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The Design and Evolution of the Beta Two-Stage-to-Orbit Horizontal Takeoff and Landing Launch System

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THE DESIGN AND EVOLUTION OF THE BETA TWO-STAGE-TO-ORBIT HORIZONTAL TAKEOFF AND LANDING LAUNCH SYSTEM

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Abstract

The Beta launch system was originally conceived in 1986 as a horizontal takeoff and landing, fully reusable, two-stage-to-orbit, manned launch vehicle to replace the Shuttle. It was to be capable of delivering a 50,000 lb. payload to low polar orbit. The booster propulsion system consisted of JP fueled turbojets and LH fueled ramjets mounted in pods in an over/under arrangement, and a single LOX/LH fueled SSME rocket. The second stage orbiter, which staged at Mach 8, was powered by an SSME rocket. A major goal was to develop a vehicle design consistent with near term technology. The vehicle design was completed with a GLOW of approximately 2,000,000 lbs. All design goals were met. Since then, interest has shifted to the 10,000 lbs. to low polar orbit payload class. The original Beta was down-sized to meet this payload class. The GLOW of the down-sized vehicle was approximately 1,000,000 lbs. The booster was converted to exclusively air-breathing operation. Because the booster depends on conventional air-breathing propulsion only, the staging Mach number was reduced to 5.5. The orbiter remains an SSME rocket-powered stage.

Nomenclature

ATF	Advanced Tactical Fighter
EW	empty weight
GLOW	gross lift off weight
HSCT	High Speed Civil Transport
HTOL	horizontal-takeoff-and-landing
I_{sp}	specific impulse $\{(lb_f \bullet sec)/lb_m\}$
JP	hydrocarbon jet engine fuel
L/D	lift to drag ratio
LH	liquid hydrogen
LOX	liquid oxygen
SSME	Space Shuttle Main Engine
SSTO	single-stage-to-orbit
TSTO	two-stage-to-orbit

*Member AIAA.

λ' propellant mass fraction {propellant mass/(GLOW - payload mass)}

Introduction

Since the beginning of the "Space Age" and before, interest has been strong in air-breathing HTOL launch vehicles. The advantages seem obvious; the air provides the oxidizer, significantly increasing I_{sp}, and winged vehicles using runways remove the need for special launch platforms, thus allowing simplified launch operations and more versatile basing. Both SSTO and TSTO vehicles have been examined in the past. Unfortunately, the propulsion and materials technology were not advanced enough to design a practical vehicle.

While air-breathing HTOL SSTO vehicles are still a formidable challenge, propulsion and materials technology have caught up with the TSTO making it an attractive concept. The Beta launch system is such a TSTO concept. This paper will discuss the design guidelines and characteristics of the Beta launch system and its evolution from Beta I to Beta III.

Design Goals

The primary goal of the Beta design studies was to define a fully reusable HTOL manned launch vehicle concept using near term technology. "Near term" meaning technology which would be mature enough for incorporation into a production vehicle assuming a ten-year vehicle development cycle starting from the time of the studies. Near term low risk technology dictated a two stage design (in order to meet vehicle propellant mass fraction requirements) with a rocket second stage (to avoid high risk undemonstrated scramjet propulsion). The design mission is shown in Figure 1. The vehicle was required to have a self ferrying capability. That is, the booster is capable of ferrying itself along with a mated unfueled orbiter. The booster was to be air-breathing with at least a sufficient amount of low speed air-breathing engine thrust to meet the ferry requirement. A bottom mounted second stage was also desired for a more natural separation procedure during staging, the heavier orbiter being dropped from the lighter more aerodynamic booster. As shown in Figure 2, this mounting technique also permits easy ground mating operations with the orbiter simply being towed into place under the booster.

Beta I

Beta I was conceived by the Air Force, Wright Laboratory, Flight Dynamics Directorate in 1986 to meet the above design goals and a contract was awarded to the Boeing Space and Defense Group to analyze and refine the initial design.[1] It was sized to have a payload capability of 50,000 lbs. to low polar orbit. The vehicle is depicted in Figures 3 and 4, which are 3-view drawings of the orbiter and booster.

The orbiter is a lifting body design based on the X-24B experimental vehicle. The lifting body design was adopted to meet an Air Force requirement for an orbiter with high cross range capability. The orbiter has a cold structure design consisting of a graphite/polyimide structure and aluminum/lithium propellant tanks, with an external thermal protection system similar to that of the Shuttle, but of more advanced and durable design. The propulsion system consisted of a single LOX/LH fueled SSME rocket engine. Orbiter gross weight is 600,000 lbs.

The booster is of a hot structure design with non-integral propellant tankage. The structure consists of titanium with René 41 in the hot areas and carbon-carbon leading edges. The GLOW of Beta I is 1,900,000 lbs.

The booster propulsion system consists of two podded over/under turboramjets, see Figure 5, and an SSME rocket. There were three requirements which drove the design of the booster propulsion system. A side-mounted podded type design was required to accommodate the bottom mounted orbiter. Second, the self ferry requirement made it desirable to use JP fuel for the low speed propulsion system. Third, the desire to use existing advanced design turbine engines for low speed propulsion; the most advanced available at the time were those designed for the ATF. The high speed propulsion system would consist of LH fueled ramjets. The ATF engines are too small to provide enough thrust for the fully loaded Beta I vehicle during the launch mission with a reasonable number of engines, so only enough engines to accommodate the ferry mission were provided. The SSME, along with the orbiter SSME, provides the additional thrust needed for low speed acceleration before ramjet operational speed is reached. Propellant is cross fed from the booster to the orbiter during the boost phase. The operating schedule of the propulsion system during booster operation is shown in Figure 6. Staging occurs at Mach 8. The orbiter SSME is not shut down after the ramjets are fully operational, even though that would be more efficient, because the engine does not have a restart capability.

Wind tunnel models of the booster and orbiter were fabricated and tested from subsonic Mach numbers to Mach 8. The models were tested both in a mated condition and separately. Although the models were designed to perform separation tests, these were never accomplished due to lack of funds. Despite the inability to do the separation tests, the wind tunnel tests did prove the soundness of the aerodynamic design and the feasibility of flying the booster with the open cavity on the underside after orbiter separation.

A New Mission

Subsequent to the design of the Beta I, interest in the United States shifted to deploying payloads of about 10,000 lbs. to low polar orbit (about 18,000 lbs to the Space Station). In 1990, NASA's Lewis Research Center became interested in examining the possibility of developing a near-term two-stage air-breathing launch vehicle to meet this requirement. The Lewis design goals were very similar to those of the original Beta, with the exception of the payload size. Therefore, it was determined that Beta I would be an ideal starting point for the studies. The main question that needed to be answered was: "Could the vehicle be viably downsized to one fifth of its payload size?"

Beta II

The Air Force was just finishing their contract with Boeing when Lewis approached them about downsizing Beta to deliver a 10,000 lbs. payload to low polar orbit. The Air Force agreed to extend the contract for the downsizing study with Lewis funding. This gave Lewis access to the expertise which had been developed at Boeing and at Wright Laboratory, thus greatly expediting and enhancing the Beta II design study.

Upon examining Beta I in more detail, it appeared that the downsizing may afford the possibility of enhancing Beta's operability and maintainability even further. If the booster rocket engine could be dispensed with, the number of propulsion system types on the booster could be reduced, thus reducing spare parts inventories and maintenance requirements. Historically, high performance liquid rockets have been maintenance intensive.

Subsequent to the Beta I study, NASA and industry initiated the HSCT research program. The projected service date for such an aircraft matched very closely that required for the development of Beta. The turbine engines being studied for the HSCT were roughly double the size of the ATF engines. This, combined with the downsizing of Beta, opened up the possibility of designing a purely air-breathing booster propulsion system using turbine engines which could be available from another source.

The evolution of the Beta launch vehicle, beginning with Beta I, is shown in Figure 7. The downsizing process is shown by the first four boxes in the figure. Since the use of a rocket during the boost phase was undesirable, the ramjets would be the only source of propulsion during the high speed portion of the flight and, therefore, would have to operate at full power in a high dynamic pressure environment. It was felt that Mach 6.5 would be an upper limit for a practical conventional ramjet under these more severe temperature and pressure conditions. The first step in the downsizing process was to reduce the staging Mach number to 6.5. The propulsion system remained the same in this step. As would be expected, the GLOW increased. Next, the turbine engine size was increased, the booster rocket engine was removed and the orbiter rocket was not fired. This new propulsion system schedule is shown in Figure 8. This exclusively air-breathing booster propulsion system design resulted in a 29% reduction of GLOW, as shown in Figure 7. Finally, the payload was reduced to 10,000 lbs. and the vehicle aerodynamics recalculated for the smaller vehicle, resulting in an initial Beta II GLOW of 1,200,000 lbs. This vehicle is the Interim Beta II listed in Figure 7. The weight included a conservative 20% booster growth margin and a 10% second stage growth margin based on stage empty weight. A larger growth margin was included in the booster weight to account for the additional uncertainties in estimating the weight of the air-breathing propulsion system.

The interim Beta II booster is depicted in Figure 9. The general shape of Beta I was retained at this point. The orbiter, which had a gross weight of 345,000 lbs., is depicted in Figure 10. The orbiter was changed to a wing-body configuration because of the higher structural efficiency of this type of airframe as opposed to the original lifting body design. Structural efficiency is more important in the smaller Beta II orbiter and NASA did not have the high cross range requirements of the Air Force. The SSME rocket engine propulsion system was retained for the orbiter.

The interim Beta II propulsion system is shown in Figure 11. It was an over/under design consisting of 5 HSCT turbine engines mounted below a ramjet duct. Since turbine engines of a fixed size were being used, enough engines had to be installed to overcome transonic drag. The inlet capture area was sized as a compromise between engine airflow requirements at high speed and inlet transonic spillage drag alleviation. The ramjet was mounted on top to allow access to the airframe for a large bypass duct to reduce the transonic spillage drag. It was recognized that the 5-turbine-engine arrangement was not ideal, but the initial contract task did not have enough resources to allow for further design iteration; therefore, this design was adopted as an interim solution. Even though it was not possible to obtain a more optimum air-breathing propulsion system design at the time, the design task did prove the feasibility of the vehicle.

Subsequently, a more rigorous aerodynamic analysis was undertaken. This analysis included reshaping the booster in an effort to improve its L/D. The curves marked Interim Beta II and Fixed Inlet Beta II in Figure 12 show the improvement in L/D that resulted from this effort.

A variable capture area inlet was incorporated into the propulsion system to further reduce transonic spillage drag. The capture area is at a minimum during transonic flight and opens to full capture at about Mach 4 and above. Figure 13 depicts the minimum and maximum capture area positions of the inlet. The upper surface of the nacelle is included in the vehicle aerodynamics. Therefore, when the capture area varies the vehicle drag also varies, as can be seen in Figure 12 by comparing the curves labeled Fixed Inlet Beta II and Final Beta II. Although the vehicle drag increases in the transonic region, it is more than compensated for by the reduction in inlet spillage drag and the net effect is a positive one. The benefit of the variable capture inlet can be seen in Figure 14. The shorter acceleration time for the variable inlet vehicle results in less fuel usage and therefore a lighter vehicle. The variable capture inlet also removed the requirement for the large bypass duct so that a more conventional over/under layout of turbine engines on top and ramjet on bottom could be used as depicted in Figure 13.

Preliminary thermal management analysis results indicated that it may not be possible to cool the ramjet without exceeding stoichiometric fuel-air ratios in the Mach 6 to 6.5 regime. It also appeared that the inlet may require active cooling at these Mach numbers. Therefore, lower staging Mach numbers were examined. It was determined that reducing the staging Mach number to 5.5 would result in only a 5% growth in GLOW while significantly reducing the risk in meeting the ramjet cooling requirements. Even with this reduction in staging Mach number, the booster aerodynamic and propulsion refinement effort resulted in a 17% reduction in GLOW from the interim design (1,000,000 lbs. vs 1,200,000 lbs.), see Beta II in Figure 7. The current Beta II booster design is shown in Figure 15. The reduction in staging Mach number resulted in an orbiter weight growth to 400,000 lbs. and an increase in λ' from 0.811 to 0.827. Figure 16 displays the weight breakdown of the booster and the orbiter.

Beta III

The JP/LH fuel combination on the booster provides a very good compromise between volumetric efficiency and high specific impulse. However, it does add the complexity of a dual fuel system. Also, comments received from launch vehicle operations people indicate that LH fuel systems require high amounts of maintenance and operational activities.

Beta III, the final vehicle presented in Figure 7, has evolved from Beta II as a booster that is fueled by JP only. Except for the fuel change, the propulsion system is the same over/under turboramjet layout. JP fueling of the ramjets is made possible by the emerging endothermic hydrocarbon fuel technology which increases the heat sink available in hydrocarbon fuels. Since this technology is in the early stages of development, the Beta III propulsion system has a higher development risk than Beta II, but the increased operational efficiency may warrant the extra risk.

Beta III is in the early stages of design. The staging Mach number is expected to remain at 5.5. The GLOW is about 1,500,000 lbs. This increase in GLOW is due to the lower energy content of JP vs LH, higher system weight of the endothermic fuel cooling system and the addition of two more turbine engines per nacelle to maintain a sufficient thrust to weight ratio.

Operational Characteristics

Beta's principal mission is to provide flexible low cost access to space. The vehicle design is a major step in that direction. The booster is essentially an airplane. No launch pads are required and stage mating can be accomplished with standard airplane towing equipment. Vehicle processing would be done in airplane hangar-like facilities. In addition, it is envisioned that payload processing will occur off line from orbiter processing with standard payload interfaces being provided by the orbiter to which all payloads would conform.

An advantage of the two-stage air-breathing booster design is the possibility of performing offset launches. In this type of launch profile, the booster cruises for up to several hundred miles before going into the launch trajectory; in effect, changing the point of launch relative to the earth's surface. This makes possible one base operations for both polar and easterly launches from the United States, greatly enlarged launch windows and satellite rendezvous within one and one-half orbits.[2] One base operation from Kennedy Space Center can be accomplished by using the offset launch capability to perform polar launches, see Figure 17. The vehicle would takeoff from Kennedy, fly a subsonic cruise across Florida and then turn south in the Gulf Of Mexico to go into the polar launch trajectory. The orbiter is essentially at orbital flight conditions before encountering any land mass and the booster can complete its turn for the return flight to Kennedy within the confines of the Gulf.

Another key aspect to Beta's cost effectiveness is its versatility. Once the booster is developed, it would be capable of carrying other types of payloads besides the orbiter. Some possibilities are shown in Figure 18. A primary expansion of capability could be accomplished by developing an expendable upper stage. Developing such an upper stage would allow the placement of medium weight payloads into orbit, Figure 19. The expendable upper stage may also be applicable, perhaps with modifications, as an upper stage for a future expendable heavy lift launch vehicle.

An experimental hypersonic research aircraft could also be carried by the Beta booster. This would permit an evolutionary research path to attaining the ultimate goal of an SSTO or hypersonic cruise vehicle. As depicted on the left side of Figure 20, a hypersonic research vehicle which is dropped from Beta would not need a low speed propulsion system and therefore would be less risky and costly to develop. The research aircraft development could concentrate on its main mission, that is, to investigate hypersonic flight. Also, as shown on the right in the figure, Beta would still remain an important launch vehicle even after the development of an SSTO. In addition to providing a back-up to the SSTO, with the expendable upper stage it would remain the main vehicle for launching medium size payloads.

Finally, once the booster is developed, it could also be used as a carrier to launch a high speed cargo transport aircraft, which would cruise at about Mach 5. Because the cargo transport propulsion system could be of much simpler and lighter design than one required to operate from takeoff to the cruise Mach number, a longer range and/or larger payload could be achieved than for a single aircraft. In this scenario, there would be a Beta booster stationed at each end of the route.

Conclusion

Beta is a viable and robust air-breathing two stage horizontal takeoff and landing launch vehicle. It is of conservative design with large growth margins included. Beta II/III are in a weight class similar to advanced versions of the 747 and the Russian AN225.

Beta is designed for low cost airplane-like operations. It can take off and land from standard Strategic Air Command runways and is fully recoverable and reusable. Stage mating can be accomplished with standard airport equipment and the vehicle is self ferryable.

Beta can provide a near term solution to lower cost manned access to space and Space Station Freedom support. With the inclusion of expendable upper stages, Beta II/III has the capability to place up to 45,000 lbs. into low easterly orbit.

Finally, development of a TSTO launch vehicle such as Beta would permit an orderly and evolutionary progression to the development of air-breathing SSTO and hypersonic cruise vehicles.

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2. Lt. Col. Alan J. Parrington, USAF: Toward A Rational Space-Transportation Architecture: Airpower Journal, Winter 1991, Pages 47-62

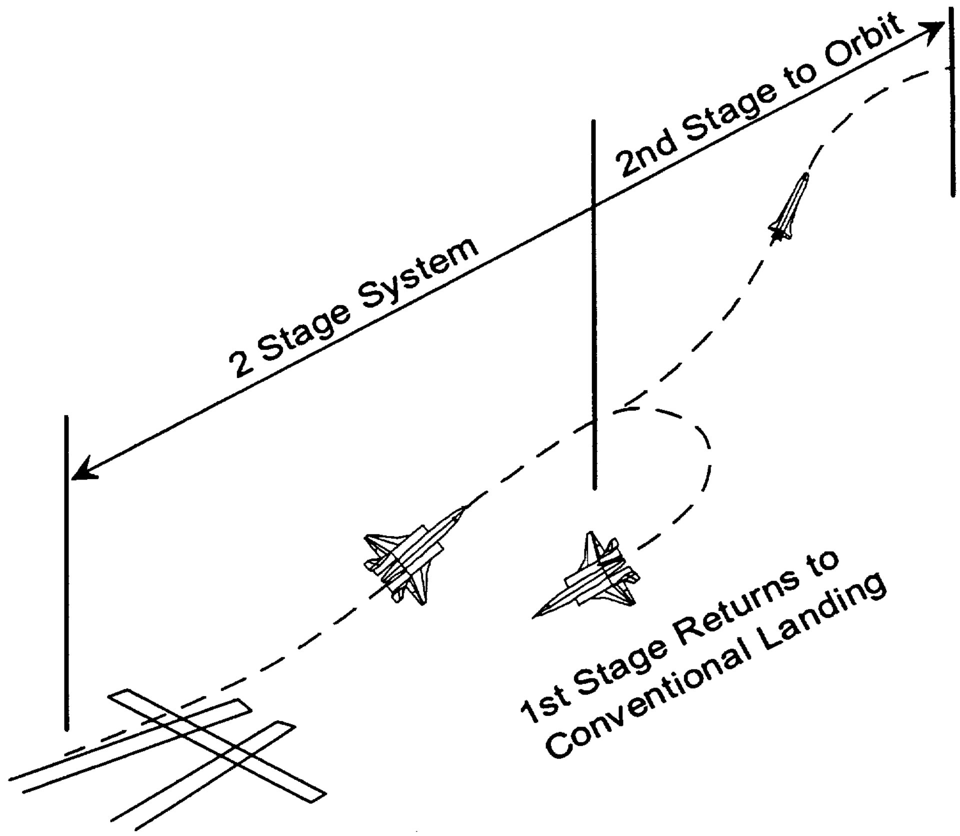


Figure 1. Beta Design Mission

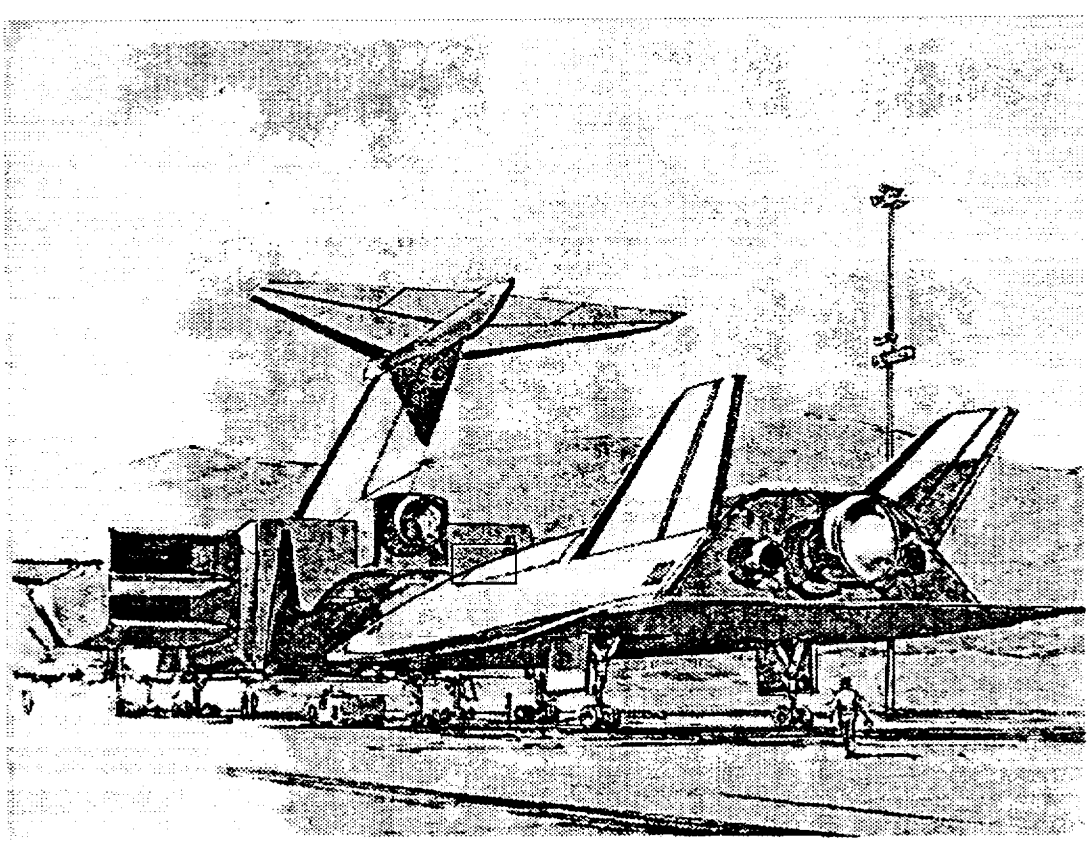
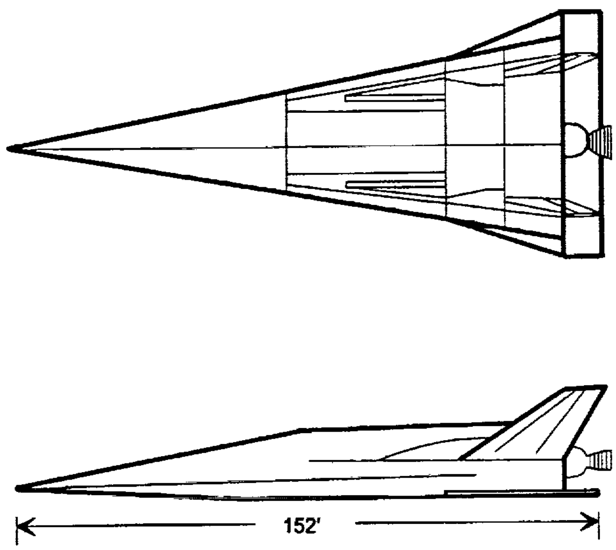


Figure 2. Mating Operations



GLOW = 600 K lb.

Payload = 50 K Low Polar

Growth Mar. = 2%

1' = 0.805

Materials
- *Graphite Polyimide*
- *Ceramic Tiles (TPS)*
- *Aluminum/Lithium (Cryo Tanks)*

Propulsion
- *1 SSME*
- *LOX/LH RCS*

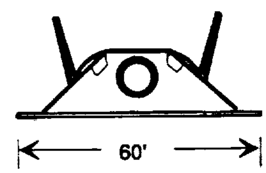
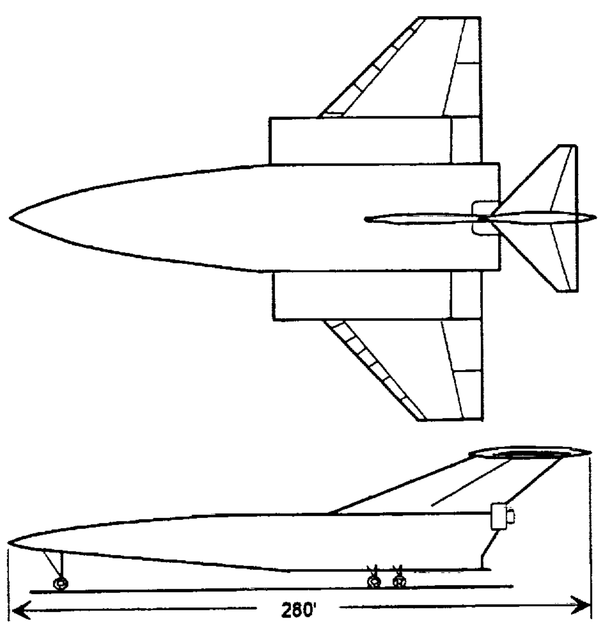


Figure 3. Beta I Orbiter Concept



GLOW = 1.9 M lb.

EW = 4.39 K lb.

Growth Margin = 2% EW

1' = 0.66

Materials
- *Titanium*
- *René 44*
- *Carbon-Carbon (leading edges)*

Propulsion
- *8 ATF turbofans (JP)*
- *2 Ramjets (LH)*
- *1 SSME Rocket (LOX, LH)*

Stages M = 8

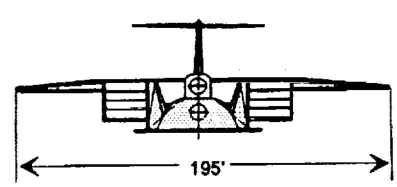


Figure 4. Beta I Booster Concept

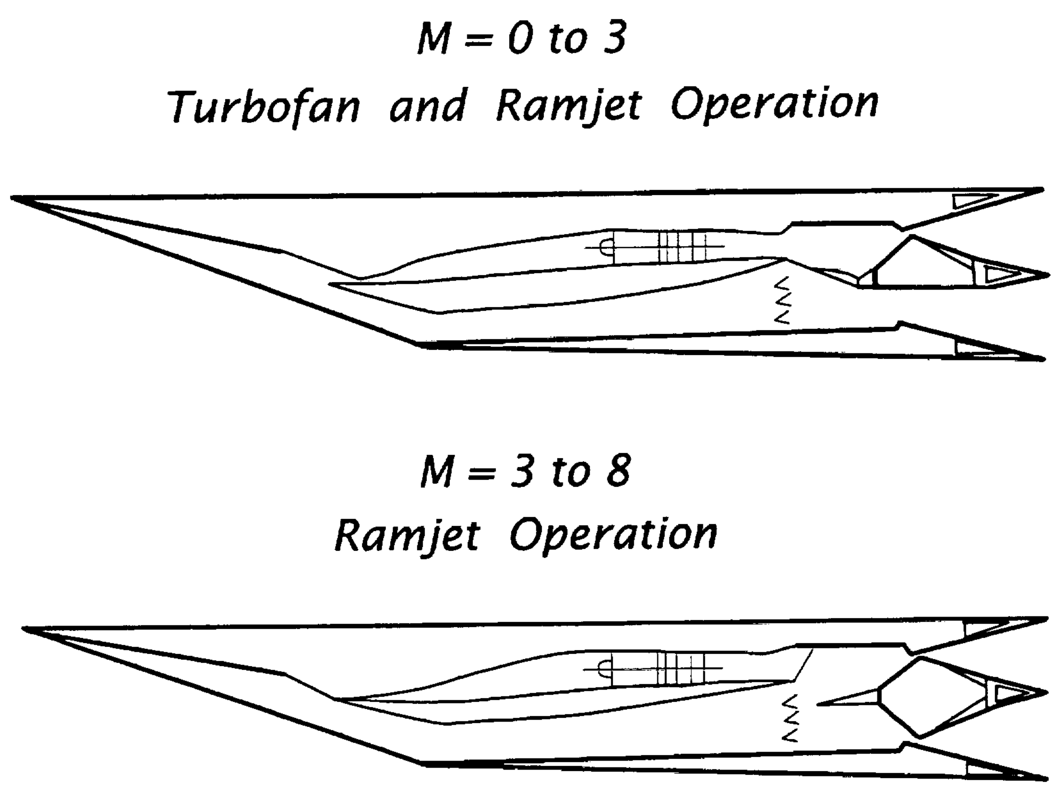


Figure 5. Beta I Nacelle Concept

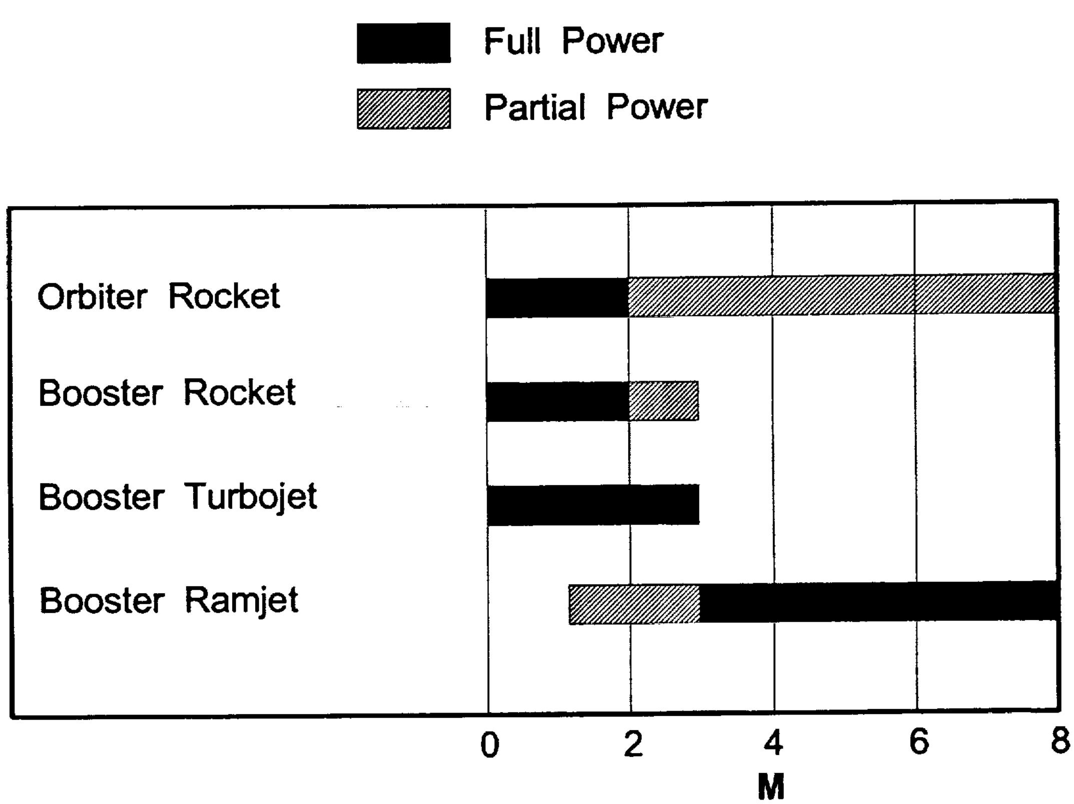


Figure 6. Beta I Engine Operating Schedule

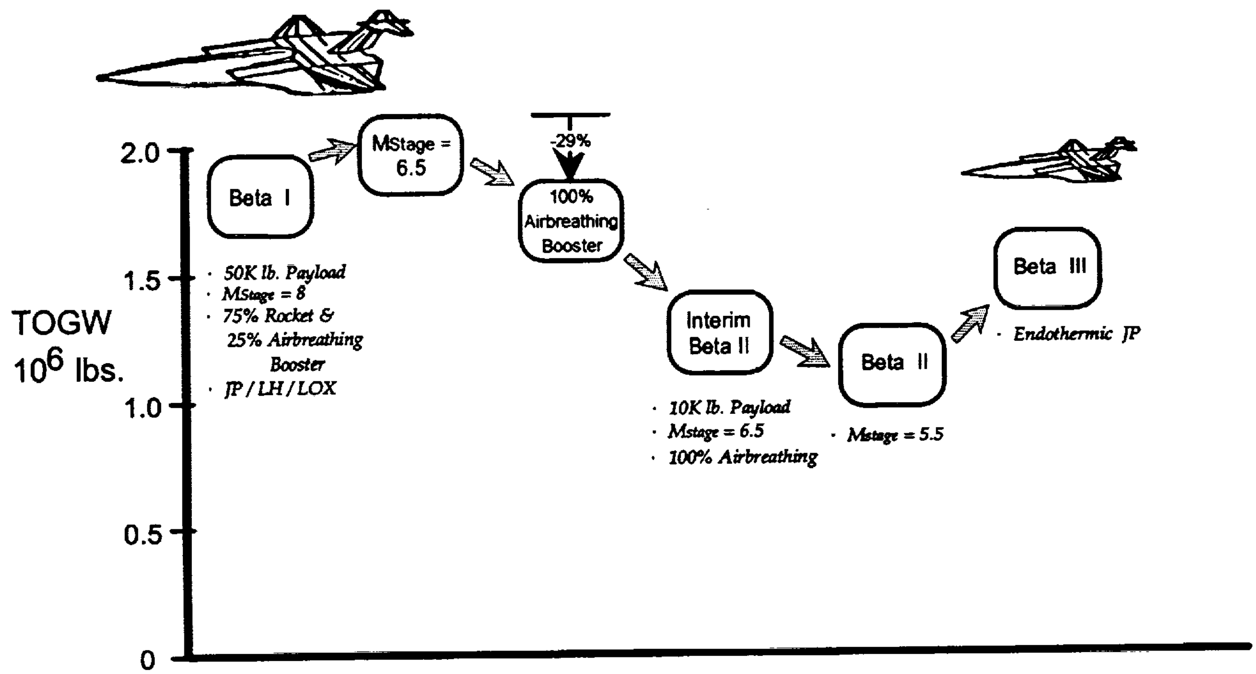


Figure 7. Evolution of Beta Airbreathing Launch Vehicle

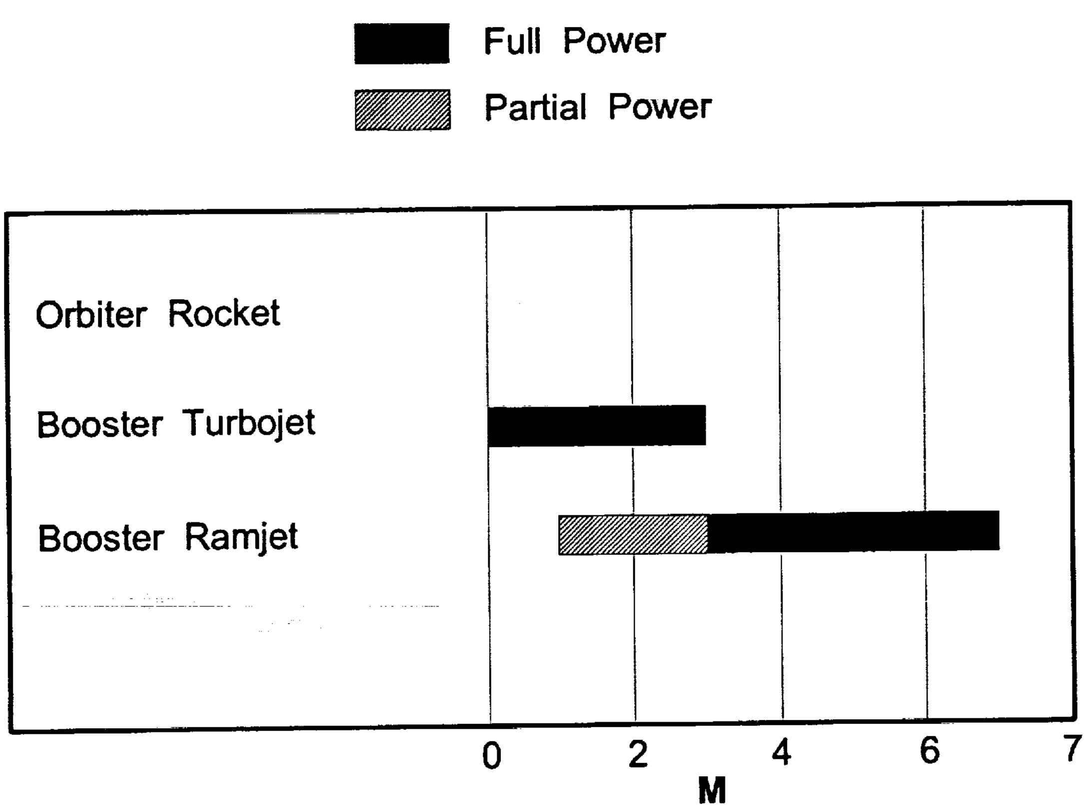
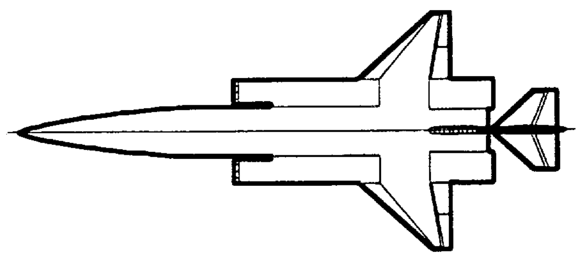


Figure 8. Beta II Engine Operating Schedule



GLOW = 1.2 M lb.

EW = 490 K lbs.

λ' = 0.436

Materials
René 41
Inconel 718
Carbon-Carbon (leading edges)

Propulsion
10 HSCT Turbine Eng.
2 Ramjets

Stages M = 6.5

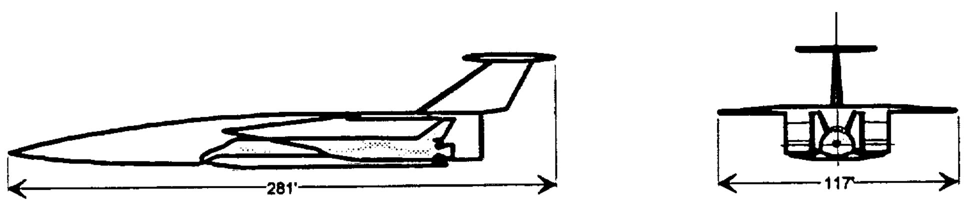
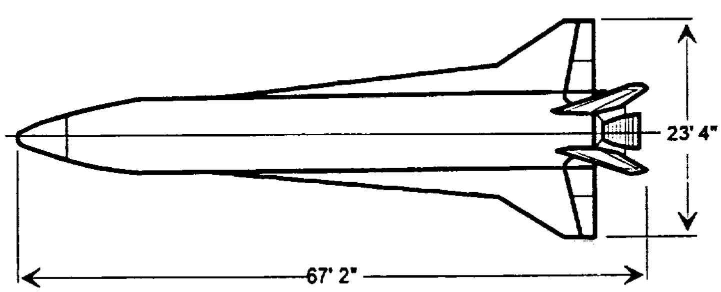


Figure 9. Interim Beta II Booster Concept



GLOW = 345 K lb.

Payload = 10 K lb. (low polar)

λ' = 0.811

Materials
Graphite Polyimide
Ceramic Tiles (TPS)
Aluminum/Lithium (Cryo tanks)

Propulsion
1 SSME
2 RL10
LOX/LH RCS

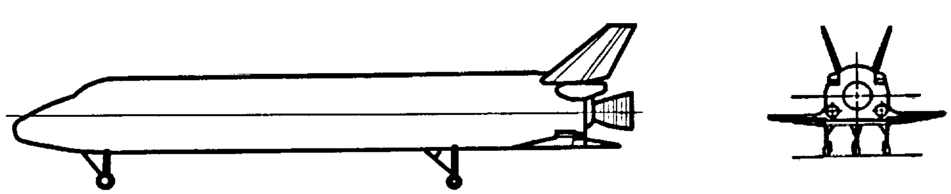


Figure 10. Mach 6.5 Staging Beta II Orbiter Concept

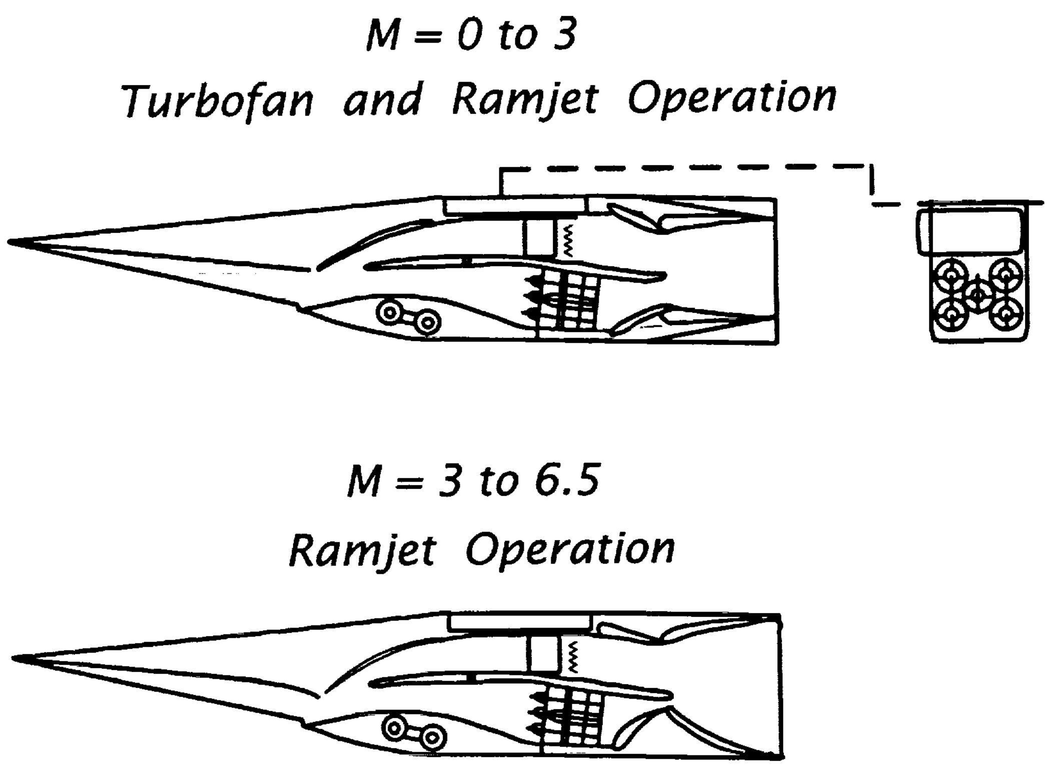


Figure 11. Interim Beta II Nacelle

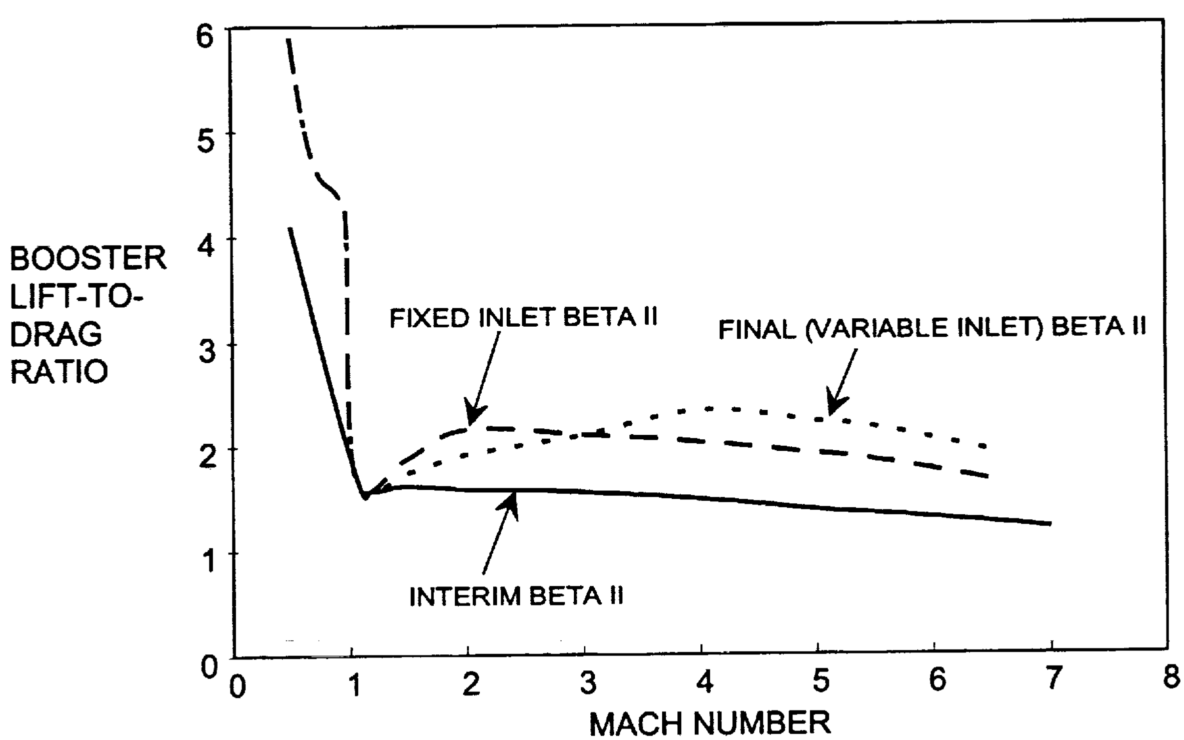


Figure 12. Beta II Lift to Drag Comparison

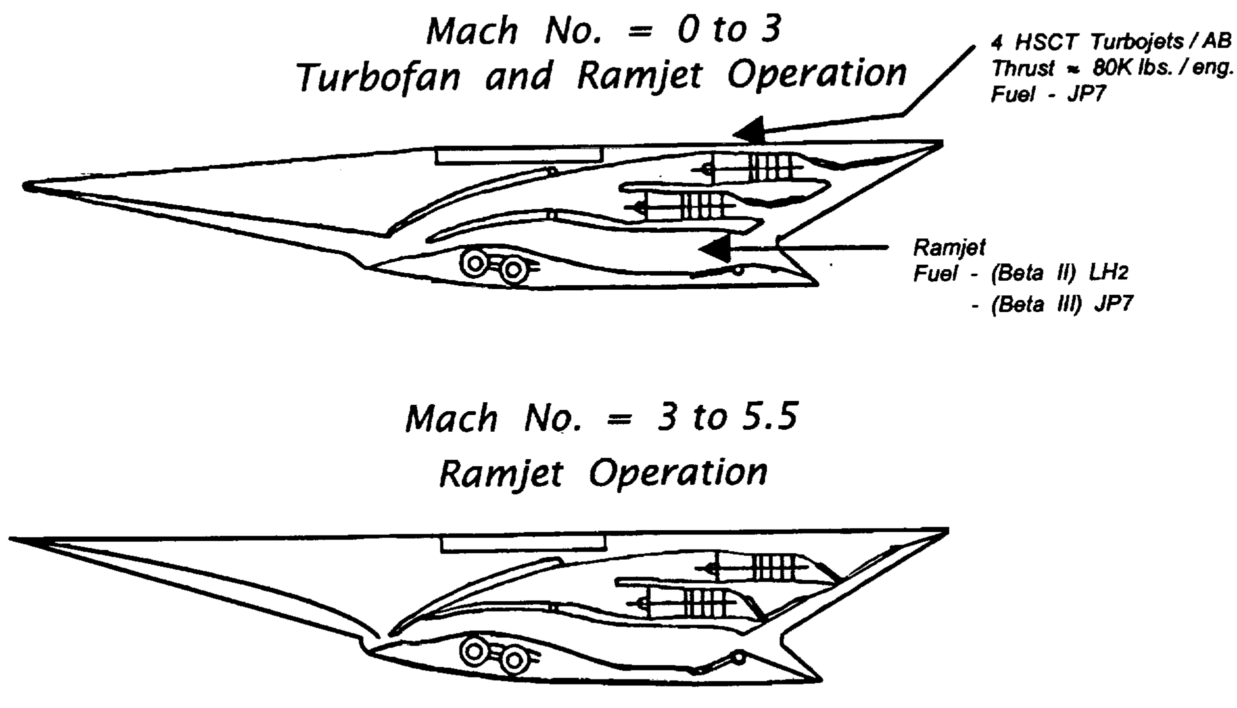


Figure 13. Beta II Nacelle Concept

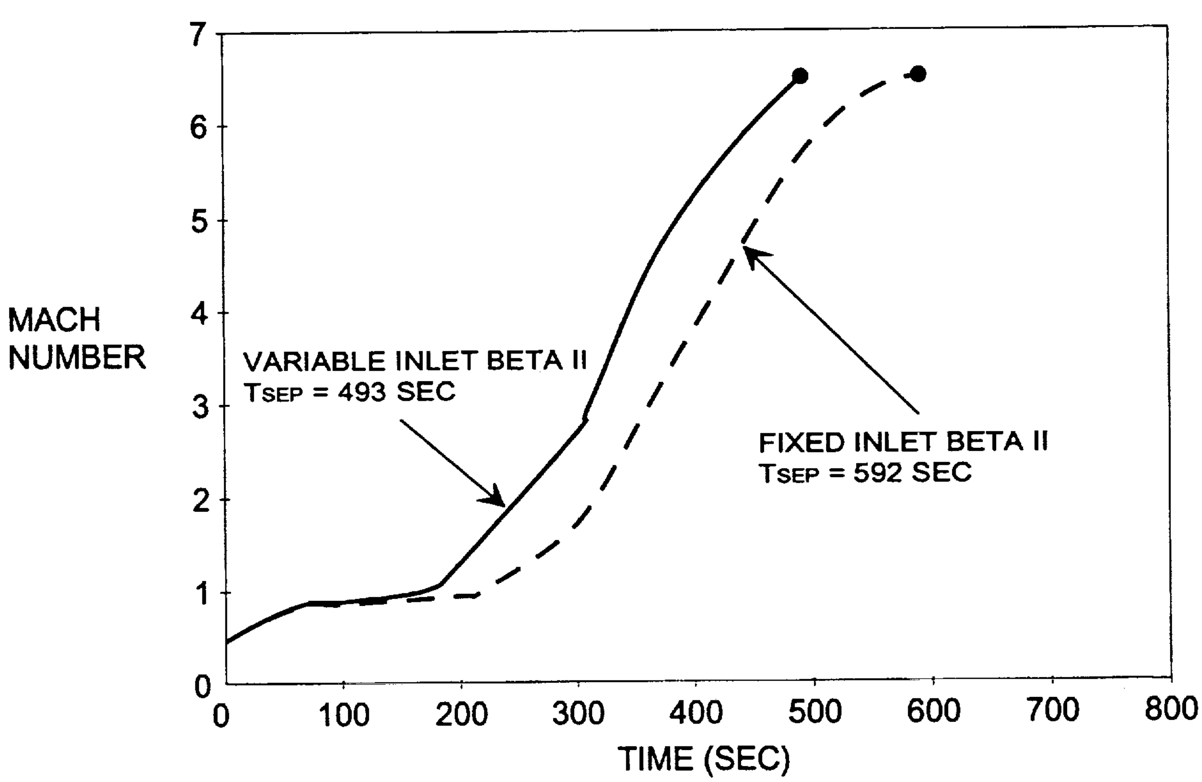


Figure 14. Inlet Study Trajectory

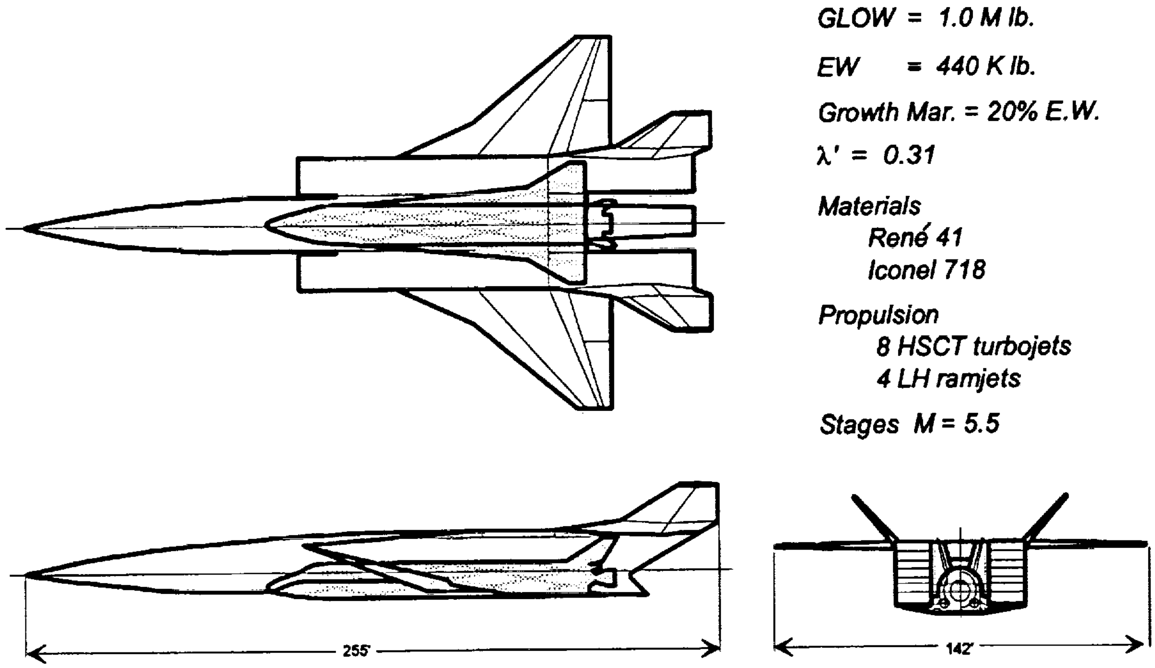


Figure 15. Beta II Booster Concept

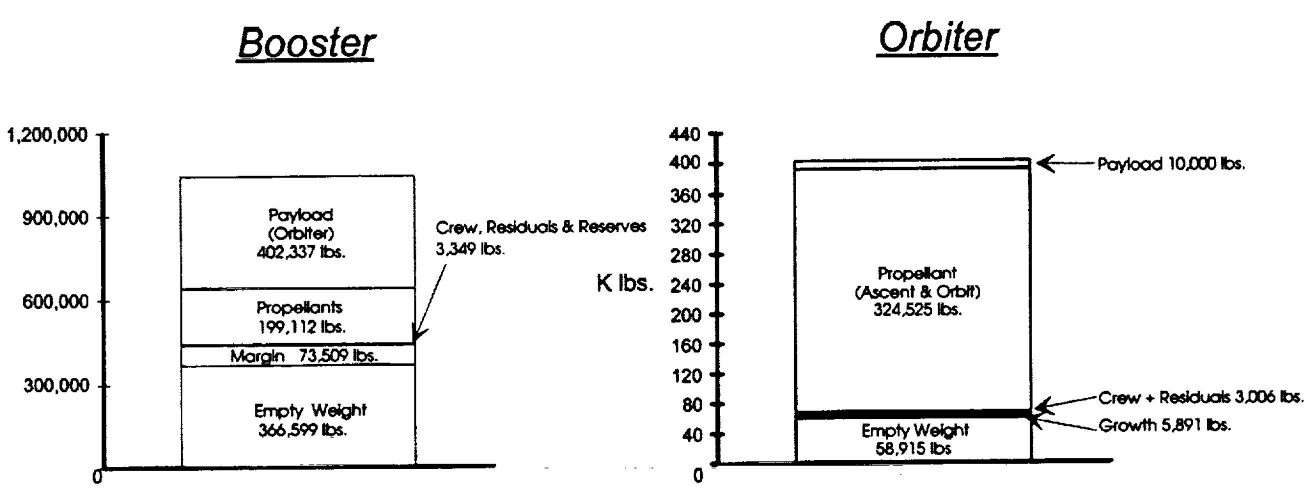


Figure 16. Beta II Weight Breakdown

Polar Launch From KSC

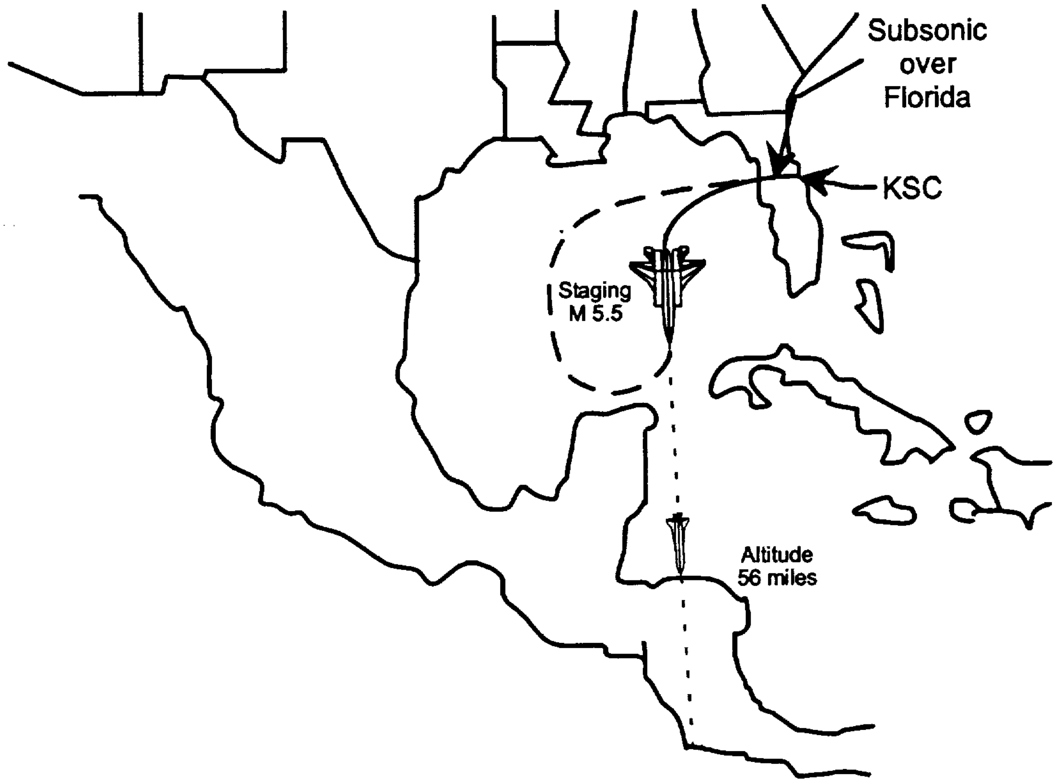


Figure 17. Single Site Operation

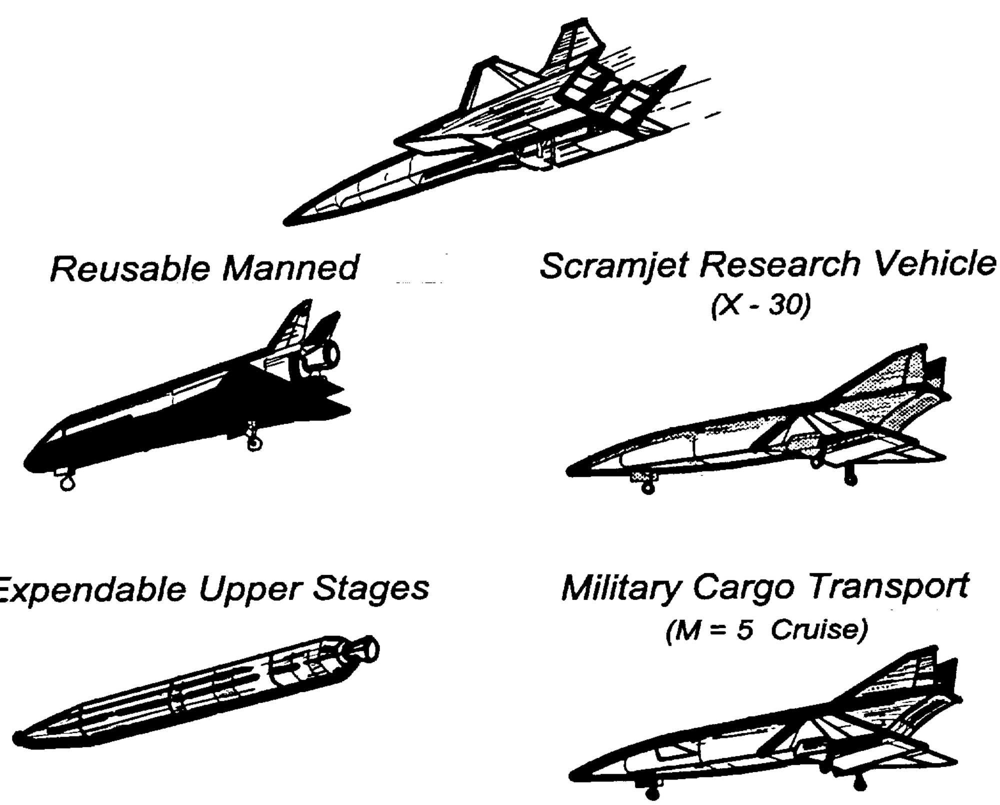


Figure 18. Beta II Versatility

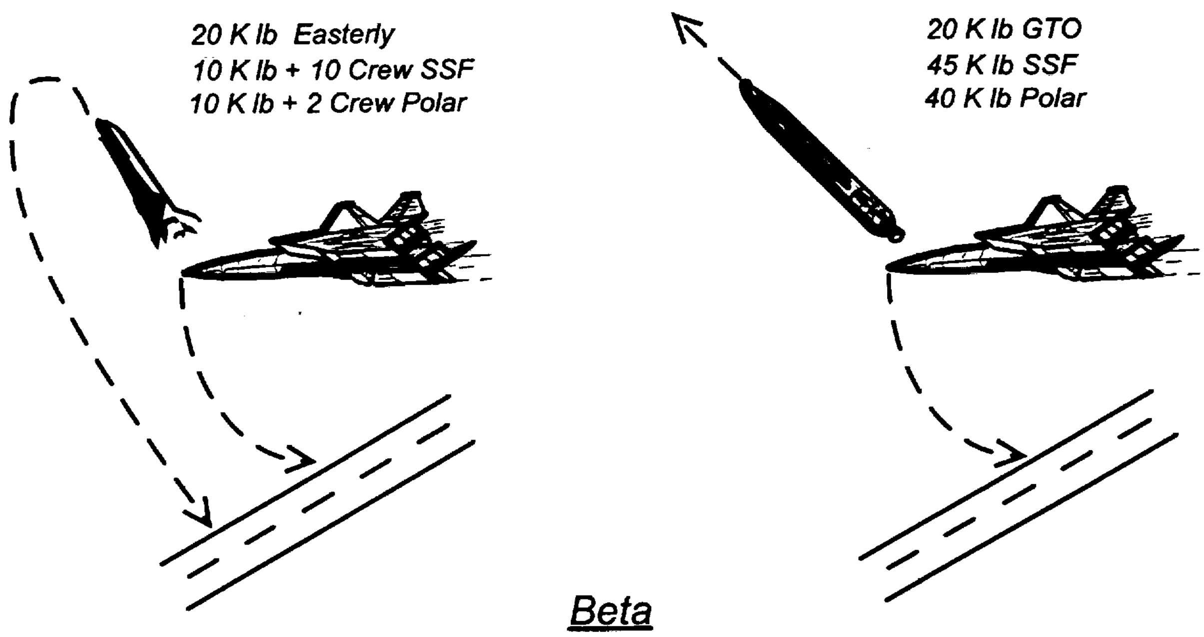


Figure 19. Year 2005 Launch Vehicle Architecture

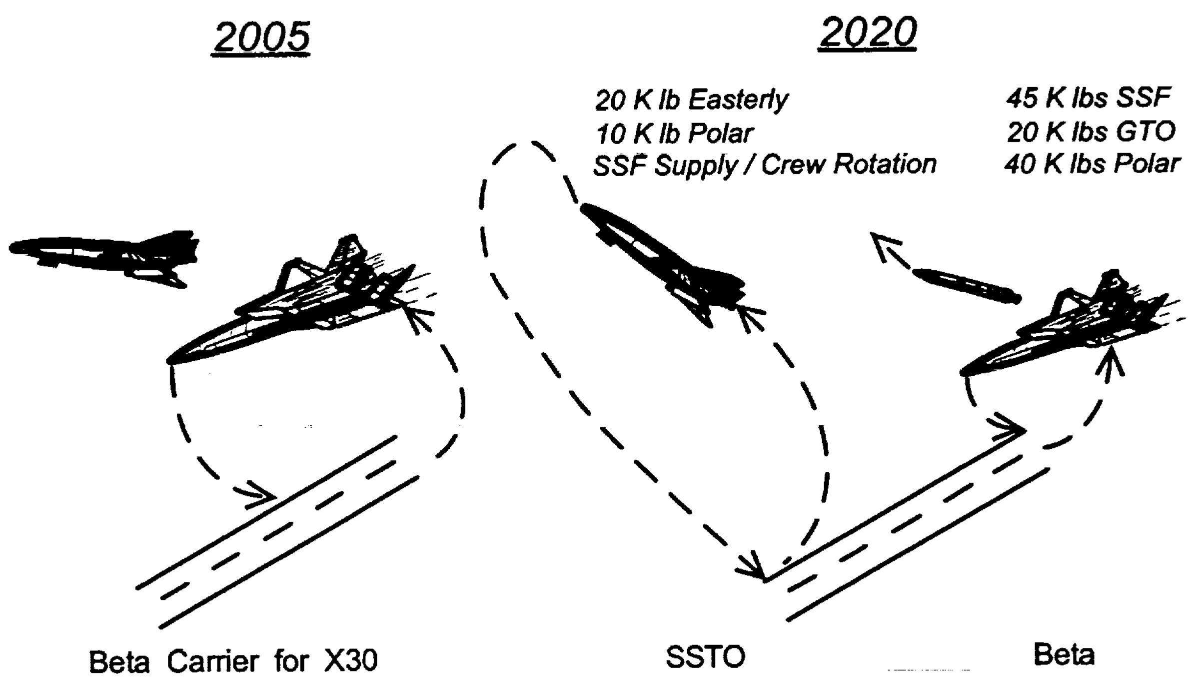


Figure 20. Beta Enhances SSTO Development

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13. ABSTRACT ***(Maximum 200 words)***

The Beta launch system was originally conceived in 1986 as a horizontal takeoff and landing, fully reusable, two-stage-to-orbit, manned launch vehicle to replace the Shuttle. It was to be capable of delivering a 50,000 lb. payload to low polar orbit. The booster propulsion system consisted of JP fueled turbojets and LH fueled ramjets mounted in pods in an over/under arrangement, and a single LOX/LH fueled SSME rocket. The second stage orbiter, which staged at Mach 8, was powered by an SSME rocket. A major goal was to develop a vehicle design consistent with near term technology. The vehicle design was completed with a GLOW of approximately 2,000,000 lbs. All design goals were met. Since then, interest has shifted to the 10,000 lbs. to low polar orbit payload class. The original Beta was down-sized to meet this payload class. The GLOW of the down-sized vehicle was approximately 1,000,000 lbs. The booster was converted to exclusively air-breathing operation. Because the booster depends on conventional air-breathing propulsion only, the staging Mach number was reduced to 5.5. The orbiter remains an SSME rocket-powered stage.

14. SUBJECT TERMS
Hypersonic; Two-stage-to-orbit; Launch vehicles; Reusable

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