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Pioneer Rocketplane Conceptual Design Study

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The Pioneer Rocketplane is a two-seat, F-111-sized aircraft powered by turbofan engines and a kerosene/oxygen-burning RD-120 rocket engine that, using an expendable upper stage, boosts a 3000-lb satellite to a circular low Earth orbit. The Rocketplane takes off with its turbofan engines and climbs to approximately 20,000 ft, where it meets a tanker aircraft, taking on about 48,000 lb of kerosene jet fuel. The Rocketplane then moves to a second tanker aircraft, where it takes on about 130,000 lb of liquid oxygen. After disconnecting from the tanker, the vehicle ignites its rocket engine and climbs to an altitude of 70 miles. Although never reaching orbit itself, the Rocketplane is outside the sensible atmosphere. It opens its payload bay doors and releases the upper stage, which ignites and delivers the satellite payload to its intended low Earth orbit. The doors are then closed, and the aircraft reenters the atmosphere and lands. The second phase conceptual design study is described in which prior configuration design and optimization studies have been integrated into a viable baseline air vehicle concept on which performance analysis is conducted.

Nomenclature

C_{L_α} = slope of wing lift curve
M = Mach (velocity relative to speed of sound)
M_{dd} = drag divergence Mach number (Ref. 2)

Introduction

THE authors have completed a conceptual design study of the Pioneer Rocketplane concept, in which a piloted, airbreathing aircraft equipped with an additional rocket engine is used to loft an upper stage into space delivering a small satellite to low Earth orbit (LEO). Study results indicate that the concept is technically viable and offer a low-risk means to provide affordable access to space. The study included air vehicle layout, analysis of aerodynamics, weights, thermodynamics, propulsion, performance, and mission analysis. Air vehicle performance analysis was done using the RDS-Professional computer program,[1] which includes a sophisticated and user-friendly implementation of classical, proven analysis methods.[2]

Overview of Market Analysis

The design requirements for the vehicle design study reported on were based on prior market research conducted by Pioneer Rocketplane Corporation. This used the Federal Aviation Administration (FAA) 1998 LEO Commercial Market Projections report, combined with publicly available sources and internal research. Of the many proposed systems listed in the FAA report, 75% have satellite weights under 3000 lb (Fig. 1), which was, therefore, used as the baseline payload. Many of these satellites will never be built, and so a more believable market scenario was built on the FAA robust market scenario of five Big LEO, four Little LEO, and three Broadband systems. Market projections have historically underpredicted the actual market demand for satellite launches and telecommunications services and so the optimistic end of the FAA projection was selected to better reflect the likely future.

For LEO military, scientific, and remote sensing satellites, a rate of two 1000-lb satellites per year was assumed based on recent trends. Some communications constellations have published estimates of the rate at which replacement satellites will be needed (replenishment). For the others, replenishment rates of 5–10% per year were assumed. At this time, the Teledesic constellation does not have definite values for its orbit, number, or size of satellites, so that the planned values for the Celestri constellation (which has been merged into Teledesic) are used as an approximation. The market scenario is shown in Table 1. Only launches during the 2002–2007 time frame were included in this market study.

For initial market analysis, a conservative market capture assumption was used. The fraction of each market segment captured by Pioneer will depend on price savings relative to competitors. If Pioneer's price is equal to or higher than the competition's, it is assumed there will be no sales. If Pioneer is at 75% of the competitor's price, a 30% share is assumed, and a 50% share is assumed where Pioneer's price is 25% of the competition's. Figure 2 shows the results of these assumptions as applied to the market data in Table 1, with an overlay financial analysis of the return on investment of the Pioneer Rocketplane venture resulting from this market capture. This indicates that a price of $10–11 million per launch will maximize return and result in a capture of about 30% of the under 3000-lb satellite market. This equates to a price of about $3700/lb to LEO vs the space shuttle cost of about $20,000/lb.

Overview of System Concept and Flight Operations

The authors believe that the most desirable space launch system would be one that permits horizontal takeoff and horizontal landing, allowing it to operate with the flexibility and affordability of aircraft. The ideal system would be able to operate from commercial runways and require little facilities investment. It would be capable of flight to any orbital inclination and would be capable of self-ferry including transportation of its payload. It would be preferable to avoid dependence on exotic technologies or dangerous flying practices such as towing or in-flight separation of aircraft. Most design studies indicate that to be truly affordable over the long haul, it should be reusable.

Various system concepts have been devised in response to these desires, but the one that the authors feel offers the most promise involves aerial propellant transfer, in which an aircraftlike vehicle

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Table 1 Market scenario

System name	Number of satellites in constellation	Individual satellite weight, lb	Year deployment begins	Number of replenishment satellites per year
Big LEO				
Globalstar	56	985	1998	6
ECCO	54	1550	2001	6
Ellipso	17	2200	2001	1
Laredo	72	1500	2006	5
Salina	96	3775	2004	5
Little LEO				
FAISat	38	332	2001	4
E-sat	6	250	2001	0.5
LEO one	48	275	2002	5
KITComm	21	220	2003	3
Broadband				
Celestri	70	7000	2002	7
Skybridge	68	1770	2003	10
M-star	84	4400	2005	5
Science and remote sensing				
Various	——	1000	——	2
Ongoing maintenance				
Iridium	——	1516	——	12

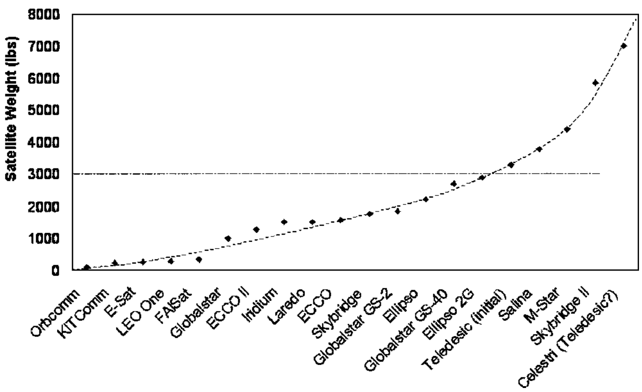

Fig. 1 Weights of projected satellites.

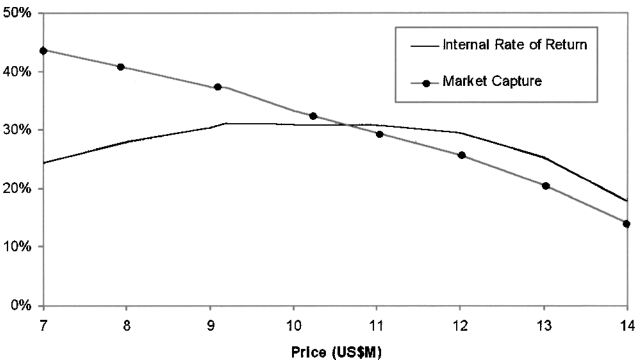

Fig. 2 Market capture and financial return.

takes off at a fairly light weight then onloads sufficient fuel and oxidizer to boost it out of the atmosphere. Aerial propellant transfer has been a mature technology for decades, with thousands of refuels occurring each month. The idea of applying the same concept to aerial transfer of liquid oxygen (LOX) is new and unproven, but LOX transfer on the ground has been routine for almost a century and applying that experience to aerial transfer should be a simple matter of "pipes and pumps," largely using off-the-shelf components.

Aerial propellant transfer has several technical advantages. The wing of the air vehicle does not need to lift the full gross weight required for space flight, and the airbreathing engines can be much smaller for the same reason. The undercarriage is greatly reduced in weight, as is the overall structural weight of the aircraft. These effects significantly reduce the total weight of the vehicle and, hence, improve its propellant mass fraction. Because the rocket engine is not fired at low altitudes, its nozzle can be optimized for high altitudes only and, hence, achieve better specific impulse, reducing the rocket fuel and oxidizer required for the first-stage boost.

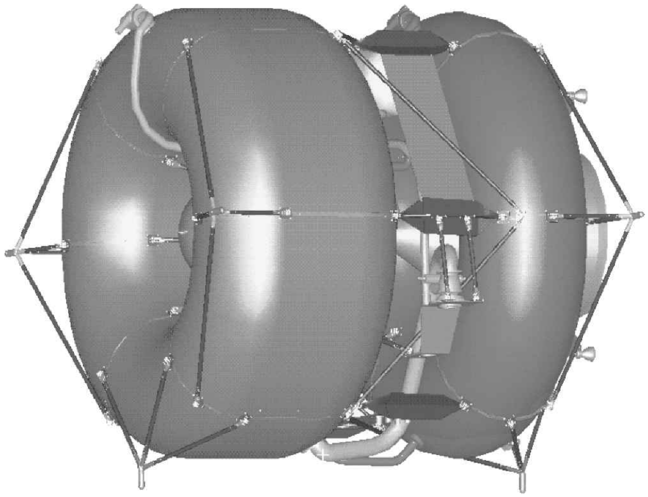

Fig. 3 Preliminary upper stage design.

A typical California-based trajectory would deliver a satellite to an 85-deg inclined orbit. The Rocketplane would take off from Vandenberg Air Force Base and cruise north over the Pacific to rendezvous with tankers. The tanking is performed entirely in American airspace. During the tanking the Rocketplane turns south to match the exact heading required to match the target orbit. The rocket engine is ignited off the coast of Washington, and the vehicle heads for space. After ejecting the upper stage and payload at apogee, the Rocketplane reenters west of Monterey and completes its deceleration west of San Luis Obispo. To land at Vandenberg, the Rocketplane performs an aerodynamic turn at hypersonic speed placing it on a heading for the same runway it took off from. This turn offers an opportunity to manage energy bleedoff to ensure a correct approach to landing when landing without restarting the jet engines. Note that at no time is the Rocketplane over populated areas, as desired by the FAA.

The largest recurring cost element for each Rocketplane launch will be the upper stage. The authors chose to sacrifice some payload carrying ability to achieve minimum upper-stage costs by using relatively inexpensive LOX–kerosene rather than a more efficient, but more costly, LOX–liquid hydrogen propellant combination. LOX–kerosene is also denser, reducing the size of the upper stage, which reduces the size, weight, and cost of the Rocketplane vehicle itself.

Orbital calculations were run by Pioneer staff using the well-known POST program and determined the upper-stage characteristics required to attain orbit for a 3000-lb payload assuming release at 400,000 ft at Mach 15. Because the upper stage rides inside the Rocketplane in a protective payload bay, an external aeroshell is not required, allowing a weight savings. Figure 3 shows an initial baseline upper-stage design, featuring torroidal tanks wrapped around the engine and weighing 20,000 lb including propellant. Ongoing studies continue to refine upper-stage design to reduce cost and increase weight to orbit, with current calculations indicating a capability to place about 4000 lb into a 220-n mile. orbit at 57-deg inclination.

Vehicle Concept Design

The basic mission concept requires takeoff from a normal airfield (military or civil), climb under FAA control to about 16,000 ft at Mach 0.7, rendezvous with the first tanker and jet propellant (JP) fuel onload, rendezvous with the second tanker and LOX onload, and breakaway and rocket ignition. The vehicle then climbs through Mach 2.2 at about 50,000 ft and at some point shuts down the air-breathing jet engines. On rocket thrust alone, the vehicle follows a ballistic trajectory to apogee at about 400,000 ft and coasts to a reentry, reaching a maximum of about Mach 15. Landing is made either with jet engines restarted, or, in an emergency or for a heavy-load mission, the landing can be done deadstick. Key design requirements are summarized as follows: 1) upper stage weight equal to 20,000 lb (3000 lb to 220-n mile orbit), 2) payload bay that is 27 ft long and 8.86 ft diameter, 3) compatible with tanker operations (>15,000 ft and $M \sim 0.7$–0.8), 4) fuel/LOX weight and volume sufficient to provide ~400,000 ft apogee at ~13,200 fps, 5) normal aircraft Federal Aviation Regulations (FAR) operations, 6) commercial airfield capable (balanced field length less than 10,000 ft), 7) aircraftlike turnaround and maintenance, 8) good handling qualities especially during refueling, and 9) substantial ferry capability (1000 n mile plus) with payload.

The selected configuration concept (Fig. 4 and Table 2) resembles a cross between the space shuttle and the F-4 Phantom. The aerodynamic configuration is a swept delta wing with single vertical tail, with four elevons and a single rudder. Because the design is configured to be slightly unstable subsonically, the elevons also act as mild flaps for takeoff and landing. The vernier pods are configured to augment pitch stability, and the covers that move aside to allow the verniers to pivot are configured as split ruddervator/speed brakes.

The payload bay is centered about 12 ft forward of the center of gravity, which is close enough to avoid a serious shift in center of gravity when the payload is out. The payload bay has two side-opening doors using (probably) a piano-type hinge. There is no access to the payload bay from the cockpit.

LOX is carried in two large nonintegral metallic tanks totaling volume for 130,000 lb of LOX. Both tanks are tapered (the front one only slightly) to ease the sliding of the tanks into the airframe structure. It is expected that if a tank needs to be replaced, the fuselage would be disassembled at the payload bay front or rear bulkhead for that purpose.

Jet fuel is carried largely in the wing box, holding 40,000-lb fuel. The remaining 11,800-lb fuel required to total 51,800 lb for rocket, residuals, and the reaction control system (RCS) is located in the lower corners of the payload bay and in a donut tank around the RD-120.

Two General Electric Aircraft Engines (GE) F-414 turbofan engines are mounted on the back of the wing root. Fixed heat-resistant fairings encircle the nozzles to protect them during reentry. Air intakes are forward of the wing root and include simple pivoting plate closure devices. Fixed-geometry single ramp inlets are used because the velocity is kept to moderate supersonic speeds until a very high altitude is reached and the jet engines are shut down shortly thereafter.

Table 2 Current configuration baseline

Parameter	Value
Length	85.5 ft
Span	49 ft
Height (static)	28 ft
S_{ref} wing	1,000 ft
A	2.4
$\lambda = C_t/C_r$	0.15
Sweep leading edge	50
t/c average	0.10
W_e (goal)	35,000 lb
$W_{takeoff}$	118,220 lb
W_{glow}	237,500 lb
W_{crew}	440 lb
$W_{payload}$	20,000 lb
W JP5	
F-414	10,720 lb
RD-120	50,000 lb
W LOX (posthookup)	130,000 lb

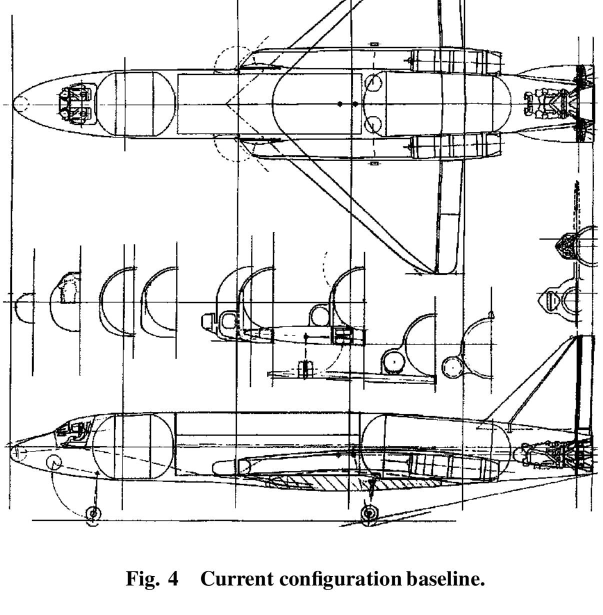

Fig. 4 Current configuration baseline.

Vehicle Analysis

Aerodynamic analysis for the design was done using the RDS-Professional program,[1] using methods described in Ref. 2. Subsonic parasite drag was estimated by the component buildup method. Supersonic wave drag was determined by the equivalent Sears–Haack technique. Base drag was analyzed using equations in Ref. 2 and included any time the rocket motor was not operating. Transonic drag was determined by empirical fairing between M_{dd} and the supersonic wave drag. Total parasitic drag results are shown in Fig. 5.

Drag due to lift was calculated by the leading-edge suction method using a calculated C_{L_α} based on data compendium (DATCOM) methods.[3] A leading-edge suction schedule typical for fighter aircraft was employed, based on design lift coefficient. Resulting lift-to-drag ratios are shown in Fig. 6.

The weight analysis was performed using statistical equations originally developed by Vought Corporation, with suitable adjustments to account for composite materials and the impact of Rocketplane operation.[4] Weight items that cannot be accounted for with

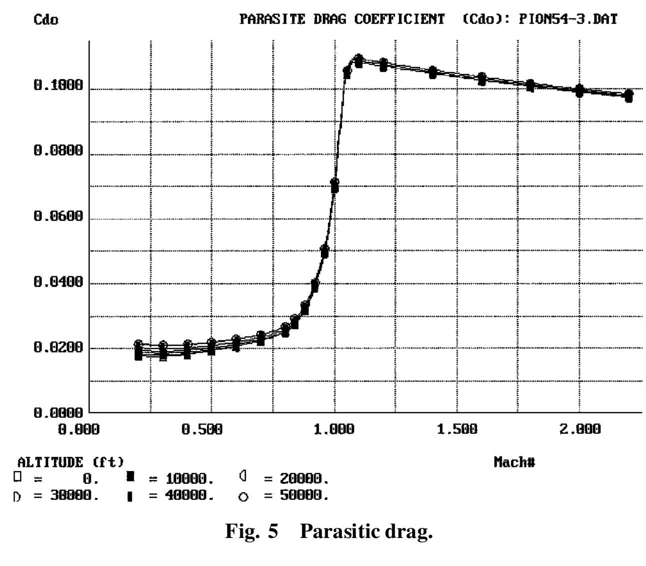

Fig. 5 Parasitic drag.

Table 3 Weight items

Item	Weight
Rocket RD-120	2,328 lb
Rocket fuel system	125
LOX tanks	996
RCS	295
TPS (~1.1 lb/ft^2 blanket)	3,302
Payload handling	150
Engine Mounts	197
Vernier engines	836
Weight margin, 6%	2,179
W_e miscellaneous subtotal	10,408 lb
Avionics	
Uninstalled	536.6 lb
Installed	745.6 lb

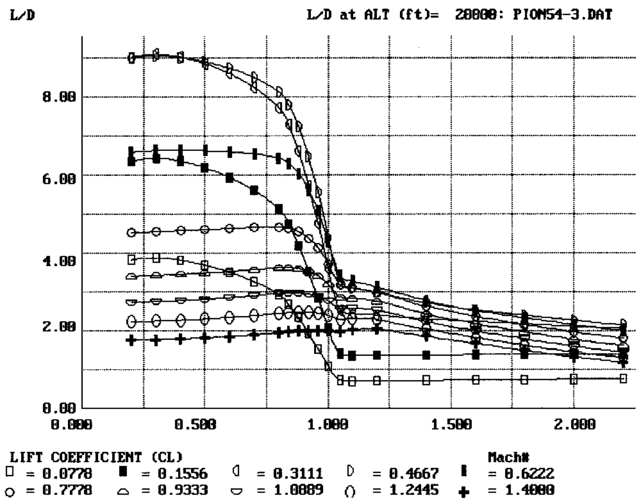

Fig. 6 Lift-to-drag ratio.

Table 4 Weights summary

Parameter	Value, lb
Structures group	14,839.0
Wing	4,083.5
Horizontal tail	0.0
Vertical tail	567.6
Fuselage	7,954.4
Main landing gear	908.3
Nose landing gear	324.9
Engine mounts	49.5
Firewall	90.4
Engine section	25.0
Air induction	835.5
Propulsion group	5,868.9
Engine (s)	5,108.0
Tailpipe	26.0
Engine cooling	169.3
Oil cooling	46.1
Engine controls	31.2
Starter	49.3
Fuel system	439.0
Equipment group	3,851.8
Flight controls	678.3
Instruments	250.0
Hydraulics	0.1
Electrical	1,063.0
Avionics	745.6
Furnishings	496.1
Air conditioning	575.6
Handling Gear	43.1
Miscellaneous empty weight	10,408.3
Total weight empty	34,968.0
Useful load group	83,232.0
Crew	440.0
Fuel used	10,878.0
Oil	114.0
Payload	20,000.0
Passengers	0.0
Fuel for rocket	51,800.0
Takeoff gross weight	118,200.0

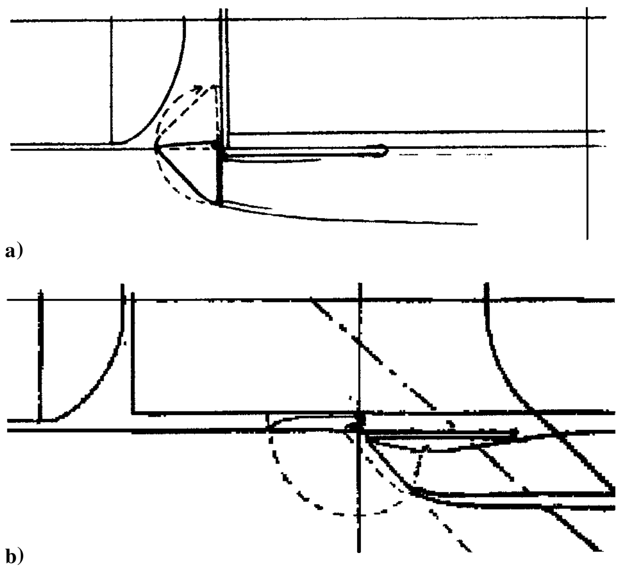

Fig. 7 Alternative inlet closure devices.

statistical equations are given in Table 3 and were developed in concert with consultants and Pioneer staff. These include a thermal protection system (TPS) (carbon–carbon nose caps, thermal blankets, etc.) sized by thermodynamics analysis, and various space-related hardware sized by study of existing systems. Weight results are given in Table 4 including a 6% empty weight margin.

Two leading candidates (out of many) for the inlet closure device are shown in Fig. 7. Figure 7a shows a concept in which a triangular-shaped device rotates about 90 deg. What was the side of the fuselage becomes the flap that closes the inlet, and a smoothly shaped fairing that had been hidden in the fuselage swings out to provide a roughly conical surface in front of the nacelle. This offers low actuation loads, but adds length and volume to the aircraft to provide a space for the fairing in the retracted position. Also, because the fairing must retract into the space between the payload bay and the forward LOX tank, the inlet must be moved forward, which requires a much longer inlet duct and nacelle, adding weight, drag, and propulsion losses. Finally, this concept only works with a normal shock inlet.

Figure 7b shows a concept sketch that uses a simple plate that swings out about 135 deg to cover the inlet front face of an oblique shock inlet. With the extra angle of the inlet front face, this closure device is about as streamlined as the other concept in the closed position, takes up far less fuselage space, and does not require additional nacelle/duct length. On the negative side, this concept probably has higher actuation loads and also leaves an indented step in the fuselage side contour when the inlet is blocked. This may cause local heating.

Standard installation analysis was conducted on the uninstalled GE F-414 data, using estimated values for pressure loss coefficient based on similar inlets. Bleed was assumed at 3% and a historical bleed loss coefficient was applied.

Figures 8 and 9 show rate of climb in maximum afterburner, first at takeoff gross weight representing capabilities immediately after liftoff when carrying the full 50,000 lb of jet fuel for the rocket. This is conservative compared to the current operational concept in which the aircraft takes off with a reduced jet fuel load. Figure 9 shows rate of climb at the point of tanker disconnect, when all fuel and LOX has been onloaded. Although climb is marginal under

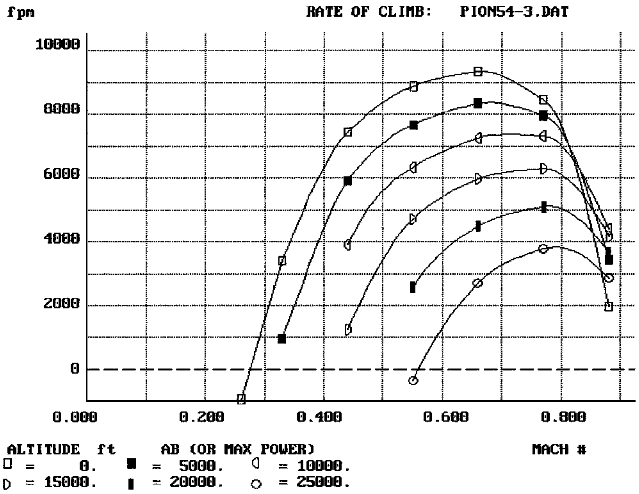

Fig. 8 Initial rate of climb (takeoff weight, maximum afterburner).

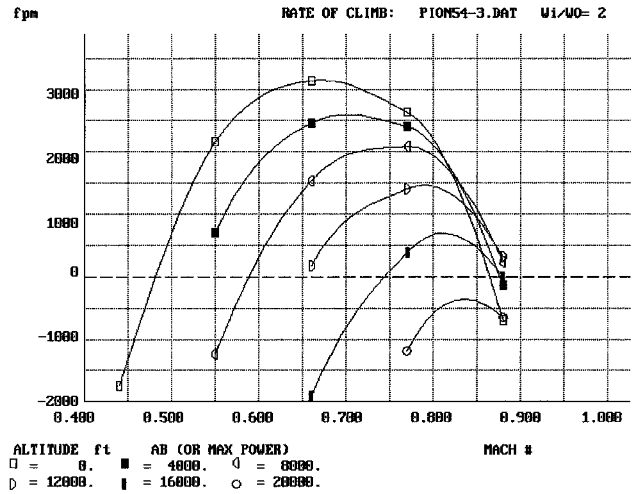

Fig. 9 Rate of climb at tanker disconnect (GLOW = 237,500 lb, maximum afterburner).

those conditions, the jets can in fact keep the aircraft in the air for the final stages of LOX onload.

The baseline mission for the Rocketplane is unusual in that it has neither range nor loiter segments. The aircraft simply takes off, then climbs up to and rendezvous with a waiting tanker aircraft. The air vehicle was analyzed over this mission, and it was learned that the fuel onboard at takeoff weight is marginal if only LOX is onloaded, that is, if only one tanker is used. However, by onloading jet fuel as well as LOX, it is only necessary to carry aloft sufficient jet fuel to climb and rendezvous with the first (JP) tanker, which makes it quite easy to perform the baseline mission. It is possible that later design studies including perhaps use of a more advanced turbofan engine may yield a design which can comfortably perform the total mission without the need for aerial transfer of jet fuel (see Table 5).

Table 5 Fuel used during flight to tanker

Mission segment	Fuel used, lb
Start and taxi	766
Takeoff	915
Optimal climb	3,214
6 min. maximum dry	2,146
Total fuel used	7,041
Aircraft gross weight	114,363

From the analysis described, it is evident that the Rocketplane concept for a piloted rocketplane incorporating aerial propellant transfer and an expendable upper stage can place a 3000+ lb payload into a LEO using only proven technologies and standard aircraft design practice. Risks appear low, with only the actual design of the upper stage and the implementation of aerial LOX transfer as items of any concern.

Conclusions

The authors have completed a conceptual design study of the Rocketplane concept, including a revised configuration concept drawing and analysis of the concept's aerodynamics, weights, propulsion, performance, and mission capabilities. Study results indicate that use of both JP and LOX onload provides a viable approach to attaining system performance goals. A configuration with wing-root-mounted engines and a simple plate inlet closure device appears best. There appear to be no show stoppers of a design or technology nature to prevent the successful development of such a satellite-launching, piloted rocketplane concept. One of the attractive features of the Rocketplane concept is that the risk areas all involve relatively normal engineering development items, not fundamental breakthroughs or unique and groundbreaking applications.

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