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OPTIMIZATION OF ASCENT TRAJECTORY AND RELATED DESIGN ISSUES FOR AN AERIAL PROPELLANT TRANSFER ROCKETPLANE

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Pioneer Rocketplane is designing and building a new reusable launch vehicle, to begin commercial operations in 2001. The "Pathfinder" rocketplane uses the technique of "aerial propellant transfer" to enable lower costs for reaching orbit without using unproven technologies. The optimum trajectory and design-trade-offs for this concept are very different from pure rocket vehicles or others using highly advanced propulsion technology. Design trades showed that a lower altitude for beginning rocket-powered flight produced higher performance by reducing dry weight of wings and air-breathing engines. Staging conditions were constrained by payload environmental requirements, first stage reentry limits, and second stage trajectory optimization, limiting staging to a narrow range of conditions.

INTRODUCTION

Pioneer Rocketplane is designing and building a new reusable launch vehicle, to begin commercial operations in 2001. The Pathfinder rocketplane uses the technique of aerial propellant transfer to enable lower costs for reaching orbit without using unproven technologies. The optimum trajectory and design-trade-offs for this concept are very different from pure rocket vehicles or others using highly advanced propulsion technology.

The Pathfinder appears to be a conventional aircraft with an RD-120 rocket engine mounted in its tail. The vehicle begins a satellite launch mission by taking off on turbofan engines from a typical airport runway. At 20,000 - 30,000 ft. altitude it takes on-board additional propellant, including all of the liquid oxygen required for rocket-powered flight. After the aerial propellant transfer (APT) is concluded and the tanker aircraft moves away, the Pathfinder lights its main rocket engine and boosts itself into a parabolic trajectory. The payload and upper stage then ejects from the Pathfinder and ascends to orbit. Meanwhile the Pathfinder reenters the atmosphere and returns to its take-off runway under the power of its turbofan engines.

Aerial propellant transfer provides several advantages for launch vehicles. Since the vehicle never takes off or lands at its maximum gross weight the structural weight of the

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wings and landing gear is reduced compared to a similar horizontal take-off launch vehicle taking off with all propellants on board. The energy to lift the propellants to the tanking altitude is provided by a separate, cheaper, vehicle, thus reducing the demands on the launch vehicle's propulsion system. APT also compares favorably to techniques such as carrying the launch vehicle to altitude on another vehicle. APT will provide a higher level of safety, as it is a new application of a proven technology -- more air-to-air refueling is done every day than separations of two manned vehicles in flight have ever been done.

The Pathfinder system design has been developed by Pioneer Rocketplane starting in 1995 and is now, with the 4.0 version baseline, a closed design that can meet its performance requirements. Pioneer hews closely to a philosophy of using off the shelf parts and technologies wherever possible in its design to reduce risk, cost, and time to first flight. The performance of the system is optimized for placing commercial satellites in orbit. "Performance", in this paper, refers solely to the mass that can be placed in orbit rather than velocity or mass fraction. A commercial vehicle must be optimized for supporting customers rather than technical elegance. The reference mission orbit for payload numbers in this paper is 85° inclination, 350 km altitude circular.

This paper will discuss the design issues affecting the rocketplane's ascent trajectory. Aerodynamic and reentry issues will be examined to find the constraints on the trajectory. Trade-offs are made between subsystems to find the optimum configuration for the entire rocketplane system.

ANALYSIS

Methods

Most analysis on the rocketplane system has been done with proven tools. Ascent trajectories were generated by using the Optimal Trajectories by Implicit Simulation (OTIS 3.0) optimization code, which generated an optimized trajectory given initial and final conditions and flight path constraints. Upper stage trajectories were generated through a spreadsheet model which has been validated against OTIS. Aerodynamic performance was analyzed by a proprietary code. Reentry limits were analyzed by NASA Ames using the Hypersonic Aerospace Vehicle Optimization Code (HAVOC) and GASP 3-D software.

Benefits from Wings and Turbofan engines

Figure 1 shows how wing lift and turbofan engine thrust compare to the thrust of the main rocket engine. This illustrates one of the key advantages of the aerial propellant transfer rocketplane concept--by using the wing lift to fight gravity losses, more of the rocket thrust can be used for acceleration than for a corresponding vertical take-off launch vehicle. The turbofan engines produce relatively little thrust, but with an effective Isp of 2000 sec that thrust is effectively free, and keeping the turbofans on is desirable to support abort options in the first minute of ascent. The turbofan engines continue producing thrust until the rocketplane reaches Mach 2.2 and are then turned off and safed. This provides a significant advantage to the rocketplane compared to a vertical take-off system.

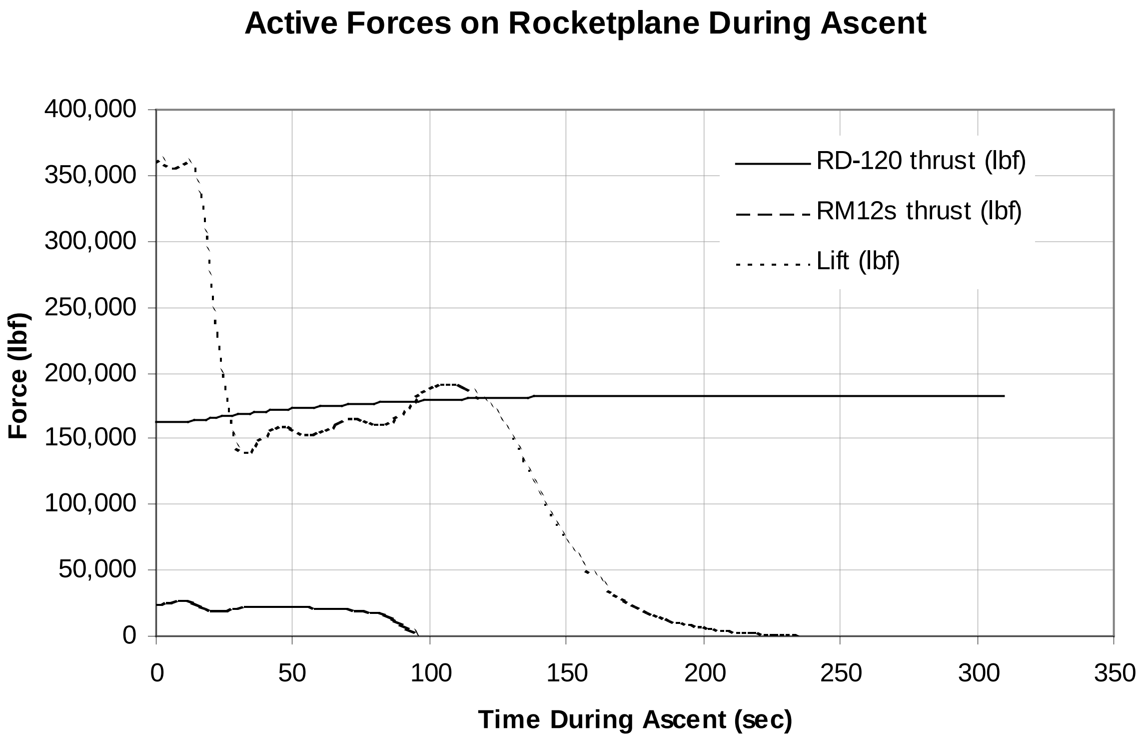

Figure 1: Active forces on rocketplane during ascent.

Rocketplane Ignition Conditions

The Pathfinder, unlike most launch vehicles, does not begin its rocket-powered ascent at a specified point such as a launch pad. It travels to the ignition point under its own power and the favorability of initial conditions such as velocity and altitude depends on the rocketplane's abilities, not those of a mothership or other launch assist system. One disadvantage of the APT concept is that achieving a higher or faster ignition point can't be done by augmenting a lower stage that will then fall away, but only by increasing the dry weight that must be carried to space. The rocketplane's performance is driven most strongly by its initial conditions and dry weight, so a careful series of trades must be made to balance those drivers against each other to properly size the aerodynamic flight systems of the rocketplane.

The first major design change to support this was changing the light-off altitude from 30,000 ft to 20,000 ft. This required truncating the nozzle of the RD-120 rocket engine from its flight to its ground test configuration, at a penalty of 9 sec of Isp and 5000 lbs of thrust. Supporting the rocketplane in flight at its fully loaded weight could now be done with F-404 turbofan engines instead of heavier F-100s, and the wing size could be reduced from 2000 to 1000 ft^2 . These changes reduced the dry weight of the aircraft by 4700 pounds, producing a net performance increase of 450 lbs (12%). Additional factors were not fully quantified but also indicated this was a favorable change, specifically the reduction in rocketplane base drag, ease of packaging a smaller nozzle, and lower costs for smaller turbofan engines.

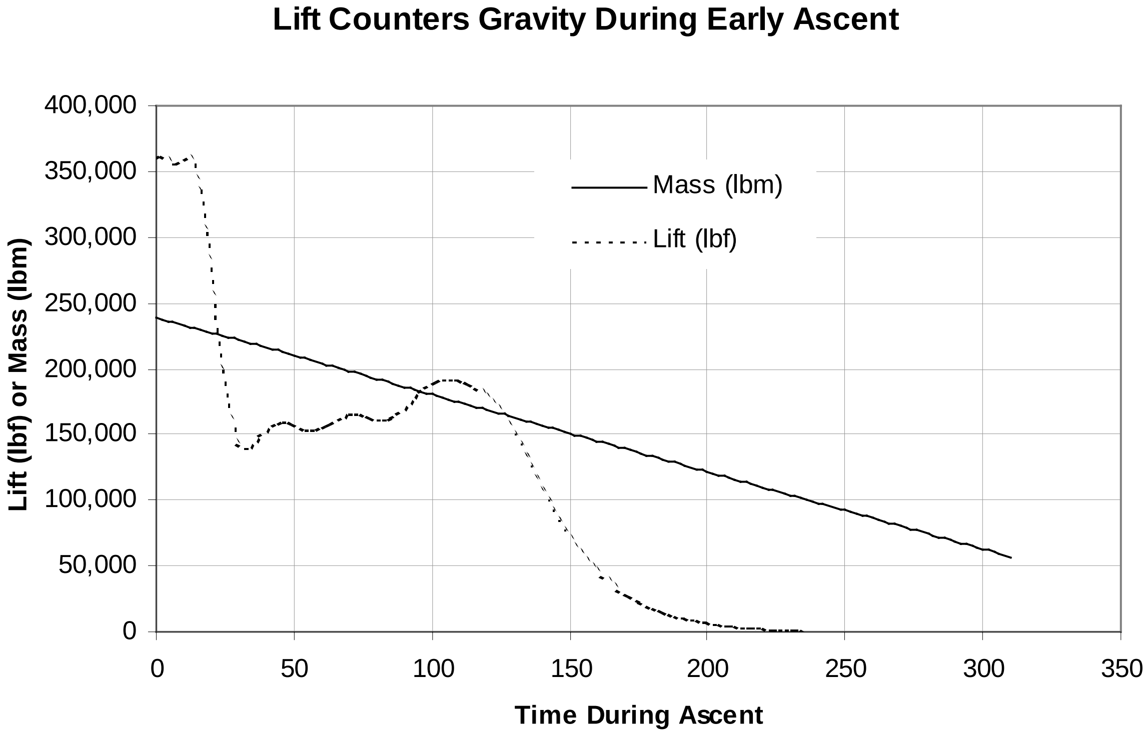

Figure 2: Comparison of rocketplane lift to weight during ascent.

The key parameters under consideration in the initial conditions analysis were the rocketplane light-off altitude, flight path angle, and velocity, and the rocketplane wing size and turbofan engine type. The weight of the rocketplane was assumed constant for all items other than the wings and turbofans. Each parameter was analyzed independently to find the effect on payload delivered. Each practical combination of wing sizes and turbofans was analyzed by the aerodynamicist to find the resulting initial conditions for ascent.

Increased wing size, even without allowing for the additional dry weight, was a performance reducer during the ascent phase. Maximum lift was constrained by structural design limit of the wings, which had been limited to 360,000 lbf (a 1.5 g pull-up maneuver at light-off) to reduce the weight of the wing structure. As shown in figure 2, the wing is only used for maximum lift during a small portion of the ascent, and the baseline wing area is sufficient to produce this. Increased wing area produces additional drag, which reduces performance. The total wing area was constrained to be over 900 ft^2

by the requirements of take-off lift, fuel storage volume, and reentry lift and drag. The final wing size of 992 ft^2 was decided by aerodynamic requirements for tanking.

Additional turbofan thrust was beneficial, if no additional dry weight was required. The penalty for additional dry weight was severe (one pound of payload was lost for every 10.5 pounds of dry weight added to the rocketplane). Only four turbofan engine types were considered at this stage in the design--the F100, F414, RM12, and F404. The F414 and RM12 had the best effective thrust to weight ratios of the four candidates, which made them the finalists. Larger turbofan engines would need a thrust to weight of 16:1 to provide an advantage on ascent. Smaller turbofan engines than these were not considered, as they would be inadequate for meeting the performance requirements for take-off. The RM12 (full name F404-GE-RM12) engine provided 65 pounds of payload more than any of the other options and has been chosen as our baseline turbofan engine (see Figure 3).

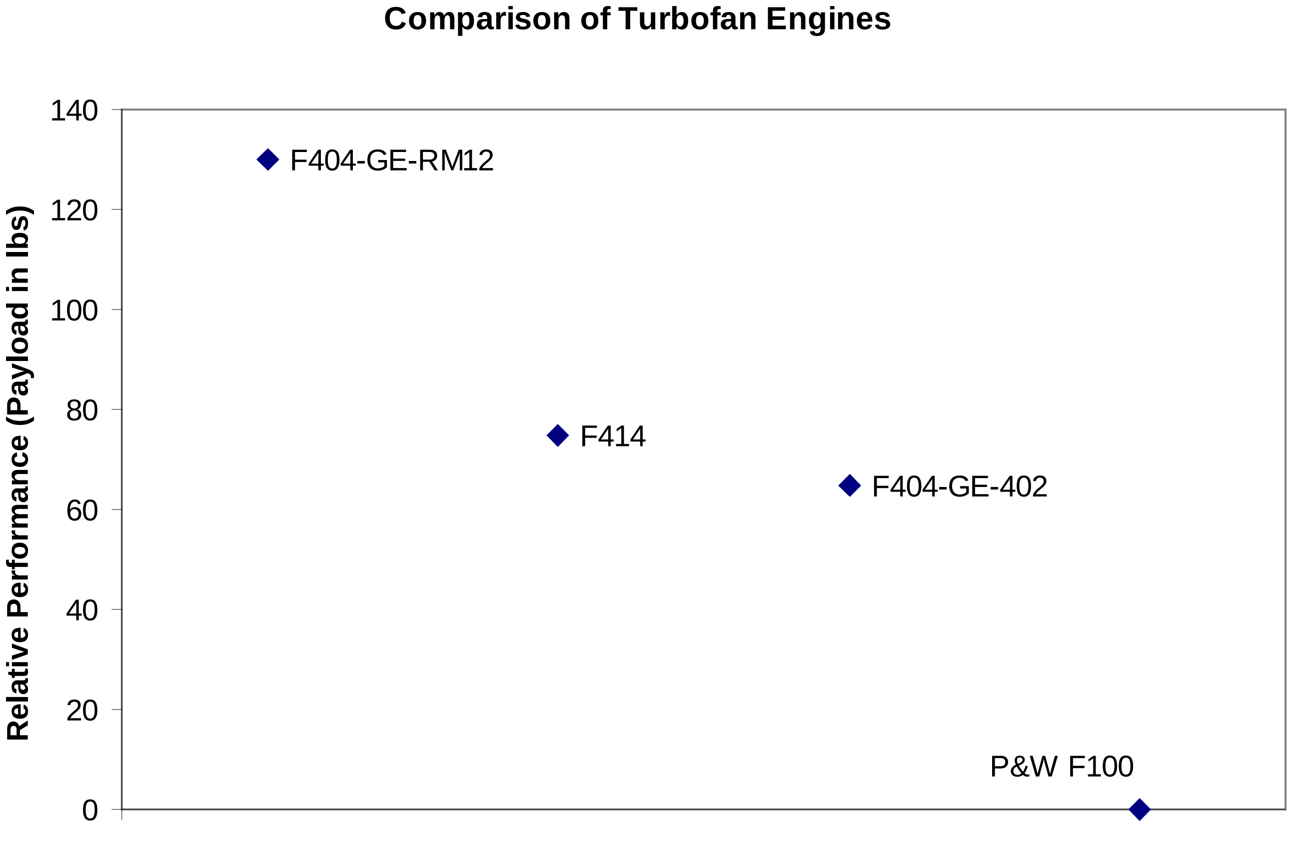

Figure 3: Effect of payload performance of turbofan engine options.

Altitude and velocity at rocket engine light-off are very closely related to payload delivered--the higher and faster, the better. An addition pound of payload would be gained from each 62.5 ft. of altitude or 2.2 f/s of velocity. The flight path angle at light-off has a very minor effect, with a -0.73° angle only costing one pound of payload. This discovery sent the aerodynamics staff back to consider the option of building a rocketplane that could not stay up in the air with a full load of propellant. Rather than maintaining constant level flight at the highest altitude the rocketplane could handle while fully loaded, the new tanking profile had the rocketplane begin tanking at 30,000 ft and halfway through the process begin descending until the tanks were full and the rocket engine was ignited, down to between 16,000 and 20,000 ft altitude. The savings in dry weight that this allowed greatly exceeded the penalty for a slight descent rate at light-off. The Pathfinder may be the only continuously powered vehicle to start its ascent to orbit with a negative flight path angle.

The optimum configuration for the rocketplane was found to be the minimum aerodynamic performance that supported a safe take-off and reentry. Wing size was reduced to 992 ft^2 with F404-GE-RM12 turbofan engines. This allowed rocket ignition at 18,800 ft and Mach 0.76, supporting a payload for the design reference mission of 3555 lbs.

Upper Stage Ignition Conditions

The main engine cut-off (MECO) condition of the rocketplane needed to be selected to maximize the payload delivered by the upper stage, while not violating the constraints on rocketplane reentry or atmospheric exposure for the payload.

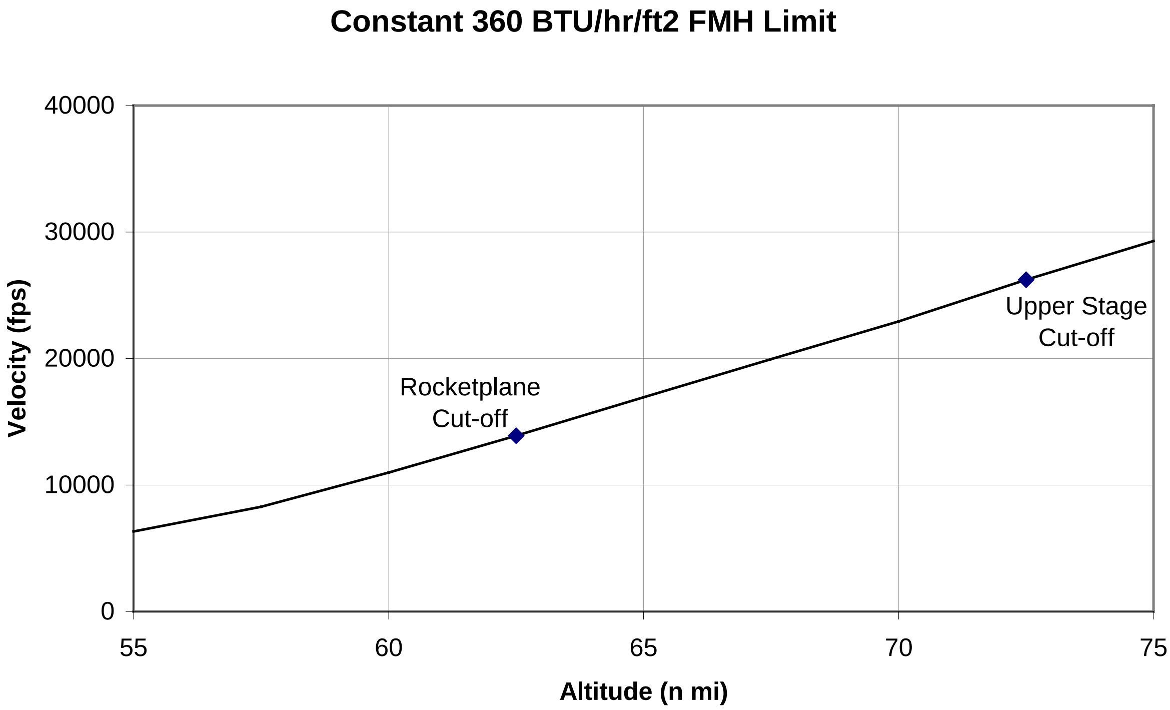

Figure 4: Minimum altitude limits for staging.

The rocketplane system has no fairing for the payload, so once the payload bay doors are opened the payload is exposed to the ambient environment. The rocketplane burn-out altitude may be freely selected, but the payload bay doors must be kept shut until atmospheric density has fallen to where the free molecular heating on the payload will meet customer requirements.

Analysis quickly showed that shaping the rocketplane ascent trajectory to achieve a high burn-out altitude was preferable to a low burn-out altitude with a coast to the required altitude. The time between rocketplane MECO and upper stage ignition must be minimized to achieve maximum payload delivered. By constraining the ascent trajectory to terminate where the FMH requirement is met, no additional coast time is needed and a prompt staging can occur.

The amount of time allocated to staging--the deployment of the upper stage and separation maneuver of the rocketplane--has a direct impact on performance. The minimum for this is constrained by the deployment mechanisms for the payload bay doors and upper stage assembly and the rocketplane's capability for maneuvering to a safe distance.

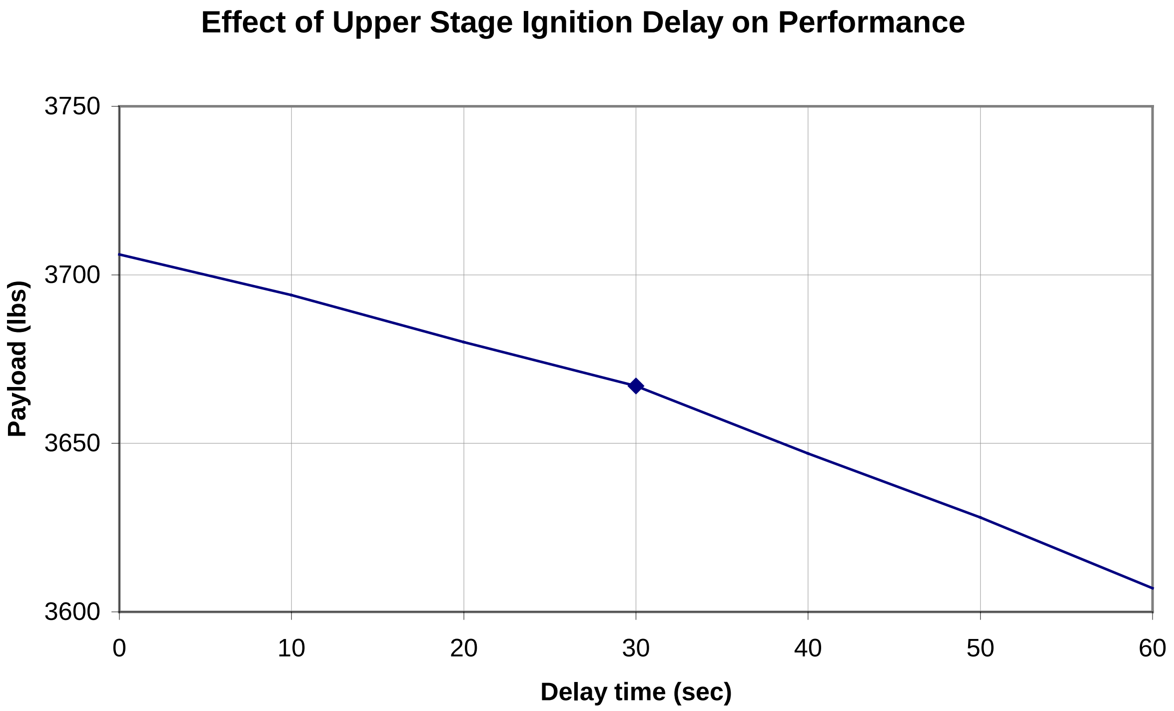

Figure 5: Performance effect of time between rocketplane MECO and upper stage ignition.

30 seconds was defined as the minimum acceptable delay for the 4.0 design baseline. Future design work is intended to allow this to be lengthened to increase operational

flexibility. When launching a payload smaller than the system's maximum capacity, the ignition delay time will extended to increase operational margin.

The rocketplane reentry must be at a shallow enough angle to ensure peak temperatures on the thermal protection system do not exceed the reusability threshold. This is a function of the speed and angle at which the rocketplane reenters the atmosphere, but for a specific configuration can be considered a function of the flight path angle at MECO (to maintain consistency with other constraints). The limiting case is for a rocketplane reentry with the satellite payload still on board following an aborted deployment. The satellite is limited to no more than 2.5g's of normal acceleration, so the rocketplane must reduce its pull-up maneuver and go deeper into the atmosphere, significantly increasing heating relative to a nominal reentry.

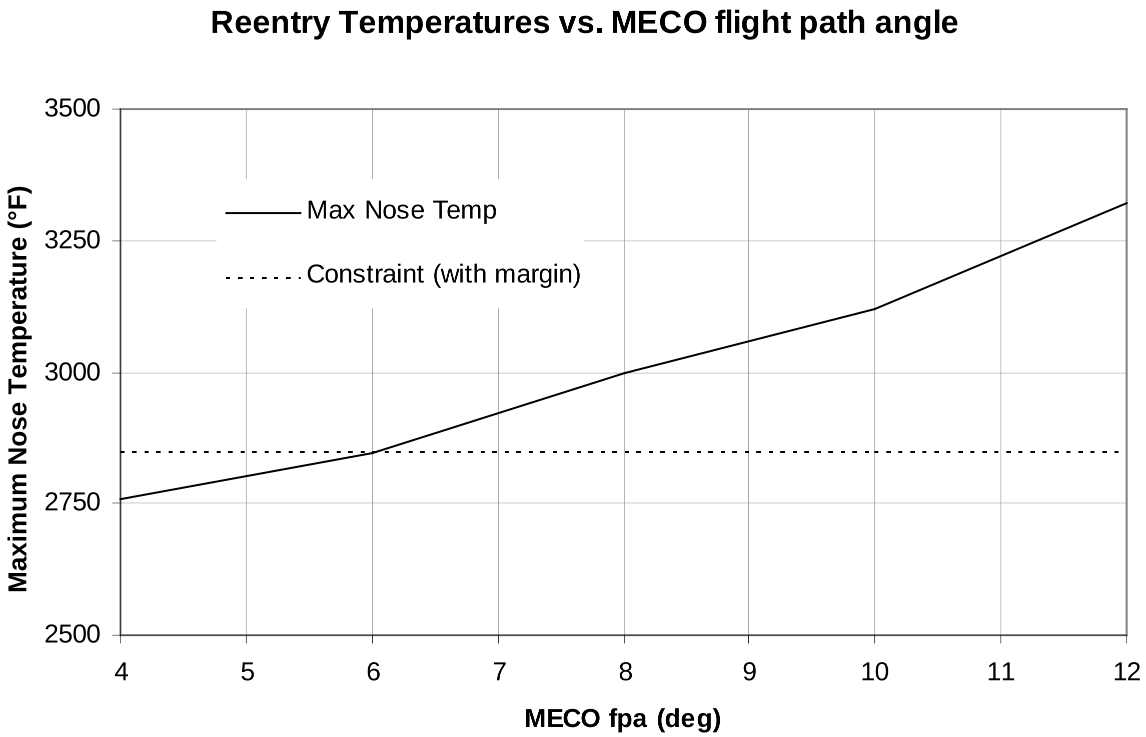

Figure 6: Reentry constraint on rocketplane MECO flight path angle.

Performance is a nonlinear function of the MECO flight path angle (FPA). Too low an angle increases the gravity losses on the upper stage while too high an angle reduces the useful velocity the rocketplane imparts to the upper stage. Figure 7 shows that payload is maximized with a MECO FPA of 10°.

To meet the constraints of the system a MECO FPA of 6° was selected. This has a 60 lb. (2%) penalty over a maximum payload trajectory. Performance could be increased but would require damaging the rocketplane or its payload in the event of an abort. The satellite's g-limit could be met at the expense of overheating the rocketplane to where some thermal protection system tiles would need to be replaced. Keeping the reentry temperatures within safe limits would require up to a 4g pull-up maneuver, which could damage most satellites. Customers with marginally overweight payloads could negotiate such launches with Pioneer, but they would not be part of nominal operating procedures.

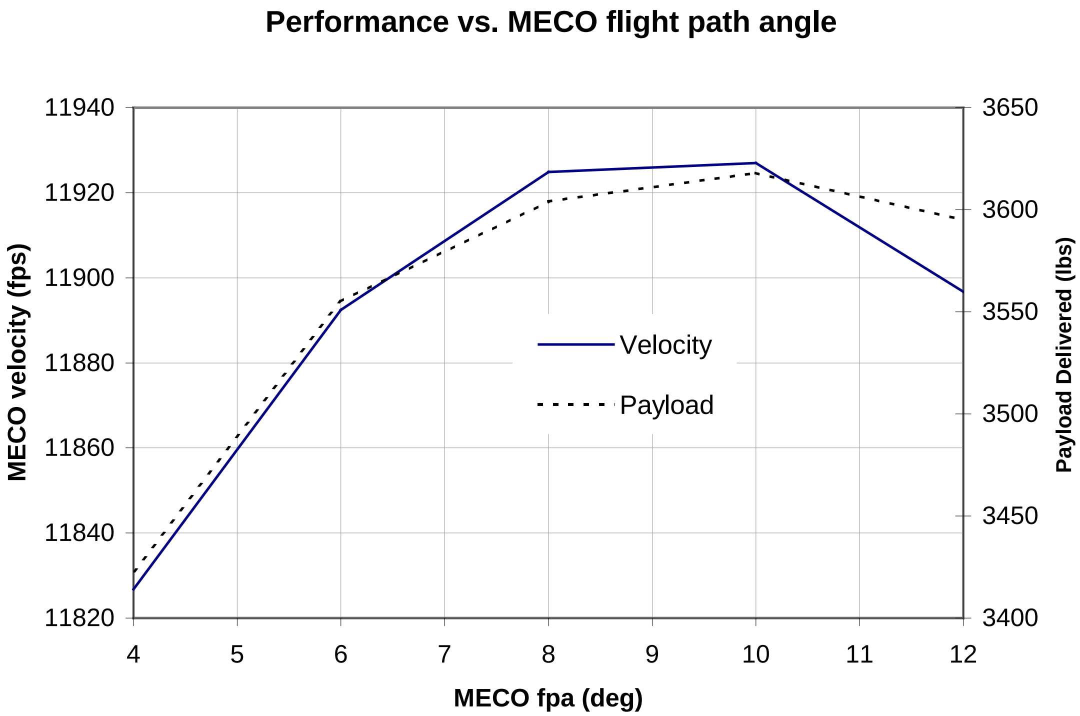

Figure 7: Performance as a function of MECO flight path angle.

CONCLUSIONS

Analysis of the Pathfinder rocketplane system shows that all system constraints can be met while providing a performance level supporting typical low earth orbit telecommunications satellite payloads. The driving constraints are maintaining the aerodynamics performance to complete LOX tanking, free molecular heating on the satellite, reentry temperatures, and keeping the rocketplane clear of the upper stage at ignition.

All analysis and design work on the Pathfinder system has made it clear that minimizing the dry weight of the rocketplane vehicle has the strongest effect on payload performance. Initial altitude and velocity, specific impulse, and thrust can all be sacrificed to improve mass fraction.

The rocketplane trajectory is constrained between the minimum MECO altitude to allow the payload to be ejected and the maximum apogee altitude to allow a comfortable reentry. To achieve maximum payload performance the trajectory must be as close as safely possible to both those constraints.

The Pathfinder rocketplane system is capable of performance small and medium-class LEO communications satellite launches. Once operational, the Pathfinder will dramatically lower the costs for new satellite systems and enable a new expansion of the use of space.

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