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A Trade Study on the Effects of Augmentation on Two Single-Stage-To-Orbit (SSTO) Vehicle Concepts

by

Mark Andrew Johnson

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I. Abstract

This thesis presents the results of studies conducted to determine the effects of augmentation, in the form of modern, expendable, strap-on boosters, on two rocket single-stage-to-orbit (SSTO) concept vehicles. The first vehicle considered was a winged-body rocket SSTO concept from NASA's Access-To-Space study, designed to deliver a 25,000 lb payload to the International Space Station (220 nmi circular, 51.6° inclination orbit). Augmentation was used to increase payload capability, increase weight growth margin, decrease payload costs (per pound), and compensate for less advanced material technologies. The second vehicle was a scaled down version of the first vehicle, functioning as an advanced technology demonstrator (ATD), capable of carrying 2000 lb to a 100 nmi circular orbit. Augmentation was used to reduce the scale of the vehicle. This resulted in the ability to fly the unaugmented vehicle sub-orbitally for initial tests, then use augmentation to reach orbital levels. A potential for reduced operational costs is gained due to the reduction in core vehicle dry weight and propulsion requirements.

For both vehicle concepts, three different expendable, strap-on boosters, representing solid, liquid, and hybrid propulsion, were used. They were the Castor IV-A, the Ariane L40 (PAL), and the AMROC H-1800 (prototype), respectively. The goal was to demonstrate that augmentation can provide benefits to current rocket SSTO designs, and to determine which booster was best suited to this application. Various levels of augmentation were tested for each of the SSTO concepts.

For the first vehicle, payload increases of up to 70% were gained with the Castor, 95% with the L40, and 67% with the H-1800. Weight growth margin was increased up to 26% with the Castor, 30% with the L40, and up to 25% with the H-1800. The payload cost analysis was performed using core vehicle operational cost estimates from Space Shuttle, Shuttle II, and Access to Space analyses. The benefits from augmentation depended on the cost per baseline flight. The Access to Space estimate was the lowest used

in this study. At this level, the Castor IV-A delivered reductions of up to 34%, while the H-1800 provided up to a 27% reduction. The L40 provided little or no reductions at this level. Finally, it was determined that augmentation can be used to compensate for less advanced material technologies in most of the vehicle's primary subsystems.

For the second vehicle, reductions in vehicle dry weight of up to 15% were achieved. However, this was not enough to reduce engine requirements by at least an integer level, thus without a detailed cost analysis, it is inconclusive whether augmentation will definitely reduce operational costs for this vehicle.

II. Acknowledgments

I would like to thank the people of the Vehicle Analysis Branch at the NASA Langley Research Center for the opportunity to pursue this project and for all their help and support. I would especially like to thank Dr. Ted Talay for serving as my NASA advisor, Bobby Braun for helping me learn POST, Roger Lepsch for his help with weights and sizing, Walt Engelund for his help with aerodynamics, and Arlene Moore for her help and advice on cost analysis. I would also like to thank Garry Qualls for his memorable lunch time adventures and his never-ending belief that I would never finish this project.

Special thanks go to my family and friends, especially my parents, for their moral support.

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V. Nomenclature

AMROC	American Rocket Company
APAS	Aerodynamic Preliminary Analysis System
ATD	Advanced Technology Demonstrator
CONSIZ	Configuration Sizing Program
GLOW	Gross Lift-Off Weight
HRM	Hybrid Rocket Motor
ISS	International Space Station
KSC	Kennedy Space Center
LaRC	Langley Research Center
LEO	Low Earth Orbit
LRM	Liquid Rocket Motor
NASA	National Aeronautics and Space Administration
OMS	Orbital Maneuvering System
POST	Program to Optimize Simulated Trajectories
SRM	Solid Rocket Motor
SSME	Space Shuttle Main Engine
SSTO	Single Stage To Orbit
SSV	Single Stage Vehicle
TPS	Thermal Protection System
TSTO	Two Stage To Orbit
VAB	Vehicle Analysis Branch
VTHL	Vertical Take-off Horizontal Landing
WB-001	Winged Body 001 Vehicle Design

1. Introduction

While the space industry continues to expand, launching an increasing number and variety of payloads into orbit, there is a recognized need for a new, reliable, and affordable launch system. In an effort to find a potential successor to the aging Shuttle fleet, NASA conducted the Access to Space study. The study was conducted to determine the best long-term option for future reusable space transportation systems. It defined requirements for these systems based on our current national policy, which was in turn based on budgets, world conditions and situations, and user needs. The requirements were broken down into two major groups - mission requirements and vehicle requirements. Mission requirements dealt with issues such as payload size and mass, target orbit, mission frequency (flight rate) and duration, and whether or not to have manned or unmanned capability. The vehicle requirements were concerned with how the vehicle would be designed. Whether it should be operations driven or performance driven, how robust (weight margin) it should be, the degree of reliability required, and safety/abort requirements were all matters for investigation. The primary mission defined by the study was that of resupplying the upcoming International Space Station (25,000 lb to 220 nmi circular orbit, 51.6° inclination).

The study investigated a variety of vehicle concepts such as rocket two-stage-to-orbit (TSTO) (of varying degrees of reusability), rocket single-stage-to-orbit (SSTO), combined rocket/airbreather air launch, combined two-stage, and combined single stage vehicles. Each system was compared based on how it satisfied the mission and vehicle requirements.

The airbreathing and combined rocket/airbreathing systems were eliminated because, although the estimated operations requirements of the airbreathing systems were similar to those of the rocket systems and despite some advantages in mission capabilities, there was less technical risk and complexity associated with the rocket systems owing to the wealth of knowledge and experience accumulated over time.

Another particular area of controversy which started before the Access to Space study was conducted and continues today is that of two-stage versus single-stage rocket systems. Proponents of TSTO systems point out that these vehicles exhibit lower gross and dry weights and lower sensitivity to weight growth compared to SSTO vehicles. They also claim that TSTO vehicles can accommodate larger payload class missions, have the potential for larger weight growth margins, and can easily utilize lower-risk technologies. SSTO vehicles, on the other hand, avoid the added complexity of developing, manufacturing, and operating two dissimilar vehicles, eliminate duplication of vehicle subsystems, and are not concerned with the integration and separation complexities inherent in TSTO systems. If advanced levels of technology can be utilized, the differences in weights between SSTO and TSTO systems become less of an issue. The sum of development and operational costs, the life-cycle cost, becomes more important. SSTO systems may then be more cost effective than TSTO systems. With existing technology levels, however, SSTO would suffer from increased development risk, reduced margins and robustness, and limited safety features for the crew (if there is one).

The conclusions of the Access to Space study were that fully reusable, rocket SSTO should be the goal for the nation's future reusable launch system. It exhibited low recurring costs if designed for operational efficiency. The study also concluded that the rocket SSTO would only be successful from an operations, reliability, and safety point of view if advanced subsystem technologies (e.g. lightweight materials, structures, and propulsion systems) are made available.

Of the vehicle concepts examined in the Access to Space study, one design, created by the Vehicle Analysis Branch (VAB) of NASA's Langley Research Center, became the preferred option. It is a winged-body SSTO, taking off vertically and landing horizontally (VTHL). It is expected to have a dry weight of just over 200 klb and from the outside looks very much like a scaled-up version of the Space Shuttle orbiter. To perform its mission, the design incorporates many new technologies such as Al-Li propellant tanks, composite structures, advanced TPS, and tripropellant propulsion. Use of these is deemed necessary to achieve the mass fraction required for a SSTO of its size. The government / aerospace industry X-33 program was initiated to help validate these technologies. A small scale version of this SSTO vehicle (or a similar concept), the X-33 advanced technology demonstrator (ATD), is planned.

Typical questions that might be asked are: "Could this single stage vehicle (SSV) be used to perform other missions in addition to being used for the Space Station?," or "How much will it cost to demonstrate these new technologies?," or "What happens if the required levels of technology cannot be met or are prohibitively expensive?" It is proposed for this thesis that augmentation of the rocket SSV (either the full scale SSTO or the smaller ATD), in the form of expendable strap-on boosters, is a potential answer to these questions and can serve as an intermediate step between multi-stage and single-stage rocket systems.

Using augmentation for these types of applications is not a totally new idea. Investigation of the use of strap-on, rocket augmentation to enhance the performance of reusable launch vehicles began back in 1985 with the Shuttle II family of vehicle concepts. This analysis was also conducted by the Vehicle Analysis Branch at NASA LaRC. For part of the Shuttle II study, strap-on rocket boosters (expendable solid and reusable liquid) were used on a vertical takeoff rocket SSV to increase the vehicle's payload capacity, allowing it to deliver a 39,000 lb space station module to low earth orbit (LEO). Without the augmentation, the vehicle could carry a 20,000 lb payload to LEO for space station servicing.

Augmentation was also analyzed as part of a technology demonstrator version of a LOx/LH$_2$ SSV designed during the Access to Space study that used SSME derivatives. Augmentation was used to reduce the vehicle's scale and propulsion requirements, which can lead to lower development and operations costs.

Until now, no detailed analysis had been performed using augmentation on the current tripropellant rocket SSTO vehicle designed by VAB, nor have there been any attempts to determine the economic viability of such a design. The analysis described in this thesis increases the general knowledge on how augmentation can enhance the capabilities of SSTO vehicles, and specifically how it increases the flexibility of the winged-body SSV designed by VAB.

Objectives and Approach

The primary goal of this study was to show that augmentation, in the form of strap-on rocket boosters, can be used to enhance the performance of two current SSTO vehicle concepts. The applications for augmentation investigated in this study were increasing payload capability, reducing payload costs (per pound), increasing weight growth margin, compensating for immature or unfeasible material technologies, and reducing core vehicle scale. Three different strap-on boosters, the Castor IV-A, Ariane L40, and AMROC H-1800, representing solid, liquid, and hybrid propulsion, respectively, were used and their effects on each vehicle compared against each other.

The two SSTO vehicle concepts analyzed are products of the NASA Access to Space study. The first vehicle analyzed was designed largely by the Vehicle Analysis Branch at NASA Langley Research Center. It is a winged-body, VTHL concept, utilizing tripropellant propulsion, and is referred to as WB-001. It is designed to deliver a 25,000 lb payload to the International Space Station at a 220 nmi, 51.6° inclination orbit. The second vehicle is a scaled-down version of the first vehicle intended to serve as an advanced technology demonstrator (ATD). It can carry 2,000 lb to a 100 nmi, 28.5° inclination orbit.

Increasing a vehicle's payload capacity is perhaps the most obvious application of thrust augmentation with strap-on boosters. This analysis was performed on the full-scale, WB-001 vehicle. The analysis is important because the WB-001 has a significantly lower payload capability than the Space Shuttle (25 klb vs. ~40 klb at 51.6°), which it may ultimately replace. Currently, the only other U.S. launch system with the Space Shuttle's level of payload capacity is the Titan 4 family of launch vehicles (39-48 klb for Titan 4 vs. 55 klb for Shuttle at 28.5°). It is generally prudent to have more than one launch vehicle option for a particular class of payloads in the event of a launch vehicle failure or stand-down. By increasing the payload capability of the WB-001, added mission flexibility is created (since the vehicle can now capture missions which were previously beyond its performance abilities). In turn, this creates a level of launch system redundancy in the case that the Titan 4's are unavailable.

Augmentation also creates the opportunity to lower the cost (per pound) of flying a payload on the SSV. This application has obvious benefits as it would make it more affordable to launch heavier payloads (or groups of lighter payloads). This analysis was not performed in the past studies of augmentation mentioned above because of a lack of accurate figures of vehicle operational costs. Reliable cost figures still don't exist, and probably won't until the vehicle is actually built, but estimates have been made for the Access to Space vehicles and the Shuttle II concepts. Average operational cost figures also exist for the Space Shuttle. These figures were used in the cost analysis performed in this thesis and show the trends in payload costs as augmentation is added. From this analysis, it will be seen whether or not added augmentation provided decreased costs (per pound), or if there is a limit to the benefits that can be gained from strap-on boosters.

Other new analyses were performed dealing with the advanced material technologies required to make the SSTO concepts possible. As an alternative to increasing payload capability, analysis was performed to translate the performance gains from augmentation into increases in the core vehicle's weight growth margin - the percentage of the vehicle's dry weight allocated to accommodate weight growth during development and construction. SSV's are very sensitive to any weight growth and thus SSTO concepts are often designed using optimistic weight growth margins. Use of augmentation could allow a more conservative margin to be used while still maintaining the current level of vehicle performance. The effects of lower levels of material technology were also determined to see if augmentation can be employed as a way to compensate for immature or unfeasible subsystem material technologies. If some subsystems were forced to grow in weight due to heavier materials, the weight of the complete vehicle might grow to a point where its performance could suffer or where the design could become unfeasible. Augmentation would allow the vehicle to still be built and retain the current level of performance despite a higher than expected vehicle weight.

All of the analyses described above were performed on the WB-001 vehicle. Augmentation was also analyzed with an advanced technology demonstrator (ATD) concept and was used to reduce the scale (size and weight) of the vehicle. This smaller, lighter vehicle would also have lower propulsion requirements (propellant and engines). Dry weight and engine requirements are factors in determining the development and operational costs of a launch vehicle. The ATD vehicle is intended to validate the SSTO concept and prove many of the advanced materials necessary to make the full-scale vehicle a viable option, therefore, any reduction in costs that can be achieved through using augmentation could allow more test flights to be conducted or a lower overall program cost to be achieved.

To perform the analysis, several computer based tools were used. Trajectory calculations were performed by POST (3-d version) (Appendix G) [3]. APAS (Appendix I) [11] was used to generate estimates of aerodynamic drag for each of the boosters used. Weight and sizing analysis was accomplished using CONSIZ (Appendix H) [6]. All of these tools are typically used in an iterative loop when developing new vehicle concepts. The analysis procedure varied slightly between the two vehicles due to different testing objectives. The WB-001 vehicle is a fixed design, and thus augmentation was used to increase the capabilities of the existing vehicle, not to design an entirely new vehicle. Some resizing was performed on this concept, however, as will be explained later. The objective in analyzing the ATD vehicle was to reduce the scale of the vehicle in order to ultimately reduce development costs. Thus, a new design was effectively generated with each level of augmentation. Figure 1 illustrates the flow of the analysis procedure for each vehicle.

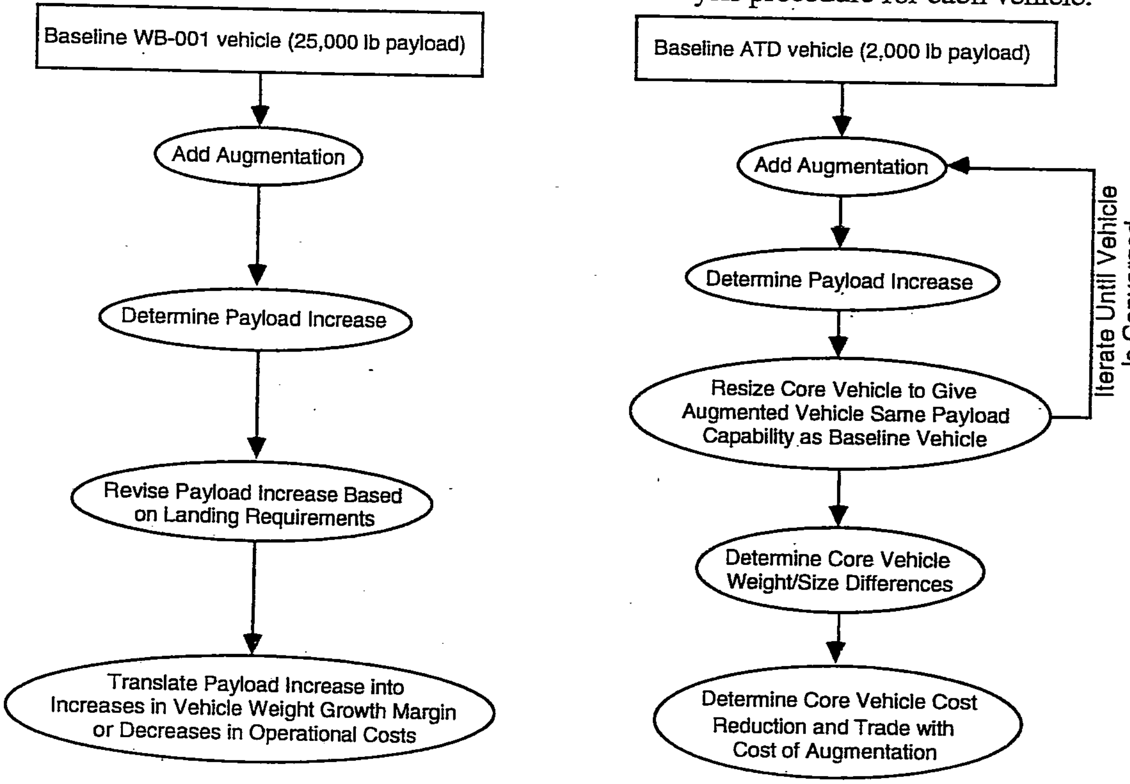

FIGURE 1: ANALYSIS PROCEDURE FLOW DIAGRAM

To determine the effects augmentation has on the performance of the SSV's analyzed, it is necessary to find the ascent trajectory that maximizes the burnout weight (the weight after main engine cut-off and before OMS orbit circularization) of the core vehicle for each vehicle/booster configuration analyzed. The burnout weight associated with each augmented case can then be compared with that of the original, unaugmented case to determine the performance increases obtained.

For the all of the ATD portion and some of the WB-001 portion of this study, it was necessary to revise the vehicle design by scaling it. To do this, information about the vehicle configuration and materials used in its construction was required. By using parametric equations that defined the vehicle size and weight, based on variables such as material densities, mission requirements, and propulsion parameters, the vehicle (or specific subsystems) was scaled geometrically. For the payload analysis performed on the WB-001 vehicle, scaling was performed on the vehicle's wing and associated subsystems to satisfy landing load requirements. For the ATD, the entire vehicle was reduced in scale as a result of added augmentation.

It is understood that adding augmentation to a SSTO changes the vehicle into a multistage one; however, it is felt that using augmentation in certain situations will lead to a SSTO vehicle with increased mission flexibility, potentially lower cost, and a shorter development time. This study will increase the general knowledge about current SSTO vehicles and illustrate the benefits of using augmentation to increase payload and growth margin, and reduce costs.

2. Vehicle 1: WB-001

Overview

The first vehicle, designated WB-001, is a winged-body, vertical-take-off/horizontal-landing vehicle developed primarily by the Vehicle Analysis Branch (VAB) at NASA LaRC. It was designed to perform a space station resupply mission, which involves delivering a 25,000 pound payload to a 220 nmi circular orbit with a 51.6 ° inclination (the orbit of the International Space Station (ISS)). It is a dual-fuel concept, burning a combination of kerosene, hydrogen, and oxygen during the first portion of the ascent, then switching to only hydrogen and oxygen for the remainder of the flight. It is proposed to use engines derived from the Russian RD-701 dual-fuel engine now under development. The vehicle is 185.6 ft long and has a dry weight of 200,300 lb. For more detailed specifications and a diagram of the WB-001, see Appendix A. Information about the baseline trajectory of this vehicle is located in Appendix B.

Since this is a fixed design, the primary goal was to determine how augmentation would affect the payload capability, payload costs, and growth margin of the vehicle as if the vehicle had already been built. Later, some vehicle resizing was allowed to accommodate the larger landing loads the vehicle would experience if it returned from orbit with the increased payload.

Analysis Method

The analysis of the WB-001 concept vehicle started by obtaining baseline specifications. These were the optimum ascent trajectory (for maximum burnout weight) and the vehicle's weight and size for performing the ISS resupply mission. These were determined by VAB when the design was developed. Based on an inspection of the structural model of the vehicle, the size of the boosters, and the total augmentation thrust relative to the core vehicle, the maximum number of strap-on boosters of each type to be tested was determined. Up to six Castor IV-A [5,8] SRM's, four Ariane L40 [8,13] LRM's, and two AMROC H-1800 [12] HRM's were tested for a total of twelve different levels of augmentation. Only boosters of the same type were tested together.

Even though this is only a case study and the goal of this project was focused on examining the performance increases gained by using strap-on boosters, it is important to keep in mind where on the vehicle the boosters could be attached. As part of the work performed for the Access-to-Space study, some structural analysis of the WB-001 vehicle was performed by VAB to determine the loading throughout the structure. It was determined that the best attachment points for the boosters would be on two of the stiffening rings on the hydrogen tank located in the aft of the vehicle (private conversation with Garry Qualls of Analytical Services & Materials, Inc.) (see figure 2.1). The first ring is the thrust ring where much of the loads generated by the main engines are channeled. The second is the ring connected to the main wing beam, carrying much of the wing loads. It is likely that some type of attachment rails would have to be designed in order to evenly distribute the thrust loads of the boosters if augmentation was to be used.

Two structural assumptions were made during the analyses performed for this thesis. The first assumption involved the attachment hardware mentioned above. It was felt that the weight of the booster attachment hardware was small compared to the weight of the booster, therefore it was neglected. The second assumption dealt with the effects of added thrust loads on the core vehicle structure. The added thrust of any attached boosters will increase the acceleration experienced by the vehicle during the early phases of ascent. This additional acceleration will increase the loads carried by the structure and could necessitate a stronger structure to accommodate them. During the structural analysis performed by VAB, however, consideration was given to the fact that at launch there is an initial shock due to the ignition of the engines. The structure is designed to tolerate this load with some safety margin. Therefore, it was assumed that the increased acceleration due to the boosters would not affect the vehicle's structural weight.

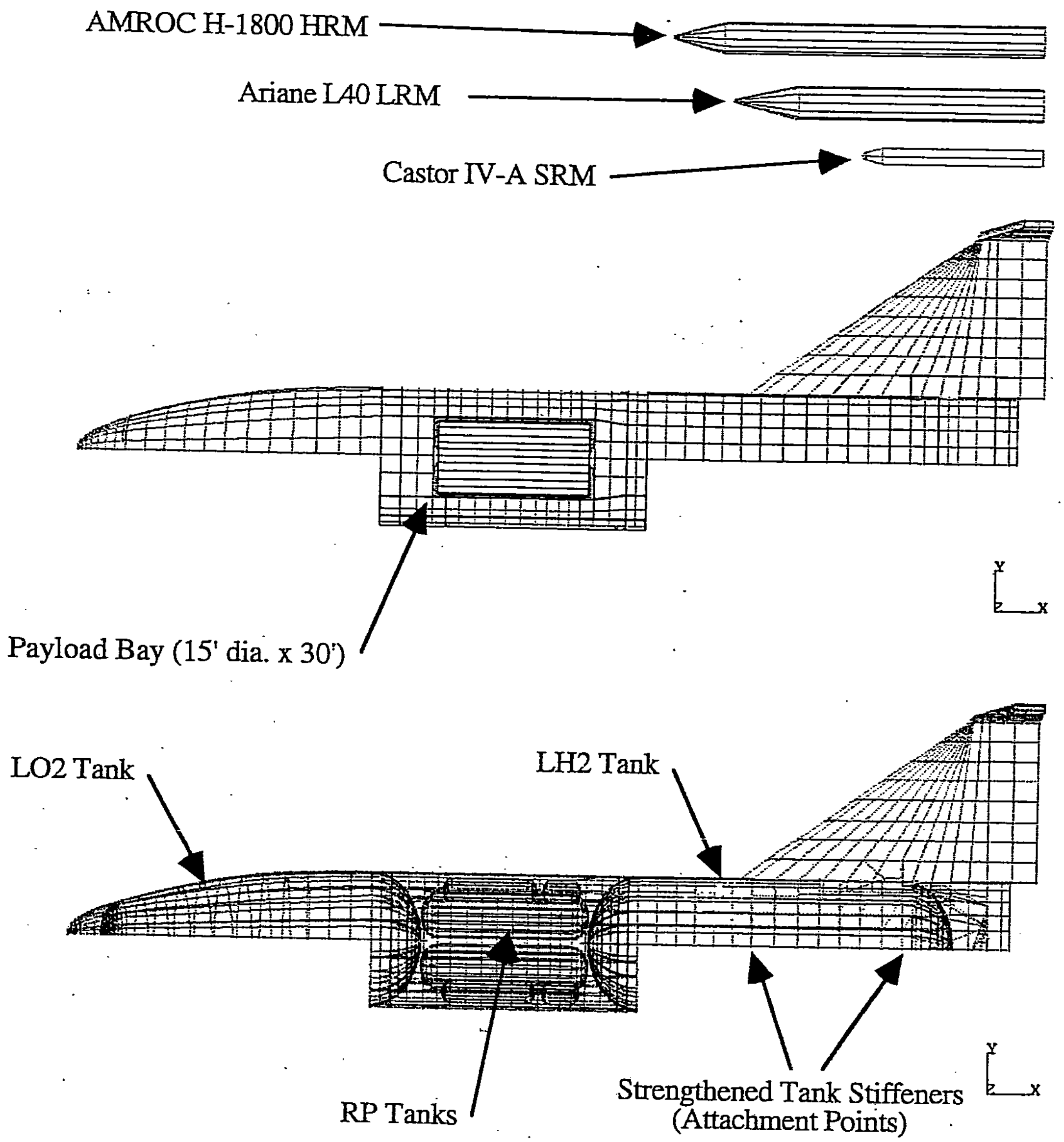

FIGURE 2.1: STRUCTURAL DIAGRAM OF SSV WB-001 USED TO DETERMINE FEASIBLE LOCATIONS FOR BOOSTER ATTACHMENT

Each level of augmentation was analyzed at both a 51.6° (Space Station) and a 28.5° (due east) inclination orbit assuming a Kennedy Space Center (KSC) launch site. Although the missions for the two orbits would most likely be different (different altitude, mission duration, payloads, etc.), they were kept the same to better illustrate the effects of augmentation alone. The mission specifics are outlined in Appendix B.

For each level of augmentation, the optimum trajectory that would maximize the burnout weight of the vehicle (weight of vehicle and payload) was determined. The increase in payload was found by subtracting the burnout weight of the baseline WB-001 vehicle and adding the result to the payload capability of the baseline vehicle. This figure would be enough if the mission called for only delivering the payload to orbit but not returning with it (or returning with a payload of less than 25,000 lb). To be able to return with a heavier payload, the vehicle must be designed to withstand the loads experienced during landing (primarily wing loads and landing gear loads) while carrying the additional weight of the payload. The WB-001, since it is was intended to perform Space Station resupply missions, is designed to be able to return with a 25,000 lb payload, not just to deliver it to orbit and return empty. Thus, if a larger payload is carried to orbit through the aid of augmentation, the current WB-001 would not be able to bring it back. To correct for this, the vehicle was scaled until the landing load requirements were satisfied. Scaling for each augmentation case yielded a new vehicle (different GLOW and wing area) and a revised payload capability which was slightly lower than the result found for the fixed (not scaled) vehicle configuration.

All scaling of the core vehicle was photographic - any part that was scaled was scaled equally in all three dimensions. Photographic scaling allowed the aerodynamic data of the unaugmented, unscaled vehicle to be used with reasonable certainty that the changes in aerodynamic performance would be minimal. To further minimize the changes to the vehicle design, only the wing (and the systems associated with it) was resized - the fuselage, tankage, and engines were held fixed. At the highest levels of augmentation, the increase in wing area was less than 12%. It was assumed that scaling the wing up to no more than ~10-15% would allow the use of the aerodynamic coefficients of the original, unmodified vehicle and still yield acceptable results (private conversation with Walt

Engelund of VAB). This was fortunate, since a wind tunnel model would have to be created to generate more accurate aerodynamic data, and creating a new model for each separate level of augmentation was hardly feasible.

In the initial trajectory analyses, the aerodynamic effects of the strap-on boosters were not included. It was assumed that, since the boosters are small relative to the core vehicle, are attached at the rear of the vehicle, and are aerodynamically shaped, the additional drag generated would be minimal - on the order of 1-3%. In an attempt to verify this, simple aerodynamic models of the boosters (i.e. a cone and cylinder) were created, and drag data for each of the booster types were generated. The additional drag was added to that of the core vehicle according to the level of augmentation being analyzed. The data generated did not include interference effects, so a margin of 20% was added in an attempt to account for them. It is understood that these effects could be significant compared to the component drag, but there was no way to more accurately account for them without wind tunnel modeling, which, as mentioned above, was unfeasible with the time allowed. Based on this approach, the assumptions were correct - the additional drag affected the payload-to-orbit values of the highest augmented cases by less than three percent for the Ariane L40, and less than one percent for the Castor IV-A and the AMROC H-1800.

Normally, vehicle resizing and trajectory analysis are performed in an iterative loop to arrive at a vehicle design. To avoid the need for loops, which can be very time consuming with so many test cases to analyze, a special procedure was used. After determining the optimum trajectory for a particular augmentation level, several additional trajectories (typically 3-5) were calculated over a range of GLOW values (5000 lb GLOW difference between cases). The core vehicle GLOW was traded with the total mass of propellant burned by the core vehicle to find the point where the propellant burned by the augmented vehicle was the same as that of the unaugmented one. The GLOW at this point is the GLOW for the scaled core vehicle. Using this figure then allowed the weights and sizes of all of the vehicle systems to be determined using the weights and sizing parametrics.

In addition to finding the payload increases possible through the use of augmentation, other areas were examined, such as the effects of augmentation on vehicle weight growth margin, the use of augmentation to compensate for less advanced construction materials, and the potential for augmentation to lower the costs of launching heavier payloads (or groups of smaller payloads).

Weight growth margin is defined as the percentage allowance for vehicle dry weight growth during its design and construction. Both vehicles in this study were designed assuming a 15% margin. Whether or not this is adequate is a topic currently being debated in the aerospace industry. Advanced high performance aircraft have been known to weigh only a few percent over their design weights; however, the Space Shuttle Orbiter grew around 25% during its development due to reasons such as insufficiently mature engine and TPS technologies. [2]

Another way to view using augmentation is its use to increase vehicle weight growth margin. The current SSTO vehicles incorporate a number of advanced technologies (such as aluminum-lithium (Al-Li) propellant tanks, composite structures, advanced TPS, and tri-propellant propulsion). Currently, with only a 15% margin, if some of the technologies are not mature enough or determined to be heavier than expected at the time of construction, vehicle performance would likely be reduced. Alternately, development costs could increase as an effort must then be made to reduce weight in other vehicle systems to compensate. Augmentation can be employed, in the case that a particular subsystem technology was lacking, to maintain the original design level of performance.

Another potential benefit of augmentation to be studied is the reduction of vehicle payload costs, which depend directly on vehicle operational costs. Reusable vehicles have been heralded as being the best way to make space flight less expensive. After the experience of the Space Shuttle, with its high operations costs, it is apparent this is not yet the case. Totally or mostly reusable vehicles may one day be the most cost effective way to launch payloads into space, but with our current level of expertise in these vehicles, it is not the case today. Currently, there is a great deal of knowledge and experience on how to build relatively low cost, reliable, expendable rockets. For example, the Castor IV is widely used on a variety of launch vehicles, costs less than $1 million each, and has a high reliability record of 99.7%. [5] Using these to augment new, reusable concept vehicles may prove to be the most cost-effective and low-risk way to get these vehicles built and carry larger payloads, in order to further our knowledge and expertise.

Results

Payload Increases

As stated earlier, analysis was performed for three types of strap-on boosters for each of two different orbits (51.6° and 28.5° inclination). Figures 2.2 through 2.7 illustrate the payload increases possible using augmentation. For consistency, each analysis was based on a final orbit of 50 x 100 nmi and a mission duration of 5 days. The vehicle carries enough on-board OMS propellant to maneuver the unaugmented vehicle (and all of the revised-for-payload-return vehicles) into a 220 nmi circular orbit. Since the trajectory optimization method used in this thesis does not calculate OMS propellant weights, the initial augmented trajectories carry the same OMS load as the unaugmented vehicle (i.e. the OMS load for a 25,000 lb payload), so the actual payload carried to orbit would be slightly less than what is shown on the first curve. This is a minor drawback of the analysis procedure used on this vehicle, since if the trajectory analysis and vehicle resizing had been used in an iterative loop (as they were for the ATD portion of the study (as illustrated in the right half of figure 1)), the OMS weights would be accounted for directly. To correct for this, the required OMS loads were calculated separately for each of the augmented cases using the equation [1]

$$M_{OMS} = M_{INS}\left(1 - e^{\frac{\Delta V}{I_{sp} g}}\right)$$

where:
ΔV = required OMS velocity change, ft/s (1100 ft/s)
g = gravitational acceleration, ft/s^2 (32.2 ft/s^2)
I_{sp} = vacuum specific impulse of OMS propellant, s (462.2 s)
M_{INS} = vehicle insertion mass (burnout mass in POST), lb
M_{OMS} = OMS propellant required for vehicle, lb

then the revised payload figure is found from:

$$\text{New Payload} = \text{Payload}_{POST} - \left(M_{OMS} - M_{OMS_{unaug}}\right)$$

where: $M_{OMS_{unaug}}$ = OMS propellant required for unaugmented WB-001 vehicle, lb (19368 lb @ 51.6°, 20026 lb @ 28.5°)

The payload to orbit values corrected for OMS load are shown in figures 2.2 through 2.7 as "OMS Revised."

To provide the capability to return with a payload heavier than 25,000 lb, the wing of the WB-001 vehicle had to be scaled to satisfy the landing loads associated with a 2.5 g pull-up maneuver. As mentioned earlier, only the wing and the subsystems associated with it were scaled - all other subsystems (such as the fuselage, propellant tanks engines, etc.) remained fixed. This scaling, resulted in a new vehicle design for each augmentation case analyzed. The new vehicles, because of their larger wing, are heavier than the unaugmented vehicle. This extra weight resulted in a further reduction in payload capability. The curves showing the payload capabilities of vehicles designed to return with payloads greater than 25,000 lb are labeled "Sizing Revision" in the figures. A table of the results shown in figures 2.2 through 2.7 is located in Appendix K.

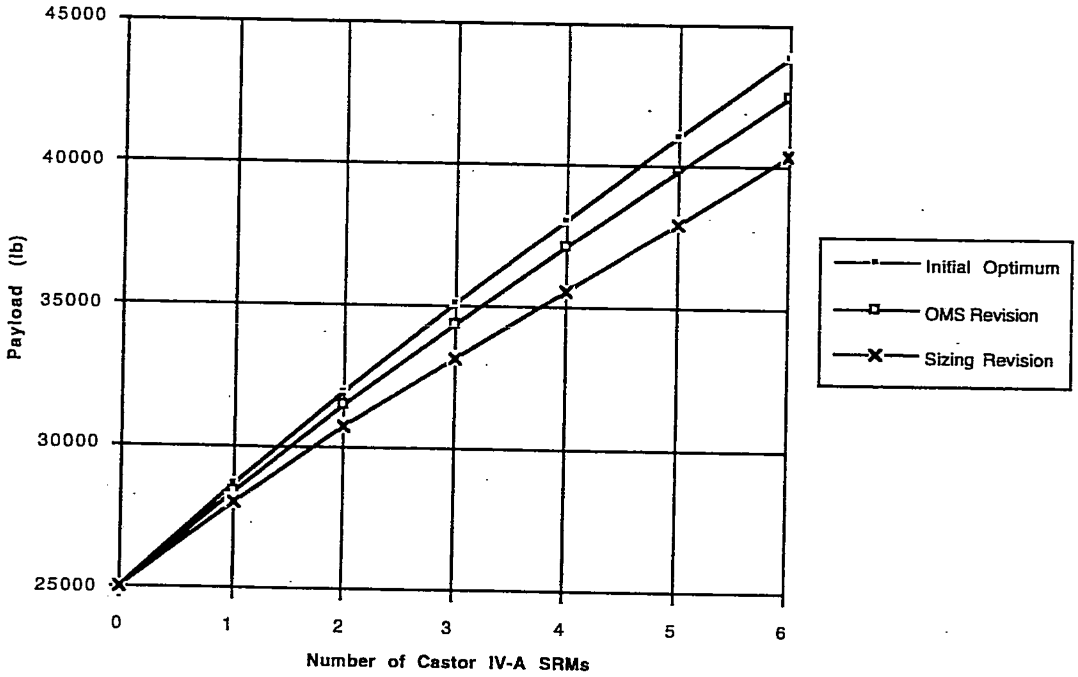

FIGURE 2.2: PAYLOAD TO 51.6° ORBIT USING CASTOR IV-A SRM'S

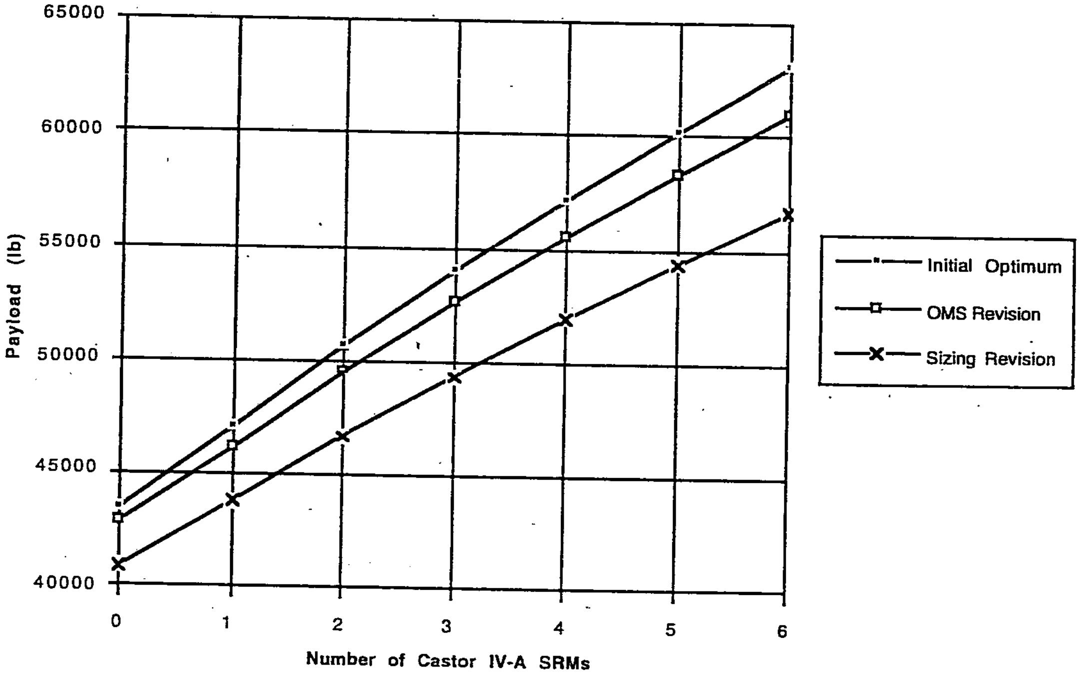

FIGURE 2.3: PAYLOAD TO 28.5° ORBIT USING CASTOR IV-A SRM'S

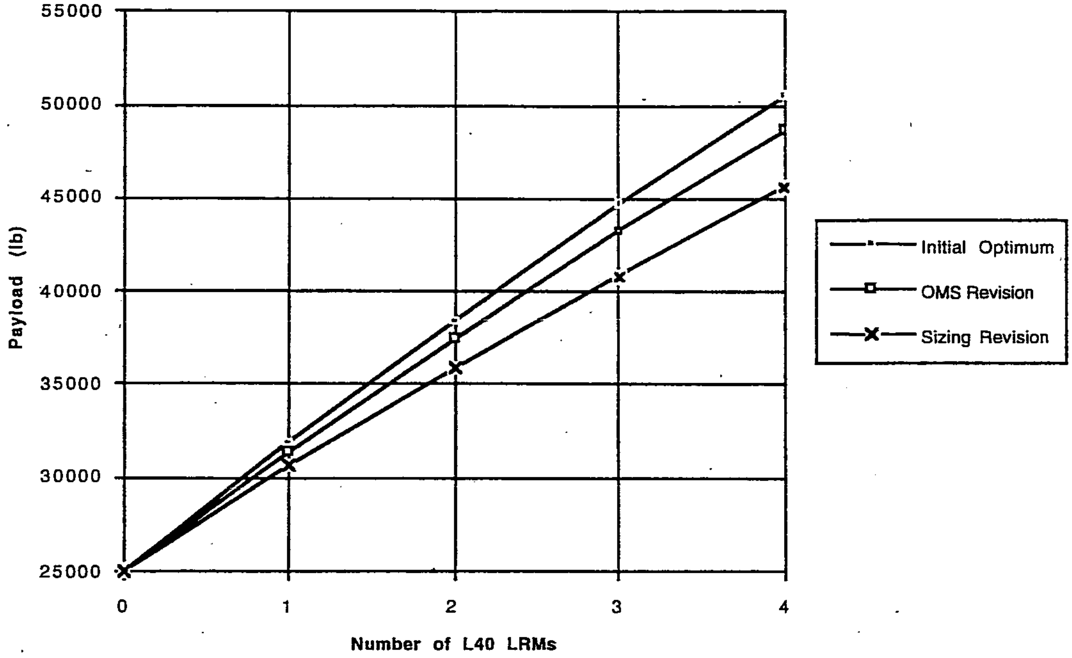

FIGURE 2.4: PAYLOAD TO 51.6° ORBIT USING ARIANE L40 LRM'S

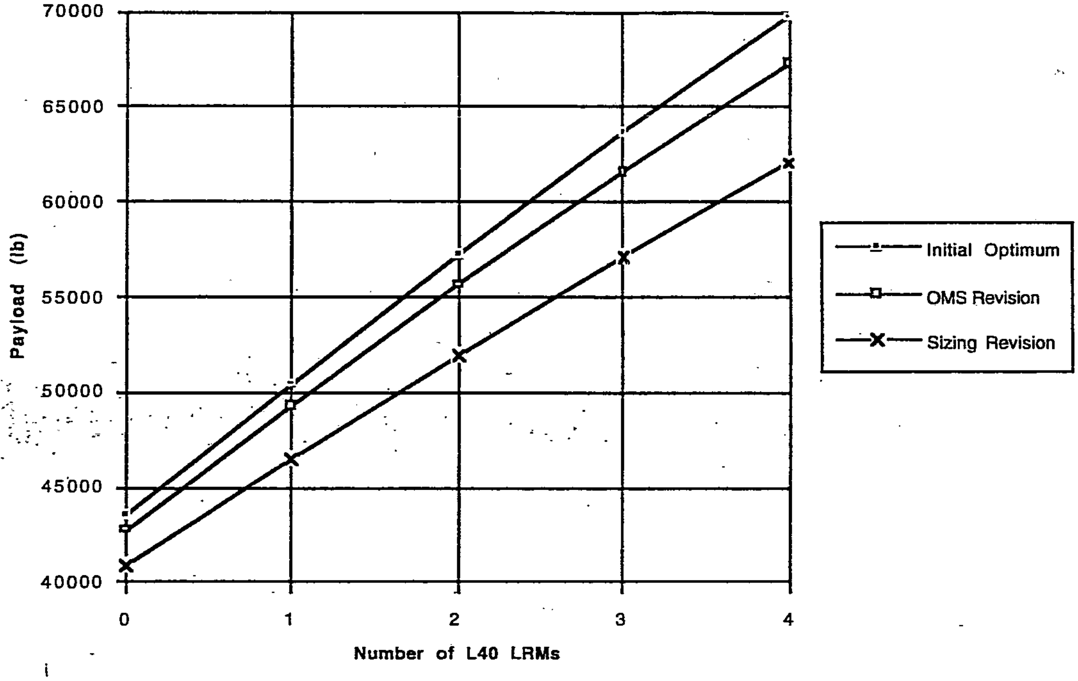

FIGURE 2.5: PAYLOAD TO 28.5° ORBIT USING ARIANE L40 LRM'S

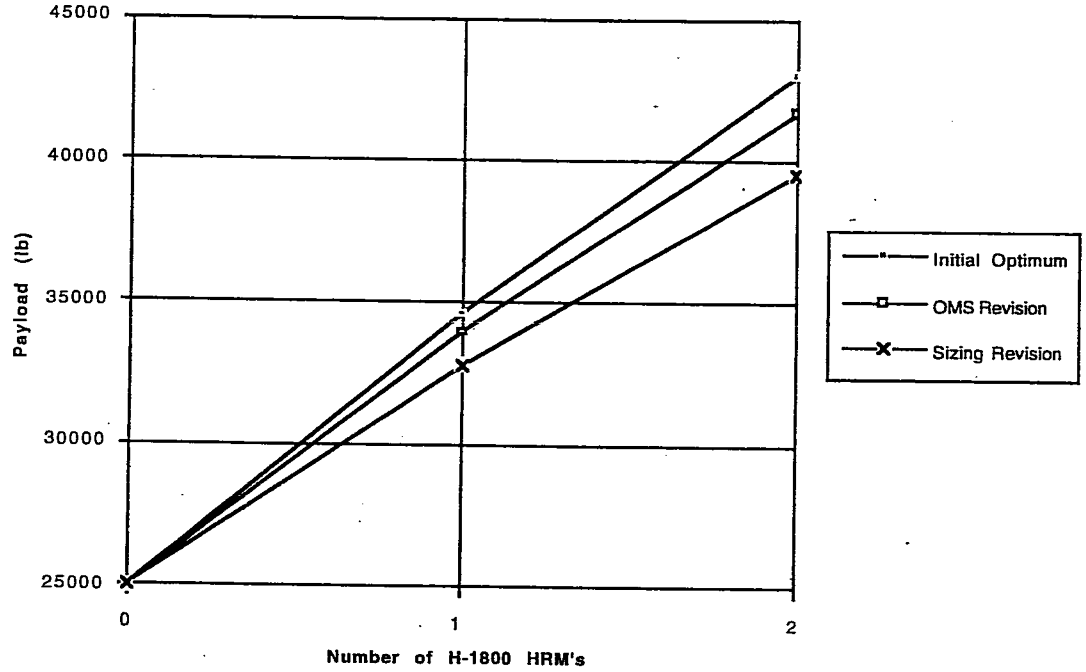

FIGURE 2.6: PAYLOAD TO 51.6° ORBIT USING AMROC H-1800 HRM'S

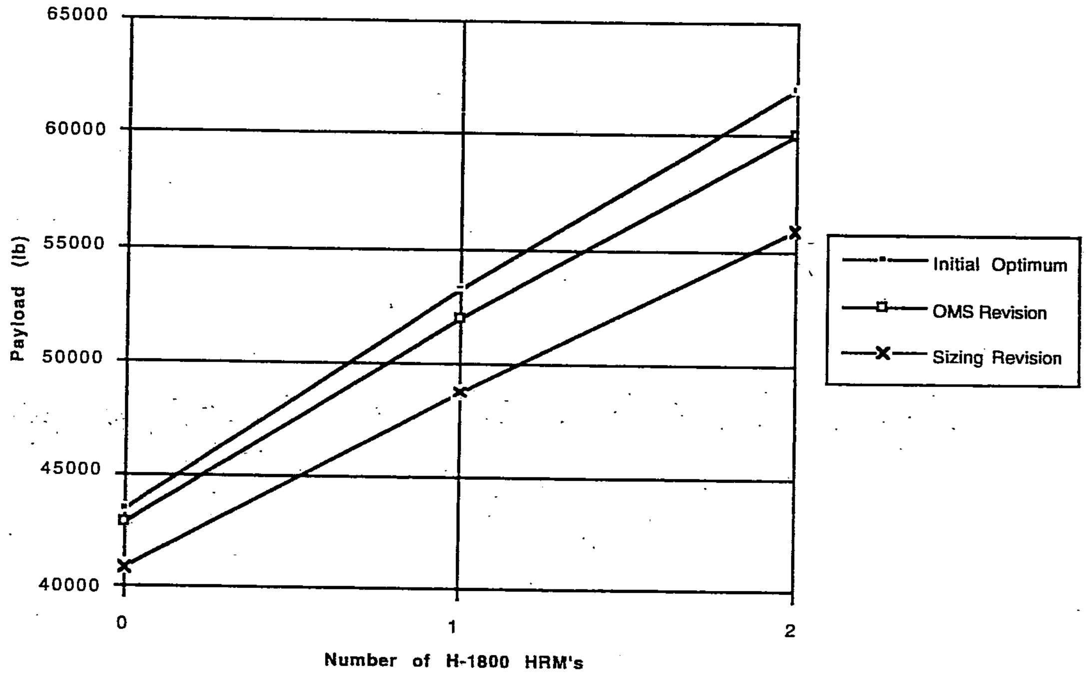

FIGURE 2.7: PAYLOAD TO 28.5° ORBIT USING AMROC H-1800 HRM'S

As can be seen from the charts, augmentation can be used to almost double the original payload capability of the WB-001 vehicle in some cases. With the maximum levels of augmentation tested, the Castor IV-A can increase the 51.6° payload by up to 17.5 klb (70%); the Ariane L40 can increase it by up to 23.7 klb (95%); and the AMROC H-1800 can provide an increase of up to 16.8 klb (67%). This assumes that no more than 25,000 lb of the payload carried into orbit is returned with the vehicle. If the full payload taken to orbit must be returned, then the increases drop to 15.4 klb (62%) for the Castor IV-A, 20.9 klb (83%) for the Ariane L40, and 14.6 klb (58%) for the AMROC H-1800, as indicated by the lower curve ("Sizing Revision").

There are several ways the boosters can be compared. One way would be to compare the charts of payload to orbit. Obviously, additional payload capacity could be gained simply by increasing the number of boosters. This is not always feasible, since consideration must be given to the physical placement of the boosters on the core vehicle and the increased structural stresses produced by the increased thrust levels. Some consideration of these areas was given initially when determining the number of boosters to be tested in this study. Also, some boosters are more cost effective. It may be worth sacrificing a small amount of performance if a particular booster is significantly cheaper than others.

From a performance only perspective, a good way to compare the boosters is to normalize the data relative to some performance specification. Figure 2.8 compares the payload increase gained for each augmentation case to the total impulse required to achieve it. Total impulse is found by integrating thrust over the burn time of the rocket motor. The best system, from a purely performance point of view, yields the greatest increase in payload for the lowest total impulse. In other words, the best system achieves the largest gains from the lowest effort. On the figure, the best booster choice will lie on a line with the greatest slope. From figure 2.8, it can be seen that the Castor IV-A yields the greatest slope. The H-1800 is very close, making it a close competitor.

Although the solid propellant Castor IV-A has the lowest specific impulse, it is more efficient due to the fact that solid boosters typically have the highest mass fractions (ratio of propellant weight to gross booster weight). Liquids tend to be lowest due to the additional machinery required (pumps, tanks, piping, etc.). Additionally, the liquid boosters also burn over a longer period of time, resulting in greater gravity losses. Hybrids fall in between since half of the propellant (either the fuel or oxidizer) is a solid while the other half is a liquid.

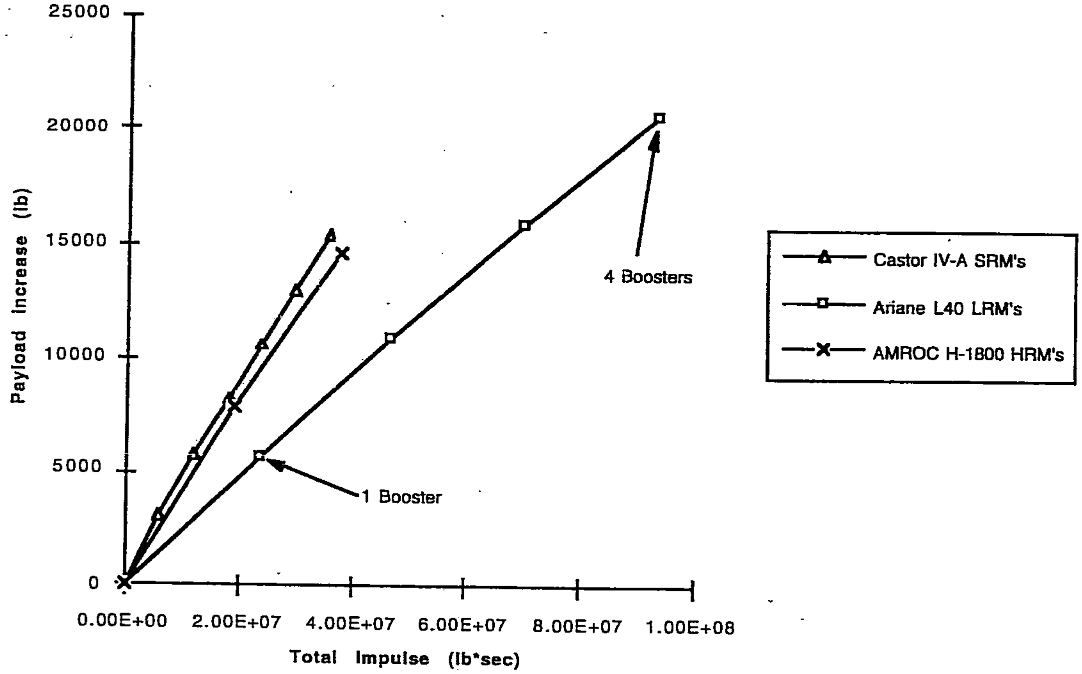

FIGURE 2.8: PAYLOAD INCREASES FOR EACH AUGMENTATION CASE VS. TOTAL IMPULSE

Payload Cost Reductions

Another benefit of using expendable strap-on boosters to increase payload capability is the effect on payload cost. If the payload gained by using augmentation (ignoring resizing effects) is examined, a comparison can be made of the relative cost per pound of payload. Since good estimates of the operational cost of the WB-001 vehicle are difficult to obtain, the current cost of operating the Space Shuttle (approximately $400 million per flight based on eight flights per year) was used as an upper bound in order to show the relative cost savings that can be achieved by using augmentation. It is called an upper bound for several reasons. First, Shuttle was built using 1970's technology. Much of the computer equipment has limited capabilities that require complex (and thus expensive) "work arounds" to achieve the performance required for each mission. Second, the complexity of the system as a whole is inherently expensive. Each flight requires a disposable External Tank, solid rocket boosters (which due to their reusability must be retrieved, inspected, refurbished, and reloaded after an earlier flight), and the Orbiter, which undergoes labor intensive servicing after each mission. Each component and the preparation associated with it adds to the overall cost. Finally, it is doubtful that a vehicle would be developed if it cost more to operate than the Space Shuttle. It is expected that the successor to the Space Shuttle must be an improvement, not only in performance and reliability but in cost as well. Cost analysis performed on the Shuttle II family of launch vehicle concepts by the Vehicle Analysis Branch concluded that operations costs could be reduced by a factor of four compared to Shuttle when the vehicle is operated like the Shuttle (i.e. full recertification after every flight) or even by a factor of 16 if operated like a commercial airliner. The Access to Space also conducted a cost analysis on the fully reusable concepts it investigated and predicted operations costs on the order of $33 million for the rocket SSV (based on 43 flights per year).

The analysis presented here used the Shuttle costs, the conservative Shuttle II estimates (4x reduction), and the Access to Space estimates to determine whether continuous reductions in cost per pound are achieved as augmentation is added, or if there is some limit to the cost effectiveness of augmentation. The cost per pound was found from the following equation:

$$\text{Cost per lb} = \frac{C + (n \times B)}{P}$$

where:

C = assumed cost per flight for core vehicle ($400, $100, or $33 million)
n = number of boosters attached to core vehicle
B = cost of one booster (see Appendix E)
P = payload mass afforded by booster(s) attached

Estimates of the cost of the structure used to attach the boosters to the core vehicle and of the processing costs for the boosters themselves were unknown and therefore were not included in the analysis. Figures 2.9 through 2.17 show how augmentation can reduce the cost per pound of payload relative to the unaugmented vehicle under these assumptions. Tables of the data used to generate these figures are located in Appendix K. The data are normalized to the cost per pound associated with the 51.6° Space Station mission. It should be noted however that, as with the operational costs of the core vehicle, which will vary according to the flight rate, the costs of the boosters will vary with the number used (number purchased) per year. Lower usage rates translate into higher booster costs, which translate into higher costs per pound of payload.

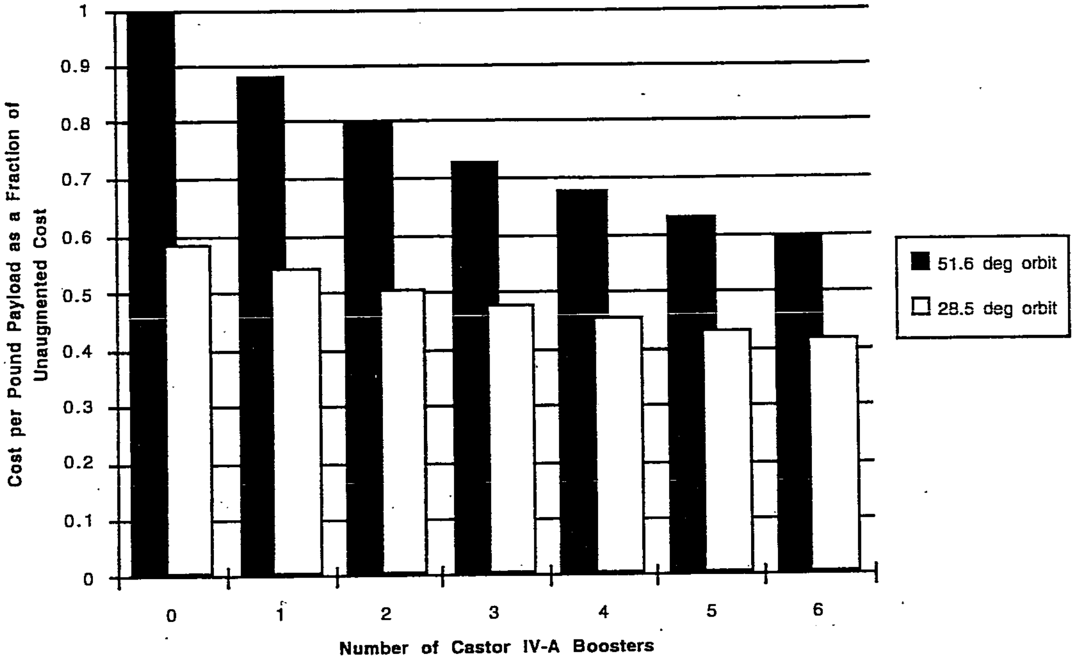

FIGURE 2.9: EFFECTS OF AUGMENTATION USING CASTOR IV-A BOOSTERS ON SSTO PAYLOAD COST PER POUND (BASED ON SHUTTLE COSTS)

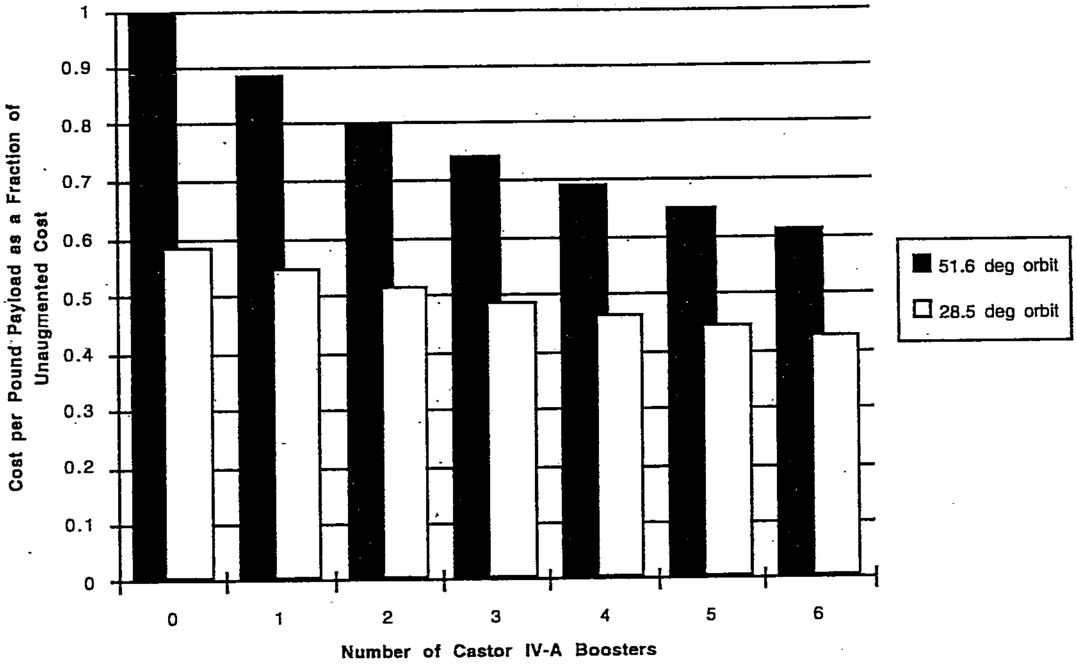

FIGURE 2.10: EFFECTS OF AUGMENTATION USING CASTOR IV-A BOOSTERS ON SSTO PAYLOAD COST PER POUND (BASED ON SHUTTLE II ESTIMATES)

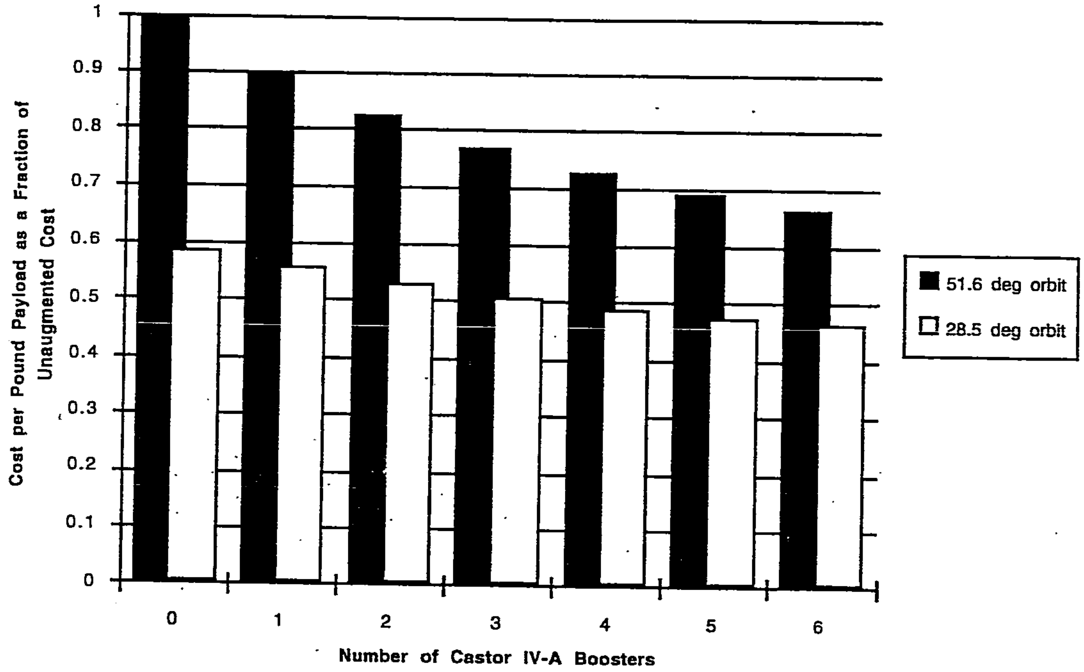

FIGURE 2.11: EFFECTS OF AUGMENTATION USING CASTOR IV-A BOOSTERS ON SSTO PAYLOAD COST PER POUND (BASED ON ACCESS TO SPACE ESTIMATES)

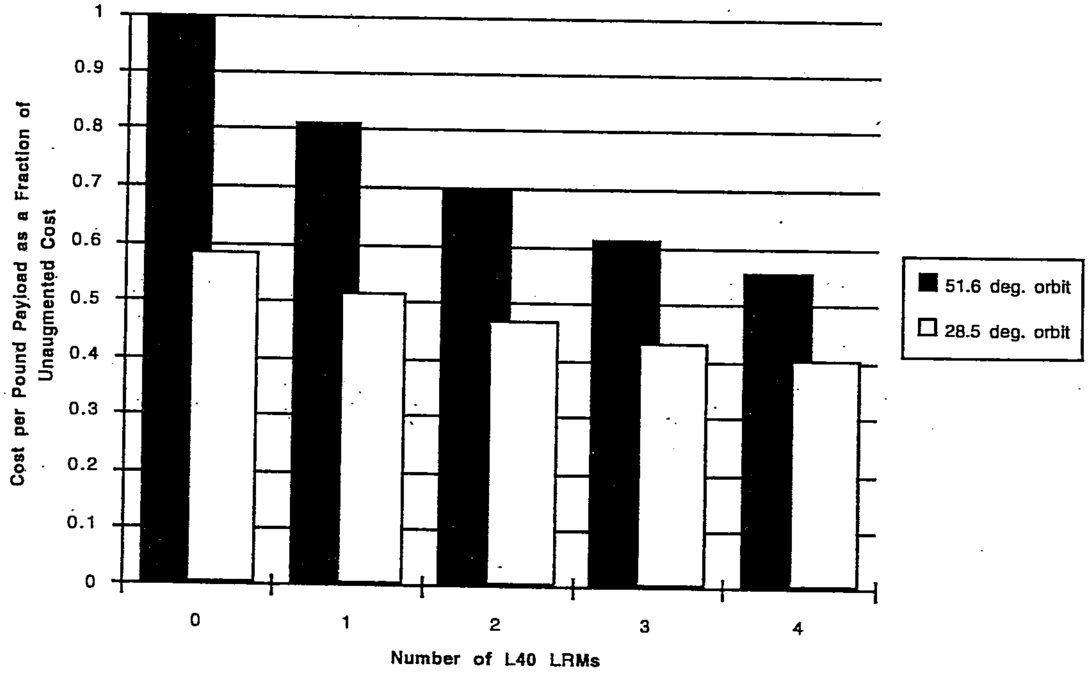

FIGURE 2.12: EFFECTS OF AUGMENTATION USING L40 BOOSTERS ON SSTO PAYLOAD COST PER POUND (BASED ON SHUTTLE COSTS)

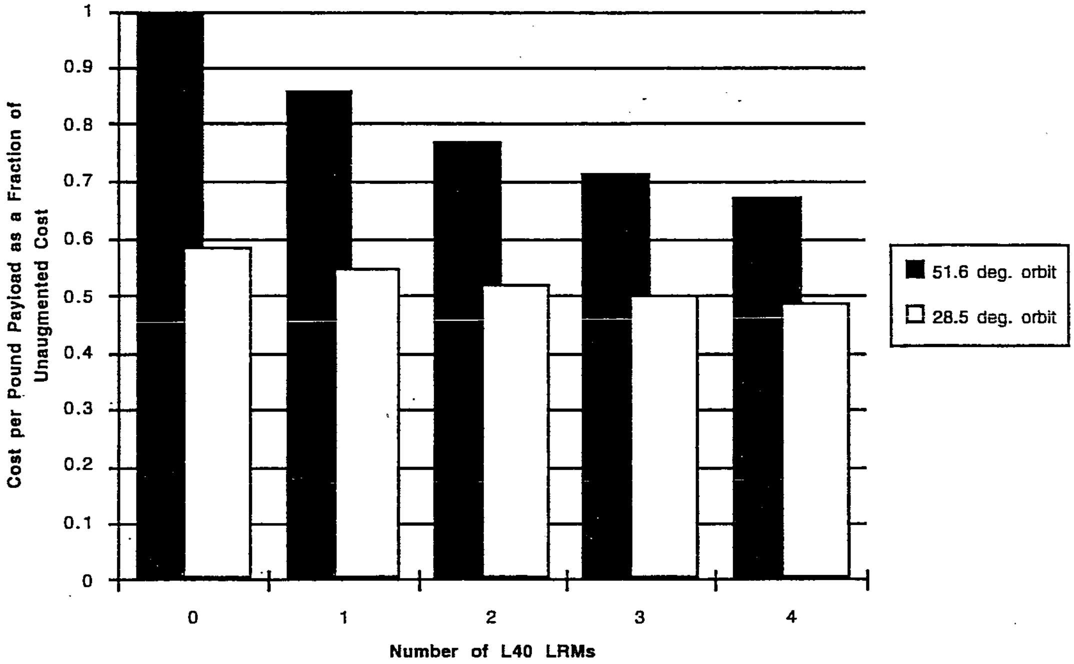

FIGURE 2.13: EFFECTS OF AUGMENTATION USING L40 BOOSTERS ON SSTO PAYLOAD COST PER POUND (BASED ON SHUTTLE II ESTIMATES)

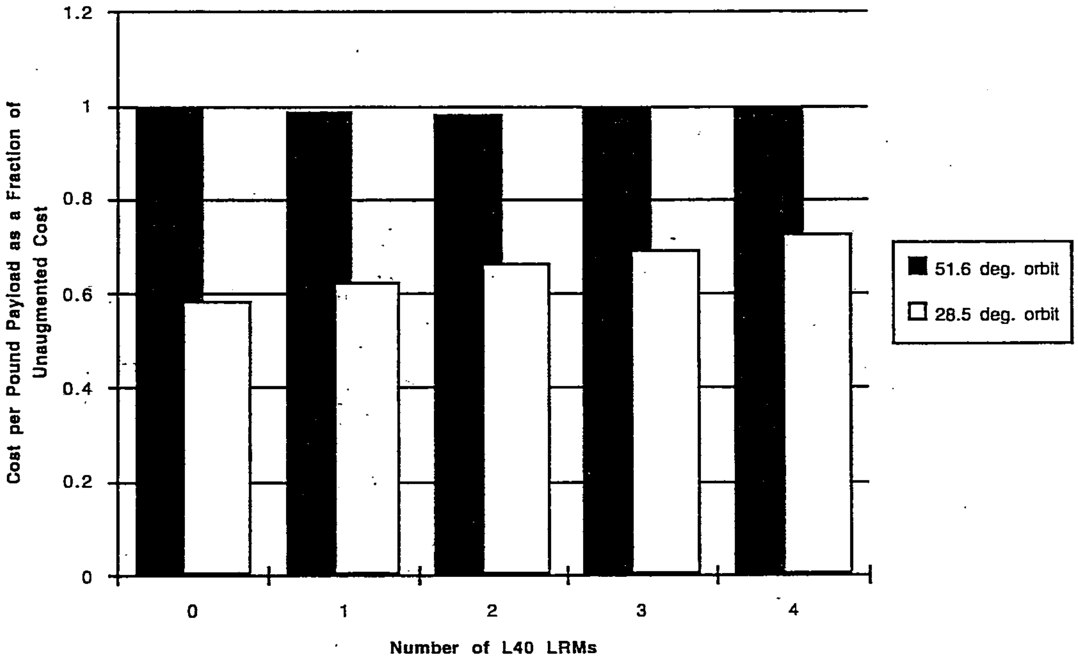

FIGURE 2.14: EFFECTS OF AUGMENTATION USING L40 BOOSTERS ON SSTO PAYLOAD COST PER POUND (BASED ON ACCESS TO SPACE ESTIMATES)

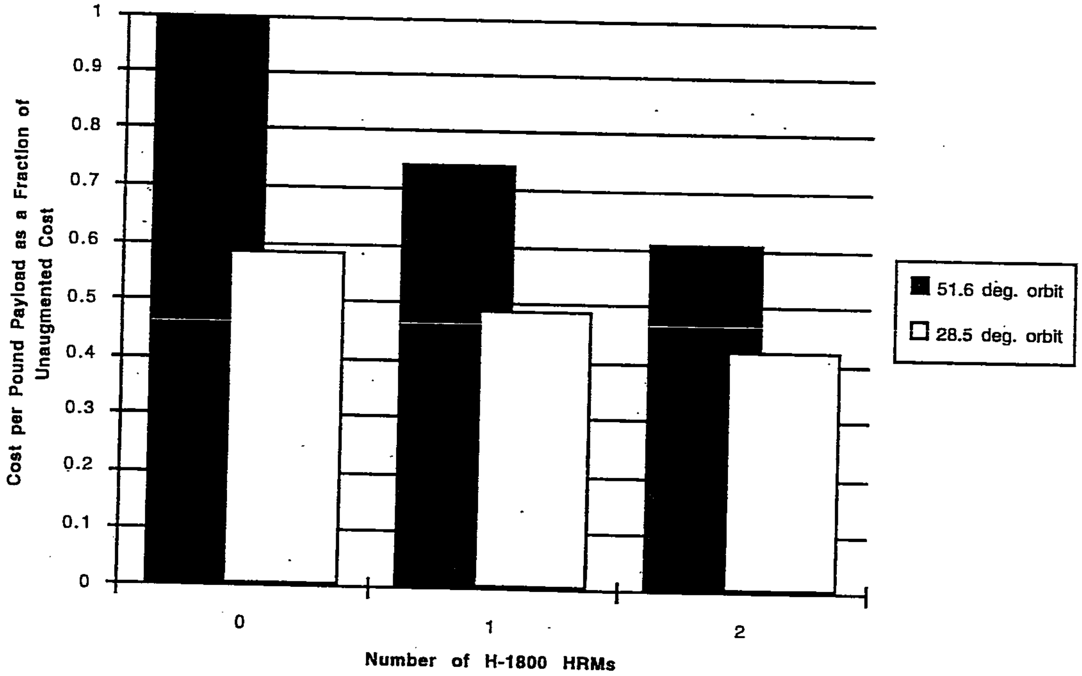

FIGURE 2.15: EFFECTS OF AUGMENTATION USING H-1800 BOOSTERS ON SSTO PAYLOAD COST PER POUND (BASED ON SHUTTLE COSTS)

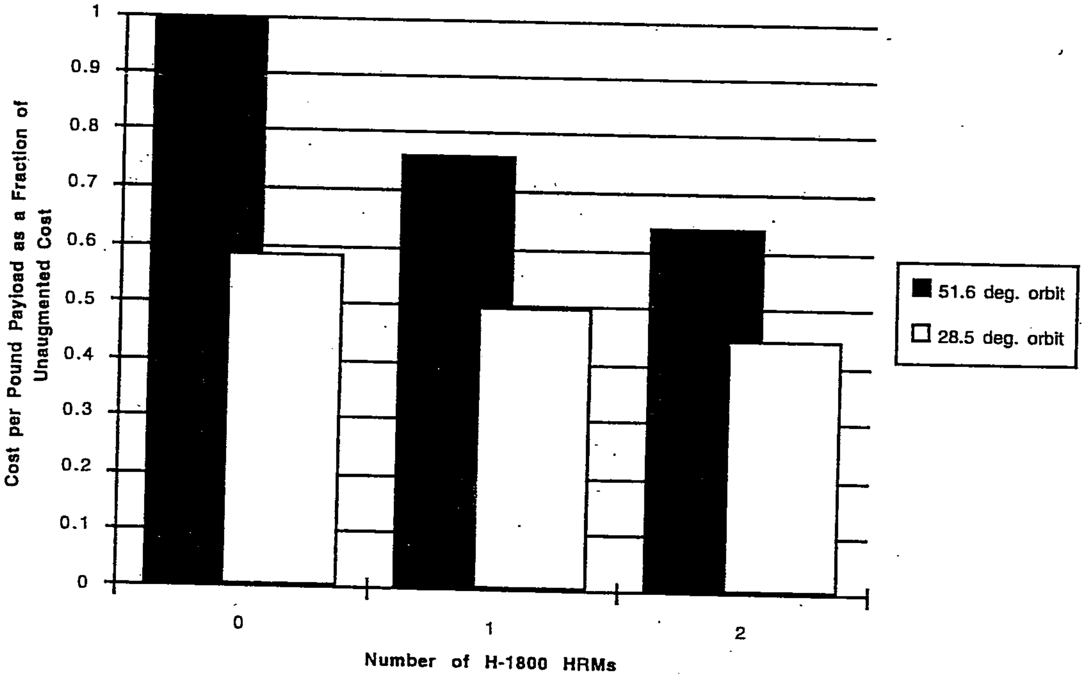

FIGURE 2.16: EFFECTS OF AUGMENTATION USING H-1800 BOOSTERS ON SSTO PAYLOAD COST PER POUND (BASED ON SHUTTLE II ESTIMATES)

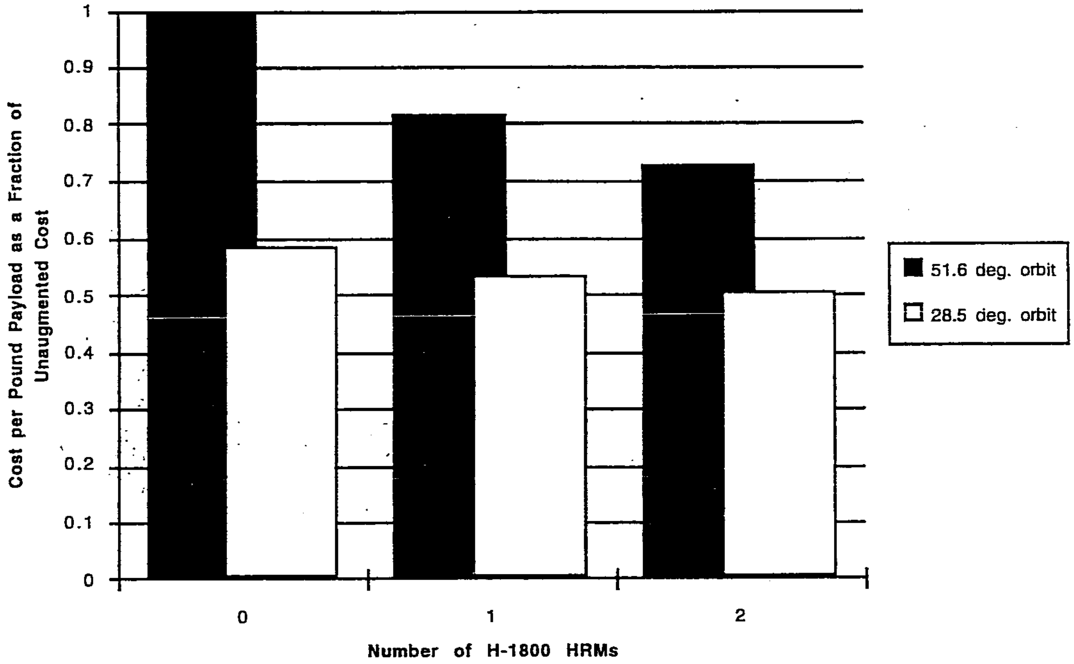

FIGURE 2.17: EFFECTS OF AUGMENTATION USING H-1800 BOOSTERS ON SSTO PAYLOAD COST PER POUND (BASED ON ACCESS TO SPACE ESTIMATES)

Examination of the charts yields some interesting conclusions. Using the Shuttle costs as estimates of the operations costs for the WB-001 doesn't reveal any startling differences between the boosters analyzed; however, the L40's yield a slightly lower cost per pound with a slightly higher payload than the Castor's and H-1800's and would probably be the best choice if the core vehicle's operational costs were extremely high. When the Shuttle II estimates of $100 million per flight is used, an interesting observation can be made. The cost curves for the L40 boosters are noticeably flatter than those of the Castor IV-A's and the H-1800's. This is due to the cost of the boosters being a more significant fraction of the core vehicle operational cost than with the Shuttle cost data. At the Access to Space cost level of $33 million per flight, the cost of the boosters (at the highest levels of augmentation) is now of the same order of magnitude as the core vehicle's operational cost. Thus, the range (number of boosters added) over which augmentation will be cost effective will be smallest compared to the other two cost figures (Shuttle and Shuttle II). Because of the high cost of the Ariane L40's (~$7.8 million each) compared to the Access to Space cost estimate, they are no longer cost effective. At a 51.6° orbit, cost per pound decreases only 1-2% until two boosters are used. After that point, the cost actually begins to increase. At a 28.5° orbit, use of the L40's is not cost efficient at all - the payload cost per pound increases 3-4% per booster from the start. Additionally, the curves for the AMROC H-1800 have flattened more noticeably than the Castor IV-A's, which still provide greater reductions over the H-1800's as the level of augmentation is increased. If the Access to Space cost estimate proves to be the most accurate, the Castor IV-A's would be the best choice for use as propulsion augmentation. They can provide a reduction in payload cost per pound of up to 33% (at a 51.6° orbit). The AMROC H-1800's are only about 5% more expensive (cost per pound), and as more experience is gained in hybrid propulsion, they may become a better choice in the future. The high cost of the Ariane L40 makes this booster not at all feasible at the Access to Space cost level. At a 28.5° orbit, the L40 actually increases the cost per pound by as much as 24%!

Additional savings could be realized from a reduction in vehicle flight rate. With the increased payload capability gained from augmentation, it might be possible to reduce the number of flights per year, which could save in operational costs. However, this would have to be traded with the likely increase in booster costs due to the lower usage rate.

Increases in Weight Growth Margin

As an extra measure of security, augmentation may be used as a way to increase vehicle weight growth margins. Currently, the WB-001 and ATD vehicles are designed using a 15% margin. Some feel that this is inadequate for technology driven vehicles such as these. The margin percentages for the augmented cases were found by taking the increase in payload capacity, adding it to the weight set aside for margin on the vehicle (15%), and dividing by the vehicle dry weight without margin included. Figures 2.18

through 2.20 show how augmentation can increase this to more conservative levels. Tables of these results can be found in Appendix K.

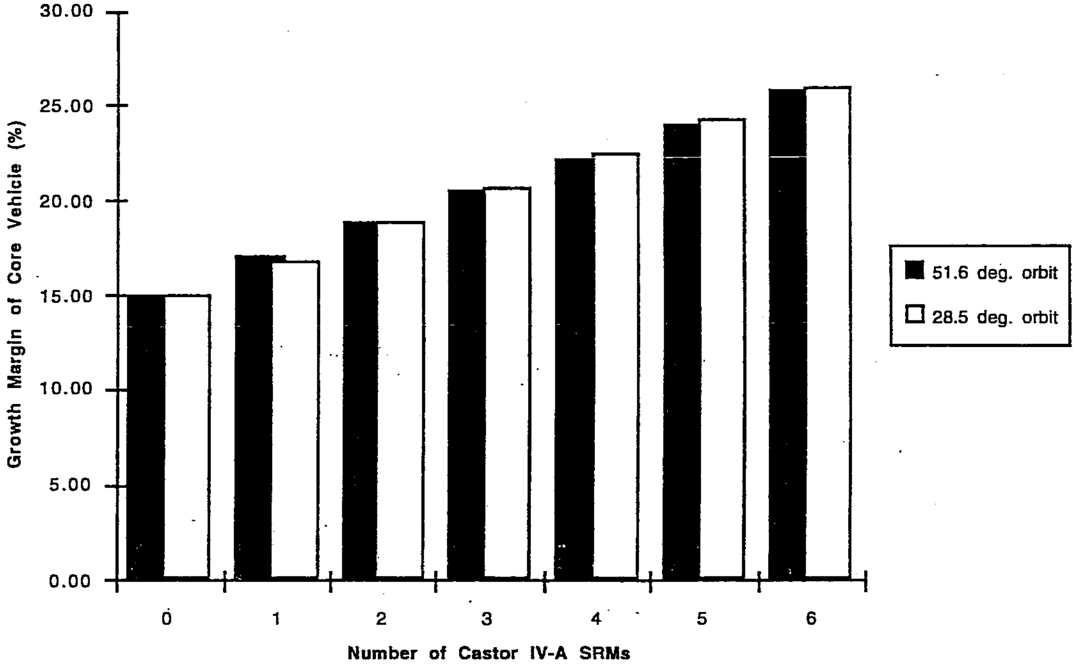

FIGURE 2.18: INCREASES IN WB-001 WEIGHT GROWTH MARGIN USING CASTOR IV-A BOOSTERS

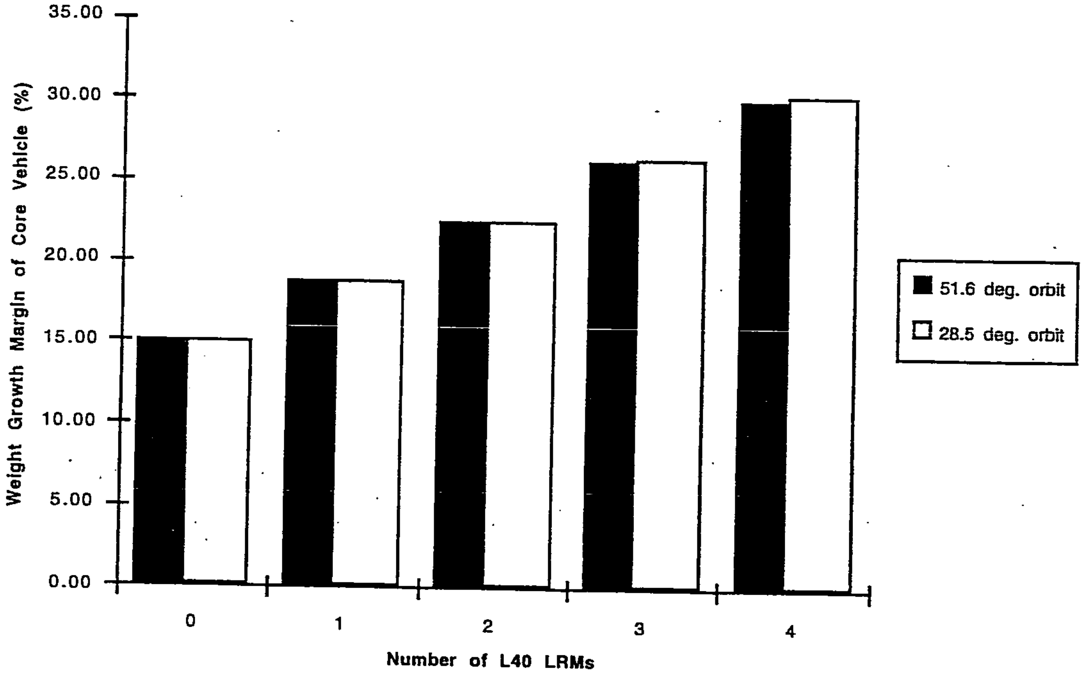

FIGURE 2.19: INCREASES IN WB-001 WEIGHT GROWTH MARGIN USING L40 BOOSTERS

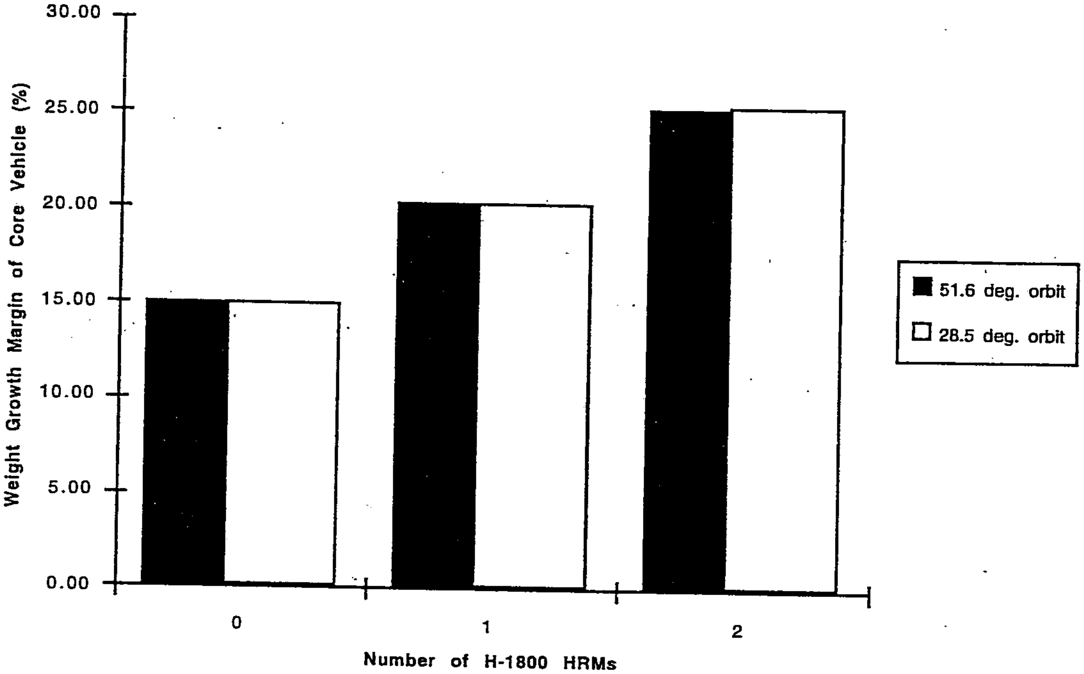

FIGURE 2.20: INCREASES IN WB-001 WEIGHT GROWTH MARGIN USING H-1800 BOOSTERS

The charts show that augmentation can increase the vehicle's weight growth margin up to 20-25%, which is more in line with what is felt necessary by industry. The Castor IV-A can increase the margin to 26%, the H-1800 can increase it to 25%, and the L40 can increase it to as high as 30%. Part of the reason a 15% margin was chosen for the unaugmented design is that, since SSV's are very high performance vehicles, relying on a great deal of advanced technology, they are very sensitive to weight growth (i.e. adding a pound of weight will actually cause the vehicle to grow more than one pound to accommodate it). Increasing the margin by 10% would have resulted in a vehicle with almost a 35% higher dry weight. Figure 2.21 shows the sensitivity of the WB-001 to increases in weight growth margin. Also included are curves showing the sensitivity of the augmented vehicles.

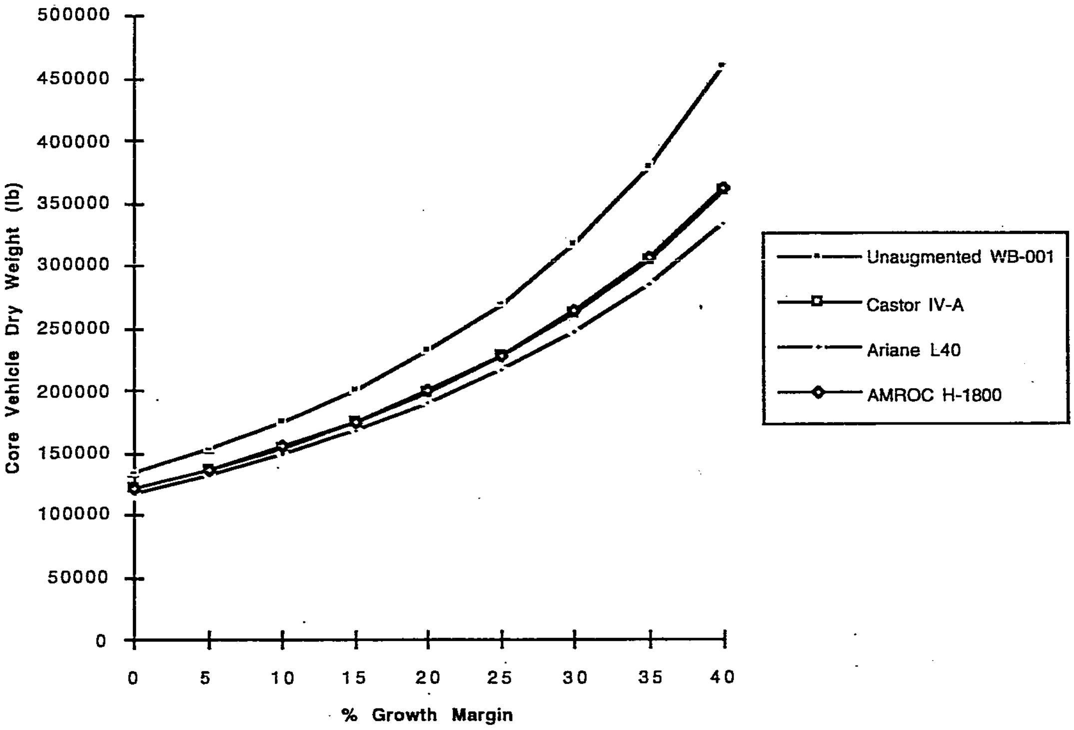

FIGURE 2.21: SSTO VEHICLE SENSITIVITY TO WEIGHT GROWTH MARGIN

Two trends can be identified from figure 2.21. First, the dry weight of the vehicle grows rapidly as margin increases, but decreases as augmentation is added. Second, the slopes of the curves decrease as augmentation is added, meaning that augmentation has the effect of decreasing (although only slightly) the core vehicle's sensitivity to weight increases.

Compensating for Less Advanced Materials

The SSV depends on many advanced materials to make it a viable option for a new launch vehicle. Some are not yet mature, and, if they are not ready in time, the vehicle would be forced to grow to accommodate the technology available. This means a higher vehicle weight, which can mean a higher cost. It should be noted that the increases in cost do not necessarily come directly from a higher vehicle weight. Instead, if a vehicle is very sensitive to weight growth (as SSV's typically are), the increases in cost come from the additional requirements from other systems (especially propulsion) necessary to compensate for the additional mass. Table 2.1 outlines the levels of advanced technologies planned for the WB-001 vehicle. Figure 2.22 shows the effects changes to subsystem materials have on the vehicle's dry weight. For each bar on the chart, only the specified systems were altered. All other systems are assumed to remain at the advanced level described in table 2.1. A table of vehicle dry weights for each of the configurations is located in Appendix K. The density of the materials used in the vehicle weight calculations is 0.058 lb/in^3 for graphite/epoxy composite, 0.098 lb/in^3 for Al-Li 2195, and 0.101 lb/in^3 for Al 2219. Accounting for differences in strength, the subsystem weight reductions (compared to Al 2219) for Al-Li 2195 are 20% if used in the wing, and 18% if used elsewhere. Composites increase this to 40% for the wing, and 35% when used in the structure. The parametrics defining the vehicle configuration were based on aluminum construction, thus the reduction factors for any subsystem constructed using Al 2219 will be zero. To change the subsystem material to Al-Li or Gr/Ep, the appropriate reduction factor was changed to one of the factors listed above and the vehicle size and weight recalculated.

Subsystem	Material Technology
Wing	Composite (Gr/Ep)
Basic Structure (fuselage, thrust structure, engine bay, etc.)	Composite (Gr/Ep)
Secondary Structure (payload bay, bay doors, body flap, etc.)	Composite (Gr/Ep)
LH_2 Tank	Al-Li 2195
LO_2 Tank	Al-Li 2195
RP Tanks	Al-Li 2195

TABLE 2.1: BASELINE WB-001 SUBSYSTEM MATERIAL TECHNOLOGIES

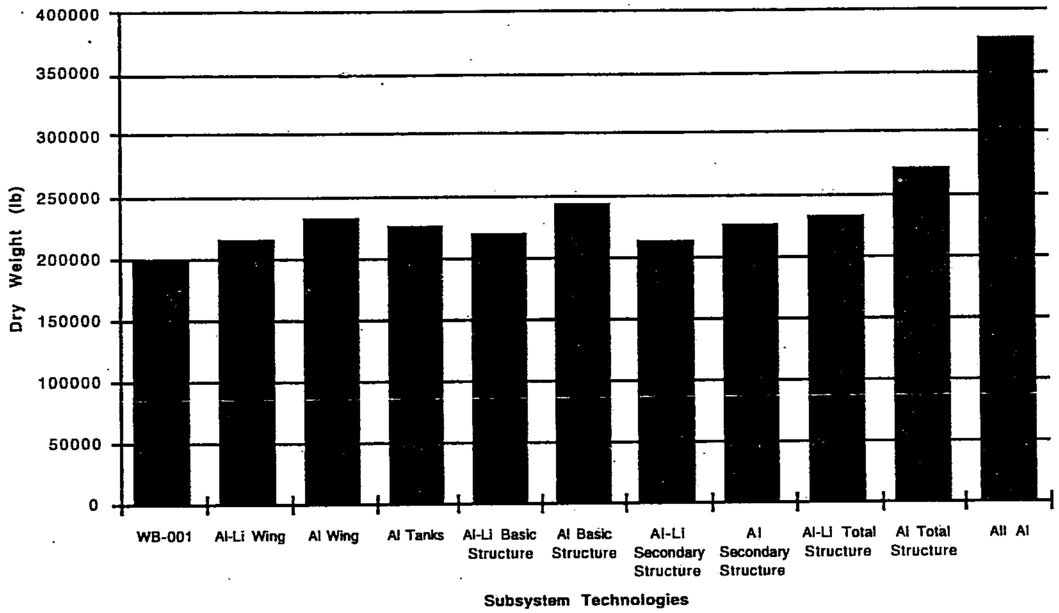

FIGURE 2.22: EFFECTS OF SUBSYSTEM MATERIAL TECHNOLOGIES ON SSTO VEHICLE DRY WEIGHT

Since some of the weight increases are relatively low, augmentation could conceivably be used to compensate for a lower material technology if the need were great enough (e.g. if the cost of the advanced technology were too high, or if the required development time were too great).

Examination of the chart and the increased payload capability of each booster (up to (17.5 klb for Castor IV-A, 23.7 klb for Ariane L40, and 16.8 klb for AMROC H-1800) indicates that augmentation can be used to compensate for a few of the lower subsystem technologies, such as an Al-Li wing, an Al-Li basic structure, or an Al-Li secondary structure. Compensating for an aluminum structure (basic or complete) however would likely prove to be difficult (Al basic structure adds 42.8 klb, and Al complete structure adds 70.6 klb to dry weight), and compensating for an all-aluminum vehicle would be virtually impossible (as the vehicle dry weight nearly doubles from ~200 klb to ~379 klb). Compensating for Al tanks (+25.9 klb) or an Al secondary structure (+24.6 klb) is just slightly beyond the capabilities of the L40, and would be possible with the addition of one more booster. Compensating for an aluminum wing (+31.3 klb), or a total structure made from Al-Li (+32.2 klb) is beyond the capabilities of the levels of augmentation analyzed in this thesis. Further analysis is required to determine the feasibility of compensating for these two cases.

3. Vehicle 2: Advanced Technology Demonstrator (ATD)

Overview

A slightly different approach was taken with the ATD study. The purpose of the ATD (as its name states) is to serve as a platform for demonstrating newly developed technology (advanced engine concepts, lighter materials, etc.). Unlike the WB-001, the ATD concept is not at a stage where the design is fixed in size. Thus, the goal here was to find out how the scale of the vehicle could be reduced by adding augmentation. In general, smaller vehicles are lighter and cost less to develop and operate than larger vehicles with similar configurations. Thus, it is possible that cost savings could be realized by reducing the scale of the vehicle through augmentation.

The ATD is not intended to perform the full-scale mission of the WB-001 (or any payload mission for that matter). Nevertheless, it would be beneficial if the vehicle were able to carry some payload to orbit. To follow an earlier ATD study conducted by VAB, which focused on a vehicle using SSME derivatives and LOx, LH_2 propulsion, the ATD in this study was designed to carry a 2000 lb payload to a 100 nmi circular, 28.5° inclination orbit, unaugmented. With this payload capability, the ATD could make an ideal launch platform for small satellites, while at the same time proving the technologies necessary for the full-scale SSTO - the WB-001 or a similar vehicle. A baseline vehicle was designed for both 51.6° and 28.5° orbits. Appendix C provides the weights and sizing statement for the baseline 28.5° orbit vehicle. Appendix D provides trajectory information.

Analysis Method

As mentioned above, the goal of the ATD portion of this study was to reduce the scale of the vehicle by using augmentation. Although it is not the only factor, vehicle dry weight is used as an indicator of the relative cost of launch vehicles in this study. As mentioned earlier, cost reductions are realized mainly from decreased requirements on costly systems such as propulsion. The degree of these reductions will depend on the degree of dry weight reduction. Additionally, smaller vehicles often cost less due to the lower operational costs incurred (e.g. support requirements, construction facilities, and refurbishment). Unlike the WB-001 vehicle, it is not necessary for the unaugmented vehicle even to be able to reach orbit. As its name suggests, the purpose of the ATD is to demonstrate and prove the technologies needed to develop a full scale SSTO vehicle. If development costs for an unaugmented vehicle capable of flying to LEO are high and available funding is tight, one strategy would be to fly the unaugmented vehicle to sub-orbital levels initially, then use augmentation to reach orbit later. This approach will still allow effective tests and incremental demonstrations of the vehicle's capabilities, and has the potential to reduce the vehicle's operational costs.

Starting with the baseline ATD (either the 28.5° or the 51.6° orbit inclination version) various levels of augmentation were added, scaling the vehicle at each level to keep the payload capability fixed. The same expendable strap-on boosters were used as with the WB-001 vehicle - the Castor IV-A (solid), the Ariane L40 (liquid), and the AMROC H-1800 (hybrid). Up to three Castors were tested, two L40's, and one H-1800. To rescale the vehicle for each level of augmentation, the iterative loop of trajectory optimization (for maximum burnout weight) and vehicle resizing outlined in figure 1 was used. Instead of turning the increased performance gained from augmentation into increased vehicle payload, the payload was held fixed and the gains were used to make the core vehicle smaller..

When a converged vehicle was obtained at each step, the resulting vehicle dry weight was recorded for comparison against the baseline vehicle and the other augmentation configurations.

Results

In comparing the ATD vehicles, the only parameters allowed to change between vehicles were the booster specifications. The mission involved carrying 2000 lb to a 100 nmi circular orbit and remaining on orbit for 5 days. The mission duration would most likely be shorter and would vary according to specific mission requirements, but it was kept at the same level as the WB-001 for comparison purposes, except in one case. This additional case is a reduced mission scenario - the mission is only 0.2 days long and the vehicle carries no payload. It was only analyzed in an unaugmented configuration. This provided a chance to compare the significance of augmentation and reduced mission requirements for a smaller vehicle like the ATD, since it was not a fixed design and could be scaled. Figures 3.1 and 3.2 compare the dry weights and engine requirements of the ATD core vehicle for the six different augmentation levels and the reduced mission case tested at 51.6° and 28.5° orbits. Also included is the unaugmented WB-001 vehicle to illustrate the reduction in vehicle scale for the ATD's lower payload capability. A table of this data is located in Appendix K.

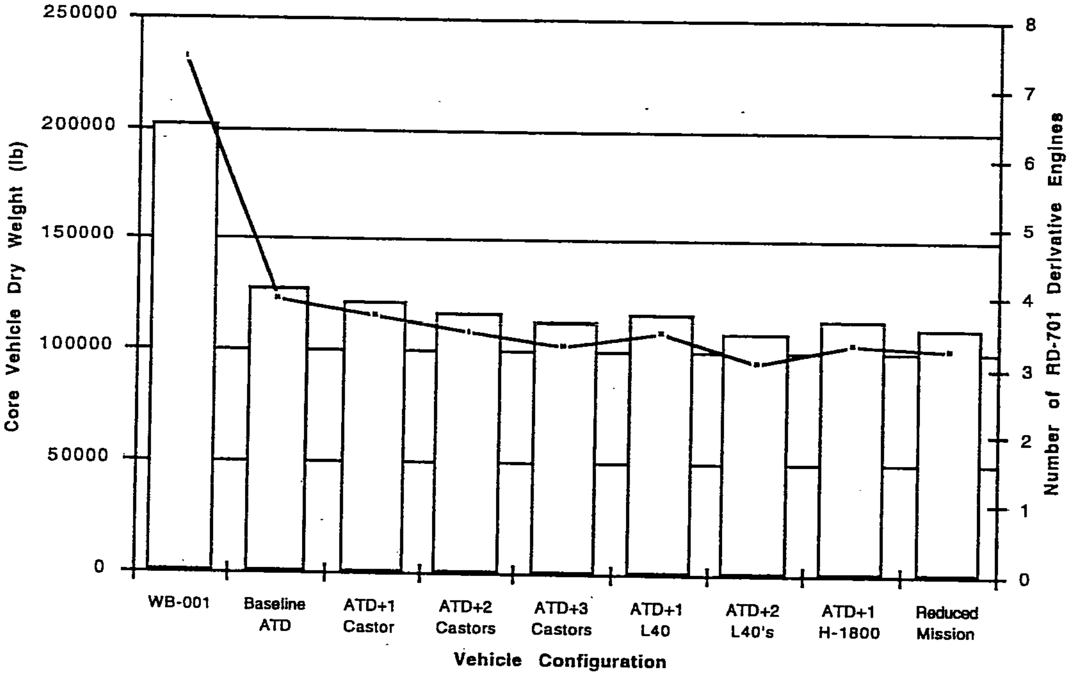

FIGURE 3.1: ATD DRY WEIGHT REDUCTION USING AUGMENTATION (28.5° ORBIT)

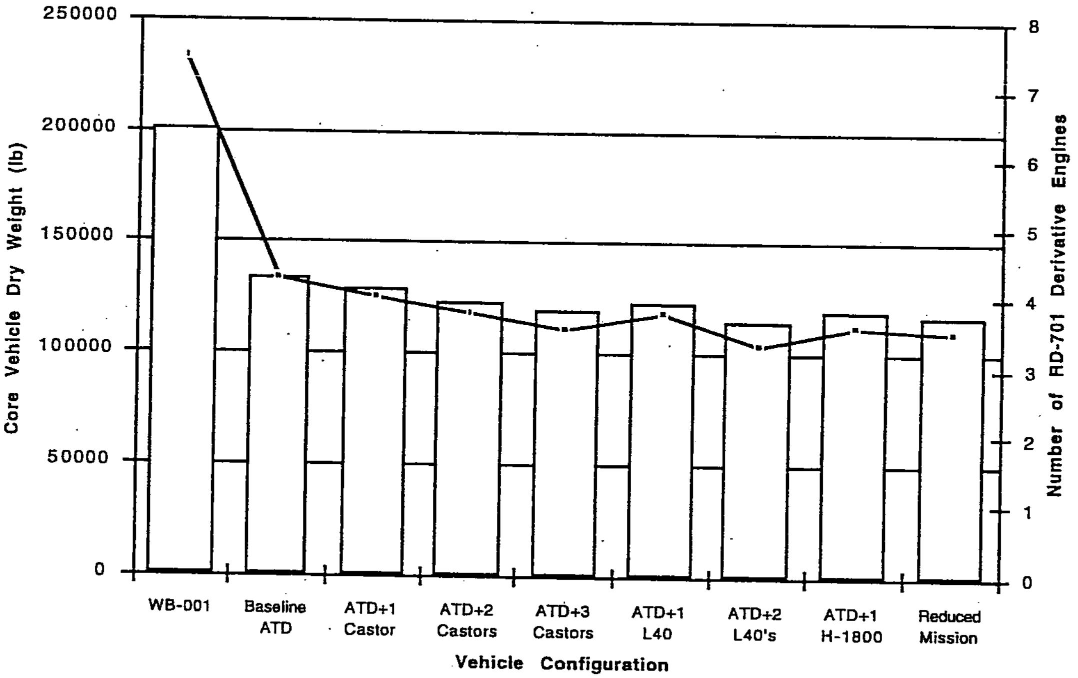

FIGURE 3.2: ATD DRY WEIGHT REDUCTION USING AUGMENTATION (51.6° ORBIT)

A cost analysis was not performed on the ATD because, although it is technically a scaled down version of the WB-001, it is an entirely new vehicle. Cost analysis in general is a very sensitive issue, and although costing equations do exist for the WB-001, they are still only good for rough estimates and should not be applied to a vehicle such as the ATD presented here.

It can be argued however that as the vehicle's dry weight is reduced, assuming the same levels of technology, its cost would decrease. Figures 3.1 and 3.2 show that almost 20000 lb can be cut from the dry weight of the ATD. A lighter vehicle will save money in material costs during vehicle construction and lower propellant usage during operation. Perhaps most importantly however, a lighter vehicle can mean fewer main engines required to place it in orbit. This is shown by the axes on the right side of the figures. It should be noted that the engines are the same RD-701 derivatives as used on the WB-001. The engine data used in the analysis is that of the RD-701, so if a vehicle requires a fractional number of engines, the design of the derivative engine would be scaled such that an integer number of engines were used. Each engine is expensive and has large maintenance requirements. Thus savings can be gained by lowering the number of engines that must be purchased and maintained on a vehicle.

Castor IV-A augmentation reduced dry weight by 11%, H-1800's reduced it by ~10%, and Ariane L40's provided a 15% reduction. With the levels considered here, the reductions in propulsion requirements were not great enough to reduce the engine requirements by even a single engine.

One might claim that an integer reduction is obtained (from five engines to four) by rounding up the number of engines to the next integer level. Since these engines are scalable, as mentioned above, the correct method would be to scale the baseline engine requirements to some integer level, apply this scale factor to the other cases, and *then* round these figures up to find the integer reductions most likely to be achieved. For example, at a 51.6° orbit, the baseline vehicle requires 4.26 engines, while the case using two L40's requires 3.32 engines. Scaling the baseline requirement to four engines results in a 3.12 engine requirement for the augmented case. This would *now* be rounded up to four, since the engine size has been fixed, thus no reduction in engines has been achieved.

Using two L40's nearly achieved an integer reduction, but due to their high cost would not be a cost-effective choice. Additionally, it is interesting to note that the reductions achieved by simply reducing the mission requirements of the ATD (13% reduction in dry weight) prove greater than those achieved with the Castor IV-A or H-1800, and nearly as great as those achieved with two L40's. This seems to indicate that augmentation, as used in this analysis, may not be significant in reducing vehicle scale for this type of vehicle. Certainly, a more detailed cost analysis - starting with operations and development cost estimates tailored specifically for the ATD (not scaled versions of the WB-001 equations) - would make it clearer whether or not augmentation is worth applying to this vehicle. If the cost saved by making a smaller vehicle is greater than the cost, over the flight lifetime of the vehicle, of the strap-on boosters necessary to keep its performance abilities at the original level, then it may be worth considering using augmentation on the ATD. A lower cost may also make it more likely that the vehicle would be built.

4. Conclusions

This study has demonstrated that, even though it essentially would make a SSTO vehicle a multistage one, augmentation can provide significant benefits to a SSV. The increased payload capability gained through the use of augmentation will give a SSV such as the WB-001 increased mission flexibility. It would operate primarily as originally intended (delivering payloads to Space Station, for example), but when the need arose, it can launch heavier payloads. Lower costs per pound of payload might be realized by using the SSV with augmentation, rather than by developing a vehicle specifically designed for larger class payloads. In the case of the WB-001 vehicle, augmentation can also be employed as a way to increase weight growth margin, reduce weight growth sensitivity, or compensate for lacking subsystem technologies. For vehicles such as the ATD presented here, augmentation allows the vehicle to be made smaller. This approach has the potential to lower the vehicle development and operations costs due to reduced material costs and lower propulsion system requirements while still allowing the vehicle to serve as a platform for proving the technologies needed for a full scale SSV.

From the three booster types in this study (the Castor IV-A, the Ariane L40, and the AMROC H-1800), the Castor seems to be the best candidate for SSTO. Its high performance, low cost, and excellent record of reliability give it an advantage over the other two. It was able to increase the WB-001's payload capability by as much as 70% with six boosters, or increase the vehicle's weight growth margin to as much as 26%. Using cost estimates from the Access to Space study, the Castor's showed continued cost reductions over the entire range of augmentation analyzed (up to 34%). The hybrid H-1800 was close to the Castor's abilities, and as more experience is gained in hybrid propulsion, hybrids could prove to be increasingly better candidates for applications such as this. The H-1800's were able to increase the WB-001's payload by as much as 67% with two boosters, or its margin up to 25%. And although slightly diminished compared to the

Castor's, the H-1800's were still able to reduce the WB-001's cost per pound of payload by as much as 27%, even at the low Access to Space cost levels. The Ariane L40's, although able to achieve a payload increase of 95% with four boosters and deliver a weight growth margin of up to 30%, were not as efficient as the Castor IV-A's or the AMROC H-1800's - from either a performance or a cost-effectiveness point of view. Little or no cost reductions were achieved at the Access to Space cost level. As with many decisions, cost is a significant factor in determining which booster is best for this type of application.

Using strap-on boosters to compensate for less advanced construction materials is a potential application on vehicles such as the WB-001. Although it would probably be difficult to employ augmentation as a means to overcome the penalties suffered by using aluminum on the major subsystems, it can be used if Al-Li was used in place of composites, or if aluminum was used in place of Al-Li in some of the smaller subsystems, such as the structure and the wing. Aluminum tanks, an aluminum secondary structure, an Al-Li complete structure, and an aluminum wing would require levels of augmentation higher than what were analyzed in this thesis, but it appears that these levels can be achieved.

There is a limit to the practicality of augmentation in cases such as those presented here. For "fixed design" vehicles such as the WB-001, the benefits of augmentation can only be utilized up to a certain point. The payload bay is designed to be a 15 ft diameter by 30 ft long cylinder and this cannot be changed. As a result, the vehicle is volume limited and at some point the extra mass capability gained through augmentation will begin to be wasted. This point depends on the density of the payload(s). Dense payloads are feasible that could fully benefit from the performance gains achieved through augmentation. For example, a payload canister filled with liquid oxygen (which could serve as propellant for an interplanetary expedition) would weigh on the order of 370,000 lb. This type of payload may be a bit extreme compared to the communications satellites that make up the bulk of today's payloads, but it illustrates the type of application for which augmentation can be used. For payloads with densities on the order of current communications satellites, the upper limit for weight would be lower. Further gains would require a vehicle redesign to allow for a larger payload bay.

The conclusion reached concerning augmentation and the ATD was that it does not appear that augmentation can provide significant benefits. Reductions in the dry weight of the ATD core vehicle ranged up to 15%, but the engine requirements were not even reduced by a single engine for the range of augmentation analyzed. Detailed cost equations need to be developed specifically for the ATD before any definite conclusions can be drawn whether or not augmentation would be cost effective for this particular application. Savings in materials and propellant requirements can be realized, but without a detailed cost analysis, it is too difficult to determine whether or not these savings can offset the cost of the boosters over the lifetime of the vehicle.

Practicality concerns also exist for the ATD over where to attach all of the strap-on boosters. Since the vehicle is relatively small, space is limited, and at some point there will simply be no place to attach additional boosters to the core vehicle. This did not become an issue during this study due to the relatively low levels of augmentation analyzed. Additionally, one must not lose sight of the ATD's original purpose - to demonstrate and prove the advanced technologies necessary for developing a full scale SSV. A large degree of augmentation might seem to hamper that goal by dominating the vehicle and making its operations and performance characteristics difficult to evaluate.

If these concerns and potential benefits are kept in mind, augmentation can be used to increase the efficiency (in performance, cost, etc.) of new SSTO concept vehicles until sufficient knowledge and experience can be gained such that one can be developed that is widely accepted as affordable and practical.

5. Future Work

There are areas where extensions of this study can be performed. First, a wider selection of boosters can be tested. The three described in this report were chosen as representatives of the three main methods of rocket propulsion - solid, liquid, and hybrid. Certainly there are more boosters that could be applied to this particular application (e.g. the Castor 120, and IV-XL, Hercules GEM, AMROC H-900, etc.). Also, determining the limit of the number of boosters that can be attached to the vehicles would be useful. Next, improved aerodynamic modeling of the vehicle configurations can be performed. If a more in-depth investigation of augmentation of SSTO vehicles is authorized, wind tunnel analysis of the ATD vehicle alone and configurations of boosters and core vehicle (both full-scale and ATD) should be performed. Also, since it was not the focus of this study, attachment requirements of the boosters can be analyzed in detail. Most likely, some sort of attachment structure would have to be designed for the particular booster employed. Finally, a detailed set of cost estimates should be developed for the ATD. This would better indicate whether or not augmentation would make the ATD more cost effective.

6. References

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Appendix A. Weight and Sizing Statement for WB-001 SSTO Vehicle (baseline)

```
                    WEIGHT STATEMENT - LEVEL I (lb)

          unmanned ssv dual-fuel, rd-701, horz. 30 ft p/l bay,
                        25klb p/l - 51.6 inc.

  1.0 Wing                                              10823.
  2.0 Tail                                               1902.
  3.0 Body                                              62357.
  4.0 Induced environment protection                    19580.
  5.0 Undercarriage and aux. systems                     7018.
  6.0 Propulsion, main                                  52929.
  7.0 Propulsion, reaction control (RCS)                 3626.
  8.0 Propulsion, orbital maneuver (OMS)                 2276.
  9.0 Prime power                                        2339.
 10.0 Electric conversion and distr.                     6331.
 11.0 Hydraulic conversion and distr.                       0.
 12.0 Control surface actuation                          1285.
 13.0 Avionics                                           1314.
 14.0 Environmental control                              2395.
 15.0 Personnel provisions                                  0.
 18.0 Payload provisions                                    0.
 19.0 Margin                                            26126.
                   EMPTY                               200300.
 20.0 Personnel                                             0.
 21.0 Payload accomodations                                 0.
 22.0 Payload                                           25000.
 23.0 Residual and unusable fluids                      13047.
 25.0 Reserve fluids                                     7290.
 26.0 Inflight losses                                    3804.
 27.0 Propellant, main                               2143859.
 28.0 Propellant, reaction control                       2887.
 29.0 Propellant, orbital maneuver                      19372.
                   PRELAUNCH GROSS                   2415560.
                                                            0.
Prelaunch gross                                      2415560.
     Start-up losses                                   -32127.
Gross lift-off                                       2383432.
     Ascent propellant                               -2111732.
Insertion                                              271700.
     Ascent reserves                                    -5911.
     Ascent residuals                                  -10986.
     Inflight losses                                    -3804.
     Aux. propulsion propellant                        -21565.
     Payload delivered                                 -25000.
     Payload accepted                                   25000.
Entry                                                  229434.
     RCS prop. (entry)                                   -695.
Landed                                                 228740.
     Payload (returned)                                -25000.
Landed (p/l out)                                       203740.
     Personnel                                              0.
     Payload accomodations                                  0.
     Subsystem residuals                                 -592.
     Aux. propulsion residuals                          -1468.
     Aux. propulsion reserves                           -1380.
Empty                                                  200300.
```

```
          unmanned ssv dual-fuel, rd-701, horz. 30 ft p/l bay,
                         25klb p/l - 51.6 inc.

      DESIGN DATA

payload volume (cu. ft.)                                    5300.0000
payload weight (lb)                                        25000.0000
oms delta v req. (ft./sec.)                                 1100.0000
lift-off t/w ratio                                             1.2000
mass ratio                                                     8.7723
rocket reduction factor                                        0.0000
body_length_______________ft_                                185.6408
body_width________________ft_                                 28.5831
body_volume____________cu_ft_                             105712.4688
body_tps_wetted_area___sq_ft_                              15563.9063
nose_section_area______sq_ft_                                415.4419
intertank_area_________sq_ft_                               4772.4561
aft_body_area__________sq_ft_                                907.4503
engine_bay_area________sq_ft_                               1075.4755
lox_tank_wetted_area___sq_ft_                               4831.8750
lox_tank_volume________cu_ft_                              25897.4355
lh2_tank_wetted_area___sq_ft_                               6494.8193
lh2_tank_volume________cu_ft_                              39420.7734
ker_tank_volume________cu_ft_                               4361.7295
wing_tps_wetted_area___sq_ft_                               5067.3770
carry_through_width_______ft_                                 25.8013
exposed_wing_span_________ft_                                 67.1871
exposed_wing_root_chord___ft_                                 59.5226
exposed_wing_planform__sq_ft_                               2444.5767
exposed_wing_taper_ratio_____                                  0.2324
exposed_wing_aspect_ratio____                                  1.8472
body flap length (ft)                                          8.1343
tip fins (2) planform area (ft2)                             271.5986

      SIZING PARAMETERS

Mass ratio                                                     8.7723
Propellant mass fraction                                       0.8860
Body length (ft.)                                               185.6
Wing span (ft.)                                                  93.0
Theoretical wing area (sq. ft.)                                4192.2
Wing loading at design wt (psf)                                  54.6
Wing planform ratio, sexp/sref                                   0.58
Sensitivity of volume to burnout wt (cu. ft./klb.)              383.9
Burnout weight growth factor (lb/lb)                              2.6

                                                      BODY       WING
Total volume (cu. ft.)                              105712.     13373.
Tank volume (cu. ft.)                                68888.         0.
Fixed volume (cu. ft.)                                   0.         0.
Tank efficiency factor                               0.6517     0.0000
Ullage volume fraction                               0.0300     0.0300

                                 DENSITY     FLUID VOLUME  TANK VOLUME
PROPELLANT         FRACTION   (lb/cu. ft.)    (cu. ft.)     (cu. ft.)
  lh2               0.0780        4.42          37820.        38990.
  hc                0.0987       50.50           4189.         4318.
  lox               0.8234       71.14          24813.        25580.
  lox       (Wing)  0.0000       71.14              0.            0.
```

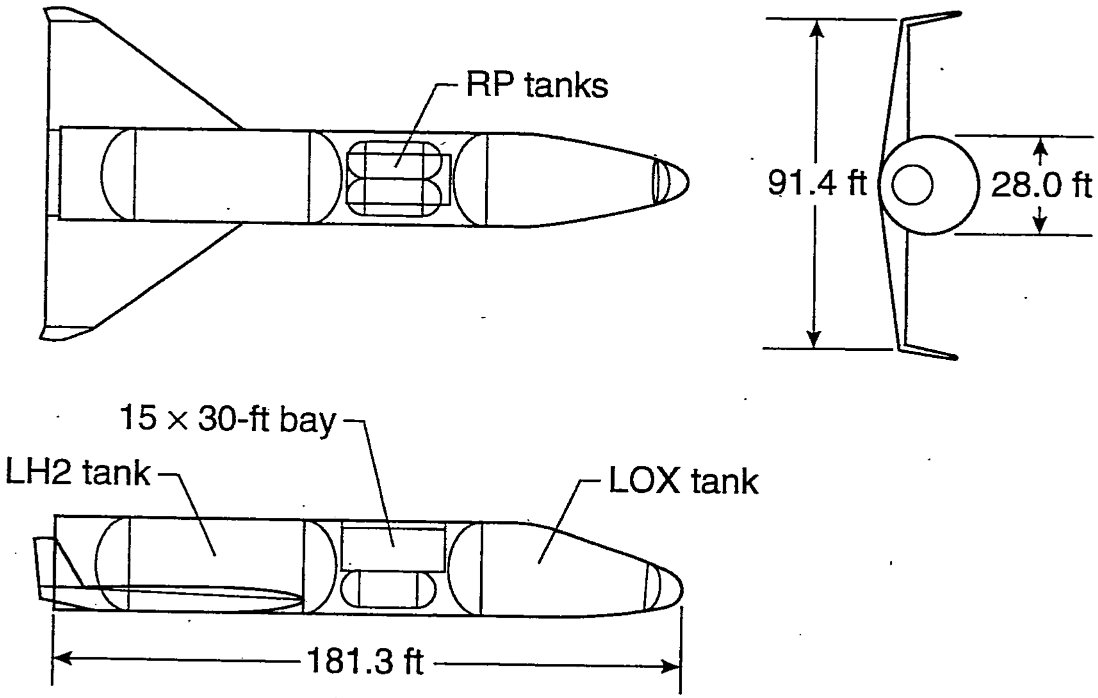


FIGURE A1: CONFIGURATION OF WB-001 SSTO VEHICLE CONCEPT

Appendix B. Baseline Trajectory of WB-001 SSTO Vehicle

This section contains ascent trajectory plots for the reference WB-001 SSTO vehicle. The reference mission [4] is to deliver 25,000 lb of payload to a 220 nmi circular, 51.6° inclination orbit with a nominal insertion orbit of 50 x 100 nmi from a KSC launch site. The mission duration is 5 days. The variables that are plotted, respectively, versus time are altitude, relative velocity, acceleration, inertial pitch angle, dynamic pressure, and normal force. Axial acceleration is limited to 3g, maximum dynamic pressure is to be no greater than 1000 psf, and the normal force on the vehicle is held to 2.5 times 2/3 the landed weight throughout the trajectory.

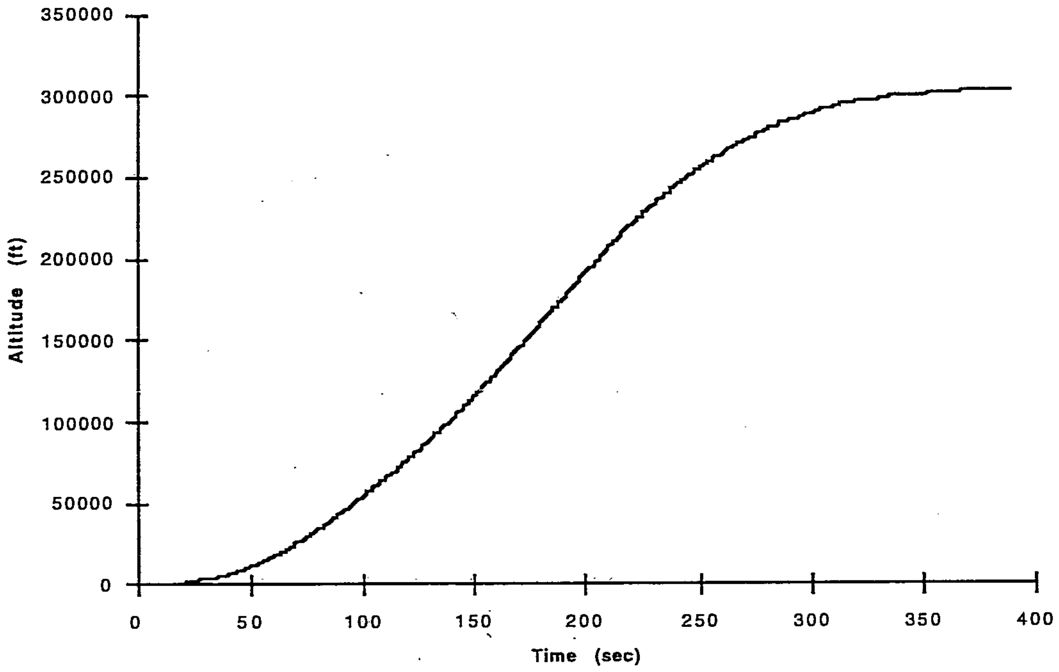


FIGURE B1: ALTITUDE PROFILE OF REFERENCE SSTO, WB-001

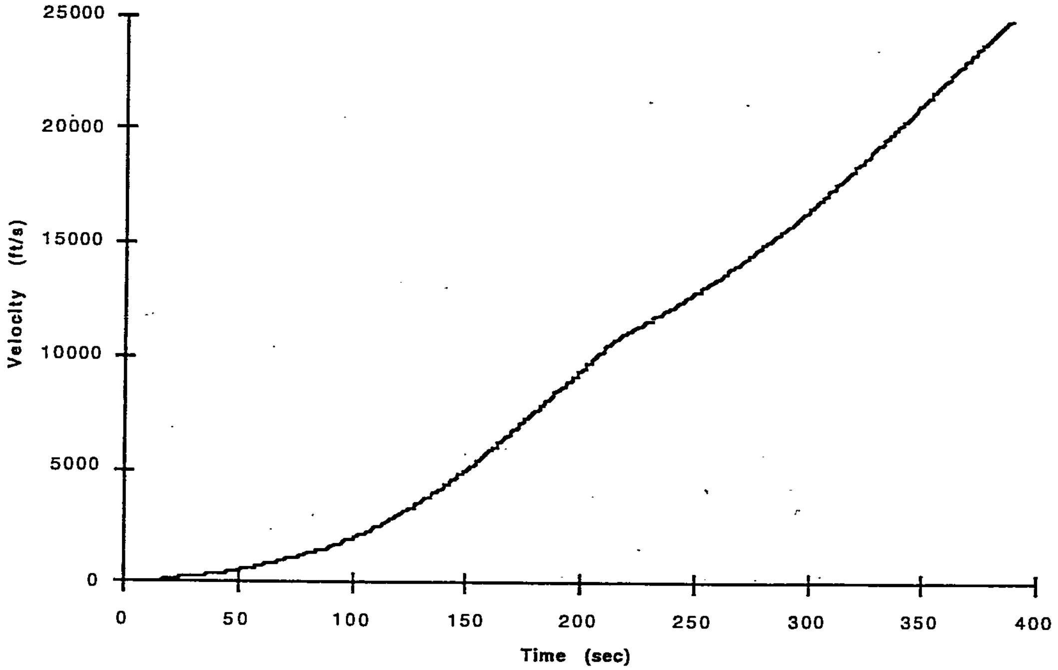


FIGURE B2: VELOCITY PROFILE OF REFERENCE SSTO, WB-001

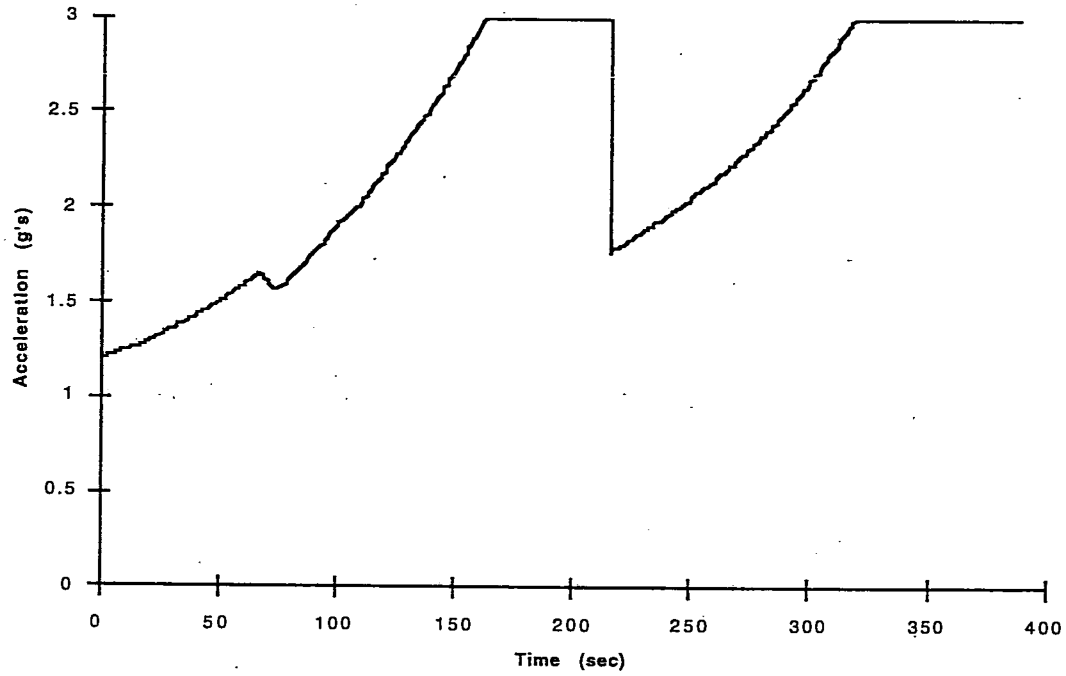


FIGURE B3: ACCELERATION PROFILE OF REFERENCE SSTO, WB-001

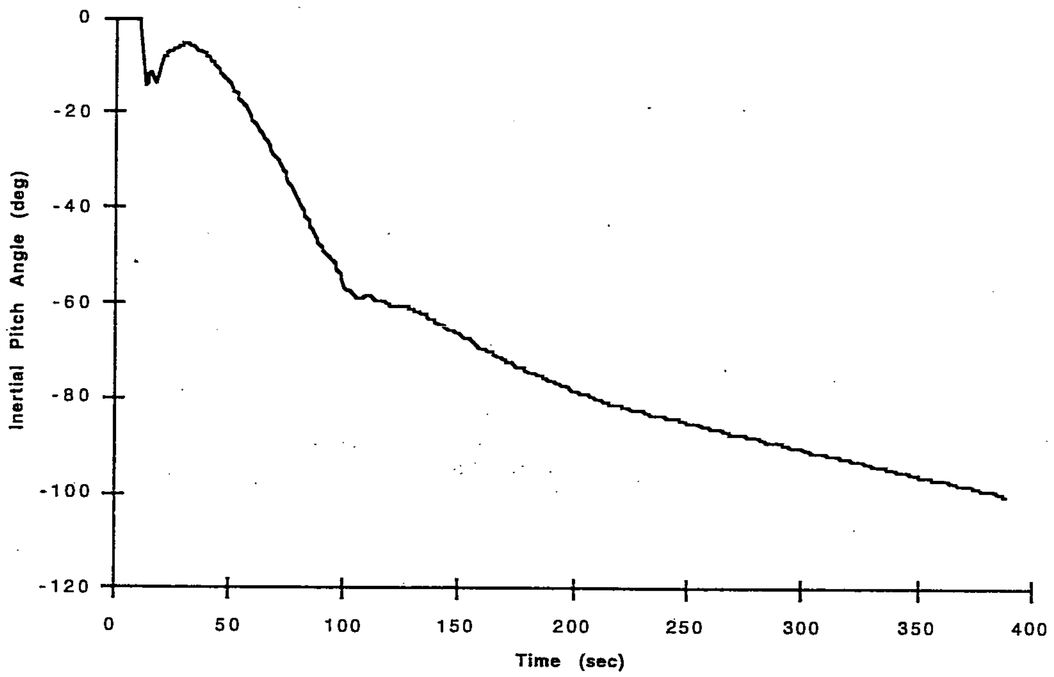


FIGURE B4: INERTIAL PITCH ANGLE PROFILE OF REFERENCE SSTO, WB-001

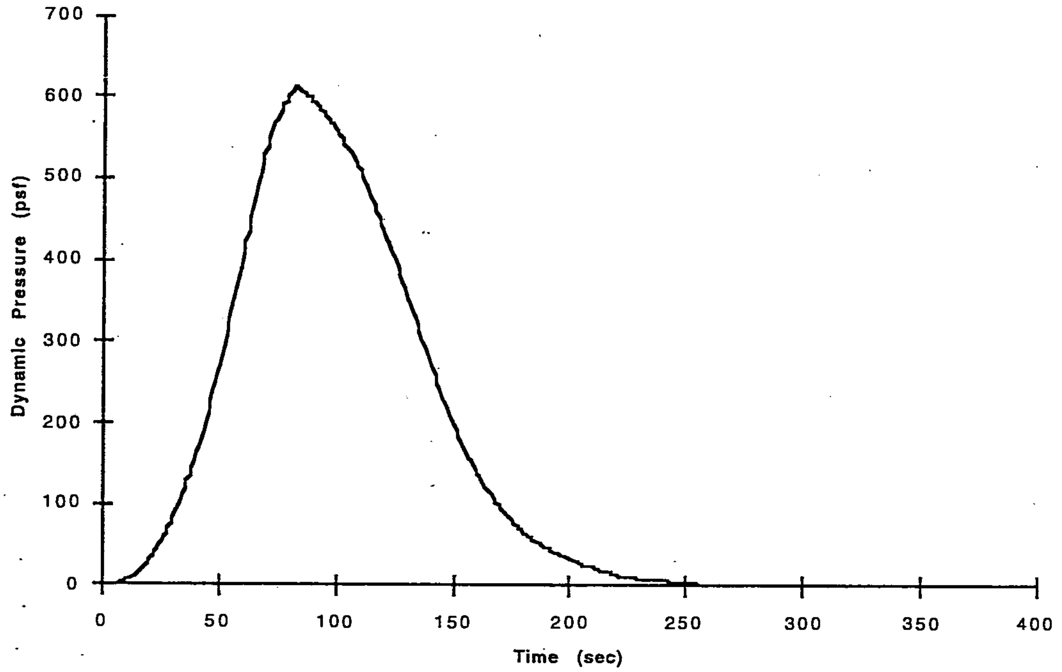


FIGURE B5: DYNAMIC PRESSURE PROFILE OF REFERENCE SSTO, WB-001

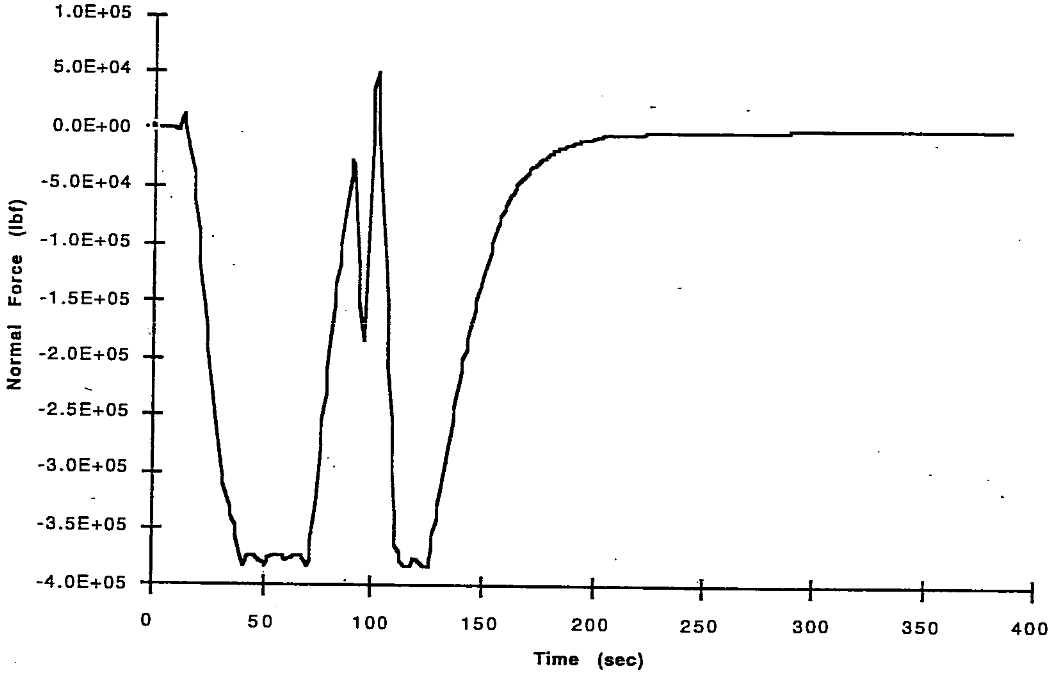


FIGURE B6: NORMAL FORCE PROFILE OF REFERENCE SSTO, WB-001

Appendix C. Weight and Sizing Statement for Advanced Technology Demonstrator (ATD) (baseline)

WEIGHT STATEMENT - LEVEL I (lb)
unmanned atd dual-fuel, rd-701, 2klb p/l - 28.5 inc.

1.0 Wing	5429.
2.0 Tail	969.
3.0 Body	41682.
4.0 Induced environment protection	13153.
5.0 Undercarriage and aux. systems	4404.
6.0 Propulsion, main	28209.
7.0 Propulsion, reaction control (RCS)	3076.
8.0 Propulsion, orbital maneuver (OMS)	835.
9.0 Prime power	2339.
10.0 Electric conversion and distr.	6152.
11.0 Hydraulic conversion and distr.	0.
12.0 Control surface actuation	777.
13.0 Avionics	1314.
14.0 Environmental control	2182.
15.0 Personnel provisions	0.
18.0 Payload provisions	0.
19.0 Margin	16578.
EMPTY	127099.
20.0 Personnel	0.
21.0 Payload accomodations	0.
22.0 Payload	2000.
23.0 Residual and unusable fluids	7025.
25.0 Reserve fluids	4021.
26.0 Inflight losses	3753.
27.0 Propellant, main	1138911.
28.0 Propellant, reaction control	1596.
29.0 Propellant, orbital maneuver	2995.
PRELAUNCH GROSS	1287400.
	0.
Prelaunch gross	1287400.
Start-up losses	-17123.
Gross lift-off	1270278.
Ascent propellant	-1121789.
Insertion	148489.
Ascent reserves	-3230.
Ascent residuals	-5845.
Inflight losses	-3753.
Aux. propulsion propellant	-4193.
Payload delivered	-2000.
Payload accepted	2000.
Entry	131468.
RCS prop. (entry)	-398.
Landed	131070.
Payload (returned)	-2000.
Landed (p/l out)	129070.
Personnel	0.
Payload accomodations	0.
Subsystem residuals	-339.
Aux. propulsion residuals	-841.
Aux. propulsion reserves	-791.
Empty	127099.

```
     unmanned atd dual-fuel, rd-701, 2klb p/l - 28.5 inc.

          DESIGN DATA

 payload volume (cu. ft.)                                   250.0000
 payload weight (lb)                                       2000.0000
 oms delta v req. (ft./sec.)                                303.0000
 lift-off t/w ratio                                           1.2000
 mass ratio                                                   8.5547
 rocket reduction factor                                      0.0000
 body_length_______________ft_                              154.4056
 body_width________________ft_                               23.7738
 body_volume_____________cu_ft_                           60826.8867
 body_tps_wetted_area___sq_ft_                            10767.0879
 nose_section_area______sq_ft_                              287.4021
 intertank_area_________sq_ft_                             3301.5793
 aft_body_area__________sq_ft_                              627.7728
 engine_bay_area________sq_ft_                              744.0121
 lox_tank_wetted_area___sq_ft_                             3342.6838
 lox_tank_volume________cu_ft_                            14901.3691
 lh2_tank_wetted_area___sq_ft_                             4493.1050
 lh2_tank_volume________cu_ft_                            22682.6855
 ker_tank_volume________cu_ft_                             2509.7363
 wing_tps_wetted_area___sq_ft_                             2729.6140
 carry_through_width_______ft_                               21.4601
 exposed_wing_span_________ft_                               49.3111
 exposed_wing_root_chord___ft_                               43.6859
 exposed_wing_planform__sq_ft_                             1316.8057
 exposed_wing_taper_ratio_____                                0.2324
 exposed_wing_aspect_ratio____                                1.8472
 body flap length (ft)                                        6.7656
 tip fins (2) planform area (ft2)                           146.3005

          SIZING PARAMETERS

 Mass ratio                                                   8.5547
 Propellant mass fraction                                     0.8831
 Body length (ft.)                                            154.4
 Wing span (ft.)                                               70.8
 Theoretical wing area (sq. ft.)                             2401.9
 Wing loading at design wt (psf)                               54.6
 Wing planform ratio, sexp/sref                                0.55
 Sensitivity of volume to burnout wt (cu. ft./klb.)           404.2
 Burnout weight growth factor (lb/lb)                           2.5

                                                   BODY        WING
 Total volume (cu. ft.)                           60827.      5287.
 Tank volume (cu. ft.)                            36596.         0.
 Fixed volume (cu. ft.)                               0.         0.
 Tank efficiency factor                           0.6016     0.0000
 Ullage volume fraction                           0.0300     0.0300

                                  DENSITY     FLUID VOLUME  TANK VOLUME
 PROPELLANT           FRACTION  (lb/cu. ft.)   (cu. ft.)     (cu. ft.)
   lh2                 0.0780       4.42         20091.        20713.
   hc                  0.0987      50.50          2225.         2294.
   lox                 0.8234      71.14         13182.        13589.
   lox         (Wing)  0.0000      71.14             0.            0.
```

Appendix D. Baseline Trajectory of ATD Vehicle

This section contains ascent trajectory plots for the reference SSTO Advanced Technology Demonstrator (ATD) vehicle. The reference mission is to deliver 2,000 lb of payload to a 100 nmi circular, 28.5° inclination orbit with a nominal insertion orbit of 50 x 100 nmi. A KSC launch site and a 5 day mission duration were assumed. The variables that are plotted, respectively, versus time are altitude, relative velocity, acceleration, inertial pitch angle, dynamic pressure, and normal force. Axial acceleration is limited to 3g, maximum dynamic pressure is to be no greater than 1000 psf, and the normal force on the vehicle is held to 2.5 times 2/3 the landed weight throughout the trajectory.

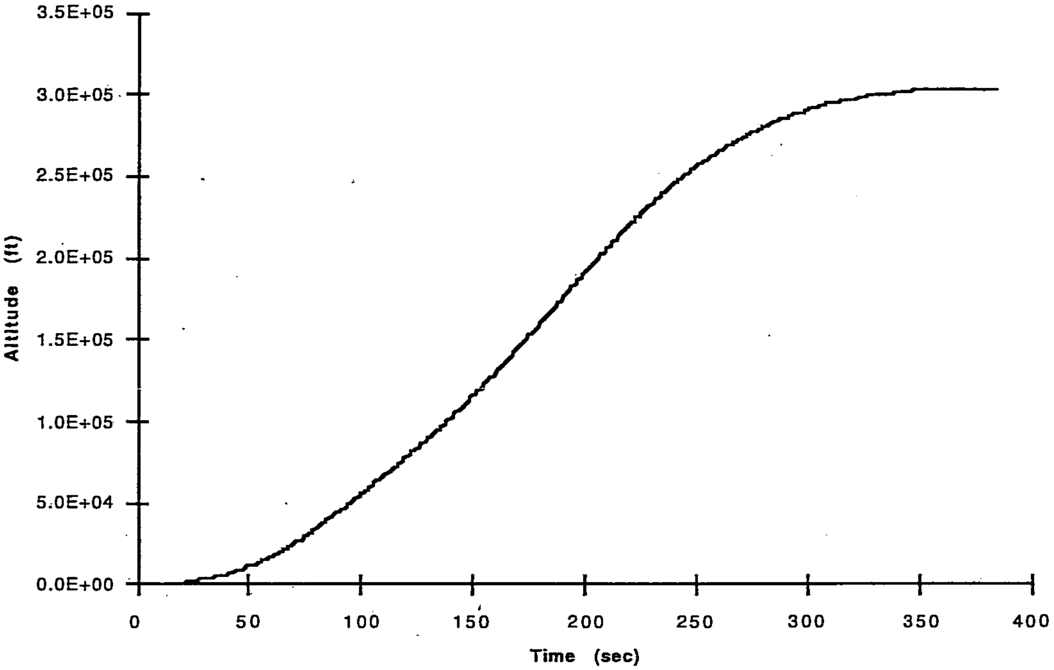


FIGURE D1: ALTITUDE PROFILE FOR REFERENCE ATD VEHICLE

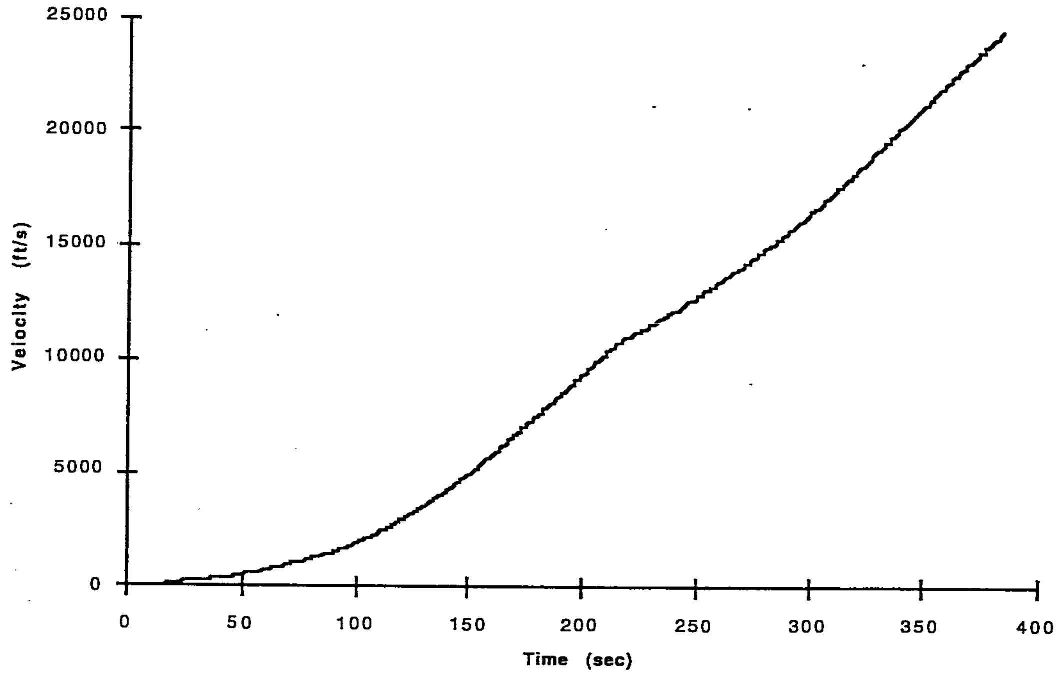


FIGURE D2: VELOCITY PROFILE FOR REFERENCE ATD VEHICLE

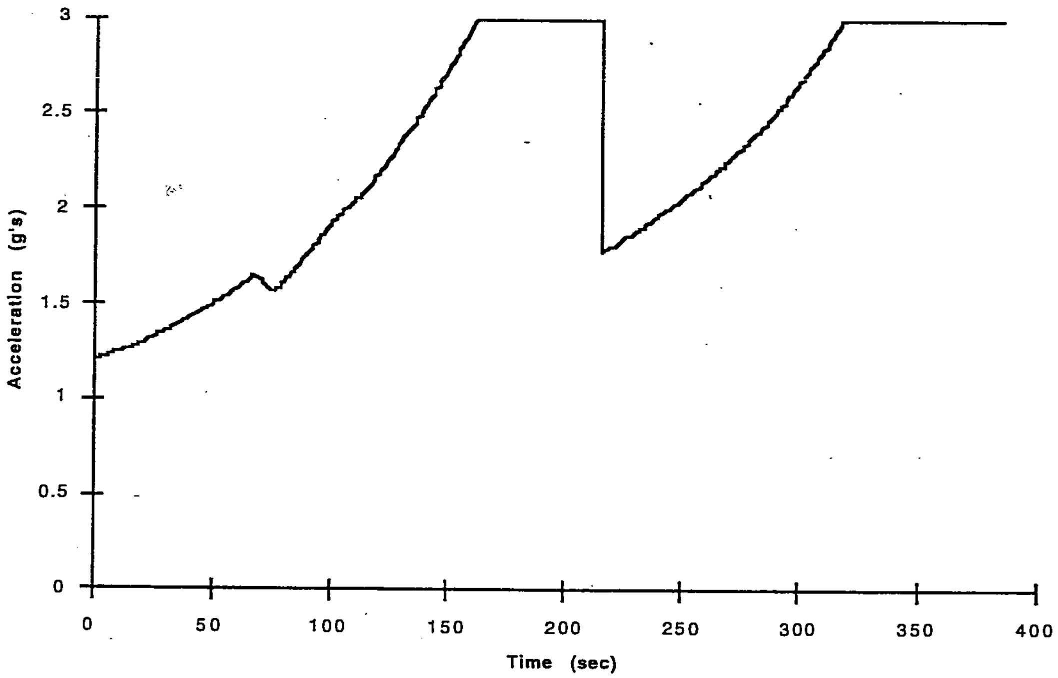


FIGURE D3: ACCELERATION PROFILE FOR REFERENCE ATD VEHICLE

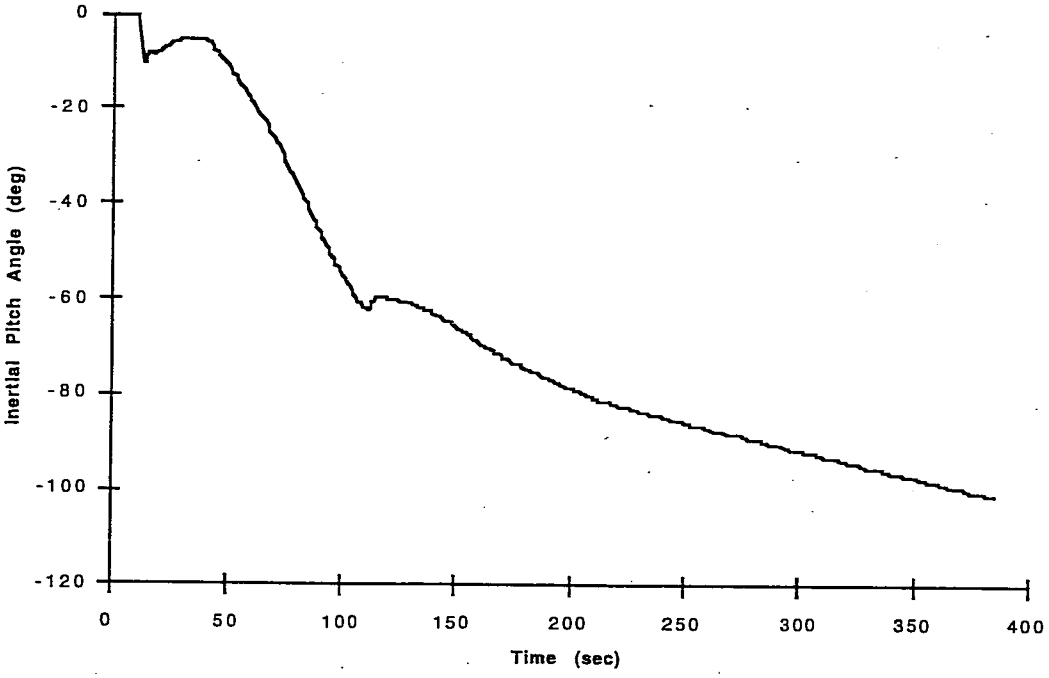


FIGURE D4: INERTIAL PITCH ANGLE PROFILE FOR REFERENCE ATD VEHICLE

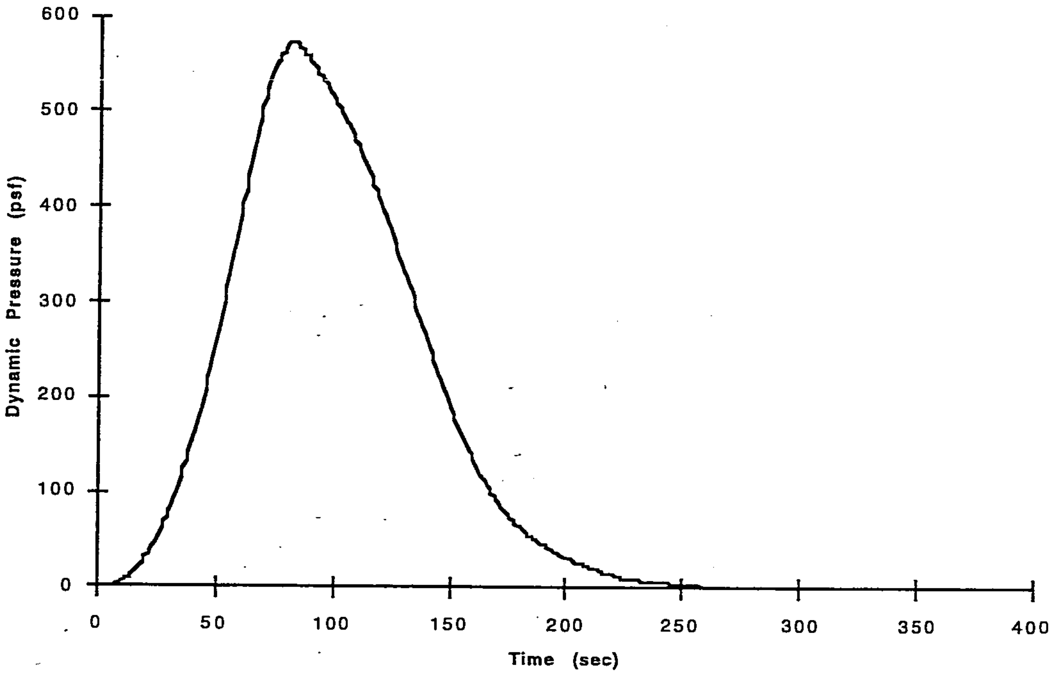


FIGURE D5: DYNAMIC PRESSURE PROFILE FOR REFERENCE ATD VEHICLE

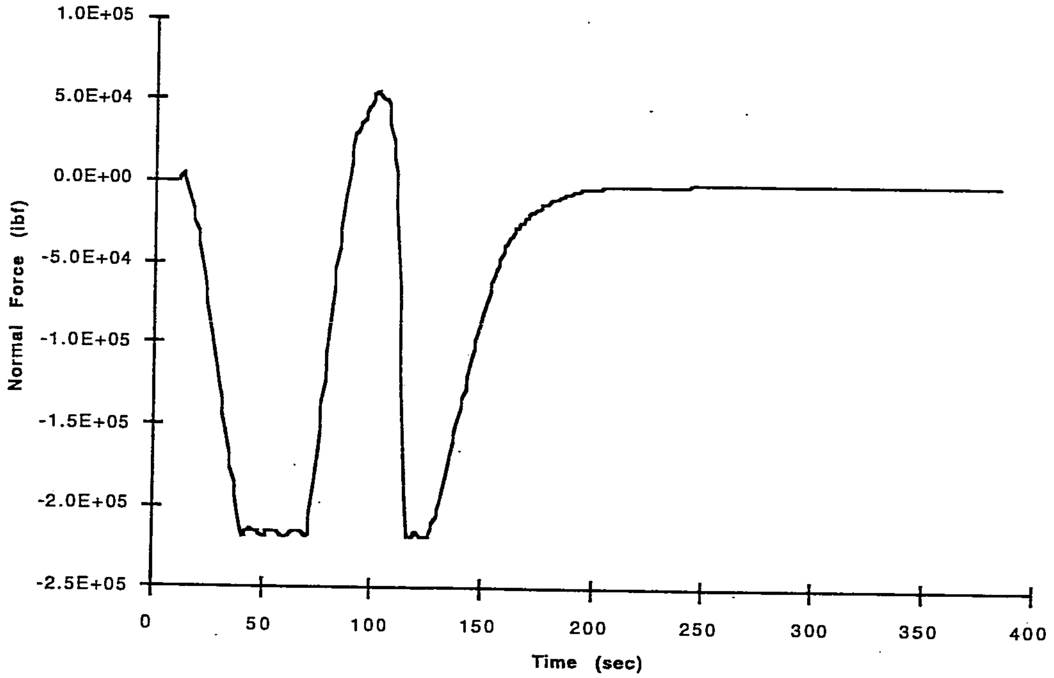


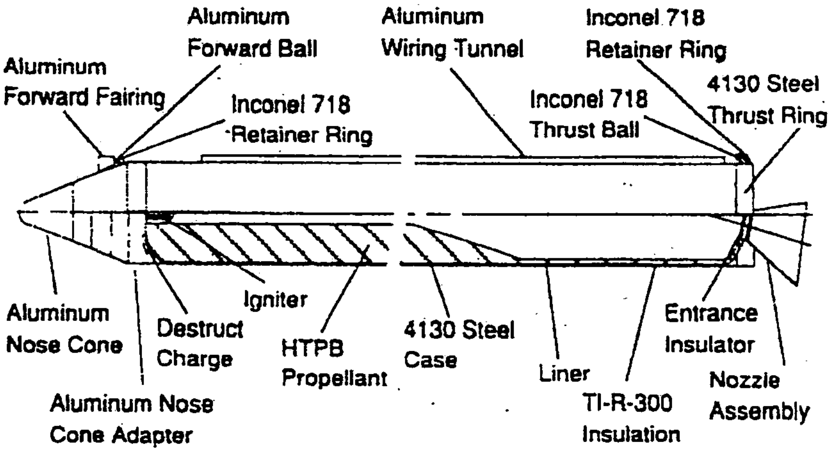
FIGURE D6: NORMAL FORCE PROFILE FOR REFERENCE ATD VEHICLE

Appendix E.   Booster Specifications

Castor IV-A SRM

[5,8]

Length	36.6 ft
Diameter	3.3 ft
Propellant Mass	22,300 lb
Gross Mass	25,800 lb
Propellant	HTPB
Average Thrust (vac)	108,700 lbf
Isp (vac)	265.7 sec
Nominal Burn Time	56.2 sec
Cost (based on 36/yr)	$690,000 each

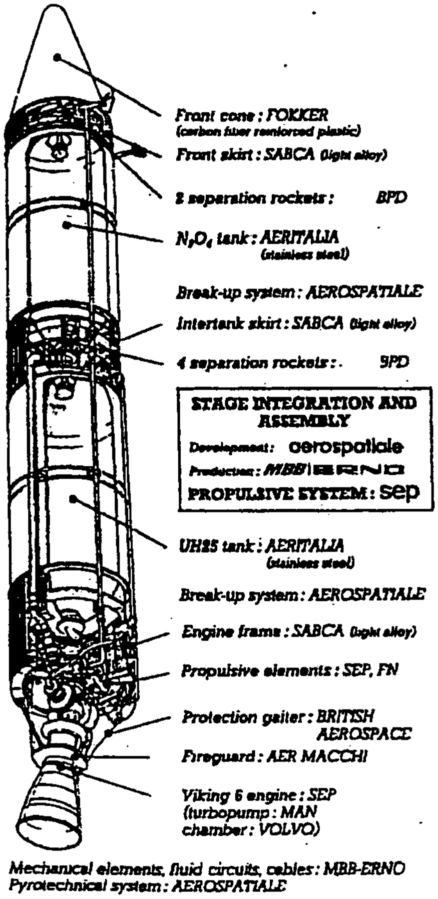


Castor IVA

Ariane L40 (PAL) LRM

[8,13]

Length	61.0 ft
Diameter	7.12 ft
Propellant Mass	86,000 lb
Gross Mass	95,900 lb
Propellant	N_2O_4 / UH25
Average Thrust (vac)	167,000 lbf
Isp (vac)	278 sec
Nominal Burn Time	140 sec
Cost [6,9]	$7,830,000

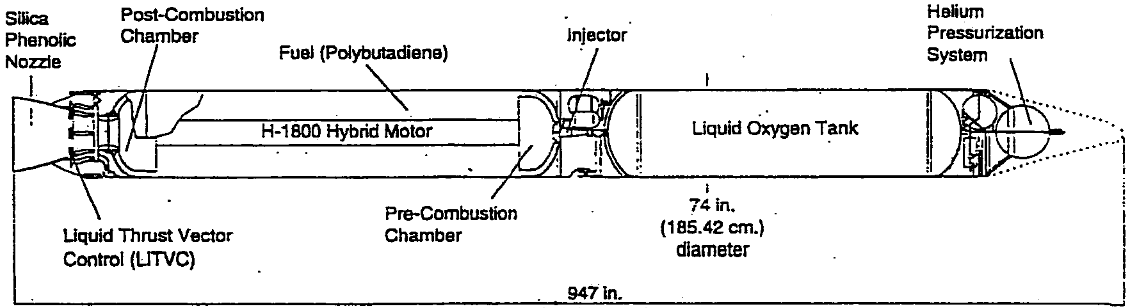


AMROC H-1800 HRM

[12]

Length	78.9 ft
Diameter	6.2 ft
Propellant Mass	66,520 lb
Gross Mass	79,970 lb
Propellant	HTPB / LOx
Average Thrust (vac)	260,530 lbf
Isp (vac)	282 sec
Nominal Burn Time	72 sec
Cost *	$3.5 million each (est.)

* Obtained through private conversation with R. Jay Kniffen, American Rocket Company (AMROC).



AMROC H-1800 Hybrid Rocket Motor

Appendix F. Booster Aerodynamic Data

The aerodynamic data for the boosters in this study involved only the zero-angle-of-attack drag coefficient, C_{D0}. Since this was an ascent trajectory, and the boosters are essentially axisymmetric bodies, it was felt that this data would be sufficient. The data was generated by DATCOM [7] (Mach ≤ 3), and APAS [11] (Mach ≥ 3).

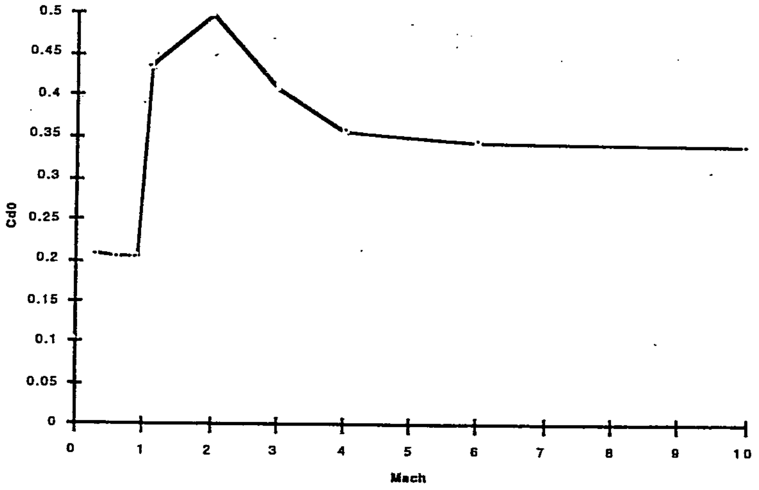


FIGURE F1: ZERO-ANGLE-OF-ATTACK DRAG COEFFICIENT VARIATION FOR CASTOR IV-A SRM

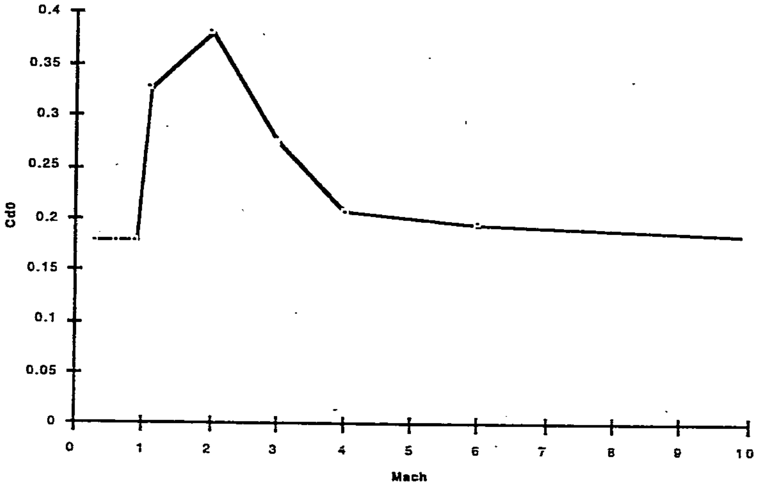


FIGURE F2: ZERO-ANGLE-OF-ATTACK DRAG COEFFICIENT VARIATION FOR L40 LRM

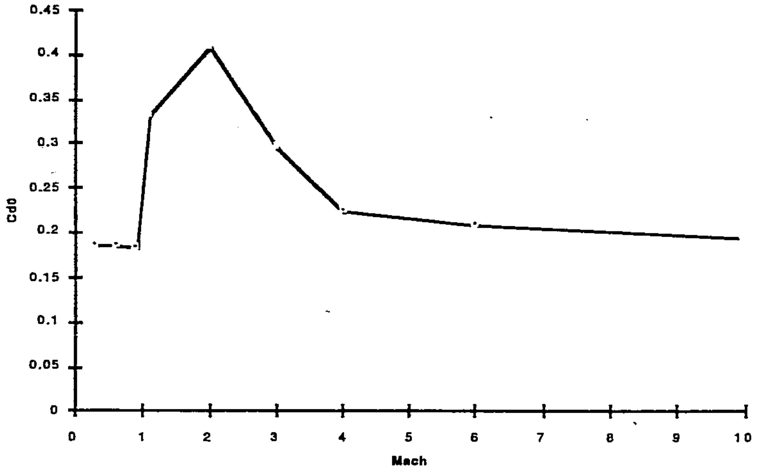


FIGURE F3: ZERO-ANGLE-OF-ATTACK DRAG COEFFICIENT VARIATION FOR H-1800 HRM

Appendix G. Program to Optimize Simulated Trajectories (POST)

POST [3] is a three-degree-of-freedom generalized point mass, discrete parameter targeting and optimization program. It has the capability to target and optimize point mass trajectories for a powered or unpowered vehicle near an arbitrary, oblate planet. It can optimize or constrain any variable it calculates. A great deal of flexibility is achieved by decomposing the simulated trajectory into a sequence of simulation phases. Each phase can be modeled and simulated according to the detail required in that particular portion of the trajectory. POST has been used to optimize ascent, entry, and landing trajectories for a wide variety of vehicles. For simplicity and speed, the 3-d version of POST was used (instead of the 6-d version). The vehicle is treated as a point mass and the trajectory is calculated using the translational equations of motion only. The rotational equations of motion are not utilized. Any rotation-dependent calculations, such as aerodynamic lift and drag, are performed through the use of lookup tables.

For this study, the optimal ascent trajectory of a SSTO vehicle augmented with strap-on boosters was calculated. The trajectory was simulated from launch to orbit insertion. The launch site was at 28.5° N latitude, assumed to be Kennedy Space Center. Two orbits were tested - 28.5° and 51.6° inclination - with the insertion orbit being a 50 x 100 nmi ellipse. Extra fuel was included for OMS burns to put the WB-001 vehicle into a 220 nmi circular orbit and the ATD vehicle into a 100 nmi circular orbit. For both vehicles studied, the burnout weight - the weight of the vehicle when it reaches orbit - was maximized. Equality constraints on the trajectory were final altitude, velocity, and flight path angle (pre-circularization of orbit), and orbit inclination. Inequality constraints were placed on allowable normal force experienced by the vehicle, dynamic pressure, and angle of attack. The independent variables that define the trajectory are the launch azimuth, vehicle pitch angle history (vs. time), time of propulsion system transition (from RP/LH_2/LOX to LH_2/LOX),and total ascent time. The major phases during the ascent were main engine transition from burning hydrogen, kerosene, and oxygen to hydrogen and oxygen, and booster burn-out and separation. The simulation was initially set up to fly the vehicle such that it "rode" the normal force limit for as long as possible - this is the most efficient trajectory, but instabilities in the implementation of this method prevented a converged trajectory (one where all of the constraints are satisfied) from being achieved with the specific vehicles and configurations analyzed in this study. This is a known problem and it was hoped that there would be a chance to fix it, but time was not available. By not flying the normal force boundary, the only effect on the trajectory would be a slightly lower burnout weight.

Inputs to POST involving the core vehicle (WB-001 or ATD) were reference length and area, gross lift-off weight, and vehicle weight at landing. Vehicle weight at landing was used to calculate the vehicle normal force limit with the equation:

$$F_{azb} = \frac{2}{3} \times 2.5 \times W_{landed}$$

which is due to the requirement that the vehicle must be able to perform a 2.5g pull-up maneuver before landing. Aerodynamic inputs for the boosters (C_{D0}) were generated by using the DATCOM method outlined in Appendix J. Aerodynamic data for the core vehicle (C_D, C_L, and C_M) were obtained from wind tunnel tests. Additional input included thrust and I_{sp} of the main engines and strap-ons and propellant and dry weights of the strap-ons as detailed in Appendix E.

Appendix H. Configuration Sizing Program (CONSIZ)

CONSIZ [10] is used to determine the weights and sizes of an aerospace vehicle and its subsystems. Information about each subsystem, in the form of parametric equations, is included in the analysis. From these equations, the weights, locations, sizes, and moments of inertia for all of the entire vehicle's subsystems are calculated. The overall weights and sizes of the vehicle are also calculated.

Vehicle sizing was performed in two different manners. A different approach was followed for each of the two SSTO concepts studied. For the WB-001 concept, vehicle resizing was used to determine a revised figure of the vehicle's payload capability due to loading requirements of the vehicle wing during landing. While attempting to keep the fuselage of the vehicle fixed, the required size of the wing was calculated. Due to the increased weight of the wing, the payload capacity of the vehicle would decrease slightly. For the ATD concept, the payload was held fixed and the entire vehicle was scaled around it.

The vehicle parametrics were defined once. To perform the scaling described above, some additional information was needed. For the WB-001 vehicle, the target GLOW and mass ratio (GLOW divided by burnout weight) were needed. For the ATD concept, only the mass ratio was required.

Appendix I. Aerodynamic Preliminary Analysis System (APAS)

APAS [11] is a set of computer programs used to perform preliminary aerodynamic analysis on a variety of aerospace vehicles. It was jointly developed by NASA LaRC and Rockwell International. It is easy to learn, inexpensive to operate, and yields useful information, but it is not intended to be a substitute wind tunnel tests or more detailed analytical methods.

Vehicle geometry can be input in one program, then analyzed using the others, all within a single interactive environment. Subsonic and supersonic analysis is done by a program called UDP (Unified Distributed Panel), which uses slender body theory and source and vortex panel methods to perform its calculations. Hypersonic analysis is based on impact theory and is performed by the Hypersonic Arbitrary Body Program (HABP).

APAS was used to generate supersonic and hypersonic aerodynamic drag estimates, as well as compare against the results achieved by the DATCOM method, for the three types of strap-on boosters examined in this study. These estimates (multiplied by the number of boosters used) were be added to the drag data of the core vehicle. Since the study involved only ascent trajectories, which typically involve relatively small angles of attack (<20°), only the zero-lift drag coefficients were computed.

It is understood that the data generated is good only for a “first-cut” analysis. They do not account for any interference effects caused by the attachment of the boosters to the fuselage. A 20% margin was added to try to compensate for this deficiency. To produce more accurate data would involve performing an aerodynamic analysis on the entire configuration (core vehicle + boosters) for each level of augmentation studied - a lengthy and possibly expensive process. If augmentation does become a serious option, a more detailed analysis, most likely involving wind tunnel simulations, would most likely be performed.

Appendix J. DATCOM

DATCOM [7] is a method developed by the U.S. Air Force used to calculate aerodynamic data. It was designed to estimate the aerodynamic coefficients of a variety of conventional configurations. It uses a mixture of conventional aerodynamic theory and empirical approximations to form sets of equations and charts that can be used over a wide range of Mach numbers. It was originally developed for predicting missile aerodynamics, and thus works best when analyzing vehicles with a missile-like shape.

Appendix K. Tables of Numerical Results

This section contains tables of the numerical results shown as charts and graphs in the main body of this report. The tables also contain some of the intermediate data used to calculate some of the results. Each table is labeled with the figure number with which it is associated.

Payload Increases

This chart contains the data used to generate figures 2.2 through 2.7. All masses are in pounds. The OMS delta V required for insertion into a 220 nmi circular orbit from a 50 x 100 nmi orbit is 1100 ft/s.

# Boosters	Burnout Wt.	Initial Optimum Pyld.	OMS Wt.	OMS Revision	Sizing Revision
0	271849	25000	19368	25000	25000
1	275512	28663	19629	28402	28066
2	278824	31976	19865	31479	30709
3	281947	35098	20087	34379	33196
4	284916	38068	20299	37137	35573
5	287878	41029	20510	39887	37963
6	290669	43820	20709	42479	40410

TABLE K1: PAYLOAD DATA FOR CASTOR IV-A AUGMENTATION (51.6° ORBIT)

# Boosters	Burnout Wt.	Initial Optimum Pyld.	OMS Wt.	OMS Revision	Sizing Revision
0	281078	43470	20025	42813	40897
1	284664	47056	20281	46143	43736
2	288287	50679	20539	49508	46637
3	291612	54004	20776	52596	49315
4	294837	57230	21006	55592	51935
5	297808	60200	21217	58351	54339
6	300657	63049	21420	60997	56653

TABLE K2: PAYLOAD DATA FOR CASTOR IV-A AUGMENTATION (28.5° ORBIT)

# Boosters	Burnout Wt.	Initial Optimum Pyld.	OMS Wt.	OMS Revision	Sizing Revision
0	271849	25000	19368	25000	25000
1	278708	31859	19857	31370	30616
2	285295	38446	20326	37488	35883
3	291469	44620	20766	43222	40865
4	297343	50495	21184	48678	45652

TABLE K3: PAYLOAD DATA FOR ARIANE L40 AUGMENTATION (51.6° ORBIT)

# Boosters	Burnout Wt.	Initial Optimum Pyld.	OMS Wt.	OMS Revision	Sizing Revision
0	281078	43470	20025	42813	40897
1	288107	50499	20526	49341	46497
2	294876	57268	21009	55628	51966
3	301257	63649	21463	61554	57137
4	307361	69754	21898	67223	62110

TABLE K4: PAYLOAD DATA FOR ARIANE L40 AUGMENTATION (28.5° ORBIT)

# Boosters	Burnout Wt.	Initial Optimum Pyld.	OMS Wt.	OMS Revision	Sizing Revision
0	271849	25000	19368	25000	25000
1	281457	34608	20052	33923	32802
2	289899	43051	20654	41765	39596

TABLE K5: PAYLOAD DATA FOR AMROC H-1800 AUGMENTATION (51.6° ORBIT)

# Boosters	Burnout Wt.	Initial Optimum Pyld.	OMS Wt.	OMS Revision	Sizing Revision
0	281078	43470	20025	42813	40897
1	290889	53281	20724	51925	48732
2	299677	62069	21351	60087	55853

TABLE K6: PAYLOAD DATA FOR AMROC H-1800 AUGMENTATION (28.5° ORBIT)

WB-001 Payload Cost Analysis

The following tables contain the data used to generate figures 2.9 through 2.17. The three levels of operations costs (per flight) were Shuttle ($400 million), Shuttle II ($100 million), and Access to Space ($33 million). To produce the graphs, divide each cost per pound figure by the cost per pound for the unaugmented vehicle at a 51.6° orbit using the Shuttle cost data (shaded cell: $16000/lb).

# of Boosters	Booster Cost	Cost/lb ($400M) 51.6°	Cost/lb ($100M) 51.6°	Cost/lb ($33M) 51.6°	Cost/lb ($400M) 28.5°	Cost/lb ($100M) 28.5°	Cost/lb ($33M) 28.5°
0	0	16000	4000	1320	9343	2336	771
1	690000	14108	3545	1186	8684	2182	730
2	1380000	12751	3221	1092	8107	2048	694
3	2070000	11695	2969	1020	7645	1941	667
4	2760000	10845	2767	963	7245	1848	643
5	3450000	10115	2594	914	6914	1773	625
6	4140000	9514	2452	874	6626	1707	609

Table K7: Payload Cost per Pound Data for Castor IV-A Augmentation

# of Boosters	Booster Cost	Cost/lb ($400M) 51.6°	Cost/lb ($100M) 51.6°	Cost/lb ($33M) 51.6°	Cost/lb ($400M) 28.5°	Cost/lb ($100M) 28.5°	Cost/lb ($33M) 28.5°
0	0	16000	4000	1320	9343	2336	771
1	7830000	13001	3437	1302	8266	2185	828
2	15660000	11088	3085	1298	7472	2079	875
3	23490000	9798	2857	1307	6880	2006	918
4	31320000	8861	2698	1321	6416	1953	957

Table K8: Payload Cost per Pound Data for Ariane L40 Augmentation

# of Boosters	Booster Cost	Cost/lb ($400M) 51.6°	Cost/lb ($100M) 51.6°	Cost/lb ($33M) 51.6°	Cost/lb ($400M) 28.5°	Cost/lb ($100M) 28.5°	Cost/lb ($33M) 28.5°
0	0	16000	4000	1320	9343	2336	771
1	3500000	11894	3051	1076	7771	1993	703
2	7000000	9745	2562	958	6774	1781	666

Table K9: Payload Cost per Pound Data for AMROC H-1800 Augmentation

Weight Growth Margin Analysis

These tables contain the data used to generate figures 2.18 through 2.20.

# of Boosters	CONSIZ Payload (lb)	Total Δ Payload (lb)	Core Vehicle Dry Weight (lb)	Original Margin (lb) (15%)	New Margin (lb)	New % Margin
0	25000	-	200300	26126	26126	15.0
1	28066	3066	201030	26221	29287	17.1
2	30709	5709	201681	26306	32015	18.9
3	33196	8196	202327	26390	34586	20.6
4	35573	10573	202908	26466	37089	22.3
5	37963	12963	203516	26546	39509	24.1
6	40410	15410	204446	26667	42077	25.9

Table K10: Weight Growth Margin Data for Castor IV-A (51.6° orbit)

# of Boosters	CONSIZ Payload (lb)	Total Δ Payload (lb)	Core Vehicle Dry Weight (lb)	Original Margin (lb) (15%)	New Margin (lb)	New % Margin
0	40897	-	201914	26337	26337	15.0
1	43736	2839	202652	26433	29272	16.9
2	46637	5740	203375	26527	32267	18.9
3	49315	8418	204054	26616	35034	20.7
4	51935	11038	204683	26698	37736	22.6
5	54339	13442	205285	26776	40218	24.4
6	56653	15756	205865	26652	42608	26.1

Table K11: Weight Growth Margin Data for Castor IV-A (28.5° orbit)

# of Boosters	CONSIZ Payload (lb)	Total Δ Payload (lb)	Core Vehicle Dry Weight (lb)	Original Margin (lb) (15%)	New Margin (lb)	New % Margin
0	25000	-	200300	26126	26126	15.0
1	30616	5616	201662	26304	31920	18.8
2	35883	10883	202994	26478	37361	22.6
3	40865	15865	204246	26641	42506	26.3
4	45652	20852	205416	26793	47445	30.0

Table K12: Weight Growth Margin Data for Ariane L40 (51.6° orbit)

# of Boosters	CONSIZ Payload (lb)	Total Δ Payload (lb)	Core Vehicle Dry Weight (lb)	Original Margin (lb) (15%)	New Margin (lb)	New % Margin
0	40897	-	201914	26337	26337	15.0
1	46497	5600	203346	26523	32123	18.8
2	51966	11069	204690	26699	37768	22.6
3	57137	16240	205981	26867	43107	26.5
4	62110	21213	207227	27030	48243	30.3

TABLE K13: WEIGHT GROWTH MARGIN DATA FOR ARIANE L40 (28.5° ORBIT)

# of Boosters	CONSIZ Payload (lb)	Total Δ Payload (lb)	Core Vehicle Dry Weight (lb)	Original Margin (lb) (15%)	New Margin (lb)	New % Margin
0	25000	-	200300	26126	26126	15.0
1	32802	7802	202226	26377	34179	20.3
2	39596	14596	203927	26599	41195	25.3

TABLE K14: WEIGHT GROWTH MARGIN DATA FOR AMROC H-1800 (51.6° ORBIT)

# of Boosters	CONSIZ Payload (lb)	Total Δ Payload (lb)	Core Vehicle Dry Weight (lb)	Original Margin (lb) (15%)	New Margin (lb)	New % Margin
0	40897	-	201914	26337	26337	15.0
1	48732	7835	203906	26596	34431	20.3
2	55853	14956	205660	26825	41781	25.5

TABLE K15: WEIGHT GROWTH MARGIN DATA FOR AMROC H-1800 (28.5° ORBIT)

Compensation for Less Advanced Materials

The following table contains the data shown in figure 2.22. The materials used in this trade were Al 2219 (0.101 lb/in^3), Al-Li 2195 (0.098 lb/in^3), and a composite graphite epoxy (0.058 lb/in^3). Accounting for differences in strength, the subsystem weight reductions (compared to Al 2219) for Al-Li 2195 are 20% if used in the wing, and 18% if used elsewhere. Composites increase this to 40% for the wing, and 35% when used in the structure. The materials used in the major subsystems of the WB-001 design are listed in table 2.1. For each entry in the table, only the specified systems were altered. All other systems are assumed to remain at the advanced level described in table 2.1. The appropriate reduction factor(s) were changed according to the material used. The vehicle was then rescaled based on the new material and a new dry weight obtained.

Subsystem Altered & Material Used	Dry Weight (lb)
WB-001 Baseline	200300
Al-Li Wing	214662
Al Wing	231608
Al Tanks	225935
Al-Li Basic Structure	219821
Al Basic Structure	243065
Al-Li Secondary Structure	212168
Al Secondary Structure	224861
Al-Li Total Structure	232475
Al Total Structure	270875
"All Al" Vehicle (Wing, Tanks, and Total Structure)	378698

TABLE K16: FULL SCALE SSV DRY WEIGHTS AT VARIOUS LEVELS OF SUBSYSTEM TECHNOLOGY (51.6° ORBIT ONLY)

Advanced Technology Demonstrator Scale Reduction

These tables show the data presented in figures 3.1 and 3.2. The dry weight is obtained from the vehicle resizing step after the iterative procedure outlined in figure 1 obtains a converged vehicle configuration. The number of engines required on the vehicle is also a result of this procedure, but is calculated as part of the ascent trajectory optimization.

Vehicle Configuration	Core Vehicle Dry Weight (lb)	Number of RD-701 Derivative Engines
WB-001	201914	7.41
Baseline ATD	127099	3.95
ATD with 1 Castor IV-A	121977	3.70
ATD with 2 " "	117357	3.48
ATD with 3 " "	113237	3.28
ATD with 1 Ariane L40	117275	3.47
ATD with 2 " "	108401	3.05
ATD with 1 AMROC H-1800	113739	3.30
Reduced Mission ATD	110865	3.25

TABLE K17: RESULTS FROM ATD SCALE REDUCTION ANALYSIS (28.5° ORBIT)

Vehicle Configuration	Core Vehicle Dry Weight (lb)	Number of RD-701 Derivative Engines
WB-001	200300	7.44
Baseline ATD	133492	4.26
ATD with 1 Castor IV-A	128212	4.00
ATD with 2 " "	123425	3.77
ATD with 3 " "	119099	3.56
ATD with 1 Ariane L40	123368	3.77
ATD with 2 " "	114084	3.32
ATD with 1 AMROC H-1800	119673	3.59
Reduced Mission ATD	116140	3.50

TABLE K18: RESULTS FROM ATD SCALE REDUCTION ANALYSIS (51.6° ORBIT)