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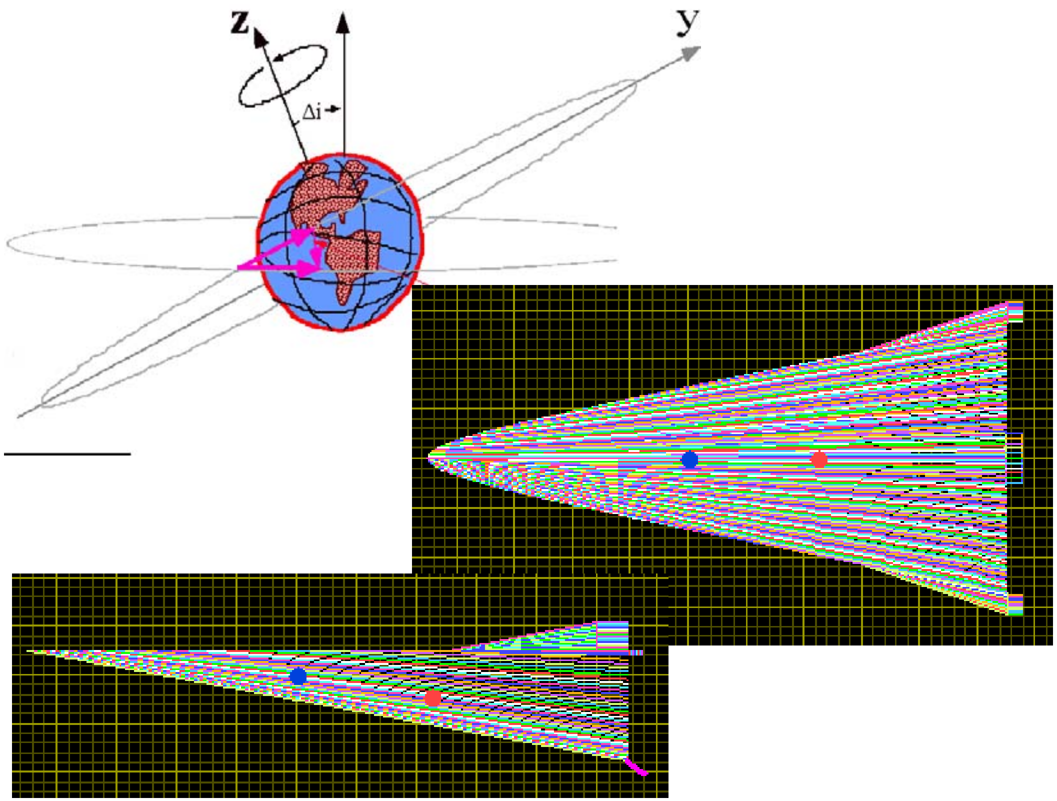
Mechanical & Aerospace Engineering

Aerodynamic and Propulsion Assisted Maneuvering for Orbital Transfer Vehicles



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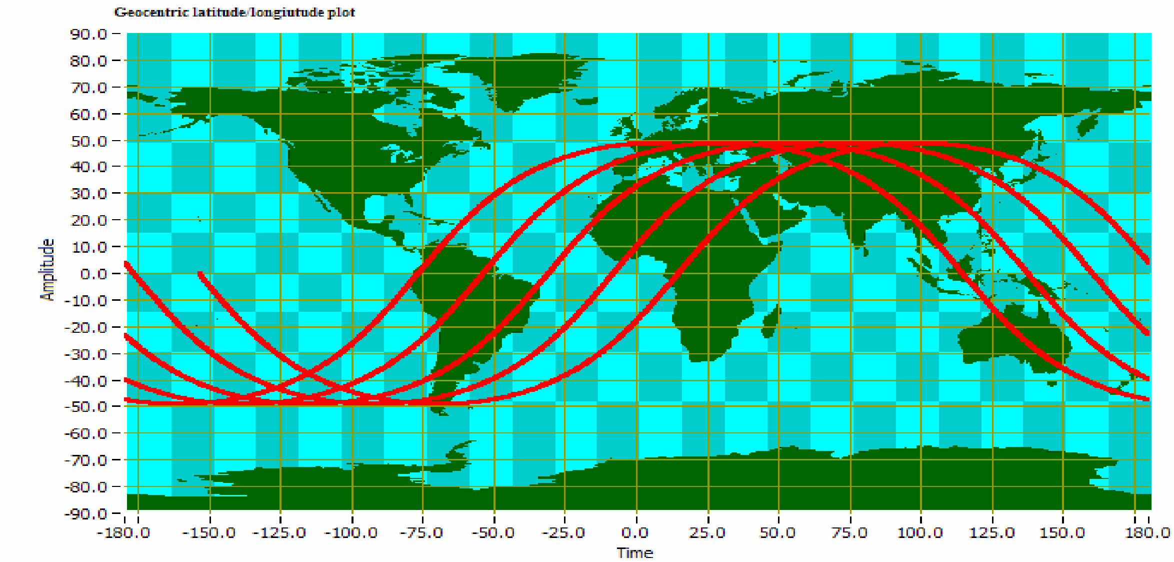
• *Work funded by California Space Grant Foundation*

CENTER FOR SPACE ENGINEERING

Outline

- The Problem
  - Enabling Responsive Space
  - Suggested Solutions
    - Aero-Assist
- Solution
  - Waverider vehicle
    - Technological Needs
    - Performance

Known Fixed Orbits



•Easy for hostile forces to predict the footprint of orbiting platform

•DoD has long sought a space-plane

•Space Shuttle can change inclination only by few tenths of a degree

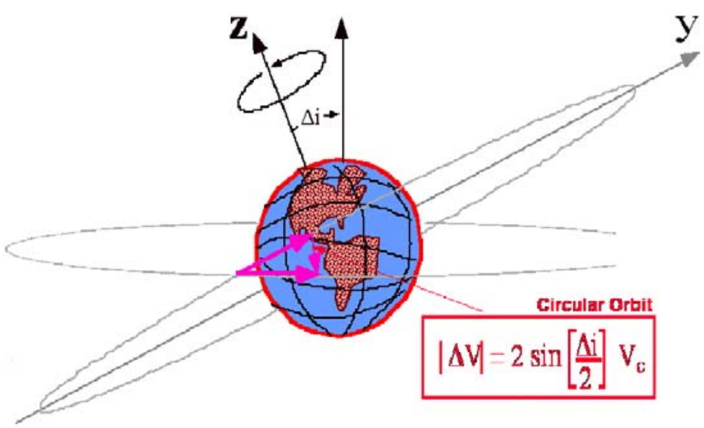
•Craft with high on-orbit agility would enable
- Rescue
- Repair
- Return
- Recycling

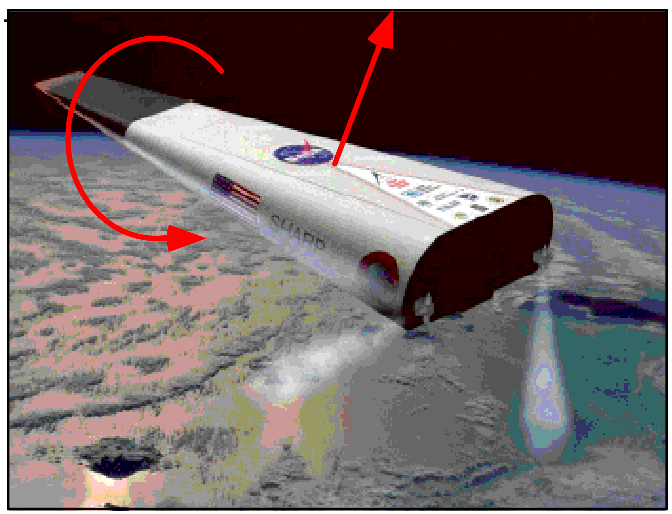
•Multiple-objective missions

Responsive Space…What is it?

- **Responsive –** Ready to launch within hours of call-up and to conduct military operations within hours of reaching orbit
- **Maneuverable –** Have maneuverability to rapidly achieve any Earth-centered orbit
- **Operable –** Must be reliable, supportable, maintainable, and robust to generate required mission rates
- **Economical –** Cost-effective to carryout DoD missions
- **Survivable –** Execute mission in spite of threats
- **Interoperable –** To maximum extent, be interoperable with joint and allied; operations concept, command and control concepts, equipment, and facilities
- **Flexible –** Capability to support variety of payloads to multiple theaters with conflicting and simultaneous requirements
- *** 2001 AFSPC ORS MNS**

Orbital Agility Comes at a Price

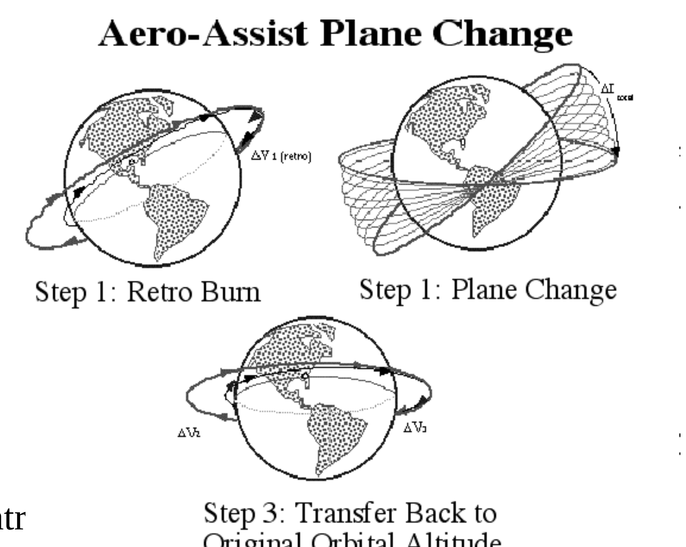




- **"ΔV" required for orbital plane change is large**
- **Re-tasking satellite "Propulsively"Lowers usable lifetime by 50-75%**

  Space Shuttle can change inclination only by a fraction of a degree

- **Most efficient method is 'aero-assisted" maneuvering … Use Lift Vector**



• L/D ~3 capable of global reach

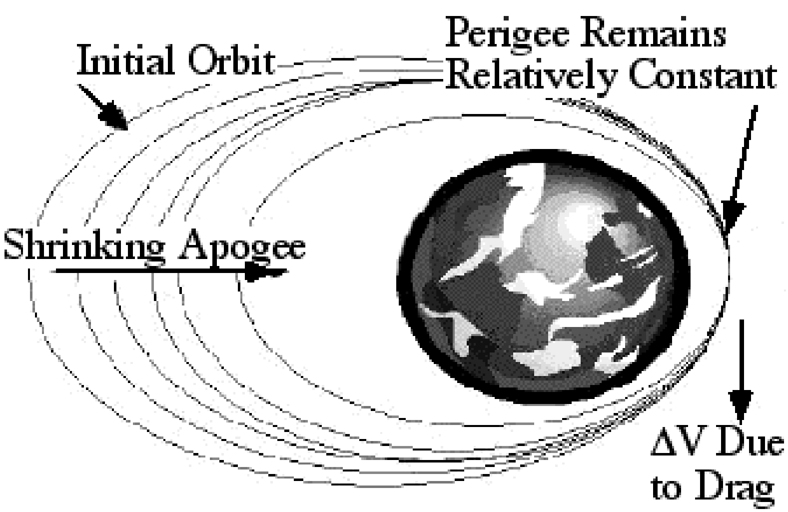
Key Needed (Enabling) Technologies

1) *High L/D Hypersonic Airframe Configurations*

2) *Sharp Leading Edges and High Temperature Leading Edge Material*

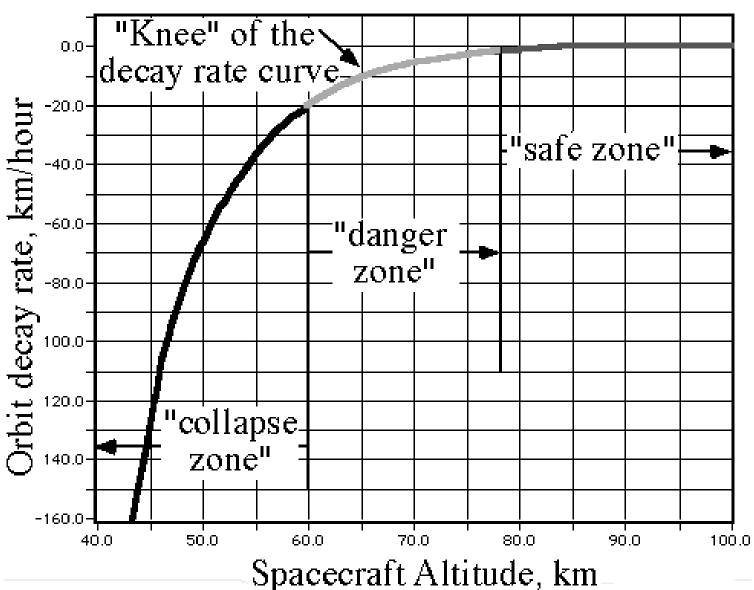
3) *Precision Restartable, Deep-Throttled Orbital Maneuvering Engines*

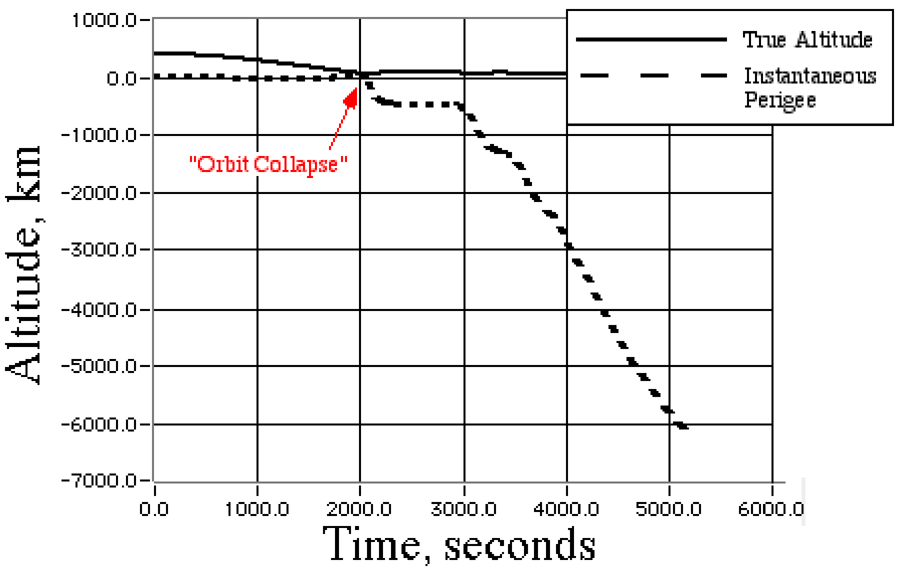
"Tickling the Tail of the Dragon"



- To obtain aero-plane change in strategically meaningful time space craft must"hover" near orbit collapse point

- Trying to perform maneuver "open-loop" Would be very risky at best -- Catastrophic at worst



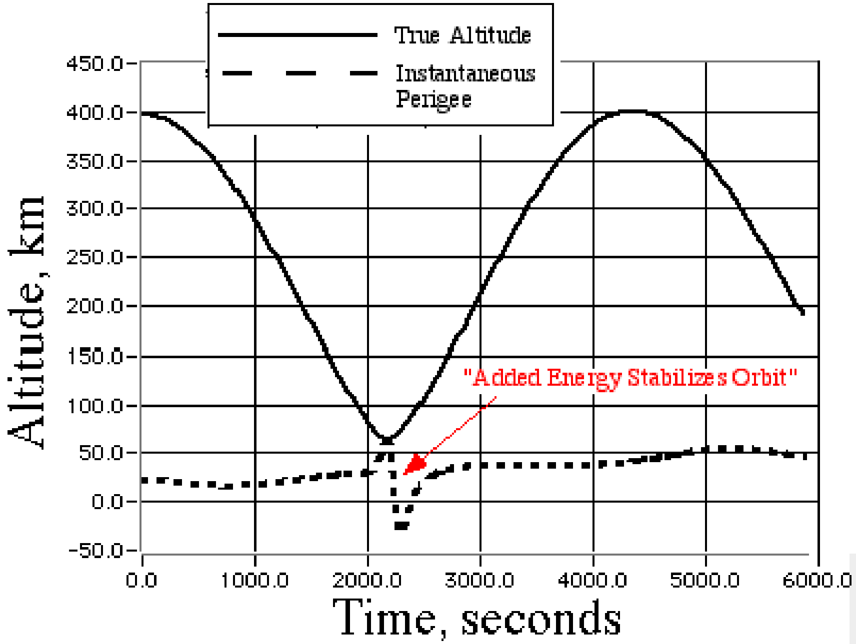


a) **No-Orbital Stabilization** (open-loop)

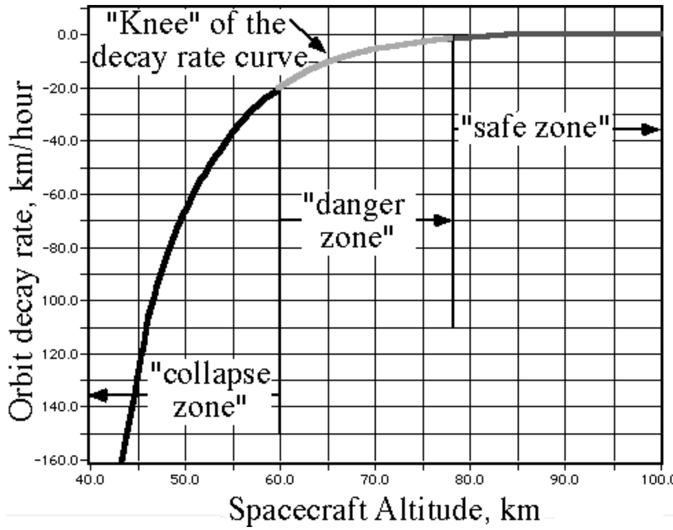
Orbit Stabilization:

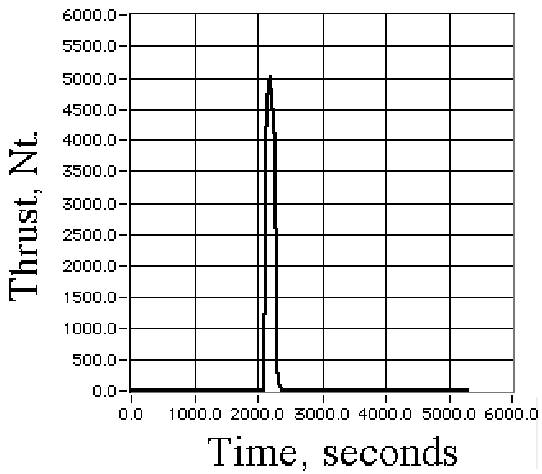
- **Modulate the engine thrust so that Orbit energy is maintained at a Predetermined Safe level**

  -- orbital energy added by the thrust modulation near orbit perigee has the effect returning the orbit apogee to its initial condition



b) Engine Used for Orbit Stabilization (closed-loop)



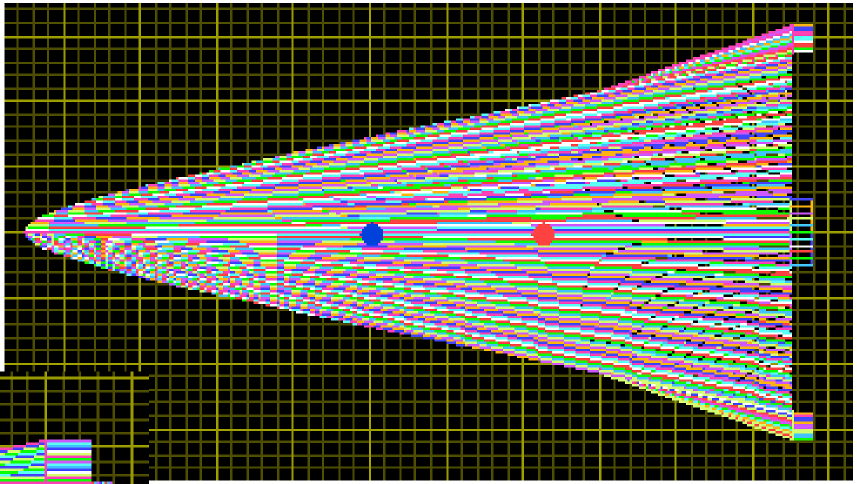


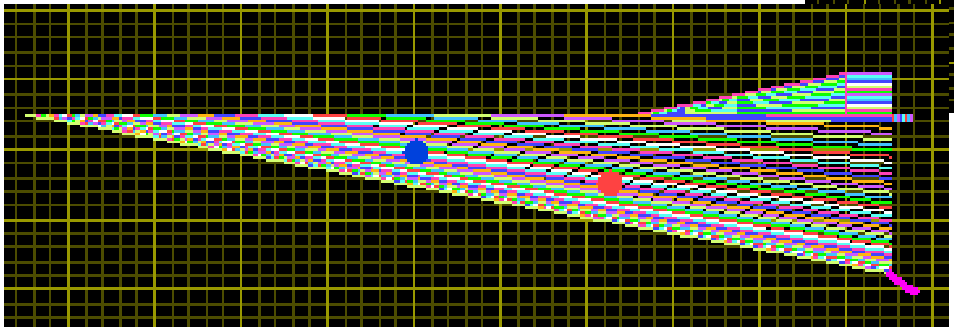
b) Engine Thrust

Why Waveriders?

- Waveriders appear to be the only craft capable of performing hypersonic maneuvers at sufficiently high Lift-to-drag ratios

- Modified to provide control authority





•Conical power law design

Waverider Aerodynamic Model

- 6-DOF data bases generated using incidence angle techniques

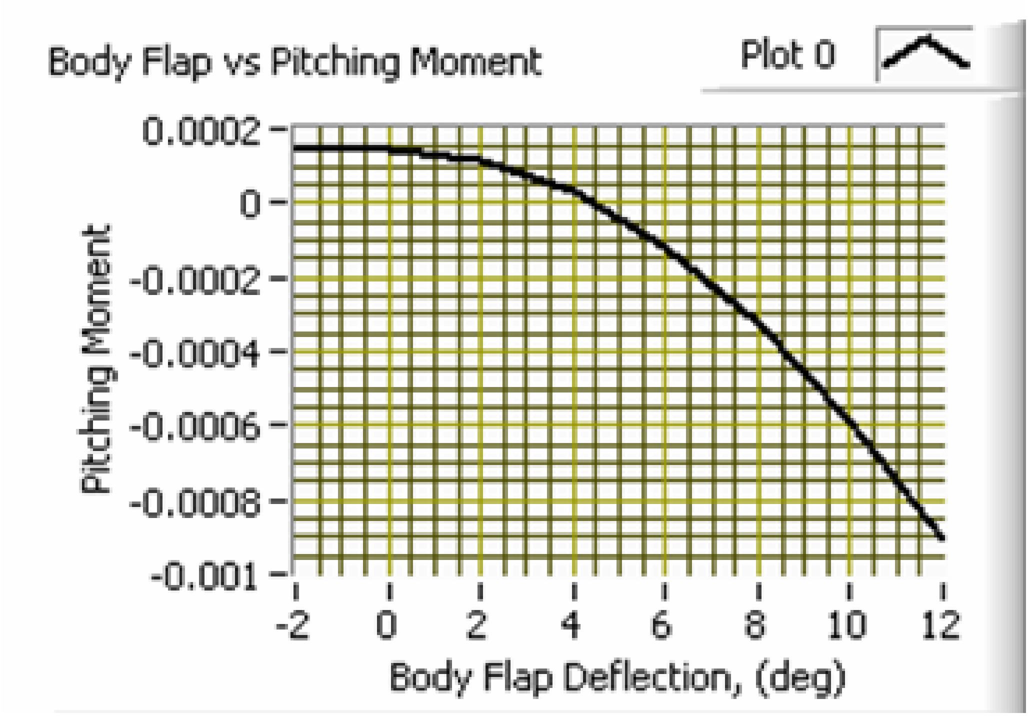
  i) Modified Newtonian flow for stagnation region

  ii) Taylor-Maccol (tangent cone) for 3-D conical sections

  iii) Oblique Shock wave (tangent wedge) used for 2-D surfaces (flaps)

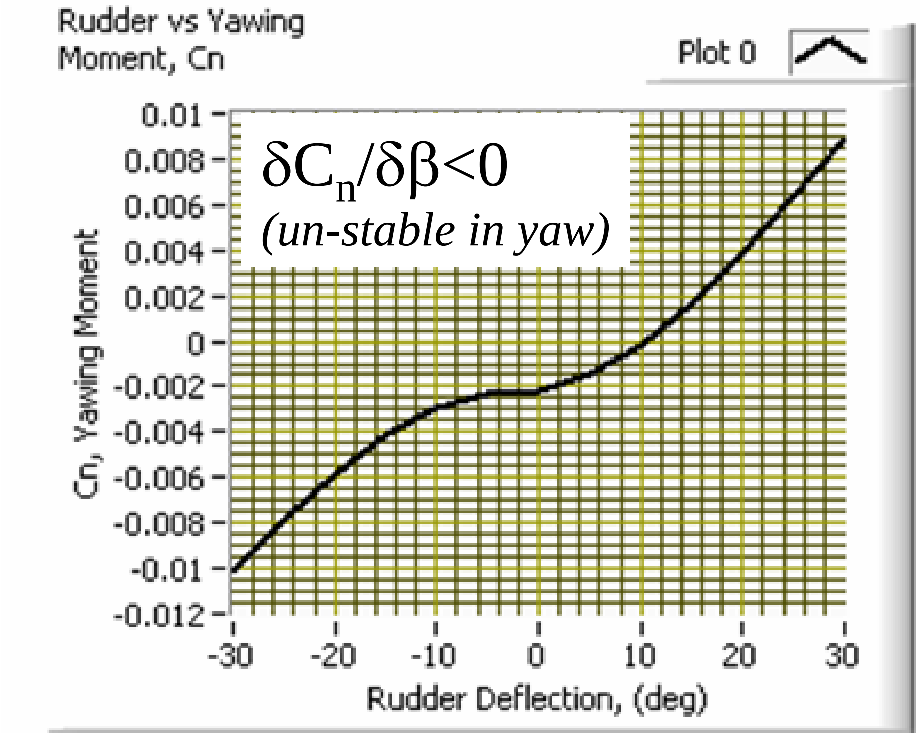
  iv) 2-D Prandtl-Meyer expansion based on local incidence used for surface element with incidence angle > 90 deg

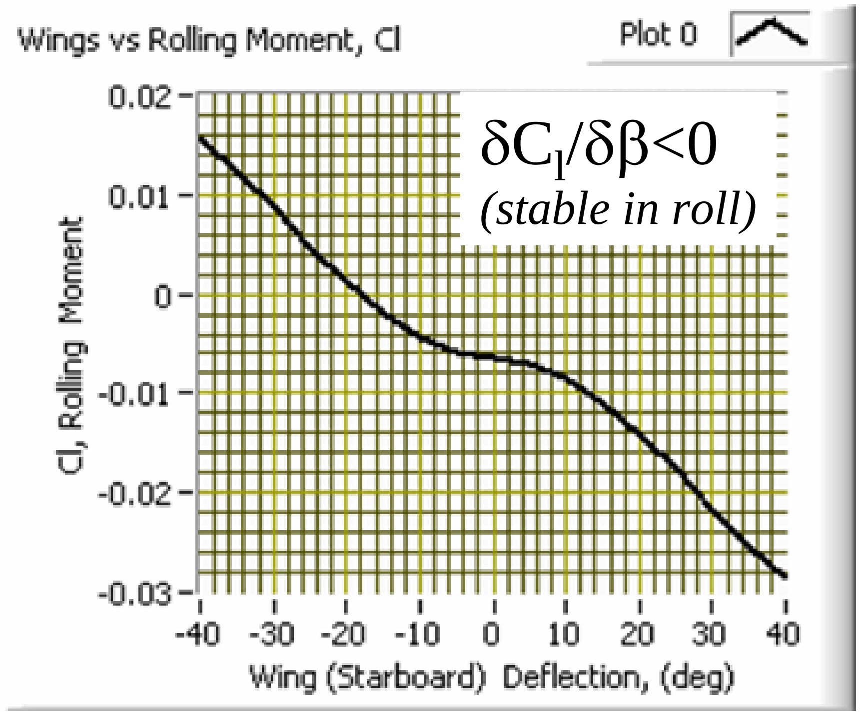
Control Surfaces Affecting Stability Derivatives



•Flaps effective below angle of attack of 3 degrees

Control Surfaces Affecting Stability Derivatives





- Sufficient control authority for ±5 degrees of beta
- Representative case from DSMC analysis

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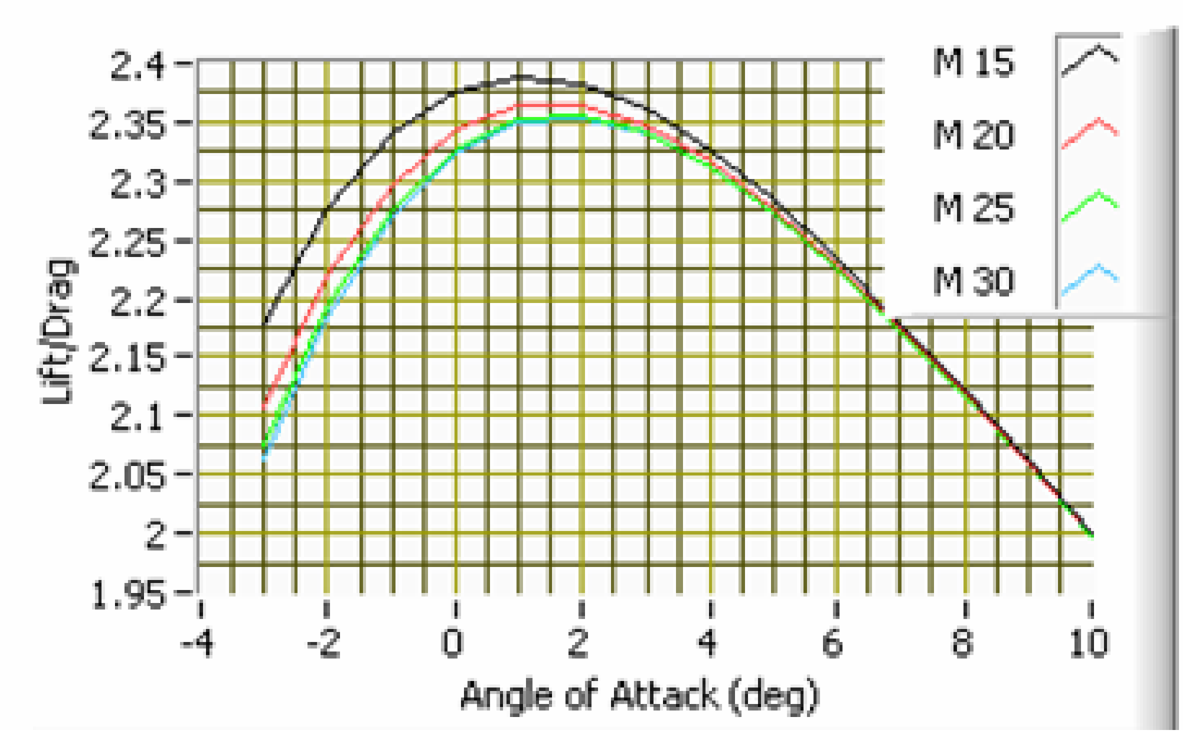
Lift/Drag and Pitching Moment



- Includes profile, skin drag, and blunt leading edge drag corrections

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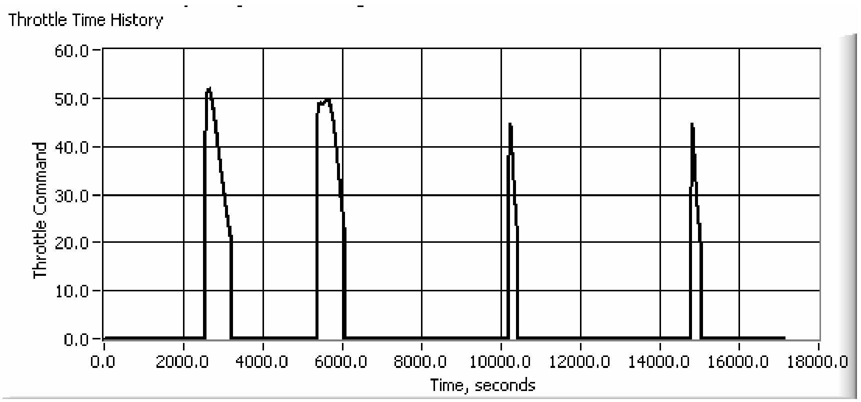
Liquid Propulsion System

- Multiple Restarts
- Throttle



LOX/CH_4
N_2O_4/MMH
LOX/ C_2H_6
N_2O_4/ C_2H_6
N_2O/ C_2H_6

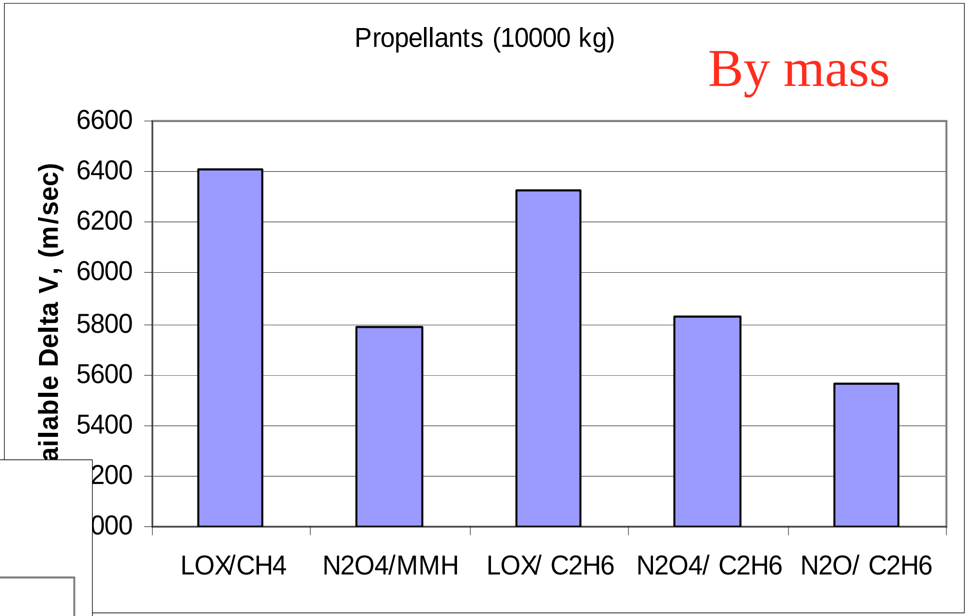
Possible Propellant Choices

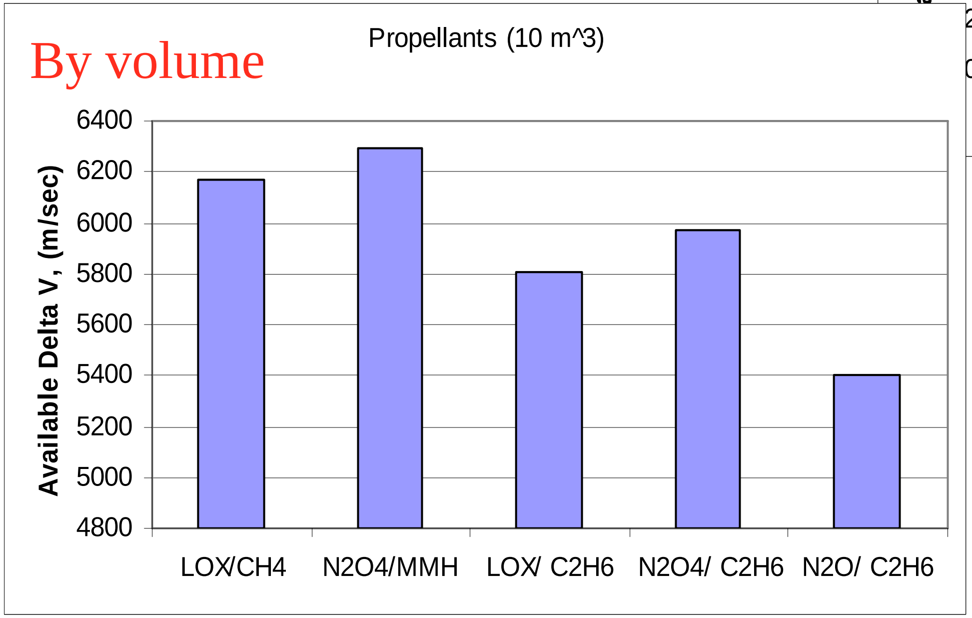
Propellants	Optimal Mixture Ratio	To, Ideal	Isp, Actual
LOX/CH_4	3.25:1	3423.84 °K	364.67 sec
N_2O_4/MMH	2.20:1	3303.88 °K	329.47 sec
LOX/ C_2H_6	3.00:1	3491.05 °K	360.10 sec
N_2O_4/ C_2H_6	4.70:1	3309.98 °K	331.873 sec
N_2O/ C_2H_6	9.00:1	3270.21°K	316.52 sec

*Results generated using CEA

Volume or Mass Limited Propellants

LOX/CH_4 has Isp=365 sec

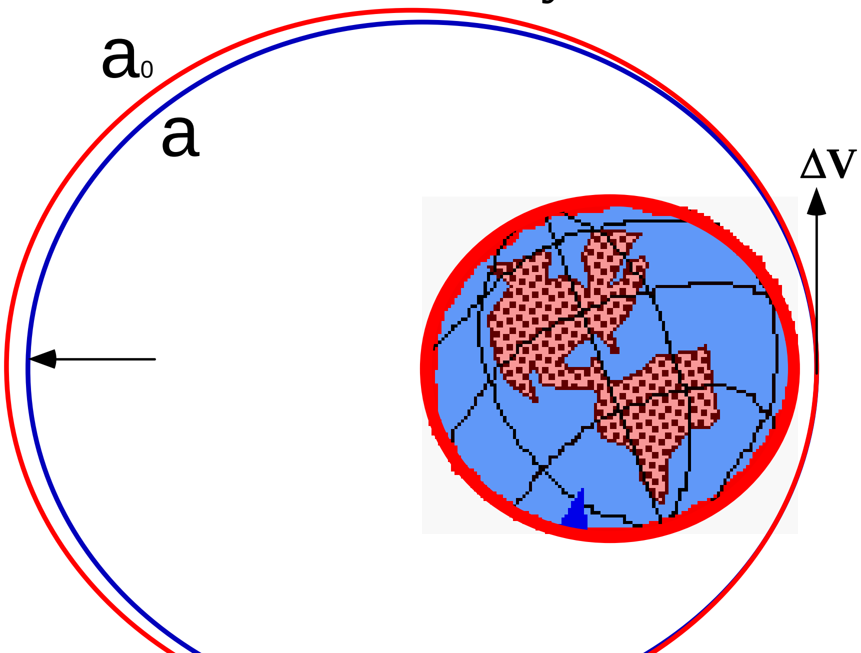




- N_2O_4/MMH has Isp=330 sec
- Advantage of storability

Precision Deep-Throttle Closed Loop Engine Demonstration

• Key to orbit Stabilization is the ability to maintain constant Orbital energy

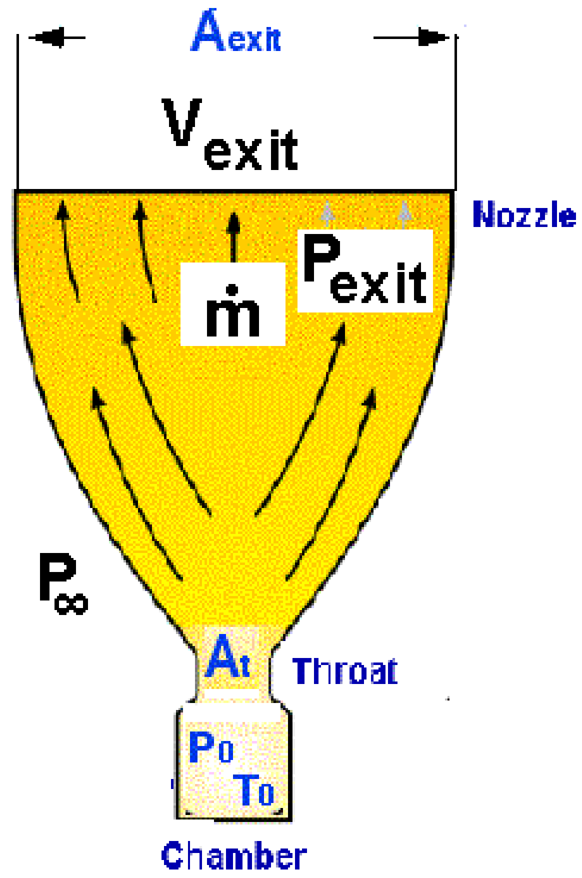


$$\left[\varepsilon_{orbit}\right]_t = -\frac{\mu}{2a_{orbit_t}} = -\frac{\mu}{2a_{orbit_0}} + \frac{\text{Energy added}}{m_{satellite}}$$

Deep-Throttle Rocket Engines

- **In theory rocket engine motor can be throttled back until the throat is no longer sonic by reducing propellant Flow rate *(injector pressure)***

- **Difficult problem in practice.**



$$T_{hrust} = \dot{m}V_{exit} + A_{exit}(P_{exit} - P_{\infty})$$

Deep-Throttle Rocket Engines

(cont'd)

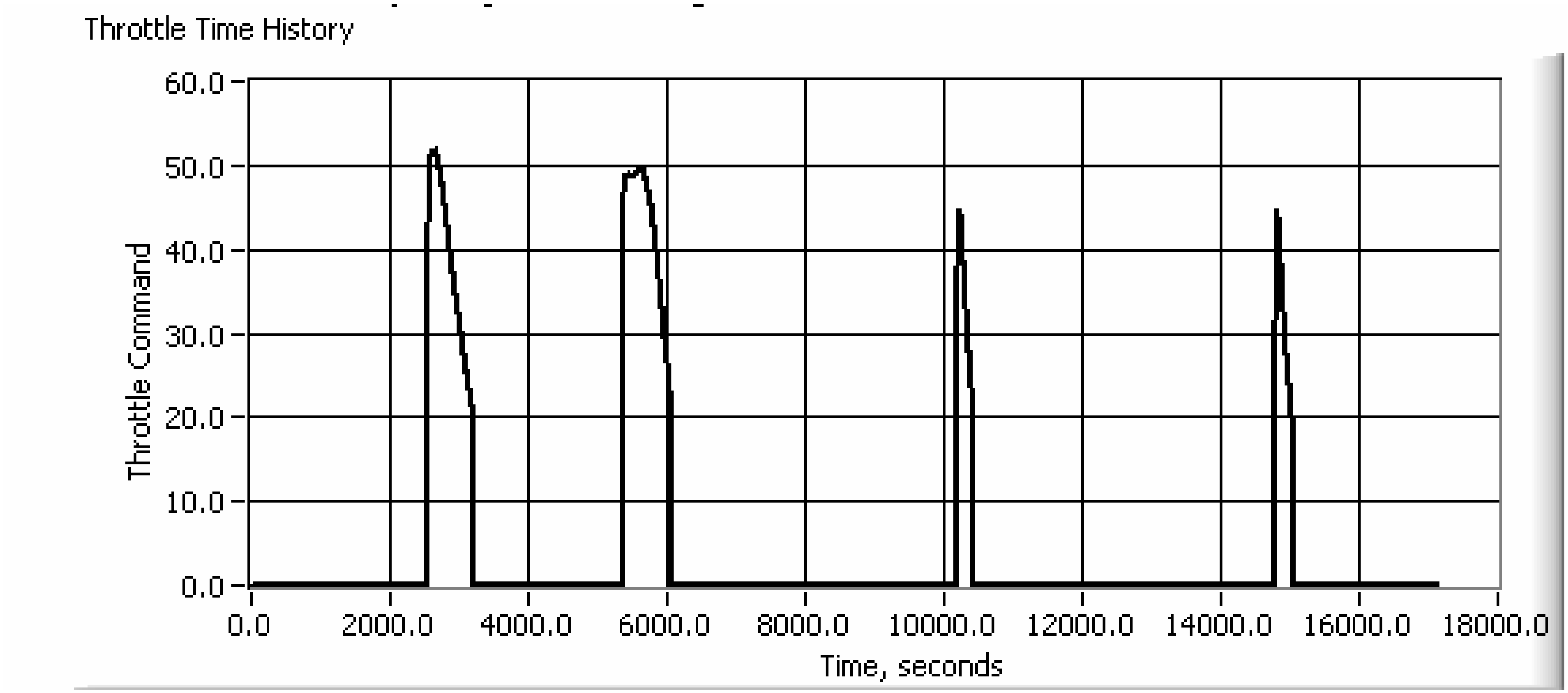
- **Essential for pressure drop across injector**
  > 25% of chamber pressure

  -- Pressure ratio insures propellant flow rates
  are independent of fluctuations in chamber pressure.

- **Fixed geometry injectors**

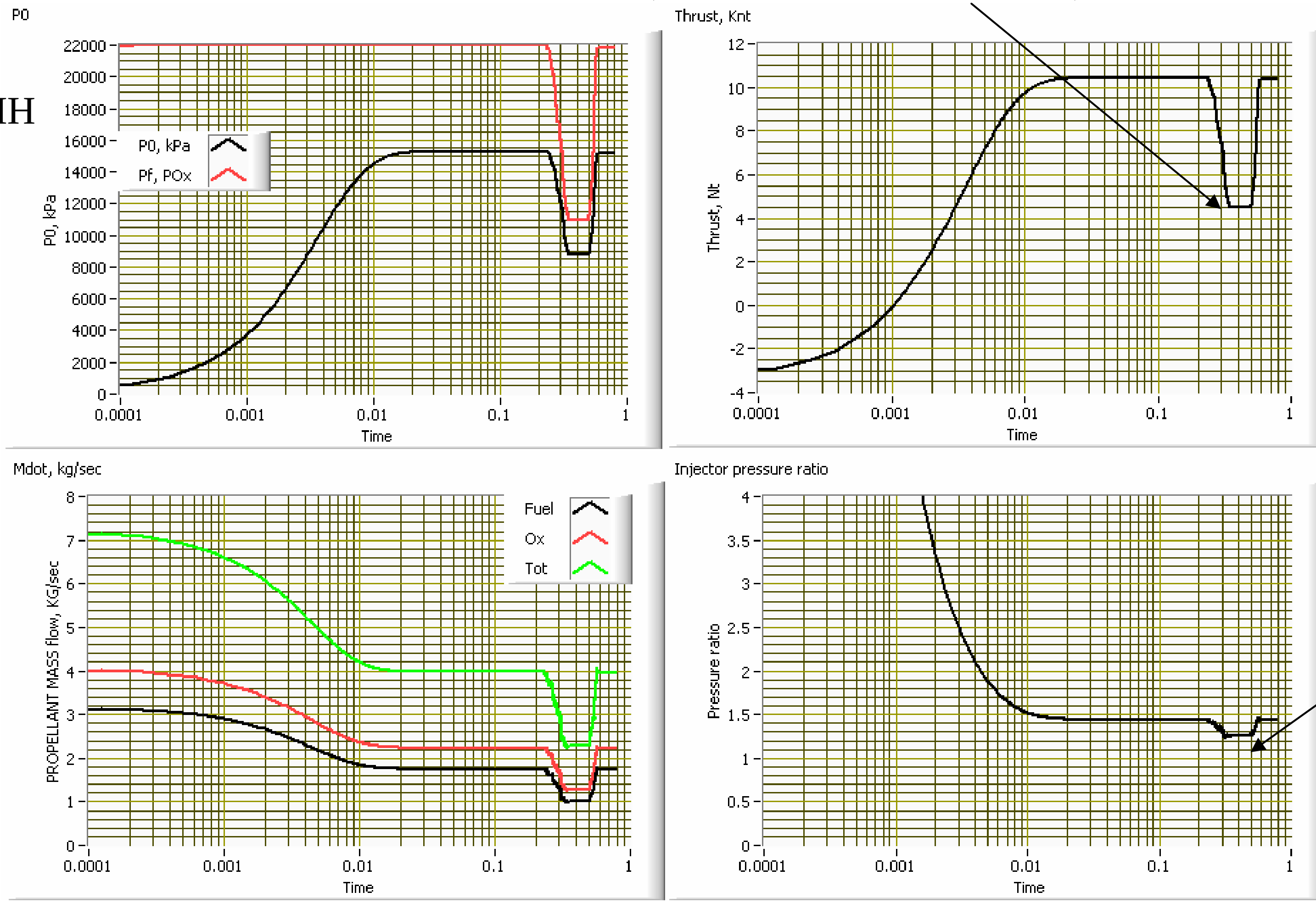
  Reduction of Propellant flow rates causes injector pressure
  to drop faster than the chamber pressure
  … until injector pressure becomes so low that coupling between
  chamber and propellant feed system occurs
  … causing combustor instability (a.k.a explosion or flameout)

Each Aero-pass will require a different level of thrust to complete the maneuver



Simulation of an Unsteady Liquid Rocket Combustion (50% Throttle)

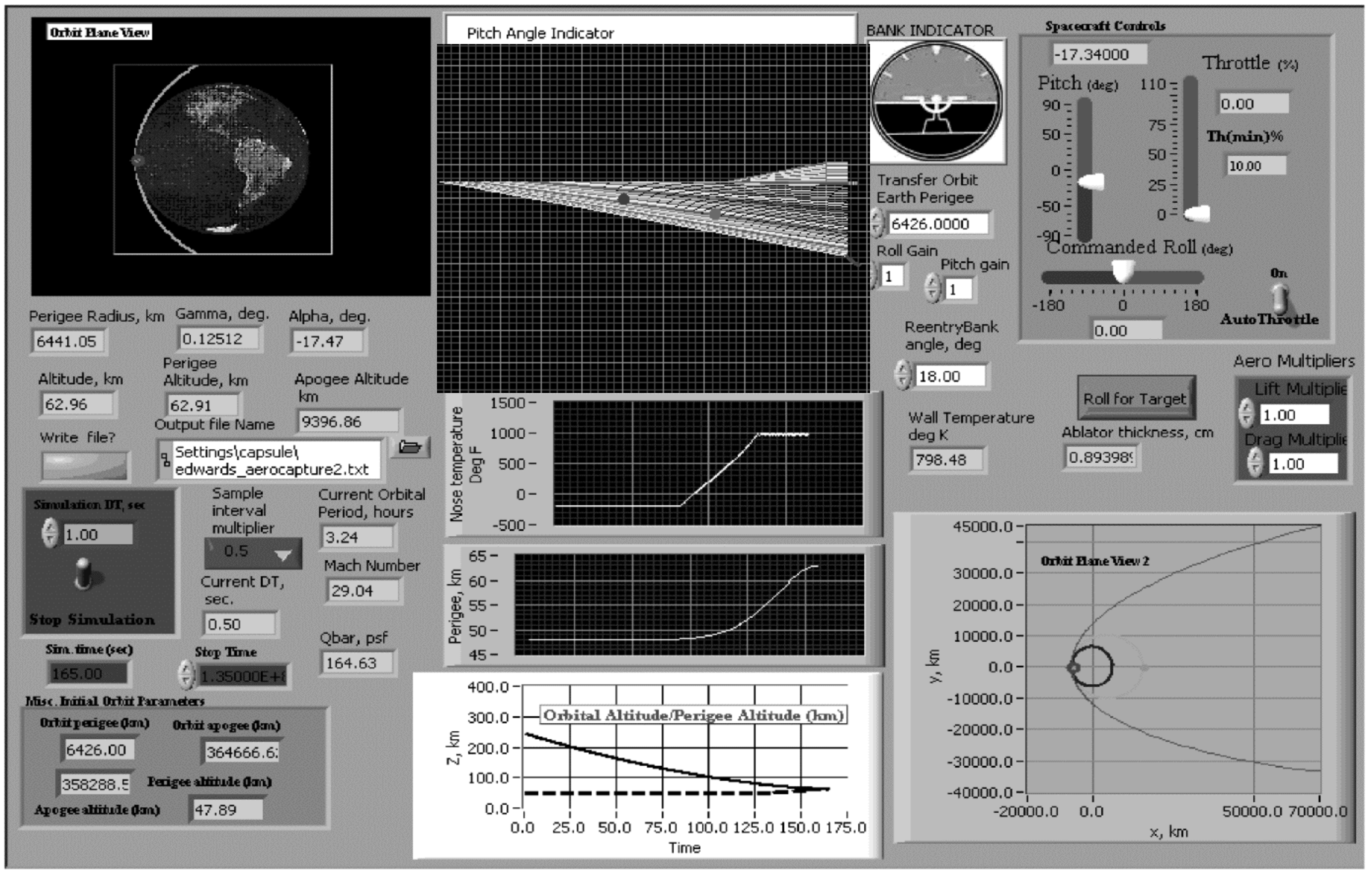
N_2O_4/MMH engine



Above stability limit 1.25

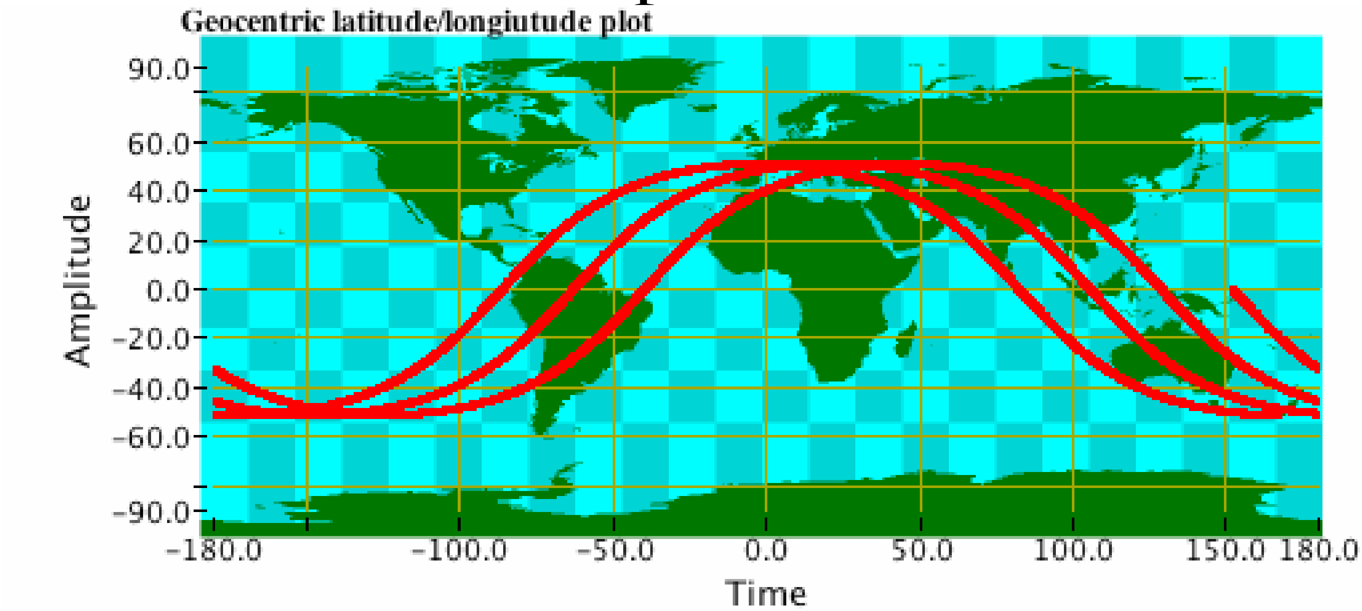
Simulation Panel

- Interactive 3-DOF Simulation used to perform analysis

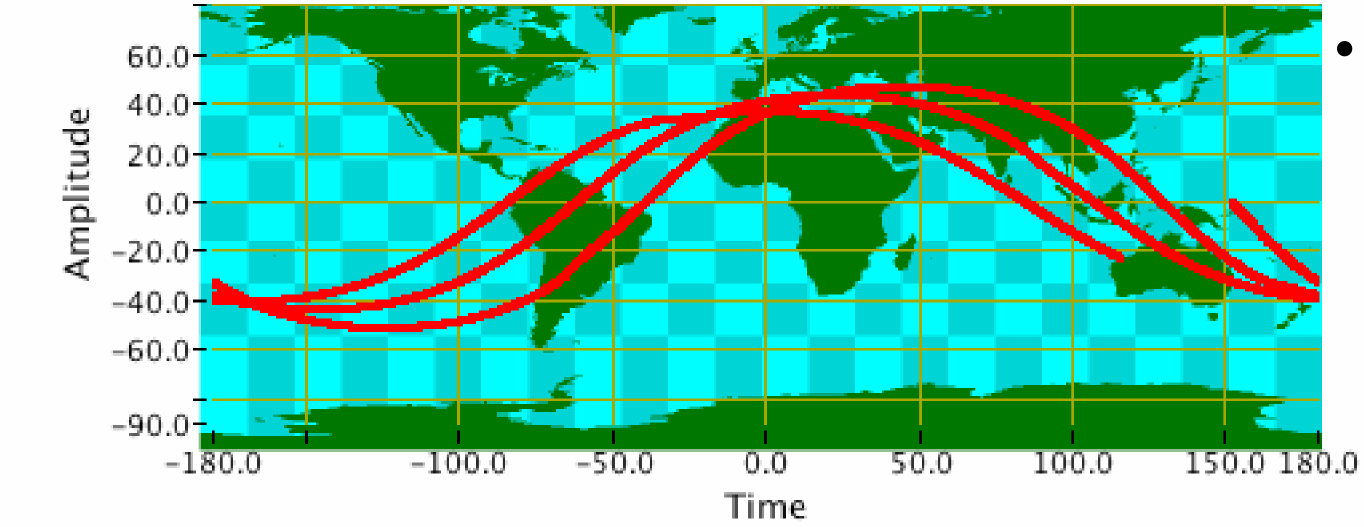


- Interactive simulations allowed a wide variety of trajectories to be analyzed and compared for the 4 configurations
- Joystick allows for Pitch, roll, and yaw, throttle inputs to be commanded

Example I: Arrival Times

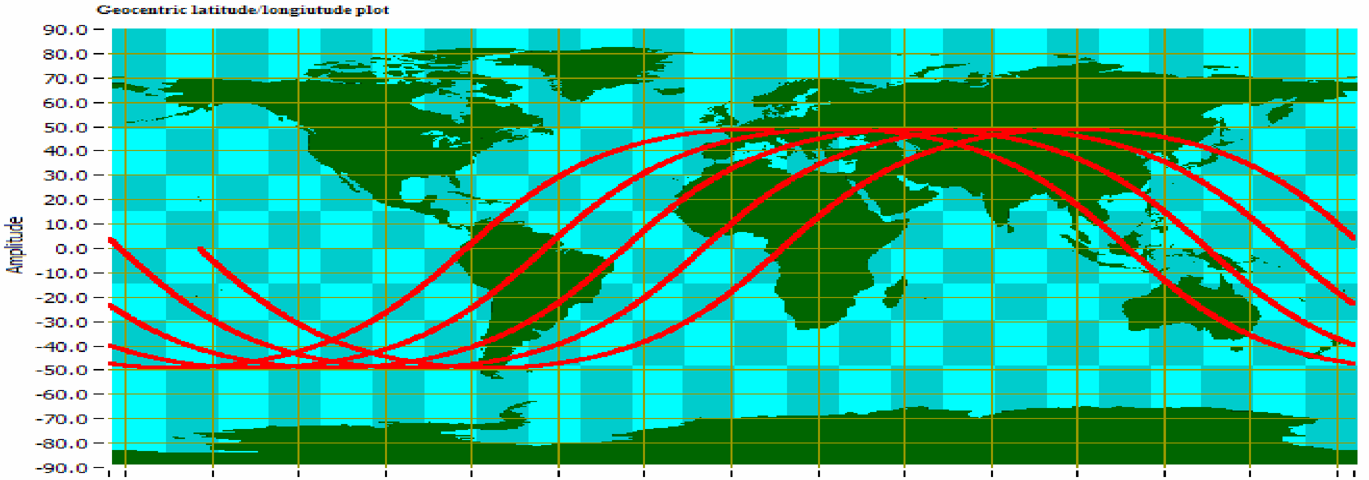


- Fixed Orbit

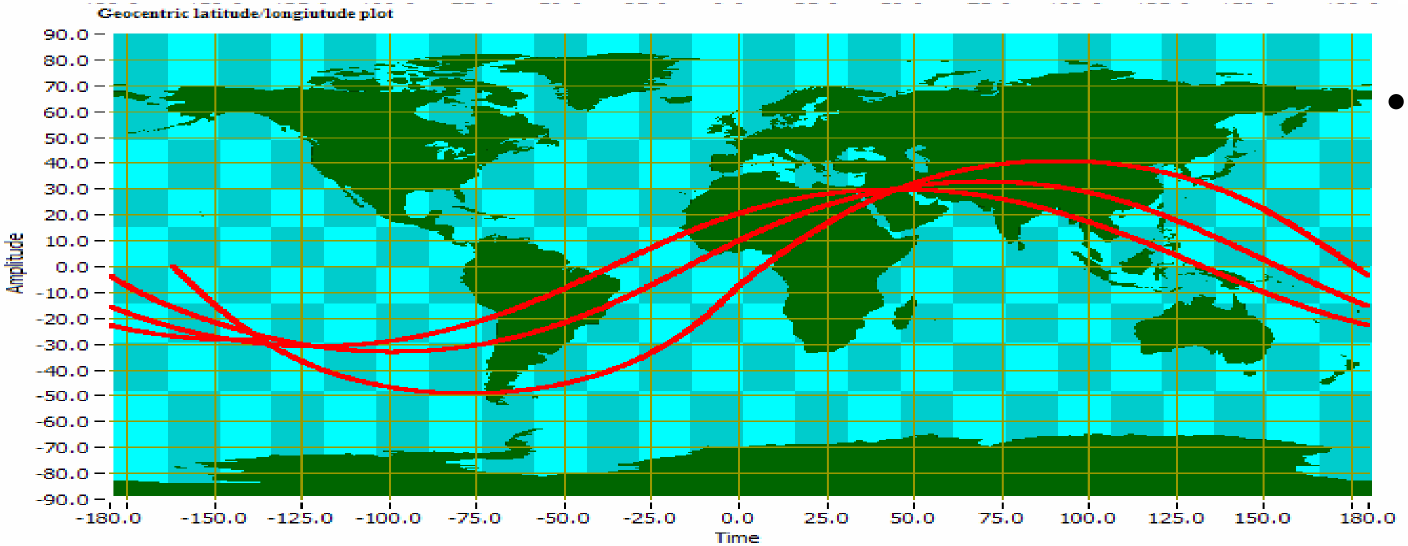


- Aeroassist Modified orbit

Example II: Arrival Times



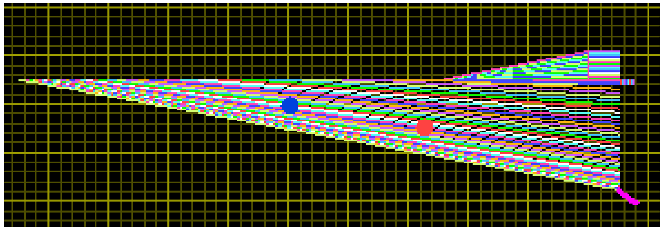
- Fixed Orbit

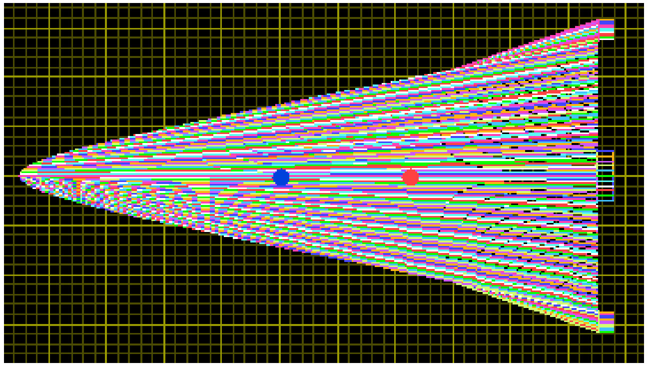


- Aeroassist Modified orbit

Conclusion

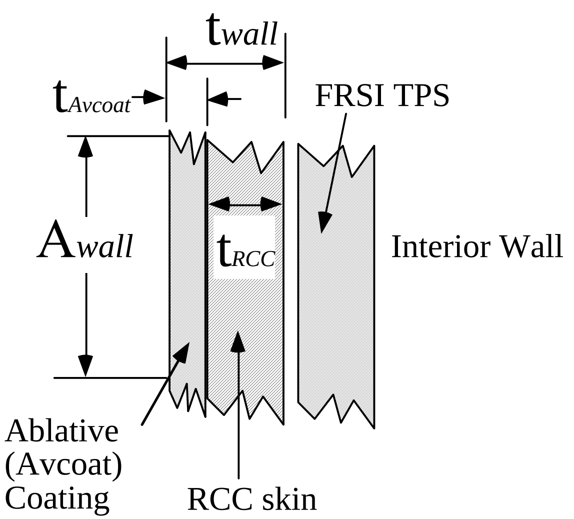
- A properly configured waverider will be capable of flight
- If equipped with a propulsion system then an aero-assist maneuver is possible
- Waveriders can help enable responsive space

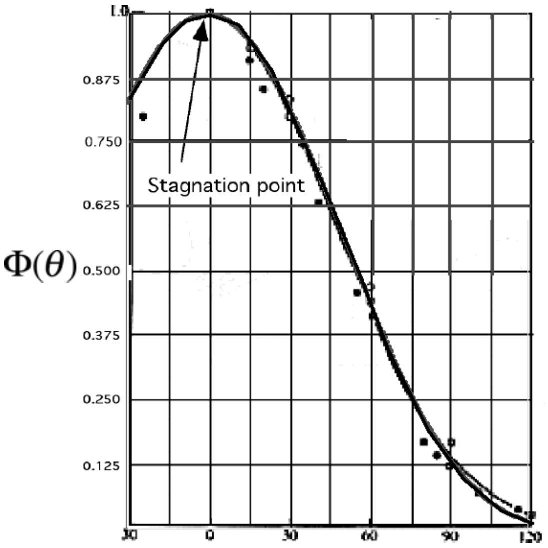


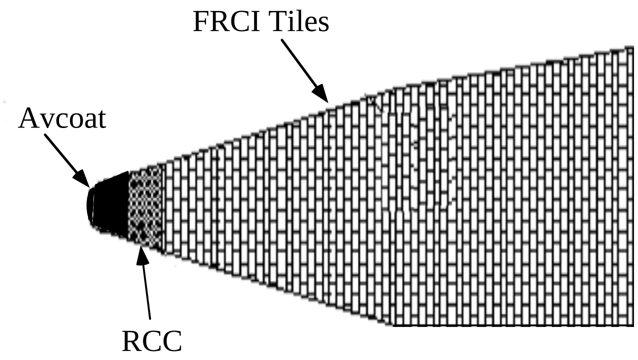


Future Work

- Thermal Modeling
- Solid Modeling
- Mass Budgets
- Hybrid Propulsion System



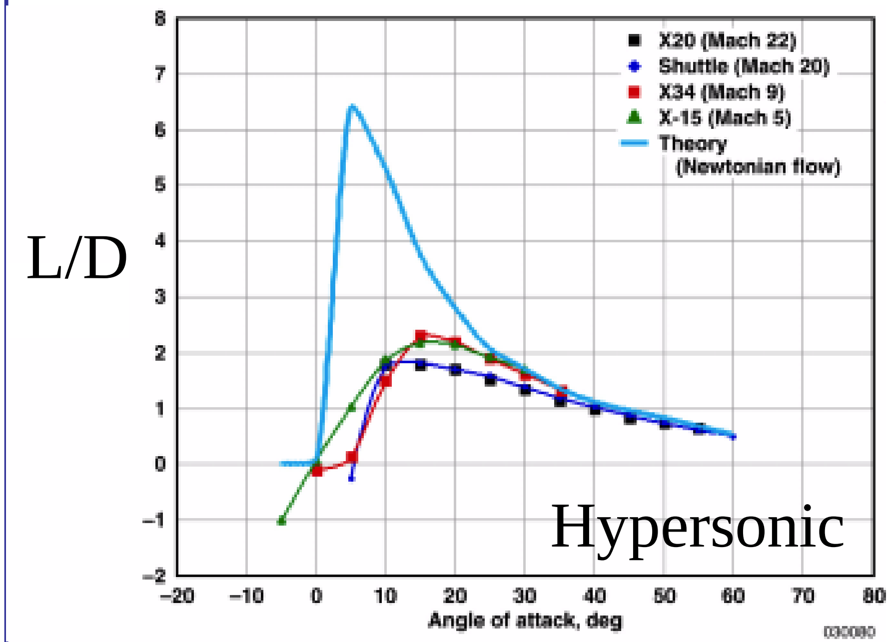




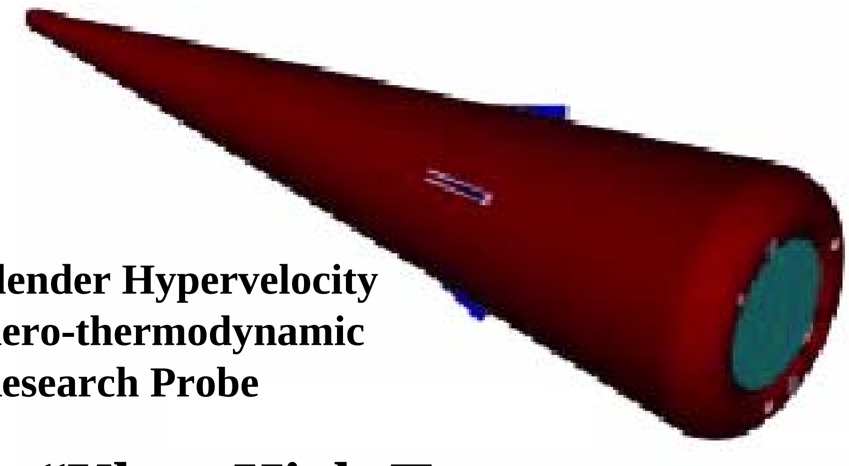
Questions?

Backup Slides

High L/D Orbital Vehicles

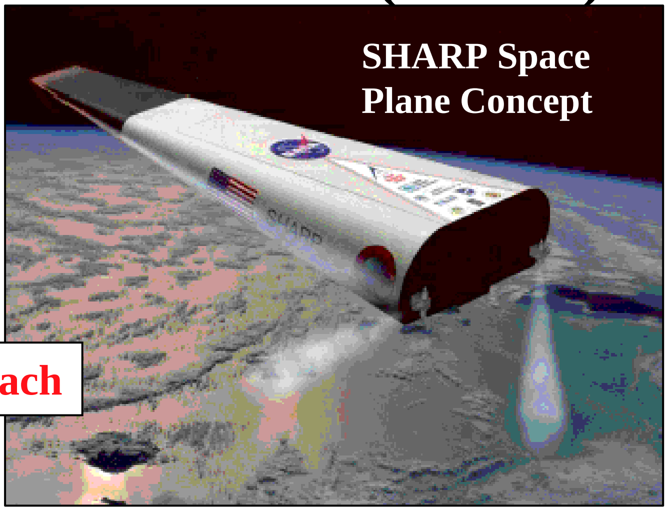


Comparison of hypersonic L/D for four wing-body reentry configurations to theoretical predictions (modified Newtonian flow).



Slender Hypervelocity Aero-thermodynamic Research Probe

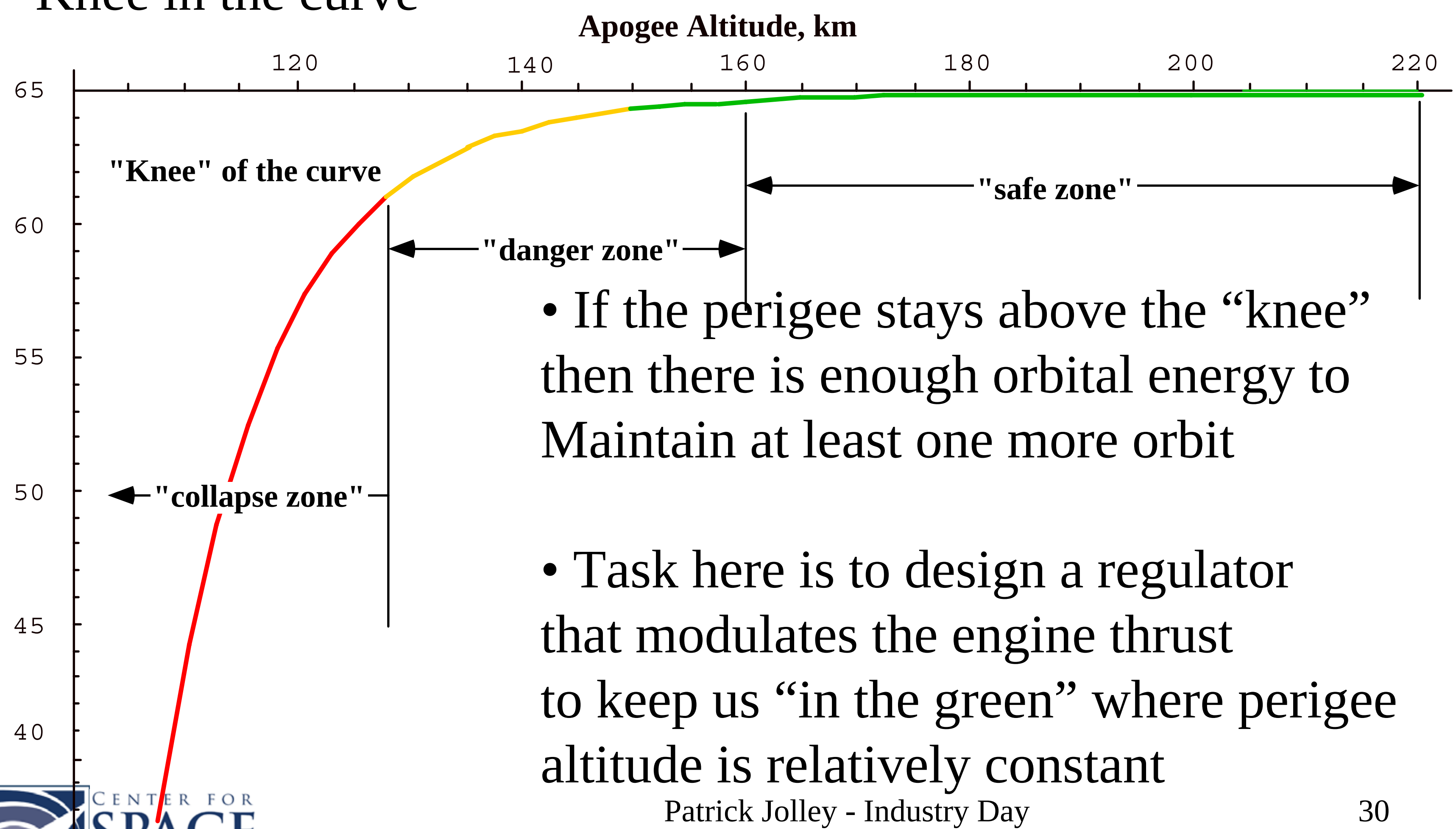
"Ultra-High-Temperature Ceramics" (UHTC)



• L/D > 3 capable of global reach

Perigee Collapse

- Key to maintaining stable orbit at very low perigee altitudes is to keep orbit apogee out of the “danger zone” just above the “Knee in the curve”

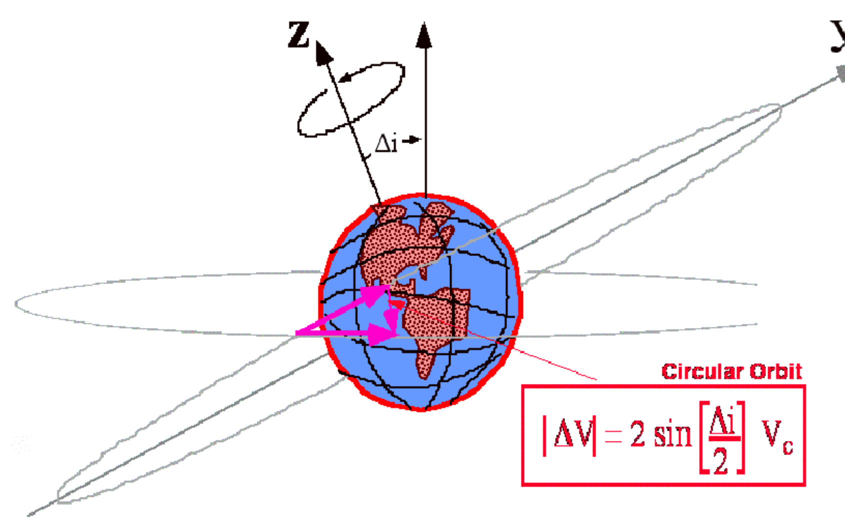


- If the perigee stays above the “knee” then there is enough orbital energy to Maintain at least one more orbit

- Task here is to design a regulator that modulates the engine thrust to keep us “in the green” where perigee altitude is relatively constant

Ways of Enabling Responsive Space

- Earth launch means
  - F-15 MSLV study
- Space based means
  - Propulsion example
    - Fuel cost
    - Or time cost for ion drives (low thrust)
  - Aero-assist example



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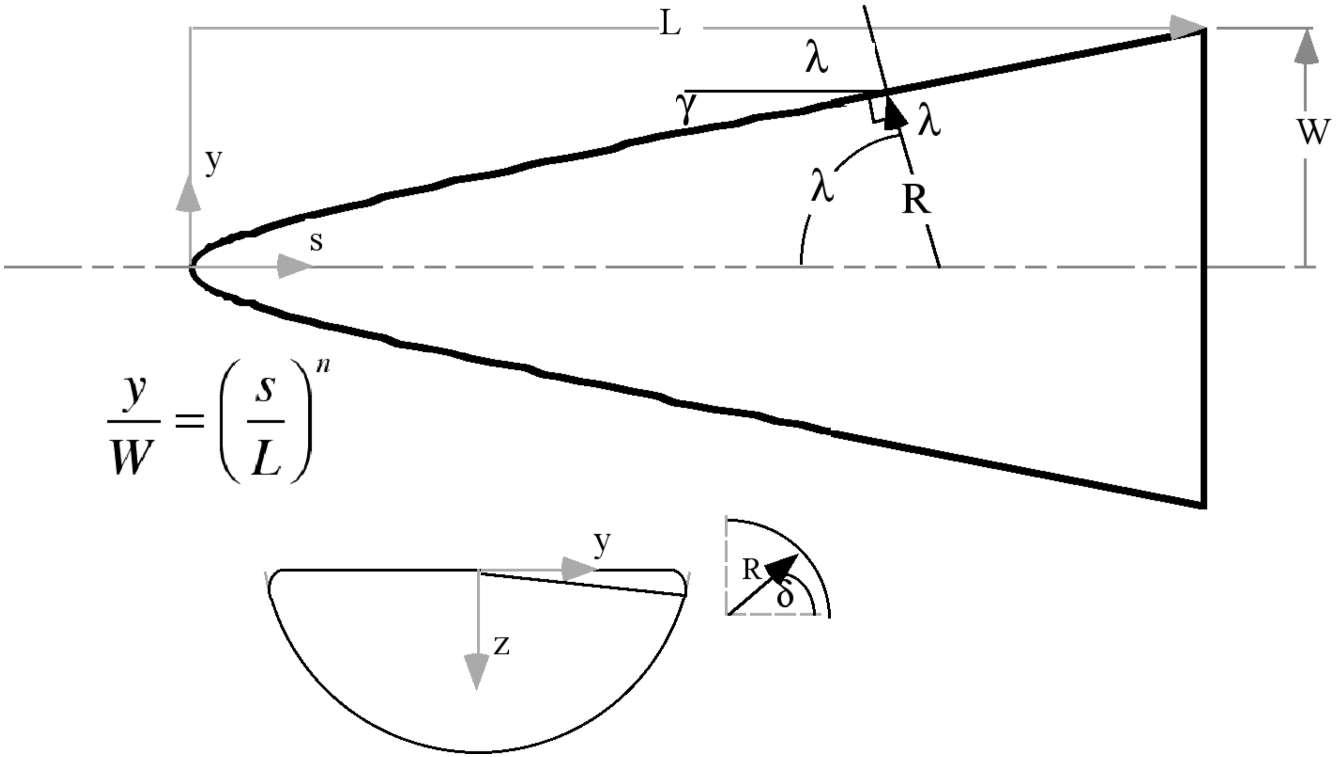
Wave Rider Leading Edge Drag Correction

$$\cos\theta = \cos\lambda\cos\delta \rightarrow \theta = \text{"}\textit{incidence angle}\text{"}$$



$$\frac{y}{W} = \left(\frac{s}{L}\right)^n$$

R: radius of blunted leading edge

L: length of body

W: half-width of body

- ***Does not include effects of control surfaces***

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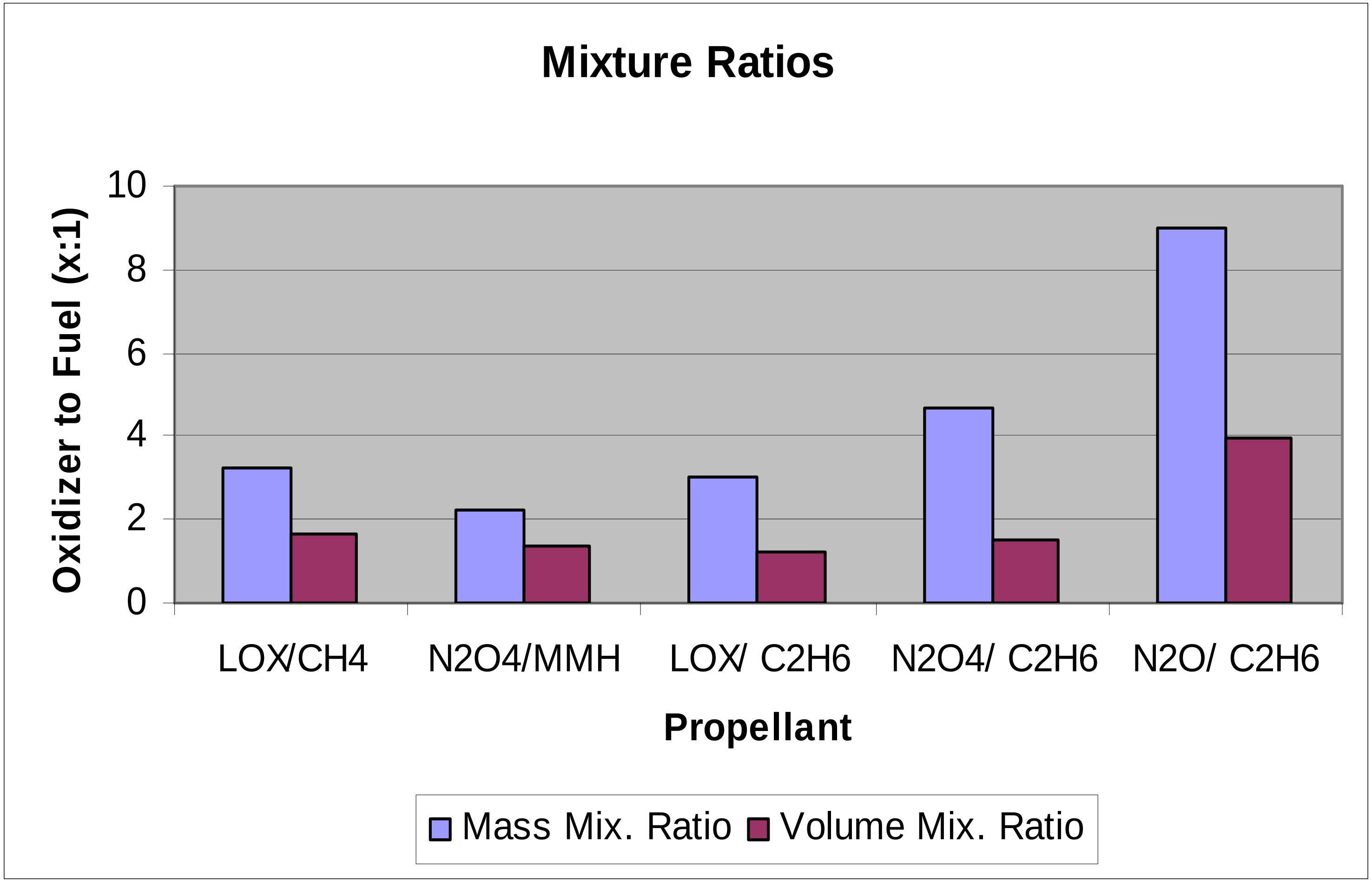
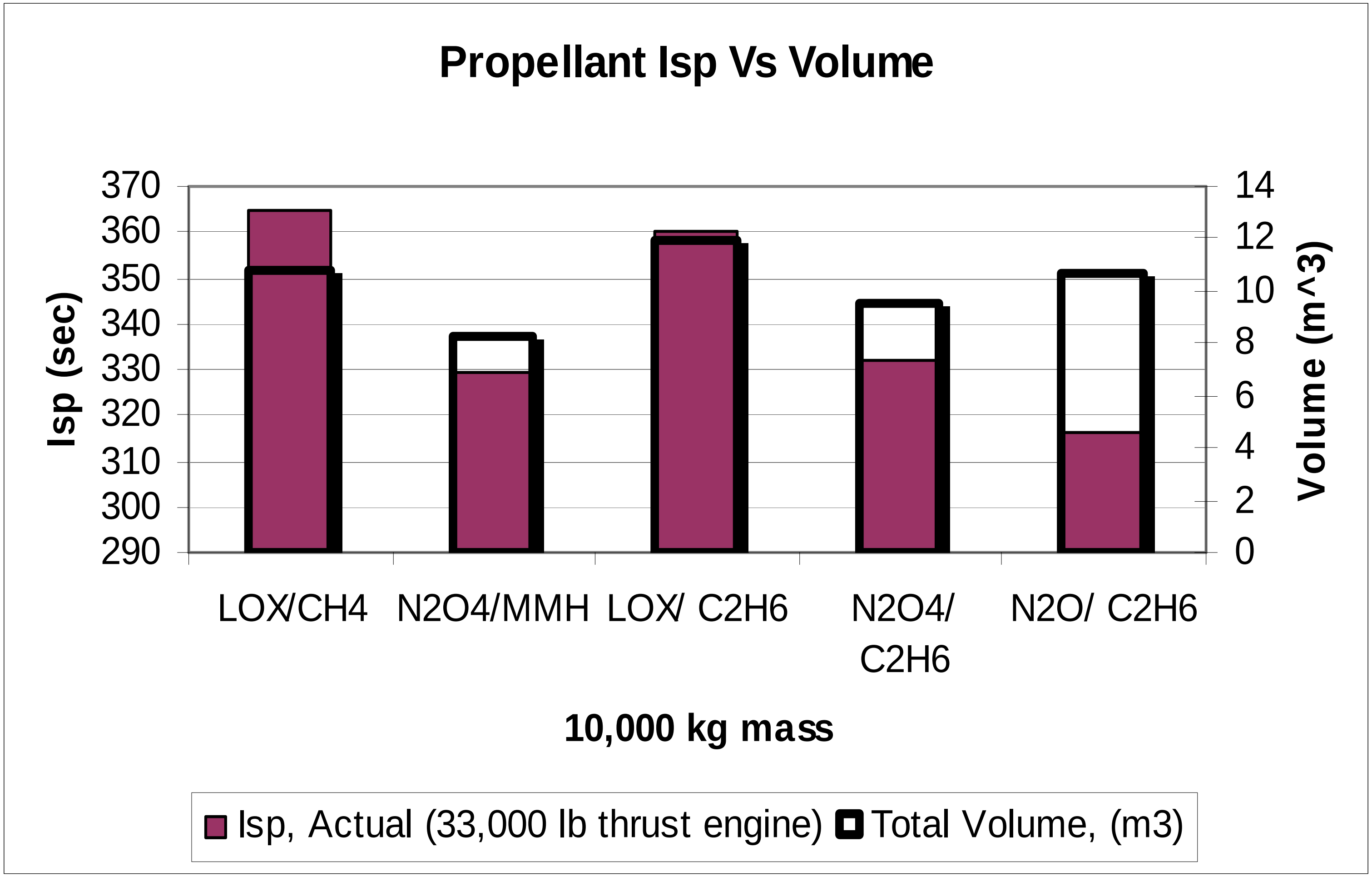
Propellant Volume Comparison

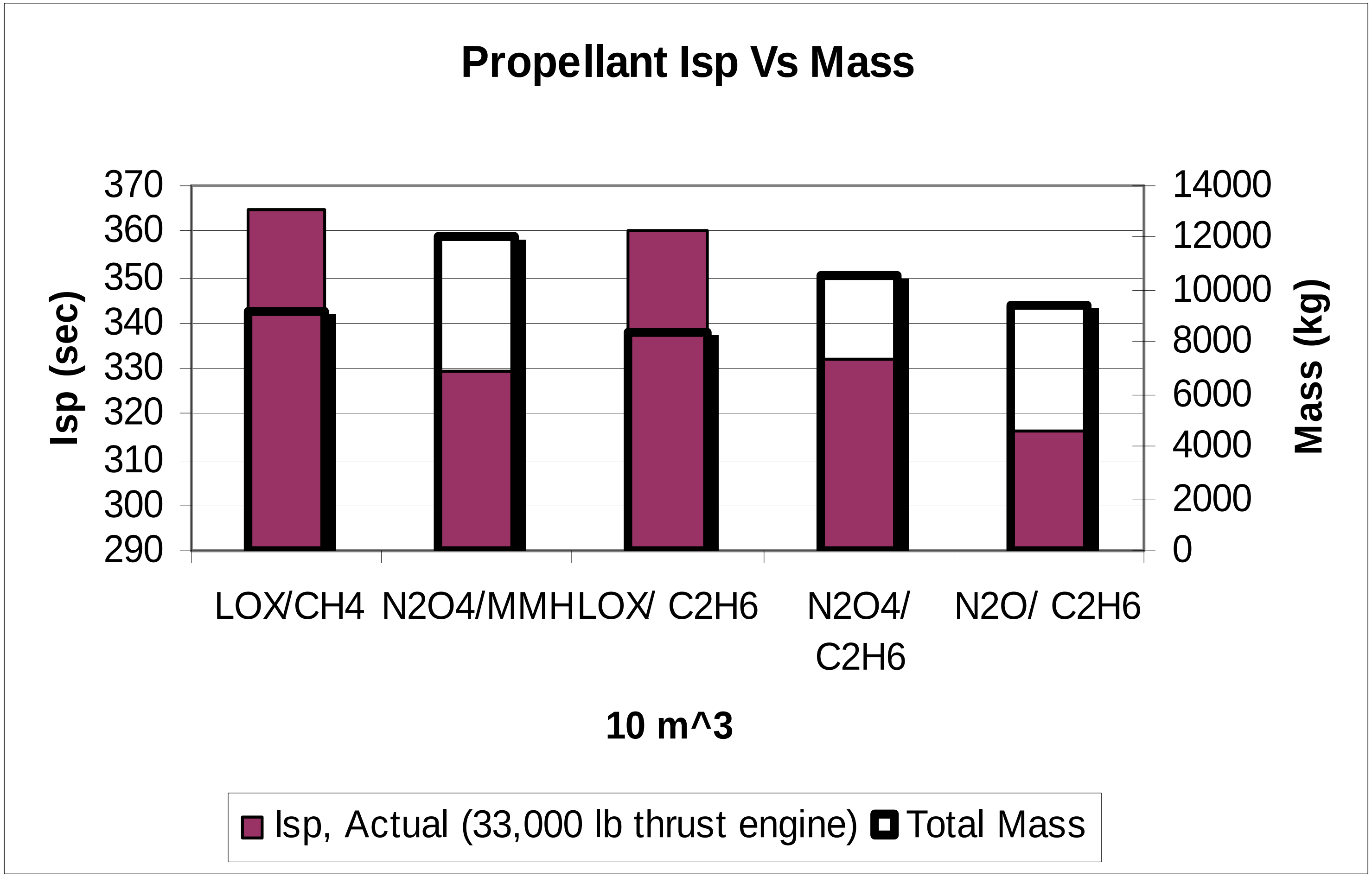
Propellants (10000 kg)	Mass Mix. Ratio	Oxidizer Mass	Oxidizer Volume, (m^3)	Fuel Mass	Fuel Volume, (m^3)	Total Volume, (m^3)
LOX/CH_4	3.25:1	7647 kg	6.703	2353 kg	4.126	10.828
N_2O_4/MMH	2.20:1	6875 kg	4.764	3125 kg	3.55	8.315
LOX/ C_2H_6	3.00:1	7500 kg	6.573	2500 kg	5.382	11.955
N_2O_4/ C_2H_6	4.70:1	8246 kg	5.714	1754 kg	3.777	9.491
N_2O/ C_2H_6	9.00:1	9000 kg	8.483	1000 kg	2.153	10.635

Propellant Mass Comparison

Propellants (10 m^3)	Volume Mix. Ratio	Oxidizer Mass	Oxidizer Vol(m^3)	Fuel Mass	Fuel Vol(m^3)	Total Mass
LOX/CH_4	1.62:1	7062 kg	6.189	2173 kg	3.811	9235 kg
N_2O_4/MMH	1.34:1	8268 kg	5.730	3758 kg	4.270	12026 kg
LOX/ C_2H_6	1.22:1	6274 kg	5.498	2091 kg	4.502	8365 kg
N_2O_4/ C_2H_6	1.51:1	8688 kg	6.021	1848 kg	3.979	10536 kg
N_2O/ C_2H_6	3.94:1	8462 kg	7.976	940 kg	2.024	9402 kg


Mixture Ratios
Oxidizer to Fuel (x:1)
0
2
4
6
8
10
LOX/CH4
N2O4/MMH
LOX/ C2H6
N2O4/ C2H6
N2O/ C2H6
Propellant
Mass Mix. Ratio
Volume Mix. Ratio


Propellant Isp Vs Volume
370
360
350
340
330
320
310
300
290
Isp (sec)
14
12
10
8
6
4
2
0
Volume (m^3)
LOX/CH4
N2O4/MMH
LOX/ C2H6
N2O4/ C2H6
N2O/ C2H6
10,000 kg mass
Isp, Actual (33,000 lb thrust engine)
Total Volume, (m3)


Propellant Isp Vs Mass
Isp (sec)
370
360
350
340
330
320
310
300
290
Mass (kg)
14000
12000
10000
8000
6000
4000
2000
0
LOX/CH4
N2O4/MMH
LOX/ C2H6
N2O4/ C2H6
N2O/ C2H6
10 m^3
Isp, Actual (33,000 lb thrust engine)
Total Mass

Exploitation of High Orbital Agility

• Emphasis on the ability to develop a high level of on-orbit "agility" – the ability to rapidly, inexpensively, and safely change orbits.

• Enhanced agility includes the ability to alter not only orbital apogee and perigee

-- a task that is routinely accomplished today

• But also develops the ability to systematically change the orbital inclination and right ascension

-- a task that is NOT routinely accomplished today

-- Space Shuttle can change inclination only by few tenths of a degree