N93-29719

THE DESIGN OF TWO-STAGE-TO-ORBIT VEHICLES

THE OHIO STATE UNIVERSITY

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Two separate student design groups developed conceptual designs for a two-stage-to-orbit vehicle, with each design group consisting of a carrier team and an orbiter team. A two-stage-to-orbit system is considered in the event that single-stage-to-orbit is deemed not feasible in the foreseeable future; the two-stage system would also be used as a complement to an already existing heavy lift vehicle. The design specifications given for this project are to lift a 10,000-lb payload, 27 ft long by 10 ft diameter, to low Earth orbit (300 n.m.) using an air breathing carrier configuration that will take off horizontally within 15,000 ft. The staging Mach number and altitude were to be determined by the design groups. One group designed a delta wing/body carrier with the orbiter nested within the fuselage of the carrier, and the other group produced a blended cranked-delta wing/body carrier with the orbiter in the more conventional piggy-back configuration. Each carrier used liquid hydrogen-fueled turbofanramjet engines, with data provided by General Electric Aircraft Engine Group. While one orbiter used a full-scale Space Shuttle Main Engine (SSME), the other orbiter employed a half-scale SSME coupled with scramjet engines, with data again provided by General Electric. This paper presents the two groups' conceptual designs, along with the technical trade-offs, difficulties, and details that surfaced during the design process.

INTRODUCTION

In previous years, The Ohio State University (OSU) Advanced Aeronautical Design Program (AADP) has focused on hypersonic design concepts ranging from 250-passenger commercial jets to 10-passenger executive jets to a Mach 10 scramjet test bed. Continuing with the hypersonic design trend at OSU, this year's project was the conceptual design of a two-stage-to-orbit vehicle. Until last year, most of the hypersonic design efforts were cruise concepts that lent themselves to optimization during the cruise regime. A two-stage-to-orbit vehicle is an accelerator, and thus no steady-state optimization is really possible.

The last space shuttle (Endeavour) has already been built, and although the space shuttle program is not near cancellation or termination, the Challenger accident showed that the U.S. space program is strongly dependent upon the space shuttle. A complementary (not replacement) orbital lift system would be a logical step, making the U.S. space program more versatile when the new system has access to space. Another consideration is that the space shuttle program incurs large operating costs by employing a veritable standing army of support personnel. These costs can be alleviated by having a system that operates as an aircraft, not a rocket, yielding an additional benefit of a quick turnaround time. This points toward a single-stage-to-orbit vehicle (i.e., NASP) or a two-stage-to-orbit vehicle (i.e., Sänger/Horus), with the latter mode less of a technology risk, as well as being nearer-term technology. Therefore, a two-stage-to-orbit vehicle is seen as a compromise between the operational costs associated with an expendable heavy lift rocket and the technical difficulties of a single-stage-to-orbit vehicle.

DESIGN SPECIFICATIONS

The design specifications for the conceptual two-stage-to-orbit vehicles were laid out to conform with vehicles of similar concept, yet allow sufficient latitude for each group to design a vehicle as they saw fit. As far as a specific mission for this type of vehicle, a quick relief flight to Space Station *Freedom,* supplying men, materials, and equipment was considered to be one of the primary missions.

It was specified that the carrier take off within 15,000 ft using only air breathing propulsion (no rocket assist), accelerate to the staging point, where the orbiter will separate and carry a 10,000-lb payload to 300 n.m. or low Earth orbit (LEO), at an orbital speed of 25,400 ft/s. The payload chosen is roughly one-fifth-scale in volume and weight of the space shuttle cargo bay. This size is estimated to encompass 90% of all current and future orbital payloads. Note that the staging Mach number and altitude are not specified and are to be determined by each group. The design specifications can be summarized as follows:

- Air breathing carrier propulsion
- Payload: 27 ft long × 10 ft diameter
  10 passengers plus
  10,000 lb (total weight)
- Low Earth orbit (300 n.m., 25,400 ft/s)
- Take off distance s 15,000 ft

DESIGN SERIES OUTLINE

A conceptual design project of this magnitude is indeed challenging, and thus the OSU hypersonic design series is expanded from the usual four-credit-hour design class to a program spanning the entire academic year. The series consists of a one-credit-hour seminar during the Autumn Quarter, a four-credit-hour Aerospace Vehicle Design Course during Winter Quarter, and a three-credit-hour Advanced Vehicle Design Course during Spring Quarter.

During Autumn Quarter a series of seminars are scheduled where professionals from industry and academia are invited to OSU to discuss not only aircraft design problems in general, but also problems specifically associated with hypersonic aircraft.

Winter Quarter is when most of the vehicle design is accomplished. The students were divided into two design groups, each having a carrier and an orbiter team. The teams were set up to duplicate industry design teams, each having a team leader and field specialists in areas such as propulsion and aerodynamics. The groups began with a calculation of weights and dimensions from an estimated ascent trajectory that included current aerodynamic and propulsion models. The staging Mach number and altitude was altered for a minimum system weight (both carrier and orbiter). Once a staging point was chosen, the task was to design two vehicles that must work together as one system. Each design team then worked to optimize their respective vehicles, mostly in the form of improving ascent trajectories. At the end of Winter Quarter, neither group had a fixed configuration due to the time involved in choosing an acceptable staging point.

Because Spring Quarter was an elective, there was a 25% reduction in students and a subsequent reorganization within the design teams, which took time and put the design groups on a tight schedule. Refinement of the ascent trajectories was continued, and the areas of stability and control, heat transfer, inlet design, and material selection were investigated. Further refining of the vehicle systems indicated that the ascent trajectory and orbiter weight were the critical elements in weight optimization.

The continuation of the design series to include a second quarter was critical due to the fact that some of the problems that occurred during Winter Quarter were not solved until the Spring Quarter, as well as allowing the students to refine their designs, and allowing more insight into the design process.

VEHICLE DESIGNS

The design groups operated independently and were in friendly competition throughout the design classes. They were encouraged to design different two-stage-to-orbit vehicles while still collaborating between groups to a small extent to aid each other in weak areas.

Although a manned or unmanned vehicle was not specified, both groups automatically used manned orbiters because passengers were assumed. At first, an unmanned carrier was considered, but after considerable debate and inquiries at Wright Patterson Air Force Base and NASA Lewis Research Center it was determined that the workload on the orbiter crew would be too great with preflight checks to allow them to fly the vehicle to the staging point.

Scarlet Group

Length	210 ft
Takeoff Distance	9860 ft
Takeoff Weight	808,210 lb
Staging Altitude	80,000 ft
Staging Mach Number	5.5
Carrier Mission Time	35 min
Carrier Mission Distance	788 mi
Time to Orbit	44 min

The Scarlet Group configuration (Fig. 1) has a takeoff weight of 808,210 lb and stages at Mach 5.5 at 80,000 ft. The primary design concept for the Scarlet Group was to gain orbital altitude and velocity quickly, while keeping the design simple. This led to a typical wing/body carrier, but with the orbiter situated within the rear portion of the carrier fuselage. This location eases the loading process, eliminates the additional drag due to an exposed orbiter, and makes staging safer during separation. Due to the minimum time (and distance) conditions set by the group, the vehicle is overpowered during the ascent trajectory to gain as much acceleration as possible, within engine and human restrictions. Extensive optimization of the ascent trajectory through energy-state methods was conducted to compensate for the overpowered propulsion system. Upon staging, the orbiter executes a full SSME thrust acceleration out of the atmosphere to achieve orbit in a total time of 44 min.

Scarlet Carrier

Length	210 ft
Wing Span	150 ft
Height	69 ft
Panform Area	8000 sq ft
Aspect Ratio	2.81
Fueled Weight	423,250 lb
Propulsion	8 GE Turbofanramjets

The Scarlet carrier (Fig. 2) is a 210-ft-long high delta wing/cylindrical body configuration to allow for simplified analysis and easy manufacturing. The eight liquid hydrogen-fueled, full-scale GE turbofanramjets are located under the wings next to the body in a square "quad-pod" formation. The canards are used during takeoff and landing, as well as during staging to enhance stability and controllability.

Scarlet Orbiter

Length	138 ft
Wing Span	65 ft
Height	13 ft
Planform Area	1311 sq ft
Aspect Ratio	1.5
Staging Weight	385,000 lb
ΔV	19,835 ft/s
Propulsion	1 SSME

The Scarlet orbiter (Fig. 3) is a 138-ft-long low delta wing/body configuration similar to the space shuttle with the exception of retractable canards to be used exclusively for landing. Near the orbital altitude the SSME is throttled back to 65%, eventually cutting thrust altogether for LEO acquisition.

Gray Group

Length	207 ft
Takeoff Distance	13,843 ft
Takeoff Weight	710,000 lb
Staging Altitude	90,000 ft
Staging Mach Number	6.0
Carrier Mission Time	137 min
Carrier Mission Distance	2300 mi
Time to Orbit	71 min

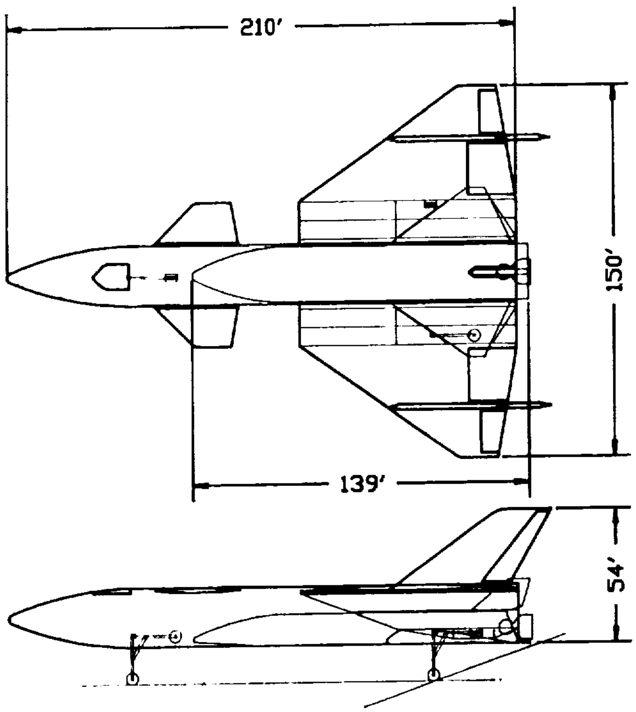

Fig. 1. Scarlet configuration.

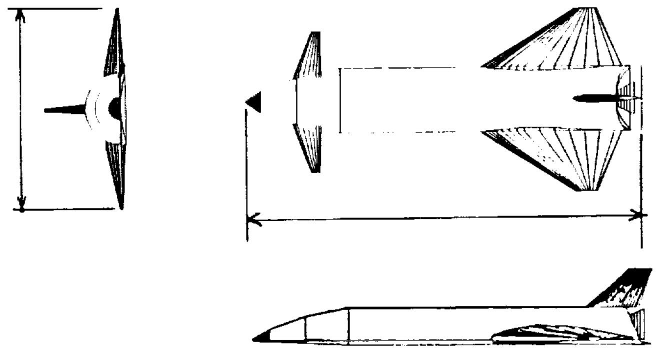

Fig. 3. Scarlet orbiter.

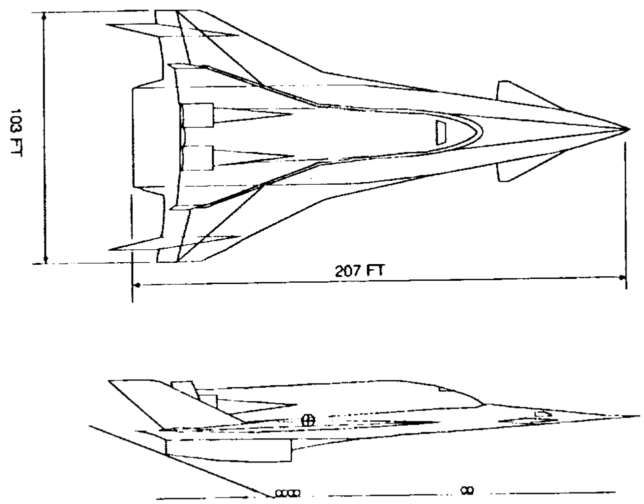

Fig. 4. Gray configuration.

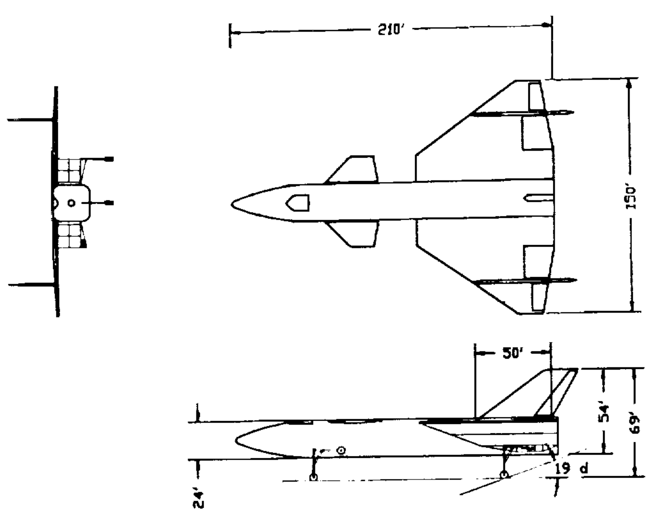

Fig. 2. Scarlet carrier.

The Gray Group configuration (Fig. 4) has a takeoff weight of 710,000 lb and stages at 90,000 ft at Mach 6.0. The Gray Group elected to design a vehicle that achieves orbit with the use of air-breathing engines. This drove the configuration to more of a blended wing/body carrier with the orbiter located in a piggy-back position. This allows the turbofanramjets to be placed together close to the centerline, allowing for a single propulsion module (inlets, engines, and nozzles). Due to the orbiter location, it will be necessary to dive during staging to make a clean and safe separation. In order to accelerate efficiently, the Gray Orbiter utilizes scramjets until Mach 12, decreasing the ΔV requirements for the rocket; thus only a one-half-scale SSME was needed. This decreased the staging weight by 63,000 lb (17%), further reducing the weight of the entire system. While efficient acceleration reduces takeoff weight, it also produces a time to orbit of 71 min.

Gray Carrier

Length	207 ft
Wing Span	103 ft
Height	46 ft
Planform Area	6500 sq ft
Aspect Ratio	1.46
Fueled Weight	390,000 lb
Propulsion	6 GE Turbofanramjets

The Gray carrier (Fig. 5) is a 210-ft-long blended cranked delta wing/body configuration giving a cleaner design. The six liquid hydrogen-fueled, 150%-scaled GE turbofanramjets are

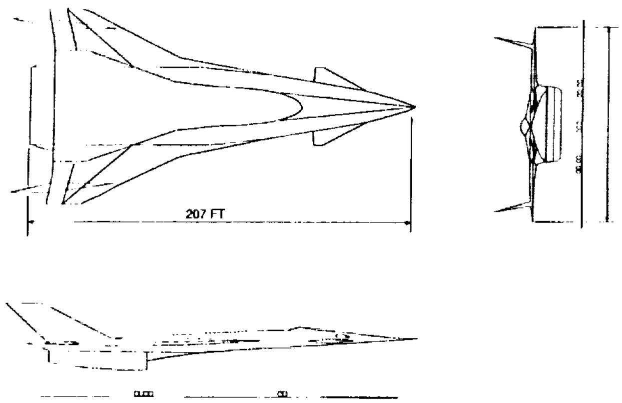

Fig. 5. Gray carrier.

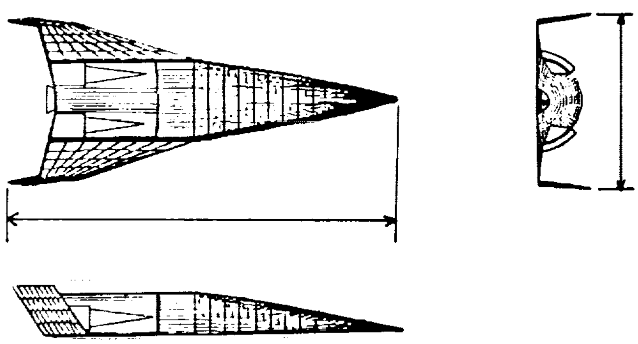

Fig. 6. Gray orbiter.

located in a row at the rear of the aircraft allowing for better engine-out characteristics.

Gray Orbiter

Length	130 ft
Wing Span	61 ft
Height	15 ft
Planform Area	1212 sq ft
Aspect Ration	0.8
Staging Weight	317,000 lb
ΔV	19,288 ft/s
Propulsion	8 GE Scramjets, 1/2 SSME

The Gray orbiter (Fig. 6) is a 130-ft-long low delta wing/half cylinder body configuration with the vertical stabilizers on the wing tips so they are not washed out at high angles of attack. The Gray orbiter employs eight GE scramjets and one-half SSME, which yields a lighter propulsion system because the scramjet oxidizer is not carried on the vehicle. This lowers the required internal volume, which further decreases the structural weight. While a scramjet and one-half SSME propulsion package is more efficient for flight through the atmosphere, lower accelerations are produced, and a longer flight time results.

DESIGN APPROACH

A two-stage-to-orbit vehicle is essentially an accelerator, making optimization for a point along the mission profile (i.e., a cruise phase) unreasonable. Therefore, optimization of the trajectory itself was considered, with the ascent being the crucial phase. Due to the accelerating nature of the mission profile, the constantly changing propulsion and aerodynamic conditions needed to be continually incorporated into the ascent profile. The following sections outline different technical aspects covered during the design process.

Propulsion

To produce an acceptable propulsion system, an engine and fuel must be matched over the required flight regime. Figure 7 shows a mass and volumetric energy density comparison for various fuels for air-breathing engines. Methylcyclohexane (MCH) is advanced endothermic fuel that breaks down into toluene and hydrogen just prior to combustion. While liquid hydrogen has a high mass energy density, a penalty is incurred due to its low volumetric density. Due to the short ranges and flight times of the vehicles there were no real volume constraints, and since weight minimization was necessary, both groups chose liquid hydrogen as a fuel for both the carrier and orbiter.

With the fuel chosen, an engine unit capable of operating over the desired mission must be employed. Figure 8 shows the performance for several candidate engines, and it is seen that the propulsion characteristics for a vehicle that operates over a large range of Mach numbers is discontinuous in nature. Because of this, the propulsion system was the final driver in the determination of the staging point.

Carrier. Since high staging Mach numbers were desired, a combination of an efficient turbofan for the subsonic and low supersonic flight regimes and a ramjet for the high supersonic and hypersonic flight regimes was chosen. Higher staging Mach numbers would be desirable to minimize orbiter weight, but the addition of another separate scramjet module was not worth the weight, drag, or complexity penalties.

The three typical turbofanramjet configurations are shown in Fig. 9: wrap-around, over/under, and tandem. Since both carriers are inherently long and thin for supersonic flight, a tandem turbofanramjet configuration was chosen by both teams due to its higher slenderness ratio (length/diameter).

General Electric provided a performance database for a turbofanramjet scheduled for entry in 2005 (Fig. 10). The performance data were given for a full-scale engine with scaling limits of 65% to 150%. The Scarlet carrier uses eight full-scale engines and the Gray carrier uses six 150%-scale engines.

Figure 11 gives the net thrust (ram drag is included) as it varies with Mach number and altitude for the full-scale turbofanramjet. The engine data assume a mil-spec inlet and nozzle. While complete inlet and nozzle designs were not completed due to time constraints, it was determined that the mil-spec requirements could be met.

Orbiter. The staging point had a significant effect on the orbiter weight. While staging altitude was a factor, the staging Mach number had the greatest impact on the orbiter weight due to the ΔV required to get to the orbital velocity of 25,400

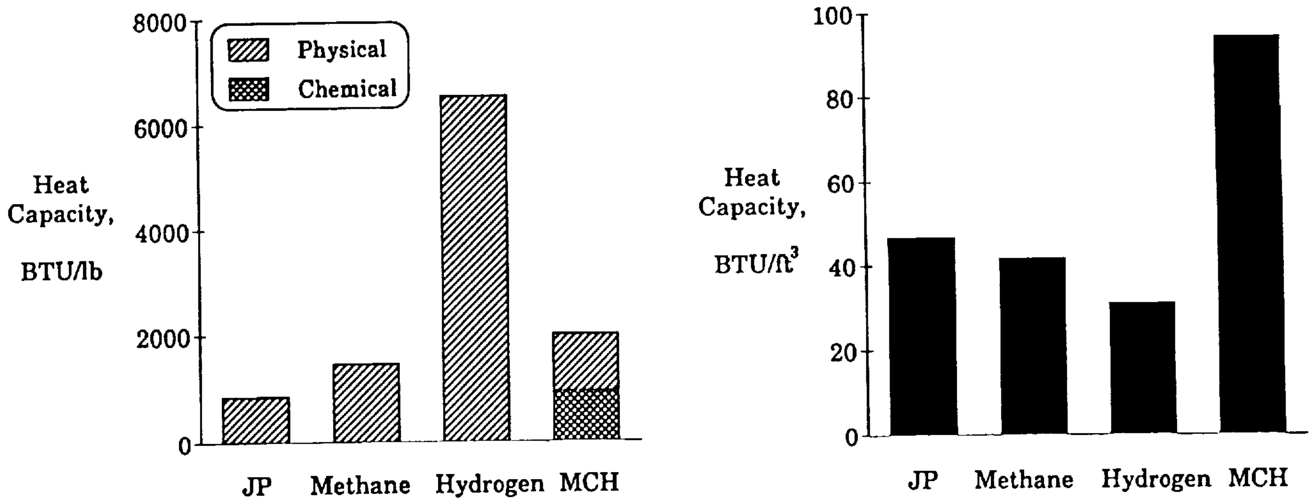

Fig. 7. Fuel comparison.

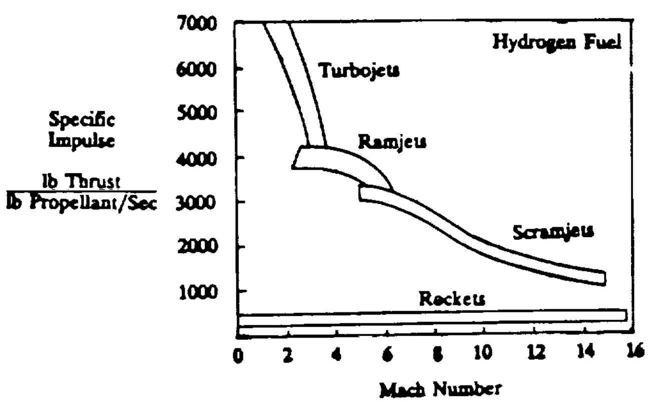

Fig. 8. Engine performance.

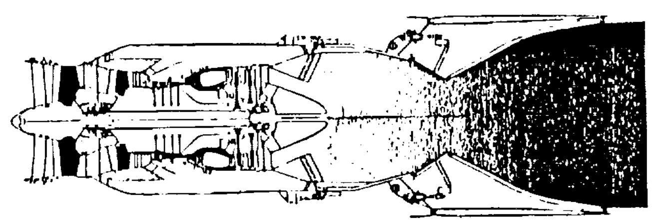

Fig. 10. G.E. turbofanramjet.

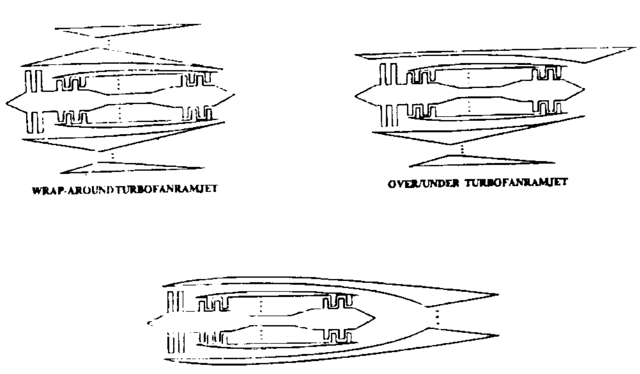

Fig. 9. Turbofanramjet concepts.

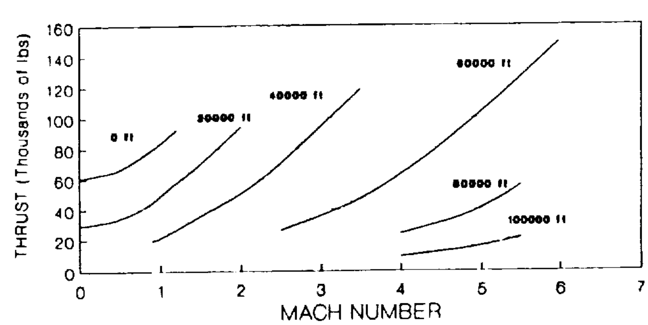

Fig. 11. Thrust vs. Mach number.

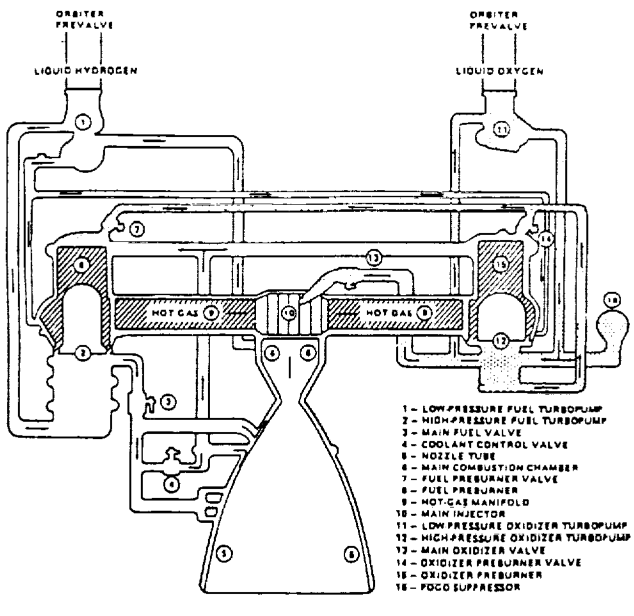

Fig. 12. SSME schematic.

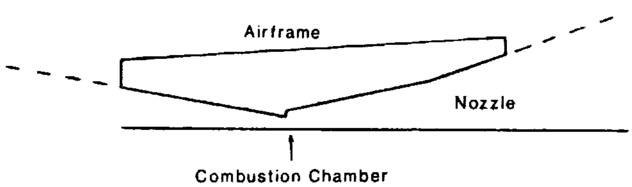

Fig. 13. Scramjet module.

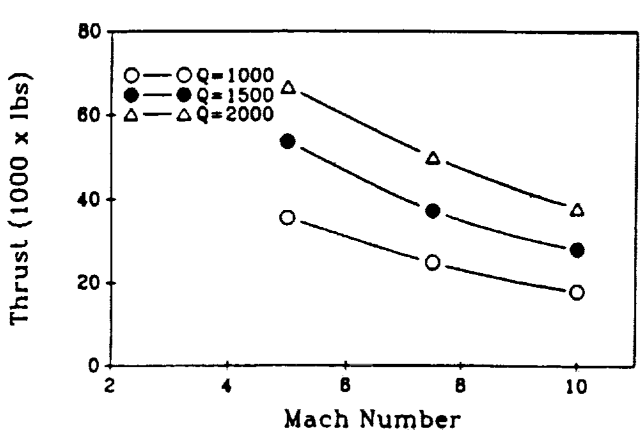

Fig. 14. Scramjet performance.

ft/s. ΔV is the main driver in the fuel weight, which accounts for about 80% of the orbiter staging weight.

Since LEO was the final destination, a rocket propulsion unit is required to accelerate through space. Due to the availability of performance and weight data, as well operational verification, both orbiter teams originally chose the liquid hydrogen/liquid oxygen-fueled SSME, schematically shown in Fig. 12. A full-scale SSME produces 470,000 lb of thrust in a vacuum. The SSME is throttled at 109% sea level thrust from ignition to near LEO, where it is throttled back to 65%. Prior to achieving orbit, the SSME is shut down and the orbiter acquires LEO with minimum thruster control.

The Gray orbiter team decided to use scramjets (Fig. 13) in order to minimize the fuel (specifically the oxidizer) use by the SSME. By accelerating to Mach 12 using scramjets, the ΔV for the SSME was reduced from 19,288 ft/s to 13,364 ft/s allowing the SSME to be scaled down by 50% in thrust and weight.

The scramjet performance data was provided by General Electric and is given in Fig. 14. The Gray orbiter team uses eight scramjets to accelerate to Mach 12 then a one-half scale SSME to achieve orbit. This propulsion system did have its penalties in the added weight and complexity of inlets and nozzles for the scramjets, an active thermal protection system, as well as a greater technology risk. Inlets for the scramjets were investigated, and a single, fixed ramp, supersonic inlet (no throat) was chosen over a movable ramp system. This was because the slight improvements in efficiency of the variable ramps did not outweigh the associated weight, length, and complexity penalties. A weight reduction of 63,000 lb (17%) was realized due to using an eight scramjet/one-half scale SSME propulsion system instead of a single full-scale SSME.

Aerodynamics

The aerodynamic analysis of the vehicles was accomplished through a variety of techniques including (but not limited to): component drag build up, comparison with similar experimental results, shock-expansion theory, and subsonic potential theory.

Carrier. A typical drag polar for both carriers is shown in Fig. 15. Notice that the highest drag coefficients occur at Mach 1.1. This drove the propulsion system to be scaled for the transonic flight regime. The low drag coefficients occurring at Mach 6 are the result of the generally sleek configuration suited for high supersonic flight.

Orbiter. As seen in Fig. 16, the typical lift and drag coefficients do not change drastically for the ascent from staging to orbit. The aerodynamic characteristics of the Gray orbiter influence its shape more than the Scarlet orbiter for two reasons: the Gray orbiter accelerates through the atmosphere using scramjets, and upon ascent from takeoff it is exposed to the freestream riding piggy back on the Gray carrier, whereas the Scarlet orbiter quickly accelerates out of the atmosphere, and is housed within the fuselage of the Scarlet carrier upon ascent.

Stability and control

Stability and control was one of the final sections of the vehicle designs considered by the two design groups. Longitudinal static stability was determined for three critical points in the mission: takeoff, staging, and landing. In addition to the stability and control problems associated with takeoff and landing operations, a two-stage-to-orbit vehicle must execute a staging maneuver. With Stability Augmentation Systems (SAS) available, static stability at staging is not a requirement, but controllability is. Fuel management systems help stability by controlling the center of gravity travel, which in turn reduces the trim drag of the vehicle.

While it is acceptable for a hypersonic aircraft to be unstable at some point along the mission profile, a two-stage-to-orbit vehicle has a special problem as there is a sudden abrupt movement of the center of gravity upon staging. This center of gravity shift is not only in the longitudinal direction, but also in the vertical direction (Fig. 17). This affects longitudinal, lateral, and roll controllability, and therefore it is necessary to know the amount of control necessary during the staging maneuver. While the vehicles are statically stable at all points along the mission profile, including before and after staging, a dynamic stability analysis was not completed for the staging maneuver.

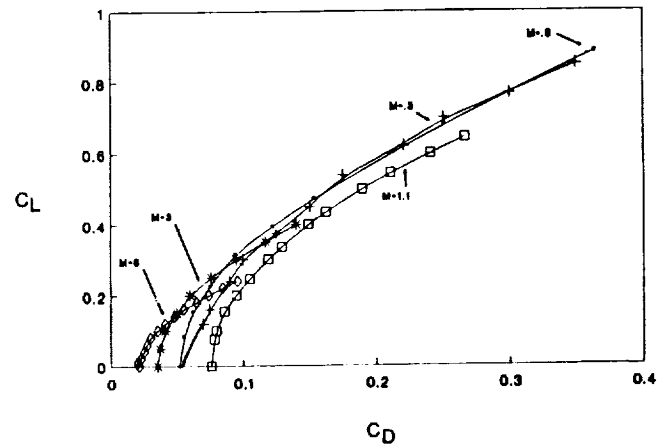

Fig. 15. Carrier C_L vs. C_D.

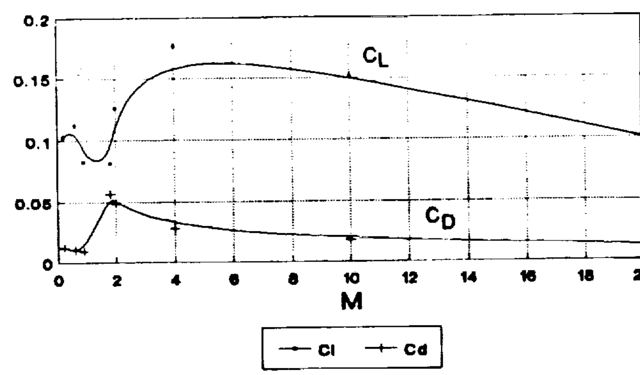

Fig. 16. Orbiter C_L and C_D vs. M.

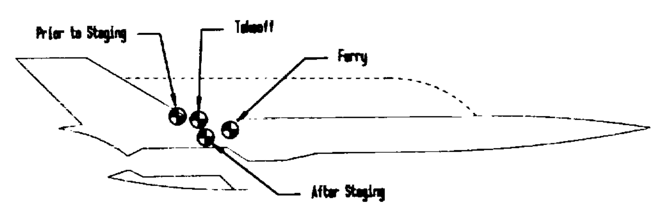

Fig. 17. Center of gravity travel.

Trajectory

Incorporating constantly changing aerodynamic and propulsion models into a specific trajectory that does not lend itself to optimization was indeed difficult. The ascent trajectory was found to be a strong force in the takeoff weight of the system due to the fuel burned during accelerating ascent. The staging point was found to be the main driver in the weight of the orbiter due to the ΔV needed required to achieve LEO. Parametric studies were conducted to show the effect of staging altitude and Mach number on the weight of the vehicle. It was found that the staging altitude had only a slight effect on the vehicle weight, whereas the staging Mach number had a significant effect, especially on the orbiter weight. As the staging Mach number increased, the carrier weight increased and the orbiter weight decreased, but the carrier weight increased at a slower rate than the orbiter weight decreased; thus, the system takeoff weight decreased for increasing staging Mach numbers. In the end, the staging Mach number was specified by the maximum speed of the propulsion unit.

Carrier. Both carrier teams followed similar flight profiles (Fig. 18) typical of two-stage-to-orbit vehicles: take off, accelerate and climb towards Mach 1, punch through the transonic regime, accelerate until a specified constant dynamic pressure (q) is attained, follow this constant q until the staging point, stage at the specified Mach number and altitude, then descend and possibly cruise at a maximum lift-to-drag ratio until landing. Both groups chose a maximum q of 1500 psf based on research into similar conceptual hypersonic vehicles. The Gray carrier team simply iterated on the trajectory profile until a minimum fuel-to-stage was obtained.

The Scarlet carrier team chose to optimize the entire trajectory profile up to the constant q intersection using energy-state methods (Figs. 19 and 20). The set of curves in Fig. 19 represent constant total energy levels (kinetic plus potential energy). The contour plot in Fig. 19 is excess power of the aircraft, which shows exactly where the vehicle can accelerate, climb, or a combination of both. By flying through the set of points where a constant energy curve is tangent to an excess power contour, a minimum-fuel-to-climb trajectory is obtained.

By further defining specific excess power as excess power divided by thrust and specific fuel consumption, the thrust pinch is seen to occur at Mach 1.6 (Fig. 20). The vehicle is actually flying from the subsonic excess power region to the supersonic excess power region. If the excess thrust (thrust-drag) is decreased, a bottleneck is produced between these two excess

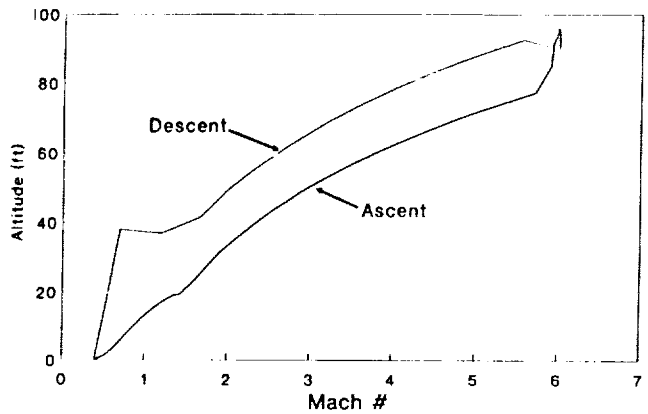

Fig. 18. Mission acceleration.

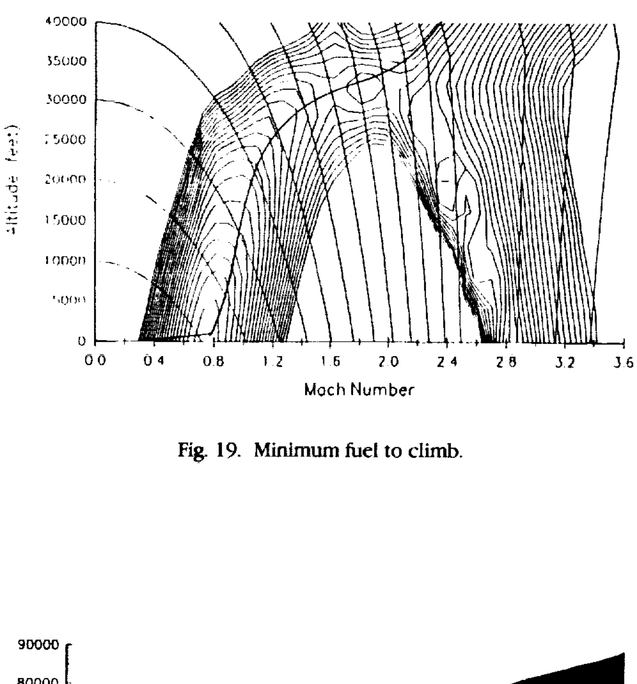

Fig. 19. Minimum fuel to climb.

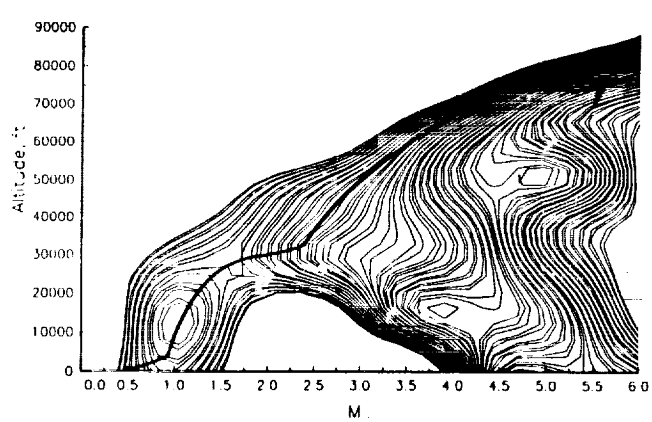

Fig. 20. Specific excess power.

power regions, and a further decrease in excess thrust completely separates the two regions. When this occurs, it becomes impossible to traverse the transonic flight regime.

Once staging occurs (the carrier and the orbiter actually separate), the carrier undergoes an instantaneous weight reduction of roughly 50%, causing the net lift of the carrier to dramatically increase. This, coupled with the stability fluctuations during staging due to the center of gravity shift, causes the staging process to be potentially precarious.

The Gray Group starts staging at Mach 6.0 at 90,000 ft, then dives while staging to avoid a collision with the released orbiter mounted on the carrier upper surface. The Scarlet Group stages at Mach 5.5 and 80,000 ft and avoids the collision problem by releasing the orbiter out from under the carrier, allowing the increase in net lift to pull the carrier up and away from the orbiter.

After staging, both carriers then descend on another constant q line that will maximize range. The Scarlet carrier will land in Florida, and the Gray carrier returns to the original takeoff location (Fig. 21).

Orbiter. Both the Scarlet orbiter and Gray orbiter design teams used ENTRAN (Entry Trajectory Analysis Program) provided by Wright Patterson Air Force Base. The code specifies a final condition on orbital altitude, speed, and weight, and then backs down an ascent trajectory. The propulsion parameters are then changed to intersect the trajectory at the desired point (i.e., the staging point).

The Scarlet orbiter uses a full-scale SSME, and therefore backed down the ascent trajectory from ENTRAN to intersect the staging point. The Scarlet orbiter mission profile consists of a 109% thrust SSME burn, throttle down to 65% thrust, and then cut thrust just before orbit is achieved in order to coast into the orbital altitude with minimum use of control thrusters. The Gray orbiter uses scramjets to accelerate and climb to Mach 12 and 150,000 ft, thus backs down the ENTRAN ascent trajectory to this point. There it initiates a full burn of the one-half-scale SSME, then cuts thrust to coast into LEO. Figure 22 shows a comparison of the two orbiter ascent trajectories.

Both orbiters execute similar reentry maneuvers by skipping off the atmosphere (Fig. 23). These reentry trajectories were also computed by ENTRAN. As the loads on the orbiter exceed a specified level the orbiter "skips" to a higher altitude losing kinetic energy and radiating heat, then descends again with decreased kinetic energy, repeating this procedure until a complete reentry into the atmosphere can be executed.

Weight

The structural weights of the vehicle were computed by comparison with similar vehicles designed by NASA, industry, and academia. The carrier design teams kept their structural weight percentage in line with similar vehicles at approximately 35% of the fully fueled carrier alone weight (no orbiter). Similarly the orbiter structural weight was approximately 10% of the staging weight. The Scarlet orbiter team went on to verify their structural weight on a component basis. By taking a survey of five similar orbiter vehicles, they were able to obtain an average

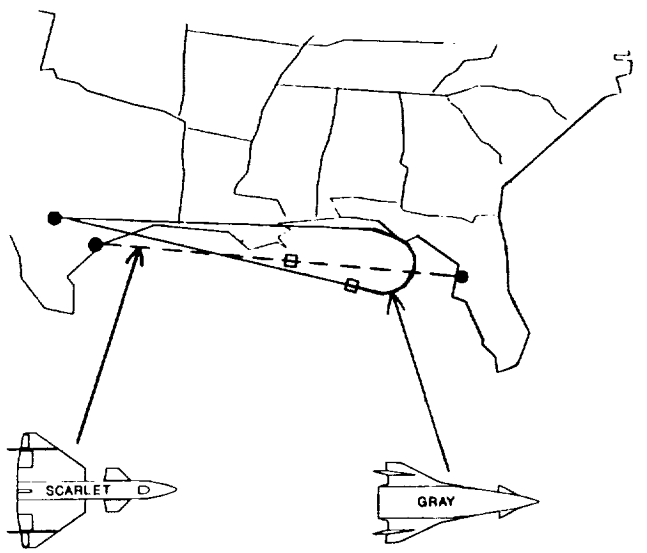

Fig. 21. Mission courses.

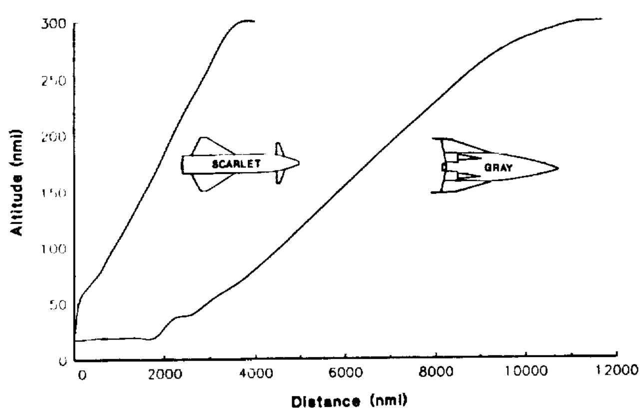

Fig. 22. Orbiter trajectories.

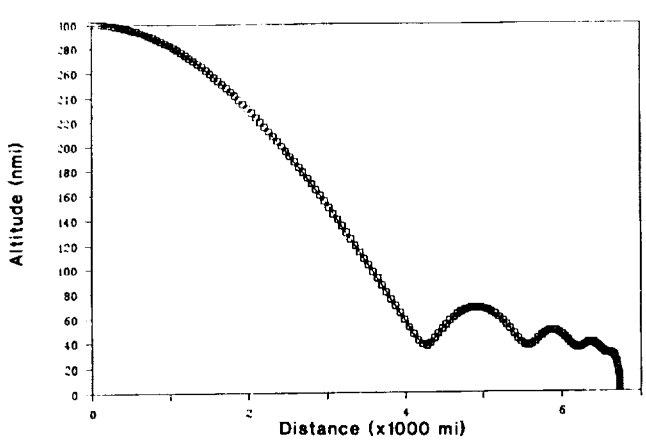

Fig. 23. Reentry trajectory.

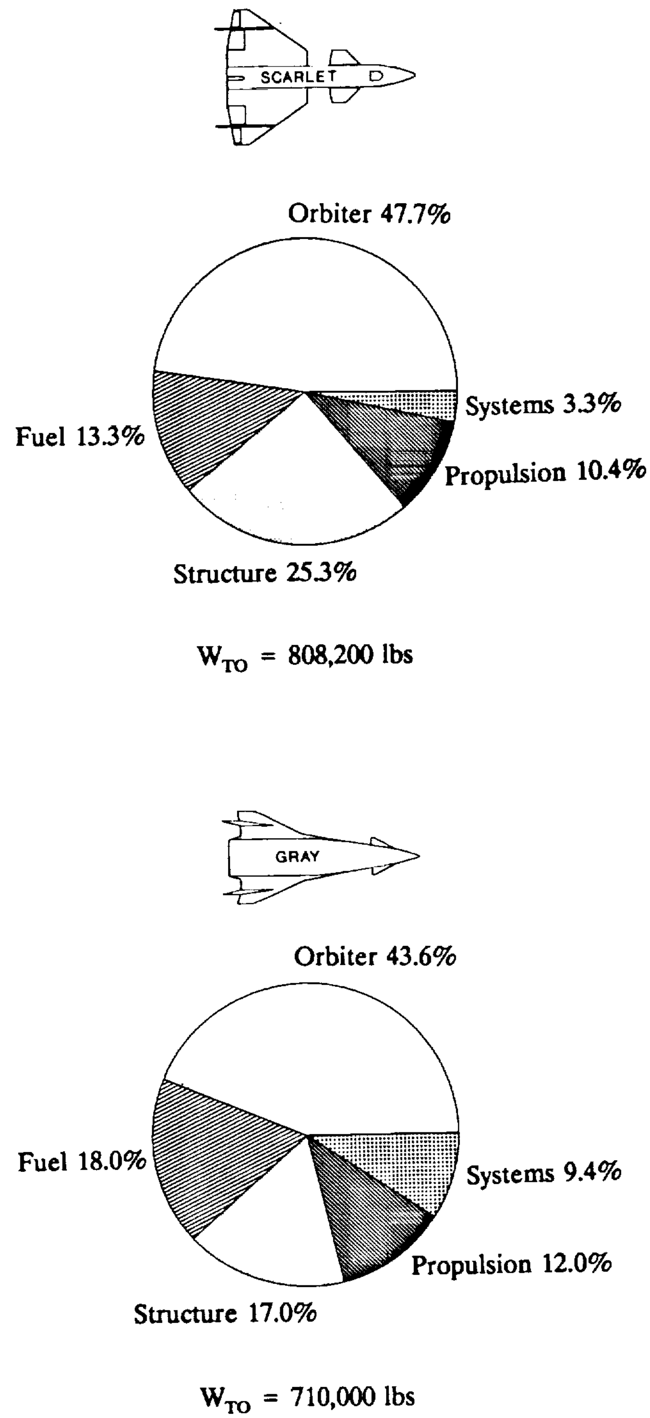

Fig. 24. Carrier weights.

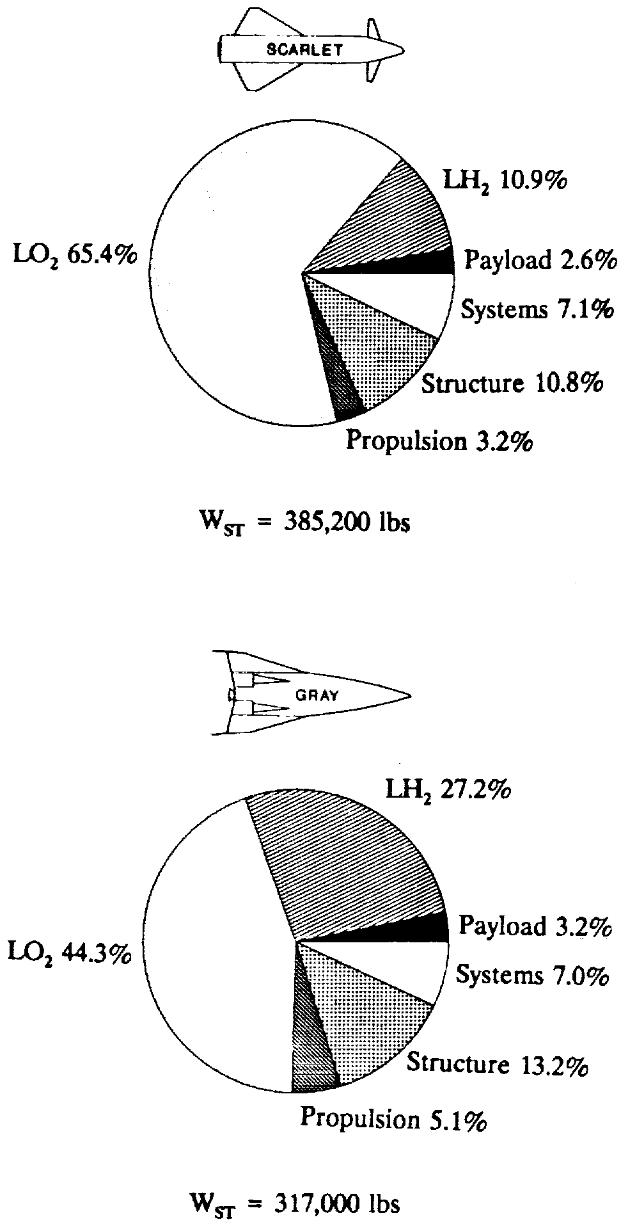

Fig. 25. Orbiter weights.

weight per area for different components (i.e., wings, fuselage, etc.) of their orbiter. They found that the original weight percentage estimation was indeed valid. Figures 24 and 25 show the carrier and orbiter weight comparisons, respectively.

The orbiter staging weight was the most significant single weight of the vehicle. Small changes in the orbiter weight produced larger changes in the system weight because the orbiter is essentially the payload of the carrier. The primary driver in the orbiter weight is the staging-to-burnout mass ratio, a strong function of staging Mach number due to the ΔV to a fixed 25,400 ft/s orbital velocity (Fig. 26).

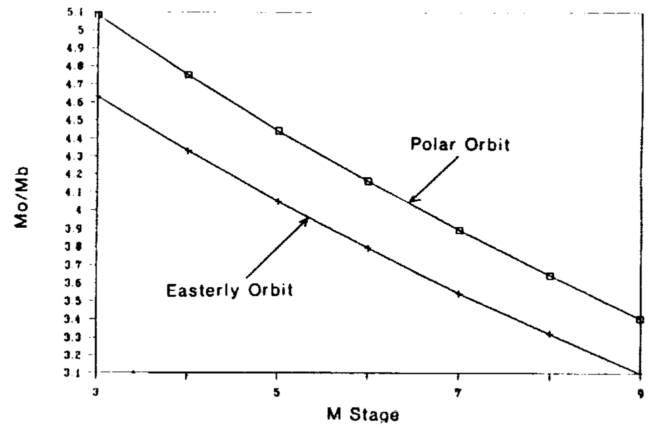

Fig. 26. Mass ratio vs. staging Mach number.

PRACTICAL EXPERIENCE

The OSU hypersonic design class is set up to give the participating students a taste of the "real world." Until this design series, the students never worked together on different parts of the same project, only on the same homework assignments as their classmates. Not only does the design team approach demonstrate the technical compromises of aircraft design, but also the personal interactions that are associated with working in a group. This academic year's project had a two-tier organization within each group; the students worked together as design teams, and the carrier and orbiter teams interacted together to form the design group. Because there was no project leader for each design group, the individual design teams compartmentalized their efforts, with the carrier and orbiter teams in each group unaware of what the other was doing. This was alleviated by the Graduate Teaching Assistant (GTA) assuming the position of project leader for both design groups. This allowed the GTA to subtly direct the projects, while still having the students actually design the vehicles (i.e., no heavy-handed intervention).

TABLE 1. Vehicle comparisons

Length	210 ft	207 ft
Wing Span	150 ft	103 ft
Planform Area	8000 sq ft	6500 sq ft
Carrier Weight	423,200 lb	390,000 lb
Orbiter Weight	385,000 lb	320,000 lb
Takeoff Weight	808,200 lb	710,000 lb
Carrier Propulsion	8 TFRJets (100%)	6 TFRJets (150%)
Orbiter Propulsion	1 SSME	½ SSME & 8 Scramjets
Staging Mach Number	5.5	6.0
Staging Altitude	80,000 ft	90,000 ft
Orbiter ΔV	19,835 ft/s	19,288 ft/s
Carrier Mission Time	35 min	137 min
Time to Orbit	44 min	71 min

SUMMARY

Two complete designs of a conceptual two-stage-to-orbit vehicle have been developed by two independent student design groups. Table 1 provides a direct comparison of the two vehicles.

These vehicles were designed as a complement to the current U.S. space program, which is heavily dependent on the space shuttle. A two-stage-to-orbit vehicle is seen as a compromise between the operating costs of a next-generation heavy lift rocket system and the technical obstacles of a single-stage-to-orbit vehicle.

The most notable contrast between the two vehicles is the almost 100,000-lb difference in takeoff weight. This is primarily due to the larger weight of the Scarlet orbiter, which must accelerate over a larger ΔV, using a less efficient propulsion system (all rocket). This produces a greater staging weight due to the amount of fuel burned, and a larger orbiter staging weight produces a larger "payload" weight for the carrier, thereby increasing the weight (and size) of the Scarlet carrier.

While there are still questions to be addressed pertaining to two-stage-to-orbit vehicles, this design project was well worth the effort of the students, providing them with insight and instruction into the conceptual design process.