



Optimization of Ascent Trajectory and Related Design Issues for an Aerial Propellant Transfer Rocketplane

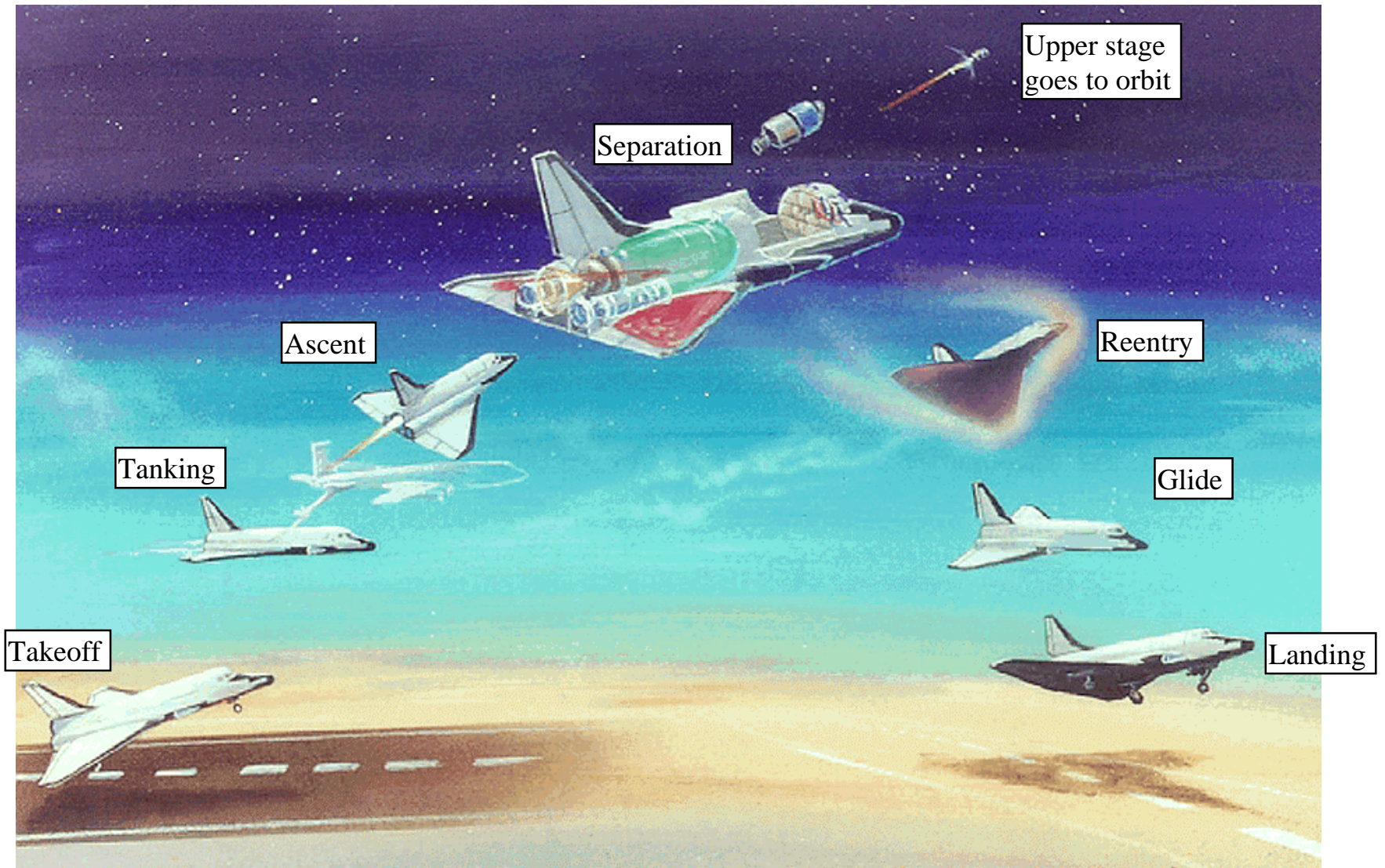
Karl Gallagher
AAS 99-129

AAS/AIAA Space Flight Mechanics Conference 1999

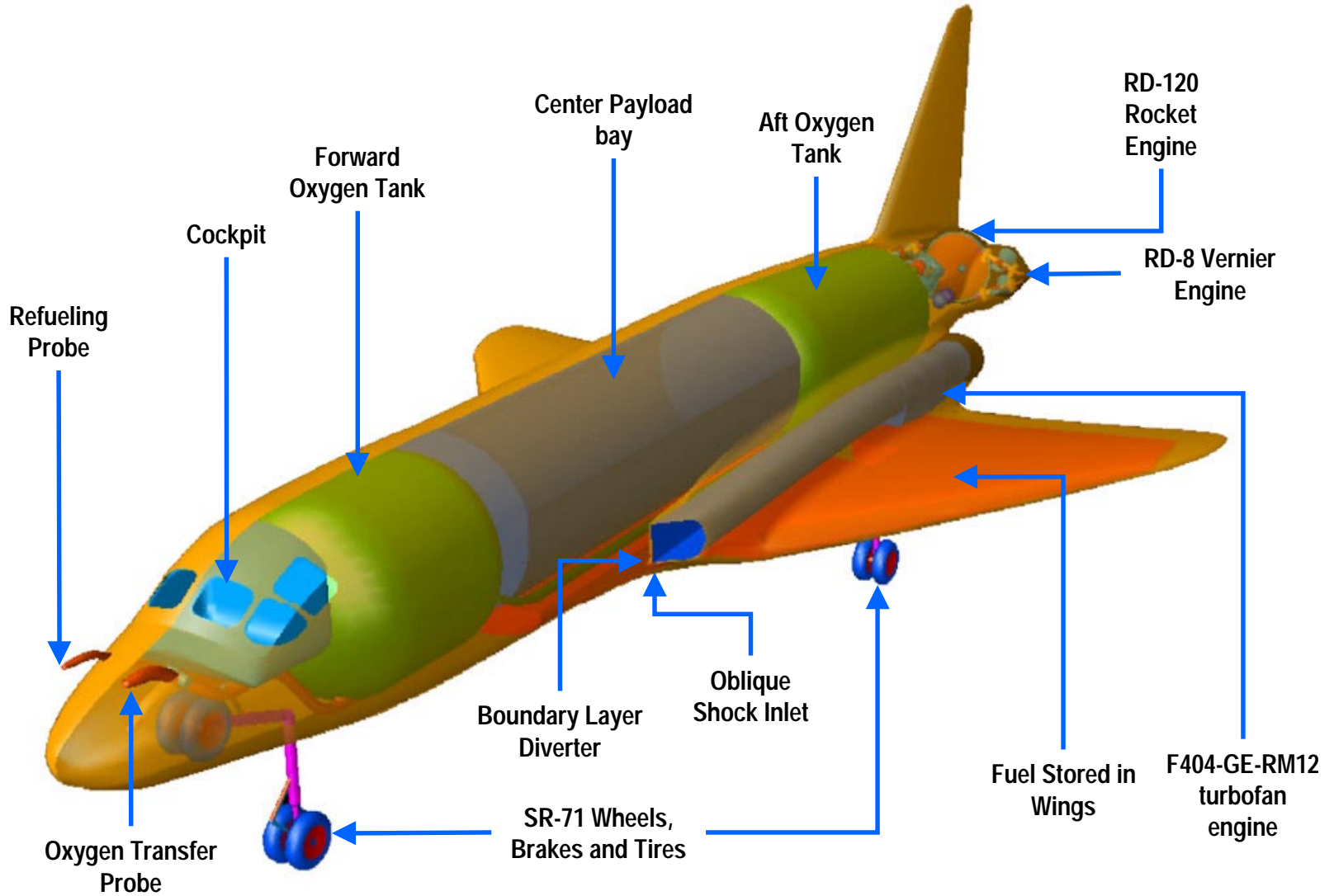


Introduction

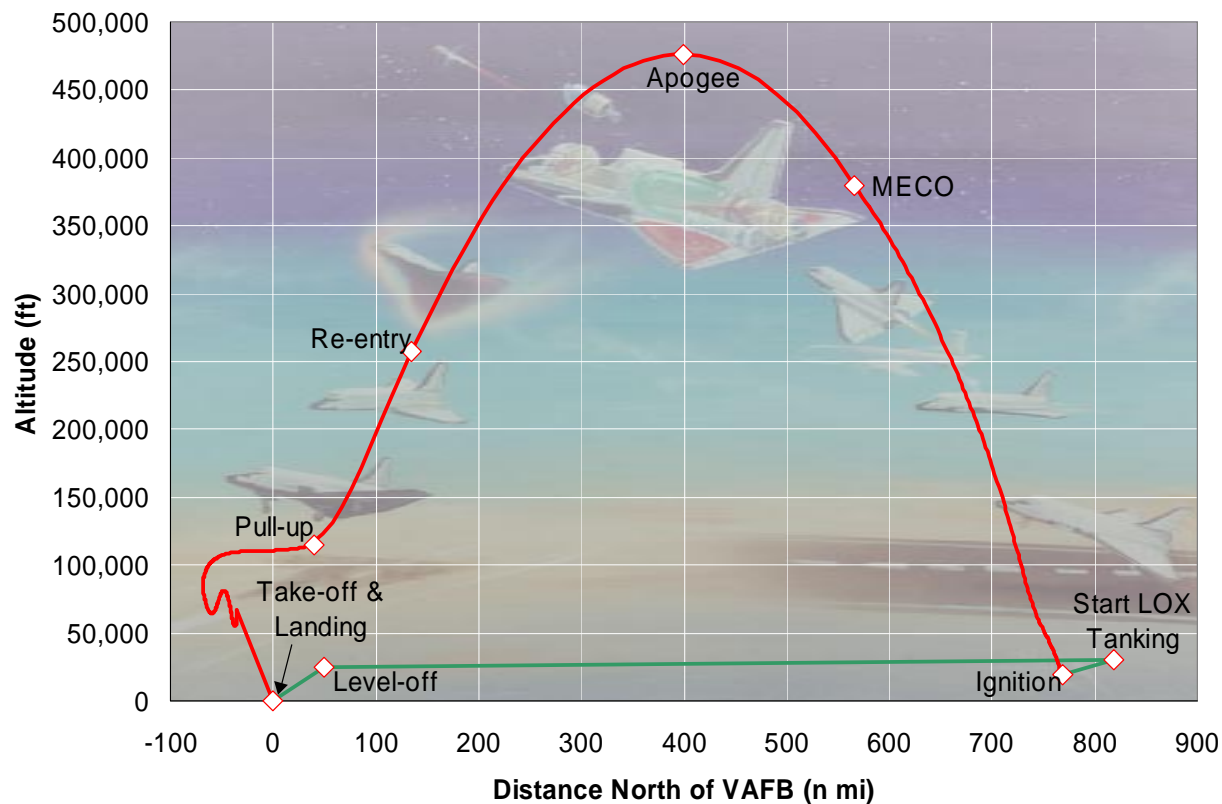
Operations Concept



Pathfinder has a simple and traditional aircraft layout



Trajectory Ground Path & Altitude



- Teledesic mission shown (84.7° inc.)
- Return to launch site option shown
- Rocketplane can take off and land at alternate locations to reduce operational complexity



Analysis

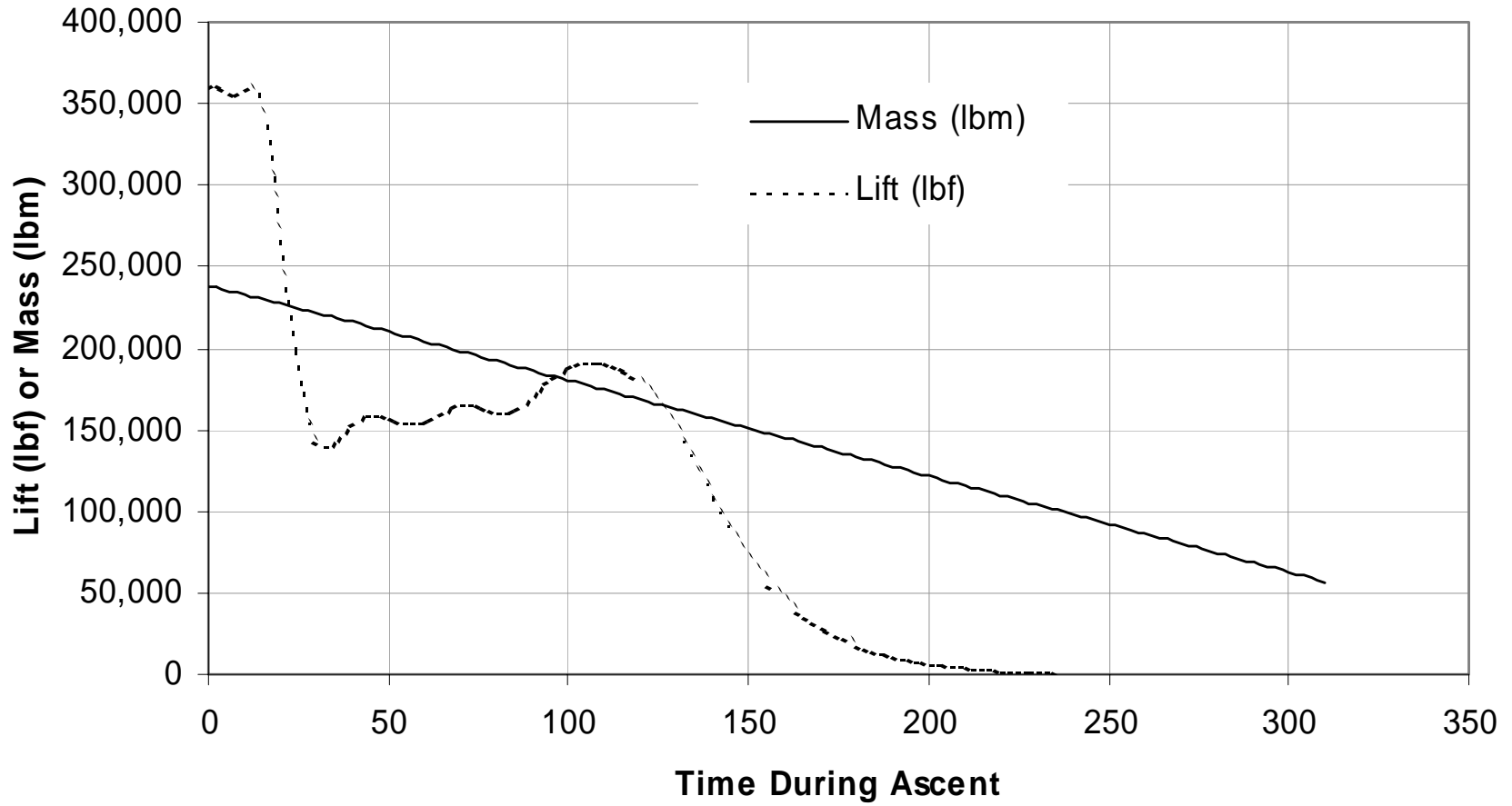
Optimization of System for Performance

- Trajectories found for potential system configurations to find optimum for commercial payload delivery
 - Ascent portion is defined as period from rocketplane main engine ignition to main engine cut-off (MECO)
- Wings and turbofan engines increased system performance
- Determining best rocket engine light-off point required trade between aerodynamic performance and dry weight
- Ascent trajectory end point constrained by free molecular heating requirements, reentry conditions, staging delay

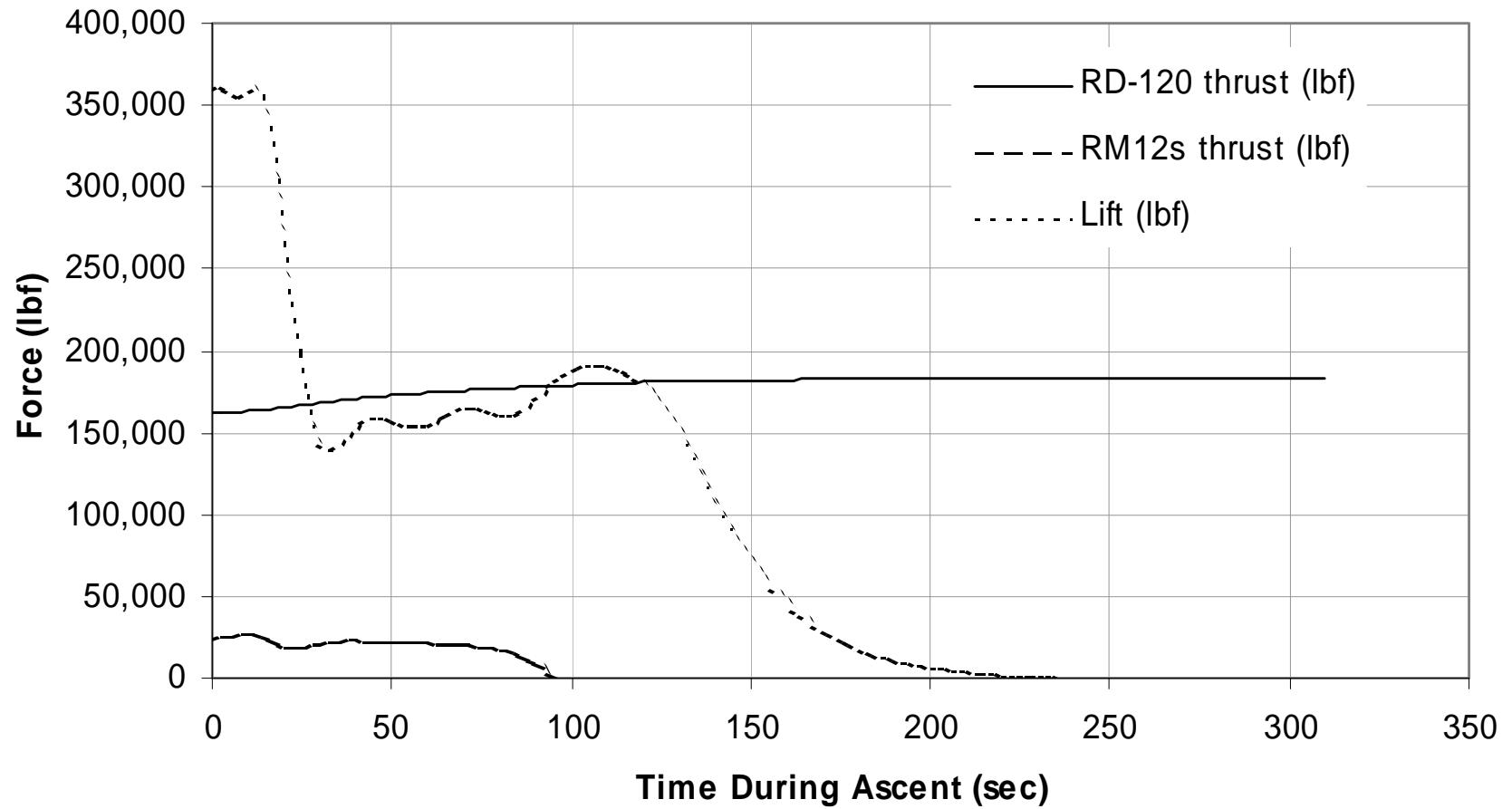
Performance Enhanced by Wings and Turbofans

- **Wing lift is a major force on the rocketplane during first half of ascent**
 - **Provides force for pull-up maneuvers**
 - **Counters gravitational force**
 - **Rocket engine only needed for acceleration**
- **Integrated wing lift is a third of total force applied to rocketplane during ascent**
- **Turbofan engines are kept on until rocketplane reaches Mach 2.2**
 - **Thrust is small relative to main rocket engine**
 - **Specific impulse is on order of 2000 seconds**
 - **Performance improved by ~2% by leaving turbofans on**
 - **Also supports abort modes**

Lift Counters Gravity During Early Ascent



Active Forces on Rocketplane During Ascent



Rocket Ignition point chosen carefully

- The rocketplane travels to the main rocket ignition point under its own power
 - Rocket ignition occurs shortly after taking on full LOX load
 - Most stressing condition for aerodynamic performance

- Additional velocity and altitude at ignition point add to performance

$$\frac{\partial h_{light-off}}{\partial m_{PL}} = 62.5 \text{ ft} \quad \frac{\partial V_{light-off}}{\partial m_{PL}} = 2.2 \text{ fps}$$

- Additional thrust and specific impulse also add to performance

$$\frac{\partial T_{RD-120}}{\partial m_{PL}} = 104 \text{ lbf} \quad \frac{\partial Isp_{RD-120}}{\partial m_{PL}} = 0.044 \text{ sec}$$

- Dry weight diminishes performance

$$\frac{\partial m_{RP_{burn-out}}}{\partial m_{PL}} = -10.5 \text{ lbm}$$

- Ignition flight path angle has little effect

$$\frac{\partial \gamma_{light-off}}{\partial m_{PL}} = 0.73^\circ$$


Truncated Nozzle Improves System Performance

- RD-120 engine is designed for ignition at 30,000 ft
 - Ignition below that leads to flow separation dangers
- Designing the rocketplane to start ascent at that altitude would carry severe penalties
 - Heavier turbofans
 - F100s in place of F404-GE-RM12s--2500 lbs
 - Larger wings
 - 2000 ft² instead of 1000 ft²--2700 lbs and 20% more drag
- RD-120 is routinely tested at sea level with truncated nozzle
 - Safe modification
 - Thrust and Isp penalties
- Trade shows truncated nozzle preferable
 - Weight savings from fans, wings outweigh Isp penalty
 - Payload performance increased by 450 lbs (12%)

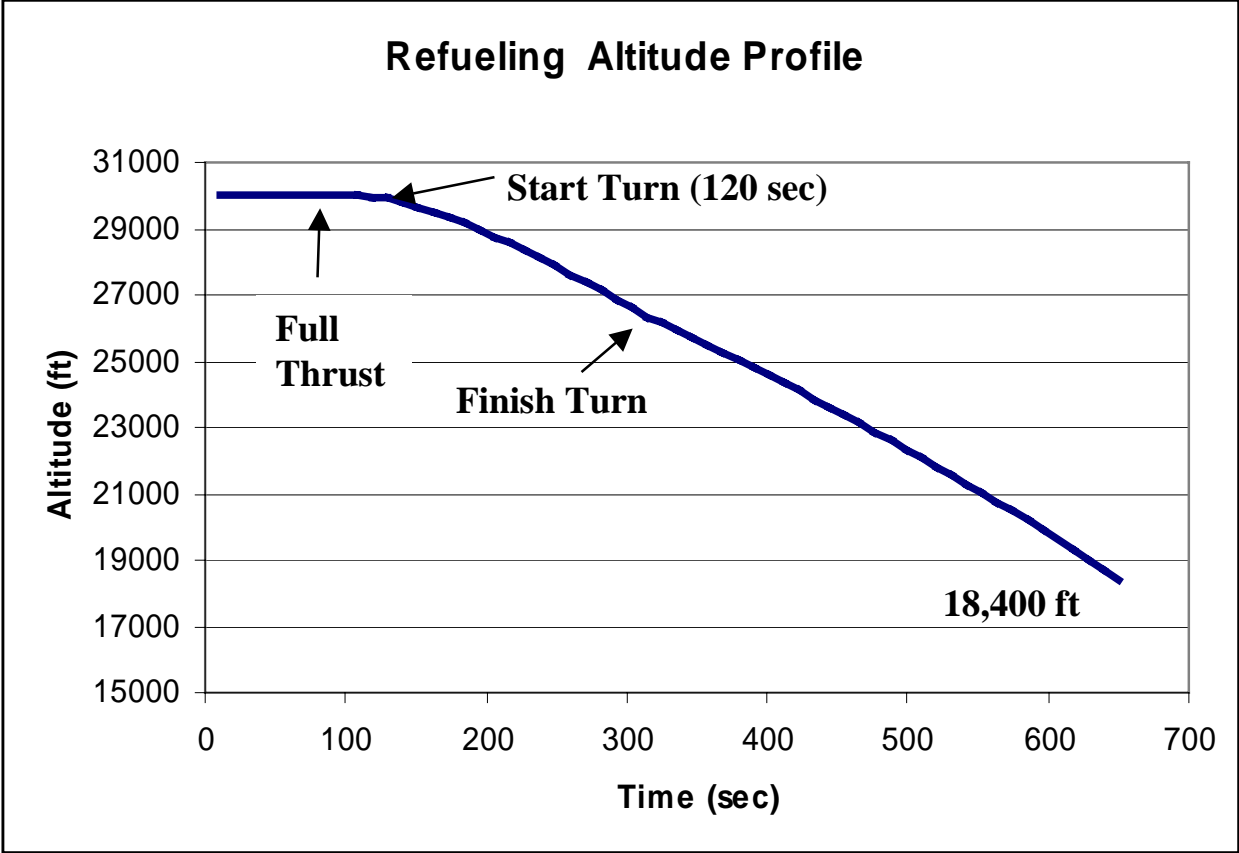
F404-GE-RM-12 Is Preferred Turbofan Engine

- **Many turbofan engines were considered for rocketplane**
 - **F-100, F404-FE-402, F404-GE-RM-12, F-414**
- **Performance analysis showed that additional turbofan power reduced performance because of added dry weight**
 - **Rocketplane should have only just enough air-breathing thrust to complete tanking**
 - **Highest thrust-to-weight engine is best**
- **Trade performed to select final engine**
 - **Best (highest, fastest) tanker disconnect conditions found for each engine option**
 - **OTIS runs done to find impact on payload performance**
- **F404-GE-RM-12 equivalent to F-414**
 - **F404-GE-RM-12 \$3M cheaper each**

Comparison of Level Flight LOx transfer and a “Sledding” LOx transfer

- Baseline LOx transfer profile:
 - Starting at: 30,000 ft M 0.8
 - Disconnect Conditions: 18,400 ft M 0.756
- F-404-RM12 aircraft is *unable* to conduct a level flight LOx transfer at *any* altitude due to tanker q limits
- F-414 powered aircraft with a descending LOx transfer:
 - Starting at: 30,000 ft M 0.8
 - Disconnect Conditions: 20,930 ft M 0.797
- F-414 powered aircraft *would* be able to conduct a level flight LOx transfer at the following conditions:
 - Maximum transfer Altitude: 15,000 ft
 - Maximum transfer Mach: 0.708
 -  Net Payload Penalty: -127 lbs

LO₂ Tanking Flight Profile

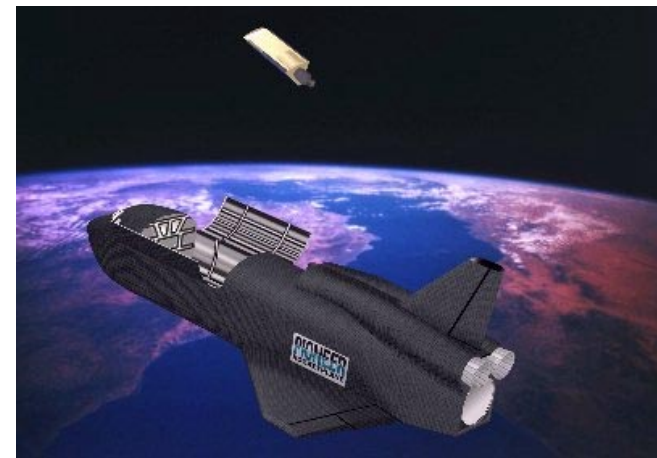
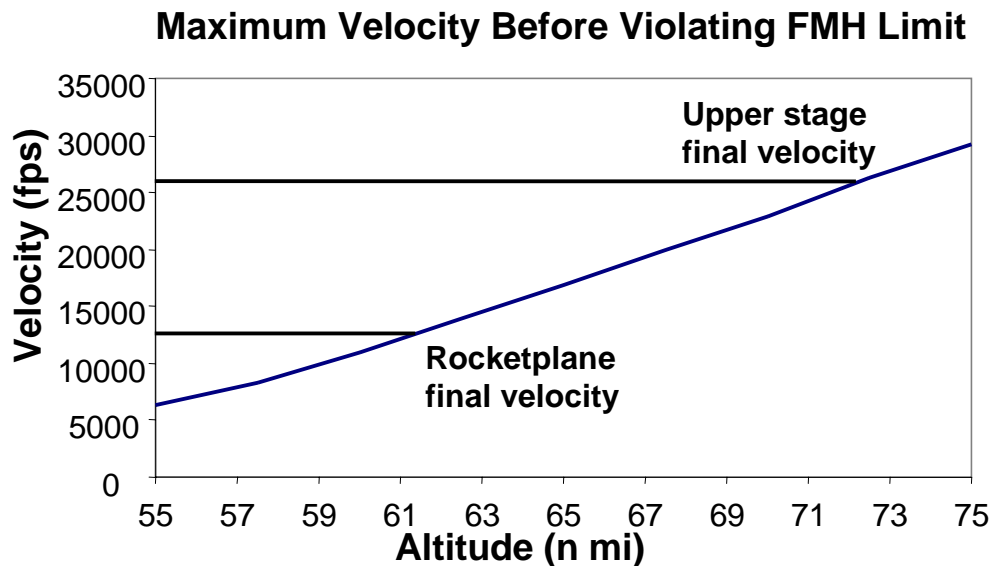


MECO Conditions Constraint-Driven

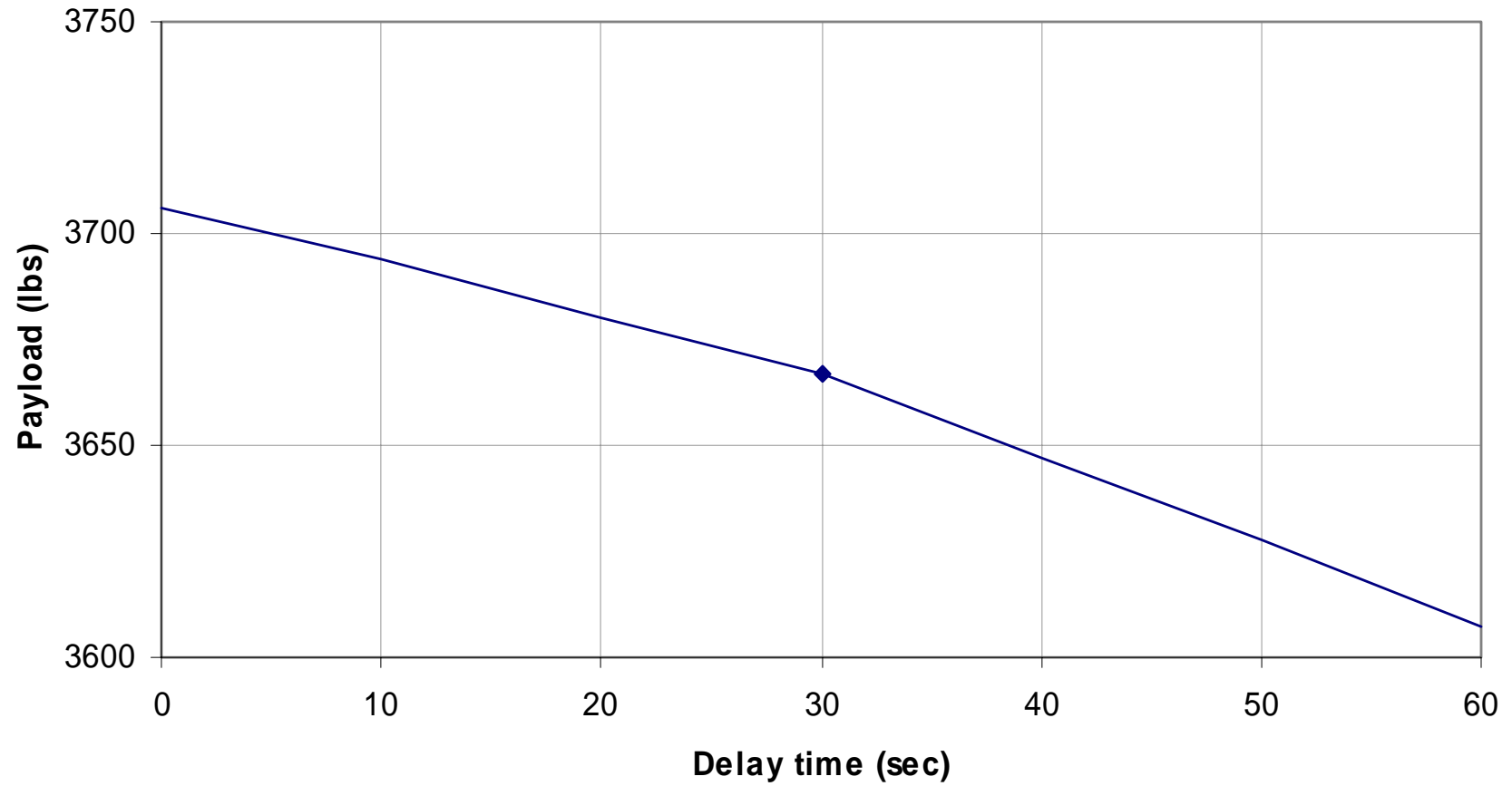
- Staging must occur promptly after MECO to reduce gravity losses
- Minimum staging altitude constrained by free molecular heating requirements of payload
- Performance and reentry heating are functions of flight path angle at MECO

Staging Altitude Driven by Customer Requirements

- Separation altitude is defined as when payload doors open, exposing payload to upper atmosphere
 - Opening doors immediately after MECO reduces gravity losses
- Max allowable free molecular heating (FMH) requirement of 360 BTU/hr/ft² for commercial payloads met with 62.5 n mi separation
- Lofted trajectory places upper stage at a high enough altitude (76.6 n mi) to avoid FMH problems when reaching full velocity

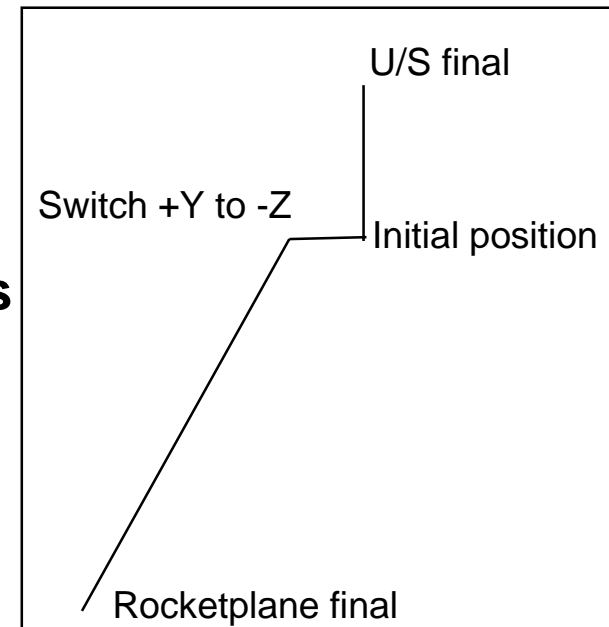


Effect of Upper Stage Ignition Delay on Performance

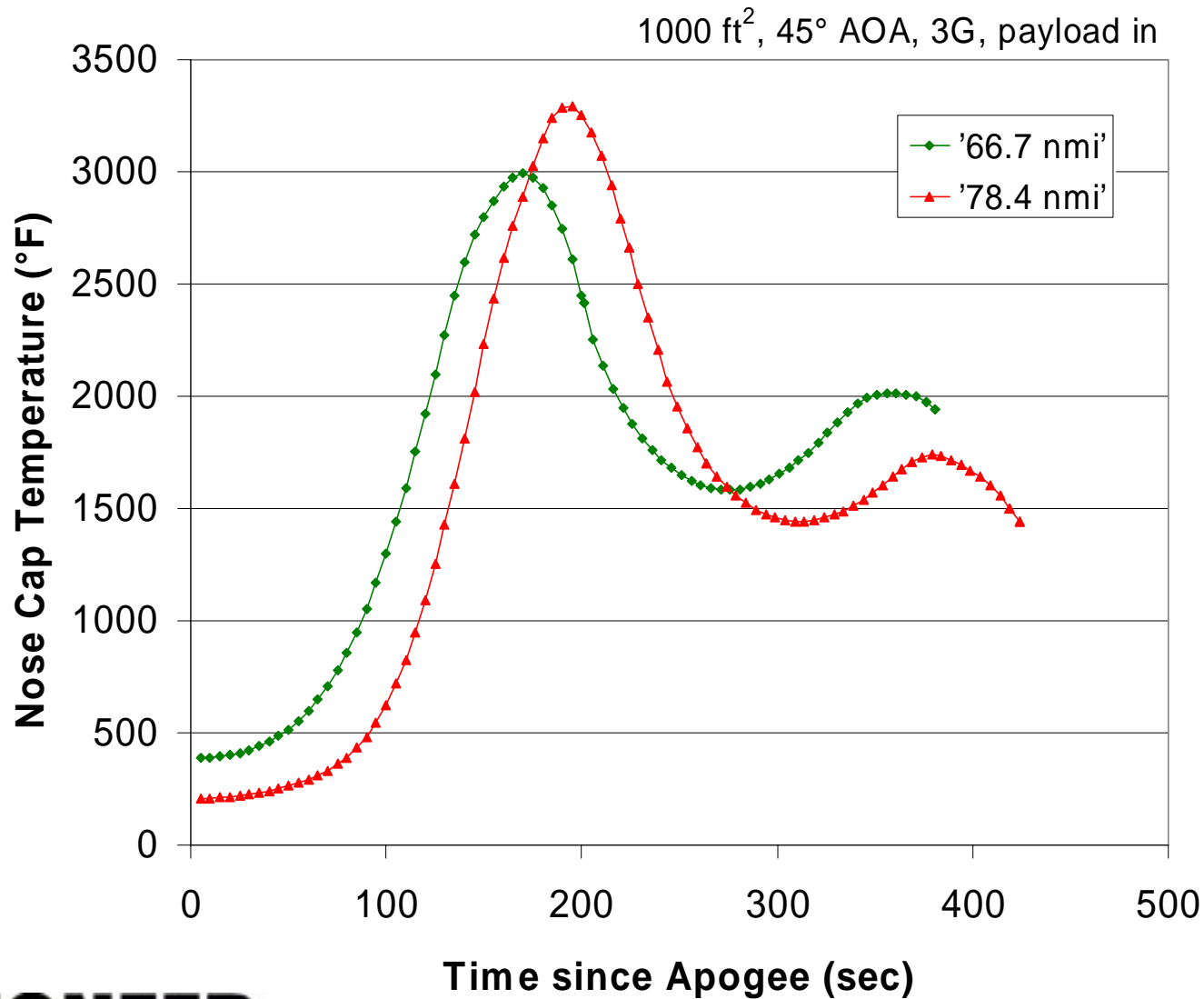


Rocketplane Maneuvers Clear of Upper Stage Before Ignition

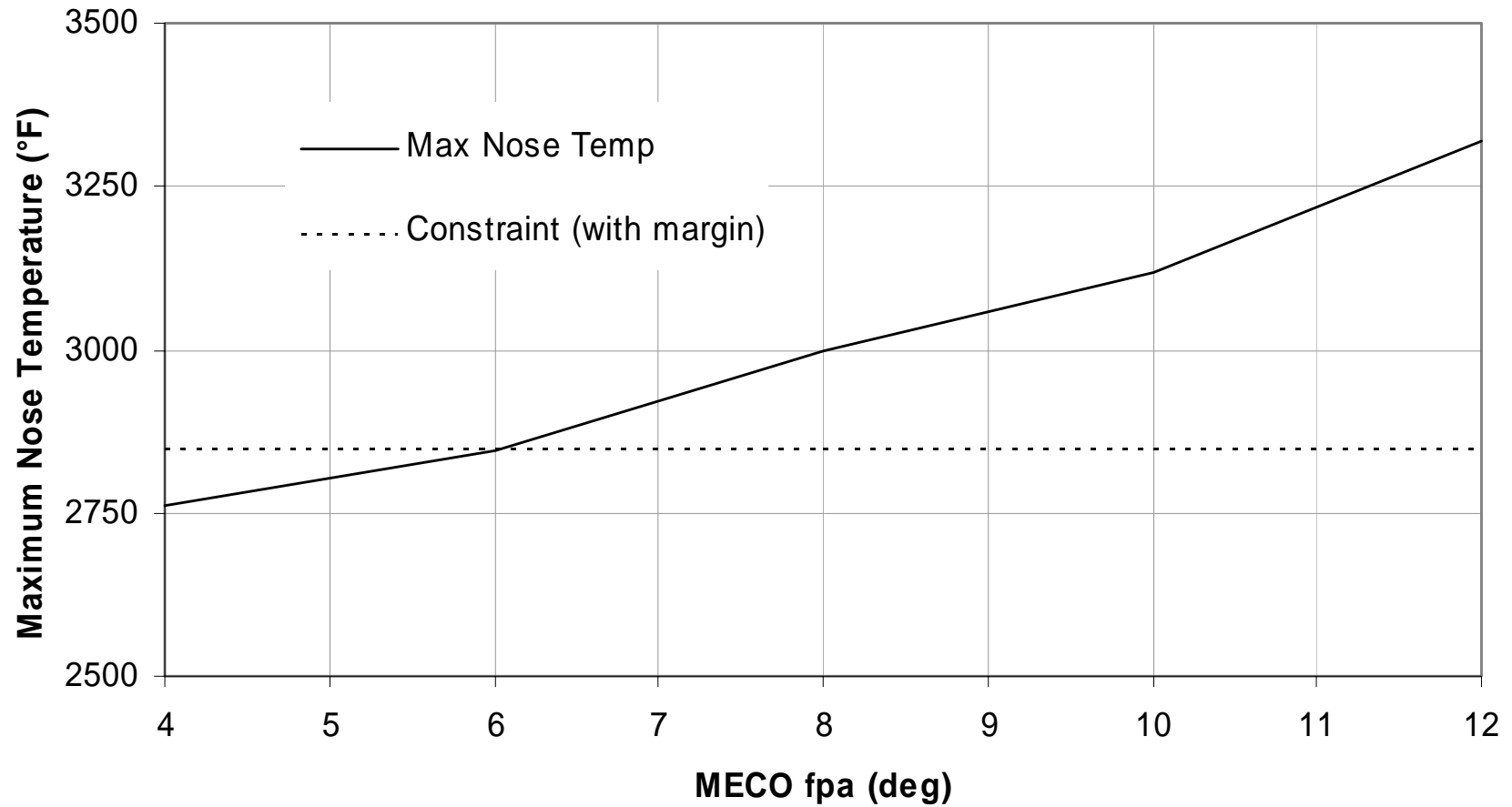
- Payload bay doors open immediately after MECO--5 sec required
- Payload stack ejected from rocketplane at 4.5 fps (3 sec)
- Rocketplane begins immediate +Y maneuver
 - 7 sec--20 ft of horizontal separation
 - Needed to keep payload clear of thruster plumes
- Rocketplane executes -Z maneuver
 - 14 sec duration, until 400 ft clearance is reached
 - Upper stage ignition command sent



Higher apogee means higher skin temperature



Reentry Temperatures vs. MECO flight path angle



Performance vs. MECO flight path angle

