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# Overview of the Beta II Two-Stage-To-Orbit Vehicle Design



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# OVERVIEW OF THE BETA II TWO-STAGE-TO-ORBIT VEHICLE DESIGN

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## Abstract

A study of a near-term, low risk two-stage-to-orbit vehicle was undertaken. The goal of the study was to assess a fully reusable TSTO vehicle with horizontal takeoff and landing capability that could deliver 10,000 pounds to a 120 nm polar orbit. The configuration analyzed was based on the Beta vehicle design, earlier completed by USAF and Boeing. NASA, USAF and Boeing entered a co-operative study to redesign and refine the Beta concept to meet the mission requirements of the present study. The vehicle resulting from this study was named Beta II. It has an all-airbreathing first stage and a staging Mach number of 6.5. The second stage is a conventional wing-body configuration with a single Space Shuttle Main Engine.

## Introduction

The National Aerospace Plane (NASP) has gained considerable attention in recent years as a flexible means of access to space. However, many technology advances are required to obtain a viable single-stage-to-orbit (SSTO) system, especially in the areas of propulsion and materials/structures. In order to design a reasonably sized vehicle with low risk technology, a two-stage-to-orbit (TSTO) configuration may be required. Such a vehicle will result in a lower gross lift-off weight (GLOW) than a comparable SSTO vehicle with the same level of technology. However, this benefit degrades as materials and structure technology result in large dry weight reductions.

In light of the above, a study was undertaken to investigate low risk methods for routine access to space. The ground rules of the study are specified in Figure 1. A near-term technology level was assumed for the vehicle. Near-term technology is defined as that which is either currently available or could be developed with low risk in the next five years. Additional ground rules specified a manned, completely reusable vehicle with a horizontal takeoff and landing capability. The baseline mission for the study required a 10,000 lb payload to be delivered to a 120 nm polar orbit.

A literature search of past work revealed such concepts as the German SÄNGER vehicle (ref. 1), the USAF/Boeing Beta concept (ref. 2) and others (ref. 3,4). The Beta concept had many unique features which were desirable for incorporation in the current study. (These features will be discussed in the following section.) Thus, after an initial evaluation, the Beta concept was chosen as the baseline configuration on which the current study was built. A cooperative program was established in order to modify the original Beta design to meet the requirements set forth in this study as well as perform additional tradeoffs to optimize the design. The participants in this cooperative effort were the NASA Lewis Research Center, the Air Force Wright Laboratory and the Boeing Defense and Space Group. The participants and their respective roles are shown in Figure 2. The vehicle resulting from this study was named Beta II.

## USAF/Boeing Beta Design

A short discussion of the original Beta design will now be given to provide background for the current study. Figure 3 shows the original USAF/Boeing Beta configuration. The most prominent feature of this system is the bottom loader configuration of the second stage in the booster stage. The bottom loader configuration results in many desirable features. First, this configuration allows expedient ground handling and mating. The mating can be accomplished without the use of special cranes. The orbiter stage is rolled under the booster from the rear and then hoisted into position using the staging mechanism. Second, because the orbiter is contained within the booster, the minimization of transonic drag becomes an easier design problem when compared to a more conventional top mounted piggyback arrangement. Finally, at stage separation, the lightly loaded booster vehicle will tend to lift away from the heavily loaded orbiter vehicle making for a cleaner separation maneuver.

The Beta configuration incorporates two Space Shuttle Main Engines (SSME), eight Advanced Tactical Fighter (ATF) turbofan engines and two ramjet propulsion pods. One SSME is on the orbiter vehicle. This rocket fires from takeoff to orbit insertion. Although firing the orbiter rocket the entire mission is not optimum, this mode of operation was deemed necessary to avoid problems of shutting down the SSME after passing through the thrust critical transonic region and then restarting it at stage separation. This SSME was throttled back to 65 percent of maximum thrust from Mach 3 until staging occurred at Mach 8 in order to minimize the impact of its low specific impulse. The remainder of the engines are mounted on the booster stage. The booster SSME is mounted just below the vertical tail. It is only used from takeoff up to Mach 3. After Mach 3 more than sufficient thrust is available from the orbiter rocket and the booster ramjets, therefore, it becomes more efficient to shut down the booster rocket. The airbreathing engines are mounted in two nacelles, one on each side of the fuselage. Like the booster rocket, the turbofan engines only operate from takeoff up to Mach 3. The turbofans are sized to provide sufficient thrust for a subsonic ferry mission of the booster carrying an empty orbiter. Therefore, the turbofans contribute only a small fraction of the total takeoff thrust when the vehicle is fully loaded. The conventional ramjets operate from Mach 1 through stage separation at Mach 8.

The original Beta system is very large, weighing 2.2 million pounds fully loaded at takeoff. The fully loaded orbiter stage weighs 600,000 lbs and is capable of delivering 50,000 lbs of payload to polar orbit.

Wind tunnel tests were performed on a model of the Beta vehicle. The results of these tests were used to calibrate and verify the analysis codes used in the original study as well as the current study of the Beta II vehicle. The test results were particularly useful in the transonic region, where accurate analytical analysis becomes most difficult. Separation tests have not been run to date. Flow interactions when the orbiter is swung down from the booster for staging is an area that requires further study.

## Trade Studies

The current study mission requirements were different than those required for the original Beta. The most significant of these mission changes are the payload and the staging Mach number. The original Beta design incorporated a 50,000 lb payload and staged at Mach 8. A 10,000 lb design payload requirement was specified in the current study because it covered the majority of projected NASA payloads. The original Mach 8 staging was considered high for conventional ramjet operation. Mach 8 staging also makes designing the inlet and handling the thermal heat loads very challenging. Therefore, to lessen the design risk, the staging Mach number was reduced to Mach 6.5 for the current study. Mach 6.5 staging is still very challenging, but is considered much more manageable in the near-term than Mach 8.

A preliminary trade study was undertaken to (1) investigate the effect of reducing the staging Mach number, (2) investigate the effect of downsizing the payload, and (3) determine the best type and mix of propulsion systems on the booster and orbiter. The original Beta aerodynamics and propulsion data were used in this preliminary trade study. Vehicle lift and drag were scaled with reference area. Each engine type was scaled up or down as required to get the performance and weight of the desired propulsion system configuration. A coupled vehicle weight analysis and trajectory analysis was used to get closure on the vehicle for each of the numerous vehicle trade-offs that were studied.

The primary results of this trade study are shown in Figure 4. The original Beta vehicle is depicted by the first column in the figure. The results for other configurations in the trade study are presented relative to this original vehicle weight. The first step in this trade study process was to reduce the staging Mach number to ease the difficulties of the airbreathing propulsion design. Although the lower staging Mach number reduced the booster propulsion system weight and complexity, it resulted in a higher overall system weight of 8% as depicted by the second column in the figure. The overall weight increased because the orbiter vehicle was required to provide a significantly larger portion of the total energy required to reach orbit. The energy required to accelerate the vehicle from Mach 6.5 to Mach 8 was supplied using a rocket engine with a lower specific impulse than the combination of ramjets and rocket used on the baseline vehicle. However, in order to develop a system with near-term/low risk materials and propulsion system, the lower staging Mach number was carried through the remainder of the study.

The use of rocket engines on the booster is a very effective means of providing large thrust margins in the critical transonic region. A rocket's high thrust-to-weight ratio provides a large amount of thrust while only adding a small amount to the empty weight. However, because it is burning both fuel and oxidizer, its propellent use is very high. Each three seconds of operation of the SSME burns the equivalent weight of one ATF engine. Therefore, it is desirable to reduce or eliminate the use of rocket thrust during the booster phase of the flight. The third column of Figure 4 shows the effect of eliminating the booster rocket entirely, not firing the orbiter rocket until separation, and increasing the airbreathing propulsion thrust as required. The optimum thrust-to-weight at takeoff for this system is .53. This resulted in approximately 27% weight reduction compared to using rocket propulsion during the boost phase.

The effect of reducing the payload to the mission requirement of 10,000 lbs is shown by the last column in Figure 4. The GLOW of the vehicle does not decrease linearly with payload reductions. In fact, the GLOW was only reduced by 50% even though the payload was cut by 80%.

The final configuration that was pursued in detail through the remainder of the study was the Mach 6.5 staged hydrogen/JP fueled design. The booster phase of the flight is entirely powered by airbreathing propulsion; a combination of JP fueled turbojets and hydrogen fueled ramjets. The new booster and orbiter configuration that was designed and analyzed will now be discussed in detail.

## Beta II Booster Design

Like the original Beta design, the Beta II booster carries the orbiter stage partially embedded inside an open cavity in its belly. This configuration is shown in Figure 5. The flight trajectory was optimized using the OTIS computer code (ref. 5). The resulting ascent trajectory is shown in Figure 6. The booster follows a 1500 lb/ft$^2$ dynamic pressure limit through most of its flight.

Aerodynamic performance for the new configuration was generated using the APAS analysis code (ref. 6). Transonic aerodynamic performance was generated by scaling the wind tunnel and analysis data of the original Beta booster and adding corrections for the new geometry. The predicted L/D versus angle of attack for the booster is shown in Figure 7. The effect of engine bypass flow which is dumped into the base area was not accounted for in the analysis. It is anticipated that taking this flow into account should reduce the predicted base drag. Perturbation on the booster design (e.g. nose fineness ratio, wing sweep, area ruling, etc.) may produce additional improvements in the aerodynamic performance.

The booster is exclusively powered by airbreathing propulsion from takeoff through the Mach 6.5 staging. The propulsion system consists of a nacelle mounted on each side of the fuselage. Each nacelle contains five proposed High Speed Civil Transport (HSCT) derivative turbine bypass engines (TBE) and a conventional ramjet module mounted in an over/under configuration as shown in Figure 8. The TBEs are full afterburning and use conventional JP fuel. They operate from takeoff up to Mach 3. The ramjets are hydrogen fueled. They are cold-flowed below Mach 1 to reduce the drag. The ramjets are ignited transonically; however, they do not produce significant net thrust until nearly Mach 2. A complete description of the engine module design is given in reference 7.

The Beta II inlet incorporates a two-dimensional two-ramp system. The first ramp is a variable angle straight ramp. The second ramp is an isentropic compression ramp which can vary its shape along its entire length to provide shock-free compression. Contrary to a conventionally designed inlet, the Beta II inlet capture area is not sized to supply the airflow demanded by the ramjet at Mach 6.5. Instead, the inlet is sized to provide maximum performance through the critical transonic region, while providing adequate thrust margin at the design condition. A complete description of the inlet design is given in reference 8.

Propulsion system performance and weight were generated using this new propulsion system configuration. The size of both the TBEs and the ramjets were independently optimized. The resulting takeoff thrust-to-weight ratio of the TBEs was .67. This thrust-to-weight is higher than the preliminary trade study predicted because the transonic L/D of the Beta II is lower than that of the Beta vehicle (Beta aerodynamic data was used in the preliminary trade study). The ramjets were sized to produce a total peak thrust of 1 million pounds. The maximum thrust occurs at Mach 4.

The structure was designed and weighed using the ground rule assumption of near-term material technology. The design uses a "warm" metal structure. Thermal insulation and active cooling outside the propulsion system are not employed. However, because the high heat loads are only encountered for a short time, the internal structure only warms slightly during the boost phase. Aerothermal heating analysis of the vehicle shows the highest equilibrium temperatures occur on the nose cap, wing and horizontal tail leading edges and the cowl lip. Columbium is used to protect these areas as depicted in Figure 9. Rene' 41 honeycomb panels are required for an additional section of the under side of the nose, and wing. Inconel 718 honeycomb panels are used for the remainder of the vehicle.

The structural design employs a conventional semimonocoque structure with non-integral hydrogen tanks. A modular structural concept is used to provide access and removal of the fuel tanks and engines. Because of the uncertainty that results from the complexity of the booster design, a 20 percent growth margin was included in the booster weights analysis. (Growth margin is a percentage of the empty weight added into the weight prediction to cover any underpredictions that may have occurred in the analysis). This large margin makes the booster design conservative.

The GLOW of the Beta II is 1.2 million lbs with a booster stage burn out weight of .88 million pounds. This weight is much higher than that predicted in the preliminary trade study (Figure 4) because of refinements in the analysis. The degraded transonic aerodynamic performance required a much higher TBE thrust-to-weight ratio as previously discussed. Also the incorporation of a 20 percent growth margin added significant weight. (The original analysis only included a 2 percent margin.) A systems weight breakout is shown in Figure 10. The payload weight shown for the booster is the fully loaded orbiter weight including a crew of two.

## Beta II Orbiter Design

No significant cross-range requirement was specified for the study mission. Therefore, a simple design was chosen for the Beta II orbiter compared to the slender lifting body design used in the original Beta study. The Beta II design is essentially a wing-body design as shown in Figure 11. A nearly cylindrical cross section was chosen for the body for maximum structural efficiency. This design resulted in a maximum L/D 30% lower than the original orbiter design. However, this reduction had very little impact on the ascent propellent since the orbiter trajectory quickly leaves the atmosphere, as shown in figure 6. The biggest impact of the lowered L/D is on re-entry cross range which as stated above was not a requirement for the study mission. The stage is powered by a single SSME which is fired from staging to orbit insertion.

The 10,000 lb payload is contained in a 14 ft diameter by 20 ft long payload bay near the center of the vehicle. The payload bay volume is large enough to carry typical payloads that are heavier than 10,000 lbs. Thus, an alternative mission with this same vehicle could deliver two crew members and 15,800 lbs of payload (or ten crew members and 10,000 lbs of payload) to the Space Station, which is in a lower energy orbit than the one defined for the baseline mission. For missions to the Space Station which require very large payloads, an expendable second stage which would carry 30,000 lbs of payload could be launched using the same booster vehicle.

Liquid hydrogen fuel is stored in a tank forward of the payload bay and liquid oxygen is stored to the rear of the payload bay. Since the orbiter engine is not fired prior to staging a propellant cross feed system is not required between the booster and the orbiter. Thermal protection of the vehicle is afforded by using a removeable external thermal protection system. Twin vertical tails are incorporated in order to provide the necessary directional stability while keeping the span short enough for efficient integration within the booster.

The orbiter weight at staging is 346,000 lb. The weight breakdown for the orbiter, shown in Figure 12, shows the stage is largely propellant. Because the orbiter design is much more conventional than that of the booster, only a 10% growth margin was included. The resulting empty weight to gross weight fraction of .15 for this stage is within the capabilities of current technology designs. For comparison, the shuttle orbiter and external tank have an empty weight to gross weight ratio of .12.

## Conclusion

This study indicates that a fully reusable TSTO vehicle incorporating conservative structures, materials and design is feasible with a reasonable GLOW. The results show that using all airbreathing propulsion in the booster stage results in a lower GLOW than using a mixture of rocket and airbreathing engines. The propulsion technology was kept low-risk by using HSCT derivative turbine engines, conventional ramjets and SSME rocket engines. The Mach 6.5 staging produced heat loads that were low enough to allow the design of a conventional structure without active cooling or exotic materials.

The ensuing Beta II design is very versatile. The baseline mission can deliver a 10,000 lb payload to polar orbit. This size of vehicle covers the majority of projected NASA payloads. For example, an alternate mission can deliver 10,000 lbs and 10 crew members to the Space Station. If an expendable stage is used in place of the orbiter, a 30,000 pound payload can be delivered to the Space Station. The design also incorporates unique features which give it the potential for low cost operations. The bottom loader configuration simplifies stage mating, eliminating the need for special cranes. The booster stage can also serve as a ferry aircraft, eliminating the need for a special aircraft for that purpose. Airplane-like operation eliminates the need for launch towers and their associated facilities. This type of operation also provides for an intact, safe abort procedure.

This study was only the first phase of a program to define a viable TSTO system. With the positive results of this study, work is continuing to further optimize the Beta II design.

## Future Work

The Beta II design is continuing to be optimized and analyzed in more depth. Alternative turbine engine cycles are being investigated and the inlet, engine and nozzle integrations are being further optimized. A detailed analysis of the propulsion system weights, structure and thermal loads is underway. Vehicle aerodynamics are being refined, particularly in the critical transonic region, to include the effect of the engine bypass flow on reducing the base drag. A reasonable GLOW was used as the primary criteria in determining the merit of the Beta II system. However, it is recognized that low cost is a much more important criteria. Therefore, a study of the Beta II vehicle costs and operational costs has begun.

Alternatives to the baseline Beta II configuration are also being considered. One option uses endothermic fuels in the booster and storable rocket propellants in the orbiter. This concept would completely eliminate cryogenic propellants from both the booster and the orbiter, thereby simplifying the design. Another option uses an air collection system that could separate oxygen out of excess air brought on board during the first stage boost phase and then store this in the orbiter. Although this adds complexity to the system, it has the potential of reducing the system GLOW.

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Study Ground Rules

- Near-Term/Low-Risk Technology
- Two-Stage-To-Orbit
- Two Man Crew in Each Stage
- 10,000 lb Payload to 120 x 120 nm Polar Orbit
- Completely Reusable
- Horizontal Takeoff and Landing

Figure 1. Definition of study ground rules

Co-operative Study Participants

| Organization | Role |
|---|---|
| NASA -Lewis | Program Manager<br>Vehicle Tradeoffs<br>Propulsion System Design<br>Mission Analysis |
| USAF-Wright Labs | Original Beta Design<br>Aerodynamics |
| Boeing-Defense and Space Group | Vehicle Design<br>Mission Analysis<br>Aerodynamics |

Figure 2. Study participants and their roles

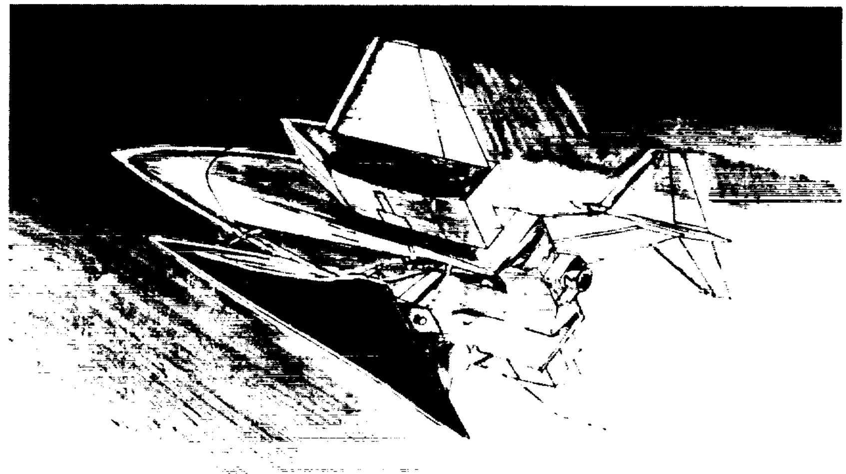
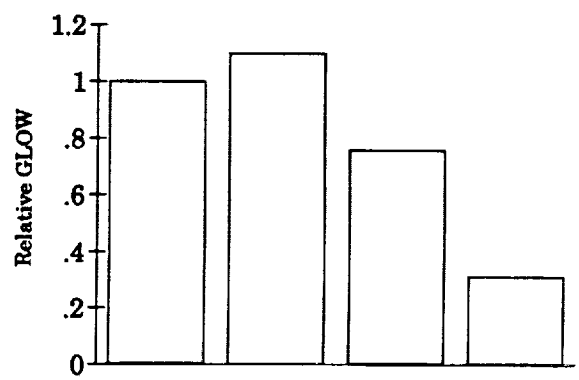


Figure 3. USAF/Boeing two-stage Beta vehicle




| | | | | |
|---|---|---|---|---|
| Payload | 50K | 50K | 50K | 10K |
| Stage Mach | 8 | 6.5 | 6.5 | 6.5 |
| Airbreathing T/W | .144 | .154 | .525 | .570 |
| Boost Rocket T/W | .472 | .504 | 0 | 0 |
| Boost Propellants | $JP/H_2/O_2$ | $JP/H_2/O_2$ | $JP/H_2$ | $JP/H_2$ |

Figure 4. Preliminary vehicle tradeoff results

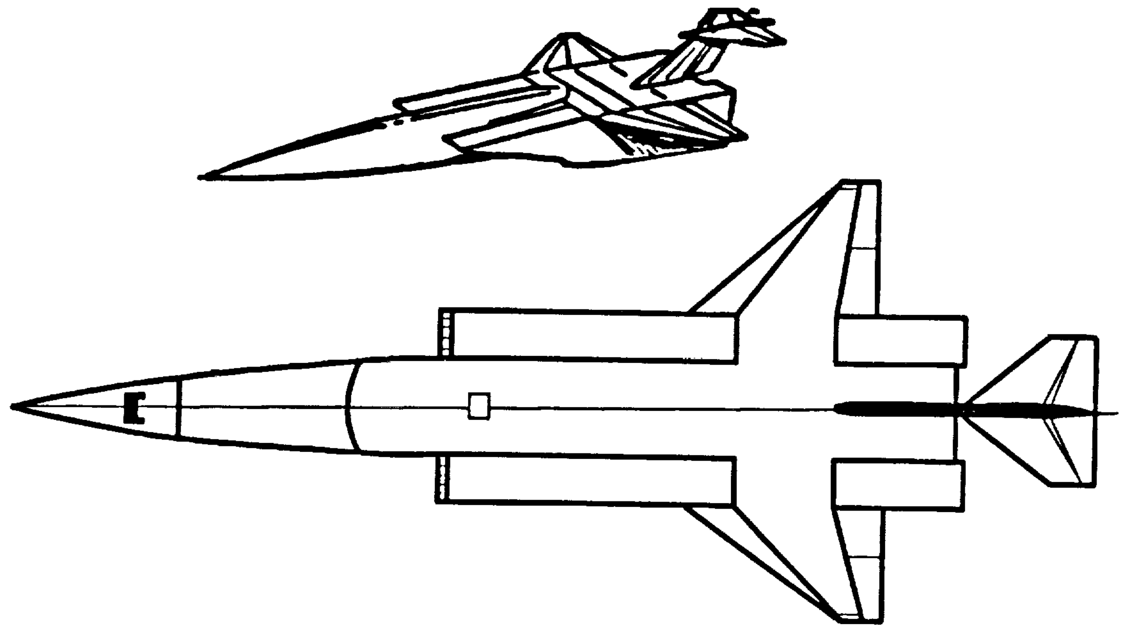


Figure 5. Beta II booster configuration

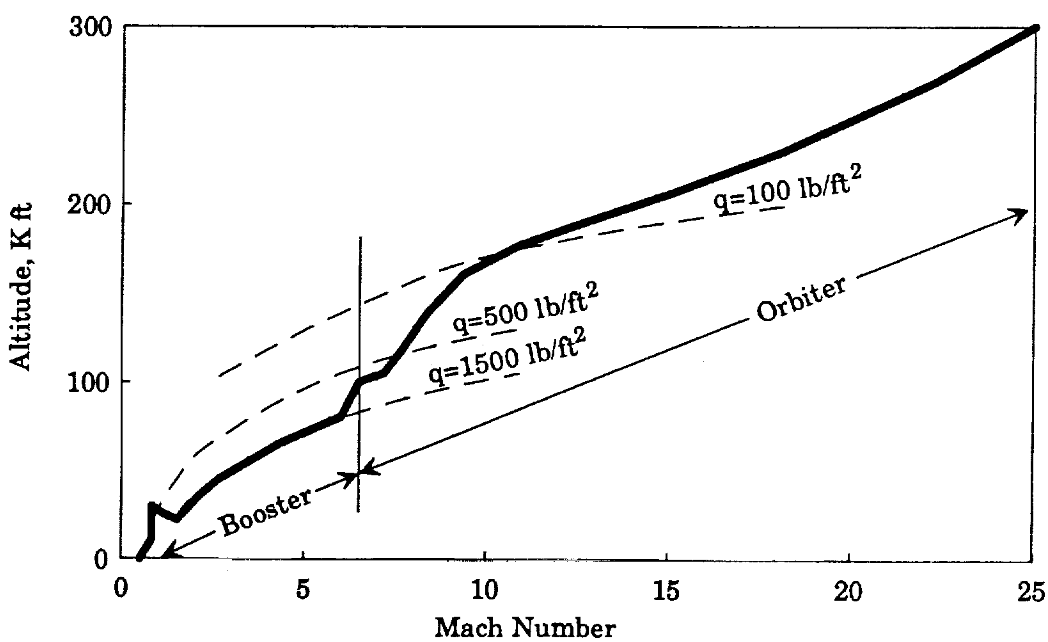



Figure 6. Altitude versus Mach number for the optimum trajectory

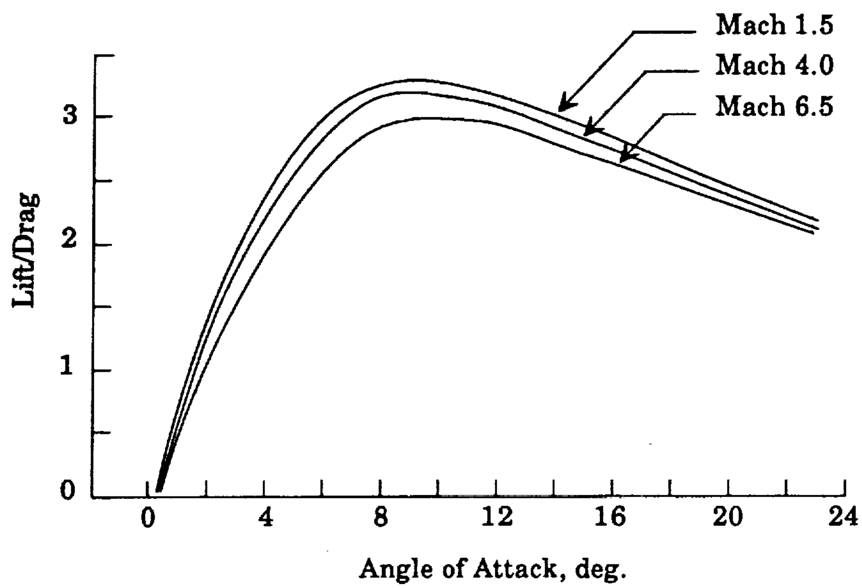



Figure 7. Beta II booster lift-to-drag ratios

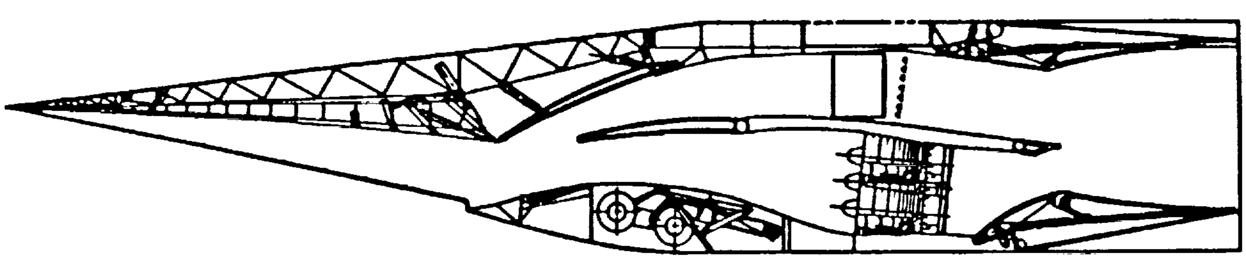


Figure 8. Beta II propulsion system nacelle configuration

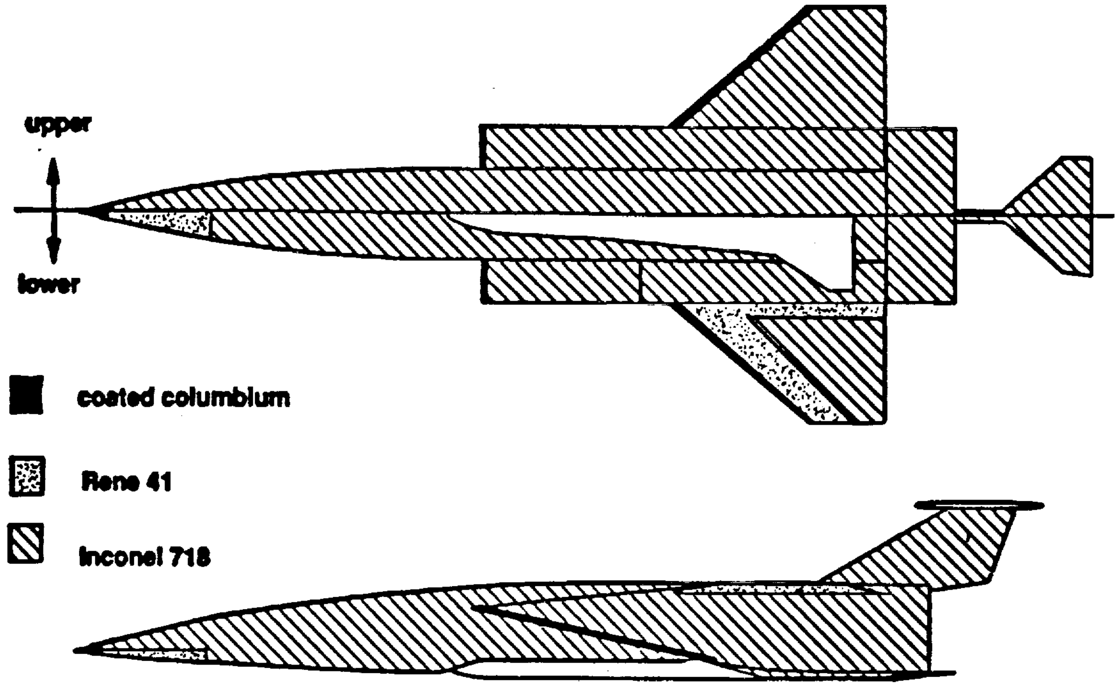



Figure 9. Beta II booster material selections

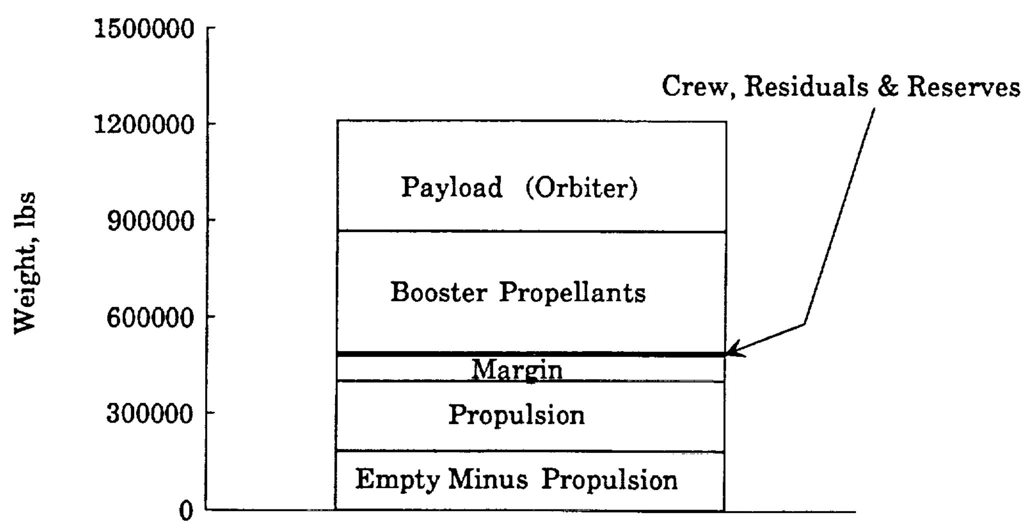



Figure 10. Beta II booster weight breakdown

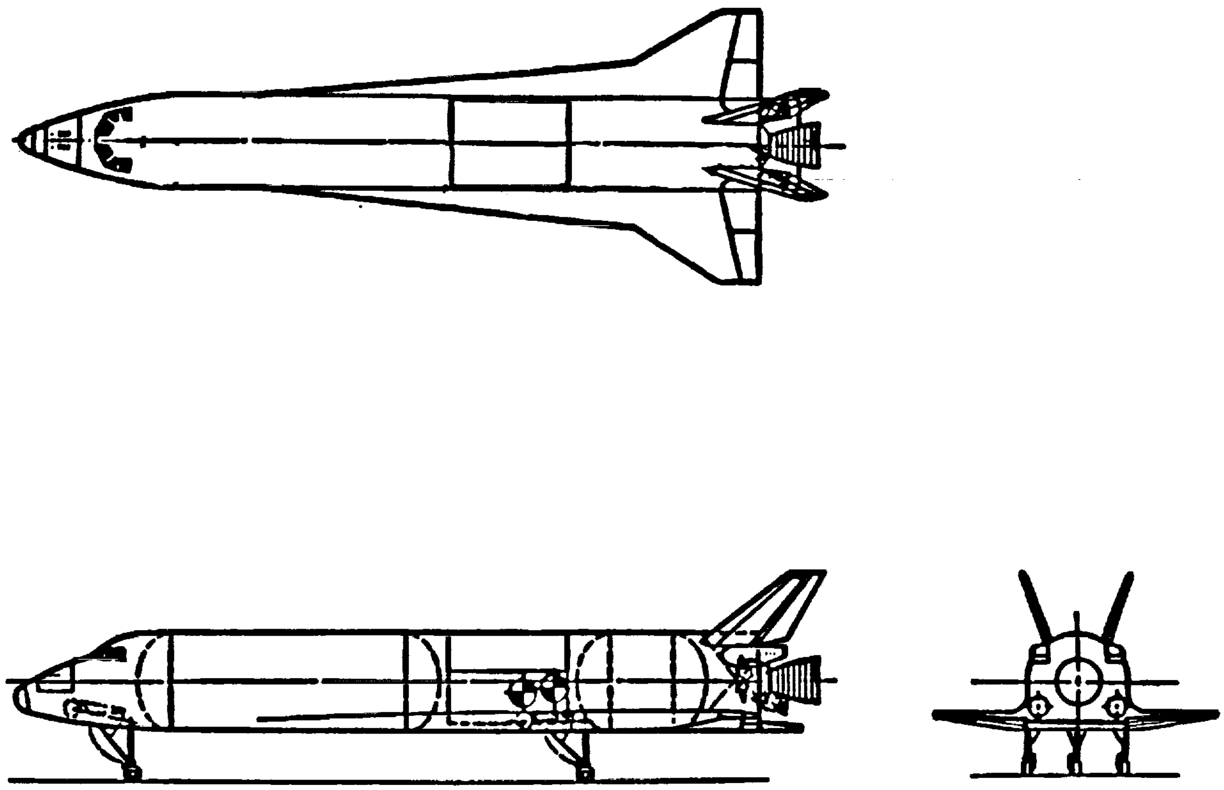


Figure 11. Beta II orbiter configuration

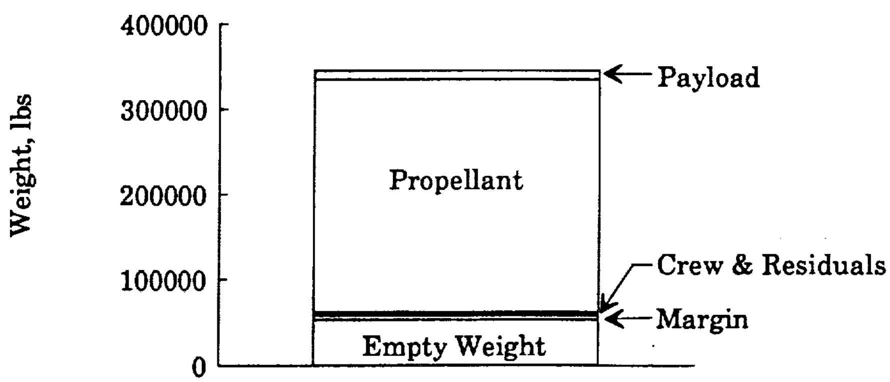



Figure 12. Beta II orbiter weight breakdown

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