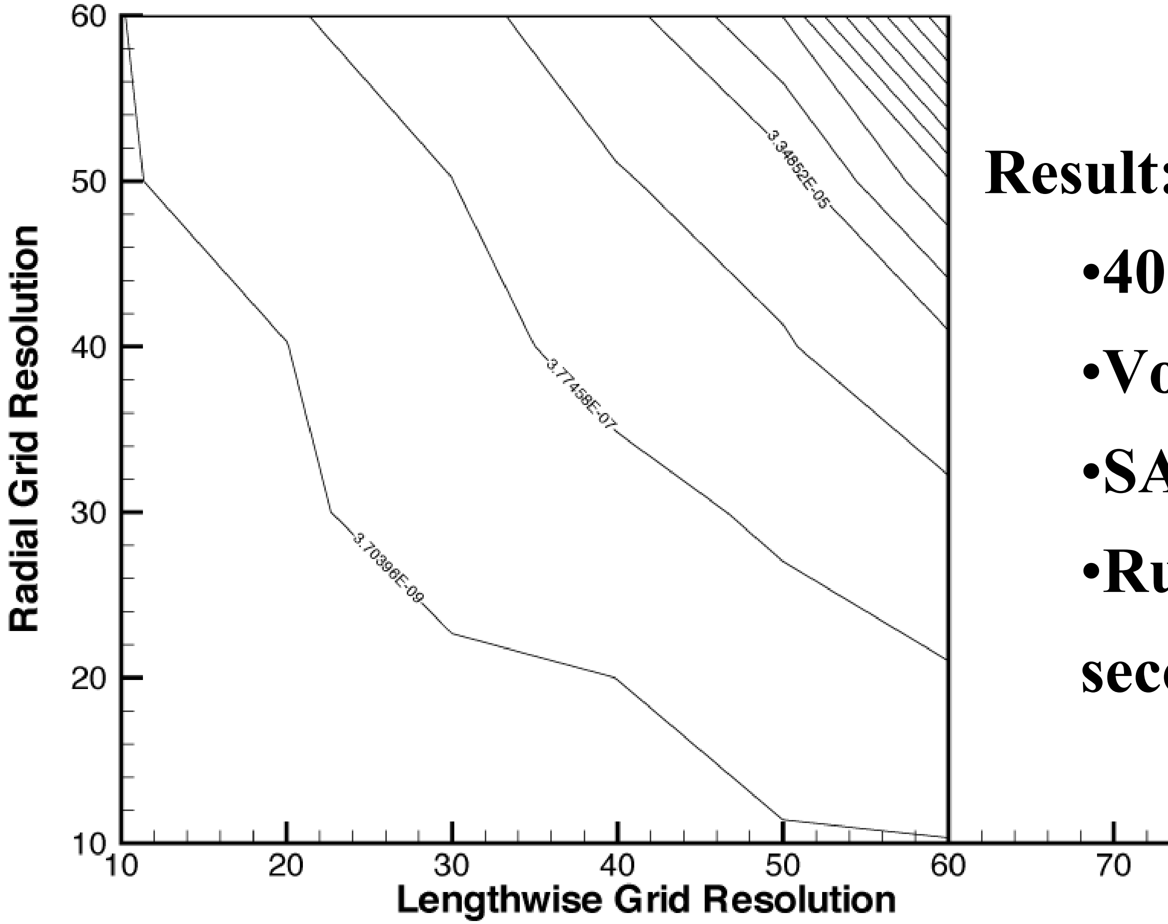
Volume Contours



Surface Area Contours



Run-time Contours



Result:

- **40 x 40 grid per surface**
- **Volume Error: 0.223%**
- **SA Error: 0.133%**
- **Run-time: fraction of a second**

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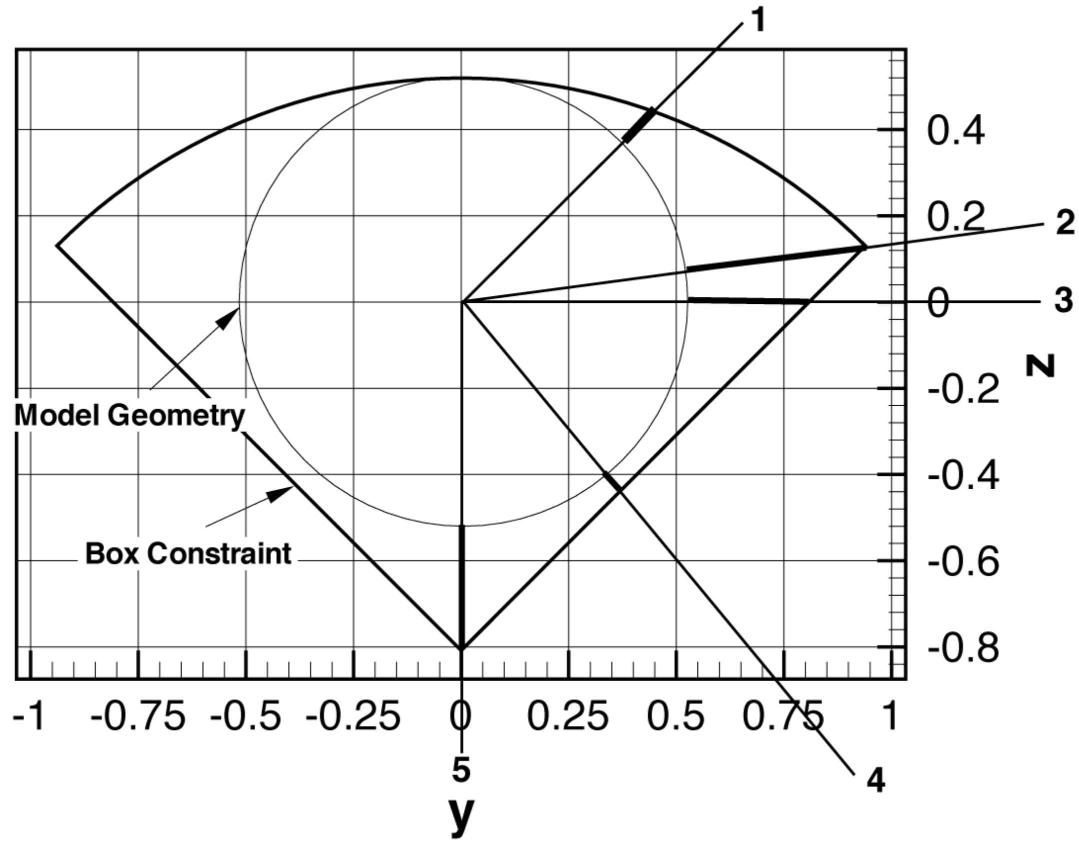
Launch Shroud Constraint



Result: 5 constraints define the launch shroud.

Surface Constraint

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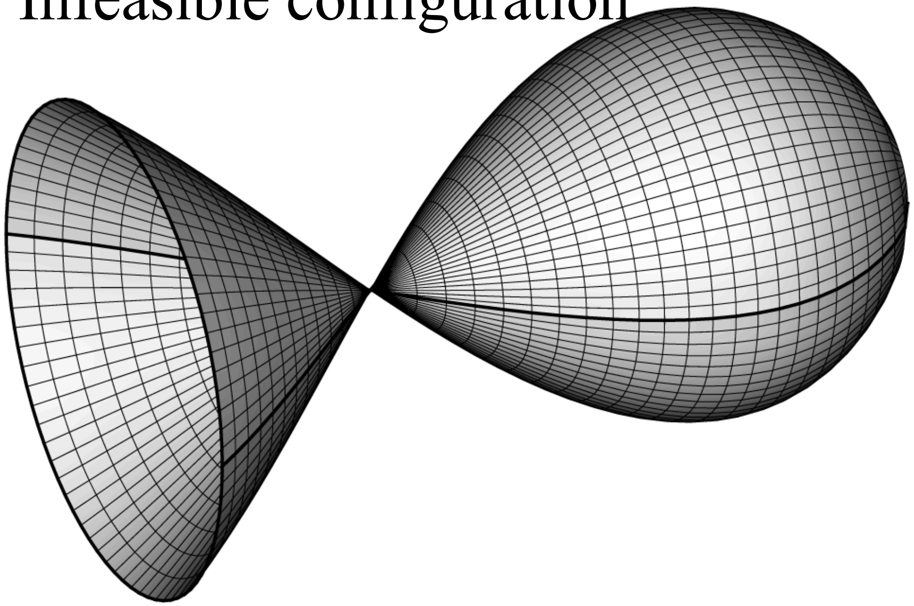
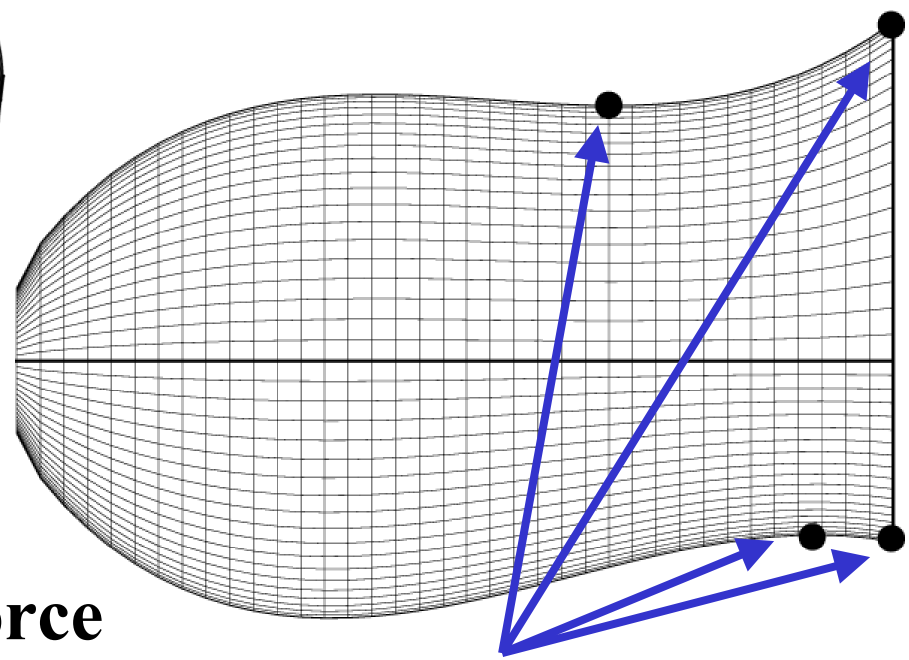
Infeasible configuration





Result: 4 constraints enforce feasible configurations.

Control points based upon configuration

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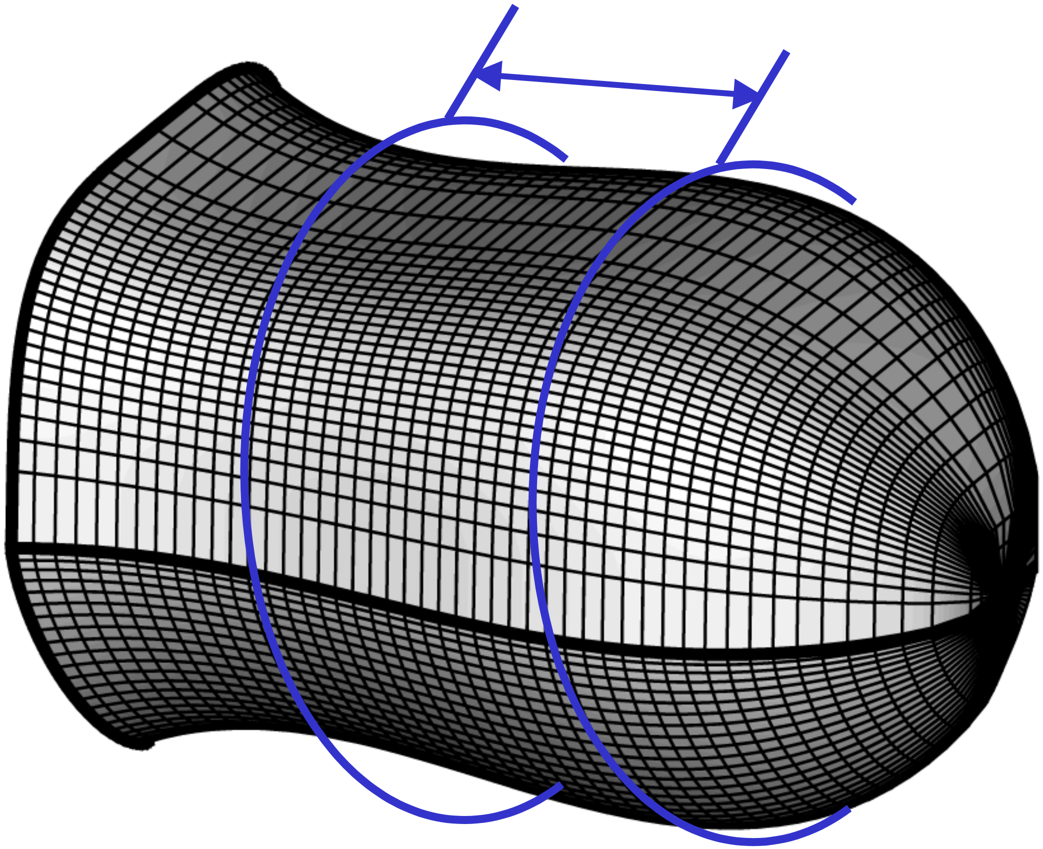
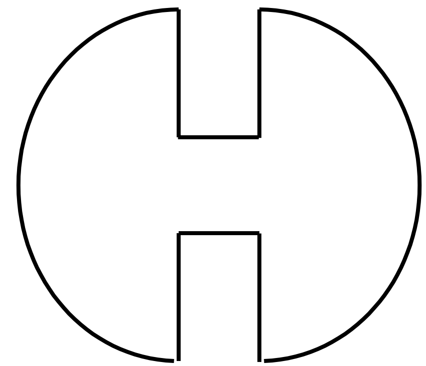
Fuel Tank Constraint





Result: 3 constraints

5	Launch Shroud
4	Surface Feasibility
3	Fuel Tank
12	**Constraints**

Objective Functions

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Three normalized objective functions are maximized:

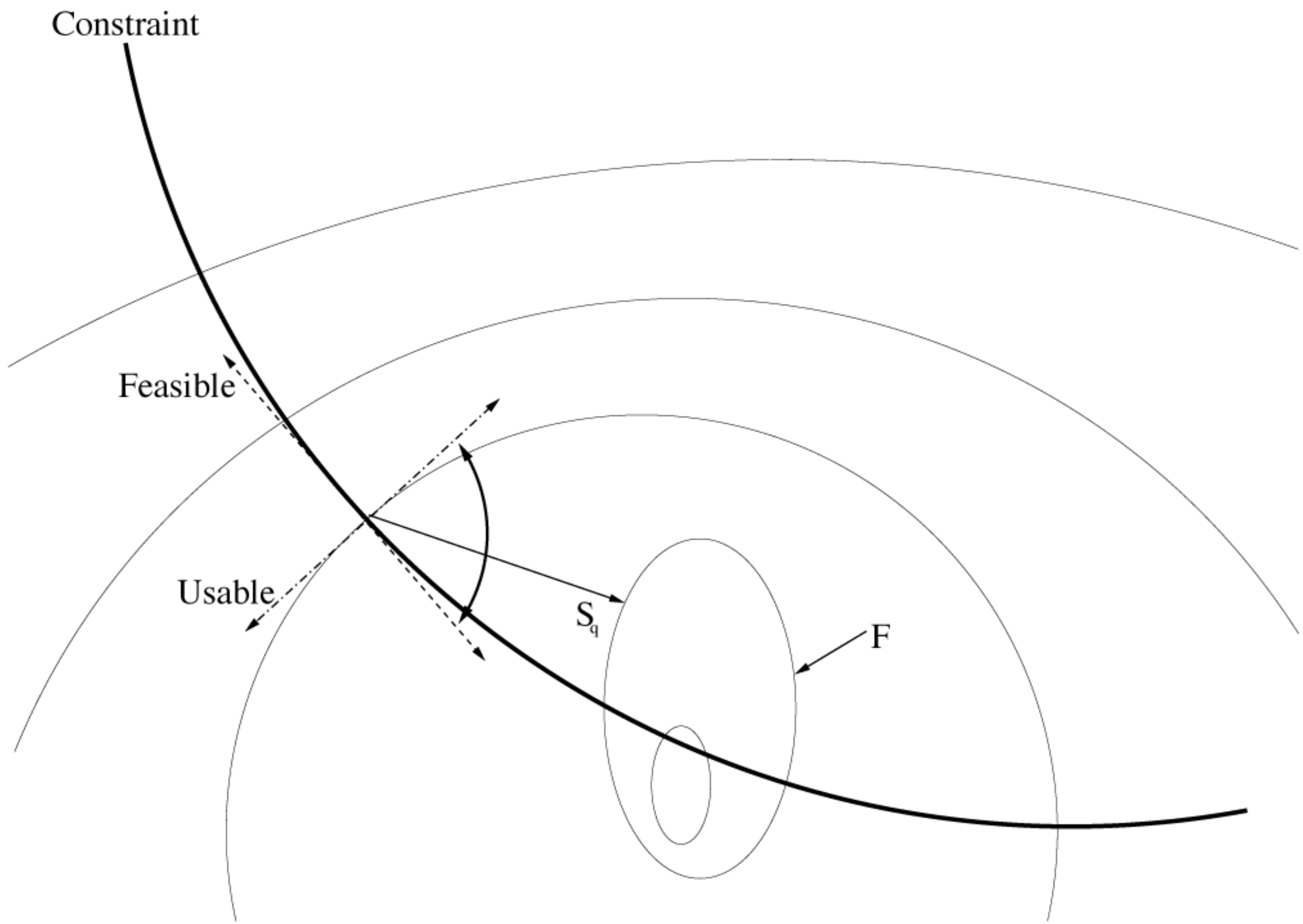
1. Volume/Drag
2. Volume • Moment$_{pitch/yaw}$
3. Volume • L/D

Two molecule reflection conditions:

1. Specular ($\xi = 1$)
2. 75% Diffuse ($\xi = 0.25$)

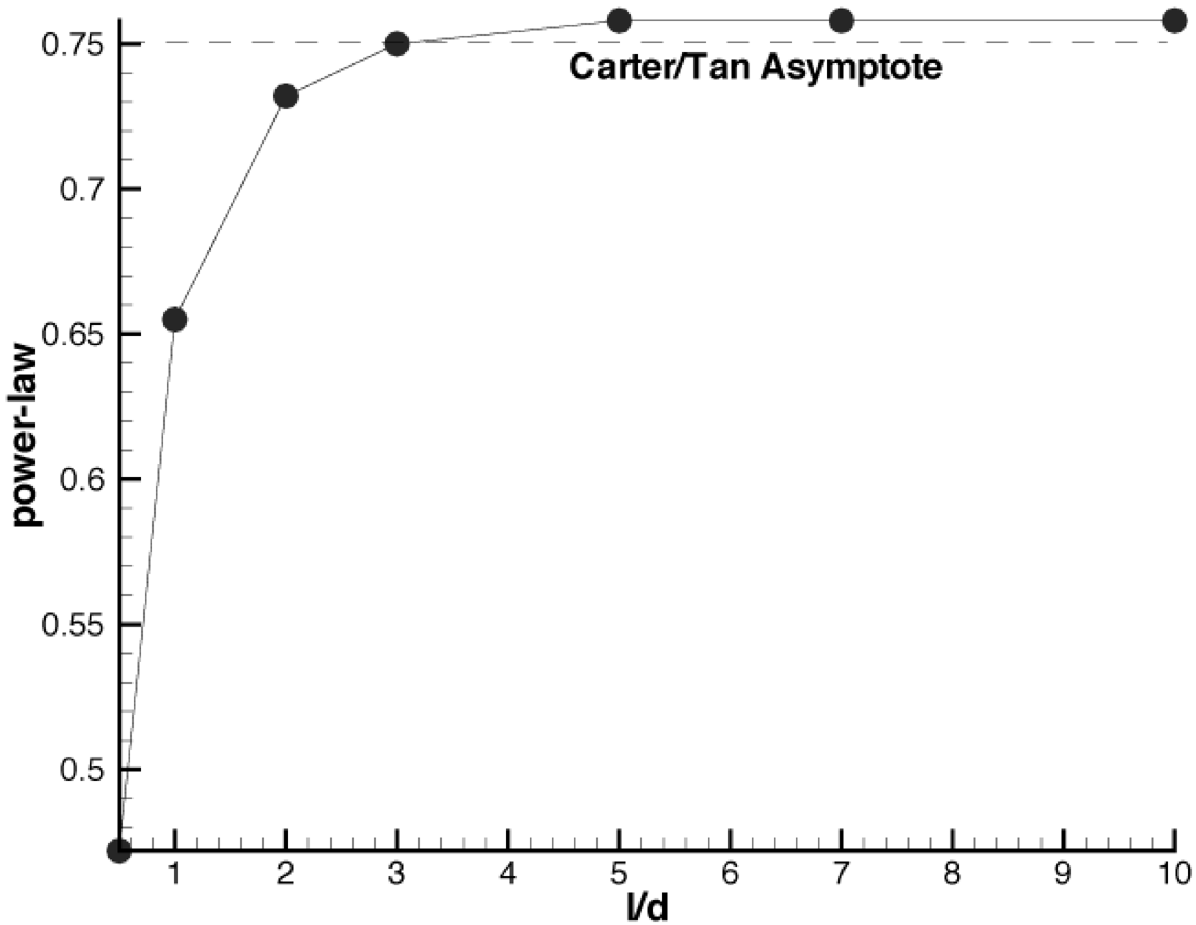
Moment$_{pitch/yaw}$ is evaluated at +5° pitch, -5° pitch, +5° yaw

Method of Feasible Directions



Comparison to Carter/Tan

For minimum drag under conditions of specular reflection and no thermal velocity, Carter/Tan predicted a solution near $x^{3/4}$.



Reduced Design Variable Studies

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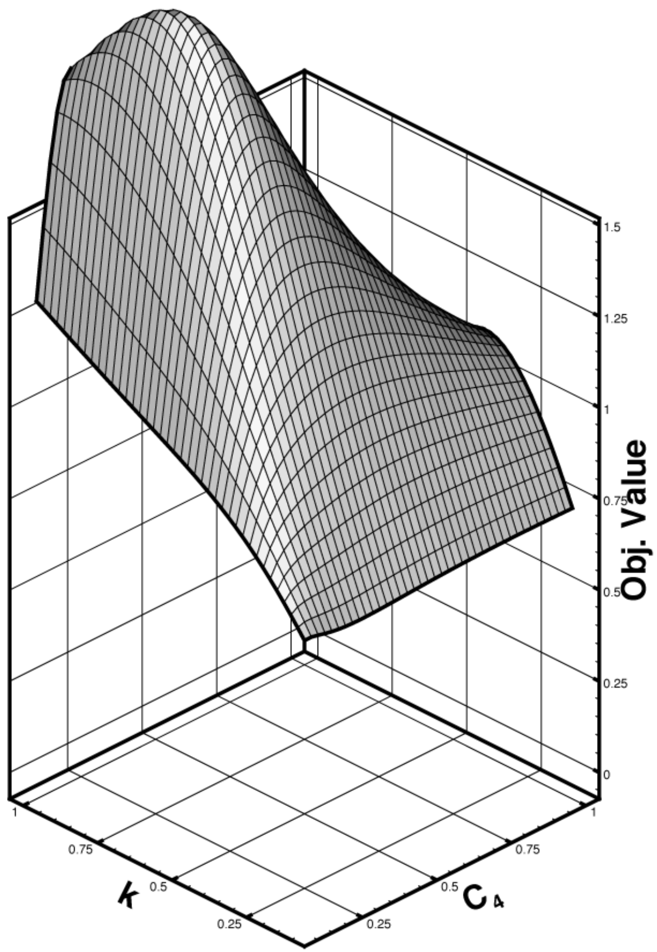
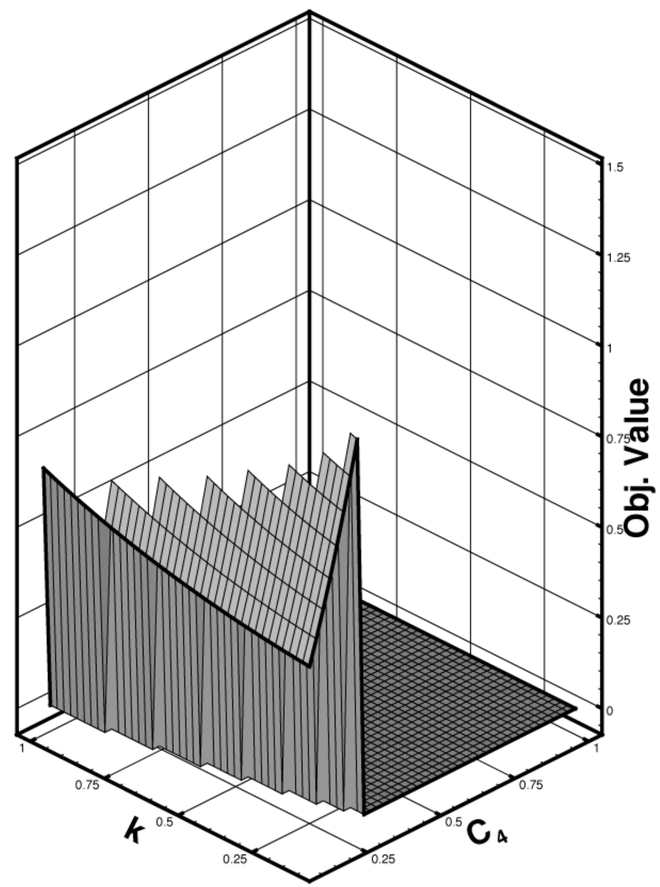
In order to generate initial designs, several reduced design variable studies are conducted (specular assumption):

- Feasible axisymmetric power-law shapes (2 DV's)
- Feasible axisymmetric polynomial shapes (3 DV's)
- Reduced drag, zero-lift (7 DV's)
- Maximum volume power-law (7 DV's)

Axisymmetric Power-Law Shapes



No constraints



Launch shroud constraints added.

Axisymmetric Power-Law Shapes (cont.)

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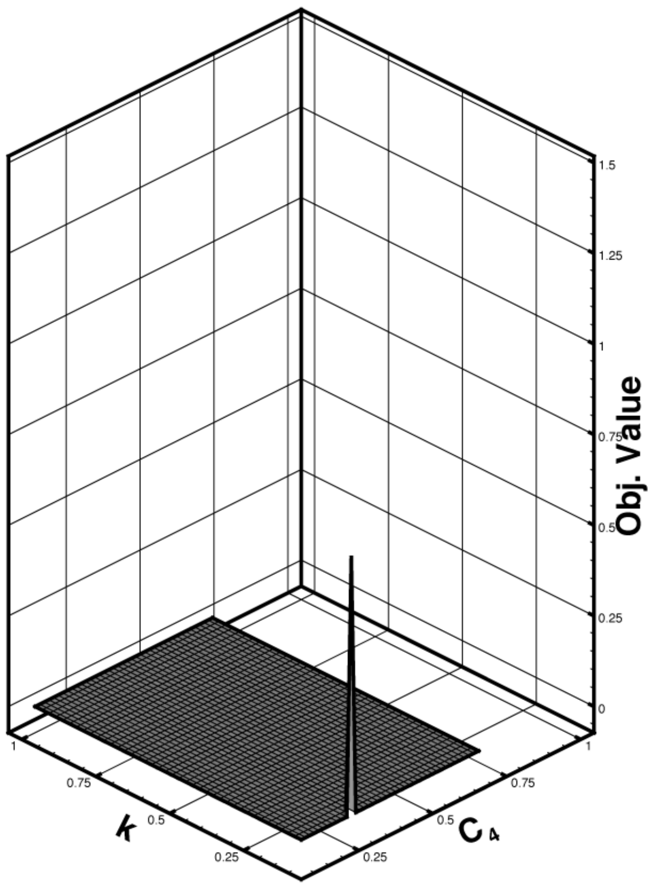
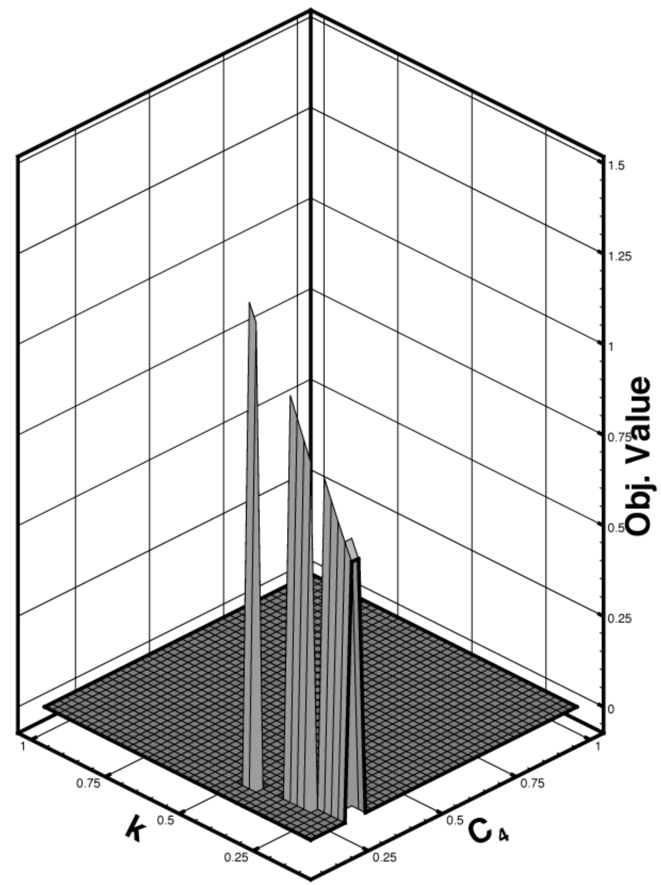


Fuel tanks added.



Fuel tank moved to rear.

Axisymmetric Power-Law Shapes (cont.)

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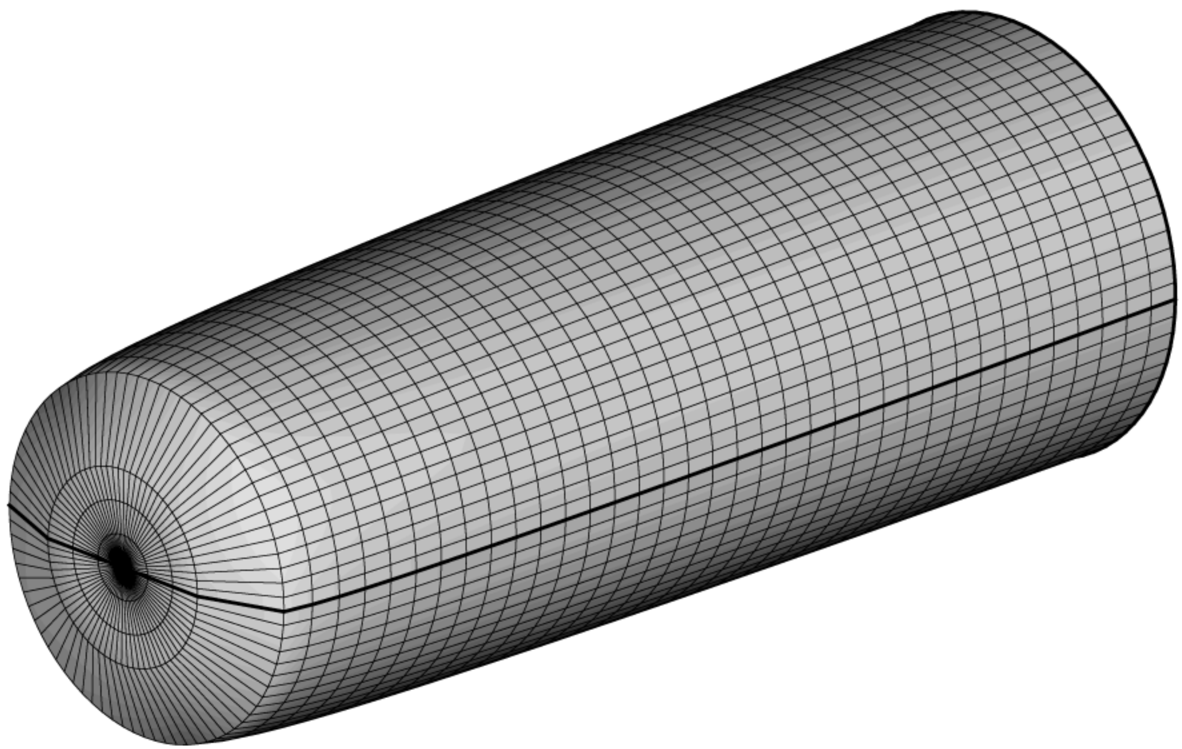

The one design feasible design of 1600 tried.

Axisymmetric Polynomial Shapes

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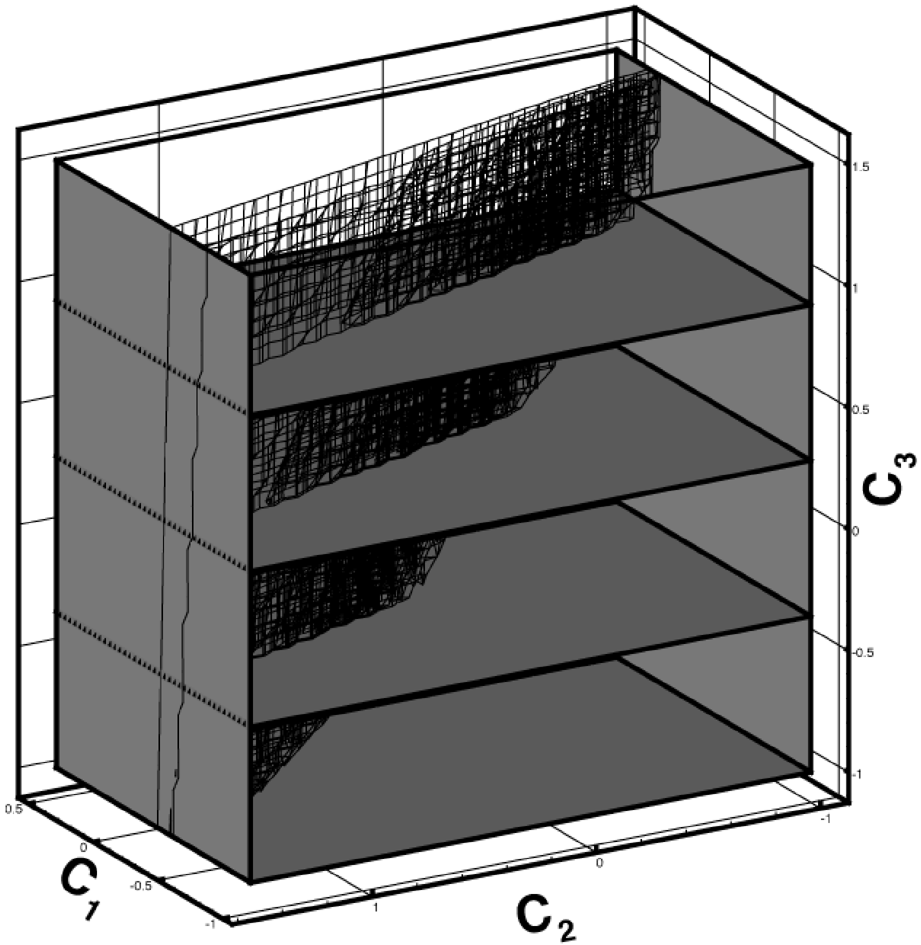
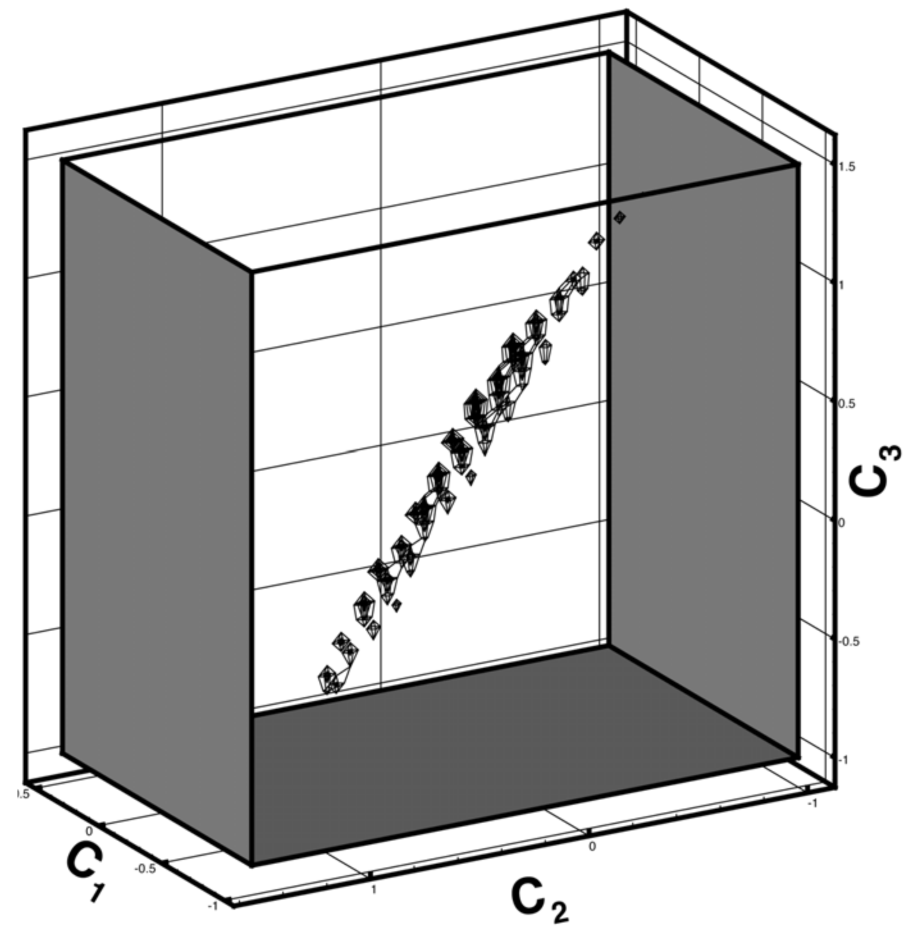
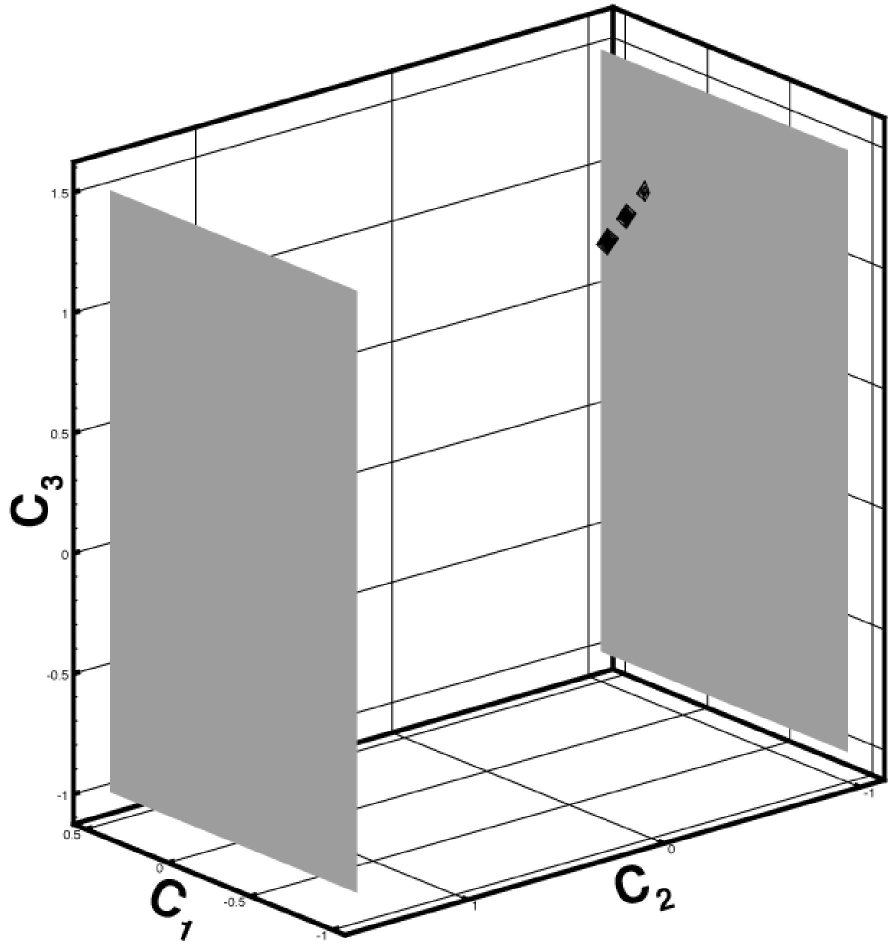


Surface feasibility.



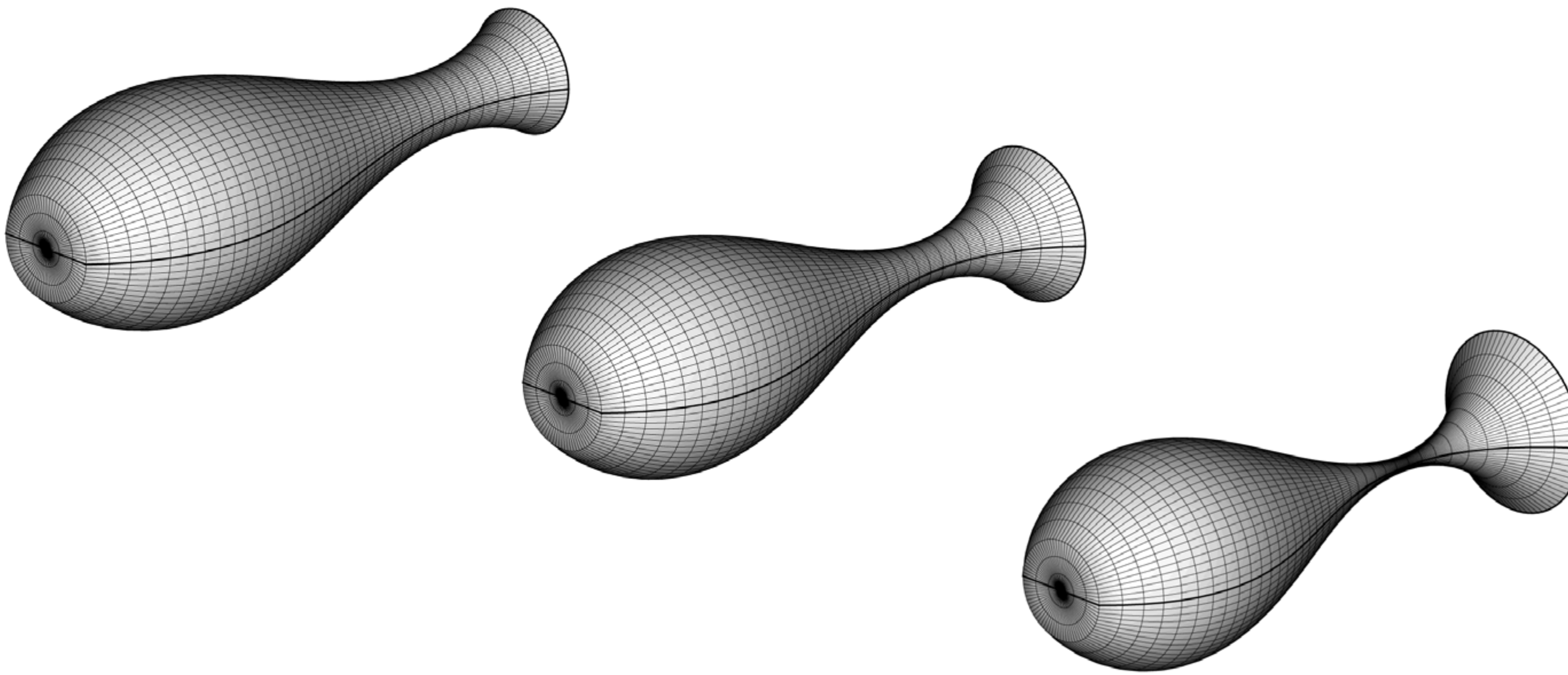
Launch shroud constraints added.

Axisymmetric Polynomial Shapes (cont.)



Fuel tank constraints added.

Axisymmetric Polynomial Shapes (cont.)



The three feasible configurations of 64,000 tried.

Zero-Lift Shapes

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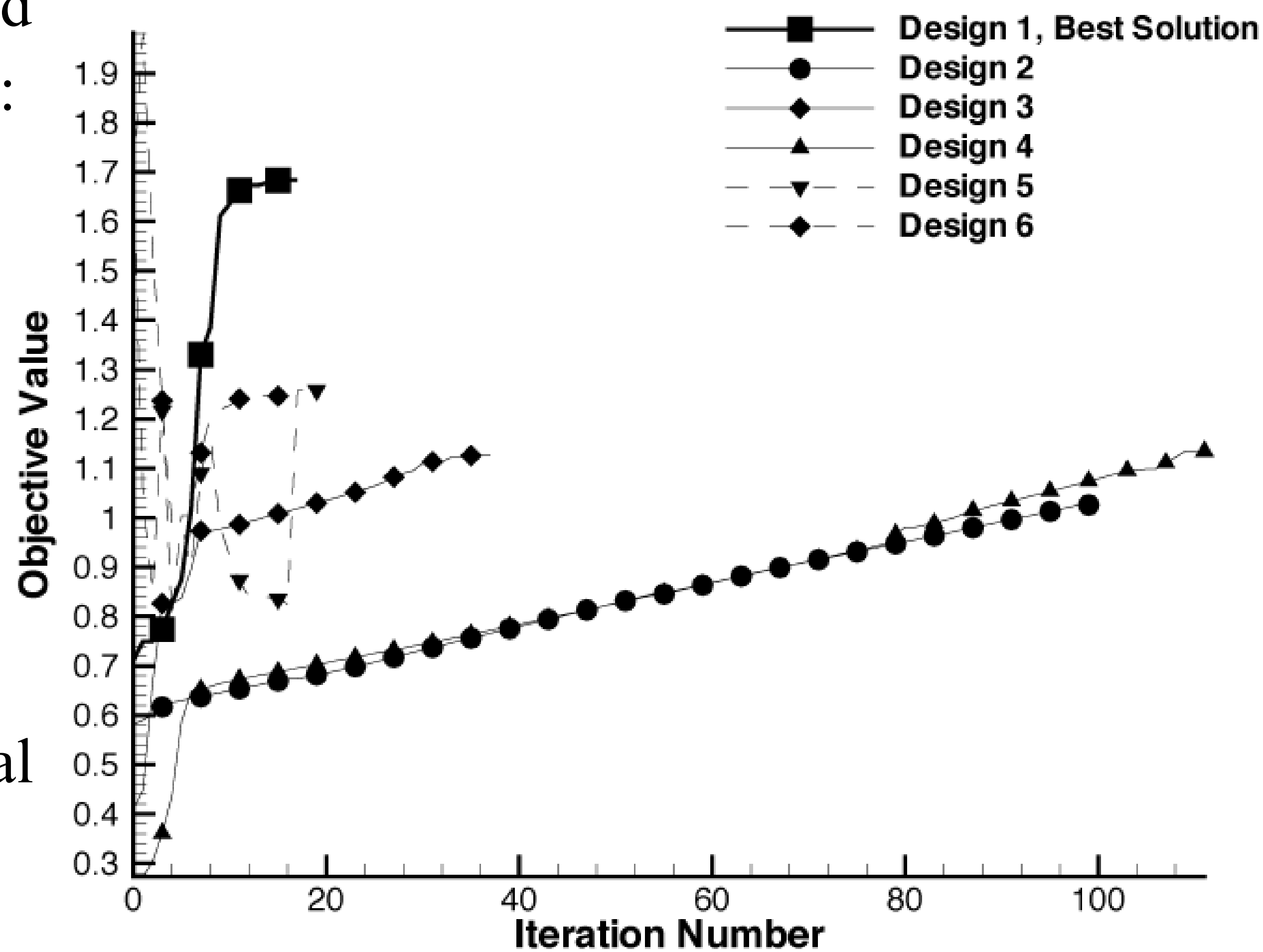
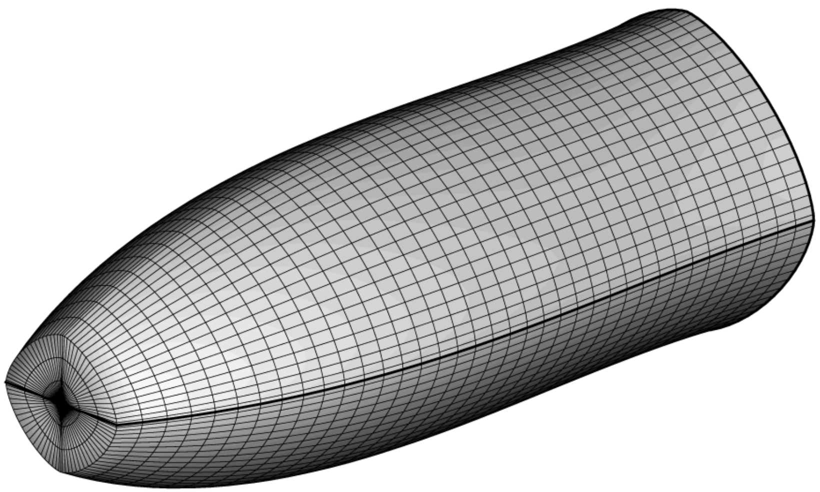
Optimized for reduced drag using six shapes:

- 1 power-law
- 3 polynomial
- 1 high eccentricity power-law
- 1 low eccentricity power-law

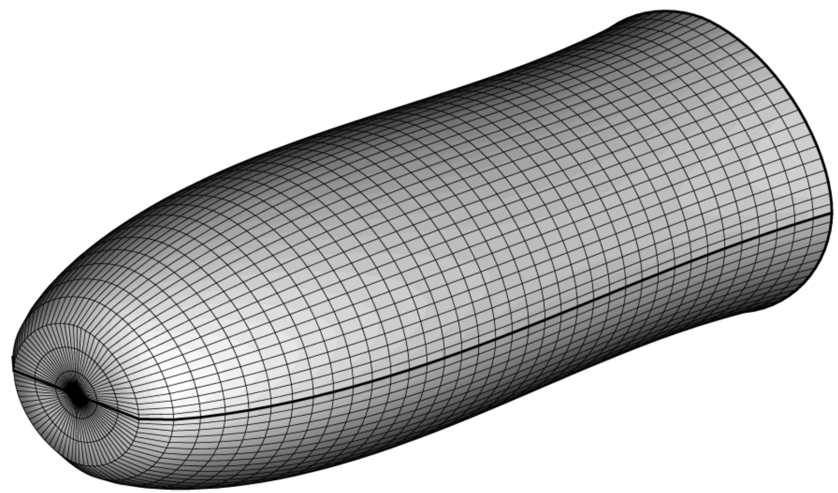
Design space has local minima.



Zero-Lift Shapes (cont.)



The "best" zero-lift shape.



The "second-best" zero-lift shape.

Maximum Volume Shapes

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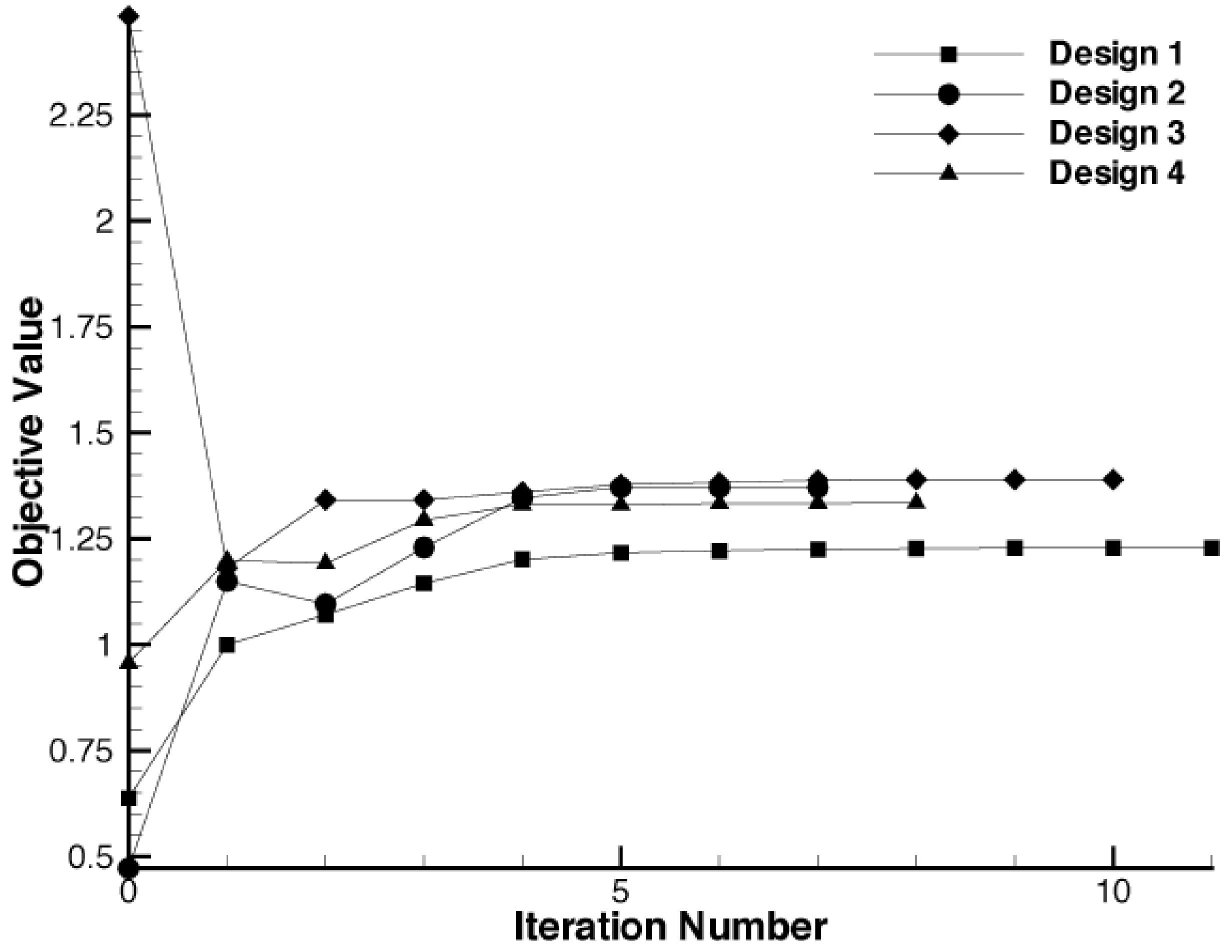
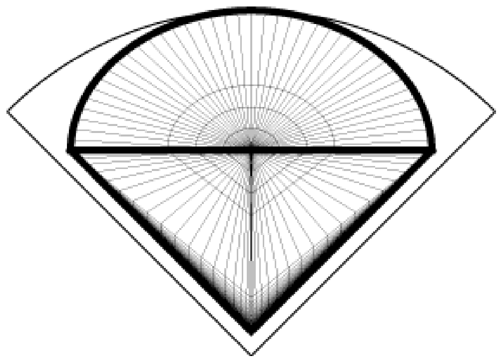
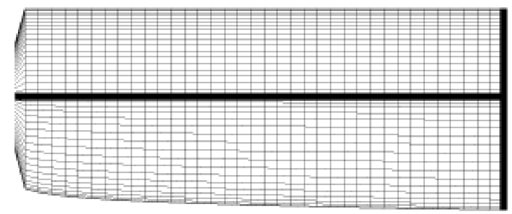
- •Power-law shapes only
- •Design space does not exhibit local minima problem.



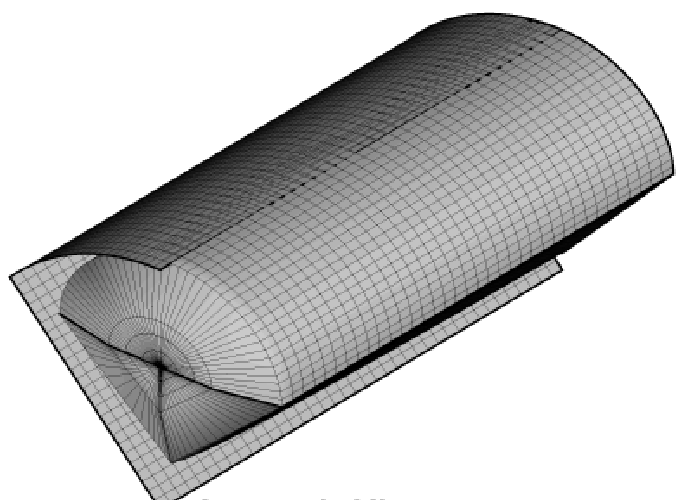
Maximum Volume Shapes (cont.)



Rear View



Profile View



Isometric View

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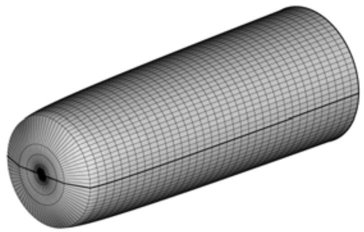
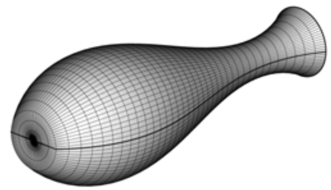
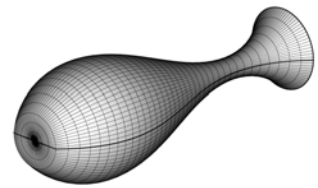
Results of Study



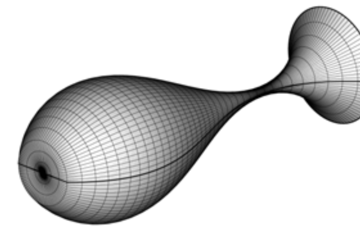
Design 1



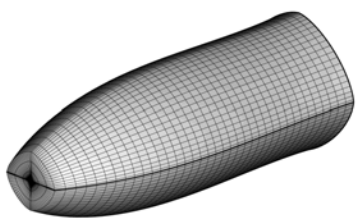
Design 2



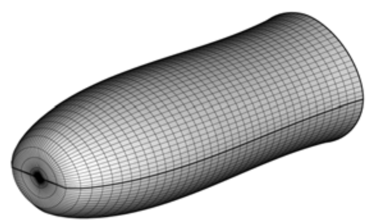
Design 3



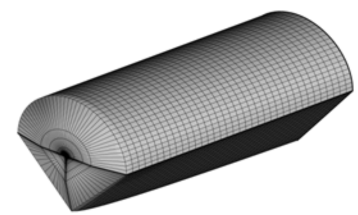
Design 4



Design 5



Design 6



Design 7

Result: Seven feasible designs.

Specular Reduced Drag Study

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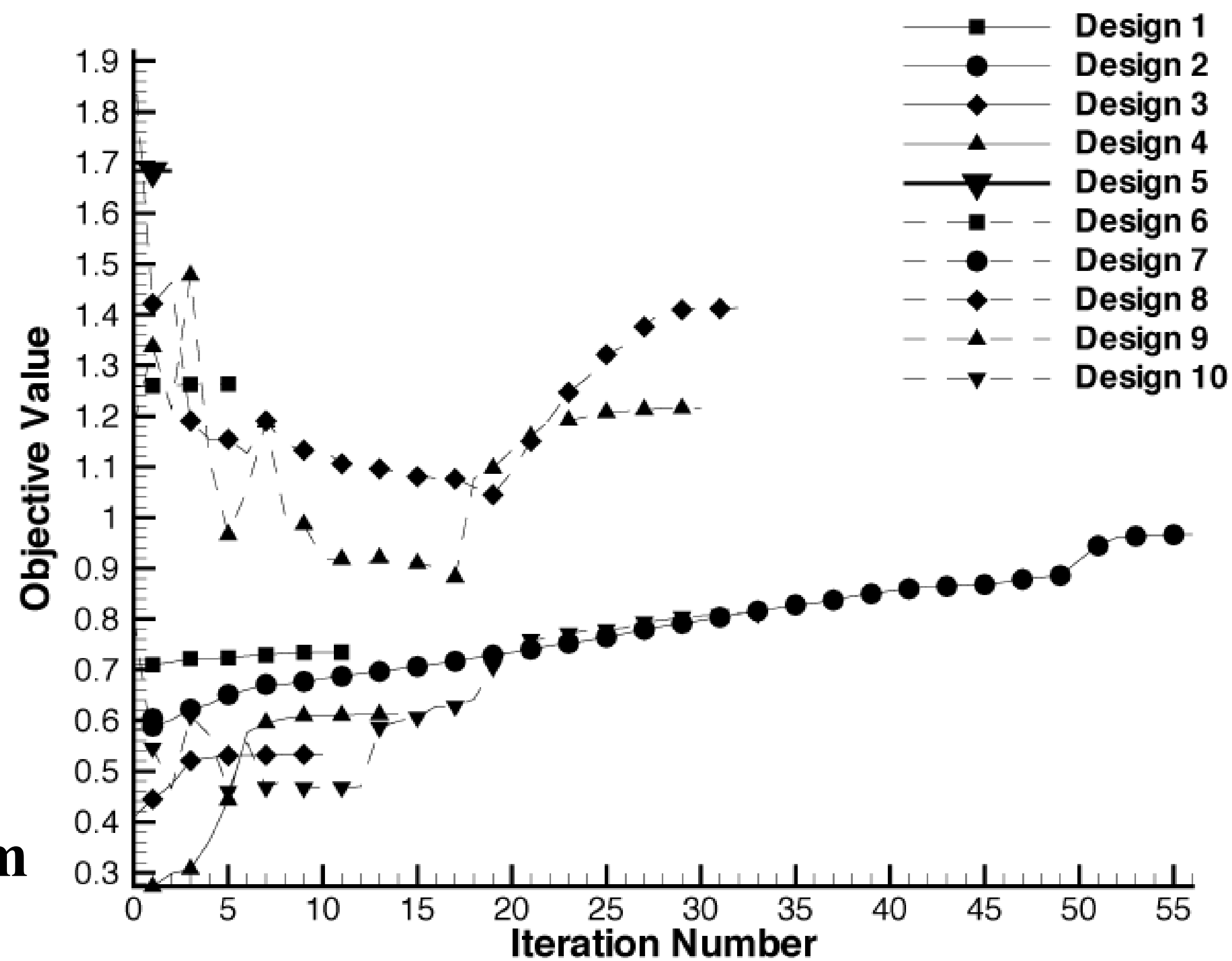
- •Three more initial designs added.
- •None of the initial designs converged to the same optimal solution.



Result: The zero-lift design is an optimum in this design space.

Specular Reduced Drag Study (cont.)

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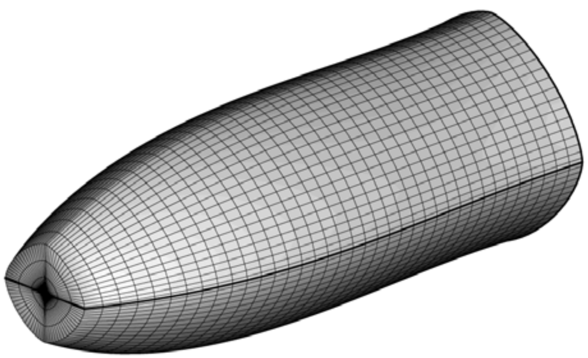

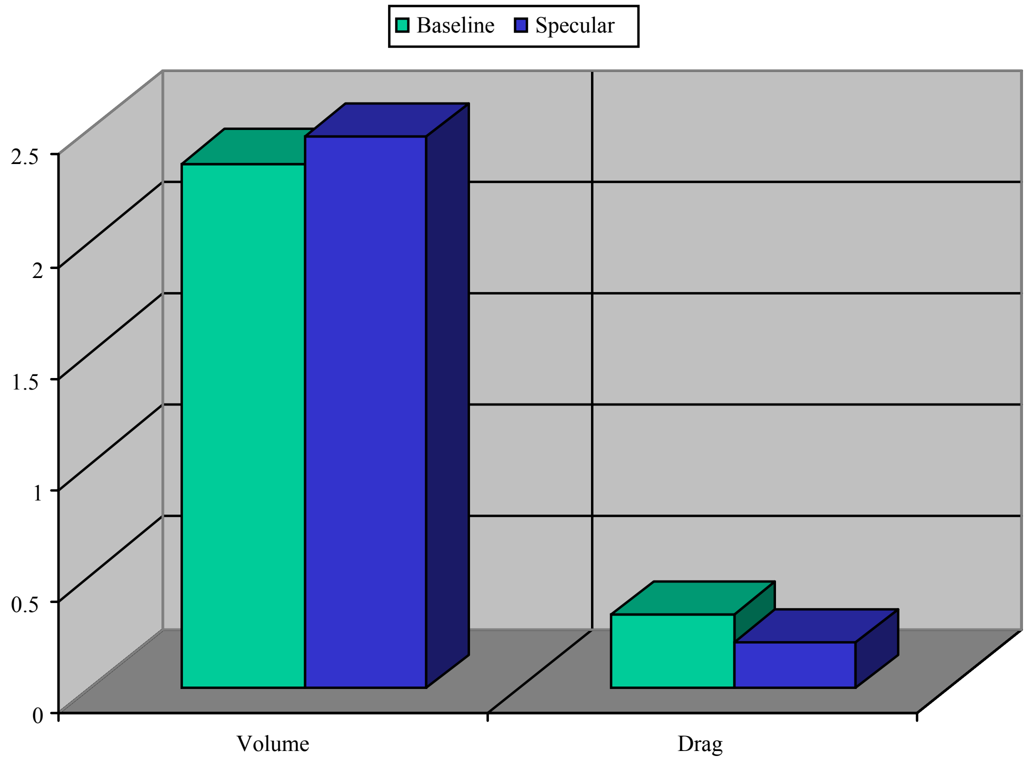

Result: Not similar to GEC cylindrical design BUT increased volume 5% and decreased drag 38%.

Specular Reduced Drag Study (cont.)

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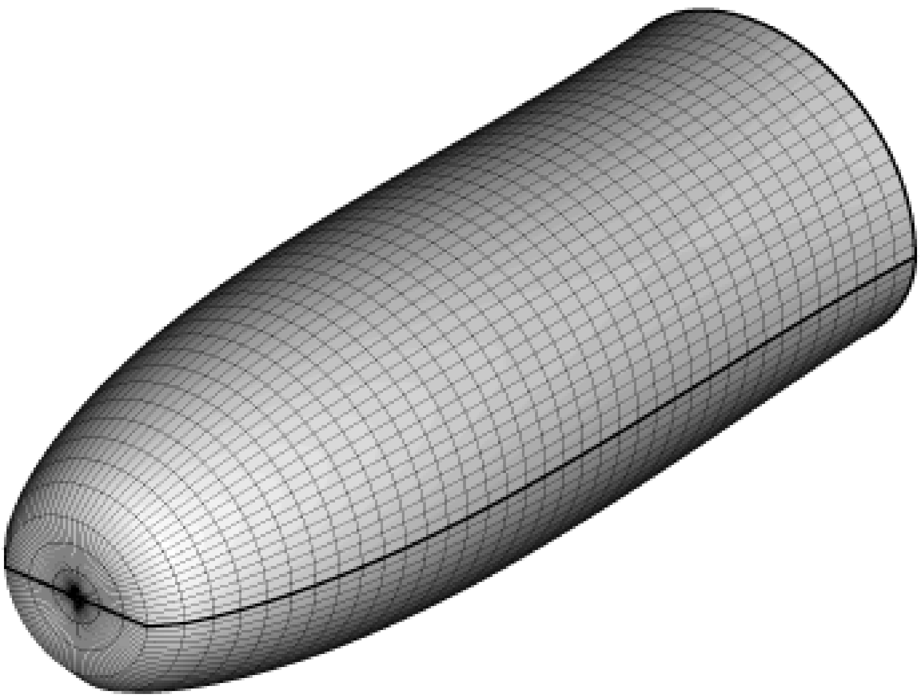

Result: Second optimum also has higher volume (8%) and lower drag (24%) and is similar to GEC cylindrical design.

Diffuse Reduced Drag Study

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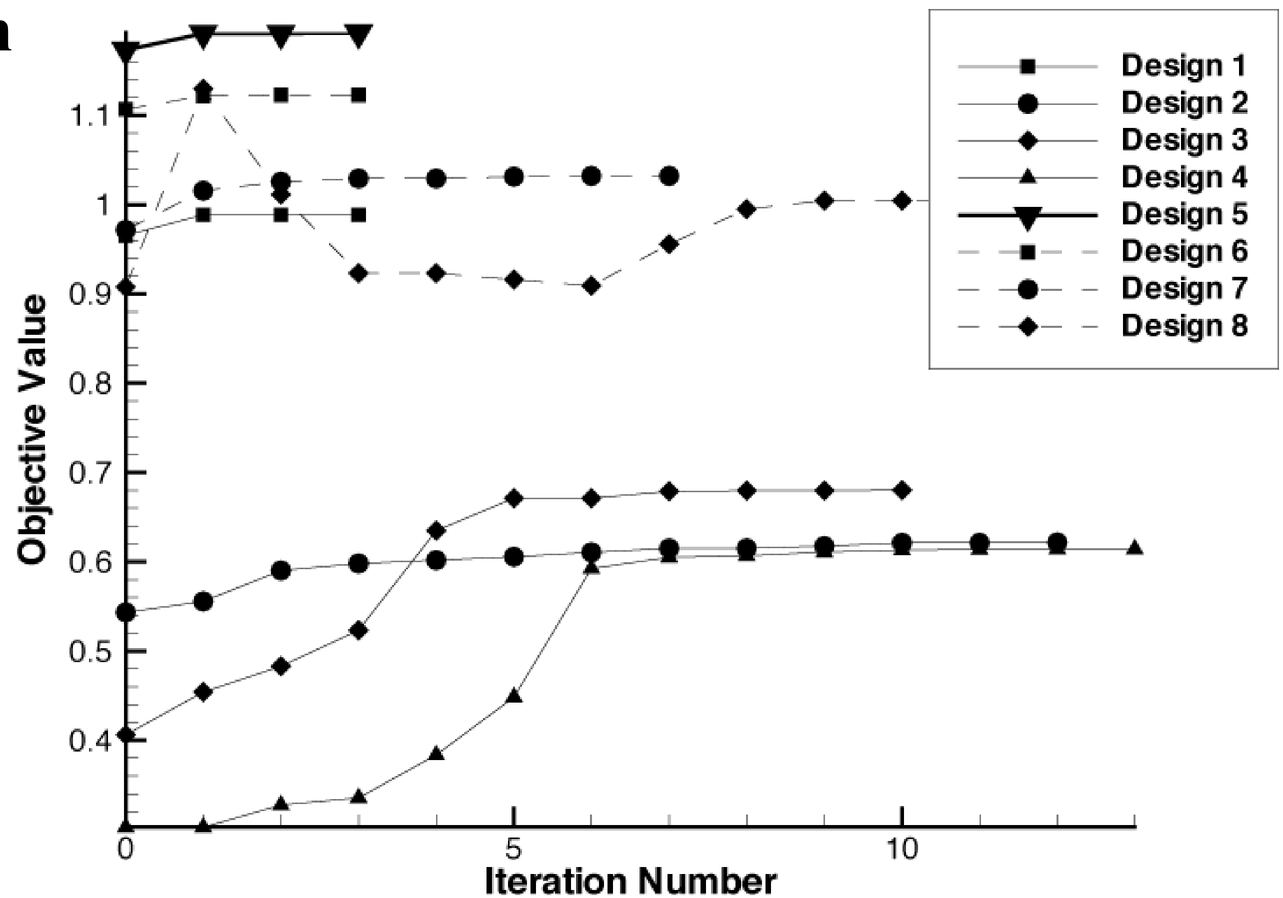
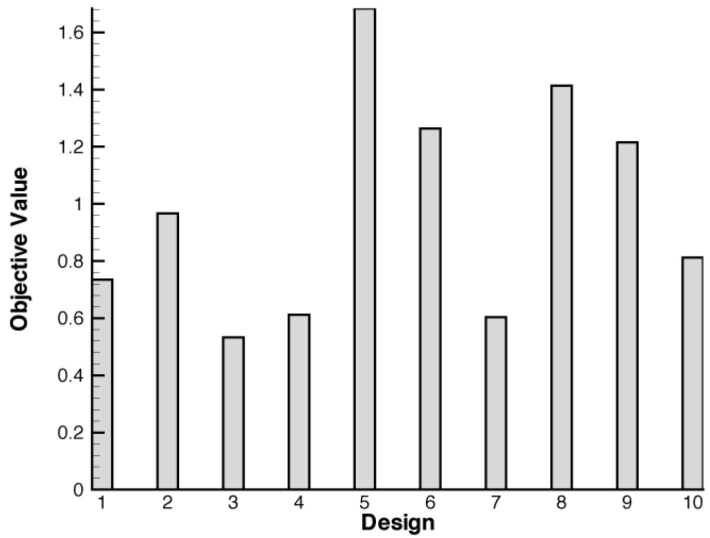
Result:

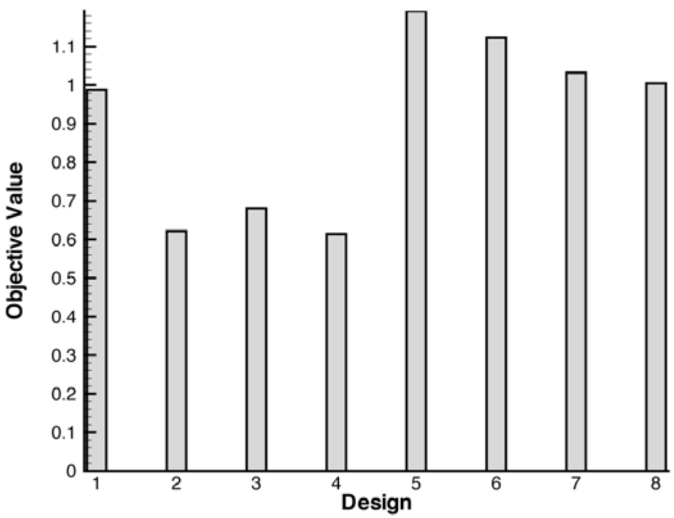
- **The zero-lift design produced the best configuration.**
- **For this constrained problem, the optimum is a weak function of reflection assumption.**



Reduced Drag Study (cont.)

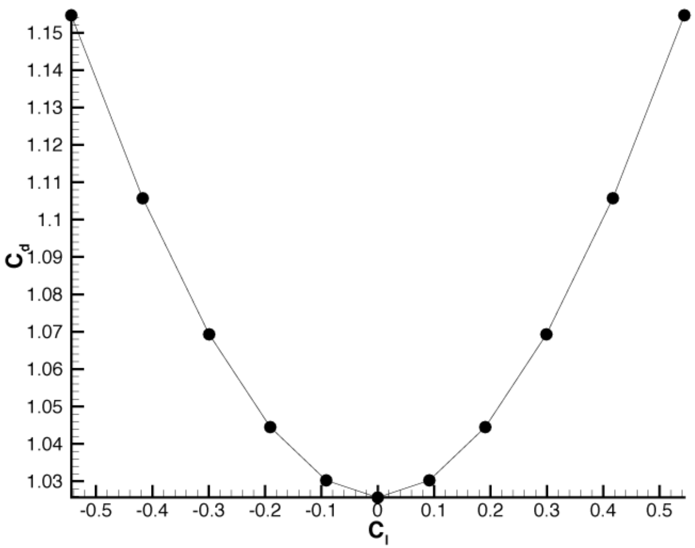


Specular

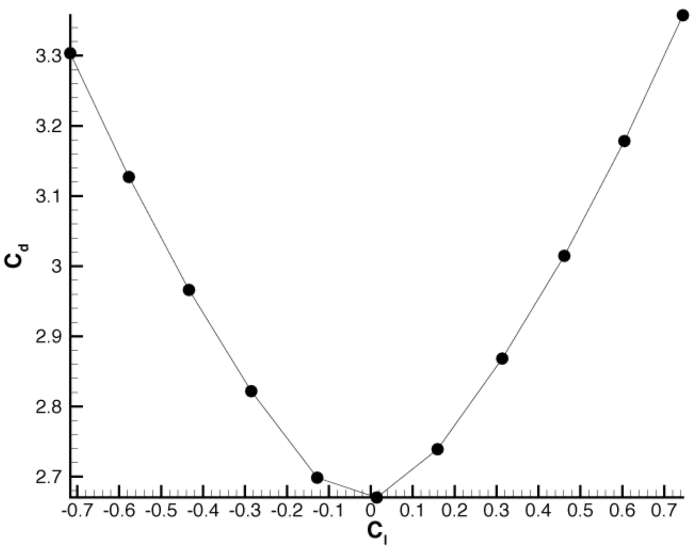


Diffuse

Reduced Drag Study (cont.)

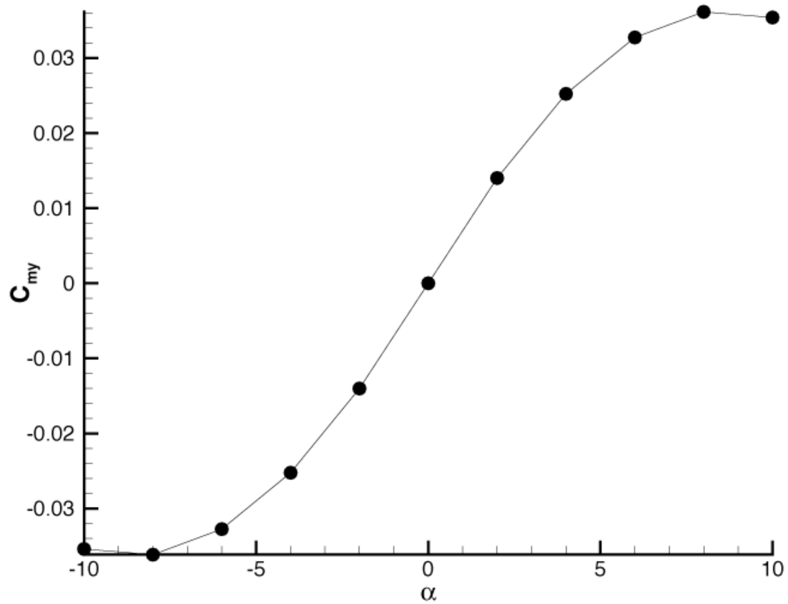


Specular

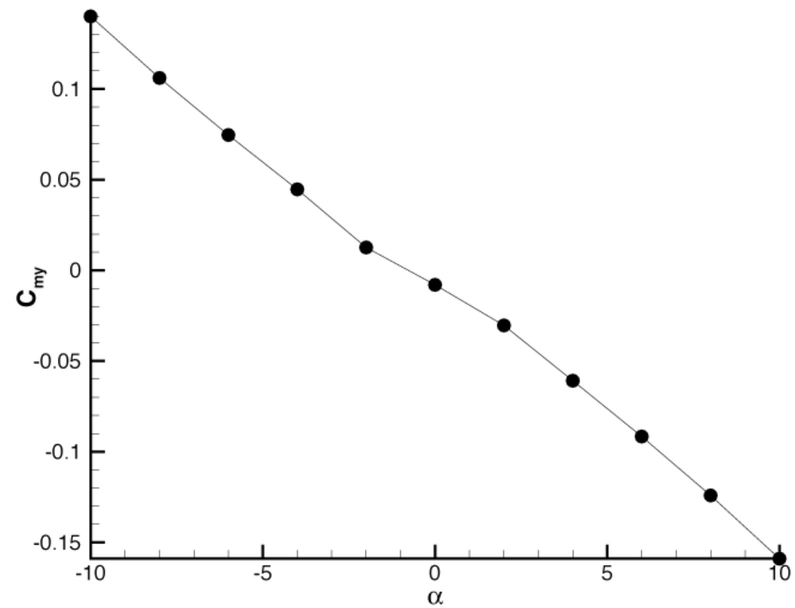


Diffuse

Reduced Drag Study (cont.)

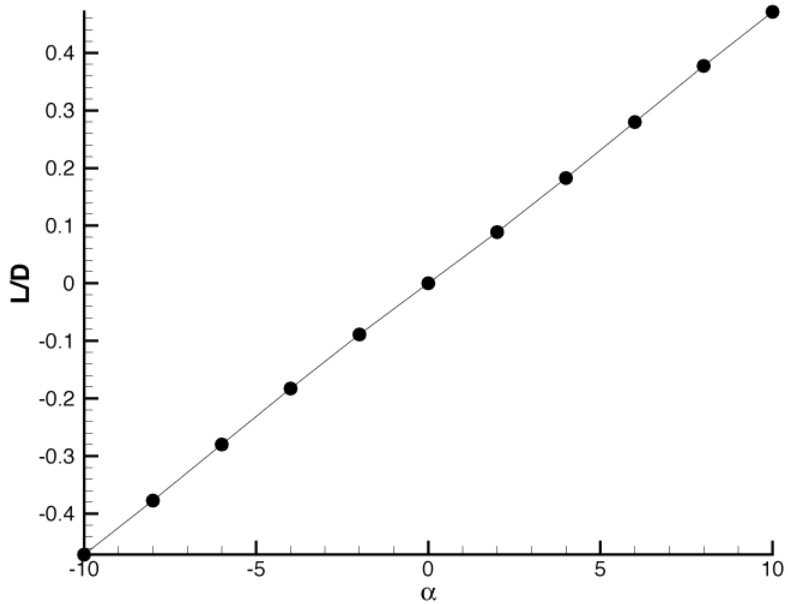


Specular

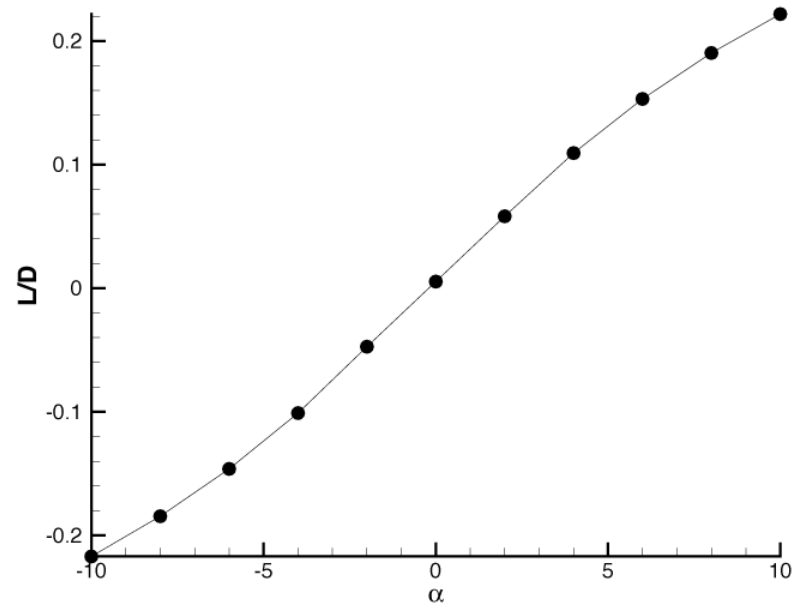


Diffuse

Reduced Drag Study (cont.)



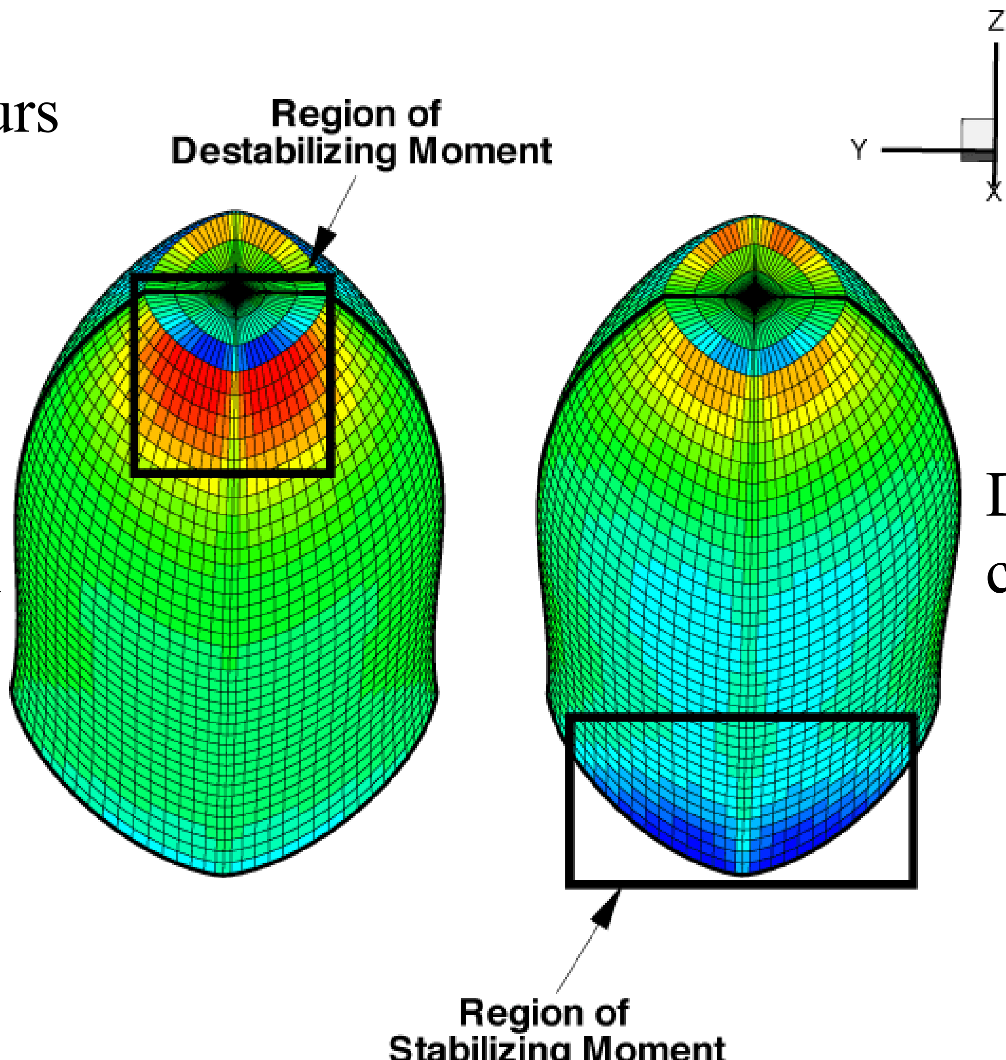
Specular



Diffuse

Reduced Drag Study (cont.)

Moment Contours



Specular configuration

Diffuse configuration

Reduced Drag Study Conclusions

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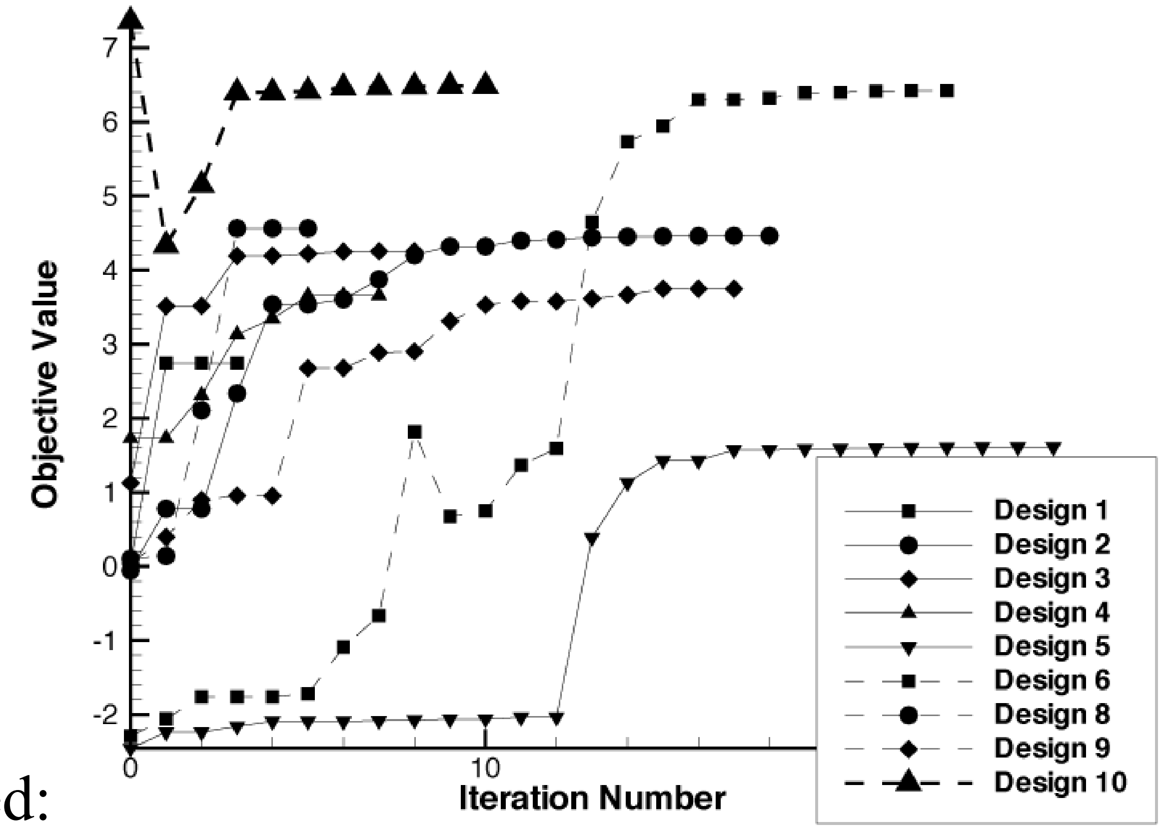
- Found higher volume, lower drag shapes compared to GEC (for both reflection assumptions).
- Design space has local optima.
- "Best" shape was zero-lift.
- Design space changed due to reflection assumption, but the "best" shape did not.
- Stability is a problem for these reduced drag shapes.

Specular Passive Stability Study

Three new constraints added:

- •Negative moment for postive pitch angle
- •Positive moment for negative pitch angle
- •Negative moment for positive yaw angle



Ten initial designs are used:

- •Maximum volume design is infeasible
- •Many local optima

Specular Passive Stability Study (cont.)

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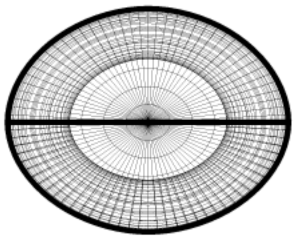
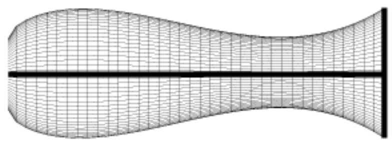
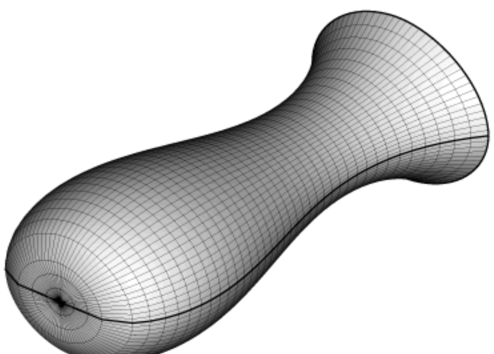


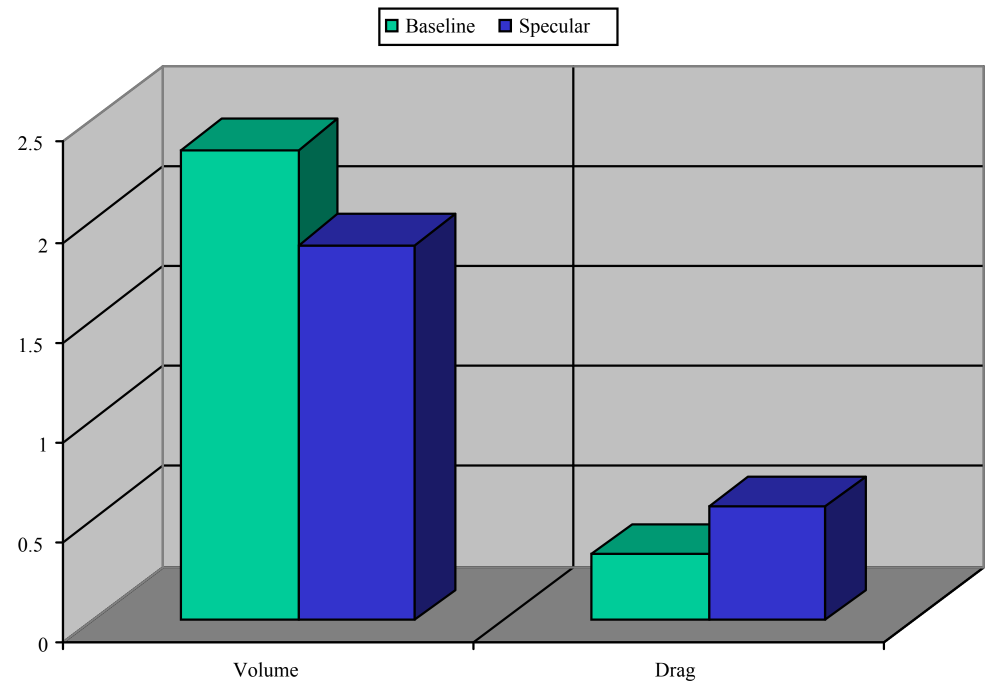
Rear View



Profile View



Isometric View



Result: Stabilizing moment can be produced through optimization, but there are tradeoffs. Volume decreased 20% and drag increased 73%.

Specular Passive Stability Study (cont.)

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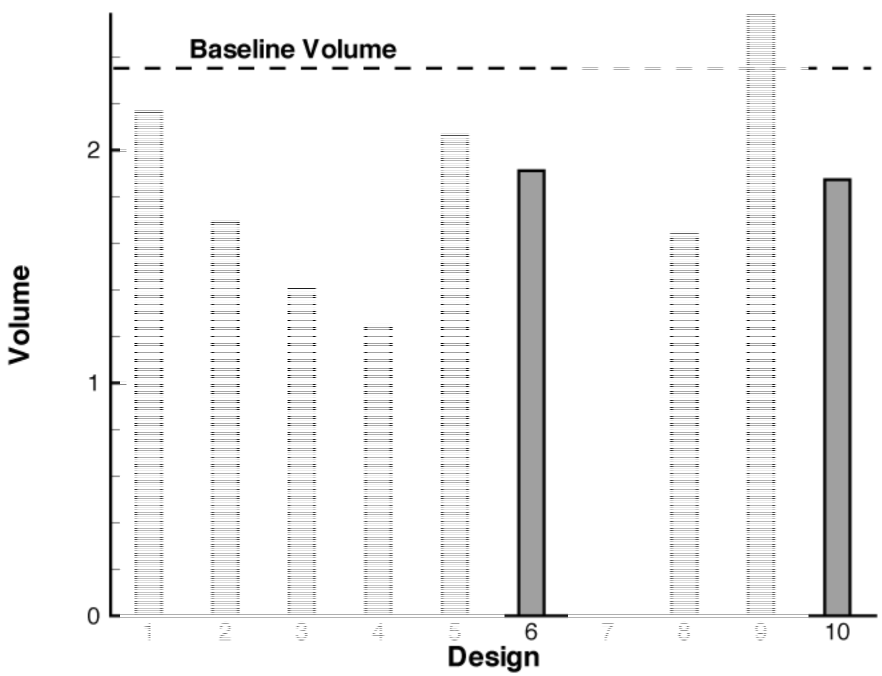

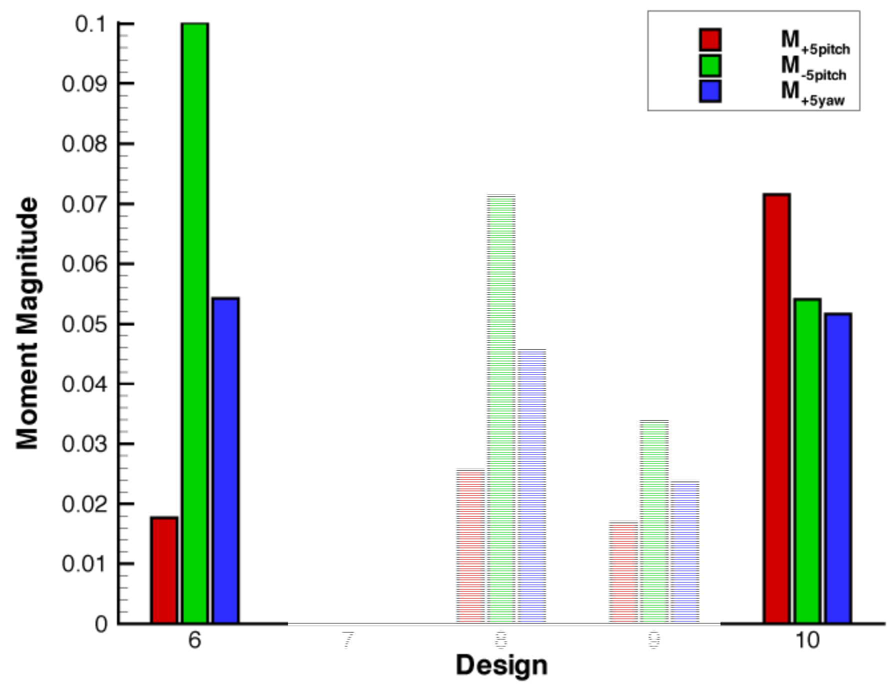

Result: Designs 6 and 10 produced similar optimized shapes, but the moments are very different.

Diffuse Passive Stability Study

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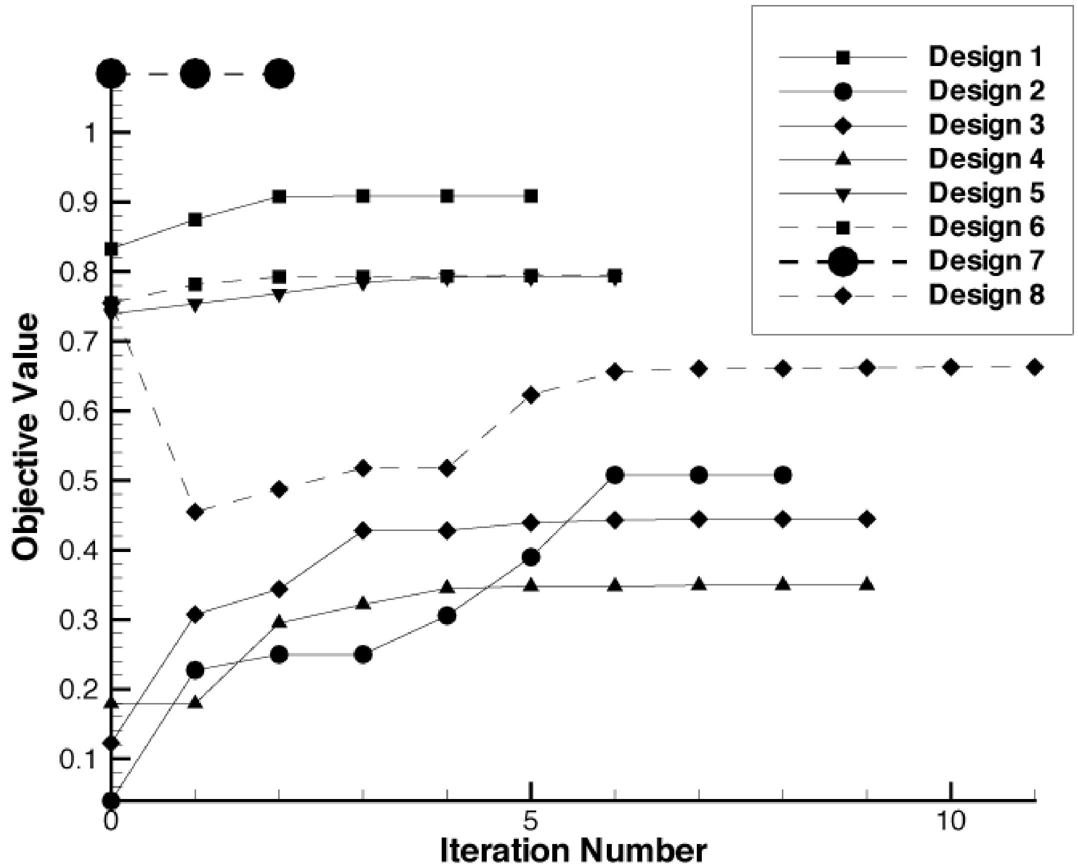
- One initial design added from "best" initial design of specular case.
- Maximum volume design now feasible due to change in reflection assumption
- Many local optima



Diffuse Passive Stability Study (cont.)

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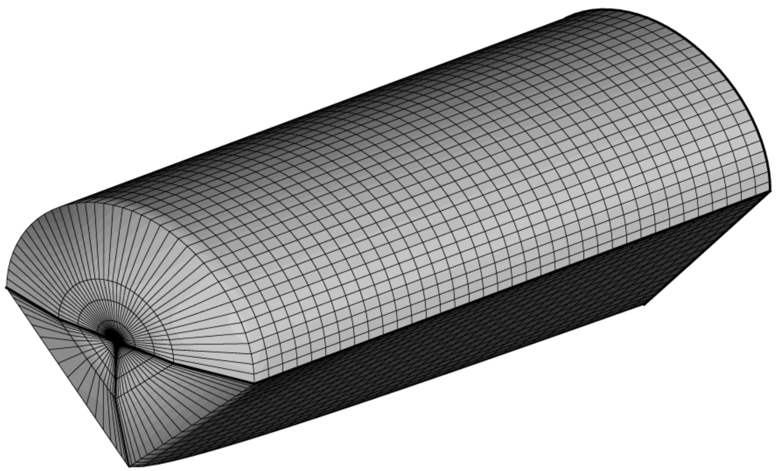
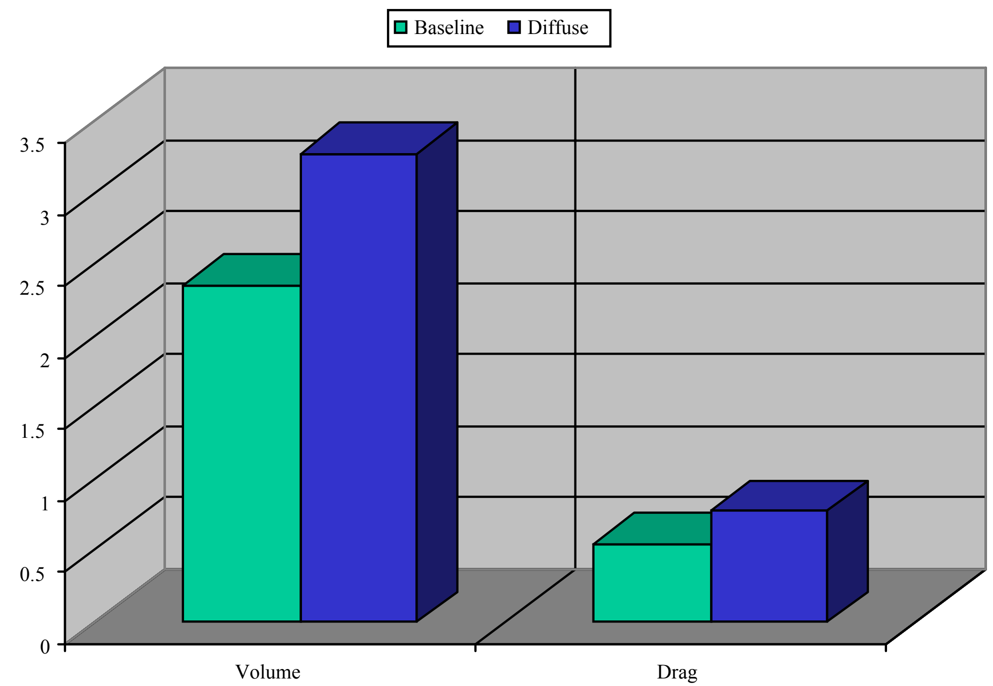
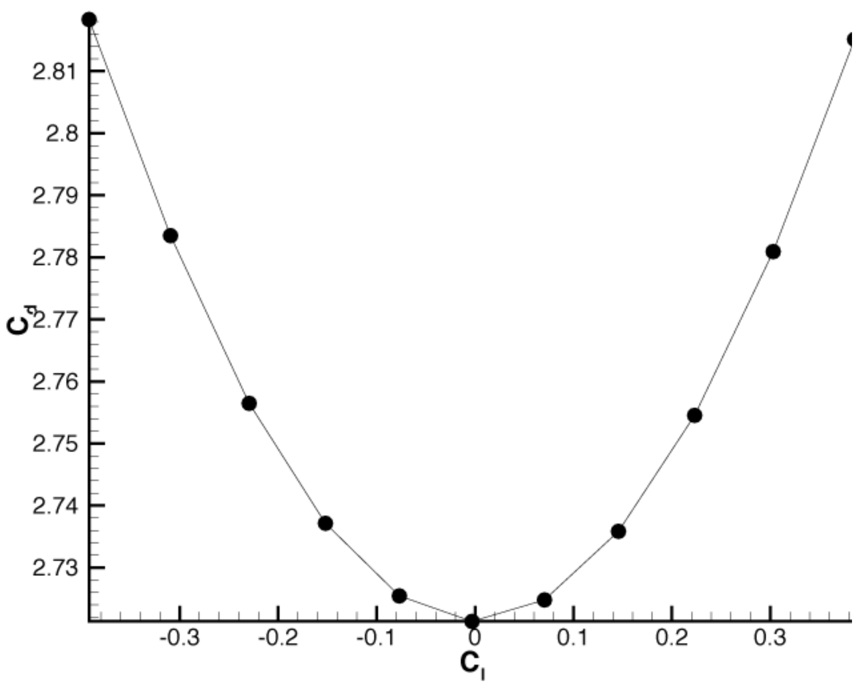




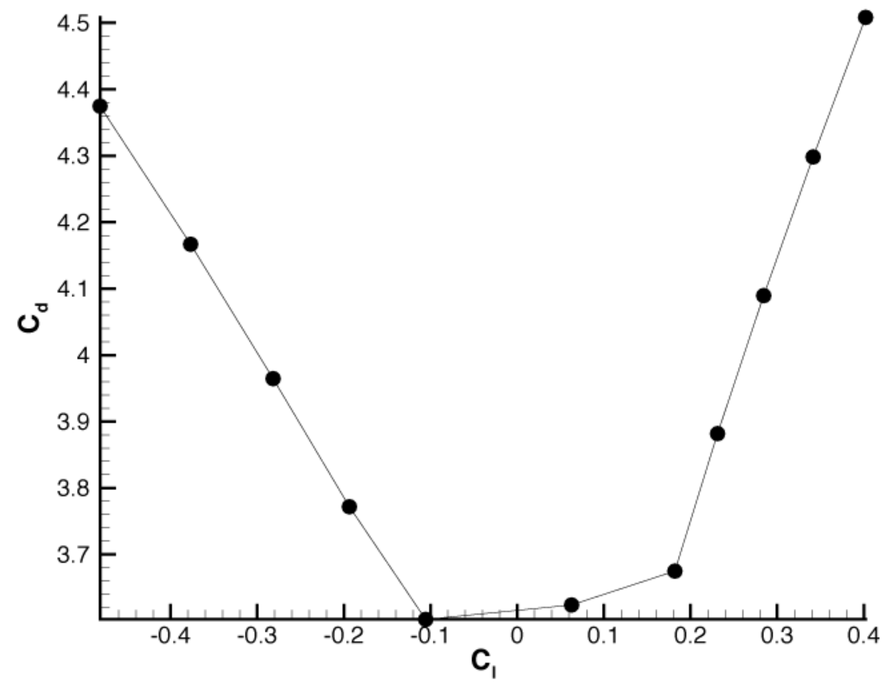
Same moment trend as with the reduced drag study. Diffuse produces significantly more stabilizing moment.

Result: Volume has increased 39% and drag has increased 43%.

Passive Stability Study (cont.)



Specular



Diffuse

Passive Stability Study (cont.)

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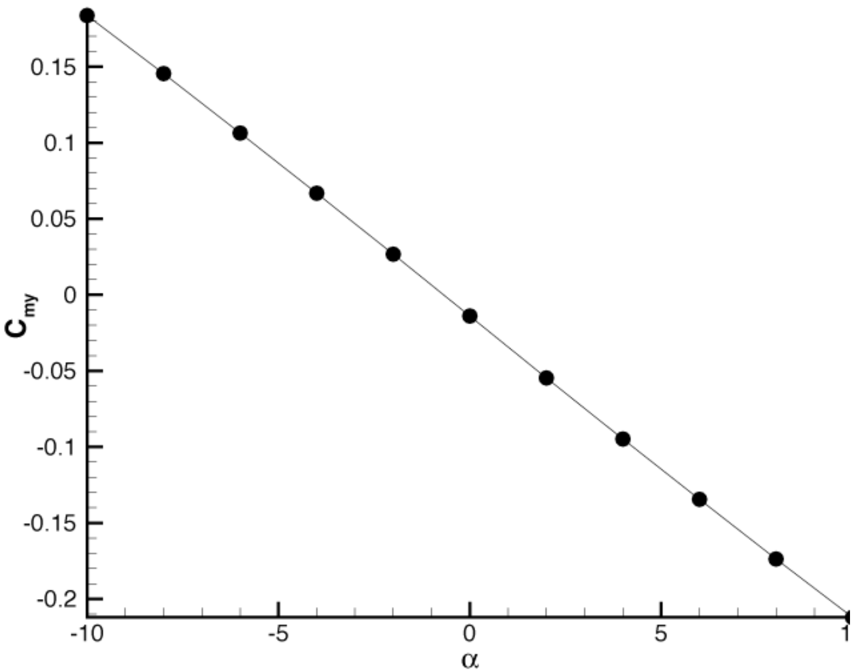
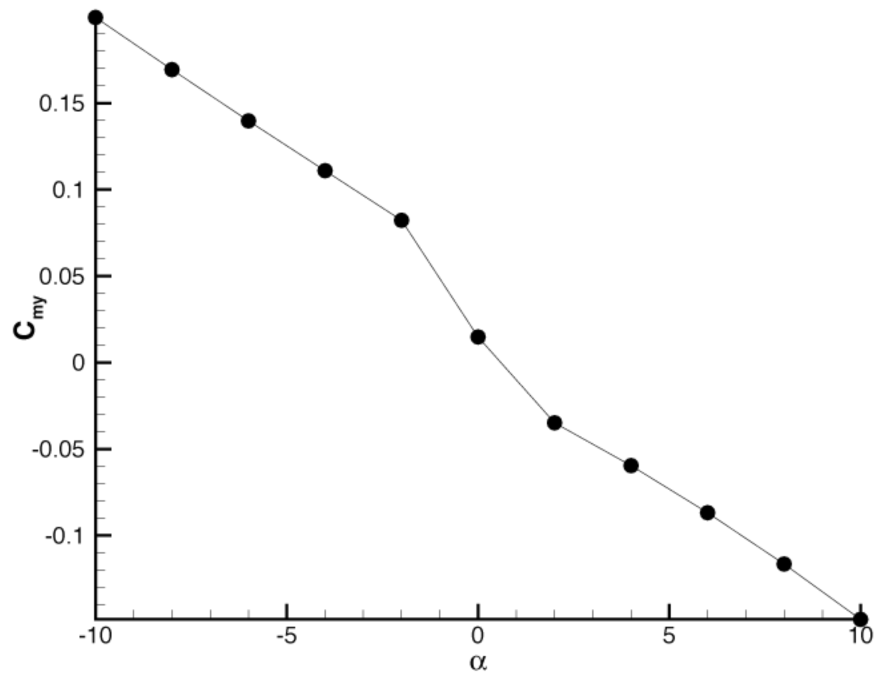
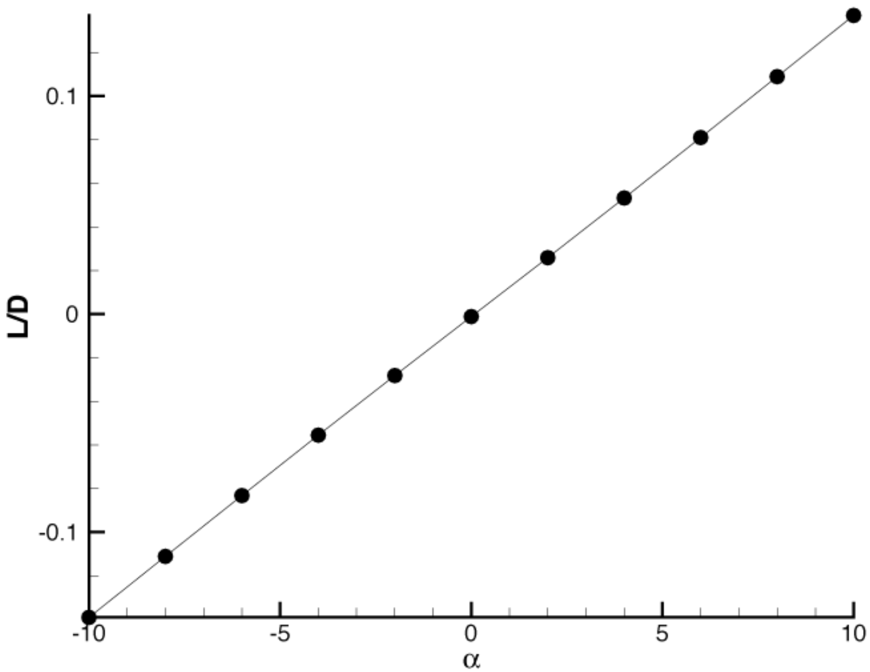


Specular

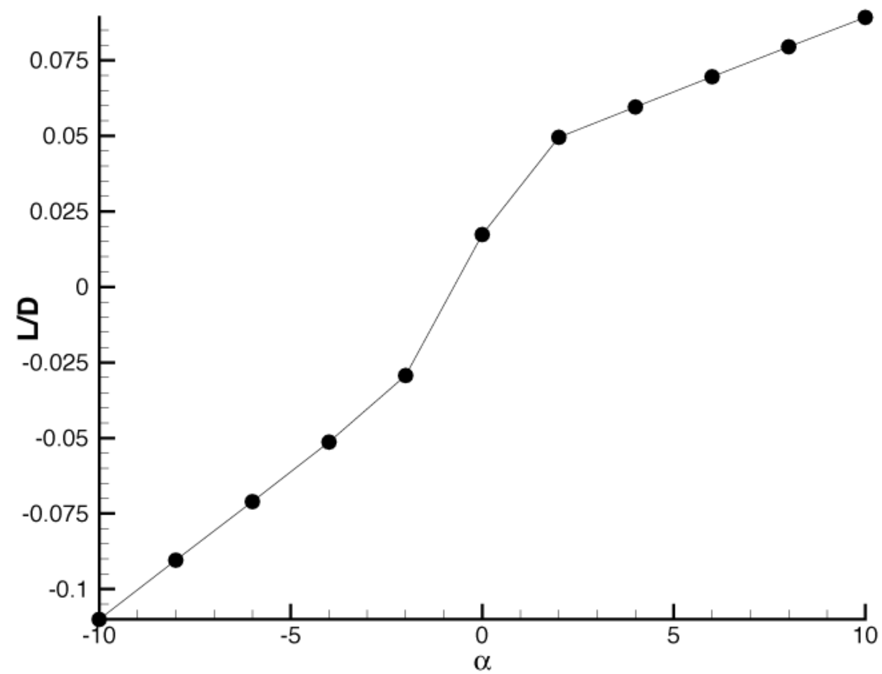


Diffuse

Passive Stability Study (cont.)



Specular



Diffuse

Passive Stability Study Conclusions

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- Under GEC design constraints, stable configurations are possible for both reflection assumptions.
- Design space changed due to change in reflection assumption.
- Drag increases significantly for stable designs.

Aerodynamic Maneuvering

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- Use lift force during atmosphere pass.
- Can be add-on, or component of existing trajectory.
- Obviously wish to minimize drag losses,maximize lifting forces.
- Thus… the goal is to seek maximum L/D without increasing $C_{D.}$

Previous Work

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- Aerolifting is not a new idea:”synergistic plane change”
  - London (1962)
  - Lau (1967)
  - Maslen (1967)
- Problems:
  - Drag can overwhelm benefits
  - Only perigee is effective
  - Require relatively high L/D

Renewed Interest

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- Microsatellites
  - Surface Area/Volume ~1/L
  - Precision flight affected by aerodynamics
  - Avoid impingement in formation
  - Plane change issues to maintain formation
- Atmosphere Dippers
  - Diving into atmosphere anyway
  - Severely fuel limited
  - I.e. GEC mission

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Aero Plane Change

Basic equations of motion:

$$\frac{du}{dt} = -\frac{1}{m}\{L\sin\theta + D\cos\theta\}$$

$$\frac{dv}{dt} = \frac{1}{m}\{L\cos\theta - D\sin\theta\}$$

$$\int_{V_1}^{V_2}\frac{dV}{V} = -\int_0^{\tan\theta}\frac{1}{[L/D]}\frac{dz}{(1+z^2)}$$

$$\Delta V_{drag} = V_1\left(1-\exp\left[\frac{-\theta}{L/D}\right]\right)$$

$$\frac{\Delta V_{aero}}{V_{circ}} = \overbrace{2-2\sqrt{\frac{1-\delta\bar{r}}{1-\delta\bar{r}/2}}}^{\text{transfer}} + \sqrt{\frac{1}{1-\delta\bar{r}/2}}\left(1-\exp\left[\frac{-\theta}{L/D}\right]\right)$$

$$\delta\bar{r} = \left(r_{apogee} - r_{perigee}\right)/\, r_{apogee}$$

Which can be expanded as:

$$\frac{\Delta V_{aero}}{V_{circ}} \cong \left\{1+\frac{\delta\bar{r}}{4}+\frac{3\delta\bar{r}^2}{32}\right\}\left[\frac{\theta}{L/D}\right] + \left\{\frac{\delta\bar{r}}{2}+\frac{5\delta\bar{r}^2}{16}+\frac{13\delta\bar{r}^3}{642}\right\} - \left\{\frac{1}{2}+\frac{\delta\bar{r}}{8}\right\}\left[\frac{\theta}{L/D}\right]^2 + \frac{1}{6}\left[\frac{\theta}{L/D}\right]^3 + \ldots$$

Propulsive Plane Change

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Most general maneuver:

$$\frac{\Delta V_{\text{orbit}}}{V_{\text{circ}}} = \left\{ 2 + \frac{\sqrt{2(1-\cos\theta)}}{1+\delta\bar{r}} \right\} \sqrt{\frac{1+\delta\bar{r}}{1+\delta\bar{r}/2}} - 2$$

minimum for

$\theta = 0.6797$ ($\theta = 38.92^\circ$)

otherwise, change in orbit:

$$\frac{\Delta V_{\text{orbit}}}{V_{\text{circ}}} = \sqrt{2(1-\cos\theta)}$$

$$\cong \theta - \frac{\theta^3}{24} + \frac{\theta^5}{1920} - \ldots$$

Optimal for modest angles

Comparison:

$$\frac{\Delta V_{\text{aero}}}{\Delta V_{\text{orbital}}} \cong \frac{1}{[L/D]} + \frac{\delta\bar{r}}{2\theta} - \frac{\theta}{2[L/D]^2} + \frac{\delta\bar{r}}{2[L/D]} \ldots$$

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To Break Even:

$$\left.\frac{L}{D}\right|_{\substack{\text{break}\\\text{even}}} = \frac{2+2\sqrt{1+2\delta\bar{r}+\left[\delta\bar{r}^{2}/4\right]-2\theta}+\delta\bar{r}}{4-2[\delta\bar{r}/\theta]}$$

$$\cong 1+\frac{1}{2}\left(\frac{\delta\bar{r}}{\theta}+\delta\bar{r}-\theta\right)+\ldots$$

At LEO: $$\left.\frac{L}{D}\right|_{\substack{\text{break}\\\text{even}}} = \frac{1.04651}{1-0.03164/\theta+0.47778\theta+0.26269\theta^{2}+0.17831\theta^{3}+0.12922\theta^{4}+\ldots}$$

$$\theta_{\text{aero}} = -\left[\frac{L}{D}\right]\ln\left\{1+\sqrt{2(2-\delta\bar{r})}-2\sqrt{1-\delta\bar{r}}-\sqrt{(2-\delta\bar{r})(1-\cos\theta_{\text{orbit}})}\right\}$$

$$\theta_{\text{aero}} \cong \left[\frac{L}{D}\right]\left\{-\frac{1}{2}\delta\bar{r}-\frac{1}{16}\delta\bar{r}^{2}-\frac{11}{192}\delta\bar{r}^{3}+\left(1-\frac{3}{4}\delta\bar{r}+\frac{5}{32}\delta\bar{r}^{2}-\frac{7}{128}\delta\bar{r}^{3}\right)\theta_{\text{orbit}}+\right.$$
$$\left.\left(\frac{1}{2}-\frac{3}{4}\delta\bar{r}+\frac{7}{16}\delta\bar{r}^{2}-\frac{11}{64}\delta\bar{r}^{3}\right)\theta_{\text{orbit}}^{2}+\left(\frac{7}{24}-\frac{23}{48}\delta\bar{r}+\frac{547}{768}\delta\bar{r}^{2}-\frac{1313}{3072}\delta\bar{r}^{3}\right)\theta_{\text{orbit}}^{3}+\ldots\right\}$$

$$\theta_{\text{aero}} \cong \left[\frac{L}{D}\right]\left\{\theta_{\text{orbit}}-\frac{\delta\bar{r}}{2}+\frac{\theta_{\text{orbit}}^{2}}{2}-\frac{\delta\bar{r}^{2}}{16}-\frac{3\delta\bar{r}\theta_{\text{orbit}}}{4}+\ldots\right\}$$

At small angles

Conclusions

- To break even, require L/D ~1.
- 3^o requires L/D~1.5
- At very small angles, break even requires L/D>1
  - Scales with $1/\theta$
  - □□□□□□□□□□□□□□□□□□□□□smaller L/D required
- Otherwise, don’t use an aero pass

Plane change with Lift

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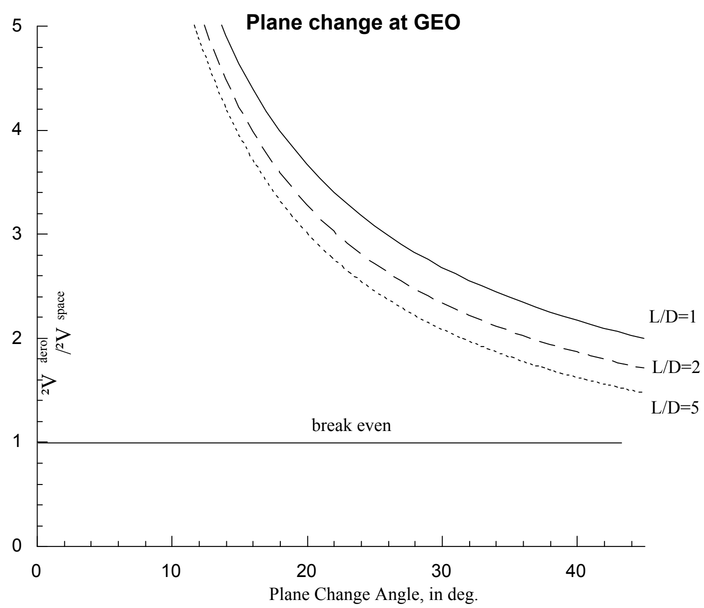
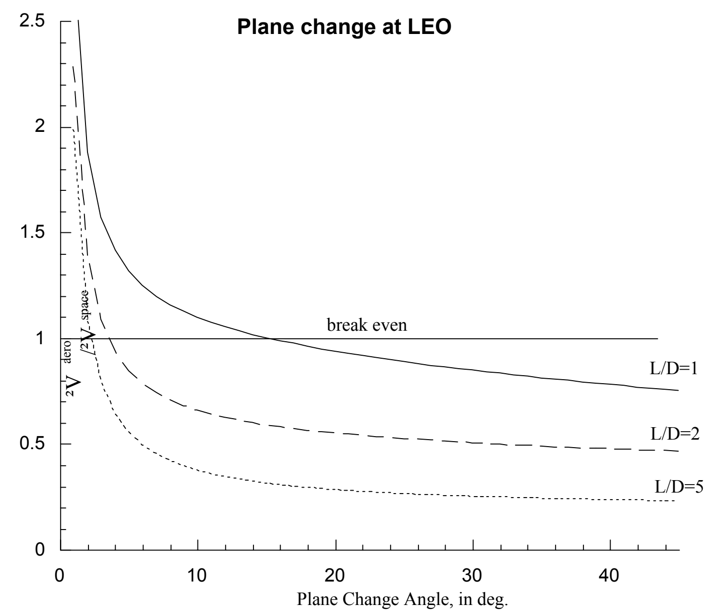
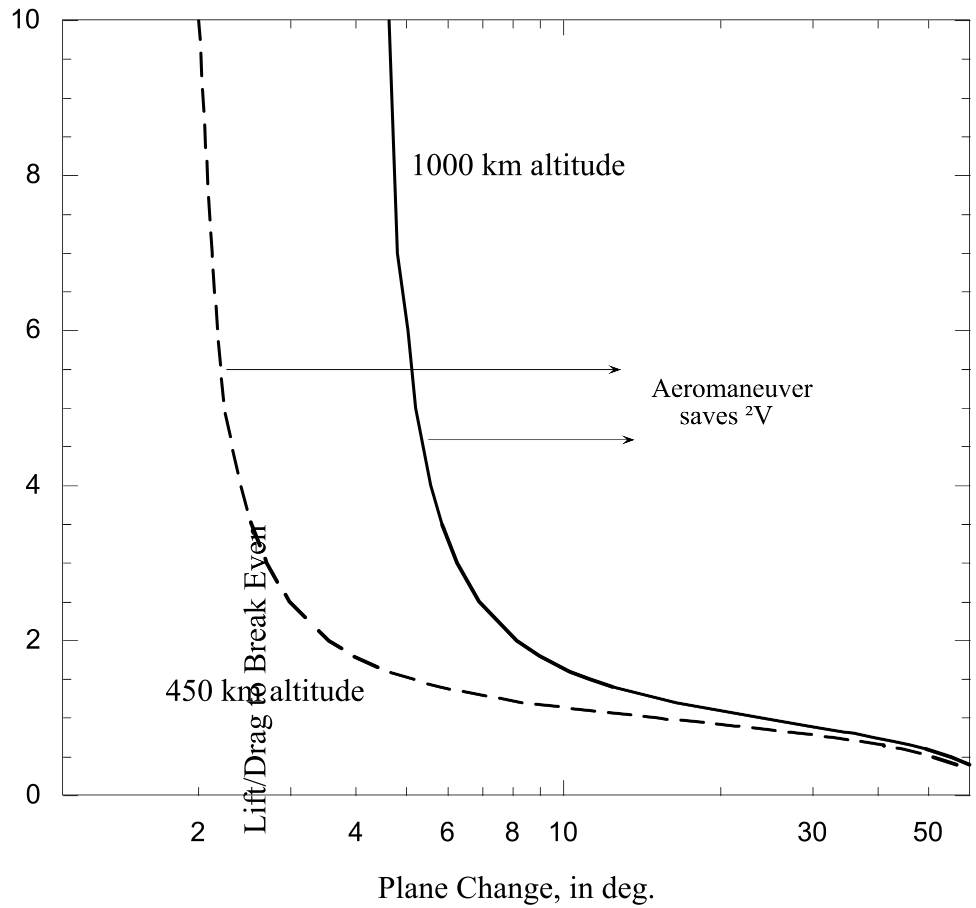




Break-even L/D



Question: How High is L/D?

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- Continuum hypersonic L/D
    - Caret wing=5-7
    - Shuttle=2.0 at 70km (Aero Data Book)
- Transition L/D's
    - Caret wing at 90km =0.3, at 120 km=0.1 (Rault)
    - Shuttle =1.2 at 90km
    - Half-cone airfoil=1.4 at 110km (Potter)
- Fully Rarefied flow : ?

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Rarefied L/D

Gas-surface interaction:

$$\frac{p}{A} = mIV_\infty\{\sin\phi + \varepsilon\sin[\delta\phi]\}$$

I=impingement

$$\frac{D}{A} = mI_m V_\infty\left[1+\varepsilon\begin{cases}\tfrac{2}{3}\sin\phi & \text{diffuse}\\ -\cos 2\phi & \text{specular}\end{cases}\right]$$

$$\frac{L}{A} = mI_m V_\infty \varepsilon\begin{cases}\tfrac{2}{3}\cos\phi & \text{diffuse}\\ \sin 2\phi & \text{specular}\end{cases}$$

Max L/D if specular:

$$\frac{L}{D} = \frac{2\varepsilon\sin\phi\cos\phi}{1+\varepsilon\left(1-2\cos^2\phi\right)}$$

maximize

$$L/D_{\max.} = \varepsilon/\sqrt{1-\varepsilon^2} \quad \text{at} \quad \phi = \tfrac{1}{2}\cos^{-1}\varepsilon$$

$$C_D\big|_{\max. L/D} = \sqrt{2}(1+\varepsilon)(1-\varepsilon)^{3/2}$$

$$C_L\big|_{\max. L/D} = \sqrt{2}\varepsilon(1-\varepsilon)\sqrt{1+\varepsilon}$$

Diffuse:

$$L/D = \left(\tfrac{2\sin\phi}{3+2\sin\phi}\right)\cot\phi$$

Interestingly, has small angle limit of 2/3, not ∞

Maximum Lift

- Maximum lift does not occur at maximum *L/D*, so may be willing to sacrifice extra drag for a bit more lift:

$$L/D_{\max.\,\text{lift}} = 2.829\varepsilon/(3+\varepsilon)$$

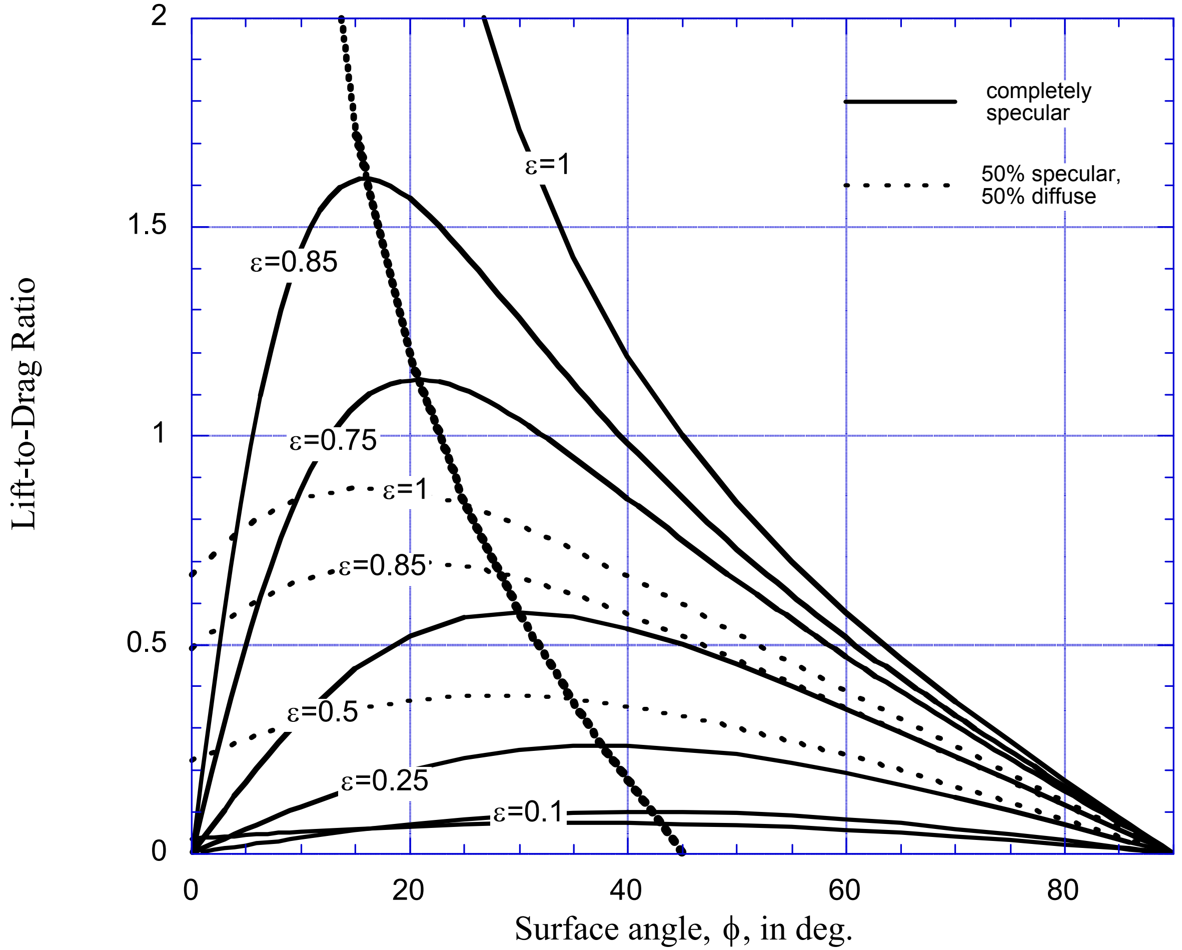
$$=0.54 \text{ at } \varepsilon=.7$$

$$\phi = \cos^{-1}\left(1/\sqrt{3}\right)$$

$$=54.74^{o}$$

- Minimum drag always at zero angle

L/D vs. Surface Angle



Lift and Drag Coefficients

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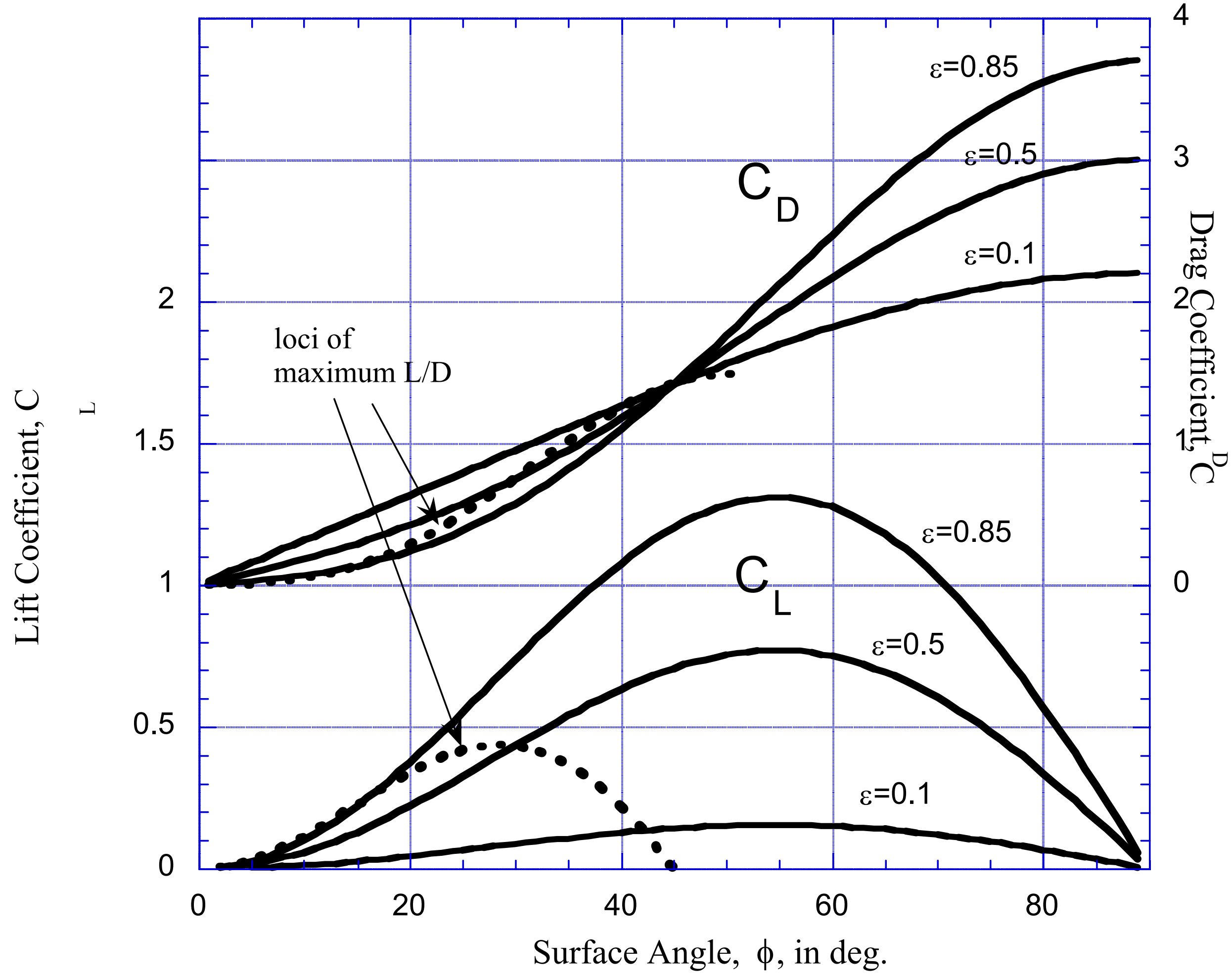
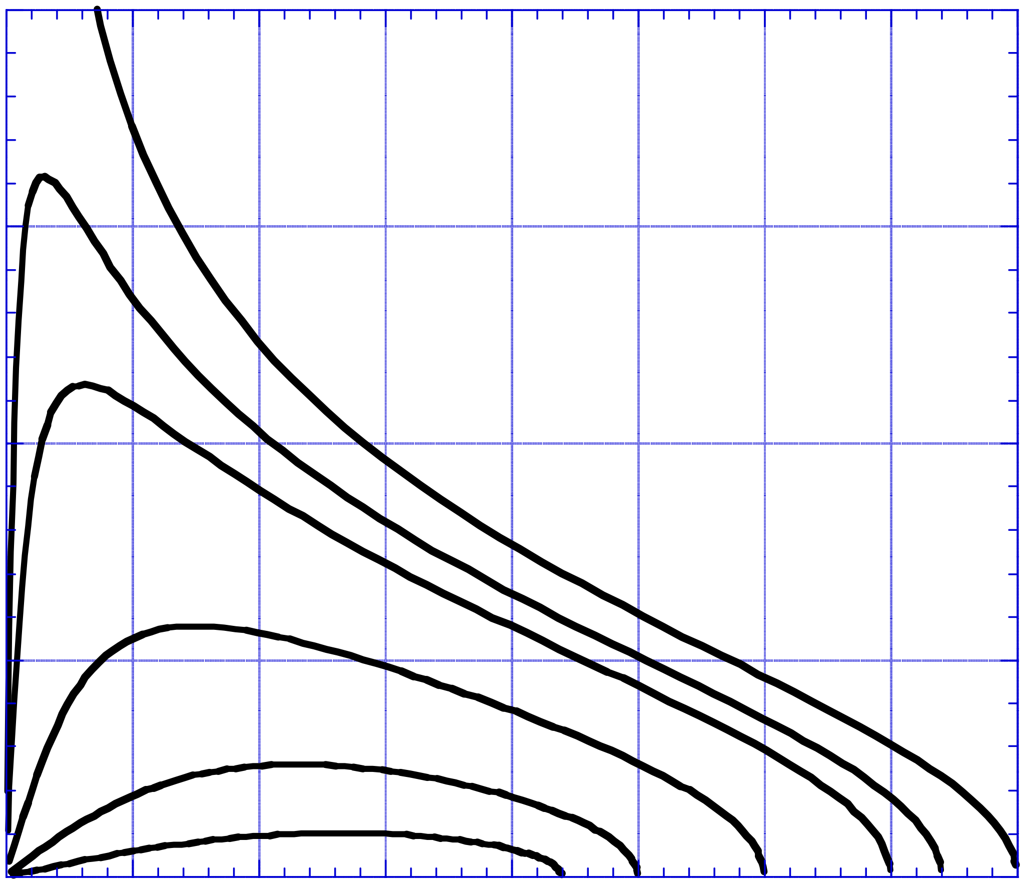


Aerodynamic Strategies

- On existing trajectory:
  - Maximize CL
  - Accept drag losses
- If trajectory can be modified:
  - Maximize L/D
  - Choose perigee altitude for desired forces

Drag Polar



Known Gas-Surface Values

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- He on sapphire
  - ε=0.25, η=0.53 (Herrero)
  - Max L/D=0.19 at 40^o
- Nitrogen on spacecraft surfaces
  - ε=0.2, η=0.4
  - Max L/D=0.135 at 31^o
- Atomic O on nickel oxide
  - ε=0.7, η~1 (Cross and Blais)
  - Max L/D~1 at 40^o Max lift L/D=1.3

Required Accommodation

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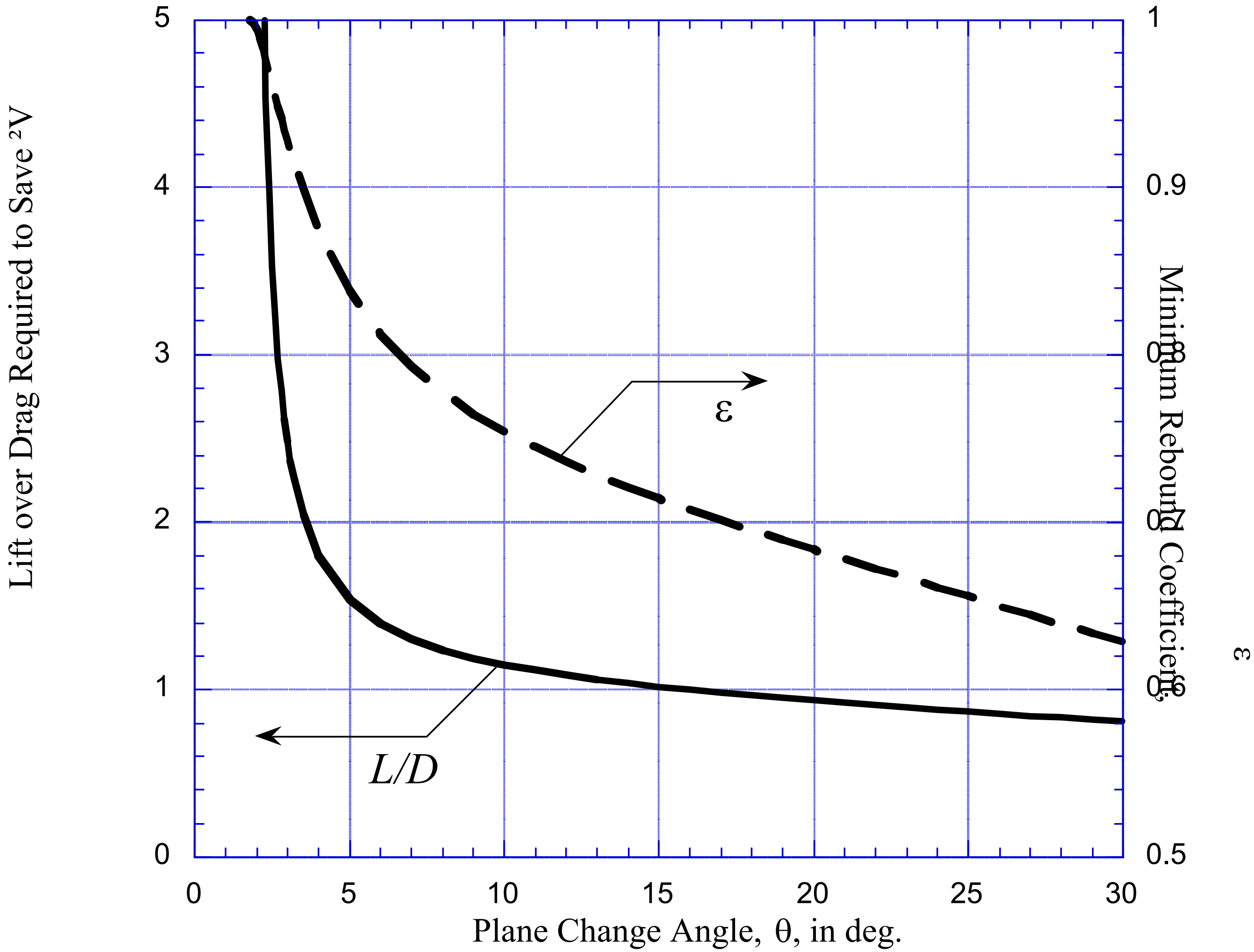

LEO, Specular reflections

Atmospheric Composition

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Altitude	N_2, m^{-3}	O , m^{-3}	O_2 , m^{-3}
120	2.4e17	6.1e16	2.8e16
130	8.8e16	3.1e16	7.9e15
140	4.3e16	1.9e16	3.3e15

Cylinder Aerodynamics

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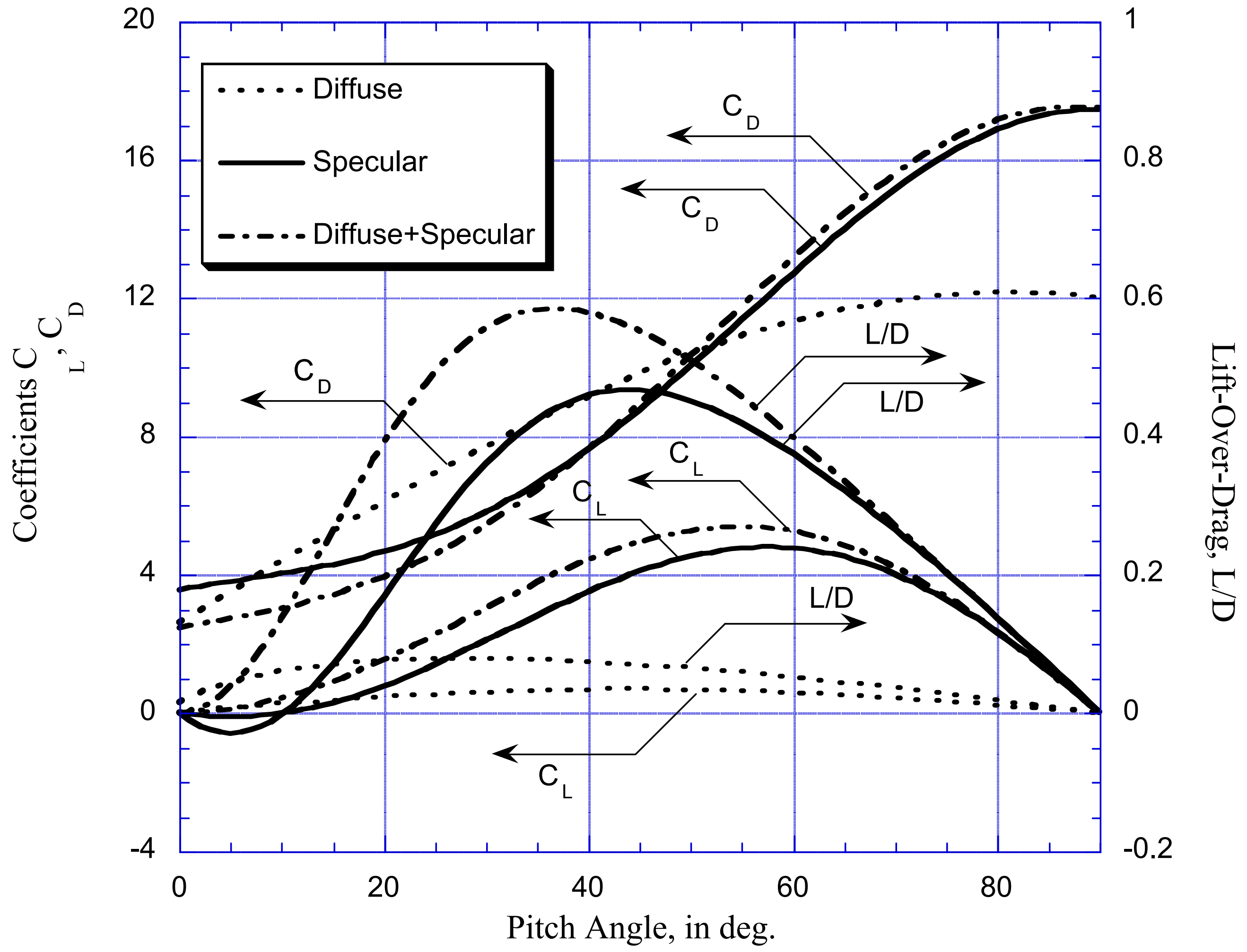

5:1 aspect ratio,

Coefficients referenced to $\alpha=0$

Velocity Magnitudes

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Total drag impulse in an elliptical orbit:

$$\int_{\text{orbit}} D\,dt \cong \tfrac{1}{2} A_{\text{ref.}} \int_{\text{orbit}} C_D \rho V^2 dt$$

$$= \tfrac{1}{2} A_{\text{ref.}} \int_0^{2\pi} C_D \rho V^2 \left(\frac{r^2}{r_{\text{apogee}}} \right) \frac{d\Theta}{V_{\text{apogee}}}$$

$$= \tfrac{1}{2} A_{\text{ref.}} V_{\text{apogee}} r_{\text{apogee}} \int_0^{2\pi} C_D \rho \left(\frac{V}{V_{\text{apogee}}} \right)^2 \left(\frac{r}{r_{\text{apogee}}} \right)^2 d\Theta$$

$$\frac{r}{r_{\text{apogee}}} = \frac{2 r_{\text{perigee}}}{r_{\text{apogee}} + r_{\text{perigee}} + \left[r_{\text{apogee}} - r_{\text{perigee}} \right] \cos\Theta}$$

$$= \frac{1 - \delta\bar{r}}{1 + \frac{\delta\bar{r}}{2}(\cos\Theta - 1)}$$

$$V^2 = \frac{\mu}{r_{\text{apogee}}} \left\{ \frac{2 - 2\delta\bar{r} + \delta\bar{r}^2 + (2 - \delta\bar{r})\delta\bar{r}\cos\Theta}{(2 - \delta\bar{r})(1 - \delta\bar{r})} \right\}$$

$$\frac{1}{A_{\text{ref}}} \int_{\text{orbit}} F\,dt \cong \tfrac{1}{2} \rho_o V_{\text{circ}} r_{\text{circ}} \sqrt{\frac{1 - \delta\bar{r}}{1 - \delta\bar{r}/2}} \int_0^{2\pi} C_F \left\{ \frac{\left(2 - 2\delta\bar{r} + \delta\bar{r}^2 + (2 - \delta\bar{r})\delta\bar{r}\cos\Theta\right)}{\left(2 + \delta\bar{r}[\cos\Theta - 1]\right)^2} \right\} \times$$

$$\exp\left[\frac{1}{h_{\text{scale}}} \left(r_{\oplus} - \left\{ \frac{1 - \delta\bar{r}}{1 + \delta\bar{r}(\cos\Theta - 1)/2} \right\} r_{\text{circ}} \right) \right] d\Theta$$

Nearly-Circular Orbits

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$$\frac{1}{A_{\text{ref}}}\int_{\text{orbit}} F\,dt \cong \tfrac{1}{2}\rho_o V_{\text{circ}} r_{\text{circ}} \sqrt{\frac{1-\delta\bar{r}}{1-\delta\bar{r}/2}} \int_0^{2\pi} C_F \exp\left[\frac{1}{h_{\text{scale}}}\left(r_\oplus - \left\{1-\frac{\delta\bar{r}}{2}[\cos\Theta+1]\right\} r_{\text{circ}}\right)\right] d\Theta$$

$$= \rho_o V_{\text{circ}} r_{\text{circ}} \sqrt{\frac{1-\delta\bar{r}}{1-\delta\bar{r}/2}}\, C_F\, \pi \exp\left[\frac{1}{h_{\text{scale}}}\left(r_\oplus + \left\{\frac{\delta\bar{r}}{2}-1\right\} r_{\text{circ}}\right)\right] I_0\left(\frac{\delta\bar{r}}{2}\frac{r_{\text{circ}}}{h_{\text{scale}}}\right)$$

Curve-fit: $\rho[kg/m^3] = 14.511 e^{-h/5.88\,km}$ Between 80km and 130km

Mod. Bessel function with large argument: $I_0(x) \approx \frac{0.4}{\sqrt{x}} e^x$

$$\frac{1}{A_{\text{ref}}}\int_{\text{orbit}} F\,dt = 0.4 \rho_o V_{\text{circ}} r_{\text{circ}} \sqrt{\frac{1-\delta\bar{r}}{1-\delta\bar{r}/2}}\, C_F \pi \frac{\exp\left[\frac{1}{h_{\text{scale}}}\left(r_\oplus - [1-\delta\bar{r}] r_{\text{circ}}\right)\right]}{\sqrt{\frac{\delta\bar{r}}{2}\frac{r_{\text{circ}}}{h_{\text{scale}}}}}$$

$$= 3.948\times 10^{10} \sqrt{\frac{1-\delta\bar{r}}{\delta\bar{r}-\delta\bar{r}^2/2}}\, C_F\ \mathrm{e}^{-0.17\left(h_{\text{perigee}},km\right)}$$

Sample Orbits, $m/C_DA=250$

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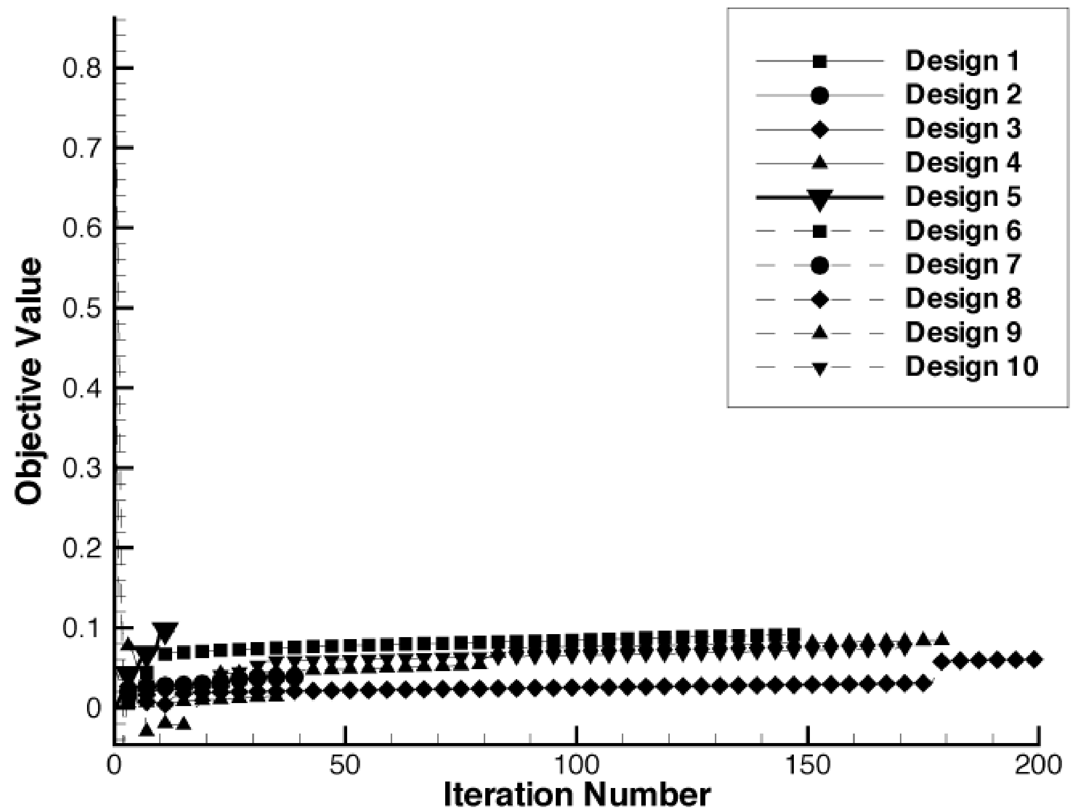
Apogee, in km.	Perigee, in km.	Velocity loss, m/s	Deflection angle, in deg., L/D=.5	Deflection angle, in deg., L/D=1	Deflection angle, in deg., L/D=2
450	80	837.3	3.489	6.938	13.9578
	90	155.1	0.615	1.224	2.46101
	100	28.75	0.113	0.225	0.45217
	110	5.332	0.021	0.042	0.08371
	120	0.989	0.004	0.008	0.01552
	130	0.184	7E-04	0.001	0.00288
	140	0.034	1E-04	3E-04	0.00053
	150	0.006	2E-05	5E-05	9.9E-05
1000	80	540.9	2.296	4.565	9.18257
	90	99.39	0.408	0.812	1.63314
	100	18.27	0.075	0.148	0.29838
	110	3.357	0.014	0.027	0.05478
	120	0.617	0.003	0.005	0.01007
	130	0.113	5E-04	9E-04	0.00185
	140	0.021	9E-05	2E-04	0.00034
	150	0.004	2E-05	3E-05	6.3E-05

Specular L/D Study

University of Maryland

- For dipping plane changes, need L/D near unity.
- Ten initial designs used.
- The zero-lift design produced the “best” final configuration. This was also the reduced drag initial design.



Specular L/D Study (cont.)

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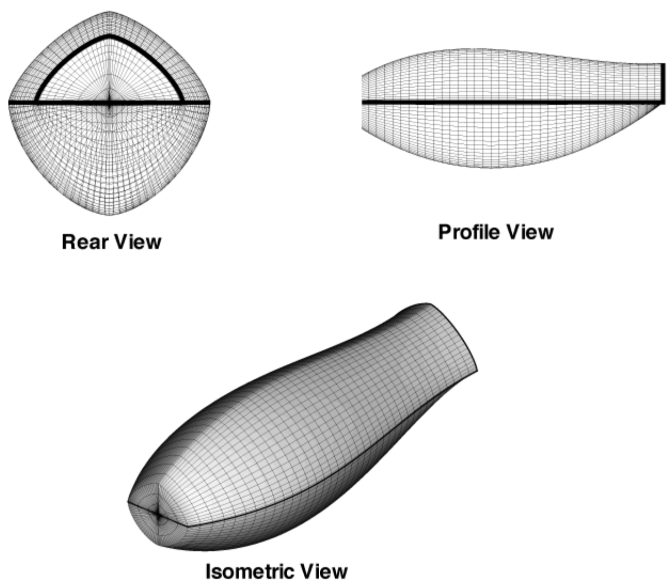

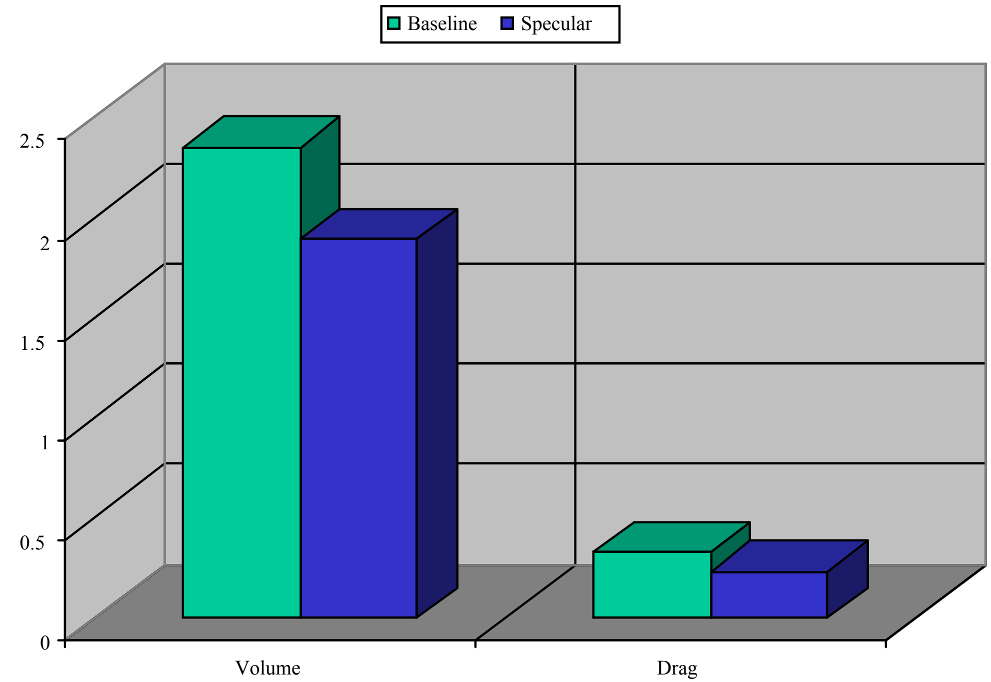

Result: Volume decreased 19% and drag decreased 30%.

Diffuse L/D Study

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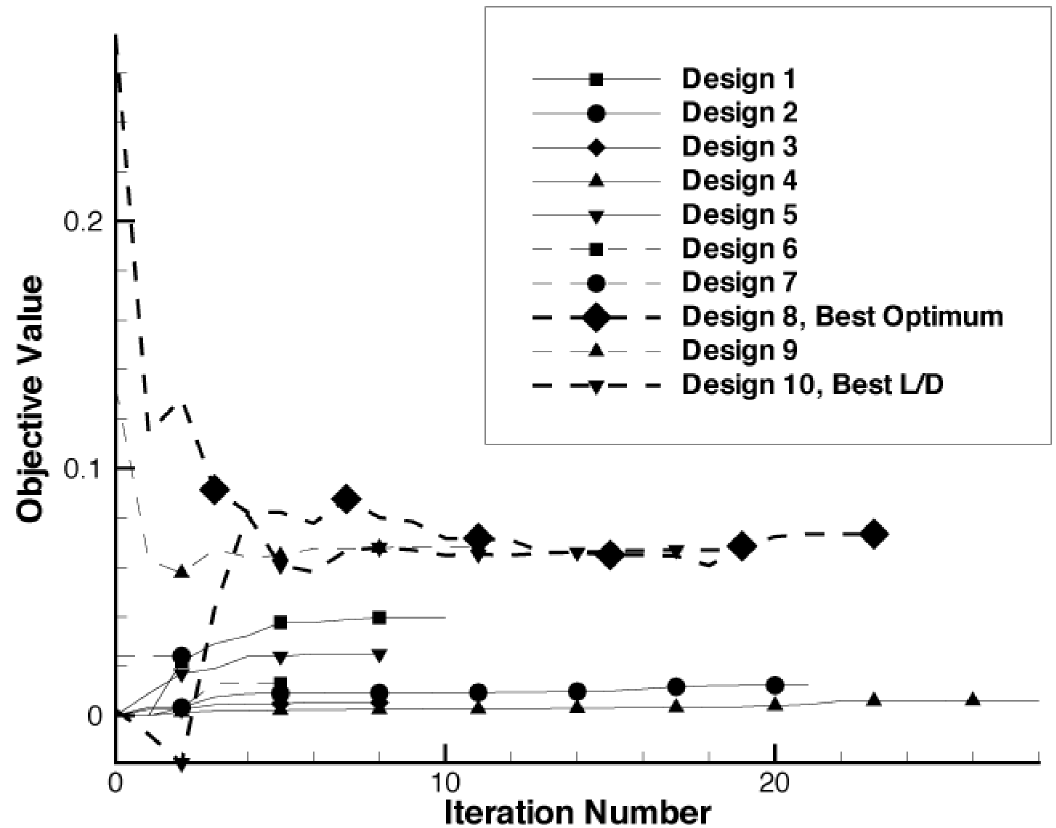
•Ten initial designs.

•Many local optima.

•Two different solutions of interest.



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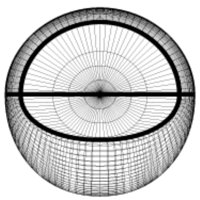
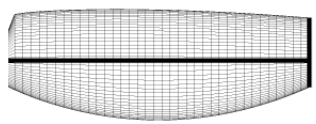
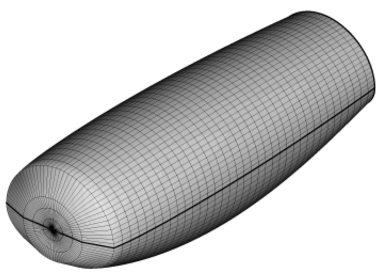
Diffuse L/D Study (cont.)



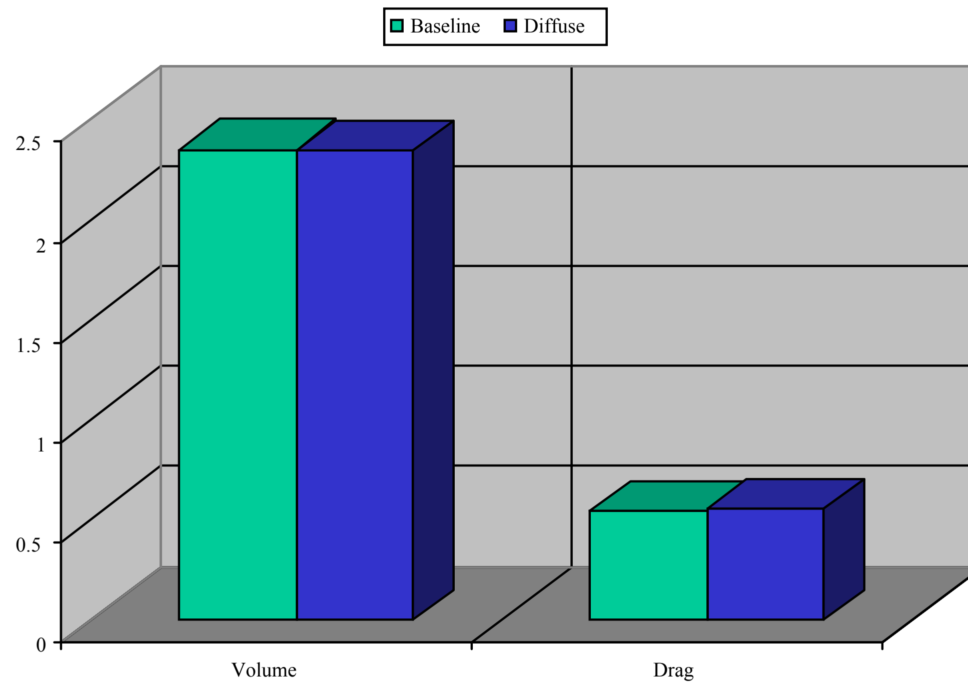
Rear View



Profile View



Isometric View



Result: Very similar to the specular solution. Volume decrease 0.2% and drag increased 1%.

Diffuse L/D Study (cont.)

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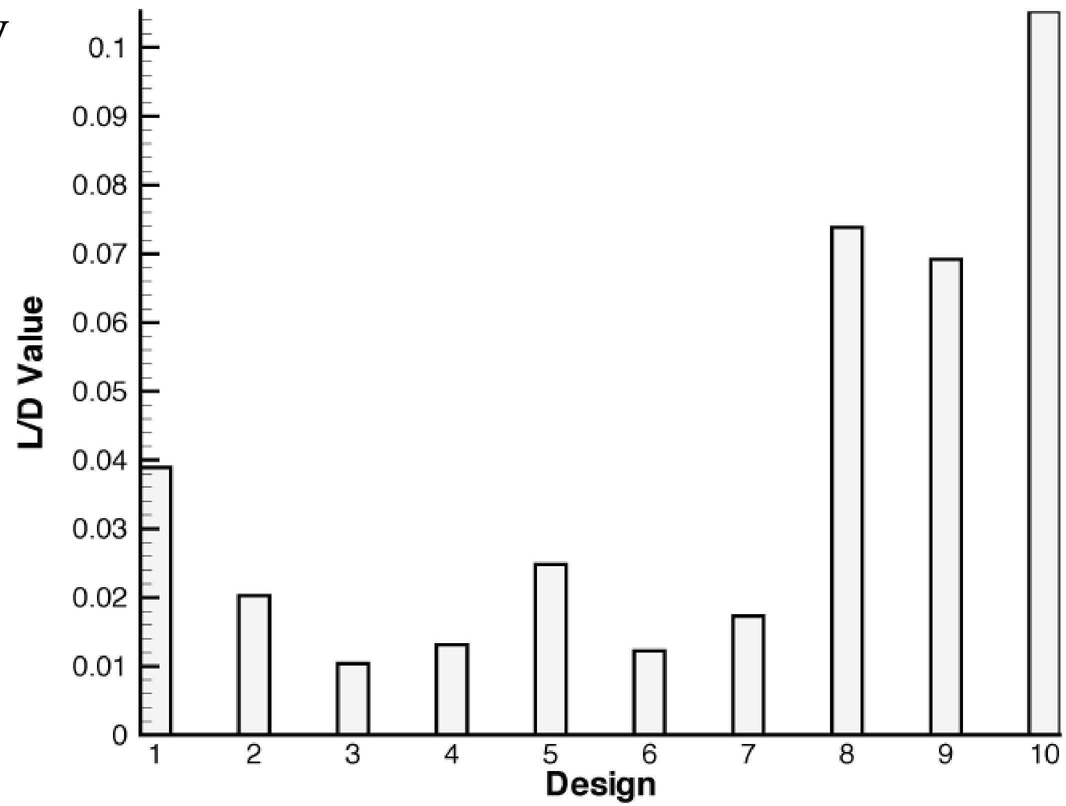
- The "best" design by objective value is not the best L/D configuration.
- The "best" L/D configuration is near the value for the specular case.



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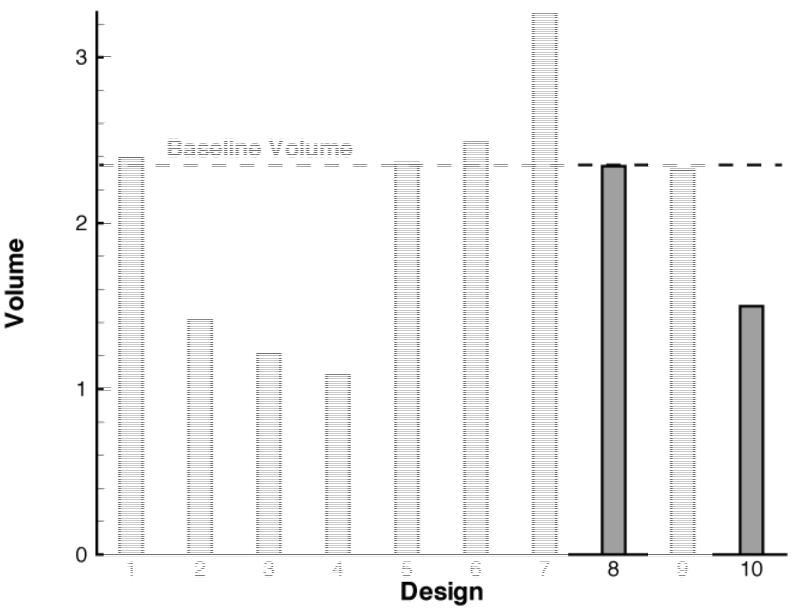
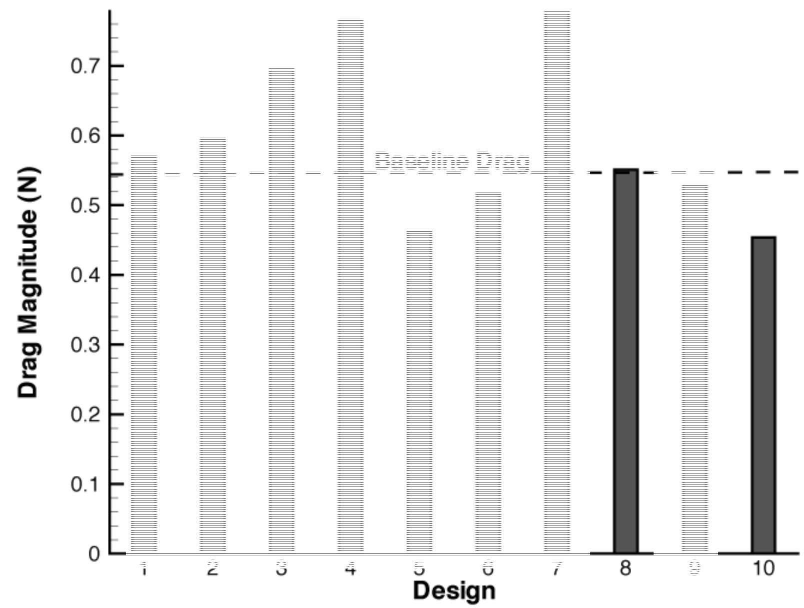
Diffuse L/D Study (cont.)





Result: Volume very poor for the "best" L/D configuration (36% loss), but drag decreased 16%.

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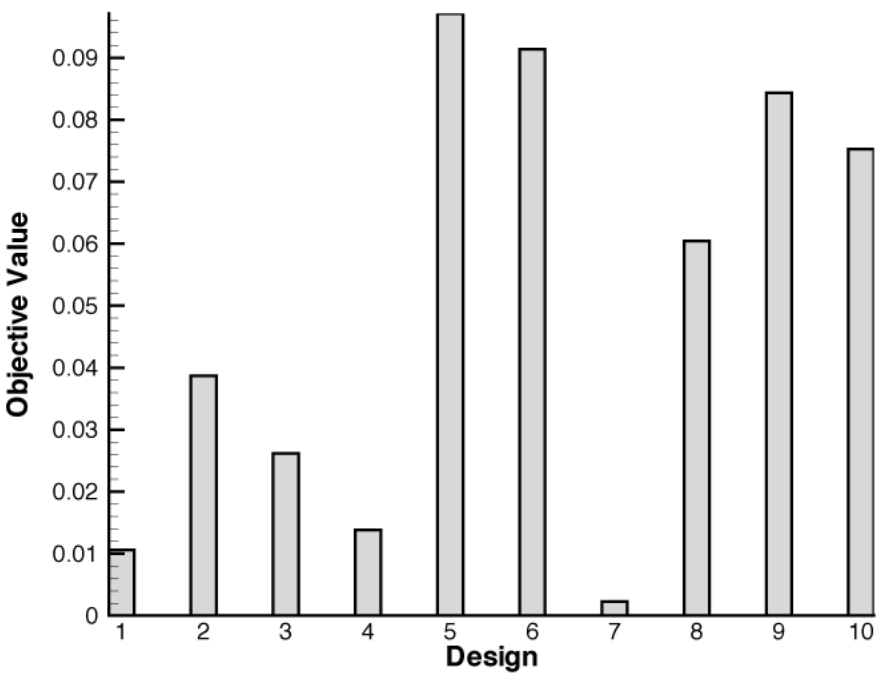
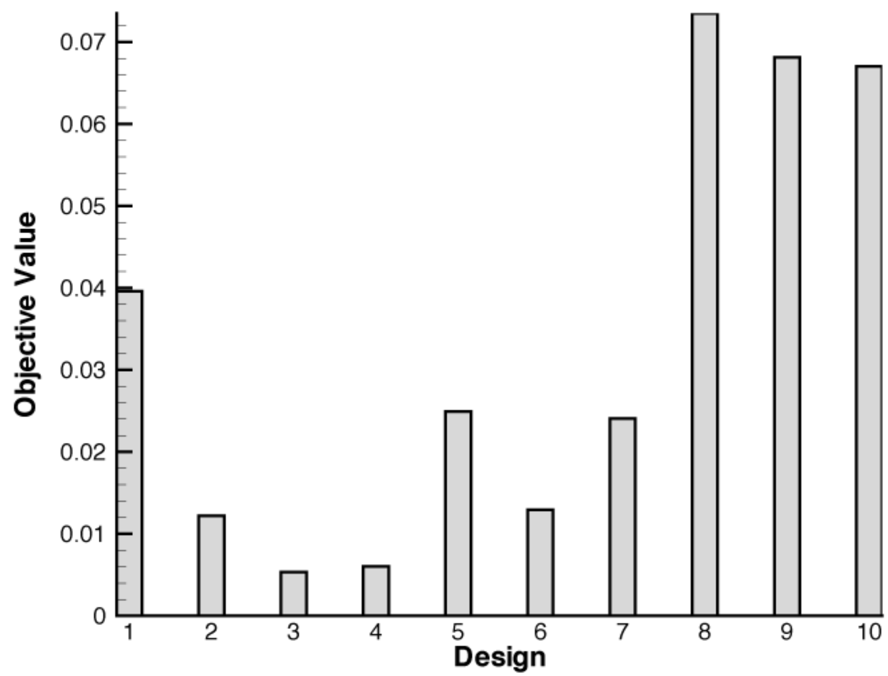
L/D Study (cont.)



Specular



Diffuse

L/D Study (cont.)

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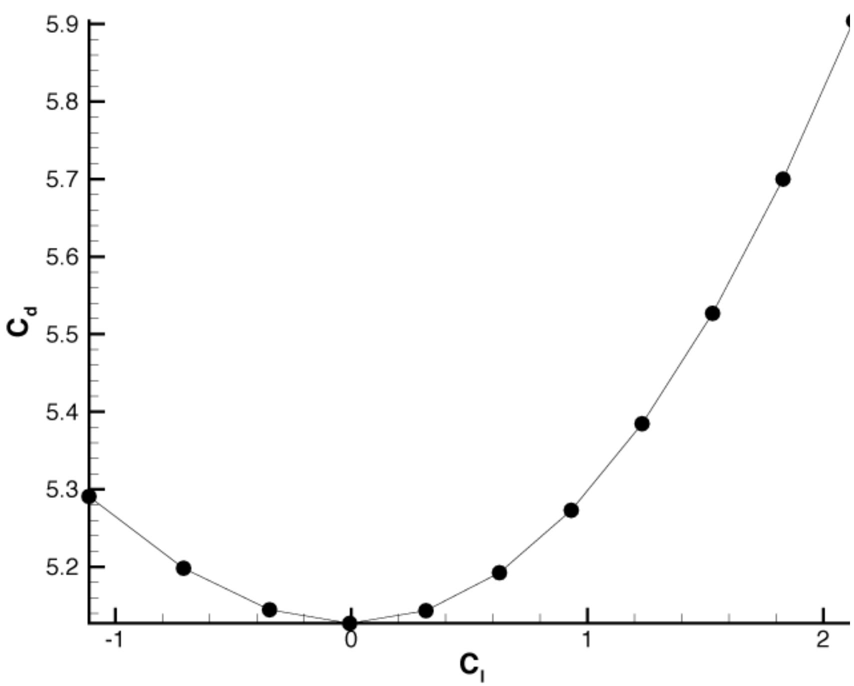
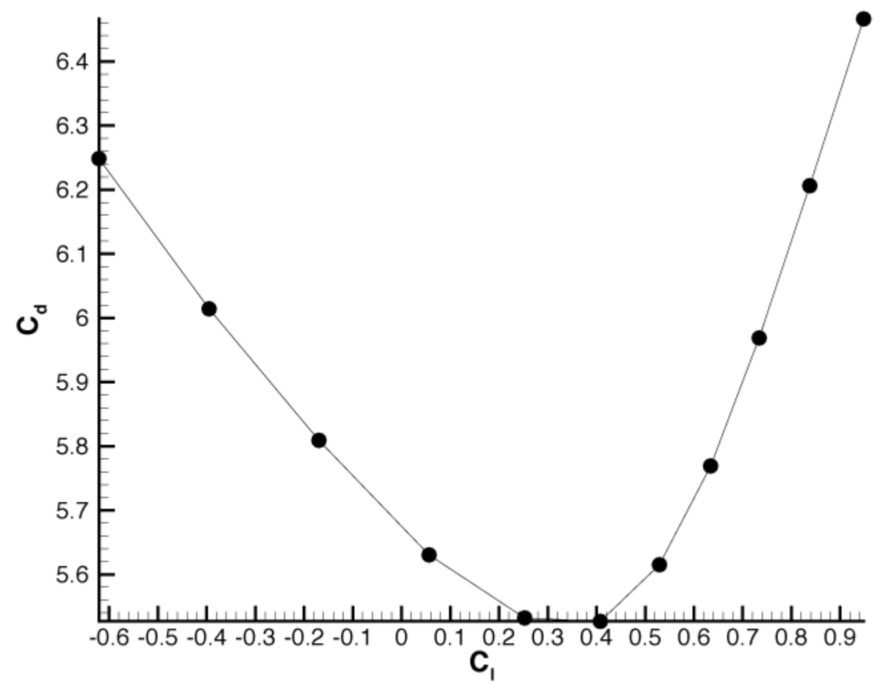
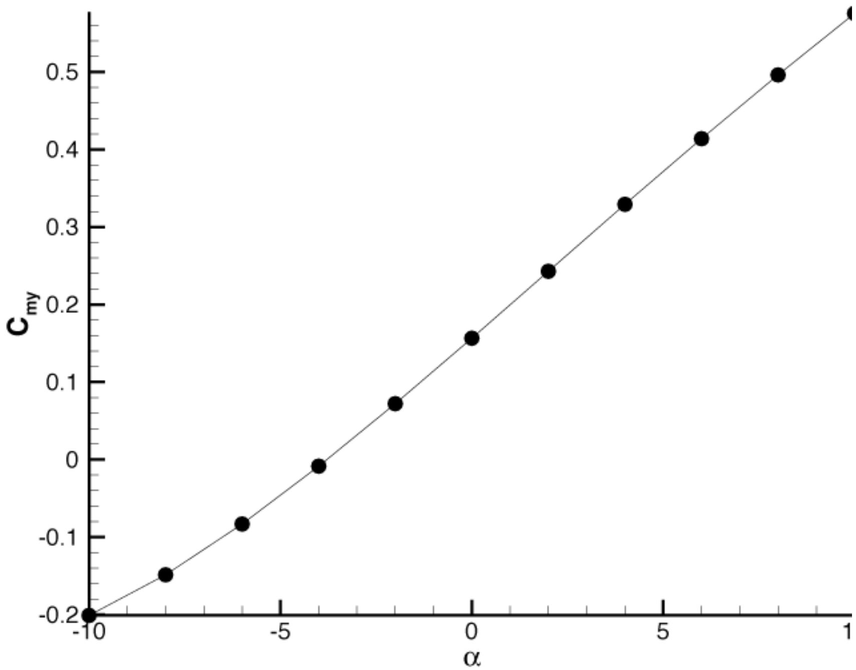


Specular

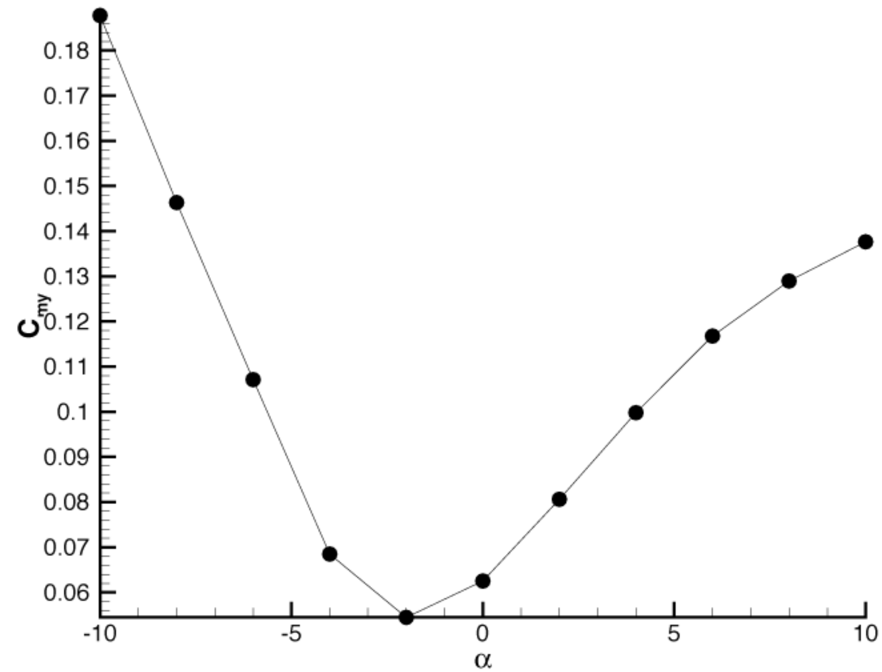


Diffuse

L/D Study (cont.)

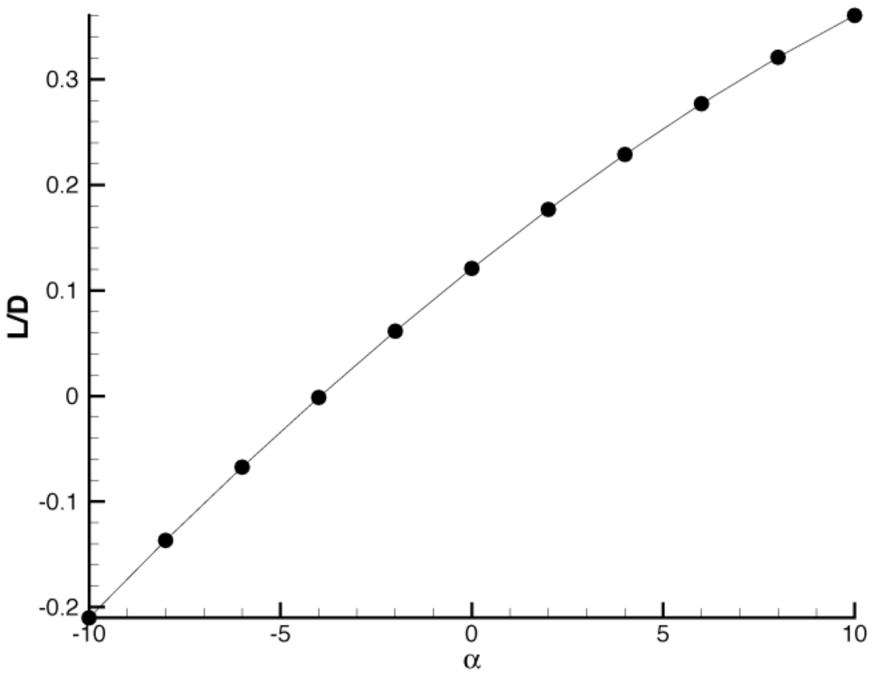


Specular

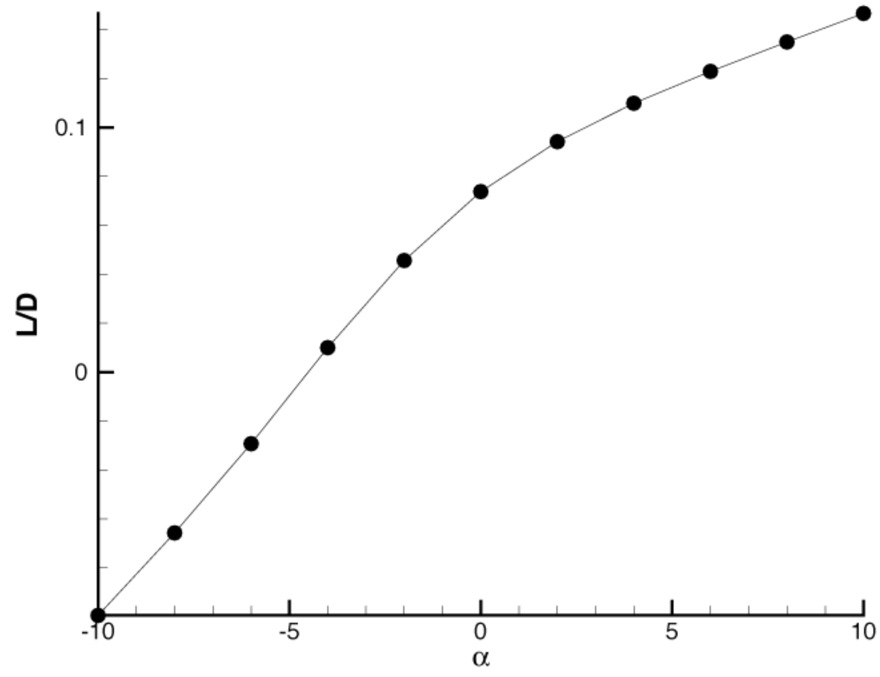


Diffuse

L/D Study (cont.)



Specular



Diffuse

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L/D Study Conclusions

- Using this GEC-specific geometry model, high L/D ratios necessary for dipping plane changes are not possible.
- The design space changes for changes in the reflection assumption.
- The L/D values possible do not change greatly for changes in the reflection assumption.
- Drag does not necessarily increase for lifting bodies.
- Stability is a concern for lifting bodies.

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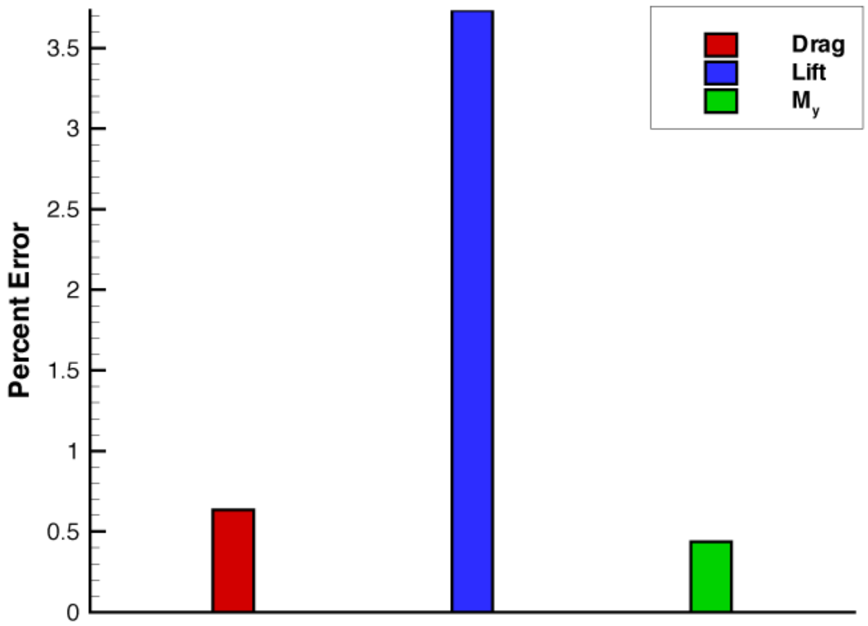
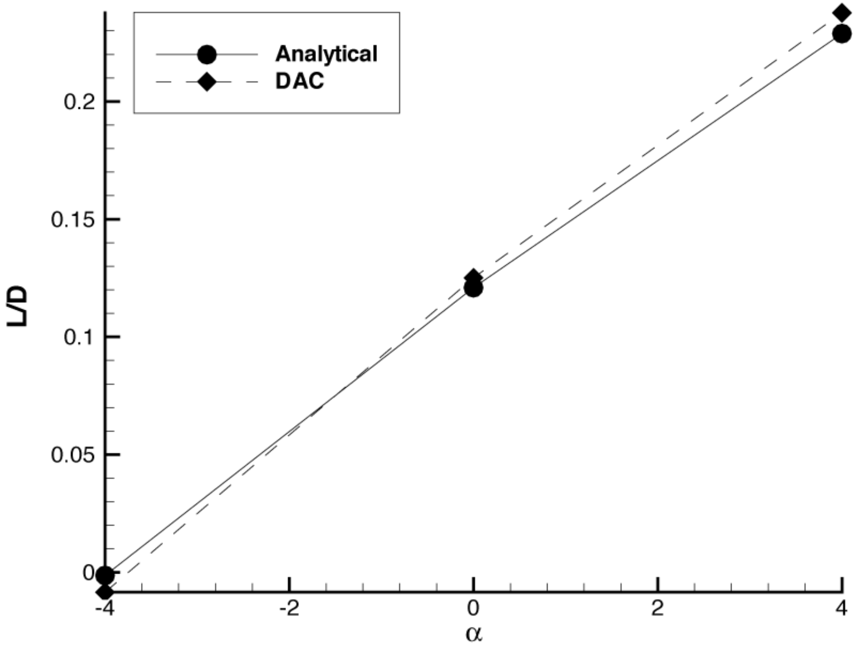
Validation: DSMC

- DSMC Analysis Code (DAC) from NASA Johnson.
- Macroscopic behavior of a rarefied gas is determined by a statistical sample.
- Uses cartesian, unstructured mesh.
- Nitrogen is used for the simulation.
- Forces, moments, and L/D trends are checked.

Specular Results





Diffuse Results

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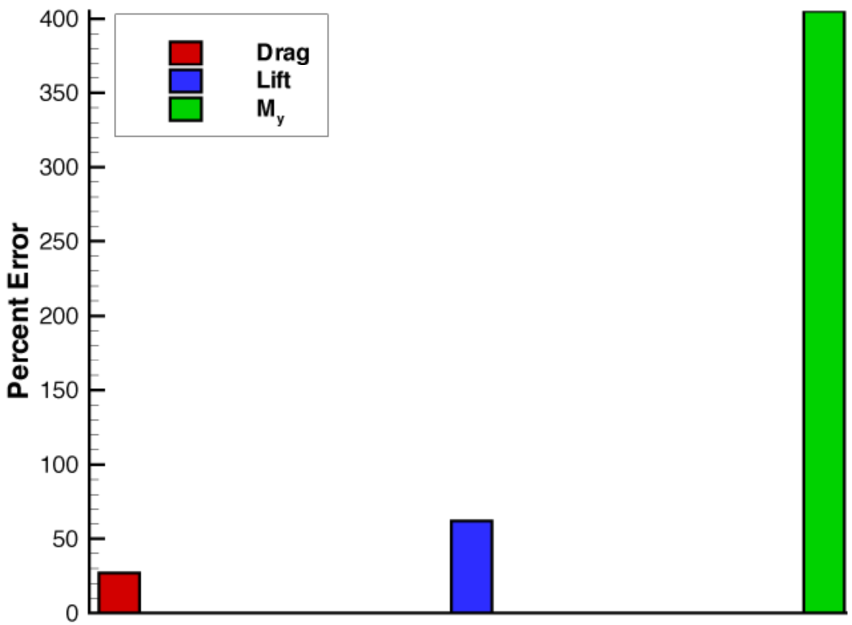

Diffuse Validation Discussion

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- The diffuse reflection model is different between the codes.
- The cosine distribution is known to be just an approximation which produces errors.
- The definition of "percent specular reflection" is different between the codes.

Conclusions

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•Reduced drag can be achieved while still increasing volume. Also, a cylinder may appropriately approximate the reduced drag body. However, these shapes have stability concerns.

•Stabilizing moment can be produced, but there are volume and drag penalties.

•Lift production does not necessarily increase the drag. However, lift production causes stability concerns.

Future Work

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•The diffuse reflection model should be more rigorously exercised before being used further.

•More needs to be known about the molecule reflection from solar cells to complete this work.

•A different formulation of the profile should be explored to take out the non-linear design variables.

•More objective functions which include stability should be explored.

•Trajectory dependence is very likely and should be included in the optimization.

Microsat Scaling

- $m/C_DA=250$ chosen from GEC probe, with $A \sim 1m^2$
- For a satellite with same type of geometry, $m/C_DA \sim [m/C_DA\,]_{1m}(L, \text{in m})$.
- Thus, velocity changes on the order of 10’s to 100’s of m/s are achievable, with total deflection angles on the order of 1-10 deg.

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Conclusions

- Aero plane change is still not practical as a stand-alone maneuver

- For missions that include atmosphere passes, or very low orbits, aerodynamic forces may be significant and useful especially true for microsats.

- Aerodynamic behavior is extremely sensitive to gas/surface interactions - specular behavior is best for high L/D, hard to obtain.

- Proper design can enhance aerodynamics

Future Work

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- Characterizing gas-surface interactions
- Seeking maximum L/D shapes in rarefied flow - analytical and numerical optimization
- Incorporate maneuver into real trajectories
- Compare aerodynamic forces to gravity torques, etc.
- Proposed lift and drag flight test.