NASA-CR-195536

Project Number: ME-ANA-TSTO

NASW-4435

IN-13-CR

204274

P. 233

# CONCEPTUAL DESIGN

# OF A

# TWO STAGE TO ORBIT SPACECRAFT

A Major Qualifying Project Report

submitted to the Faculty of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

by

Scott C. Armiger

Jennifer S. Kwarta

Kevin B. Horsley

Glenn A. Snow

Eric C. Koe

Thomas G. Single

March 4, 1993

Approved:

Professor Andreas N. Alexandrou, Advisor

#### ABSTRACT

This project, undertaken through the Advanced Space Design Program, developed a "Conceptual Design of a Two Stage To Orbit Spacecraft." The design developed utilizes a combination of air breathing and rocket propulsion systems and is fully reusable, with horizontal takeoff and landing capability. The orbiter is carried in an aerodynamically designed bay in the aft section of the booster vehicle to the staging altitude. This TSTO Spacecraft design meets the requirements of replacing the aging Space Shuttle system with a more easily maintained vehicle with more flexible mission capability.

*Everyone recognizes that our present racial, political, and international troubles are symptoms of a sickness which must be cured before we can survive on our own planet - but the stakes may be higher than that... The impartial agents of our destiny stand on their launching pads, awaiting our commands. They can take us to that greater Renaissance whose signs and portents we can already see, or they can make us one with the dinosaurs... If our wisdom fails to match our science, we will have no second chance.*

Arthur C. Clarke

"When the Aliens Come"

*Report on Planet Three*

# ACKNOWLEDGEMENTS

We would like to thank the following people for all the help they rendered in designing this MQP. **Mike Bilotta**, *MicroCadd TA*: For helping with the designs. **John Weidner**, *NASA Langley Research Center*: For his valuable insights into hypersonic propulsion. **Art Glassman**, *NASA Lewis Research Center*: For the valuable information provided concerning a variety of TSTO design issues. **Prof. Hamid Johari**, *Assistant Professor, Mechanical Engineering*: For his help in the modeling of the different propulsion sections. **NASA**: For funding and support of this educational experience. **Prof. Andreas Alexandrou**, *Associate Professor, Mechanical Engineering*: For providing us insight into the realities of engineering.

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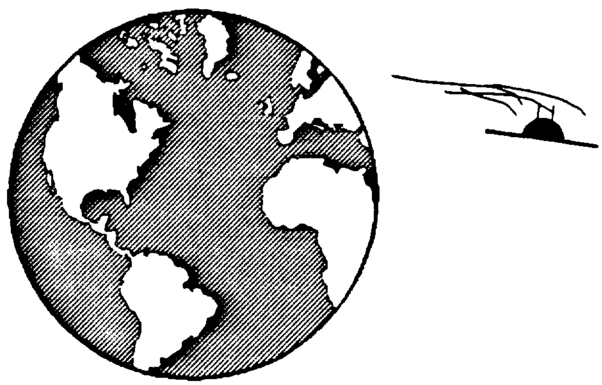
# Introduction



# Chapter 1

## 1.1 Background

Evolution is a natural phenomenon. It occurs not only in life forms but in many other areas as well. Technology is constantly evolving, improving on previous designs. An important technology for the future of mankind deals with space exploration. The space science community is always seeking better ways to perform research in space. A permanent space station has been proposed as a space research facility. A mission to Mars and a station on the moon would be excellent research opportunities as well. The technology of the current space systems is not adequate to fulfill the requirements of these proposals. A new generation of launch vehicles must be developed.

The current American fleet of space launch vehicles, which include the Atlas, Delta, Titan and the Space Shuttle, are not adequate to meet the future goals of space missions. The present inventory is unable to be fully relied upon and does not have enough lift capacity or flexibility to meet all future launch requirements. Several launch vehicles of differing types have actually blown up. Also, with proposals for space stations, moon colonization and the like these current vehicles will quickly become obsolete due to their limited lift capacity.

Current launch vehicles can be divided into three broad categories: unmanned light- and heavy-lift rockets and manned shuttle. The current unmanned light rockets are low payload (5,000-25,000 lb) vehicles. These old, but still useful, versions are the pioneering efforts of the rocket age and used predominantly older technologies, but have come through many incarnations. The other rocket category includes only the Soviet's Energia. It is capable of lifting 220,000 lbs to low Earth orbit, 70,650 lbs to the moon and even 60,000 lbs to Mars or Venus. It is truly flexible with extremely heavy payloads and the ability to piggy-back the Soviet Buran Class shuttle to orbit. It is currently the only true heavy lift vehicle in operation. Lastly is the United States shuttle category, which has a medium lift capability (40,000-55,000 lb). Table 1.1 shows a few of the most commonly used launch vehicles and some important characteristics of each.

| Vehicle | Country | Stages | Fuel Type | Launch Weight (lb) | Payload (lb) |
|---|---|---|---|---|---|
| Titan | Com'l | 3 | Solid | 1,108,000 | 25,000 |
| Atlas | Com'l | 2.5 | Liquid & Solid | 515,000 | 5,890 |
| Centaur | USAF | Vanes | Liquid | 52,750 | 13,000 |
| Delta | USAF | 2 | Liquid & Solid | 511,000 | 2,810 |
| CZ-3A | China | 3 | Liquid | 528,960 | 5,510 |
| Ariane 5 | ESA | 2 | Liquid & Solid | 1,604,000 | 15,000 |
| Energia | Soviet | 3 | Liquid & Solid | 5,000,000 | 200,000 |
| Space Shuttle | USA | 3 | Liquid & Solid | 4,500,000 | 55,000 |

**Table 1.1** Common Launch Vehicles

The Space Transportation System (Space Shuttle) has been in use since the early 1980's and has been plagued with technical failures from its beginning. The most obvious failure resulted in the death of seven astronauts aboard the Challenger explosion in 1986. Other documented failures, such as occurred in the inertial measurement units[1] and other sensors, resulted in shortened missions, delayed scheduling, and costly repairs. One particular problem with fuel temperature probes could potentially have resulted in another explosion, and may have been present on up to twelve missions before it was detected[2].

Cost overruns have also plagued the Shuttle program. The total cost for a new shuttle has been estimated at around $1 billion. Refurbishing each shuttle for another mission has been estimated at as much as half the cost of building a new shuttle. The money is spent so that the shuttle can complete its two main purposes: scientific research, and satellite launches. With plans for a space station continuing, most manned scientific research should be planned to be conducted on the space station.

Five years ago, the United States government began a policy of assigning all shuttle payloads to expendable launch vehicles, unless a manned presence was required. The unmanned Martin Marietta Titan 4 has approximately the same payload capabilities as the space shuttle[3]. The proposed space station is being designed to be lifted into orbit by shuttles, but if two unmanned boosters were used instead, experts have estimated the cost to be one-twentieth the cost of the shuttle missions. Consequently, both the Augustine Commission and the Synthesis Group for the Moon/Mars Exploration Initiative determined that a booster with heavy lift capacity would be needed to supplement space shuttle operations in the future[4].

To meet the needs of unmanned, heavy lift requirements for the space program, the National Launch System (NLS) has been proposed. The NLS consists of four different launch vehicles that would have lift capabilities ranging from 20,000 lbs in to low-earth orbit (LEO), and up to 80,000 lbs into a Space Station Freedom orbit of 220 miles[5]. These launchers would, along with the current systems, provide almost all of the lift requirements for the nation.

In order to provide easy access for personnel to reach the Space Station, NASA is proposing a Personnel Launch System (PLS) that would carry about 8 passengers and 1200 lbs of cargo to the space station[6]. These systems, in conjunction with the shuttle, would provide all the services needed for space exploration.

Because of the deficiencies in the space shuttle and the changing needs of the space program, it will be necessary to develop a launch vehicle that will perform the anticipated requirements of space science. Space scientists and aerospace engineers cannot rest on their past achievements, but must continually strive to improve and update what they have already accomplished. As chief NASA Administrator Daniel S. Goldin stated, they must strive to "find ways to do things safer, faster, better, cheaper, and to make continuous improvement.[7]" With the space station on its way, along with the development of new heavy lift boosters and launch vehicles, the shuttle will become primarily a transportation vehicle. As a transportation vehicle the present shuttle will be excessively expensive and clumsy, which is why a new, smaller two stage to orbit vehicle should be designed.

The replacement must be able to meet most of the Shuttle mission requirements (excluding the fairly large lift capacity) as well as remain inexpensive, reliable and flexible. It must be able to be launched into any orbital plane to conduct satellite repair and rescue operations. It will be a ferry from earth to the space station of both cargo and crew. Most importantly, it must be able to stage safely and quickly from more than one launch area. The current heavy lift capacities of the shuttle are proposed to be accomplished by the NLS.

## 1.2 Design Issues

The first issue in the design of a Two Stage to Orbit system deals with the propulsion systems of the orbiter-booster assembly. It needs to be decided what kind of engines will be needed to get the vehicle off the ground to the staging area. The possibilities include turbojet, ramjet, turboramjet, air-turboramjet, scramjet, rocket propulsion or a combination there of. The types and number of rocket engines needed on the orbiter must also be resolved. The possibility of a fuel transfer from the booster to the orbiter must be considered.

The orbiter must be carried on a booster into the staging area. Possibilities include a piggy-back approach where the orbiter is attached to the top or bottom of the booster, or a coupled system where the orbiter and booster are concurrent. Problems for the design will occur once the orbiter leaves the atmosphere. These include the maximum altitude the orbiter will need to achieve, the re-entry heating involved with returning a damaged satellite to earth, and safely returning to earth with a heavy payload.

The mission requirements will affect the maintenance aspects of the assembly. Various runways may need to be reinforced to accommodate the necessary weights involved with take off and landings. The mating process must be made simple enough to be completed at various locations in a minimal amount of time. The booster and orbiter must also be able to be transported as a whole to different locations. The entire assembly needs to be able to land in case of emergency.

The aerodynamics of the assembly is vitally important. The coupled and uncoupled stages need to be aerodynamically sound. The wing cross sections and the control surfaces must be designed in such a way as to maximize the lift to drag ratio and allow for maximum control of the system. The design of the spacecraft itself must accommodate all mission profiles.

Safety requirements are critical if the assembly is to be manned. Crew ejection must be simple, expedient and safe. A combination of entire cabin ejection and individual seat ejection is one possibility. Aborts should be possible from a multitude of stages. The crew compartment must fit an adequate number of crew members comfortably and safely. These are the initially obvious factors that need to be addressed, but others will become evident throughout the design process.

Once the initial design requirements are determined, the question arises as to where to start. The most reasonable starting point is to review similar designs which are currently being developed. The reason being, is to learn from others mistakes and to avoid reinventing the wheel.

Several countries are studying, and in some cases, actually starting development of demonstration vehicles for hypersonic flight, which utilize a combination of air breathing and rocket propulsion. The ultimate goal of these designs is space transportation. The design developed in this project stemmed from a study of the vehicles being developed in these leading countries. A summary of these designs is provided in Table 1.2.

| COUNTRY | MISSIONS | VEHICLE | PROPULSION SYSTEMS | FUELS | STATUS | FLIGHT DATE |
|---|---|---|---|---|---|---|
| USA | • Space launch<br>• Hypersonic flight | NASP X30 (demonstrator)<br>SSTO | • Ramjet/scramjet<br>• Rockets<br>• Various low speed systems | Cryo H2<br>• liquid<br>• slush | • Full scale module/ complete engine system tests | 1997 |
| FRG | • Space launch<br>• Hypersonic flight | Sanger (demonstrator)<br>TSTO | • turboramjet (1st stage)<br>• Liquid Rocket (2nd stage)<br>• Scramjet (future) | Cryo H2 | • Ramjet tests<br>• Turboramjet technology tests | 1999/2000 (1st stage) |
| FRANCE | • Space launch<br>• Hypersonic flight | STS 2000 (studies)<br>• SSTO | • Turboramjet/ramjet/ rocket<br>• Rocket/ramjet/rocket<br>• Scramjet | Cryo H2 | • Concept studies | 2010/2020 |
| | | • TSTO | • Turborocket/ramrocket<br>• Turbofan/ramrocket | | | |
| JAPAN | • Space launch<br>• Hypersonic flight | Space Plane (demonstrator)<br>• SSTO<br>• TSTO<br>• A-B Expend. Boosters | • Turboengine concepts<br>• LACE<br>• Ducted Rocket/ Ejector Rocket<br>• Scramjets<br>• Rocket | Cryo H2<br>• liquid<br>• slush | • LACE tests<br>• Turboramjet tests<br>• Turbojet studies<br>• Scramjet design | 21st Century |

(This table reproduced from Reference 4)

**Table 1.2 Hypersonic Vehicle and Propulsion Development**

This table illustrates several points:

- Both space launch and hypersonic cruise are mission objectives

- Hypersonic vehicles using combinations of air breathing and rocket engines are planned for first flight within the present decade

- Both SSTO and TSTO vehicles are being developed

Concentrating on TSTO designs we further note:

- First stage propulsion studies include a wide variety of turboengines, rockets and LACE: actual development to date is limited to combined cycle turboengines and LACE.

- Cryogenic hydrogen is the universal choice for fuel because of its high energy content for performance and its large capacity for vehicle and engine cooling.

- These designs feature horizontal takeoff and landing (# 600, p. 12-1 - 12-3)

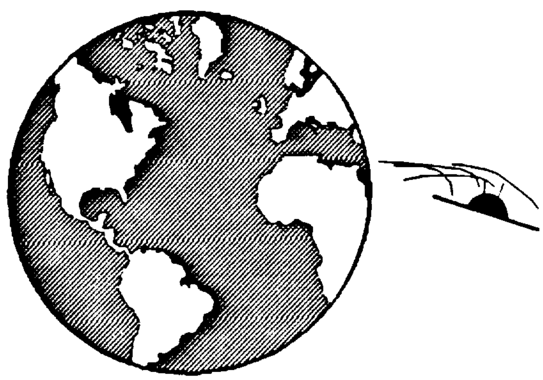
These designs and others greatly facilitated the development of this conceptual design. They were used as benchmarks to judge the accuracy and feasibility of the results obtained.

## 1.3 Proposed TSTO Vehicle Design

A horizontal takeoff system is desirable in order to maximize flexibility. To fully take advantage of its quick turn around capability a horizontal takeoff allows the vehicle to be moved from one location to another on short notice in case of weather problems affecting a particular launch site. The horizontal takeoff system would also allow the orbiter to be launched directly into a particular orbital plane without consuming large amounts of the orbiter's fuel. The vehicle would separate at 80,000 feet at a Mach number of 6.5. The system would have an "airplane like" booster with air-breathing engines which would allow for the multiple staging capability from many different air fields. A booster of this sort would increase the ease of maintenance and reliability which would reduce the turn around time involved.

Design requirements for the orbiter itself include a launch payload capability of 30,000 lbs and a re-entry payload of 50,000 lbs. The launch payload will not need to be as high as the current space shuttle due to the capacities of the proposed NLS vehicles. A 30,000 lbs payload will allow for cargo and crew to be delivered to the space station as well as other unforseen contingencies. The 50,000 lbs re-entry payload will allow for any satellite that was launched by a current shuttle to be recaptured and brought back to earth in case of a malfunction. The payload area itself must be similar to the current shuttle to incorporate the size of a satellite that may need to be recaptured, and also have the capability to be a personnel carrier. The propulsion system for the orbiter will be designed around these criteria and based on current technology.

# TSTO Design



# Chapter 2

## 2.1 Design Specifications and Drawings

Based upon a multitude of considerations, including aerodynamic and propulsive analysis, weight factors, the method of staging, and a variety of other characteristics, a final design for the booster, orbiter and mated pair was determined. This design is illustrated in the figures on the following pages. The booster and orbiter are mated in a modified piggy-back configuration. Instead of the orbiter sitting on top of the booster fuselage, there is a nest inside of the fuselage in which the orbiter sits. The nest is 72 feet long and 25 feet wide. The empty bay can be seen in Figure 2.1. While mated, the booster and orbiter are integrated aerodynamically through the use of a retractable shroud as illustrated in Figure 2.7 and Figure 2.8. During separation, the shroud retracts and the orbiter is lifted into the airflow on a hydraulic platform. This process is described more fully in Section 2.9.

The booster is a semi-conventional aircraft powered by 8 turbo-ramjet engines, each of which is approximately 16 feet long. The engines produce a total sea level thrust of 199.5 metric tons requiring an inlet area of 245 square feet and an inlet length of 69 feet. The weight of the fueled booster is 440,544 lbs. Of this weight, the liquid hydrogen fuel constitutes 160,000 lbs. Overall, the vehicle is 210 feet long and 20.5 feet tall with a maximum fuselage diameter of 35 feet. The wings are in a delta-type configuration with a changing sweepback angle as shown in Figure 2.2. This angle change is needed in order to provide enough planform area to generate lift at low velocities. The wings cross section is modeled upon an NACA 64-006 wing section with a 2 foot thickness. The wing span is 168 feet, resulting in a planform area of 10,896 square feet. By employing leading edge slats and rear flaps, this area can be effectively extended to 17,000 square feet during takeoff and landing. Due to the nature of this hypersonic vehicle, the lift and drag are highly variable and are intimately related to the chosen flight path. The intricacies of this analysis are more fully detailed in Section 2.2. As shown in Figure 2.3, the booster has two vertical stabilizers, each is 34.4 feet long and located at the edge of each wing. Each has a slight angle away from the vertical in order to provide extra control and stability. Also, the placement on the edge of the wing insures that there will be no obstacles for the orbiter to clear during staging. A forward mounted canard is used to provide control and stability for the aircraft. Because the center of gravity is located behind the center of lift, the canard will have a negative angle of attack in order to assure easily controllable flight. Each canard has a span of 15 feet with a chord of 7 feet.

The orbiter is a shuttle-type vehicle powered by two 62.5% scale Space Shuttle Main Engine derivatives. Each engine produces a sea level thrust of about 261,000 lbs with a specific impulse of 369.6 seconds at sea level. The orbiter's total weight at staging is 388,000 lbs. The majority of this weight, to 296,000 lbs, is the liquid hydrogen fuel and liquid oxygen oxidizer. The orbiter is 70 feet long with a 17 foot diameter fuselage. With the dual vertical stabilizers, the vehicle is a total of 25 feet tall. The stabilizers are located above the engine housing and are angled outward (as pictured in Figure 2.6) in order to provide additional control. These stabilizers will be used during mated flight, also. The wingspan is 50 feet with an 825 square foot planform area. Each wing has an average thickness of 2 feet. The payload cargo bay illustrated in Figures 2.4 and 2.5 is located 18 feet from the tip of the orbiter. It is 30 feet long and 15 feet in diameter. It can accommodate a 30,000 lb payload at takeoff and a 50,000 lb payload while descending. Also pictured in Figure 2.4 and Figure 2.5 are the orbital maneuvering thrusters. These thrusters will be used while in orbit to make minor corrections to the trajectory.

The following figures do not show the location of the fuel tanks or systems for either the booster or orbiter. This placement is critical, especially considering the large weights involved. For the booster, the fuel is entirely located in the wings of the craft. These wing tanks help control the shift in center of gravity caused by consumption and the eventual separation. The orbiter fuel is found in two different locations, directly behind the cargo bay and in wing tanks. Since, the vehicle operates in a vacuum the majority of the time, this placement is due to volumetric considerations instead of stability.

The mated pair are able to take off on runways that are over 13,000 feet long. This requirement limits the number of airfields from which the TSTO can operate, but this restriction was considered acceptable. After takeoff, the mated pair reach the staging altitude of 80,000 feet and the staging Mach number of 6.5 in 4.5 minutes. The booster returns to its landing point about 9 minutes later, resulting in a booster mission time of about 14 minutes. This time is optimistic because of the nature of the computer program used to analyze performance. The actual time will probably be more on the order of 16 to 20 minutes. After staging, it takes the orbiter 5 minutes to reach orbital velocity and another 16.5 minutes to reach the orbital altitude of 220 nautical miles. Thus the total time to orbit for the orbiter is 26 minutes.

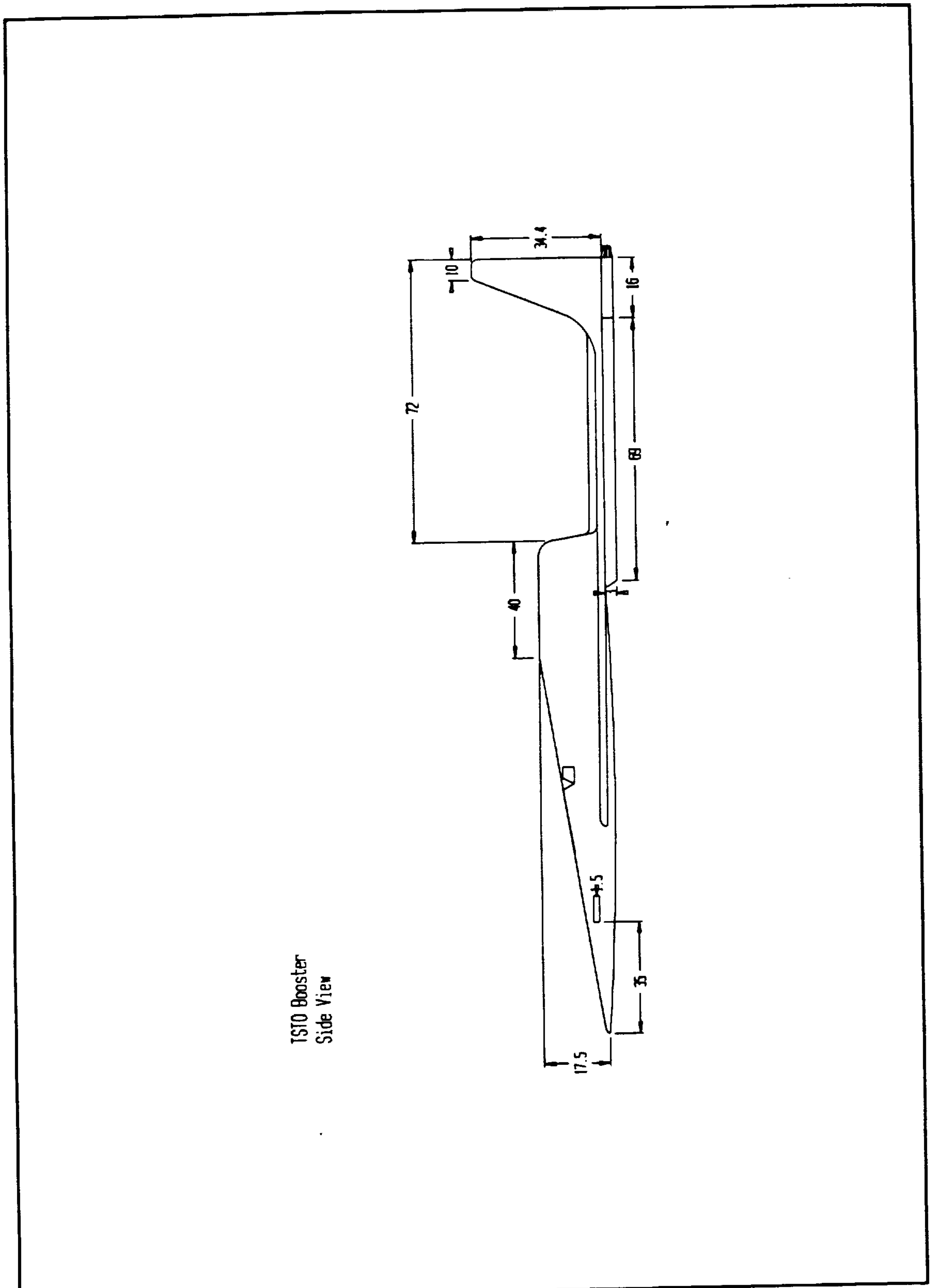



**Figure 2.1** Booster Side View

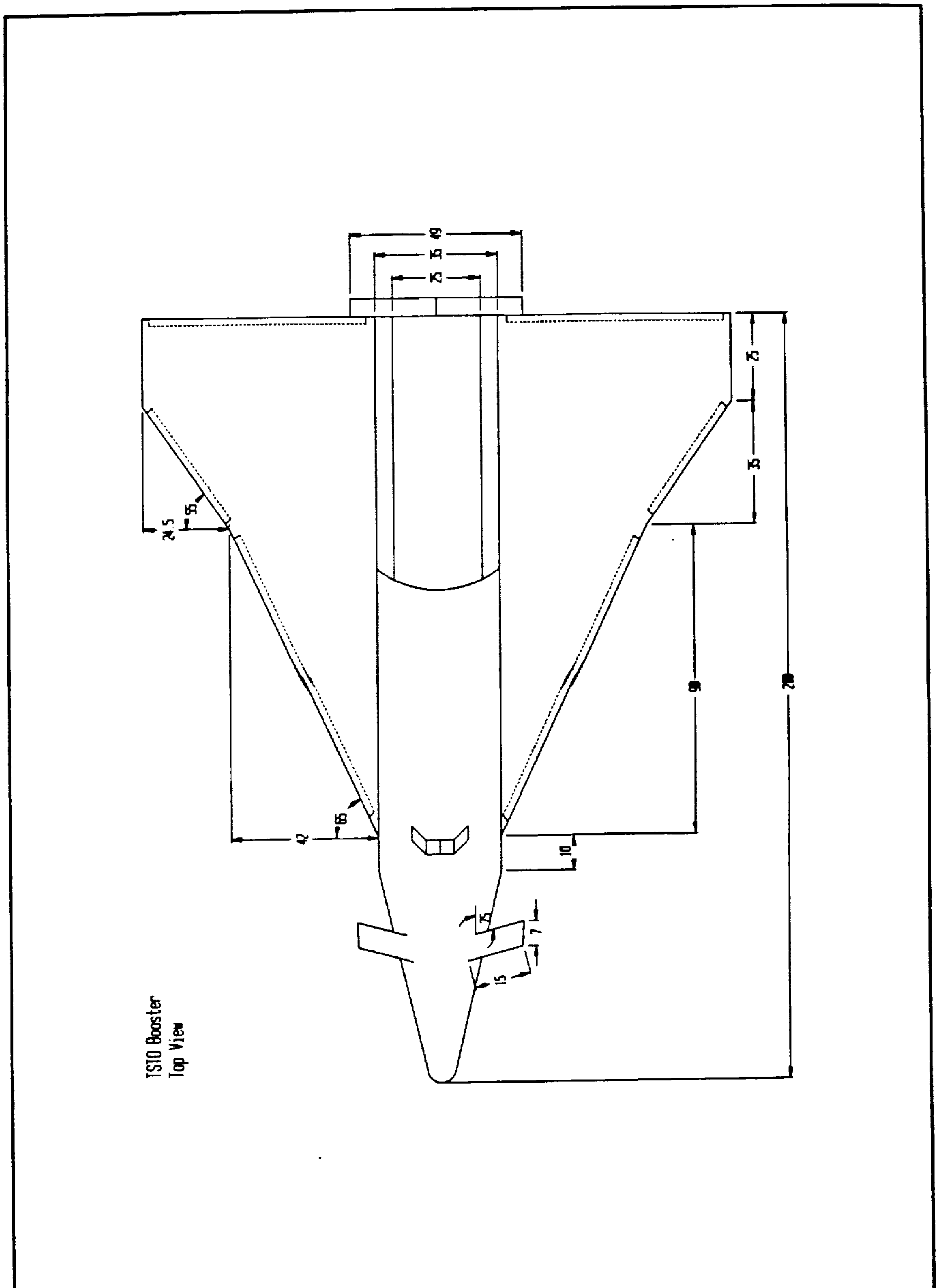



**Figure 2.2** Booster Top View

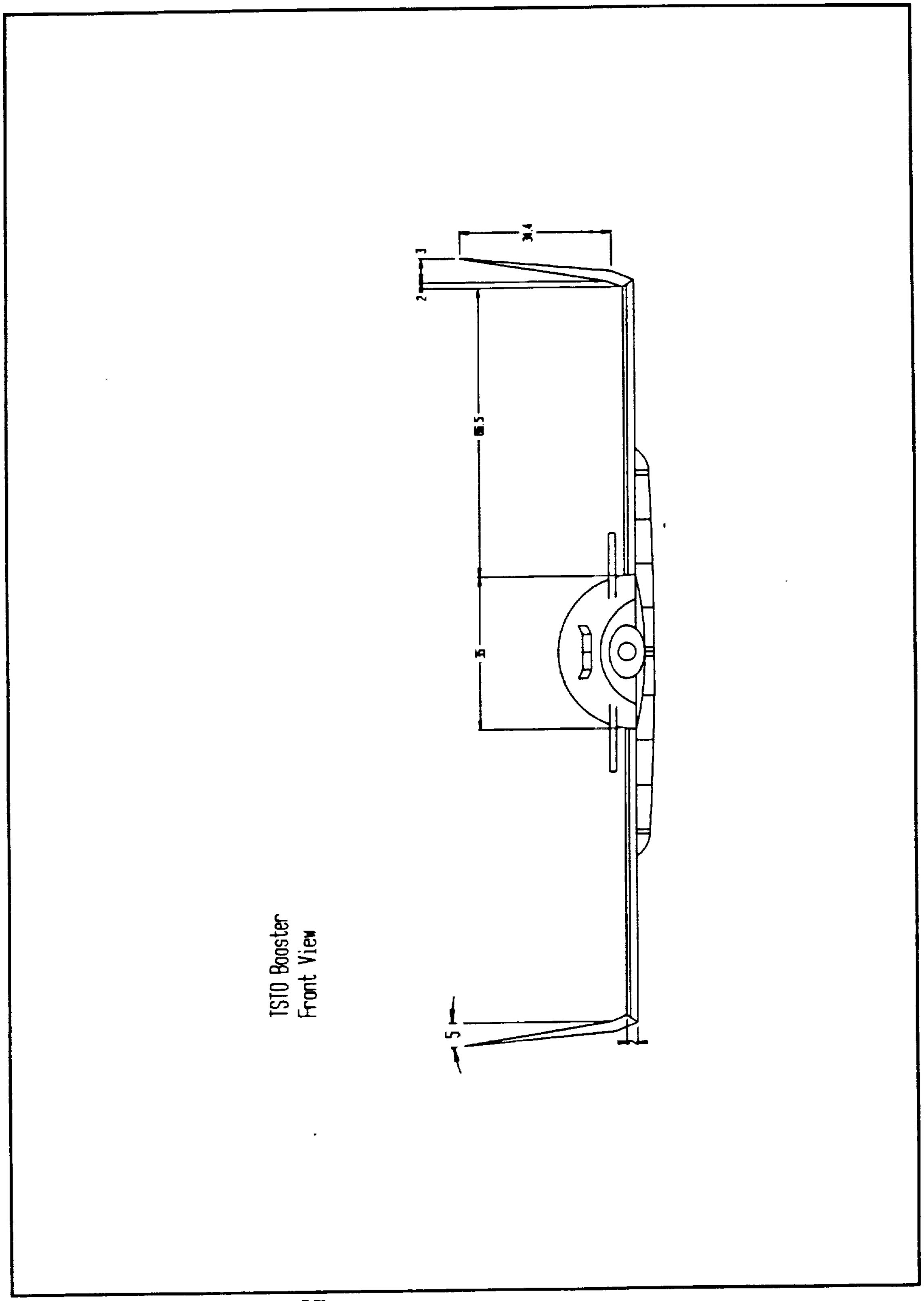



**Figure 2.3** Booster Front View

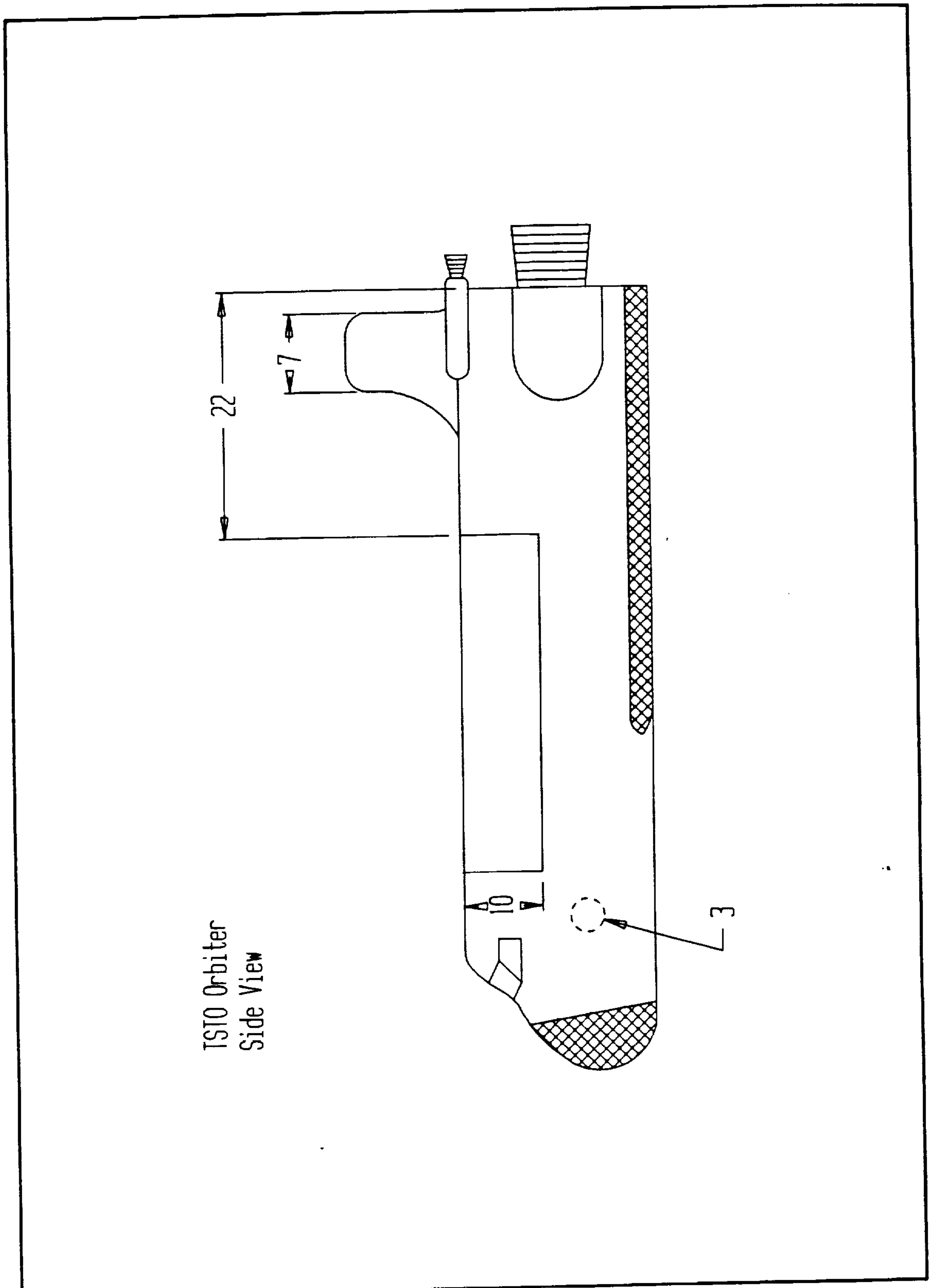



**Figure 2.4** Orbiter Side View

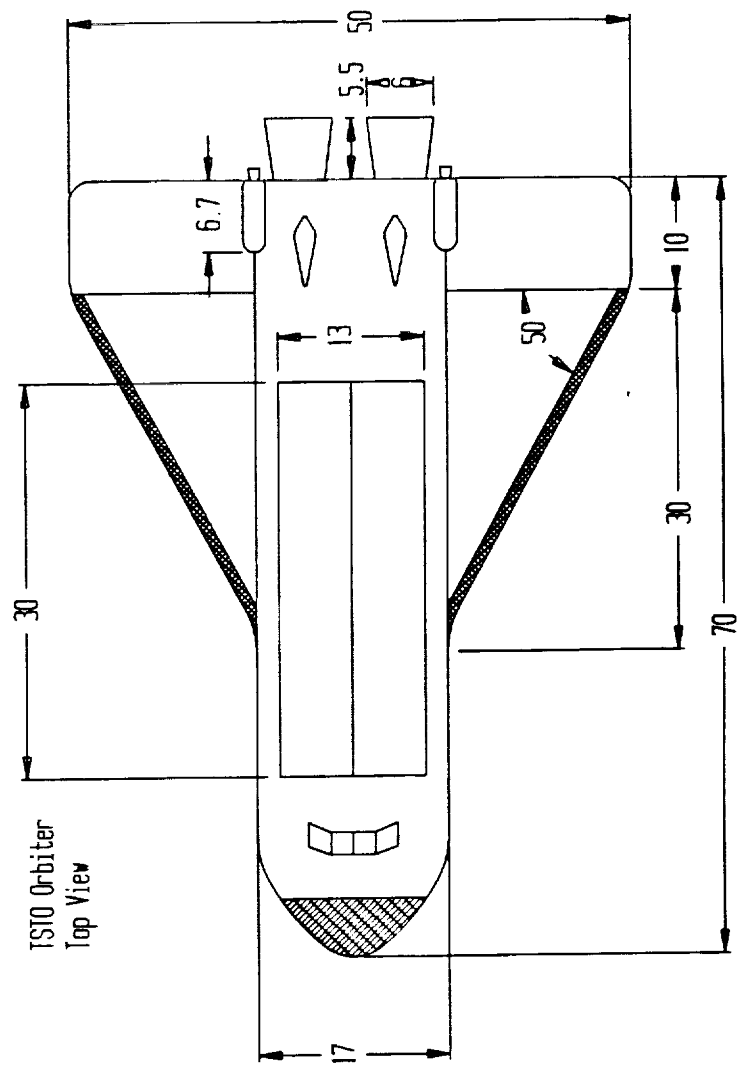



**Figure 2.5** Orbiter Top View

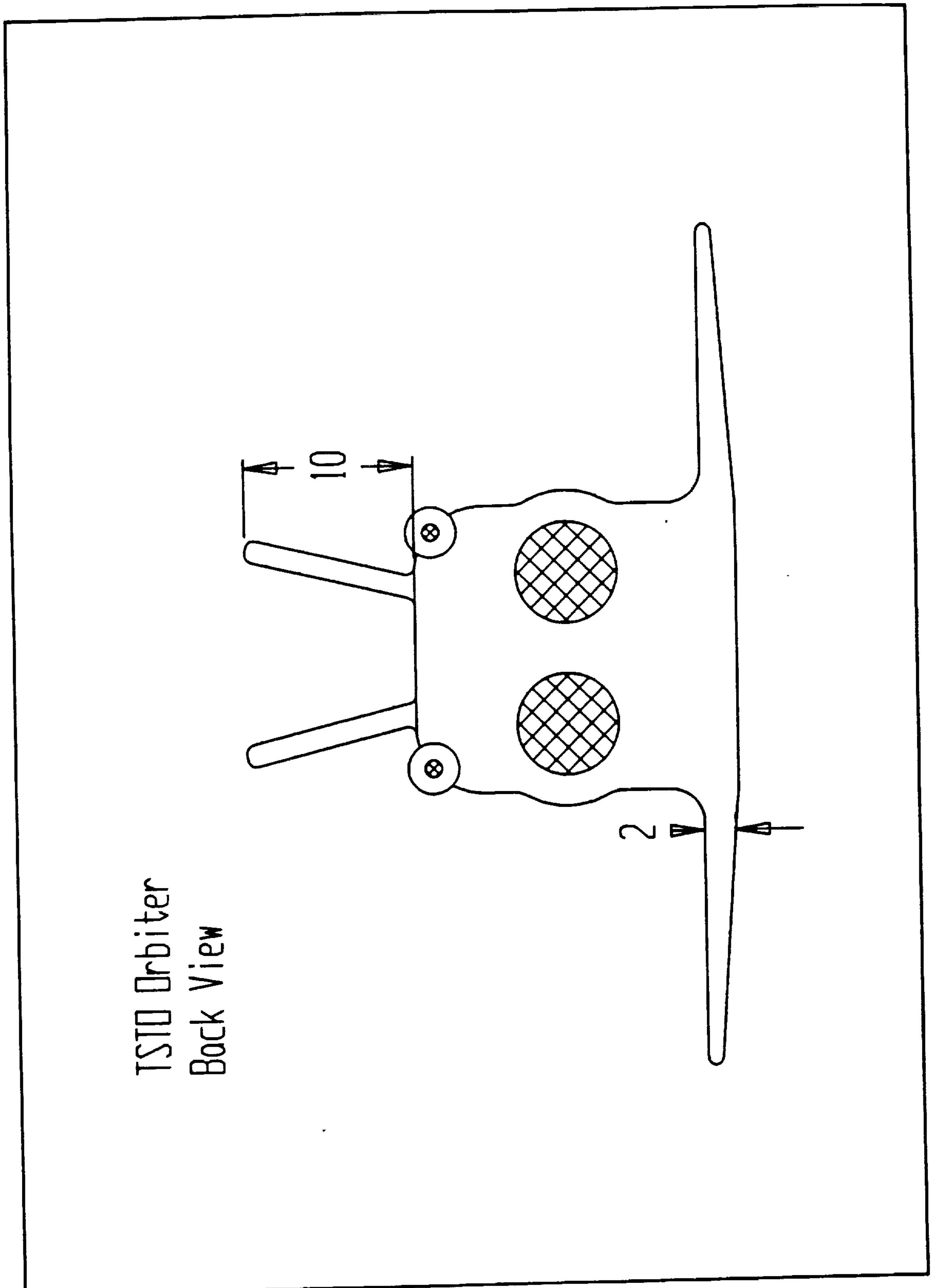



**Figure 2.6** Orbiter Rear View

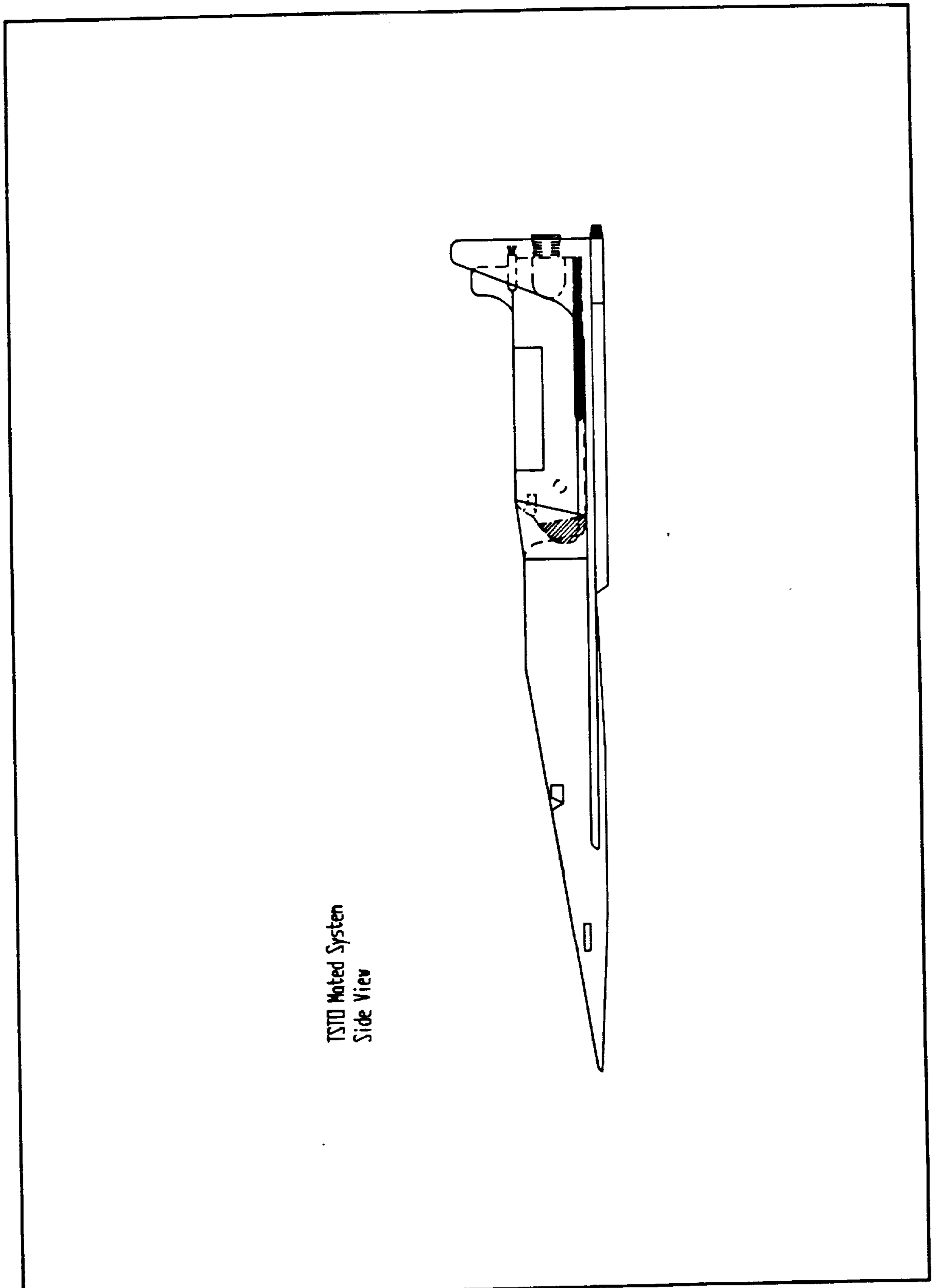



**Figure 2.7** Mated System Side View

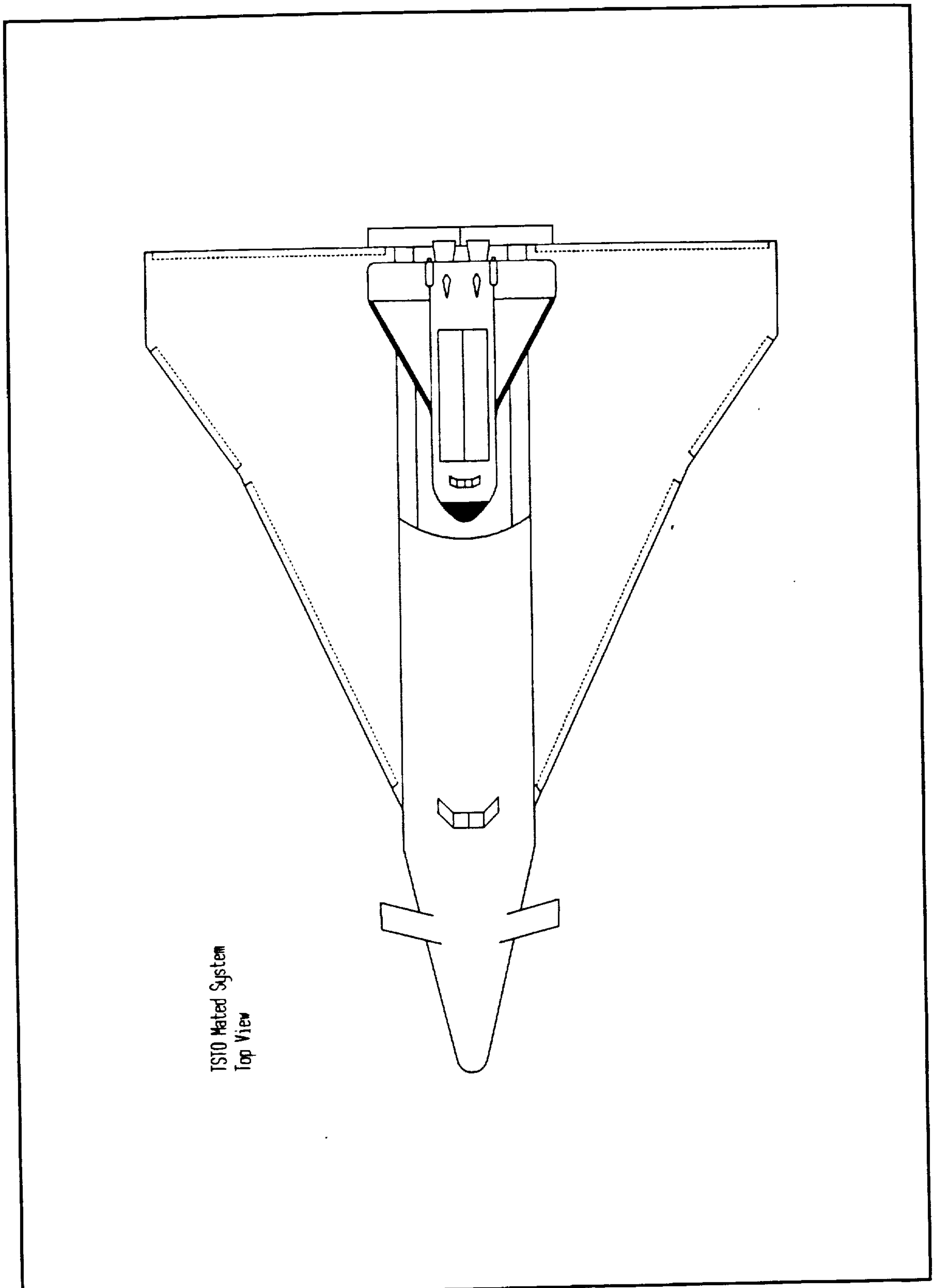



Figure 2.80 Mated System Top View

## 2.2 Aerodynamics

The aerodynamic design consists of a delta winged booster vehicle and an orbiter craft resembling the Space Shuttle. The design accounts for a piggy back system in which the orbiter nests into the fuselage of the booster. The design compensates for the surface area lost when the two vehicles separate by replacing the surface area covering the orbiter nest. For additional stability and control, canards and leading edge slats were integrated into the design. In addition to the leading edge slats, trailing edge double slotted flaps and the strake/wing concept are to be used to increase lift in subsonic flight.

The booster's delta wing integrates into the fuselage at a distance of 60 feet from the nose. The initial wing sweep is 65 degrees. At 150 feet from the nose, the sweep angle changes to 55 degrees, to increase total planform area. 185 feet from the nose the wing squares off, rounding up into vertical stabilizers. The total planform area is 10896 $ft^2$. The wings and fuselage of the booster are to molded out of smooth composite material to reduce drag.

### 2.2.1 Initial Sizing

The initial sizing of the vehicle dimensions was the first step in the design. The sizes were originally calculated from conceptual equations governing initial sizing. However, due to the drastic differences in mission profiles between the craft the equations were based on and the mission profile for the craft in this project the results of these equations were not used alone. They were used as a reference when finally deciding upon the sizing. Rather, due to the specific mission requirements of this project these sizes were compared to the sizes of existing conceptual two stage to orbit vehicle systems currently being designed and tested. It was felt that these data, which in large part had already undergone real physical testing, were more valuable to this project than the theoretical equations for aircraft. The mission profiles, weights and planform areas were taken into consideration relative to this design. The final sizes are shown on the figures in section 2.1.

### 2.2.2 Wings

The wing section necessary to meet the requirements for this mission was determined through conceptual equations. The results were then compared to data on existing airfoils in order to select the most appropriate existing wing section. (Ref. 3, Eqns. 12.6, 12.7)

$$C_{L\alpha} = \frac{2\pi A}{2+\sqrt{4+\frac{A^2\beta^2}{\eta^2}\left(1+\frac{\tan^2\Lambda_{max}}{\beta^2}\right)}}\left(\frac{S_{exposed}}{S_{ref}}\right)(F)$$

Equation 2.2.1

where

$\beta^2 = 1 - M^2$
$A$ = Aspect Ratio
$F$ = a Form Factor from Ref. 3
$S_{exposed}$ = the actual area exposed to the flow
$S_{ref}$ = the planform area
$\eta$ = an efficiency factor from Ref. 3
$\Lambda_{max}$ = maximum leading edge sweep

This equation provides the slope of the lift coefficient curve. (Ref. 3, Eqn. 12.19)

$$C_{Lmax} = (C_{Lmax})_{base} + \Delta C_{Lmax}$$

*where* $(C_{Lmax})_{base}$ *is Fig.* 12.12 *of Ref.*1
$\Delta C_{Lmax}$ *is caused by the high lift devices implemented* (*Table* 12.2 *of Ref.*1)

Equation 2.2.2

This equation provides the maximum value for $C_L$. Equations 2.2.1 and 2.2.2 create an estimate of the lift coefficient vs. angle of attack by stating a maximum value and slope of the curve (assumed to be a line) leading up to that value.

Since all conceptual equations are merely estimates, the more sources of information the better. In this case another set of equations describing lift and drag coefficients for delta wings found in Ref. 2 was used to estimate the aerodynamic properties of the design.

$$C_L = K_p \sin\alpha \cos^2\alpha + K_v \sin^2\alpha \cos\alpha$$

Equation 2.2.3

where $K_p$ is from figure 7.34 of Ref. 2 and $K_v$ is form figure 7.35. Both values are based on aspect ratio and leading edge sweep. This equation for delta wings depends on angle of attack (as did Equations 2.2.1 and 2.2.2) but are for a constant Reynold's number. Thus, the values generated by these equations were of limited but valuable use to this design.

The values for the design were first determined from Equations 2.2.1 and 2.2.2 for the flight path and other mission requirements. Equation 2.2.3 was then used to calculate the same variables as the previous method at the particular points in the flight path where the equation was valid. This provided two estimates of the theoretical values at specific instances. The two values were compared and found to correlate quite well. However, the differences were noted and adjustments to the values were made accordingly. Based upon the results of these equations and the concepts in Ref. 3, airfoil section NACA 64 - 006 was selected.[8]

### 2.2.3 High Lift Devices

In order to increase lift, drag and stability when necessary, high lift devices were utilized. As a leading edge device, slotted leading edge flaps (slats) were implemented. Slats are useful in both the subsonic and transonic regimes. By reducing the buffeting tendency which occurs in transonic flight slats preserve the usable lift that is often decreased considerably in the regime. The slats also increase the angle at which the craft will stall.

In order to increase subsonic lift further trailing edge double slotted flaps were used. The advantages to slotted flaps are numerable. The slot allows pressure to equalize between the top and bottom surfaces of the wing which reduces separation. This in effect increases lift and decreases drag. By extending, the flaps increase the planform area which also increases the lift while also increasing drag.

The final high lift concept utilized was the idea of the strake/wing combination.

By having very highly swept sections of the wing starting further toward the front of the booster and blending into the main wing it is believed a strake effect will be created. This effect has many benefits, including minimal flow interference for the main wing at moderated to high angle of attack (due to the strake vortex), and less required area for maneuver lift. For the strake portion, benefits include a strengthened vortex from the main wing up-wash and a significant contribution to the total lift from a relatively light weight and small area structure. (Ref. 1) These high lift devices used in combination were determined most practical for this mission.

### 2.2.4 Lift

The lift created by the aircraft was first determined from the data calculated for the wings. Next, the lift generated from the canard, fuselage and other lift factors was determined. The high lift devices on the wings were the final components added to the lift of the booster. Taking all of these factors into account along with the angle of attack and mission requirements allowed a theoretical set of coefficients to be generated. The final piece to the puzzle was historical data from actual testing of other TSTO designs. These data were used in order to find the best flight path and general shape of the graphs of lift and drag versus Mach number, particularly in the transonic regime. The theoretical values were then adjusted to correlate to the pattern of the historical data, resulting in the data used for this design. Graphs and tables of lift coefficients versus Mach number were then generated. The final number which were used in the computer modelling program are contained in the tables and graphs for each component of the flight mission located in Appendix B.

### 2.2.5 Drag

The drag for a supersonic craft carefully designed with smooth molded composite skin can well be estimated by

$$C_D = C_{D,o} + KC_L^2$$

Equation 2.2.4

The parasite drag, $C_{D,o}$, comes from

$$C_{D,o} = C_{fe}(S_{wet}/S_{ref})$$

Equation 2.2.5

where $C_{fe} = .0020$

and $S_{wet}$ and $S_{ref}$ are determined from aircraft specifications and geometry. The $C_L$ is taken from the table, which takes into account slats, flaps, velocity, and angle of attack. The K's are taken from Figure 12.36 of Ref. 3 which plots K versus Mach number and $C_L$.

Next, another equation for drag was implemented. This equation is subject to the same constant Reynold's number restriction as the second theoretical lift method, and the variables $K_p$ and $K_v$ are the same as for that equation.

$$C_D = C_{Do} + K_p \sin^2\alpha \cos\alpha + K_v \sin^3\alpha$$

Equation 2.2.6

These values allow for a set of calculated $C_D$ versus Mach number values similar to the calculated $C_L$ values found above. The historical data was used in the same manner as it was in determining the lift values. Resulting from this process was the drag coefficient values which were used in this project. The plots and tables of the final numbers used in this project for each component of the flight mission are located in Appendix B.

### 2.2.6 Transonic Regime

As there are no equations available that estimate $C_L$ or $C_D$ in the transonic regime well, the values listed in the tables were interpolated. Value leading up to, entering in and exiting out of transonic flow were first calculated. Charts graphing experimental data of supersonic craft lift and drag values in the transonic regime were used to find the basic tendencies. The values used in the tables and graphs for this project are approximations which most closely follow the historical data with the relative parameters of this design taken into account when comparisons were made. The results of this process are contained in Appendix B.

## 2.3 Initial Weights

In order to do even the most rudimentary calculations concerning the performance of the TSTO vehicle, the weight of the system must be estimated. Since the exact components and the associated weights are not known, a more practical approach would be to get an approximate weight by comparing this system to other conceptual designs. Once specific information about each system is known, then this initial value can be refined. The determination of the orbiter weight is obviously an important step in the design process. Assuming the orbiter propulsion system consists of a single Space Shuttle Main Engine derivative, the propulsion weight is 6885 pounds mass.[9] Also, a payload of 30,000 pound-mass has been set by the design team. In order to quantify the total dry weight, it is necessary to determine the weight of the systems and structures of the orbiter. This was accomplished by assuming that the orbiter in this project was approximately the same size as the grey orbiter which is part of a TSTO design completed by students at Ohio State University.[10] This yielded a structure weight of about 42000 pound-mass and a system weight of 22000 pound-mass. The total dry weight of the orbiter is approximately 100885 pound-mass. It was assumed the fuel weight was 74 percent of the total weight of the orbiter. This value is comparable to other TSTO systems studied. This assumption yielded a total orbiter weight of 388,000 pound-mass with a 6:1 hydrogen to oxygen mixture ratio. The total weight breakdown is as follows:

ORBITER

| | |
|---|---|
| Engine | 6885 lbm |
| Payload | 30000 lbm |
| Structure | 42000 lbm |
| Systems | 22000 lbm |
| LO2 | 41016 lbm |
| LH2 | 246099 lbm |
| TOTAL | 388000 lbm |

Assuming that the orbiter is 45 percent of the total lift-off weight, which is approximately in line with other TSTO designs, a total lift-off weight of 862000 pound-mass was found. The booster weight would then be 474000 pound-mass. An ideal value for the structural weight of the booster is 35 percent of the total booster weight.[11] An assumed a value of 32.5 percent and this resulted in a structural weight of 154000 pound-mass. Again, by using comparative weights, an approximate weight breakdown follows:

BOOSTER

| | |
|---|---|
| Engine | 95000 lbm |
| Structures | 154000 lbm |
| Systems | 50000 lbm |
| Fuel | 175000 lbm |
| TOTAL | 474000 lbm |

The total weight follows as:

$$W_T = W_B + W_O = 474000 + 388000$$

$$W_T = 862000 \text{ lbm}$$

## 2.4 Final Weights

Through the analysis of the performance of both the booster and orbiter vehicles, it was found that the engine characteristics and fuel requirements for each mission facilitated a need to revise the weights of each vehicle. Initially, only a single Space Shuttle Main Engine (SSME) derivative was used on the orbiter, but it was not powerful enough to deliver the vehicle to its orbit with an adequate fuel reserve. Thus, the engine was upgraded to 125% of the thrust. In order to conserve space in the orbiter, this large single engine was divided into two 62.5% scale engines with an approximate weight of 4000 pounds each. The length of a single 125% scale engine would be about 200 inches. This size engine would be very difficult to integrate into the orbiter layout. The analysis revealed that with the two smaller engine configuration there was not enough fuel approximated in the initial weight estimations for the return to Earth. Thus, the total fuel weight was increased by 8885 pounds. The materials selected, along with further research into historical data, allowed for both the structural and systems weights to be reduced by an equal amount of 5000 pounds each. These changes kept the total weight of the orbiter at 388000 pounds. In addition, these new values still seem to be in accordance with other TSTO systems that were studied. The new weight breakdown for the orbiter is as follows:

ORBITER

| | |
|---|---|
| Engines | 8000 lb |
| Payload | 30000 lb |
| Structures | 37000 lb |
| Systems | 17000 lb |
| LO2 | 42286 lb |
| LH2 | 253714 lb |
| TOTAL | 388000 lb |

The booster weights were revised during analysis as well. By knowing the sea level thrust and sea level thrust to weight ratio for each engine, it was determined that each engine weighs 9561.7 pounds. Through the use of the booster performance program, it was determined that eight engines would be needed. This yielded a propulsion weight of 76494 pounds. The program also showed that there was too much fuel on board. The fuel weight was then reduced by 15000 pounds. These changes resulted in a weight breakdown as follows:

BOOSTER

| | |
|---|---|
| Engines | 76444 lbm |
| Structures | 154050 lbm |
| Systems | 50000 lbm |
| Fuel | 160000 lbm |
| TOTAL | 440544 lbm |

## 2.5 Landing Gear

Developing a landing gear configuration for a TSTO booster is a very important step in designing a realistic vehicle. The major problem created by a project of this magnitude is the total weight the landing gear must support. Once this problem has been dealt with, the problem of where to store the landing gear while in flight arises. The booster is thin winged, which limits the width of the wheels. Also, other concerns such as engine inlet placement and fuel reserve locations

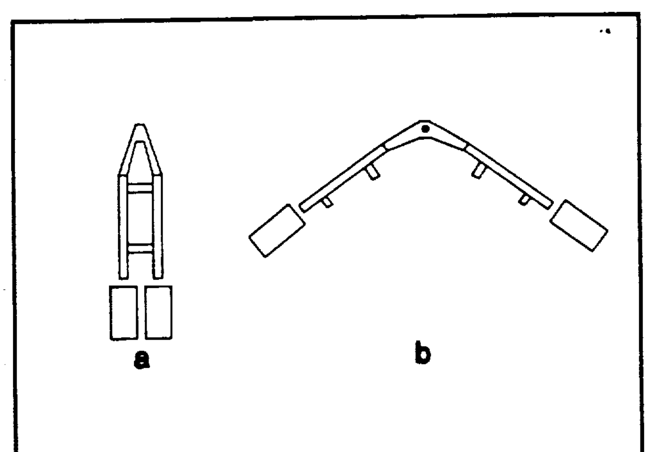



Figure 2.9 a) Landing gear down configuration. b) Landing gear retracting configuration.

must be addressed. The layout for this project places the main landing gear along the rear of the booster vehicle 10 feet in from the rear edge. The main and intermediate gear are to separate to the sides and be stored on their sides, thus reducing the width required of the wing. Figure 2.9 shows the process of extending the gear from the storage position. The nose gear will fold back into the nose when retracted as shown in Figure 2.10. Figure 2.11 shows the front view of the booster with landing gear down.

The delta wing design of the booster requires the main landing gear be placed toward the very rear of the booster since it will land with a nose up and relatively high angle of attack. This landing style causes the rear of the plane to touch down first as the moveable canards in the front gently set down the nose. The landing gear must be designed to support 90% of the total weight.[12] The maximum weight of this system occurs at takeoff with a total weight just under 830000 pound-mass. Thus, the main landing gear must support a weight of 747000 pound-mass.

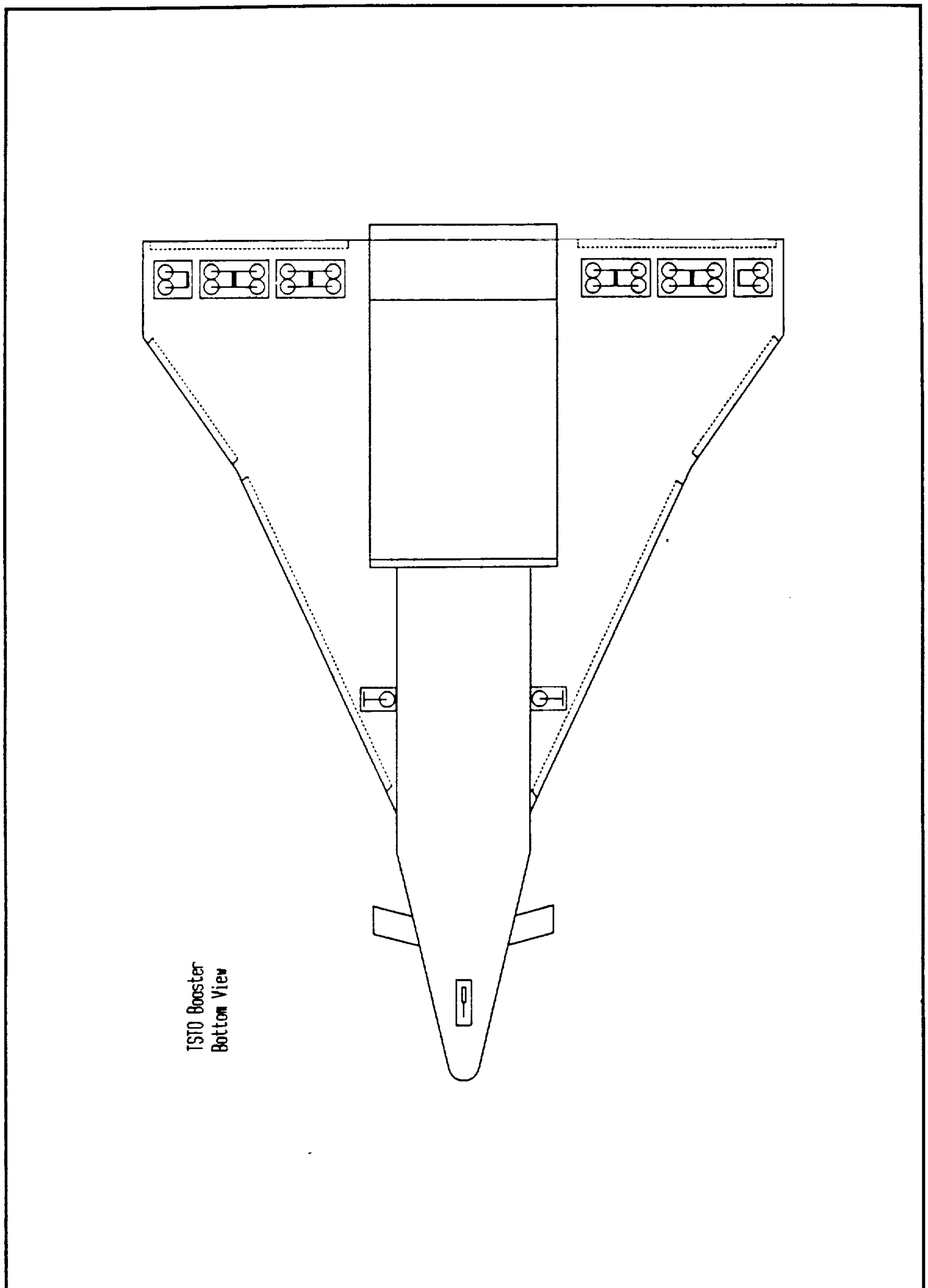



**Figure 2.10** Booster Bottom View with Retracted Landing Gear

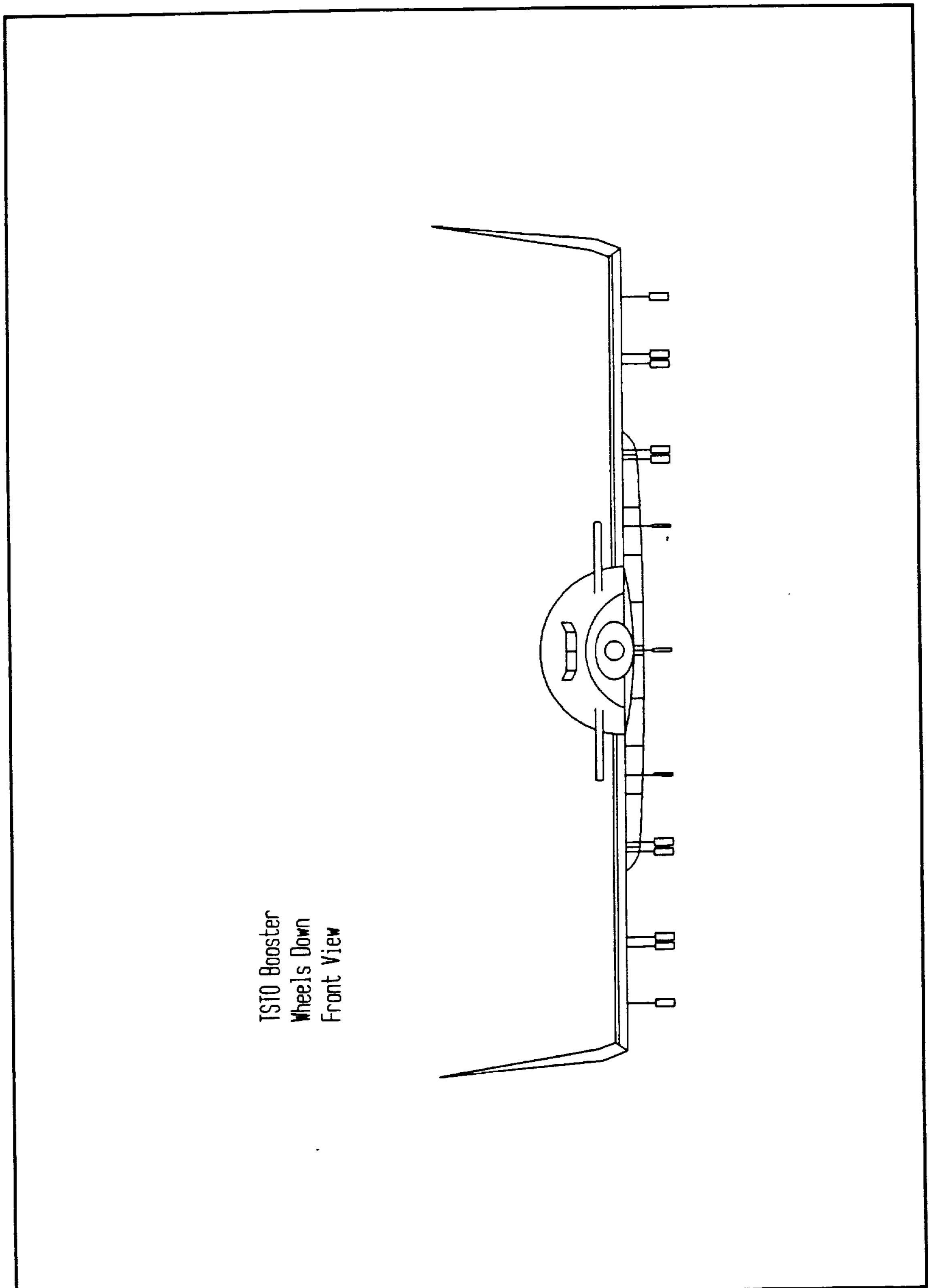



**Figure 2.11** Booster Front View with Landing Gear

A table of aircraft tire and wheel characteristics was found.[13] The largest concern at this point was total tire width. For the majority of the wing section, a usable internal width of 20 inches was available for storage of the gear. Due to the nature of the mission, a very high pressure tire capable of high speeds was needed. This fell into the Type VIII or Three Part Name family of aircraft tires. From the consideration previously listed, a 47x18-18 tire was selected for use on the main gear. Its characteristics are listed below:

| Three Part Name 47x18-18 | |
|---|---|
| Maximum Diameter | 46.9 inches |
| Maximum Width | 17.9 inches |
| Maximum Load | 43700 lb |
| Rolling Radius | 19.2 inches |
| Wheel Diameter | 18.0 inches |
| Pressure | 175 psi |
| Number of Plies | 30 |

From this data the total number of main landing gear tires was determined to be 17.09. However, safety as well as layout considerations resulted in the use of 20 tires.

The nose and intermediate tires chosen are Three Part Name 21x7.25-10 tires and exhibit the following characteristics:

| Three Part Name 21x7.5-10 | |
|---|---|
| Maximum Diameter | 21.25 inches |
| Maximum Width | 7.20 inches |
| Maximum Load | 5150 lb |
| Rolling Radius | 9.0 inches |
| Wheel Diameter | 10 inches |
| Pressure | 135 psi |
| Number of Plies | 10 |

This configuration allows for a maximum load safety factor of 2.0 in case of a blow-out. It also takes into account vision, weight considerations as well as landing sequence and overall layout.

## 2.6 Materials

The topic of materials selection was of great importance, when considering a TSTO design. The material properties needed in the structural components and those of the outer skin are similar. Both sets of materials must be lightweight with an extremely high Young's modulus in order to withstand the enormous stresses of hypersonic maneuvering. In addition, those areas exposed to the air must maintain these properties while being subjected to temperatures upwards of 2000 °F, caused by aerodynamic heating. In addition to these difficulties, the materials selected for the outer skin must be easily maintainable. One of the most time consuming operations on the current shuttle is the replacement of reusable surface insulation tiles. In order to minimize turn around time and maximize flexibility, the surface of the vehicle must be low maintenance as well as strong and able to withstand high temperatures.

The most promising concept for surface materials is that of the Thermal Protection System (TPS). This concept is similar to the tile system on the shuttle, but the new tiles are not nearly as fragile. They are much stronger and more thermally resistant than their predecessors. The tiles are of three basic designs in order to minimize weight. The most thermally resistant tile is an advanced carbon-carbon (ACC) multipost tile designed to operate at temperatures of 2300 °F. This system is also the most massive, with a mass of approximately 2.5 pounds per unit of surface area covered. The next tile system is a super-alloy honeycomb system. This consists of a fibrous insulation sandwiched between the based Inconel 617 on the outside and a titanium honeycomb on the inside. This system is designed to operate at approximately 1900 °F with a mass estimate of 2 pounds per unit of surface area covered. The final tile type is of titanium multiwall construction. This tile operates at approximately 1000 °F with a mass estimate of 0.8 pounds per unit of surface area covered. The tiles on each system would overlap in order to reduce burn-throughs at the gaps. Under each of the tile systems is a covering of either Numexfelt or a ceramic cloth to prevent the flow of hot gases beneath the tiles.[14]

This tile system provides great protection against the rigors of aerodynamic heating, but it is not the only material needed on the outside of the vehicle. In order to get the needed stress resistance, some sort of material must be used under the thermal protection system. Also, this material is needed simply as a base to which the tiles would attach. After surveying the various materials available, titanium was selected. Titanium provides high strength at a low density. In addition, if there is a problem with the tile system, the titanium outer structure will provide additional and adequate thermal protection.

In order to save weight, each of these systems will only be used where needed. On the orbiter, the surfaces exposed to the highest temperatures will utilize the ACC design. These areas include the nose, leading edges and control surfaces. The rest of the orbiter will mainly use the super alloy honeycomb system. This will provide adequate heat protection at very low weight. The titanium multiwall tile system will only be used in areas of small temperature increase.

Since the booster does not reach the upper atmosphere, a tile system probably would not be needed. The majority of the outer surface of the booster will be constructed of titanium due to the amounts of aerodynamic heating it will experience. If tiles are needed, it would only be at the nose, leading edges and control surfaces, but a much more detailed analysis would be needed to determine this.

The outer skin tile system was not the only one studied. One system involved using various alloys for both strength and thermal protection, however it has two drawbacks. If there is any type of failure, the time required to repair the system would be quite extensive. The second problem also deals with thermal failure. If any burn-through occurs, there could be catastrophic effects on the internal mechanisms of the vehicle.

Another system that was investigated involved a titanium shell with a silicon-carbon coating on areas of high aeroheating. This system has the same drawbacks as the previous one, and the silicon carbon coating is far from being fully developed and tested.

The material selection for the internal structures was much less complicated. Since thermal resistance is no longer a factor, the only considerations are strength and weight. After reviewing the possible materials, three candidates emerged: aluminum, titanium and beryllium. The major material for the super structure will be structural aluminum. It is lightweight, fairly strong and easy to manufacture. In critical areas where a high strength is needed, titanium will be used. The final material will be used sparingly, but will be very useful. Basically, beryllium use will depend on whether or not the vehicle is overweight after construction. Beryllium is lighter than both titanium and aluminum and is stronger than both. Its drawback is the high cost involved with its manufacturing. Beryllium will be used for specific parts where strength is a premium.

After considering all of the factors listed above, the tile and shell system proposed above was determined to be the best alternative for this particular TSTO system. The safety, low weight, high degree of thermal resistance and maintainability of this system naturally lends itself to a vehicle based on speed and reliability. These are the most critical material factors for a vehicle of this design. Barring any unforseen material development, these materials are the sensible choice for this TSTO vehicle.

## 2.7 Booster Layout

Several components and systems need to be considered when determining the overall layout of the booster. Only the more significant systems, such as: the propulsion system, fuel tanks and system, control system, separation system, landing gear and the cockpit will be addressed. This will be done in very general terms. Areas such as avionics, human factors engineering, or the actual operational method of the different systems contained on the booster are concepts well beyond the scope of this conceptual design. This section will primarily focus on the actual size and location within the overall design. Any overall design considerations that would have to be made are also discussed for each system.

After investigating many other similar vehicle designs, an estimate of the weight of the various systems could be made. The weight was important in determining where systems should be located in order to properly place the center of gravity (CG). The actual CG calculations can be found in Appendix A. The CG location of the mated booster and orbiter is 183 feet from the tip of the booster.

### 2.7.1 Propulsion System

Perhaps the most important aspect of the entire booster design is the propulsion system. The final system design consists of 8 parallel turboramjet engines and the accompanying inlets. This system is covered in great detail in the Propulsion Chapter and need not be discussed here except on the premise of CG and overall design integration. The propulsion system was integrated into the under-body of the booster. There are several advantages to this, of which, the biggest are improved thermal and structural integrity of the engines. The smoothly integrated design also helps reduce drag. The actual placement of the engines is very important in terms of CG.

The engines were placed at the end of the fuselage in order to keep the CG as close to the same location as possible after the orbiter separation. The overall weight of the propulsion system is 76494 pounds (not including inlet weight), which contributes greatly in CG location. The actual placement of the propulsion systems is illustrated in the overall vehicle design drawings located Section 2.1.

### 2.7.2 Fuel Tanks and Systems

The location of the fuel and fuel systems is also of great significance due to their high weight. It is necessary to store the 160,000 pounds of fuel required for mission completion in the wings near the rear of the booster. This helps align the booster and orbiter's CGs, throughout the entire mission. Also located here are the other necessary fuel systems, such as pumps and fuel lines. The fuel systems contribute another 17,500 pounds to the vehicle. Both the fuel tanks and system are considered to be located 190 feet from the tip.

The cryogenic hydrogen fuel serves other key functions besides fueling the engines. It is also used to cool engine components and the leading edges of the wings. It is internally circulated throughout these areas. The heat sink capability of hydrogen is discussed in detail in the Propulsion Chapter. These functions are all computer controlled.

The fuel tanks must be protected from extreme heat in the wing section. This is accomplished by incasing the tanks in silica fiber thermal blankets to insulate them. The wing tanks are actually divided into separate segments. As fuel is burned it is transferred from tank to tank by computer control systems in order to keep the proper CG location. This is also done at staging.

### 2.7.3 Control System

The flight control system will use current technology. It will consist of a computer aided fly by wire system. The pilot will be responsible for the actual maneuvering of the vehicle, while the computer system will aid in controlling normal stable flight conditions. The entire control system was considered to weigh 2500 pounds with the system CG being 207 feet from the tip of the booster.

### 2.7.4 Separation Systems

The separation systems are extremely important to the overall safety and success of the mission. Staging is the most critical aspect of the TSTO mission and therefore a reliable separation system is the key to successful mission completion. The actual separation system is too complex to be analyzed in this project, however, its importance should not be overlooked.

The separation system has several different components. It includes the platform the orbiter sits on, the hydraulic system that raises it, the aerodynamic shroud that helps seal the aircraft contour, and side walls to complete the aerodynamic form. It is obviously beyond the scope of this project to analyze the exact interaction and workings of these systems. The Separation section (2.9) does cover in detail the aerodynamics and stability involved in the staging operation. The important issue to recognize here is the overall weight and placement of the system. The separation systems need to be located near the orbiter nest and are considered to be 170 feet from the tip of the booster with a weight of 17,500 pounds.

### 2.7.5 Cockpit Layout

The cockpit will contain all controls and avionics necessary for the pilot to fly the booster. As already stated, this project does not deal with the actual types and layout of avionics and controls. The actual location of controls and other items necessary to mission completion would be handled by a Human Factors Engineer. The cockpit section of the vehicle also includes systems such as oxygen and any other critical life support systems. The cockpit would be laid out in such a manner that the crew would not have to leave their stations during the mission to handle any ordinary operations. The most important aspect of the cockpit to be considered in this sort of conceptual study is the overall weight and location.

The cockpit was located in such a manner as to provide the crew the necessary vantage point to control the booster. Fuselage width considerations were also factored into this design decision. The location of the cockpit was decided to be 65 feet from the tip of the booster. It has a total weight of 12,500 pounds.

### 2.7.6 Landing Gear

The location for the wheels was designed for safety and stability. The overall length of the main landing gear (from ground to fuselage) was set at 8 feet. The main gear are to be located 10 feet in form the rear of the booster. In order to increase stability, safety, and strength the wheels will be coupled into trucks of 2 or 4 wheels per location when extended. While retracted, the couples will be separated and retract in the opposite directions, as shown in Figure 2.9.

The remaining gear on the booster must support the remaining 8300 pound-mass of the vehicle, but must account for other considerations as well, such as visibility and stability during taxi. To begin with, in order for the pilots to have sufficient vision when on the ground, the nose should slope slightly downward. The nose gear are four feet from ground to fuselage, and are located centrally fifteen feet back from the tip of the nose. The intermediate gear (located toward the front of the delta wing) are located 90 feet back from the nose and are 5.622 feet in height from ground to fuselage to correspond with the slope created by the difference in height from the main to the nose gear. The main purpose of locating the intermediate gear in wings toward the front is to provide the booster with more lateral stability during its taxi maneuvers.

### 2.7.7 Other Considerations

There are of course several other systems that have not been considered in this chapter. Basically, this is because their overall weight contribution to the CG or overall impact on mission completion was not very significant. There are, however, two other factors that did get considered when determining the booster CG. They are the actual booster structure and the orbiter.

The actual booster structure contributes significantly to the overall weight of the vehicle. The structure consists of several different materials which are discussed in the Materials Section (2.6). The actual structural design was not considered, but it would more than likely involve a combination of current aircraft structural designs. The overall booster structure was considered to weigh 154,050 pounds and for the CG calculations (Appendix A) was located at 145 feet from the tip.

The orbiter weighs 388,000 pounds and it's CG is located 195 feet from the tip of the booster. The CG needed to be calculated for both the mated booster and orbiter and the booster alone. The goal was to keep the two as close to constant as possible. The result was a CG location of 183 feet from the tip for the mated pair and 182 feet for the booster alone. The difference between the two CGs is only 2 feet which should only create very minor stability problems at staging. These problems should be able to be handled by the computerized control system by transferring fuel or adjusting trim.

## 2.8 Orbiter Layout

This section is organized similarly to the Booster Layout Section (2.7). Once again, only the more significant orbiter systems will be considered. They include: engines, payload, structure, controls, life support, bay systems and the fuel system. As with the booster layout, this section will primarily focus on the actual size and location within the overall design. Any other significant design considerations are also discussed for each area of interest.

Much of the analysis for the orbiter study is based on the space shuttle, although other designs were examined. Each system will be studied in relation with its affect on CG location. The actual CG calculations can be found in Appendix A. The resultant CG of the orbiter is 52 feet from its nose tip. The independent systems influence on this location will now be studied. All locations given will be distance from the nose tip.

### 2.8.1 Engines

The engines decided upon for the orbiter were two 62.5% scale versions of the space shuttle main engine (SSME) derivative engines. The actual characteristics of these engines is discussed in the Orbiter Propulsion Section. For obvious operational reasons the engines were placed at the rear of the orbiter. The two engines weigh a total of 8000 pounds. Their center of mass is considered to be located at 67.5 feet.

### 2.8.2 Fuel and Fuel Systems

The orbiter is fueled by a liquid hydrogen with a liquid oxygen oxidizer. As in the booster, the fuel is a big contributor to the overall CG location. The majority of the fuel will be stored in wing tanks and fuel reservoirs in the fuselage section. The wing fuel weighs 142,768.25 pounds at 58 feet and the fuel reservoirs account for 153,231.75 pounds at 54 feet. The fuel tanks would utilize the same thermal protection system of those in the booster.

The fuel systems include such things as fuel lines, pumps, cooling units, etc. All fuel system operations would be computer controlled to carefully account for shifts in CG and proper flow rates to the engines. These systems were considered to weigh 5100 pounds and be located at 57 feet.

### 2.8.3 Payload

The payload could consist of various types of equipment. The orbiter will be used to help build and supply the space station, launch satellites, or ferry crew to the space station. Therefore, the actual payload weight could vary significantly. The CG calculations were done considering a maximum payload capacity of 30,000 pounds at takeoff, located at 32 feet.

### 2.8.4 Bay Systems

The bay systems consist of many different, independently operating systems. For simplicity, they were all considered as one system in order to calculate the CG. The bay systems includes such things as the machinery to open the bay doors, robot arm to help deploy or rescue satellites, any other payload support systems, and depending on the mission it may contain a special capsule. As an example, a special capsule could be configured for human transport capabilities.

After examining several configurations, an estimated weight of these systems was determined at 1700 pounds. This figure would need to be increased considerably for special missions, due to the extra sub-systems that would be needed. The human transport capsule would create a significant weight increase. The bay systems weight was considered to be located at 30 feet, which would vary depending on mission.

### 2.8.5 Controls and Pressurization

Although these two systems are completely independent of each other they are discussed together here because they have the same location when calculating CG. The combined systems have a weight of 10,200 pounds, with a location of 11.5 feet.

The flight control system will use technology similar to that on the space shuttle.

The system should end up lighter, smaller and more capable, however, due to the technology advances that have been made since the shuttle was designed. Basically, it will be run by a computer that will account for all possible variables, while in orbit. The computers will be programmed for the orbiter to make a safe, stable re-entry into the atmosphere, at which time the vehicle will fall back under pilot control.

The pressurization system is critical to the lives of the crew. It is actually a sub-system of the entire life support system, which will be discussed in section 2.8.6. The pressurization system is responsible for supplying air to the crew at the proper pressure. This allows the crew to survive in the absence of an atmosphere.

### 2.8.6 Structure and Other Considerations

The orbiter structure is the greatest contributor to the overall weight. The Materials Section (2.6) discusses the different considerations that need to be made when choosing the orbiter materials. The actual structural characteristics were not considered, but it would more than likely involve a combination of the shuttle structure and new technology. The overall structure weight is 37,000 pounds and is located at 48 feet for CG calculation applications.

Several other areas were generalized into this weight, such as the orbiter maneuvering engines, cockpit, power generation, landing gear and airlock. All of these areas are integral parts of the orbiter, however, were not considered separately for this conceptual design. This report was primarily interested in studying the flight dynamics of the vehicle. Therefore, it was beyond the scope of the study to investigate these areas in detail.

The last area to be discussed is the life support systems. Due to the limited scope of this project this area will not be covered in detail, but the basic considerations merit mention. The orbiter will need to sustain the lives of the crew during the mission which requires very specialized equipment. Everyday things necessary for life, become complex problems in space.

The life support systems need to account for sleeping, eating, and any other elements essential to survival. The orbiter must contain the systems necessary to support the survival needs of the crew. These systems could be borrowed from the current shuttle, since it too performs these same functions. The technology is available and is being perfected day by day.

## 2.9 Separation

The most important and dangerous segment of the mission profile is the separation of the booster and orbiter. The mechanics behind the separation are designed to accomplish three things. First, the mechanics must allow the orbiter and booster to separate cleanly and safely. Second, the orbiter must be in position to begin its climb out of the atmosphere on its own immediately following the separation. Finally, the booster must be aerodynamically sound and stable following the separation in order to land safely. These essential functions depend directly on the mechanics of the separation.

The design separation system consists of three moving parts. The orbiter is seated down in the booster when the two are mated. To maintain the aerodynamic shape, a movable shroud was used to integrate the hull of the booster with the orbiter. The initial step of the staging process has the shroud slide forward along the booster fuselage to allow the nose of the orbiter clearance to be lifted into the staging position. Once moved, the orbiter is no longer blocked from being raised into position.

In order to lift the orbiter into the actual separation position two elements are necessary; a platform on which the orbiter is mounted and extending arms to do the actual lifting. The platform to be used is molded in a shape which will allow it to be lowered after the separation into the position previously occupied by the orbiter. The shape will allow for an almost continuous and smooth surface for the booster in order to maintain aerodynamic integrity. The lifting arms hinge at an elbow allowing them to fold flat beneath the shuttle when mated. The arms will be hydraulically extended when activated.

The lifting arms position the orbiter at a 3 degree inclination, as shown in Figure 2.12. (At the staging speed of Mach 6.5, 3 degrees will allow the orbiter to generate the necessary lift for safe separation.) The orbiter is to be connected to the platform by a series of latches along the fuselage of the orbiter. The wings of the orbiter are exposed to the airflow. At the moment the latches release the orbiter the shuttle will lift up and back in relation to the booster due to the inclination. The result will be a safe separation. Once the booster is clear the orbiter will be in a position so that its engines will begin propelling the craft out of the atmosphere.

While the orbiter is being lifted into staging position, the third moving part goes into action. Sidewalls which are hinged and folded beneath the shuttle when mated extend up along tracks in the fuselage. When fully extended and locked the sidewalls closely resemble the shape of the fuselage. The mechanism is controlled by motors operating a cable and pulley system. Once in place, the platform lowers down onto the extended sidewalls and creates a smooth surface along the sides and back of the booster. Finally, the front shroud moves back, locking into place to create a continuous, smooth, aerodynamically sound craft easily capable of a safe landing, as seen in Figure 2.13.

The stability for the booster during and after separation is a prime safety concern. The sudden loss of weight and surface area are potential aerodynamic disasters. However, careful design of the staging procedure replaces the lost surface area quickly so that the aerodynamics of the booster in its post staging configuration are very similar to the mated system. Accounting for the lost weight requires more careful overall design. By aligning the centers of gravity of both the orbiter and booster as closely as possible, the moment created by the loss of the mass of the orbiter is minimized. In this design the centers of gravity were approximated to be roughly two feet apart. (See Appendix A for details.)

To counteract the moment created, a computerized system is to be implemented. The system will take inputs from strain gauges or load cells to measure the load the orbiter actually is applying on the booster. From this information, the computer will calculate the necessary amount of fuel it will relocate to another reserve fuel tank in order to negate the changing weight distribution along the booster. By implementing this system, the center of gravity of the booster will remain as nearly constant as possible, thus maintaining stability as well as overall handling characteristics.

Other methods of separation were considered in developing this process. The procedure of simply releasing the shuttle and letting it slide off the rear of the booster was studied, but several problems caused concern. First, there was no ability to control the attitude of the orbiter during or immediately after separation. Also, this procedure would require a complex servo-mechanism to counterbalance the transition and loss of weight during and following the separation. Furthermore, design considerations for this staging sequence create aerodynamic difficulties for the booster after the separation.

Another separating process analyzed for a piggyback launch was a vertical ejection system. During such a procedure, the orbiter would be released and forced upward as the booster craft prepared to immediately dive so as to avoid the dropping orbiter. A problem with this method would be the attitude control of the orbiter. While the orbiter would likely be able to control its attitude, much energy and fuel would be wasted in gaining the necessary pitch for its climb. Another concern was the stability of the booster. The effects on the booster from the force necessary for the ejection, the loss of weight, and the necessity to quickly dive create many problems to be dealt with. This procedure presented too many safety concerns.

The system chosen for this project implements the positive aspects of each of the above methods. By having the booster continue in level flight following separation (as in the first method) the booster will be able to regain complete stability and control before beginning its decent. From the second method the benefits of having the center of gravity of both the booster and orbiter closely align were borrowed. This allows for the booster to quickly adjust for the sudden loss of weight and maintain stability. The method chosen, while slightly complex, is able to accomplish the necessary tasks quickly, safely, and efficiently.

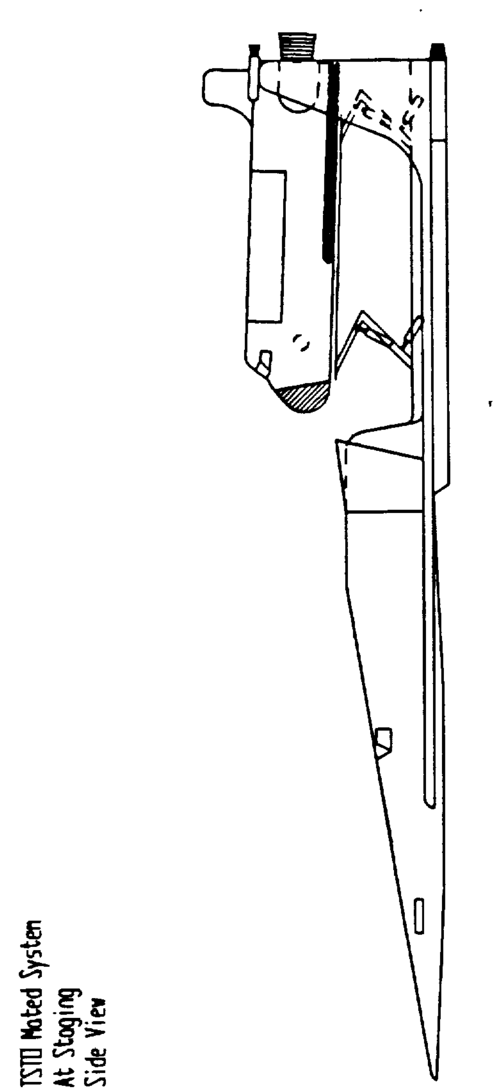



Figure 2.12 Mated System at Staging

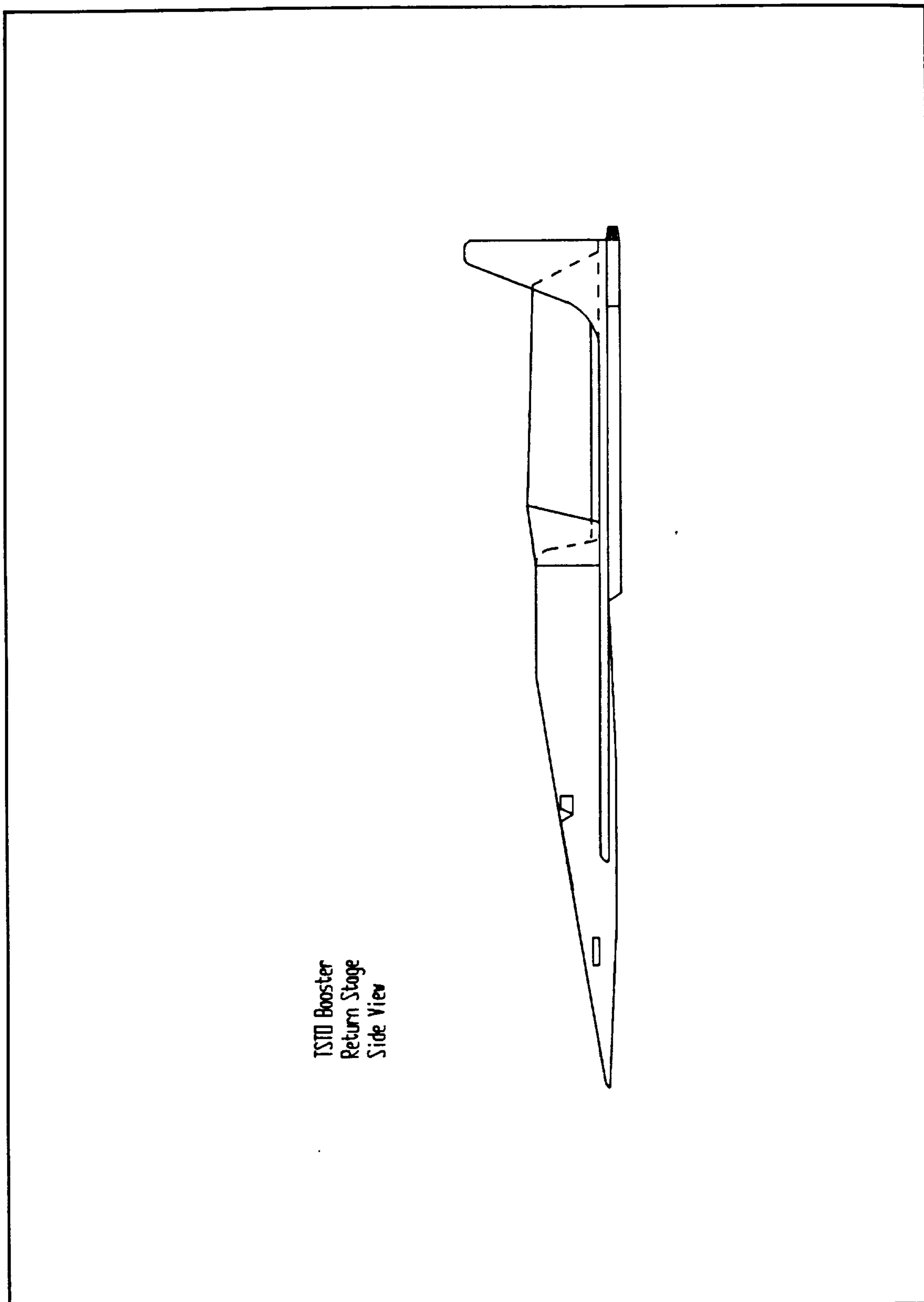



Figure 2.13 Booster Side View Return Stage

## 2.10 Safety

Safety of the crew, cargo and the general populous is vitally important when designing a spacecraft of any kind. The following are various problems that could be encountered with a TSTO mission and lists practical or possible solutions.[15]

Should the need arise for a launch pad abort, the crew of the booster would exit similarly to a takeoff abort of an airliner. The crew of the orbiter would exit through the hatch of the vehicle, which has exploding bolts to open it in case of an emergency. The windows of the orbiter are also detachable. Once the opening is created, a rope or inflatable side would be used to evacuate the vehicle.

If a mission needed to be aborted, the mated system would simply return to the launch site and land. If the mission was too far away to return, due to fuel consumption, the orbiter would separate if possible and abort to orbit. The booster would then return to Earth at the closest specified location. The orbiter will ascend to orbit and either complete the original mission or prepare for immediate re-entry.

If the separation procedure fails, the first plan of action would be to initiate a manual override. An override sequence to release the orbiter will be installed to automatically separate the vehicles if initiated. If this is not feasible, the mated system would simply return to Earth. Similarly, if either the cargo doors of the orbiter or the shroud of the booster were stuck or inactive, another manual override to the computer system. There should also be a manual crank in the cockpit of the booster (geared to properly compensate for the potential forces at Mach 6.5) due to the seriousness of a failure. A manual override system similar to this would also be used in case the platform upon which the orbiter sits were to be stuck in the up position after separation. If the platform were to be stuck down, or the release mechanism were to not work, the mated system would simply return. If the hydraulic walls stick in the down position, a backup system of hydraulics would be implemented to raise them. This would be a very critical failure, and both systems would be extensively tested before launch.

In case of a fire, the cabins of the orbiter and booster are equipped with smoke detectors and fire extinguishers. Likewise, to protect the cabin environment emergency oxygen will be carried aboard, and the air will be filtered before being recirculated in order to minimize any air contamination.

To rescue crew members in case of an emergency while the orbiter is in outer space, Manned Maneuvering Units would be used to transfer the stranded parties to either the space station or another orbiter. If a medical emergency were to arise, a medical kit similar to the one currently carried aboard the present Space Shuttle would be carried aboard the orbiter and booster. If a serious injury or disease which threatened the safety of the crew occurred, the mission would be cut short and the orbiter would return to Earth.

Since every major system is tied in to some extent to the computer system, a system similar to the one used on the present Space Shuttle would be used. This system consists of three computers for each system. If one system were to go down, depending on the seriousness of the system affected, the mission could be immediately aborted. This would allow for a working system with another system as a backup for safety.

## 2.11 Support

The TSTO vehicle is designed for various missions, and a quick turnaround time. This section describes the support facilities that would be needed to service the TSTO mission (booster, orbiter, and payload). Figure 2.14 shows the basic, standard procedure of the path through the launch facilities.

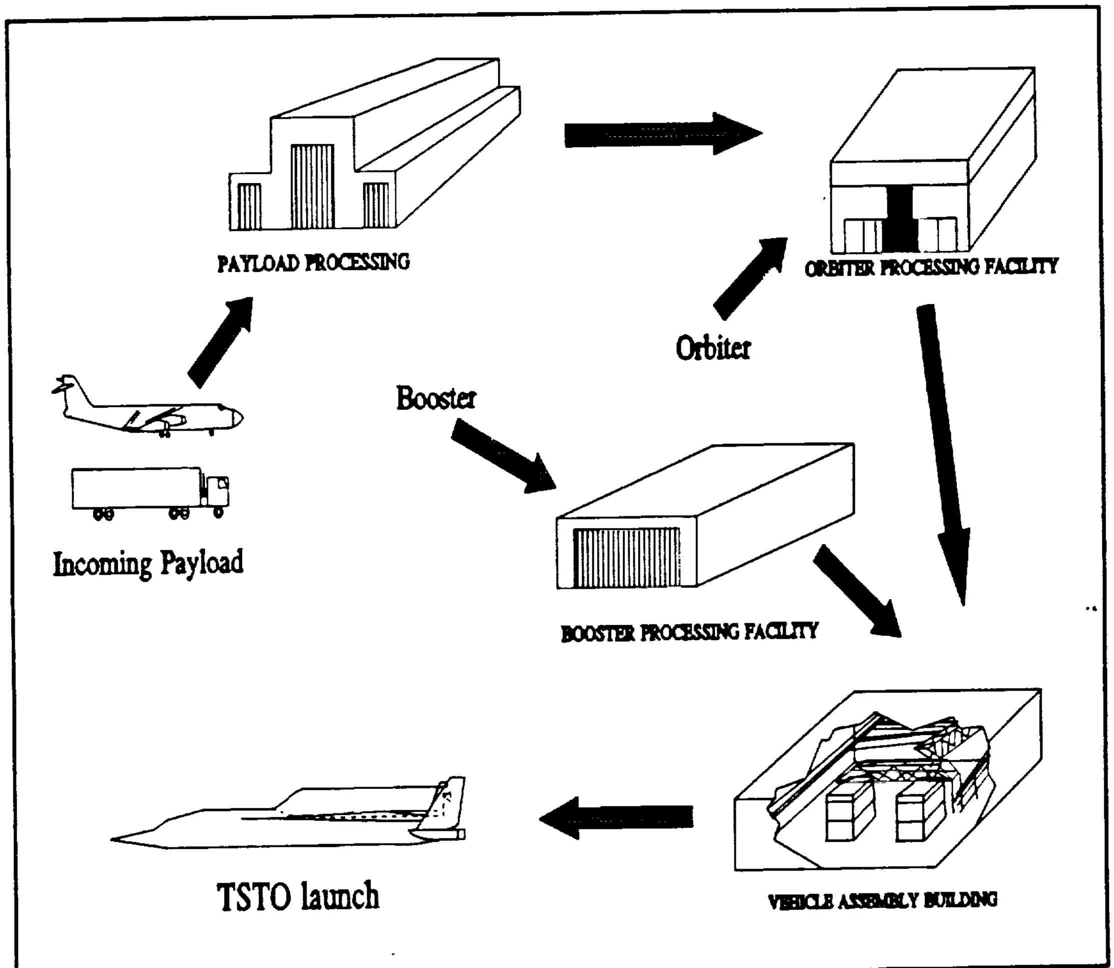



Figure 2.14 LAUNCH FACILITIES

### 2.11.1 Processing Facilities for the Booster

The booster would require facilities similar to what the Space Shuttle orbiter has now. After staging and separation, the booster would glide down to a designated landing facility (airport). The booster would be taken to a Vehicle Processing Facility (VPF) to begin checkouts and servicing. The VPF for the booster could be a large aircraft hanger. Maintenance and system checks could be made using techniques similar to those used for today's aircraft. Because the booster aircraft design has been designed similarly to current high speed aircraft, it should have a quick turnaround time. The booster could be built in modules, where the damaged ones could be pulled out and new modules put on the aircraft for faster turn-around times. The damaged modules could then be worked on while the booster is on its next mission. The VPF could be built at a large airport with enough room to support the TSTO facilities. Once the booster is checked out, it could taxi to the Vehicle Assembly Facility (VAF) to be mated with the orbiter.

### 2.11.2 Processing Facilities for the Orbiter

Upon completion of each mission, the orbiter will be brought to the Orbiter Processing Facility (OPF) to be serviced and checked out. The OPF will have a crane that will lift the Orbiter off the ground to enable maintenance personnel to work on all of the systems simultaneously. The crane will also allow payload removal and insertion.

Systems checks and maintenance will be done to the orbiter at this stage. The Orbiter's thermal systems in particular will have to be checked and refitted. The turn-around for the Orbiter should be much faster than today's Space Shuttle. The Orbiter will use pull-out modules for ease of maintenance and turn-around time. By using more advanced computers and supporting systems, the systems will be smaller, and should be easier to maintain. The existing facilities used for the Space Shuttle could be utilized until more facilities could be built at other airports.

### 2.11.3 Payload Facilities

This section describes the basic operations that must be performed to prepare a payload for launch on the TSTO orbiter. Currently, the payloads that are installed on the Space Shuttle are assembled at a processing facility at the launch site, and can be installed horizontally, or vertically in the orbiter. However, because the TSTO takes off horizontally, all of the payloads must be loaded in a horizontal position to our orbiter.

The launch facility would receive payloads for assembly and checkouts in the Payload Processing Facility (PPF). Payloads could be brought in by land or air. Typical payloads currently include Spacelab modules, satellites, various pallet and mission peculiar experiment support structure equipment, and other special structures. Future payloads could consist of space station modules, passengers, and space construction equipment. All payloads would be checked and approved before being installed on the orbiter to ensure safety, environmental concerns, security, and to save time and money of ensuring payload integrity before launch. Once the payloads have been tested and approved, they will be placed in protective canisters and transported to the Orbiter Processing Facility.

Once the orbiter has been checked out and approved for the next mission, the next payload could be loaded. Payloads can be removed from the canisters and loaded onto the orbiter here. Payloads will be hoisted in a horizontal attitude from the canister-transporter, positioned over the orbiter, lowered, and secured in the payload bay. The facility cranes support this operation. Once the orbiter has been checked out and loaded with its new payload, it will be transported to the (VAF) where it will be mated with the booster.

### 2.11.4 Vehicle Assembly Facility

The VAF will have to be an enormous structure to accommodate the booster and the orbiter. The Vehicle Assembly Building for the Space Shuttle covers 8 acres and is over 500 feet tall; however, the TSTO facility will not have to be as tall because the booster and orbiter will be mated horizontally. Huge cranes will lift the orbiter onto the booster. The entire system will be checked out and approved for launch. The crew would enter the TSTO vehicle and taxi the vehicle to the runway for launch.

### 2.11.5 Runway

The TSTO vehicle will be able to take off at some of the major airport facilities. The only problem is having the appropriate support facilities; therefore, several airports could be configured to support the TSTO. Kennedy Space Center and Vandenberg Air Force Base could be used as the first launch sites because they already have most of the facilities to support the TSTO. The TSTO would need approximately 13,000 feet of runway for takeoff.

### 2.11.6 Landing

Once separation has occurred, the booster could land at almost any large airport in the world. The orbiter, which will be landing at higher speeds, will require a longer runway, such as the one at Edwards Air Force Base, or Kennedy Space Center. Edwards AFB, which already supports the Space Shuttle could easily accommodate a new orbiter. Several existing military, as well as some commercial airports have facilities that could support the TSTO if the runways were lengthened about three thousand feet, and if the vehicle checkout and mating facilities were built.

### 2.11.7 Navigation During Landing

For navigation during landing, multiple systems will be used. The booster and orbiter will use the existing TACAN (tactical air navigation) system above 18,000 feet for landing. Under 18,000, the microwave landing system will be used. Both systems are currently used by the Space Shuttle. The Boeing 747 used to ferry the Space Shuttle could also be used to transport the new orbiter to the next airport the orbiter will be launched from.

## 2.12 Flight Dynamics

In this section, the mathematical framework for the flight dynamic simulation is presented. The first step of flight dynamics begins while the orbiter and booster are mated, ready for takeoff at the end of the runway. The weight is acting at the center of mass for the coupled system, as shown in Figure 2.15.

The weight is a function of the mass and of gravity, $W = mg$ acting normal to the earth's surface. It will remain constant while on the ground, not consuming fuel. It must be noted that the weight will be different for each flight because of different payload weights.

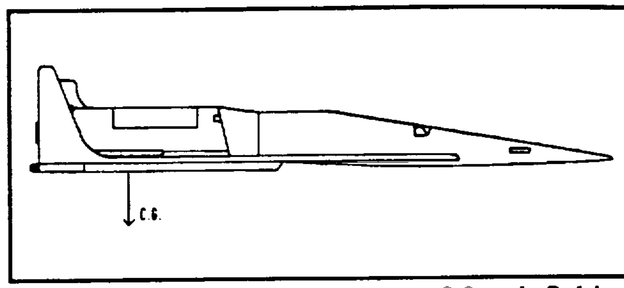



**Figure 2.15** Center of Mass, Mated Orbiter and Booster

The configuration has been designed so that the Center of Mass of the booster and the Center of Mass for the orbiter coincide with the Center of Mass for the coupled system. This means that the center of mass will shift very little if at all when the booster and the orbiter separate, allowing for control of both aircraft. It is important to look at the flight path of the system. The coupled system starts from the parked position and takes off. The system then accelerates through subsonic flight to transonic flight then to supersonic flight where staging occurs at Mach 6.5. The following governing equations are the same for each stage of flight. Note however, that the Lift and Drag will be different for each stage and will have to be typed manually into the computer program.

The equations of motion are what govern the success of the system. For the flight of the system up until staging, the governing equation is based on the dynamics shown in Figure 2.16.

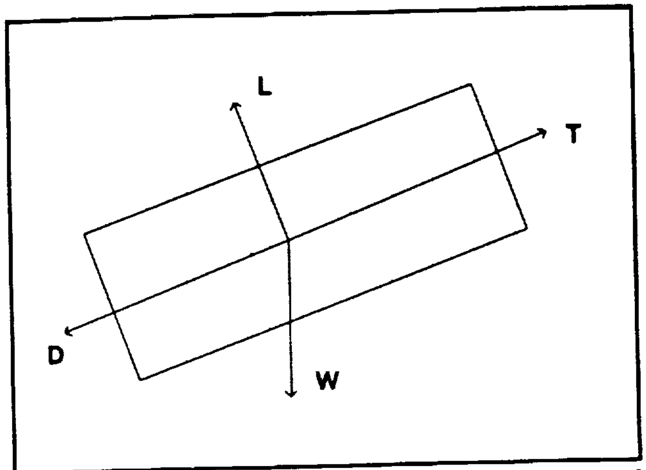



**Figure 2.16** Coupled system in flight, depicted by "box".

Knowing that the system will be moving forward, the thrust will be the resultant of the velocity, weight and drag vectors. Thus,

$$+\nearrow \quad \Sigma F_x: \quad T - D - W_f = \frac{\partial}{\partial t} mv$$

where

$$\begin{aligned} m &= \textit{mass of booster + orbiter + fuel} = m_{b+o} + m_f \\ v &= \textit{velocity of system} \\ W_f &= \textit{weight function} = (W_0 - \int_0^t \dot{m}_f \, dt)\cos\gamma \\ T &= \textit{thrust} \\ D &= \textit{drag} \end{aligned}$$

Breaking up the differential,

$$T - D - W_f = v\frac{dm}{dt} + m\frac{dv}{dt}$$

where

$$\begin{aligned}
T &= f(altitude, Mach\,Number) \\
D &= f(altitude, Mach\,Number) \\
W_f &= f(time, mass\,flow\,rate, flight\,path\,\angle) \\
v\frac{dm}{dt} &= f(time, Mach\,Number, altitude) \\
m\frac{dv}{dt} &= f(time, velocity)
\end{aligned}$$

Each of the components of the equation of motion must be examined individually and are explained in the subsequent pages.

## 2.13 Computer Codes

The computer codes in the following sections were critical for getting a quantitative evaluation of the design performance. With several separate teams working to produce data on their specific aspect of the design, a place where those values can be integrated is essential. The propulsion team produced such critical engine data as thrust and specific thrust. The aerodynamics team produced important coefficients of lift and drag data. The mission parameters team investigated optimal flight path constants including weights, staging speed, and altitude. With the following programs these separately developed design segments could be evaluated while functioning together.

The major purposes of a quantitative evaluation are to 1) substantiate the design validity with confidence 2) optimize the design and 3) ensure sufficient contingency factors. The first purpose is the most important and the main mission of this project: the design must be able to complete its intended mission. The second purpose is not difficult but rather time consuming. Many computer runs must be made to get a feel for the effect that each variable has on the performance outcome. The fine tuning of the performance outcome can then be made with specific objectives in mind. And finally, the third purpose is to ensure fuel reserves and the possibility of an aborted mission.

The analysis was broken into two portions, each with their own code. The first analysis is for the mated vehicle from takeoff to staging and the return of the booster alone. The second analysis is for the orbiter from separation point to orbit. Although the two programs share a great deal of supporting files, functions, and operations, they have different governing equations and very different methods of computing these equations.

Program TSTO12.PAS performs the first analysis, having consumed the majority of programming time. Before any other functions were developed, the Interpolate function was created. This essential function uses an independent value, reads a two column set of data, interpolates between the dependant values, and finally returns this value. After their analyses, the separate design teams provided simple tables of values, which were saved as ASCII text files that could easily be accessed by the program. If, after the program had run, an aspect of the design needed to be modified, another text file with new values was made; and, with the simple change of a constant, the program accessed this new data. This way, all input data is saved in a readily available format.

Another large hurdle which was anticipated early was the possibility that a double interpolation scheme would be needed for the calculation of thrust. The complicated engine design makes this value a function of altitude as well as Mach number. Additionally, the graphical information supplied was in a semi-log format.

These factors required the development of the DoubleInterp function. It is passed the two independent values with which to interpolate as well as the name of a file which contains the names of the files containing the data. For the thrust case, using the altitude, the function decides which two sets of the log of thrust vs. Mach number data the value falls between. Then using Interpolate, the function finds the two thrust values for these two altitudes. It then performs a third interpolation for the exact altitude to find the final value. On top of this, the valid thrust value is found by taking the inverse natural log of the interpolated value..

With each method of input completed, the next step in the program's evolution was the development of all other functions, such as Mach number, thrust, and drag. For this, the most basic global parameters had to be known so that a minimum amount of passing values could be used. Thus, the governing equation was investigated, and the basic defendants of each variable were found. From the governing equation,

$$m\frac{dv}{dt} = T - D - W\sin\gamma - V\frac{dm}{dt},$$

Equation 2.13.1

it is seen that the velocity is a function of the following macro-variables.

$$V = f(m,T,D,W,\gamma,V,\dot{m})$$

But it is also disentangled that the thrust will be a function of only the throttle setting, altitude, and the Mach number, which is a function of only the velocity and altitude.

$$T = f(V,h,throttle)$$

And the drag is a function of the velocity, the Mach number, and the density, which is a function of only the altitude. This all reduces.

$$D = f(V,h)$$

With the weigh a function of only mass, the root independents can be listed.

$$V = f(V,h,m,\gamma,\dot{m},throttle)$$

These six variables became the main global variables since all other required values can be found from them.

With the global variables chosen, each individual function was created. The only legal passing values are the global variables. The individual functions were each created in their own skeleton program and rigorously tested for accuracy, especially the Interpolate function which has many potential pitfalls. Only after all of the functions were created, were they all integrated into TSTO12.PAS. This simple procedure saved countless hours of debugging. If each function had not been independently tested before being integrated, the plentiful separate logic errors that were found could have together overwhelmed the programmer, making the task of programming quite oppressive.

In the governing equation, the velocity is a complicated function of itself, making its calculation more complicated than an explicit determination. A numerical method of calculation was required. The method chosen would determine the accuracy of the results. A fourth-order Runge-Kutta integration method was chosen. In their report an in-depth discussion of the workings of this method are discussed. Basically the method takes a series of small steps to cross each interval, calculating and using the changes along the way. A weighted average of the intermediate values is then taken for the final interval changes.

With the input and calculation aspects completed, an output procedure had to be created. Because some of the output variables were not global, they had to be calculated each time that output was needed. Also different output variable collections were tailored for the separate design teams. The propulsion team would not be as interested as the aerodynamics team in the drag force on the vehicle.

A reduced-throttle, leveled flight is better for smooth engine transition. This required a specialized flight path which had to be built into the program. It was also decided that a second leveling out before staging would be beneficial.

The program's overall performance was highly acceptable. Program TSTO12.PAS has an interval of 0.4 seconds and runs in about 30 to 35 minutes with a great deal of output.

In Appendix C, an algorithm and program listing for TSTO12.PAS can be found. In addition, there are also lists of supporting files, functions, constants, and variables along with short descriptions of each. Finally, the contents of the program's supporting files are provided.

Program ORB.PAS performs the second analysis. This second program is less complicated because the orbiter is considered a non-lifting body and does the majority of its travelling in a virtually dragless atmosphere. This program also uses the Interpolate function to access some of the same supporting files. It also uses the Mach number function, but that is the extent of its functions. It also shares the method of changing constants.

Because the governing equation is much less complicated as a function of velocity, the method of calculation is much more simple.

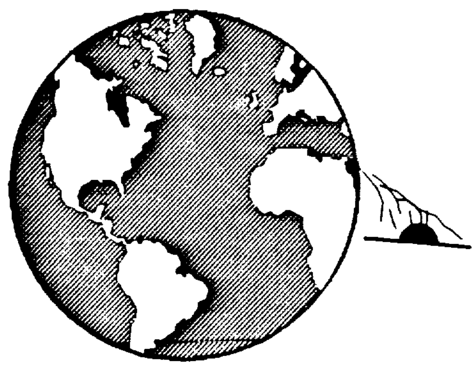
$$dv = \frac{T}{m}\,dt - \frac{D}{m}\,dt - g\cos\theta\,dt$$

Equation 2.13.2

The change in velocity for each interval can be explicitly calculated from the mass, the Mach number, velocity, acceleration due to gravity, flight path angle, and interval time.

This program also shares the method of output, but requires only one output file. In Appendix C following the description of TSTO12.PAS, is all of the same information on ORB2.PAS.

# Propulsion System Design



# Chapter 3

## 3.1 Booster Propulsion

All future design possibilities for hypersonic space launch vehicles utilize combinations of air breathing and rocket propulsion. Air breathing engines are used for at least some part of the flight envelope for several reasons. One of the primary goals in the development of such a spacecraft is reduction of propellant consumption. For this reason, air breathing engines are preferred for the first stage because they utilize oxygen in the atmosphere. This results in a significant decrease in oxidizer consumed aboard the craft. Rockets, while required for exoatmospheric flight, have very low specific impulses. Therefore, the use of air breathing propulsion within the atmosphere may result in a lighter, lower cost vehicle.

The advantage of air-breathing engines due to relative levels of specific impulse is shown in Figure 3.1. Air breathing propulsion typically has a specific impulse an order of magnitude higher at low Mach number range, and potential for significant increase, over rockets at hypersonic flight conditions. Another conclusion that can be made from Figure 1 is that no one propulsion system is optimum over the entire flight Mach number range.[16]

The hydrogen fueled parallel turboramjet engine was the engine selected for the TSTO booster. The selection process for different engine configurations included the turbojet, ramjet, scramjet, and rocket propulsion systems. The engine design was narrowed down to a Turboramjet (TRJ) engine. However, there were several possible TRJ designs that could be selected, such as an over-under configuration, in-line, or parallel TRJ. The basic types of turboramjet engines, the TRJ and ATR, are shown in Figure 3.8. There were several factors which were considered to determine the best propulsion system for the booster.

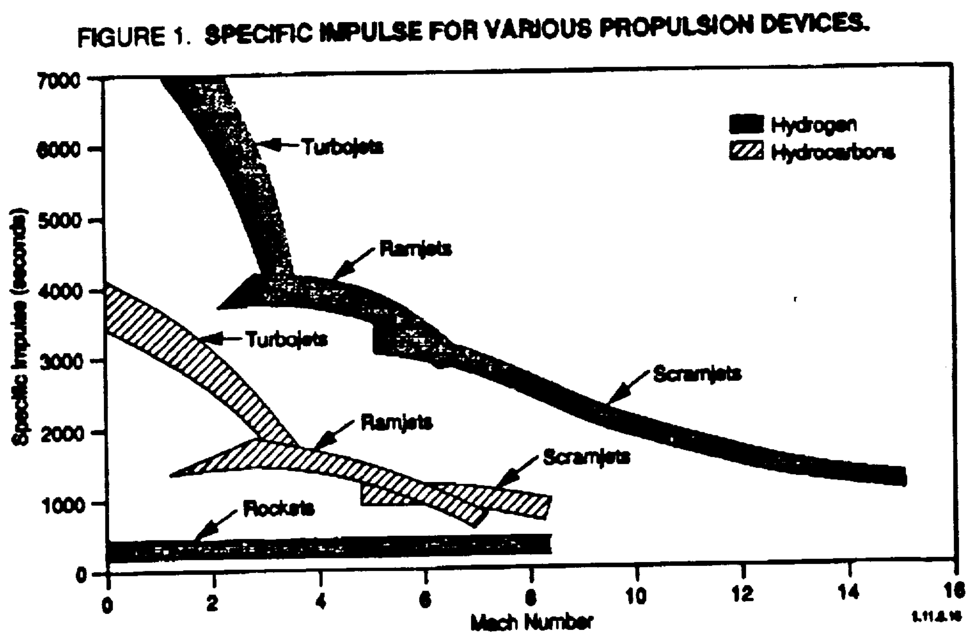



**Figure 3.1** Specific Impulse for Propulsion Systems

### 3.1.1 Engine Configuration Considerations and Selection

There are several engine development challenges to consider in the design of the new propulsion system. One of the biggest obstacles is system operation with turbojets and ramjets. The engine must have stable operation and performance over a wide operating range. The high speeds at which the engines will travel requires active cooling and thermal management to ensure safety, operation limits, and structural integrity. The propulsion system will also most likely use advanced composite materials, and will require a low density, cryogenic hydrogen fuel or a better fuel.

Several promising air breathing engines have been studied along with different types of fuel. This section presents an overview of the different engines and fuel types. The engines include the turbojet (TJ), turboramjet (TRJ), three types of air turboramjets (ATR) and supersonic combustion turboramjets (SCRAMJET). Figure 3.10 (a-d), at the end of the chapter, shows the basic configuration of each type of engine.

The TJ engine is shown in Figure 3.10(a). The biggest advantage of the TJ is its conventional design which has propelled a great many airplanes for more than 40 years. This reduces the risks that other new-concept engines are associated with.[17] The TJ engine is effective from take off to approximately Mach 3. The reasons for this Mach number limitation, which has already been discussed, is mainly due to the heat resistance limits of the turbine.

There are three configurations of the TRJ engines. They are the Over/Under, In-Line, and Parallel TRJ, shown respectively in Figures 3.12,3.14,3.15 at the end of the chapter. The TRJ is a combination of a traditional turbojet with a ramjet. The TJ portion operates from take off to about Mach 3 and the RJ engine extends the flight range up to about Mach 6 or 7. These engines can keep a high $I_{sp}$ over a wide Mach range, but have the disadvantage of the complexity of engine operation in the transition between the two engine modes. The Parallel TRJ is lighter than the Over/Under design, but needs a more complex operation-control system because of the mixing of two different flows in the ram combustion chamber.[18] The TJ in the Parallel TRJ is separate from the RJ, and must be separated from the flow after Mach 3. The Parallel TRJ has a separate burner and nozzle section for the TJ and RJ sections. The In-Line TRJ is basically the same as the Parallel, except that the TJ and the RJ use the same burner and nozzle, which saves weight but complicates the transition between the two engines during flight.

The ATR is also popular in recent space plane designs. The basic ATR, shown in Figure 3.10(d), is a high bypass ratio turbofan engine, but has a special turbine driving the fan. Its operational range is roughly equivalent to that of the TRJ. System technologies are based on turbofan and rocket engines.

There are 3 types of ATRs, shown in Figure 3.11 (a-c). The gas generator cycle ATR (ATR-GG), shown in Figure 3.11(a), uses a fuel-rich combustion gas as the working fluid in the fan-driver turbine. The expander cycle ATR (ATR-EXP), shown in Figure 3.11(b), uses hydrogen fuel, which is heated in the heat exchanger located in the combustion gas flow, as the working fluid.

The main problem limiting the ATR engine development is heat resistant fan technology. The ATR-GG has a lower $I_{sp}$ than the ATR-EXP since it uses an oxidizer with the fuel. There is also a Liquefied Air Cycle ATR (ATR-LA), shown in Figure 3.11(c). The ATR-LA is similar to the ATR-GG. In the ATR-LA, part of the air being utilized as the oxidizer in the gas generator combustor is liquefied by cryogenic hydrogen fuel. Liquefication takes place in a hydrogen-cooled liquefier installed down stream from the air intake. The ATR-LA weighs less than the ATR-EXP.[19]

Scramjet engines have the ability to operate in very high Mach number ranges, from Mach 6 up to around Mach 20. The engine concept is similar to a ramjet, where the airflow is slowed to subsonic speeds in the combustion chamber, except the scramjet combustion chamber receives the airflow at supersonic speeds. Scramjets are very complicated to design and build. There are many problems with combustion due to shockwaves at such high speeds. Scramjets are very advantageous for flight in hypersonic flight regimes, if all the technological challenges could be met.

Choosing the engine type best suited for the proposed mission involved comparing different weights, thrusts, consumption, technological risk, and other factors. As already stated, the choice of a propulsion system for the booster was between the different air-breathing engines described in the last section. The possible engine candidates were very quickly narrowed down by analyzing Figure 3.1 (specific impulse for various propulsion devices), which was already mentioned in the introduction.

As stated earlier, no one propulsion concept is optimum over the entire flight Mach number range. The goal is to find the best engine suited for the proposed flight Mach number range, which is from take off to staging (Mach = 0-6.5). From a quick look at Figure 3.1, it appears the best choice would be some sort of hydrogen fueled combination of a turbojet and ramjet. A pure turbojet engine cannot be used due to its limitation of approximately Mach 3 and it would be senseless to get into the complexities of a Scramjet since its true range of greatest efficiency is greater than the staging Mach number. The biggest reason for a TSTO vehicle over a Single Stage To Orbit vehicle is to avoid the complexities involved with Scramjet use. The SSTO vehicle is much more efficient, but much more risky to design and build. This quickly narrows down the selection to either a TRJ or an ATR engine type.

The engine selection is based on the performance characteristics of the engines. A comparison was made between a typical TRJ and the three types of ATR engines studied. Thrust and specific impulse were considered for each engine type. The data was obtained from reference 6. Data in the study was collected under the following conditions:

- The adiabatic efficiencies of the turbomachinery, combustion efficiency, pressure loss coefficients of the flow paths, and mechanical losses were assumed according to current technology.

- Variable intakes and nozzles were adopted, but geometric limitations of the intake, which means a maximum inlet opening area, was considered.

- The air intake was geometrically fixed for a Mach number higher than 4.

The data is summarized in Table 3.1, which is reproduced from reference 6. Notice that there is no difference in thrust levels between the engines. Specific impulse depends on the liquid oxygen utilization. With the exception of the ATR-GG, the specific impulse of all the engines is almost identical. Since all four engines have very similar thrust characteristics the deciding factors are weight and technological risk.

The weights of the engines of Table 3.1, reflect the use of advanced materials. This includes such materials as ceramics and advanced carbon-carbon composites. Use of advance materials may make the engines lighter by more than 30% over engines built with conventional materials.[20] When weight is combined with possible risk the optimum engine is the TRJ.

| ENGINE | $I_{sp}$ (SEC) | THRUST(S.L) (KN) | WEIGHT (KG) | THRUST/WEIGHT |
|---|---|---|---|---|
| TRJ | 3000-4000 | 147 | 1310 | 11.5 |
| ATR-GG | 2000-3200 | 147 | 970 | 15.5 |
| ATR-EXP | 3000-4000 | 147 | 1550 | 9.7 |
| ATR-LA | 3000-4000 | 147 | 1330 | 11.3 |

**TABLE 3.1**
**Engine Performance**

The TRJ has very little technological risk involved, except for the TJ/RJ transition. The engine technology already exists and has been used for many years. The TRJ weight is less than every other engine except the ATR-GG, which had a low specific impulse. However, the ATR has the additional weight of an oxidizer, which is used in combustion. Consequently, the ATR was ruled out for use in the booster propulsion system. This leaves us the choice of the Parallel, In-Line, or Over/Under TRJ configuration.

The Parallel and In-Line TRJ are an integrated engine concept that consists of a core TJ inside a cylindrical duct which forms the RJ. This results in a RJ engine that has a large surface area. In addition, the diameter at the engine face of the Parallel and In-Line TRJ requires a large subsonic diffuser ahead of the engine to meet the requirements of both the TJ and the RJ. This leads to large, wetted, internal duct areas and heat loads, and requires the simultaneous operation of both the TJ and the RJ.[21]

Also, the In-Line engine, which uses the same burner and nozzle section for both the TJ and RJ engines, has trouble delivering a steady, stable flow stream during the engine transition. Possible problems such as a flame out, and poor engine performance during the engine transition rule out the In-Line TRJ configuration. Therefore, the Parallel TRJ was chosen over the In-Line configuration.

Parallel TRJ has a higher mission capability than the Over/Under TRJ because there are two combustion systems and exhaust nozzles used in the Over/Under which adds weight. The Over/Under design allows for a shorter engine system (inlet, engine, and exhaust expansion), but also has a larger cross-sectional area. The Over/Under TRJ configuration involves the least amount of technological risk because two separate engines are used. However, the inlet design of the Over/Under TRJ is more complex than the Parallel TRJ, and more variable geometry surfaces are used.[22] The Parallel TRJ also produces more lift than the Over/Under configuration. Consequently, the Parallel TRJ was selected for the propulsion system for the booster.

### 3.1.2 FUEL SELECTION

The next consideration to be addressed is fuel type. At this point in time cryogenic hydrogen is the universal choice for fuel because of its high energy content for performance and its large heat capacity for vehicle and engine cooling. The heat of combustion for hydrogen is approximately 2.5 times as much as the hydrocarbons, which is responsible for the very high hydrogen specific impulse as compared to hydrocarbons (see Figure 3.1). Cryogenic hydrogen also has nearly an order of magnitude better heat sink capacity than hydrocarbons, which makes it much better for cooling. In this area not even endothermic fuels are comparable to hydrogen. The only disadvantage of hydrogen is its low density (4.7 LB/FT$^3$), which results in large vehicles to accommodate large fuel volume requirements. Table 3.2 shows a comparison between hydrogen and other fuels.[23](reproduced from reference 4)

| FUEL | HEAT OF COMBUSTION (BTU/LB) | LIQUID DENSITY (LB/FT$^3$) | MAX HEAT PHYSICAL | SINK (BTU/LB) ENDOT-HERMIC | CAPACITY TOTAL |
|---|---|---|---|---|---|
| HYDROGEN | 51,600 | 4.7 | 6700 | - | 6700 |
| METHANE | 21,460 | 28 | 1350 | - | 1350 |
| MCH | 18,630 | 48 | 1016 | 940 | 1956 |
| DECALIN | 18,240 | 56 | 1020 | 950 | 1970 |
| JP-7 | 18,500 | 48 | 269 | - | 269 |

TABLE 3.2
COMPARISON OF FUEL PROPERTIES AND CHARACTERISTICS

### 3.1.3 ENGINE COMPONENT DESIGN CONSIDERATIONS

The Parallel TRJ engine will operate at high altitudes, in thin air, and at very high speeds. The thermal and structural conditions at supersonic speeds dictate that the design of the airframe structure, aerodynamic shape, and especially the propulsion system. At speeds of approximately Mach 3, the hot section of a turbojet engine must be separated from flight conditions since the turbojet inlet temperature becomes the limiting factor in achieving specific thrust.[24] As a result, the compressor is no longer required to achieve adequate cycle pressure ratio; consequently, the turbojet is not able to operate above Mach 3. These high speeds also require active cooling, to cool the engine surfaces, using the hydrogen fuel as a heat sink.

Since the Parallel TRJ configuration will be used, the components of the turbojet engine will now be considered. The ramjet, which only consists of an inlet, burner, and nozzle will not be discussed in detail. The major components of a turbojet are the inlet, compressor, burner, turbine, and nozzle. In order to be able to design the best engine, it is necessary to gain a basic understanding of the engine components, the function of each part, and design limitations. The standard notation and symbolic representation of a turbojet and a ramjet are shown in Figure 3 and 4, respectively.

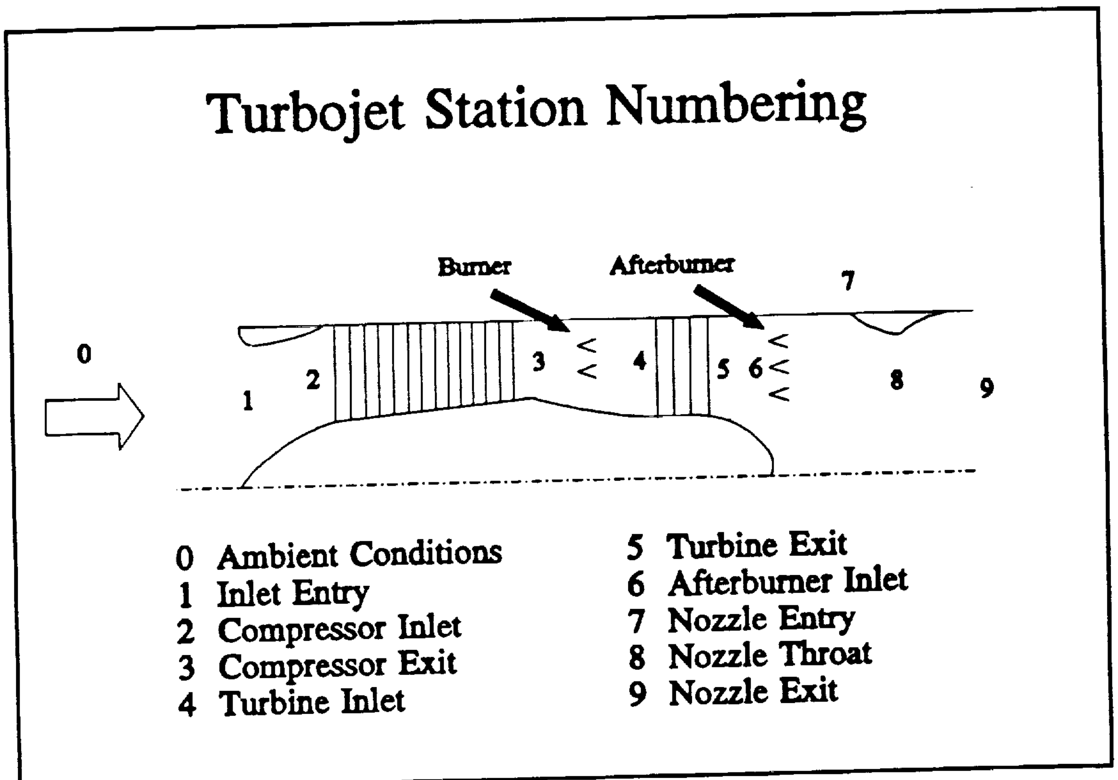



**Figure 3.2** Turbojet Notation

Inlets (1 to 2): The characteristics of an inlet depends on whether the inlet will be flown at subsonic or supersonic speeds. The TSTO spacecraft will be flown in both regimes; consequently, a good design will incorporate both supersonic and subsonic flight

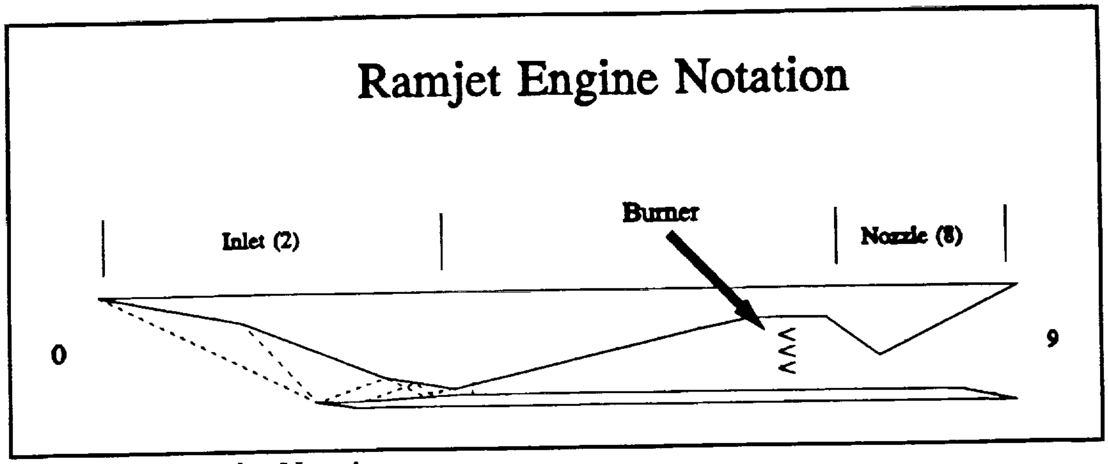



**Figure 3.3** Ramjet Notation

regimes. In either case, the requirement of the inlet is to provide the incoming air to the compressor at as high a stagnation pressure as possible and with a minimum variation in stagnation pressure and temperature. The inlet must provide a substantial diffusion of the air before it enters the engine.

The design of subsonic inlets for use with the turbojet engine is dominated by the need to retard separation at extreme angles of attack, and to retard the onset of both internal and external shock waves in transonic flight. Modern development of the best compromise design is greatly aided by the use of high-speed electronic computation, which allows for an analytical estimation of the complex flowfields and related losses to make compensations in the inlet geometry during flight by varying the geometry to the changing flight conditions.

Once the TSTO enters the transonic region, shocks waves and supersonic characteristics must be considered. Design of simple supersonic inlets for the ideal situation is easier than subsonic inlets because most of the losses occurs across shock waves, although more exacting estimates require estimation of the boundary-layer and related losses. There are many design possibilities for supersonic inlets. They include the simple normal shock inlet (which has a single normal shock wave located in the flowfield ahead of the inlet lip), internal, external, or mixed compression inlets. See Figure 3.4. Our design will use mixed compression, combined with external compression during hypersonic speeds.

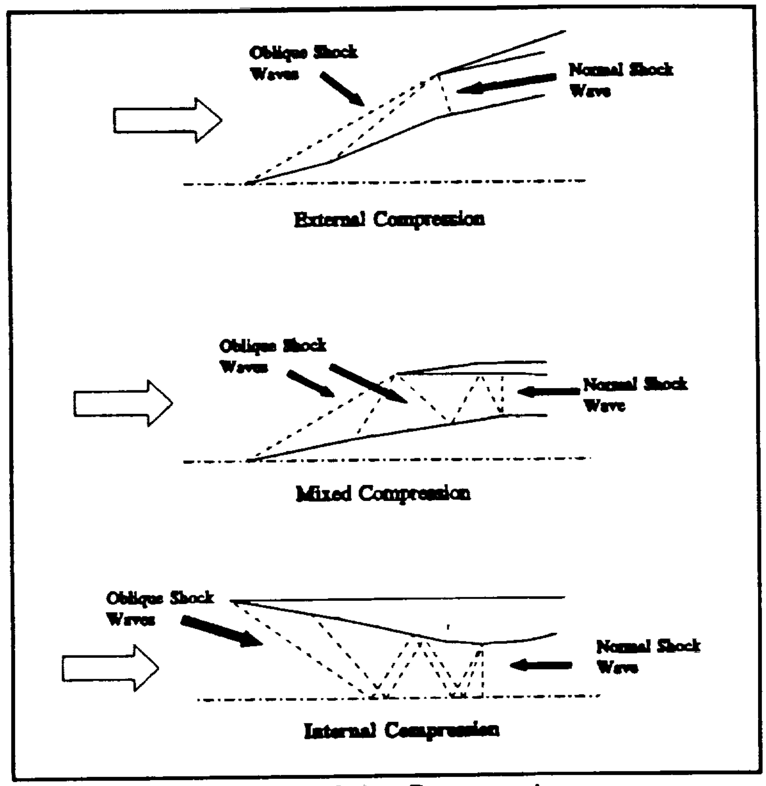



**Figure 3.4** Supersonic Inlet Compression

As the TSTO approached hypersonic speeds, an external compression shockwave must be taken into account. Figure 3.5 illustrates the boundary layer effect on the inlets in hypersonic flight. The external compression must provide a uniform distribution of air across the vehicle ahead of the inlets to

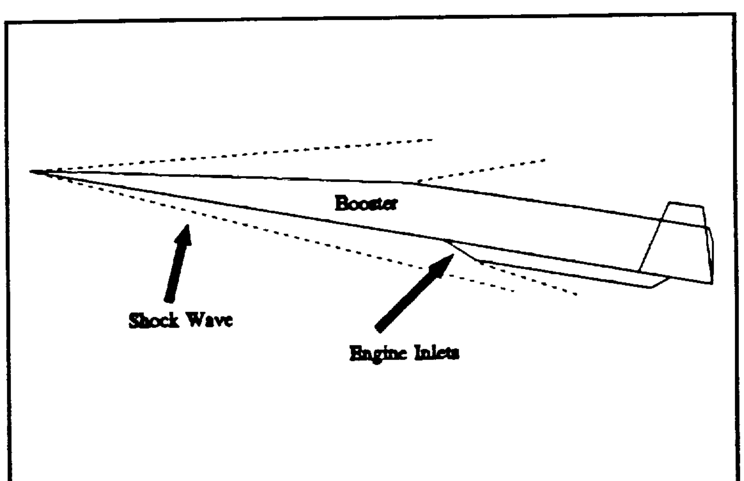



**Figure 3.5** Boundary Layer Compression

the engines to prevent a large accumulation of boundary layer in the center of the vehicle. The forebody, which can be used for external compression, determines the point of boundary layer transition. A delayed transition from a laminar to a turbulent boundary layer reduces friction drag on the vehicle. A reduced rate of boundary layer growth results in thinning the boundary layer entering the engines; consequently, increasing the airflow processed through the propulsion system. Travelling at hypersonic speeds, Mach 6 or faster, requires maximum external forebody compression to minimize the internal inlet surface area and heat load.

To operate in hypersonic conditions, the propulsion system will have to be integrated into the airframe. An integrated system uses the forward portion of the vehicle to compress the airflow and serves as the external portion of the inlet, while the aftbody completes the expansion process for the nozzle. The thrust associated with these large airframe surfaces is significant and the relative contribution to thrust of these surfaces increases with speed.[25] Integration of the propulsion system into the airframe minimizes the internal surface area of the engine module to reduce the surface area that must be protected from high thermal loads. The inlet and nozzle components are the largest in terms of external surface area, but by using airframe integration, the heat load and drag of these components at hypersonic speeds will be reduced. Because the booster will only be travelling at the low end of hypersonic flight, external compression and expansion will not be a major factor, except near staging where stability is critical.

After the external shock wave, caused by the vehicle nose, the externally compressed air enters the engine inlet. The engine inlet and the inlet ducting direct the outside air to the face of the compressor. The inlet should deliver the airflow at close to freestream velocity. Any inefficiencies in the duct result in successively magnified losses in other components of the engine; therefore, it is vitally important to have a good inlet design.

The inlet duct, which is part of the inlet (1 to 2), must deliver air to the compressor inlet under all flight conditions with as little turbulence and pressure variation as possible. Pressure drop through the duct is caused by boundary layer separation along the surfaces of the duct and by bends in the duct system. The duct must have a sufficiently straight design to be able to deliver a smooth, even airflow to the compressor. The inlet duct usually has a diffusion section before the compressor to increase the ram air velocity and static pressure at the inlet of the engine. This is called ram recovery. Total pressure recovery occurs when all of the available ram pressure is converted to static pressure, and is the ideal condition.[26]

Ram recovery is made possible by using the divergent shape of a subsonic diffuser. The area of the duct increases progressively from a point near the front of the duct to the engine inlet. Diffusion occurs, decreasing the velocity and increasing the static pressure of the incoming air just before it reaches the compressor. The choice of configuration of the entrance to the duct depends on the location of the engine on the aircraft and the airspeed, altitude, and angle of attack.[27]

In supersonic speeds, the inlet duct must still slow the incoming air to a subsonic velocity before it reaches the compressor. This may be accomplished by making the duct the shaped of a converging, diverging diffuser, shown in Figure 5.[28] The converging, supersonic section slows the incoming air to Mach 1 just past the throat, and the diverging, subsonic section further decreases the velocity and increases the pressure of the airflow before it enters the compressor. The region between 1 and 2 will have a variable cross-sectional area, which will change according to the flight conditions. A converging/diverging inlet duct will be used in our design for the reasons already discussed.

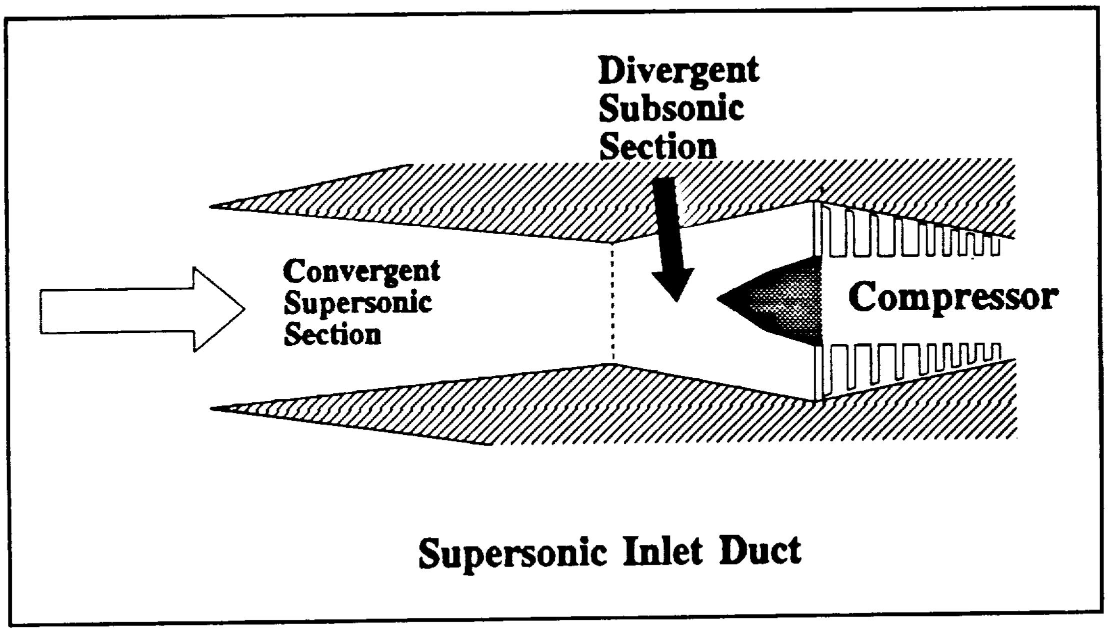



**Figure 3.6** Inlet Duct

The design of an inlet and its related control system is a demanding and complicated task, especially for an aircraft with very high Mach number capability such as the TSTO vehicle. Optimal performance at a given Mach number requires an exact definition of the inlet geometry so that shock wave strengths as well as wall impingement locations (in the neighborhood of suction slots) can be accurately determined. When inlets are flown at speeds other than the design Mach number, complex geometrical variation must occur if the inlet performance is not to deteriorate excessively. For the very high speeds at which the TSTO vehicle would travel, the configuration of the duct will be changed often during flight. This will be accomplished by a mechanical device as the speed of the aircraft increases or decreases. This structure is known as a variable geometry duct.

One of the major design considerations for the propulsion system, which was already mentioned, was to ensure that the inlet duct provides a stable airflow to the engines. Thus, the engine configuration, that will be served by the inlet, is critical to the inlet design characteristics. Consequently, the inlet design considerations affected which TRJ configuration would be used in our design. The primary benefits of the Parallel TRJ inlet versus the Over/Under TRJ are less complex shock patterns, increased inlet lift, and less variable geometry. The considerations and characteristics of the Parallel TRJ inlet necessary for the TSTO booster are discussed in the Propulsion System Conceptual Design Analysis section later in this chapter.

Compressors (2 to 3): There are two major classes of compressors used in aircraft gas turbines, the centrifugal and the axial. The centrifugal compressor takes air into the compressor near the axis and "centrifuges" the air to the outer radius. Consequently, the swirl of the outlet air is removed and the air is diffused prior to entry into another compressor stage or into the burner. The advantages of the centrifugal compressors are they are rugged and deliver a high-pressure ration per stage. They are also easily made in relatively small sizes. The disadvantages of the centrifugal compressor are that it is generally less efficient than the axial compressor and it has a large cross section compared to the cross section of the inlet flow. Centrifugal compressors are generally used with relatively small engines or as a final stage following an axial compressor in a larger engine.[29]

Axial compressors are used in most of the larger gas turbine engines. The air in an axial compressor flows in an axial direction through a series of rotating rotor blades and stationary stator vanes that are concentric with the axis of rotation. The flow path through an axial compressor decreases in cross-sectional area in the direction of the flow, reducing the volume of the air as compression progresses from stage to stage.[30]

In the axial compressors, enthalpy addition occurs in the rotating rows of compressor blades in which the kinetic energy and static pressure are usually increased. The stator rows remove some of the swirl velocity, thereby decreasing the kinetic energy; consequently, increasing the static pressure. The limiting pressure rise through an axial compressor row occurs when the adverse pressure gradient on the blade suction surface becomes so severe that flow separation occurs. When substantial separation occurs, the entire compressor may surge (a massive flow reversal) or rotating stall may result. Rotating stall is the condition where the flow in several blades becomes almost stagnant and the section of stalled fluid then rotates around the blade row. The rotating stall condition is dangerous because very large vibratory stresses can occur as the blades enter and depart the stall.[31]

Fuel efficiency increases with an increase in the compressor pressure ratio. The optimal pressure ratio is constrained by several limitations and tradeoffs. A compressor with a very high pressure ratio could require an excessively heavy casing if the compressor was to be used at its maximum capability in low-altitude conditions where a high ambient pressure exists. The high pressure also tends to increase the casing expansion and distortion. The effects of such expansion appear in increased losses due to the flow around the blade tips. This situation can be further aggravated for very high pressure ratio compressors because the high pressure blades are very small, and the tip leakage affects a proportionately larger portion of the flowfield.

Off-design performance is also greatly affected by high pressure ratios. The overall contraction of the compressor annulus area should be chosen to provide the correct axial velocity throughout the compressor for the design condition. Thus, at the off-design conditions the axial velocity distribution will not be appropriate for the then present blade speeds. An example would be the conditions existing during starting the engine where there would be very low blade speeds. At starting conditions, the increase in pressure and density across each stage of the compressor is far below that which is found when the compressor is at the design speed. As a result, the axial speed of the flow must increase greatly as the air proceeds rearward into the contracted annular cross section. This effect can become so critical that the flow can approach choked conditions. Under choked conditions, the flow tends to drive the rearward blades ("windmilling"), whereas the resultant back pressure slows the incoming flow and causes the frontward blades to stall.[32]

The high demands of the off-design considerations on the compressor have led to several innovations that are being used in today's engines. High pressure ratio compressors use bleed valves to release a portion of the air from the intermediate blade rows to reduce the axial velocity in subsequent stages. Several of the early stages of the compressor are also equipped with variable stators so that the flow can be directed in the direction of the rotation of the rotor and to reduce the angle of attack and the tendency to stall. Compressors are also built with multiple spools so that portions of the compressors are driven by their own separate portions of the turbine, which tends to adjust its speed better then the preceding axial velocity.[33]

Because this propulsion system will use an advanced derivative of today's engines, the system will use the same components that are currently being used. Consequently, this design will use a dual-axial compressor to eliminate choking, compressor surging, and excessive airbleeding. There also other advantages for using a dual-axial compressor. The dual-axial compressor will consist of a low-pressure compressor used at the compressor inlet, followed by a high-pressure compressor section. The high-pressure compressor has shorter blades than the low-pressure compressor, and is lighter in weight. Because the work of compression by the high-pressure compressor heats the air to higher temperatures than those that occur within the low-pressure compressor, higher tip speeds are possible before the blade tips attain their limiting Mach number. This is due to the fact that the speed of sound increases as the air temperature increases. Consequently, the high-pressure compressor can run at higher speeds than the low pressure compressor.[34] The size and weight of the starting system is also smaller than that of a single-axial compressor because only the smaller, lighter weight high-pressure compressor needs to be turned.

Most single-axial compressors are designed with a constant outside diameter of all of the rotor stages. This results in a constant area overall engine diameter. The dual-axial compressor, which uses the high-pressure rotor section, can considerably reduce the diameter of the engine. The high-pressure axial compressor rotor blades have a much smaller diameter than the low-pressure compressor; therefore, the external diameter of the engine is reduced. This leads to an "hourglass" or "wasp waist" configuration that has a slender midsection in which other outside engine parts and accessories can be placed to save space.[35] It can be seen that the lighter weight, greater efficiency over a wide range of flight conditions, and the smaller compressor section will be beneficial to use on the TSTO booster.

Burners or Combustors (3 to 4): Burners operate by having fuel sprayed into a central stabilized region where the fuel droplets evaporate and ignites. The burner must add sufficient heat energy to the gases passing through the engine to accelerate their mass enough to produce the desired power for the turbine and thrust for the engine. A burner must be designed to obtain a minimal pressure loss as the gases pass through the burner (3 to 4), to have a high combustion efficiency, and low risk of flame blow-out.[36] No burning should occur after the gases leave the burner exit (4).

The main configurations of combustors are the can, annular, and can-annular types. The can burner combustor system separates the airflow as it leaves the diffuser and ducts the flow into individual combustion cans. The cans are placed around the circumference of the burner section of the engine. The burner has several holes through which the air travels into the burner can. A nozzle in the can mixes the fuel into the air. A flame holder ignites the fuel rich air. The can burner must have a small diameter, which leads to a large length, and is used primarily with centrifugal compressors.

The annular type burner consists of continuous, circular, inner and outer shrouds around the outside of the compressor drive shaft housing. Holes in the shrouds allow secondary cooling air to enter the center of the combustion chamber, thereby keeping the flame away from the shrouds. The fuel is introduced through a series of nozzles at the upstream end of the burner.

The can-annular combustion chamber combines the advantages of both the can and the annular, while removing many of their disadvantages. Individual burner cans are placed side by side to form a circle of cans inside an annular chamber. The cans are essentially individual combustion chambers with concentric rings of perforated holes to admit air for cooling. Several fuel nozzles are placed around the perimeter of the forward end of the can. Each can has two holes which are opposite of each other near the forward end of the can. One hole has a collar called a flame tube. When the cans are assembled in the annular chamber, these holes and their collars form open tubes between adjacent cans to enable a flame to pass from one can to the next during engine starting. A short burner length is possible with a can-annular system, which prevents an excessive drop in the pressure of the gases between the compressor outlet and the flame area. The can-annular system also permits easier maintenance than the annular type. Consequently, the can-annular burner system was chosen to be used for the Parallel TRJ.

Turbines (4 to 5): Almost all turbines used in aircraft engines are of the axial flow type; consequently, they are similar to an axial compressor operating in reverse.

The design limitations on the turbine stage are very different from the compressor stage. The large decrease in pressure found in turbines greatly reduces the tendency of the suction surface flow to separate, so turbine stages can be designed with very large pressure ratios. The gases entering the turbine are at very high temperatures, therefore the initial turbine stages must be cooled by passing air from the compressor outlet through the turbine blades.[37]

Cooling turbines has severe performance penalties, so there is a need for the development of very high temperature materials that will allow the use of high turbine inlet temperatures with only minimal cooling provided. These new materials must operate in a very demanding environment. They must sustain high temperatures, and high centrifugal stresses. Dimensional stability must be high because if excessive creep occurs, excessive rubbing of the blade tips on the outer annulus could occur and cause catastrophic damage to the engine.

Nozzles (7 to 9): The final component of the engine is the nozzle. The nozzle accelerates the high velocity flow through a diverging nozzle. The diverging section also converts the high pressure exhaust gas to as close to the ambient pressure as possible. Major design problems occur with nozzles intended for use in aircraft such as the TSTO aircraft which have a wide Mach number range. Flight over a wide range of Mach numbers introduces a wide range of ram pressure ratios, resulting in a wide range of nozzle pressure ratios. Optimum nozzle performance occurs when the nozzle exit pressure is not far from ambient. Therefore, for nozzles with a large operating pressure ratio range, substantial geometrical variation must be possible.

Because of the relative ease of geometrical variation, two-dimensional nozzles are presently under consideration for use on missions with large area variation requirements or for missions utilizing thrust vectoring.[38] While traveling in the hypersonic regime, the aft underside of the booster will act to further expand the exhaust flow. The intense heat of the exhaust will make the use of active cooling using the hydrogen fuel necessary. Figure 3.14 shows the Parallel TRJ with flow control surfaces changing during different modes of operation.

### 3.1.4 Parallel TRJ Inlet Analysis

The parallel TRJ has a large surface area. In addition the diameter at the engine face of the combined engine requires a large subsonic diffuser ahead of the engine to meet the requirements of both the TJ and RJ. For these reasons, the parallel TRJ leads to large wetted internal duct areas and heat loads at cruise.[39]

When designing the inlet, the requirements for both engines must be considered. The turbojet inlet cowl area is a strong function of maximum turbojet operating speed. For example - a TJ operating at Mach 3 requires a 60% larger inlet cowl than if operating at Mach 2. Thus, the inlet cowl area required for a TJ is a function of both the thrust requirement of the vehicle and the operating speed of the TJ.[40] For this TSTO an inlet area would be needed to correspond to the Max operation speed of Mach 3.

The primary factors in RJ inlet design are cruise speed and altitude. Inlet area must be increased with Mach number. In addition the inlet area is inversely proportional to the flight dynamic pressure, which causes the inlet area to increase with altitude.[41]

For a parallel TRJ, if the RJ was used to cruise at Mach 5 at 30500 meters, the

TJ inlet cowl area would be about 50% that of the RJ. The RJ is therefore, the determining size factor. An inlet contraction ratio must be used to allow for a high inlet efficiency, usually an $A_c/A_t$ of about 12 is good. Optimum selection of inlet contraction and the proper allowances for boundary layer bleed is a subject that requires detailed tests and analysis and could not possibly be addressed in this project.

The geometric lines of the TRJ inlet and diffuser of Figure 3.15 (from Ref 7) are considered to be geometrically representative of a Mach 5 engine system and yield a relatively long nacelle to meet the demands of the parallel TRJ engine. These parameters are very close to those required of this project. For this reason, the same basic dimensions and data were used to size and analyze the TSTO vehicle developed and Figure 3.15 is representative of the inlet design for this vehicle. Figure 3.15 shows the case of an inlet contraction ratio of 12. The two dimensional subsonic diffuser has a total expansion angle of 10 degrees and extends from the throat to the cross sectional area equal to that of the total engine face area. Variable geometry is accomplished by a movable inlet upper wall (identified by cross hatching) which extends from the second external compression surface to a point in the diffuser where the cross-sectional area is somewhat greater than the maximum required inlet throat area at transonic speeds.

Figure 3.16, at the end of this section, illustrates spillage at lower speeds. Compressive turning across the second external compression surface is reduced at lower Mach numbers as the inlet throat area is increased to pass the combined RJ and TJ airflow at the proper contraction ratio.[42]

A large normal force also exists which would produce lift for an inlet located on the bottom portion of the airframe and would be added to the airframe lift. Shown in Figure 3.17, taken from Reference 7. Although this lift force is significant it was not considered when determining the total lift for the TSTO booster. This would be one area that could be refined to make the analysis more complete.[43]

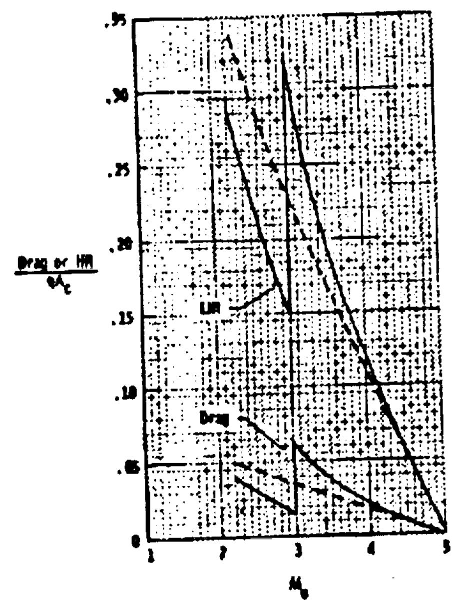


Figure 3.17 Parallel TRJ Lift Graph

### 3.1.5 TSTO Booster Engine Performance

Once a hydrogen fueled Parallel TRJ engine was decided upon, data was needed from a typical baseline engine. In order to get the program to output the flight characteristics, certain information about the propulsion system had to be imputed. This information included thrust and specific impulse as a function of altitude and Mach number. The program was then able to calculate fuel consumption and use the various thrust levels in conjunction with information on aerodynamics to calculate the flight profile. This information was determined from the performance characteristics presented in reference 6.[44]

The information was obtained from Figures 3.7 and 3.8(reproduced from

Reference 6). The thrust density, which is defined as the thrust divided by the fan frontal area, is shown as a function of Mach number in Figure 3.7. The thrust increases very rapidly with increasing Mach number for every altitude condition at a flight Mach number lower than about 4. Figure 3.8 shows the specific impulse, which is between 3000 and 4000 seconds. This is a very high value compared to the present chemical rocket engines whose $I_{sp}$ is on the order of 450 seconds.[45]

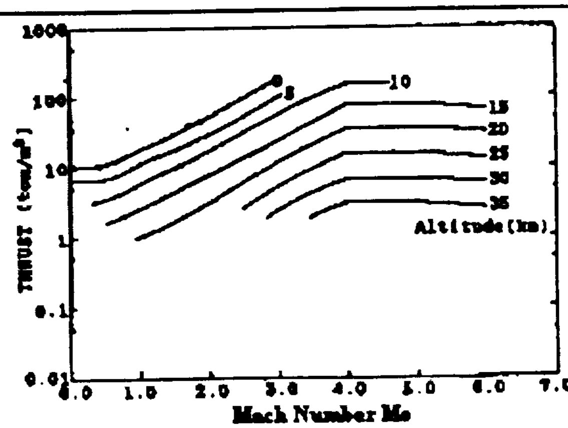


Figure 3.7 Thrust of TRJ engine

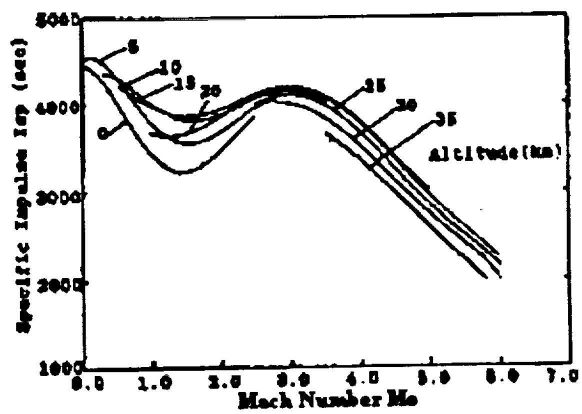


Figure 3.8 Specific Impulse of TRJ engine

Figures 3.7 and 3.8 show the performance data for the parallel TRJ that are used on the booster. Appendix C shows the actual data files of engine performance characteristics used by the program. An explanation of how they were used by the program is provided in Appendix C. The thrust data was taken directly from Figure 3.7 and interpolated by the program. Figure 3.8 was analyzed by hand to find an average specific impulse curve. Data files were then created from this average curve to be used in the program.

The thrust data used is dependent on fan frontal area of the engine. It was therefore necessary to find the size that corresponded with the thrust necessary from the engine. The thrust requirements are based on necessary thrust for takeoff. Obviously, an engine cannot be designed to meet this requirement based simply on area. Therefore, a compromise between realistic engine sizing and the number of engines had to be made. It was determined the best situation would be using 8 engines with a fan frontal area of 4.75 $m^2$ or a diameter of 2.42 m. This would give an overall engine weight, for each engine, of 9562 lbm and a sea level thrust of 199.5 metric tons.

The Parallel TRJ will operate in two modes, the TJ and RJ. The TJ engines will be used during take-off and acceleration. At Mach 2, the booster will level off at 18,000 feet in order to safely transition between the TJ and RJ engines. The inlet for the RJ engine will begin to open at Mach 2 and begin to power up. As the efficiency of the TJ drops significantly from Mach 2 to 3, the RJ will begin to produce thrust at approximately Mach 2.5. At Mach 3, the TJ shroud will close off the TJ from the airflow and power down. The RJ engine will be operating at full power at Mach 3; consequently, the booster will begin its climb to staging.

The engine performance graphs are shown in Figures 3.18-23. The first graph, Performance vs Time, shows the Specific Thrust and Mass Flow Rate versus Time. The Specific Thrust graph is very close to other studies that have been done in Japan, see References 5 and 6. The Mass Flow Rate graph takes into account throttling of the engines during flight. By comparing Figures 3.18 and 3.19, Specific Thrust and Mass

Flow Rate versus Mach Number, and Figure 3.20, Specific Thrust and Mass Flow Rate versus Altitude, the performance of the engines up to staging is apparent. It can be seen that during the engine transition, between Mach 2 and 3, 80.4 and 138.4 seconds, or 18,375 feet, that the mass flow rate and specific thrust increase. This is due to the fact that both the TJ and RJ engines are operating. The highest value for mass flow rate occurs at Mach 5.3, 160 seconds, and 35,800 feet which is where the maximum thrust is produced. This is during the steep climb and acceleration to the staging altitude and speed. The graph shows all of the key points during the flight and meets the expectations of this project.

The second set of graphs show the thrust performance versus time, Mach, and altitude. By comparing Figure 3.21, Total Thrust and Thrust Per Engine versus Time, with Figure 3.22, Thrust versus Mach, and Figure 3.23, Thrust versus Altitude, the performance of the propulsion system's thrust can be seen during the flight. The Thrust per Engine is the total thrust produced by each engine during the flight, while the Total Thrust graph includes the throttling during the flight. The engine transition is clearly shown on the graphs, with the maximum thrust being produced when both engines are in operation at Mach 3. In reality, the efficiency and thrust of the TJ drops significantly just before Mach 3, however this is not taken into account in the modelling program.

The graphs show the thrust dropping significantly as the booster approaches Mach 6. This is due to the fact that the engines have been throttled back to about 30% so that the booster does not exceed it's staging altitude and Mach number. After analyzing the performance graphs, it was realized that the booster would not need eight RJ engines.

All eight TJ engines are needed for takeoff, however only four RJ engines, operating at about 80% power would be needed during flight. Once Mach 3 has been achieved, the four RJ engines would be able to produce enough thrust to be able to achieve staging altitude and Mach number. This could lead to a design that uses four purely turbojet, or even a turbofan (which has more power during subsonic flight which would lead to a shorter take-off distance), and four Parallel TRJ. This would save weight and fuel.

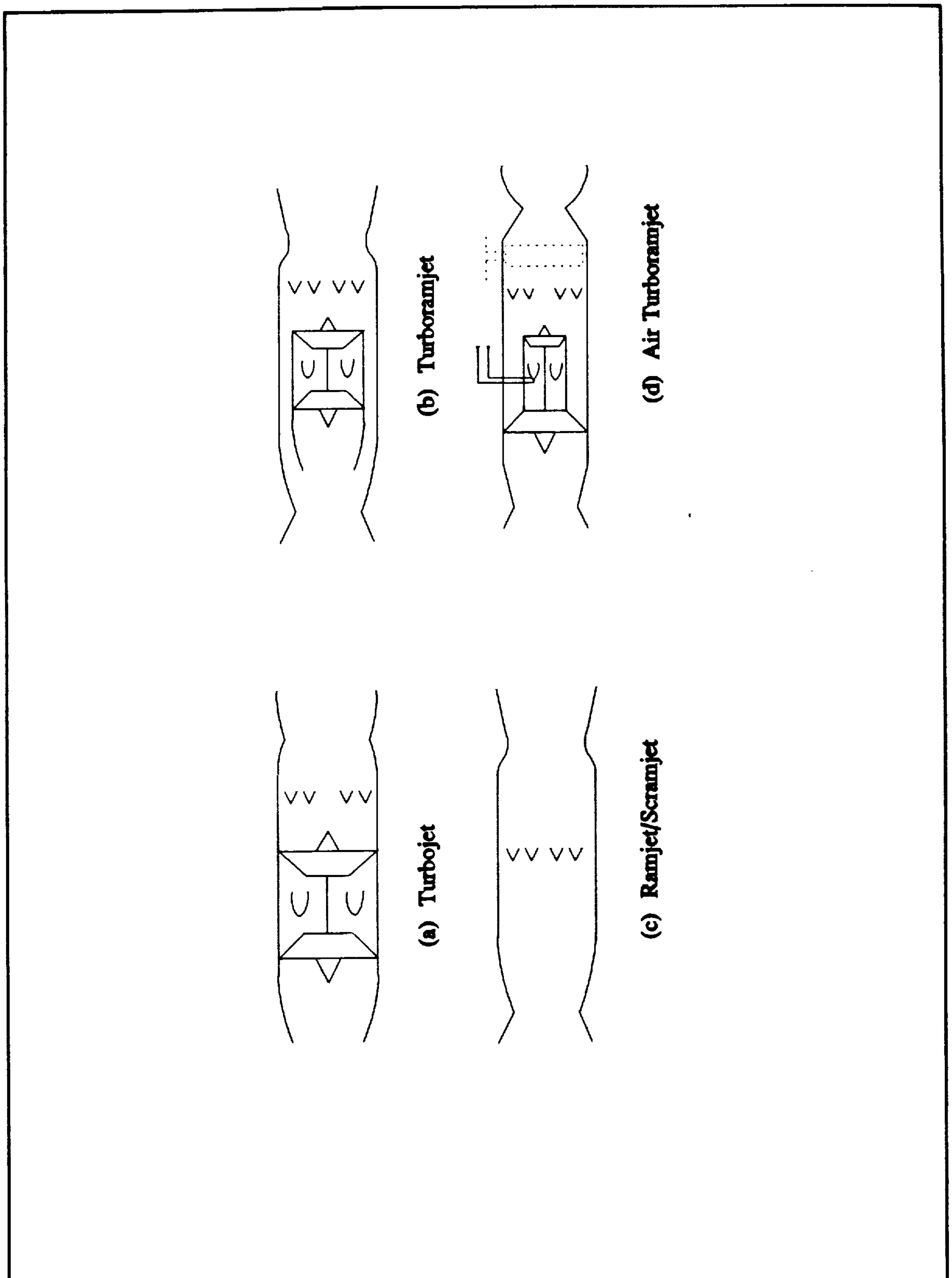



Figure 3.9 Different Engines for Consideration

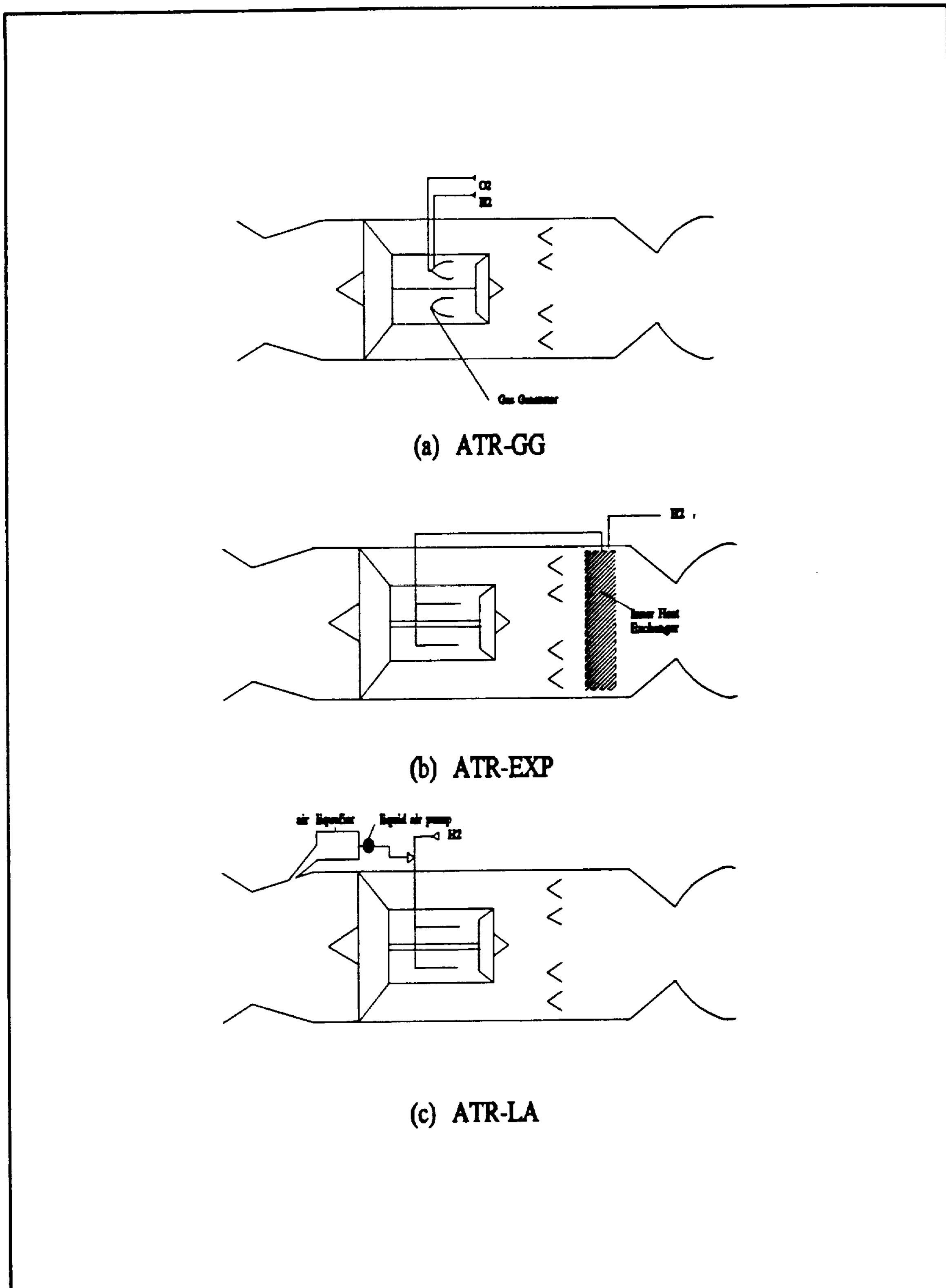



Figure 3.10 Air Turbo Ramjet Configurations

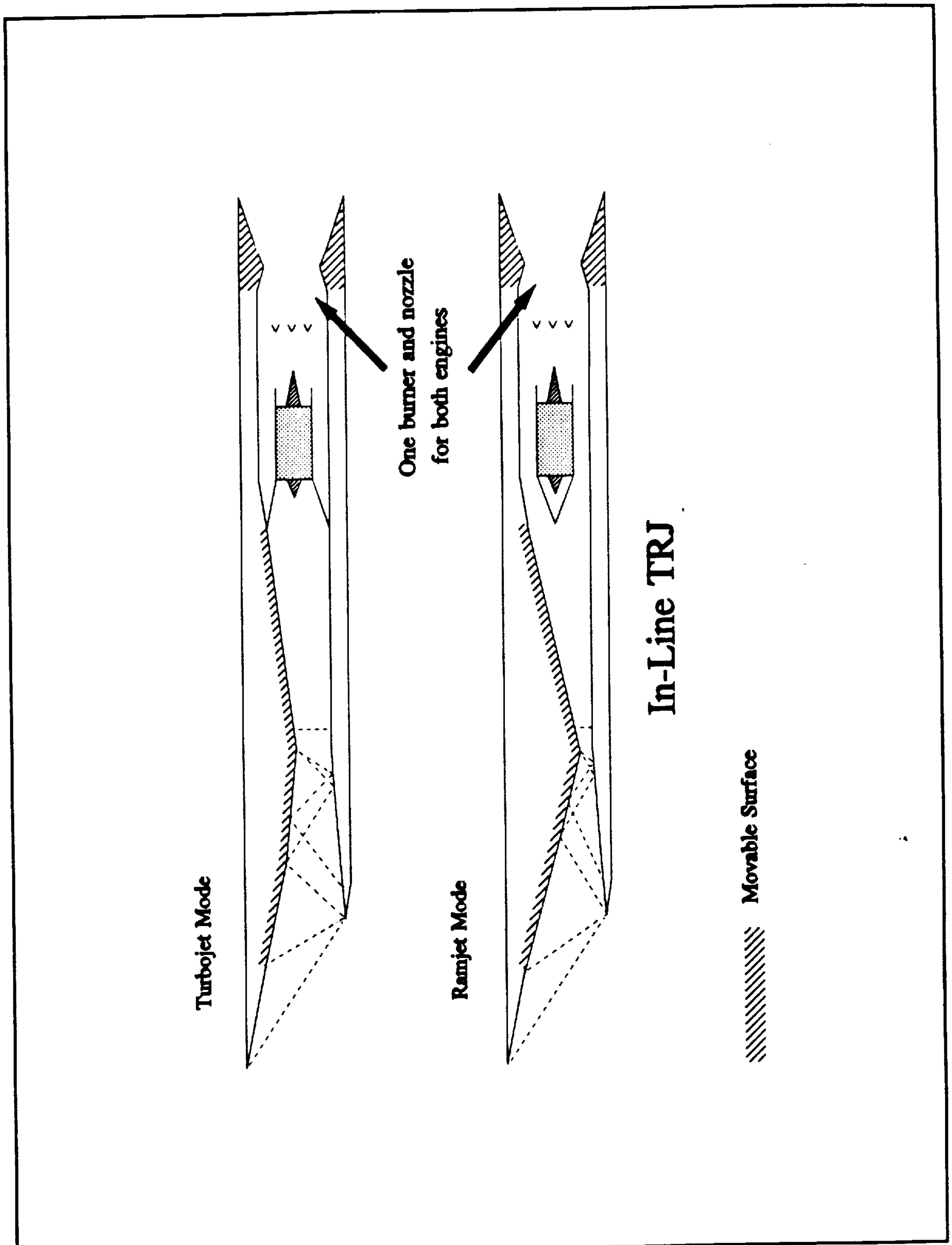



**Figure 3.11** In-Line TRJ Configuration

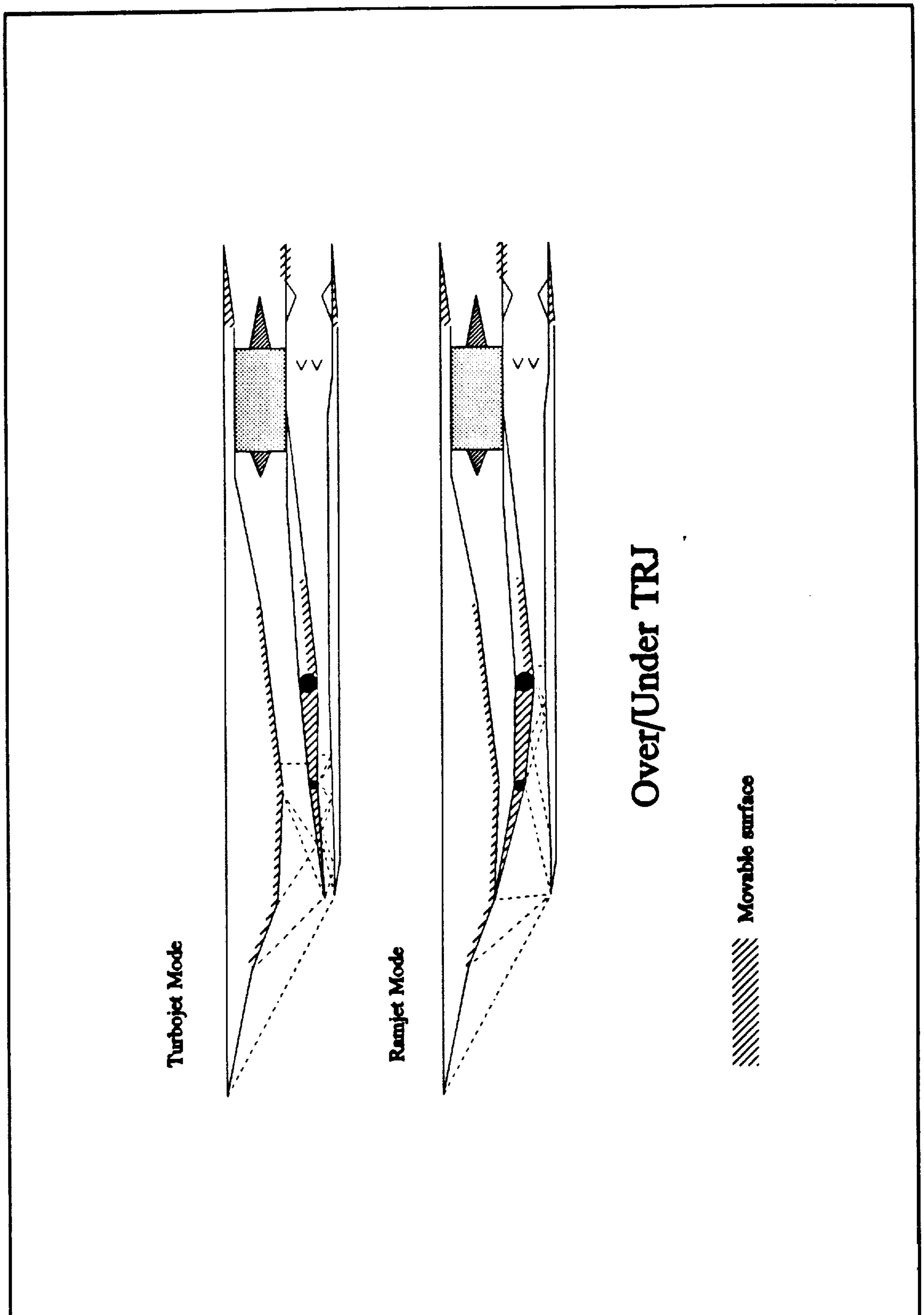



Figure 3.12 Over/Under TRJ Configuration

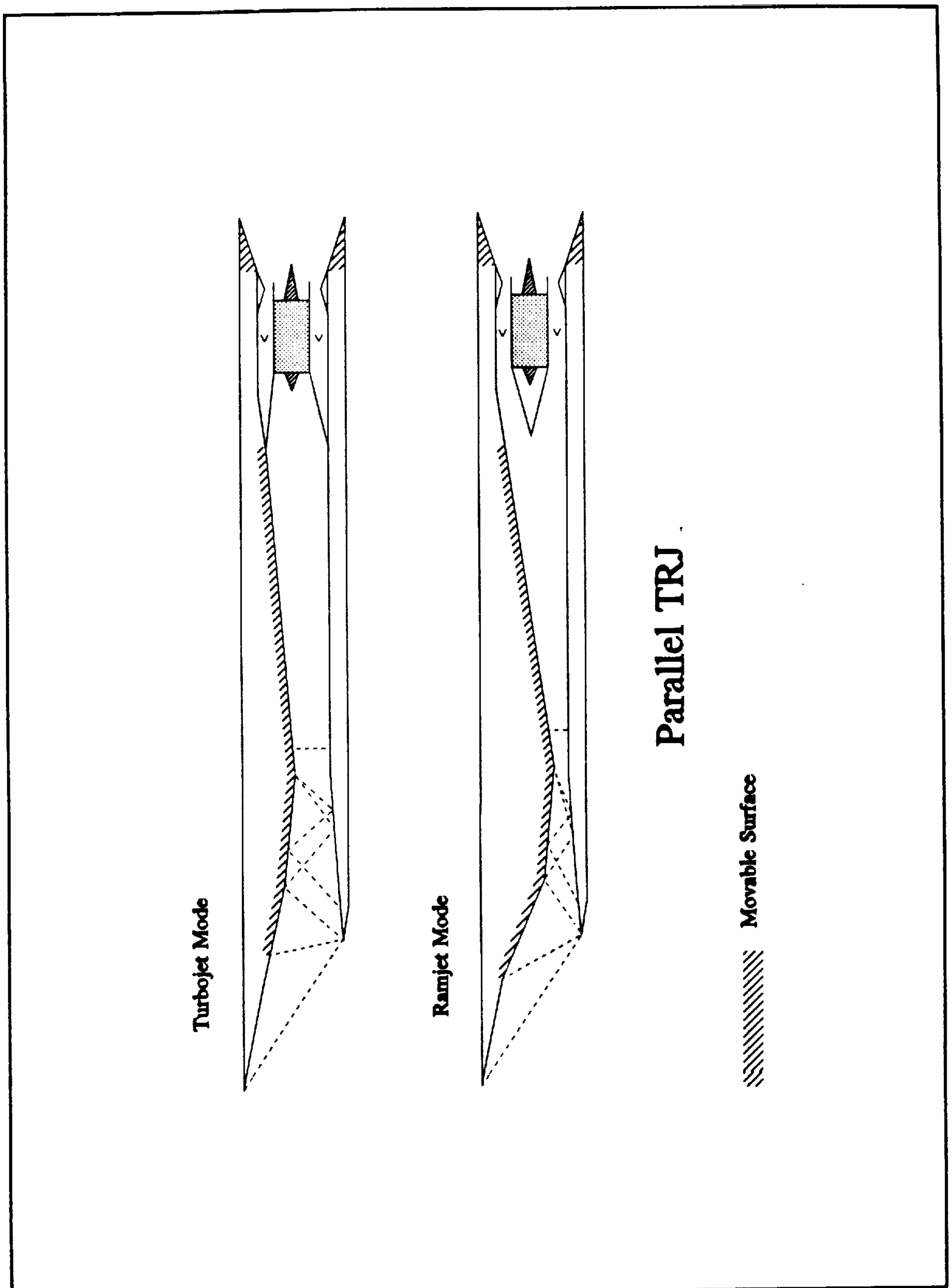



Figure 3.13 Parallel TRJ Configuration

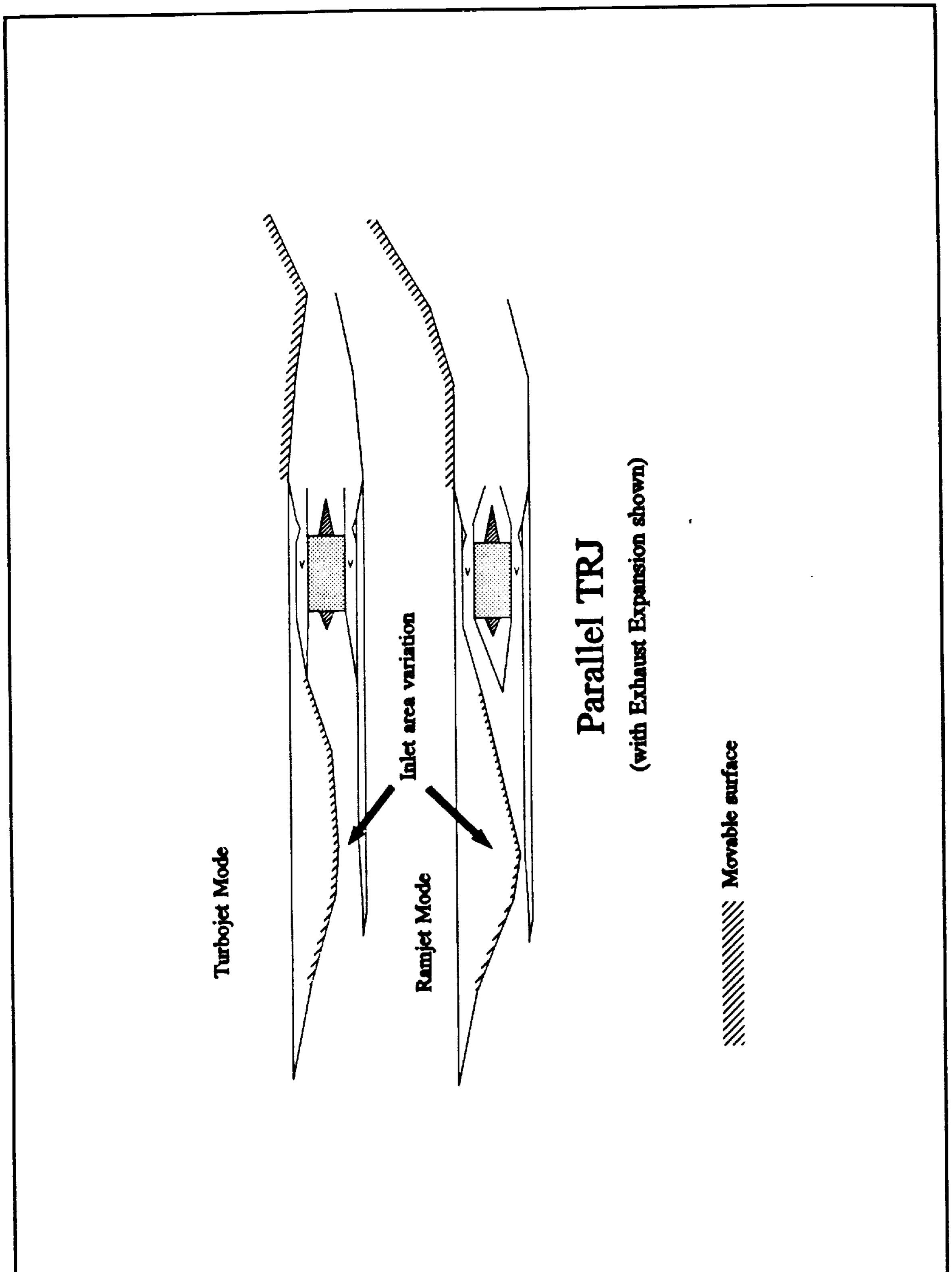



**Figure 3.14** Parallel TRJ with Area Variation

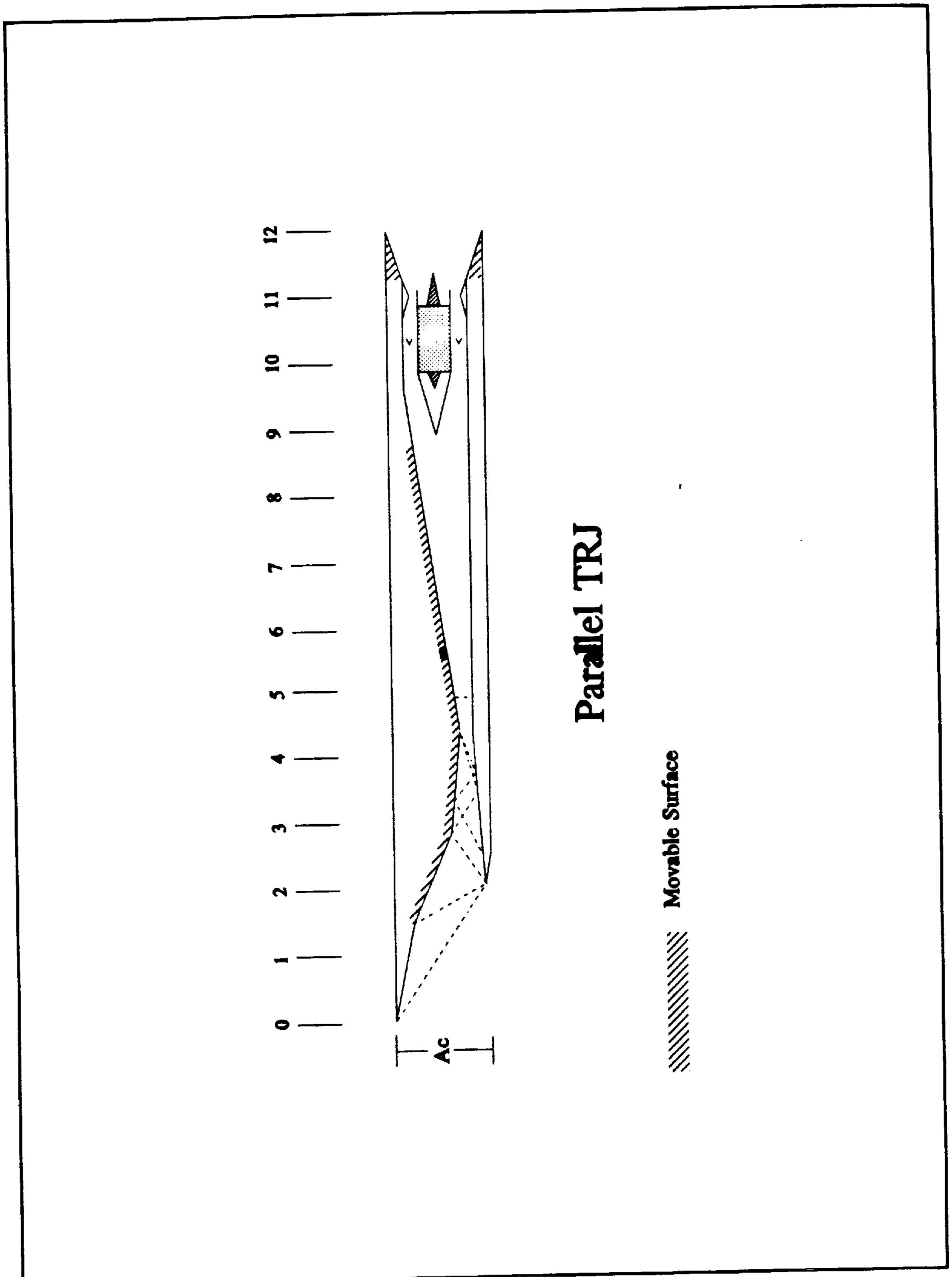



Figure 3.15 Parallel TRJ with Scale

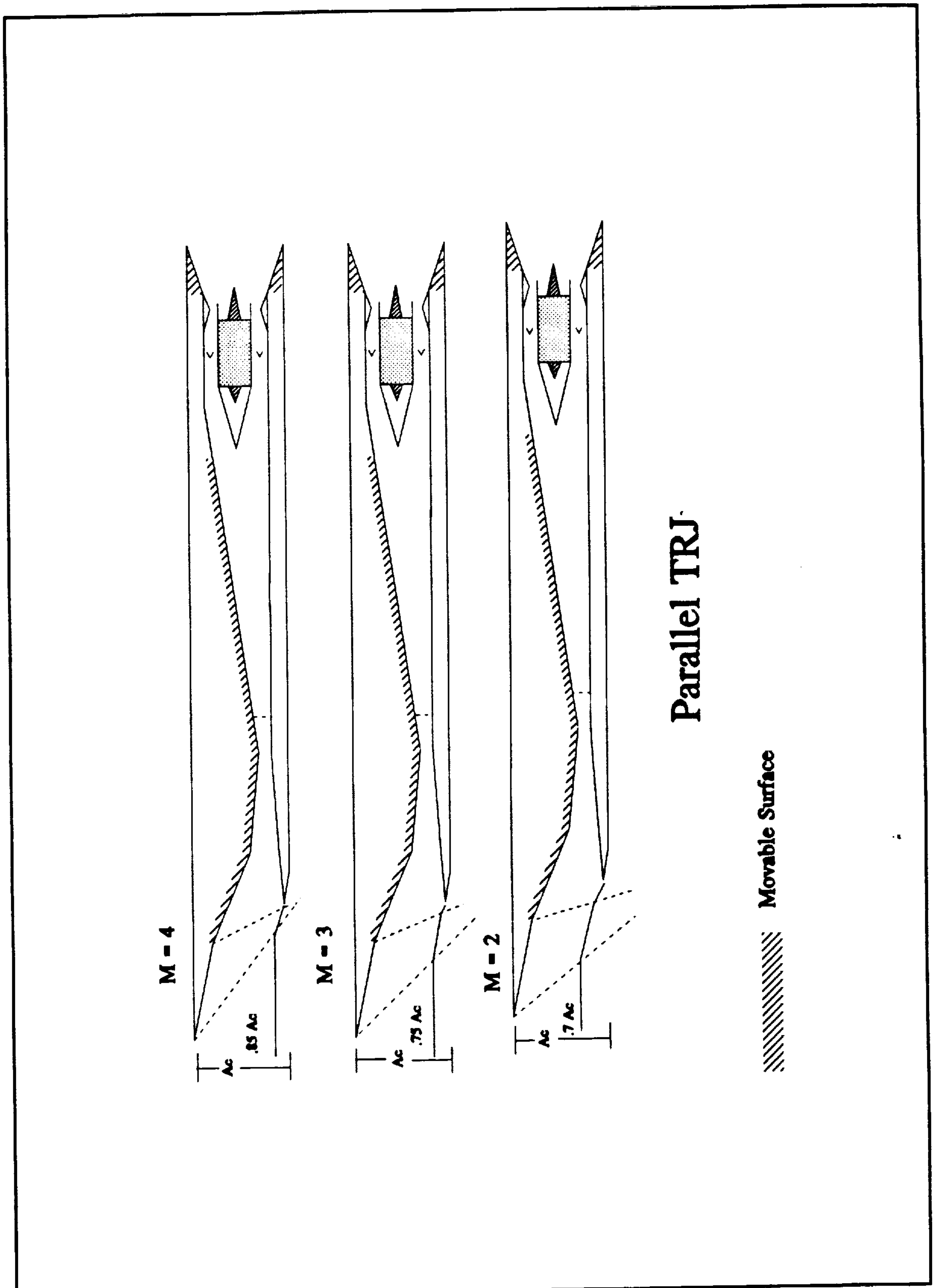
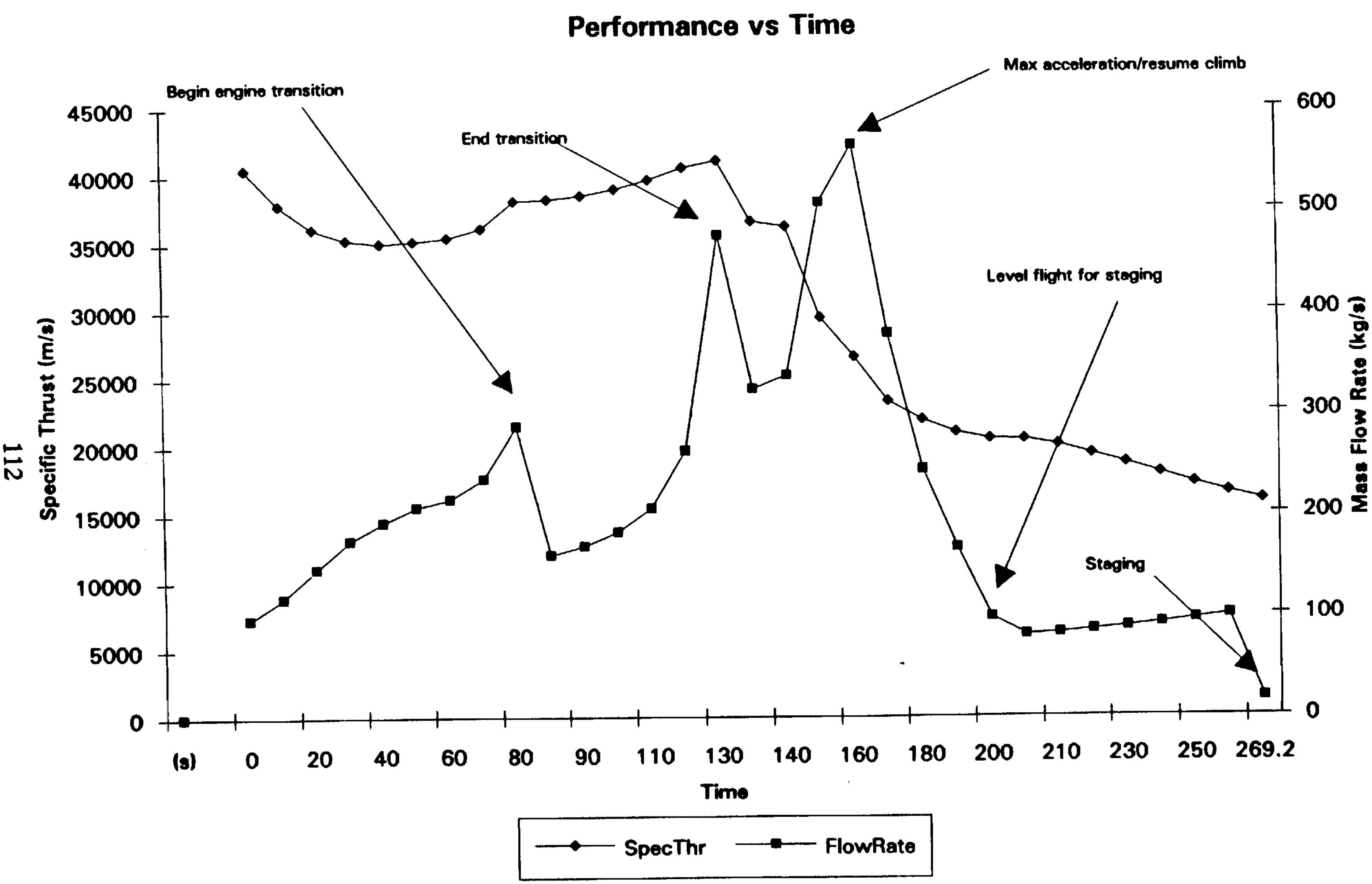



**Figure 3.16** Parallel TRJ with Shock Spillage



Performance vs Time
Begin engine transition
End transition
Max acceleration/resume climb
Level flight for staging
Staging
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
Specific Thrust (m/s)
600
500
400
300
200
100
0
Mass Flow Rate (kg/s)
(s)
0
20
40
60
80
90
110
130
140
160
180
200
210
230
250
269.2
Time
SpecThr
FlowRate


Figure 3.18

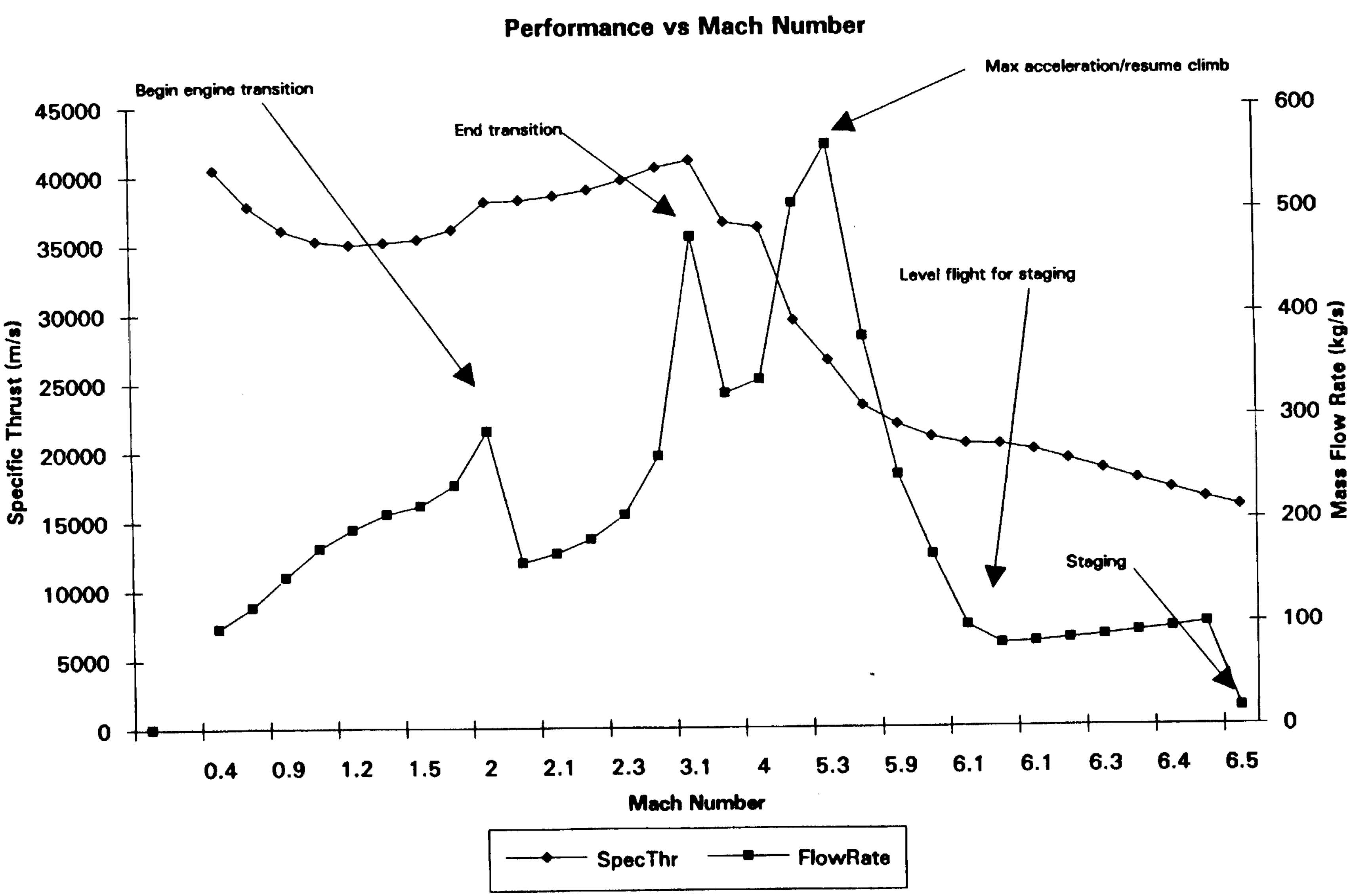
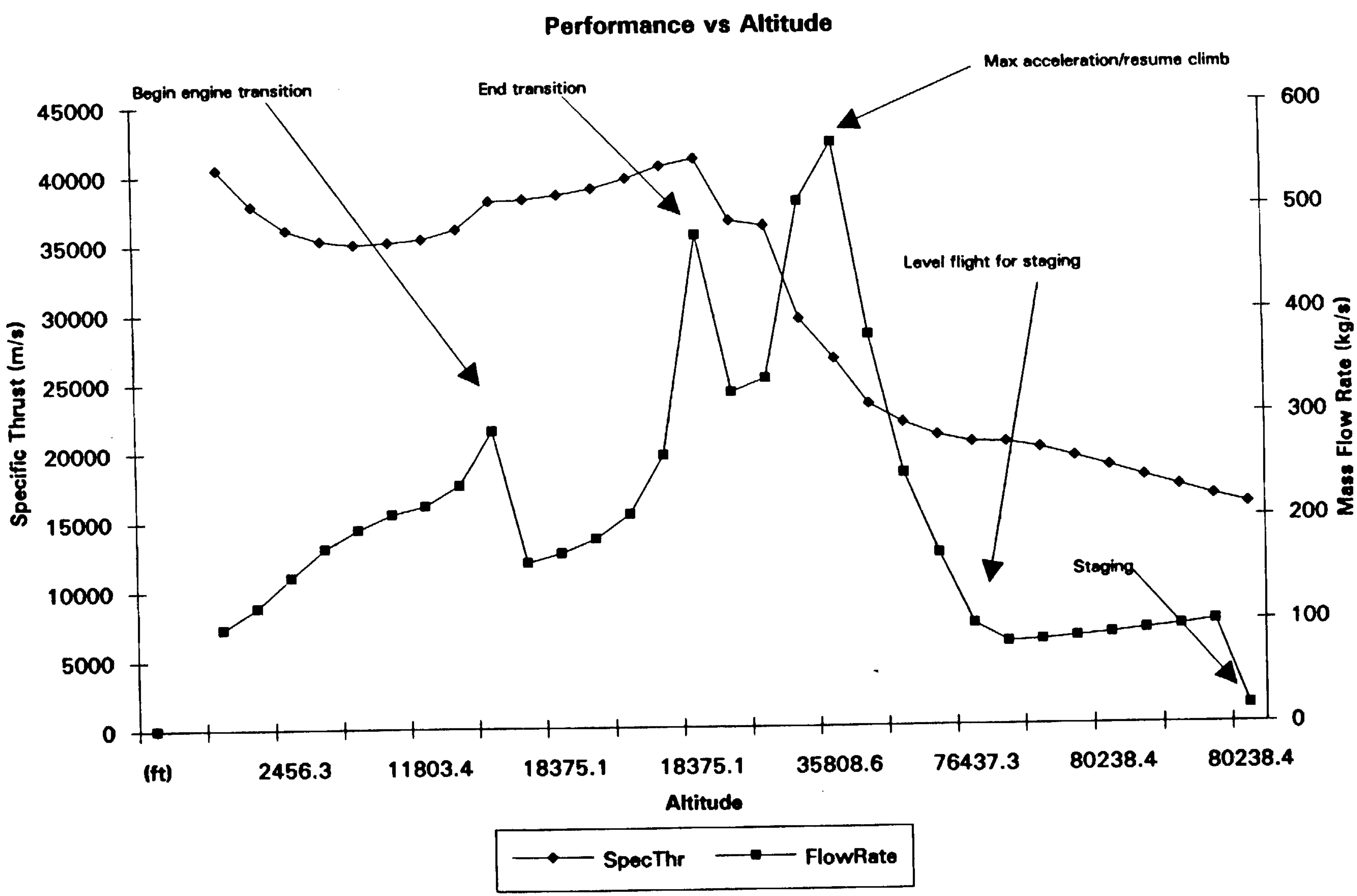

Performance vs Mach Number
Begin engine transition
End transition
Max acceleration/resume climb
Level flight for staging
Staging
Specific Thrust (m/s)
Mass Flow Rate (kg/s)
Mach Number
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
0
100
200
300
400
500
600
0.4
0.9
1.2
1.5
2
2.1
2.3
3.1
4
5.3
5.9
6.1
6.1
6.3
6.4
6.5
SpecThr
FlowRate

Figure 3.19



Performance vs Altitude
Begin engine transition
End transition
Max acceleration/resume climb
Level flight for staging
Staging
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
Specific Thrust (m/s)
600
500
400
300
200
100
0
Mass Flow Rate (kg/s)
(ft)
2456.3
11803.4
18375.1
18375.1
35808.6
76437.3
80238.4
80238.4
Altitude
SpecThr
FlowRate


Figure 3.20

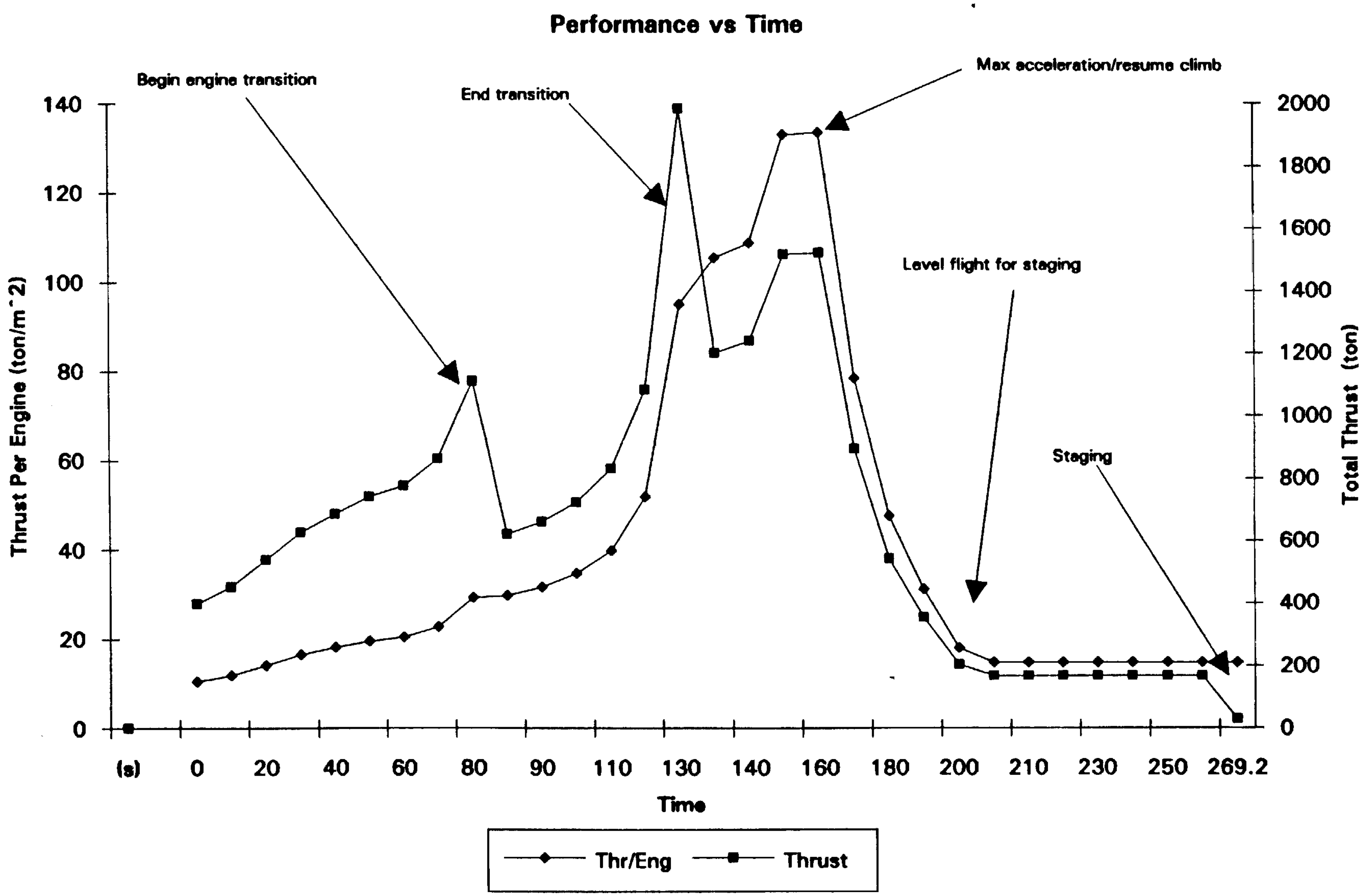
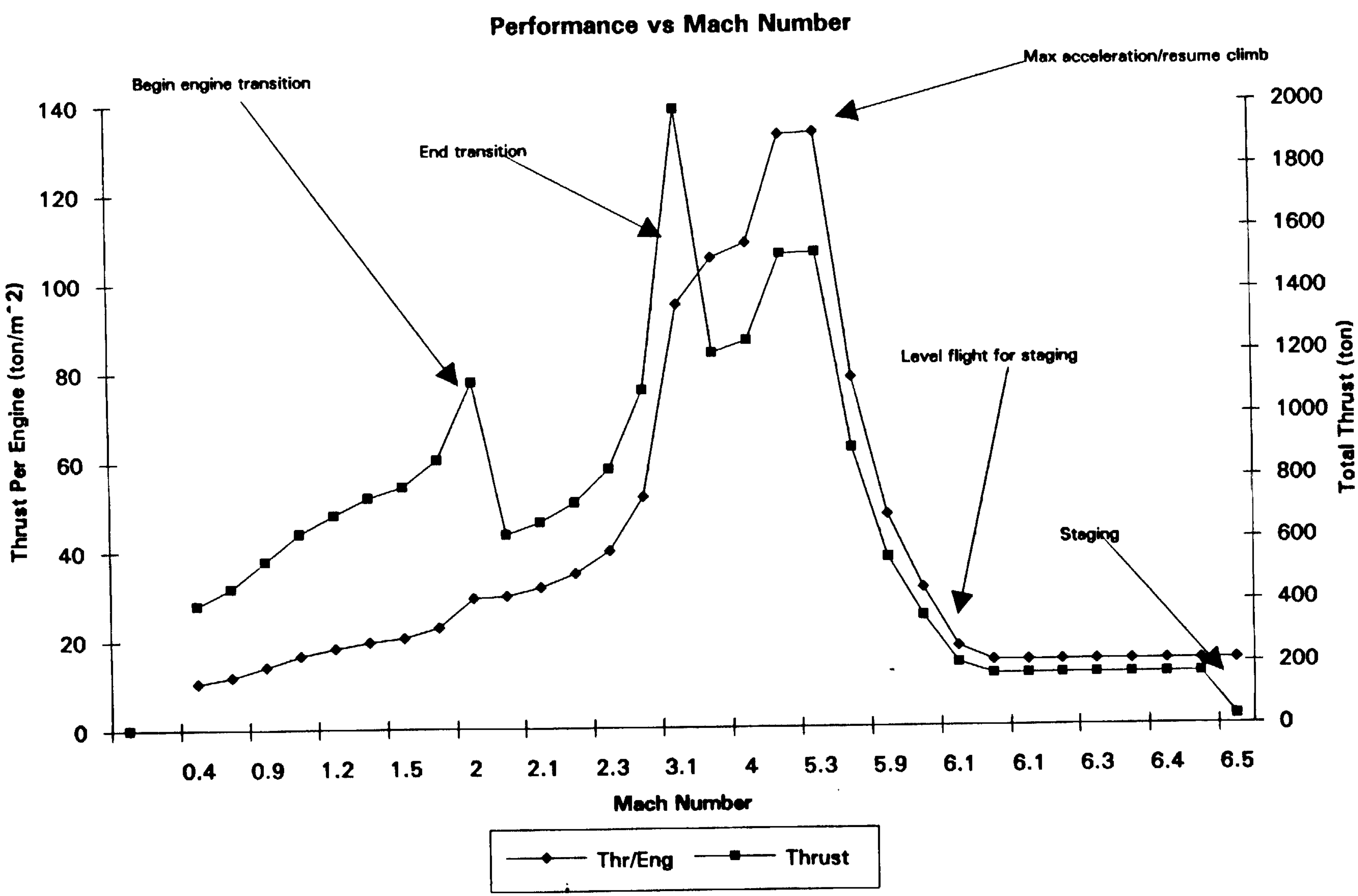

Performance vs Time
Begin engine transition
End transition
Max acceleration/resume climb
Level flight for staging
Staging
Thrust Per Engine (ton/m^2)
Total Thrust (ton)
140
120
100
80
60
40
20
0
2000
1800
1600
1400
1200
1000
800
600
400
200
0
(s) 0 20 40 60 80 90 110 130 140 160 180 200 210 230 250 269.2
Time
Thr/Eng
Thrust

Figure 3.21



Performance vs Mach Number
Begin engine transition
End transition
Max acceleration/resume climb
Level flight for staging
Staging
Thrust Per Engine (ton/m^2)
Total Thrust (ton)
Mach Number
0
20
40
60
80
100
120
140
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0.4
0.9
1.2
1.5
2
2.1
2.3
3.1
4
5.3
5.9
6.1
6.1
6.3
6.4
6.5
Thr/Eng
Thrust


Figure 3.22

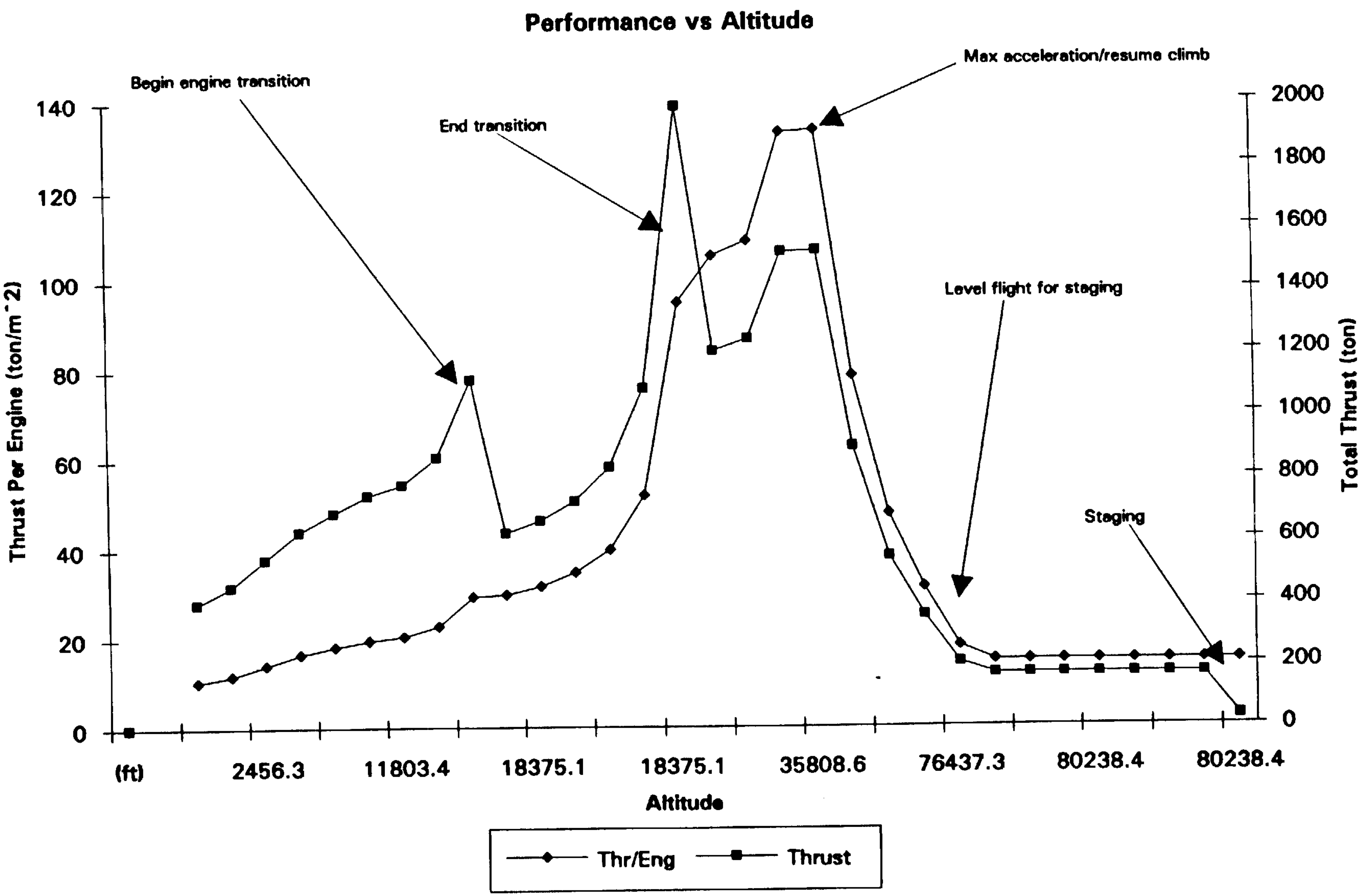

Performance vs Altitude
Begin engine transition
End transition
Max acceleration/resume climb
Level flight for staging
Staging
140
120
100
80
60
40
20
0
Thrust Per Engine (ton/m^2)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Total Thrust (ton)
(ft)
2456.3
11803.4
18375.1
18375.1
35808.6
76437.3
80238.4
80238.4
Altitude
Thr/Eng
Thrust

Figure 3.23

## 3.2 Orbiter Propulsion

### 3.2.1 Main Engines

After staging occurs, it is necessary for both the booster and orbiter to have some sort of propulsion system. The booster's system of turbo-ramjets will only be needed to allow a landing. The orbiter's engines will be used to propel it and its payload into orbit. Thus, there are many factors that need to be considered when selecting the propulsion unit that will be used. The engines must have enough thrust in order for the orbiter to achieve orbit. Also, the engines must be designed such that the fuel requirements for the mission ate not greater than the available space on the orbiter. Finally, the engines must be able to function in a vacuum due to the very nature of the orbiter mission. This final condition insures that some sort of rocket engine will be needed.

The engines needed for the orbiter section of the vehicle are two 62.5% scale versions of the space shuttle main engine (SSME) derivative engines. these engines each have the following characteristics:

| | |
|---|---|
| Area Ratio | 77.5:1 |
| Sea-Level Thrust (lb) | 261563 |
| Vacuum Level Thrust (lb) | 320938 |
| Sea-Level Isp (s) | 369.6 |
| Vacuum Level Isp (s) | 453.5 |
| Mixture Ratio | 6:1 |
| Length (inches) | 105 |
| Weight (lb) | 4000[46] |

The SSME derivative engines have the capacity to be throttled up to 109% thrust for a period of time. This added thrust has many beneficial effects. By over-throttling initially, the orbiter will have the extra thrust needed to propel it out of the atmosphere where drag effects are large.

This particular scale version of the SSME derivative engine was chosen for a few reasons. Obviously, these engines were compared with the original Space Shuttle Main Engines. A full scale derivative engine offers approximately a 10% increase in thrust with a 25% reduction in weight. This thrust increase is balanced by a 10% increase in the fuel flow rate. Even considering the increased fuel requirements, the derivative engines perform substantially better than the original engines.

The reason for using two scaled down versions of the derivative engine is closely tied to the total analysis of the orbiter's performance. Through the use of the program, it was found that 125% of a full scaled derivative engine would be needed. The use of two 62.5% engines conserves valuable space on the orbiter.

### 3.2.2 Orbiter Maneuvering Engines

While operating in space, the Orbiter will use the Orbiter Maneuvering System (OMS). There are two OMS engines mounted in pods on each side of the aft fuselage which power the Orbiter during orbital insertion and decent. The aft pod, which contains the OMS engine is shown in Figure 3.24. The OMS engines also provide thrust for large orbital changes. Each engine has a thrust of 6,000 pounds. The fuel used is monomethyl hydrazine and nitrogen tetroxide is used as the oxidizer. Helium gas forces the propellants from the tanks in each pod and into the engines. There is however, in case of emergency, a cross-feed system to transfer propellants from one pod to the other.

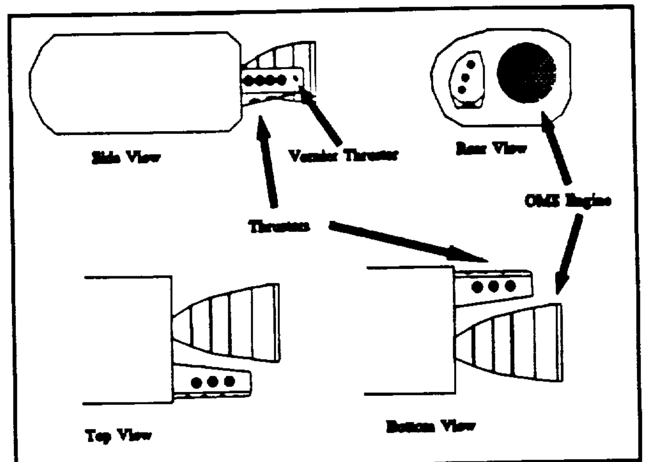


Figure 3.24 Orbiter Maneuvering System - Aft Pod

The OMS engine is designed to last a hundred missions, which is the lifetime of the Orbiter. The engine is 77 inches long and weighs 260 pounds. The engine is gimbaled in pitch and yaw.[47] The Reaction Control System (RCS) is a system of forty-four small rocket engines that maneuver the Orbiter in space. There are thirty-eight primary RCS thrusters which produce 870 pounds of thrust each. There are also six 25-pound-thrust vernier engines. The RCS thrusters are grouped in three modules, one in the Orbiter nose and one in each OMS pod. The thrusters are placed on both sides, top and bottom, to be able to vector the Orbiter in any direction. They use the same propellants as the OMS engines. The RCS in the aft section have their own propellant tanks. In case of emergencies, the RCS can be fed from the OMS. The RCS system in the nose pod is shown in Figure 3.25.

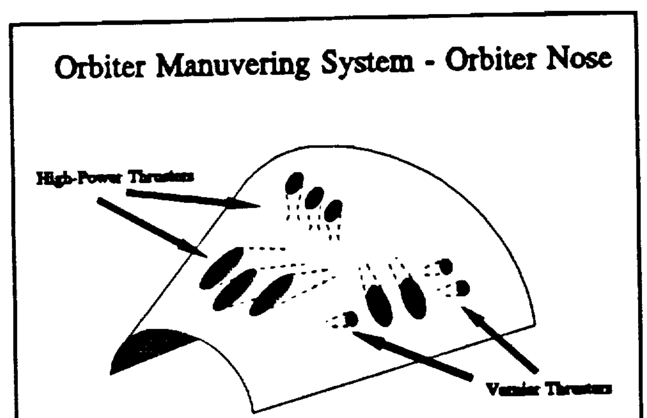
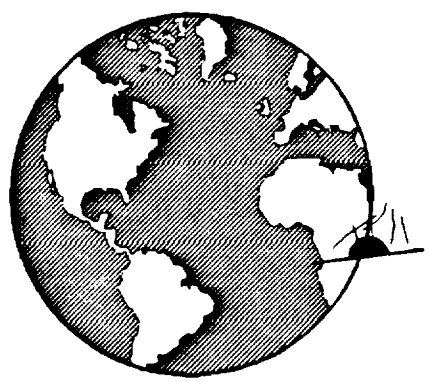


Figure 3.25 Orbiter Maneuvering System - Nose Pods

# Results and Conclusions



# Chapter 4

## 4.1 Booster Performance

In order to analyze the characteristics of the TSTO vehicle a computer program simulating the mission was required. The program generated physical characteristics of the vehicle by studying the weight, aerodynamics and propulsion of the vehicle for a specific flight path. Thus, it was necessary to set a flight path before the performance of the vehicle could be determined. It was found that an optimum path would involve an initial climb and acceleration through the transonic regime. Then the vehicle would begin a climb during which the dynamic pressure would be kept constant.[48] This path would minimize the fuel consumption, but due to the requirements of the booster engines it was impossible to follow this flight path.

The flight path created did, however, attempt to follow the basic idea behind the optimum path. After takeoff the mated system climbs at a constant angle of 3° at full throttle. As the vehicle approaches Mach 2 it levels off and accelerates until Mach 4 is obtained. The levelling off at this velocity is required to reduce stress on the engines during the transition from turbojet to ramjet mode. Also, the engines are throttled back to 55% during this phase of the flight. At Mach 4 the booster begins to climb at an angle of attack of 7.5° with a throttle level of 30% and gradually reduces the angle of attack until it reaches an altitude of 80000 feet. At this point it levels off the rest of the way and speeds to Mach 6.5 where staging occurs. After staging the vehicle throttles back to 5% and descends. It begins descent at a low angle of attack until it has lost enough altitude and speed to begin a high drag angle of attack of 7.5° which slows the vehicle until it lands.

Much of the performance of the booster deals with the propulsion of the vehicle. Although these factors are essential for a successful flight, other more elementary parameters must be studied. For instance, the range of the vehicle is critical in determining where the vehicle will be able to land. By examining the altitude versus range graph for the booster in Appendix B it is evident that the vehicle has traveled 187 miles when it begins to descend. If it is assumed that the vehicle travels in a straight line to the staging point then turns around and follows a straight line back to the airport, a total range of about 374 miles would be needed. The vehicle's range is only 315 miles for this particular flight path, but there is enough fuel left to travel 170 more miles at its descent thrust. This extra fuel would allow for a leveling off in order to return to the original takeoff runway. Also, this reserve fuel would be used in any maneuvers that were not modeled by the computer program.

Another important consideration is the forces generated by the great accelerations of the booster. By examining the acceleration versus time graph for the booster in Appendix B it is possible to determine if these accelerations are within acceptable limits. The most obvious features are the large spikes that occur at 2.5 and 6 minutes. These correspond to the changeover to ramjet and then back to turbojet. These accelerations are only in the direction of motion and do not represent total accelerations but will all be off by the same factor. The graph clearly shows that the vehicle and crew do not undergo periods of sustained acceleration. Also, the peak values are about 3 g's of acceleration. This value is high but acceptable.

The final consideration involved is the aborted mission results. If the staging process had to be aborted for some technical reasons, the vehicle would be able to land safely. Through the analysis of the computer outputs found in Appendix C, it was found that the vehicle would be able to decelerate enough to safely land. The problem is with the vehicle's range. The flight path studied for an abort would not have sufficient range for the vehicle to arrive at the staging point, turn around and return to its takeoff point. As before, there is enough fuel for the vehicle to level off and return to its point of origin. Several other performance characteristics are seen in Appendix B, but the above considerations were critical and worthy of mention in the report.

## 4.2 Orbiter Performance

After staging occurs, it is necessary to determine if the orbiter can, in fact, reach the projected orbit of 220 nautical miles. Also, it will need to be determined if there was enough fuel left in the orbiter in order to return safely to Earth. This is accomplished through the use of a computer program that analyzes the flight path by the use of Newton's Second Law. By assuming a non-lifting body, the only forces acting upon the orbiter are the thrust, drag and gravity. By integrating over a given time interval, it was possible to analyze the performance of the orbiter and obtain the results in Appendix B.

Immediately after the booster and orbiter separate, the orbiter raises its nose to an 85 degree angle with the horizontal. The vehicle maintains this attitude until 300000 feet, where the angle is then drastically decreased to 2 degrees with the horizontal. This flight path allows the orbiter to quickly exit the atmosphere where drag effects are great. Then, the decrease in angle will reduce the losses involved with the changes in gravity. In order to further facilitate this particular flight path, the throttle of the engines is lowered at the same time as the angle of attack. Initially, the orbiter produces 109% of the rated thrust of the engine. At 300000 feet, the engines are throttled back to 75% until the orbital velocity is achieved, at which time the engines are shut down.

By analyzing the graphed results of the computer output found in Appendix B, it is possible to determine how successful the orbiter was in completing its mission. The graph of altitude versus range shows the drastic change in flight path angle. The segments are straight lines because the path is set as such in the program. In actuality, this path would be slightly parabolic, but the deviation would be small enough for this to be a good approximation. The velocity versus altitude graph in Appendix B shows the large impact of the drag force. Even though the thrust is rated at 109% only about 5% of the total change in velocity is achieved by 300000 feet. Of course, this result is misleading unless the time scale is also studied. By examining the velocity versus time graph, it can be found that it only takes 35 seconds to reach 300000 feet, while it takes 5 minutes to attain orbital velocity. Again, the flight path angle is the reason for this disparity. Finally, the acceleration data shows that the flight is not too stressful on the vehicle and crew. Although 3 g's are sustained for 35 seconds, the crew should be safe in the pressure suits they will be wearing.

The orbiter achieves orbital velocity at 444000 feet which is nowhere near the target orbit of 220 nautical miles. It takes the orbiter an additional 17 minutes to reach that altitude. This yields a time to orbit from staging of 22 minutes. In order to circularize the orbit, a small burn is initiated a few moments before apogee of the transfer. Once this orbit is achieved, the orbiter is left with a 14.5% fuel reserve which will be sufficient for re-entry. When it is time to return to Earth, the orbiter will initiate a full burn. The orbiter will drop into the atmosphere where it will employ a skip re-entry and then land at the designated runway, and safely complete its mission. During decent, the orbiter will be controlled much the same way that the Space Shuttle is. The orbiter will not be flying under power, it will be gliding. The orbiter has been designed with two vertical stabilizers, canted away from its centerline, for controlling yaw. For roll and pitch control, the elevons and flaps will be used. The elevons are used mainly during landing approach and during staging. The flaps will be used as an airbrake, and for landing.

## 4.3 Summary and Recommendations

After an analysis of each major design aspect was completed and integrated, the results show that this conceptual Two Stage To Orbit vehicle can safely and efficiently complete the mission requirements outlined in the introduction. The performance of this design in its main objective, mission derivatives, and each mission step was highly successful.

While many of the systems in the design were not studied in depth, the customized systems for this design were and they were found to be plausible. The design was performed with technological realities in mind. Throughout the project, no part of the design requires technology that does not either exist today or is not capable of being developed in the near future, given the necessary resources. This fact adds a certain amount of realism to a "conceptual" design. In addition, historical data as well as current information from other TSTO's was used to reflect the tendency of theory to be inadequate under the actual conditions of nature. These considerations also lend practicality to this design.

This TSTO design has great versatility. The horizontal takeoff allows for the vehicle to launch and land at several different sites, as well as simplifying the transportation of the system from site to site. Throughout the design, the need for a quick turn around time was a reminder not to use any low quality or overly complex components.

This vehicle will fill a valuable niche in the future vision of manned space science. With the space station program gaining momentum, heavy lift drone boosters are the most feasible way to lift the components and machinery. A very reliable and versatile vehicle with a quick turn around time is needed to ferry the workers to construct future space stations and colonies, as well as to transport the scientists and supplies. This TSTO design has this capability as well as the ability to capture disabled satellites and return them safely to Earth. These abilities are essential for the space program to attain its desired future.

## 4.4 Recommendations

This project was the development of a theoretical design for a TSTO vehicle. The next step in the design process would be to make in depth studies of particular areas. During the initial design process, several areas deserving more attention were noted. As a follow up to this project, it is recommended that one of the following areas described below be studied in great detail. The Most important areas and particular points of interest resulting from this design are listed below.

Aerodynamics

The aerodynamic properties used to describe the characteristics of this design are based on theoretical equations and historical data. A much more complete study is required. Physical testing of a model would provide the most accurate information. A detailed study of the mated system, the lone booster after separation, the lone orbiter on its ascent out of the atmosphere and on its re-entry are needed. Also, the aerodynamic effects which the booster has on the orbiter during staging must be investigated.

Separation

The separation segment of this project is purely theoretical. The procedure and mechanisms presented in this project are believed to be plausible, however a model of the systems simulating the staging process needs to be built. This model could then be used in a wind tunnel to study the safety and aerodynamics involved in the separation process. It could also be used to refine the procedure, such as determining how high the orbiter must be lifted and at what angle of inclination in order to get the best performance.

Stability

The booster vehicle was designed in accordance with the principles governing stability. The actual behavior of the vehicle was not possible to measure. A detailed analysis of the booster both alone and mated would provide valuable information, particularly if there are large differences. A stability analysis of the orbiter must also be performed. Of particular interest is the stability of the booster during its transition when separation is actually taking place.

Propulsion

While studying the booster propulsion system, it was noted that eight turboramjet engines were not necessary throughout the mission. It is possible that a system of six or perhaps even four turboramjet engines would suffice for the needed thrust at high mach numbers (when the ramjet would be in use). This may lead to a mixed system of turboramjets and turbojets to achieve maximum efficiency. The turbojets (which weigh less and consume less fuel than the turboramjets) could be used from takeoff until the turboramjets had converted to ramjet mode, then be turned off. This possibility merits a more in depth study.

Cost Analysis

While cost was always a factor when choosing between different systems or materials, an overall cost analysis or breakdown was never performed. One reason for this is the fact that some costs (such as turboramjet development) are not known. In order to be a legitimate design for future consideration, costs must be known.

In addition to the above areas, several sub-systems need consideration. The following sub-systems need to be turned from theoretical ideas to actual engineered and specifically designed components:

Safety systems
Fuel systems
Computer systems
Avionics
Environmental Layout (Cockpits)
Orbiter Operations

Once each of the above suggested studies of the initial theoretical TSTO design presented in this project have been completed, the next step of the design process can be determined. If the studies show this design to be plausible (with whatever changes necessary), the design would move on to the testing of a completely functional model. If they show the design to be unworkable or not worthy of further consideration, this project and design become what they started out to be: a learning experience and source from which to draw.

# Endnotes

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31. Oates, p 14.

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# APPENDIX A

## Center of Gravity Calculations

## Center of Gravity

Since the majority of the total weight components are estimates, as are the distances, the weight components used for the initial estimate of the center of gravity location are those found in the revised weights section of this report. The titles of the components are just that, titles covering a broad array of weights. Many different systems are combined into the weight and distance estimations used for this calculation

| Orbiter Component | Weight (lbm) | Distance From Nose (ft) |
|---|---|---|
| Engines | 8000.00 | 67.5 |
| Payload | 30000.00 | 32.0 |
| Structure | 37000.00 | 48.0 |
| Controls | 10200.00 | 11.5 |
| Bay Systems | 1700.00 | 30. |
| Fuel Systems | 560.00 | 57.0 |
| Fuel Tanks 1 | 153231.75 | 54.0 |
| Fuel Tanks 2 | 142768.25 | 58.0 |

$X_{cg}$ = ($\Sigma$ weight x distance)/($\Sigma$ weights)

$X_{cg,orbiter} \approx$ 52 ft

| Booster Component | Weight (lbm) | Distance From Nose (ft) |
|---|---|---|
| Engines | 76494.0 | 205.0 |
| Orbiter | 388000.0 | 195.0 |
| Structure | 154054.0 | 145.0 |
| Fuel System | 17500.0 | 190.0 |
| Cockpit Systems | 12500.0 | 65.0 |
| Controls Systems | 2500.0 | 207.0 |
| Separation System | 17500.0 | 170.0 |
| Fuel (in wings) | 160000.0 | 190.0 |

$X_{cg}$ = ($\Sigma$ weight x distance)/($\Sigma$ weights)

$X_{cg,\text{mated booster}} \approx$ 183 ft

The orbiter sits seven feet in from the rear of the booster while mated, the alignment of the centers of gravity can be checked in the following manner:

<u>Center of Gravity From Rear Edge</u>

Booster: 210 (total length) - 183 ($X_{cg}$ from nose) = 27 ft

Orbiter: 70 (total length) - 52 ($X_{cg}$ from nose) = 18 ft

Mated Difference: 27 - 18 + 7 (relative orbiter-booster mated positions) = 25 ft.

Thus, the difference of the centers of gravity while mated is

27 - 25 = 2 ft

# APPENDIX B

## Performance Graphs

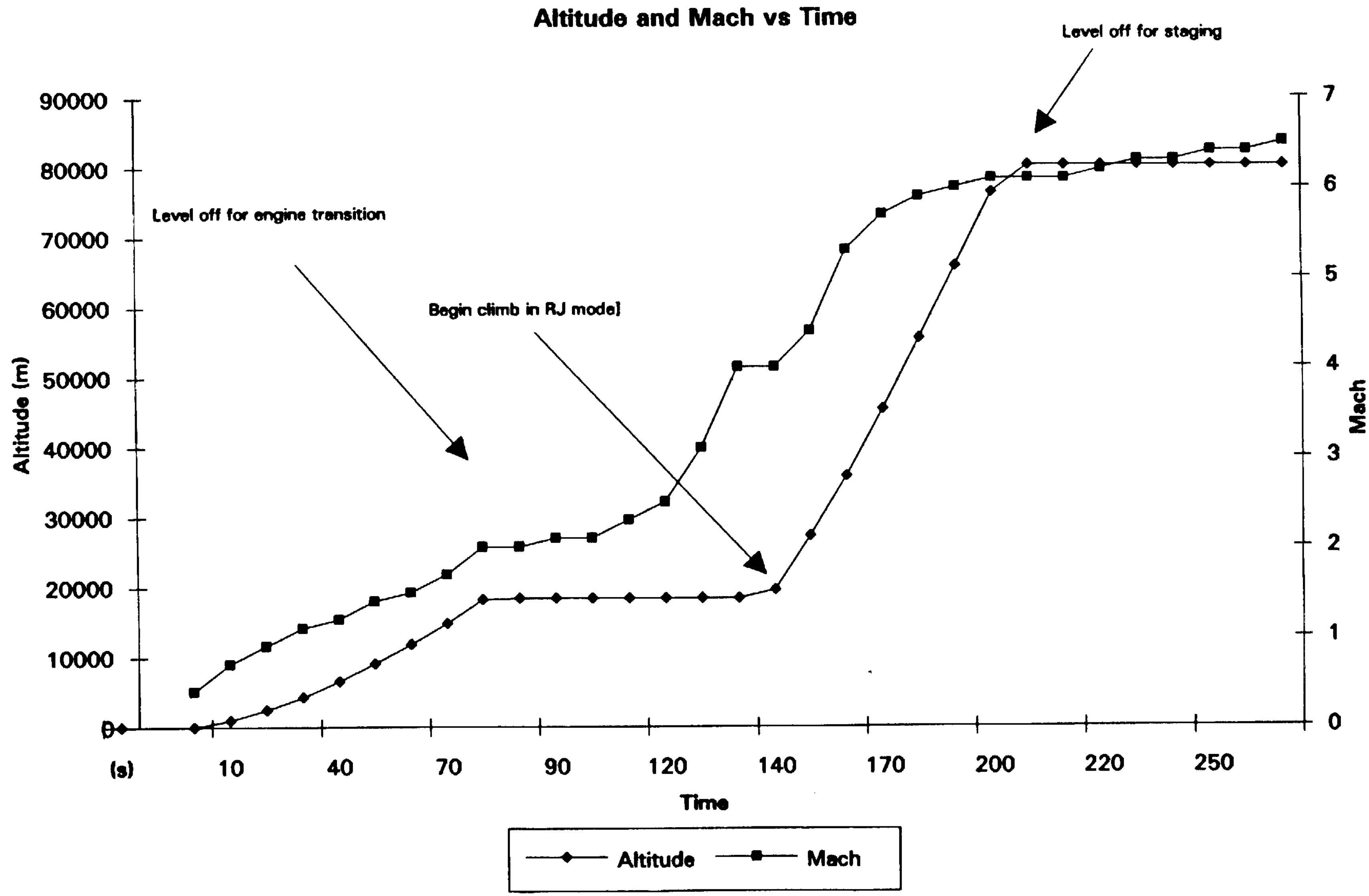

Altitude and Mach vs Time
Level off for staging
Level off for engine transition
Begin climb in RJ model
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
Altitude (m)
7
6
5
4
3
2
1
0
Mach
(s)
10
40
70
90
120
140
170
200
220
250
Time
Altitude
Mach

Figure B.1

## Booster Altitude vs Range

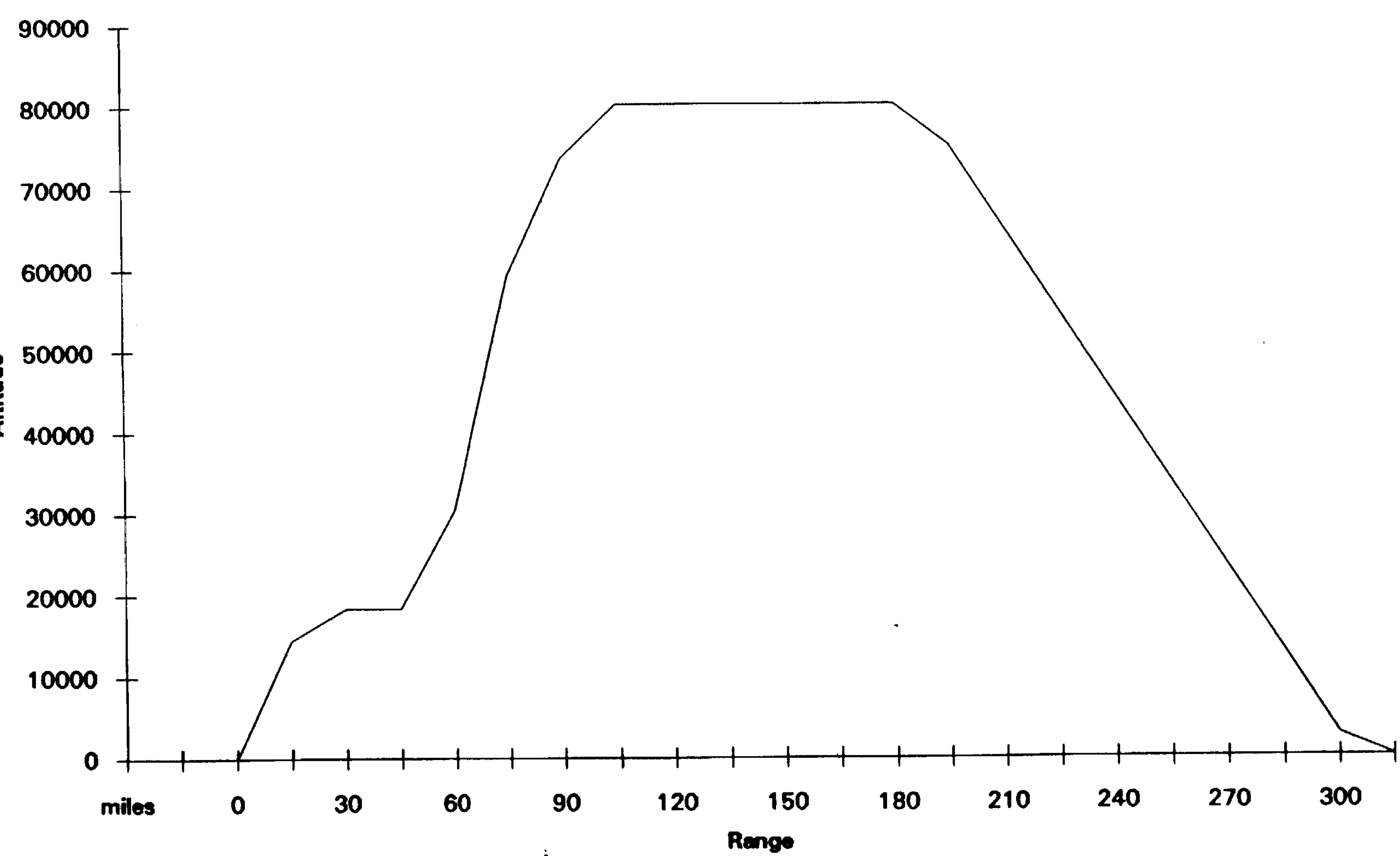



Figure B.2

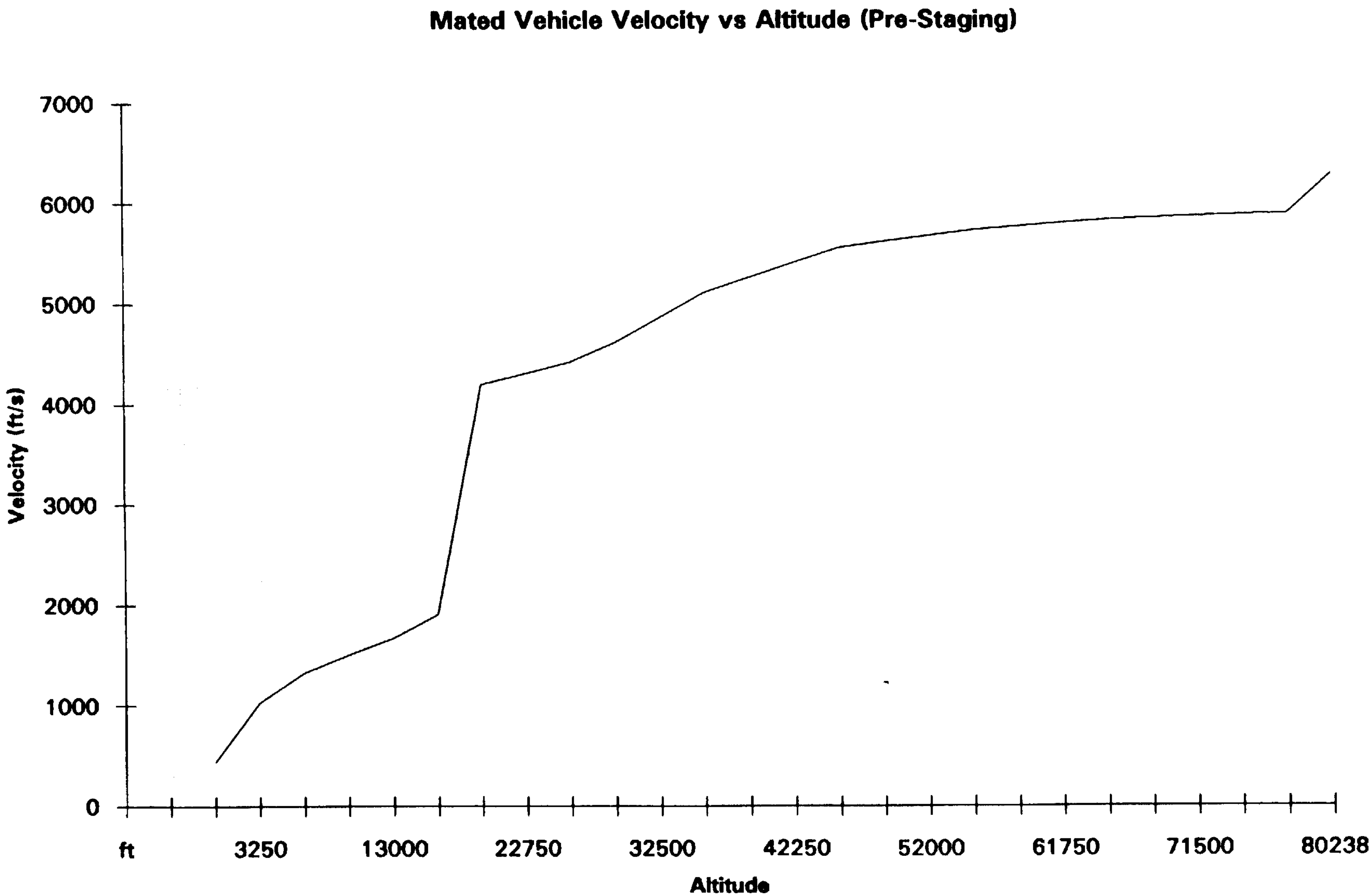

Mated Vehicle Velocity vs Altitude (Pre-Staging)
7000
6000
5000
4000
3000
2000
1000
0
Velocity (ft/s)
ft
3250
13000
22750
32500
42250
52000
61750
71500
80238
Altitude

Figure B.3

Booster Velocity vs Altitude (Post Staging)

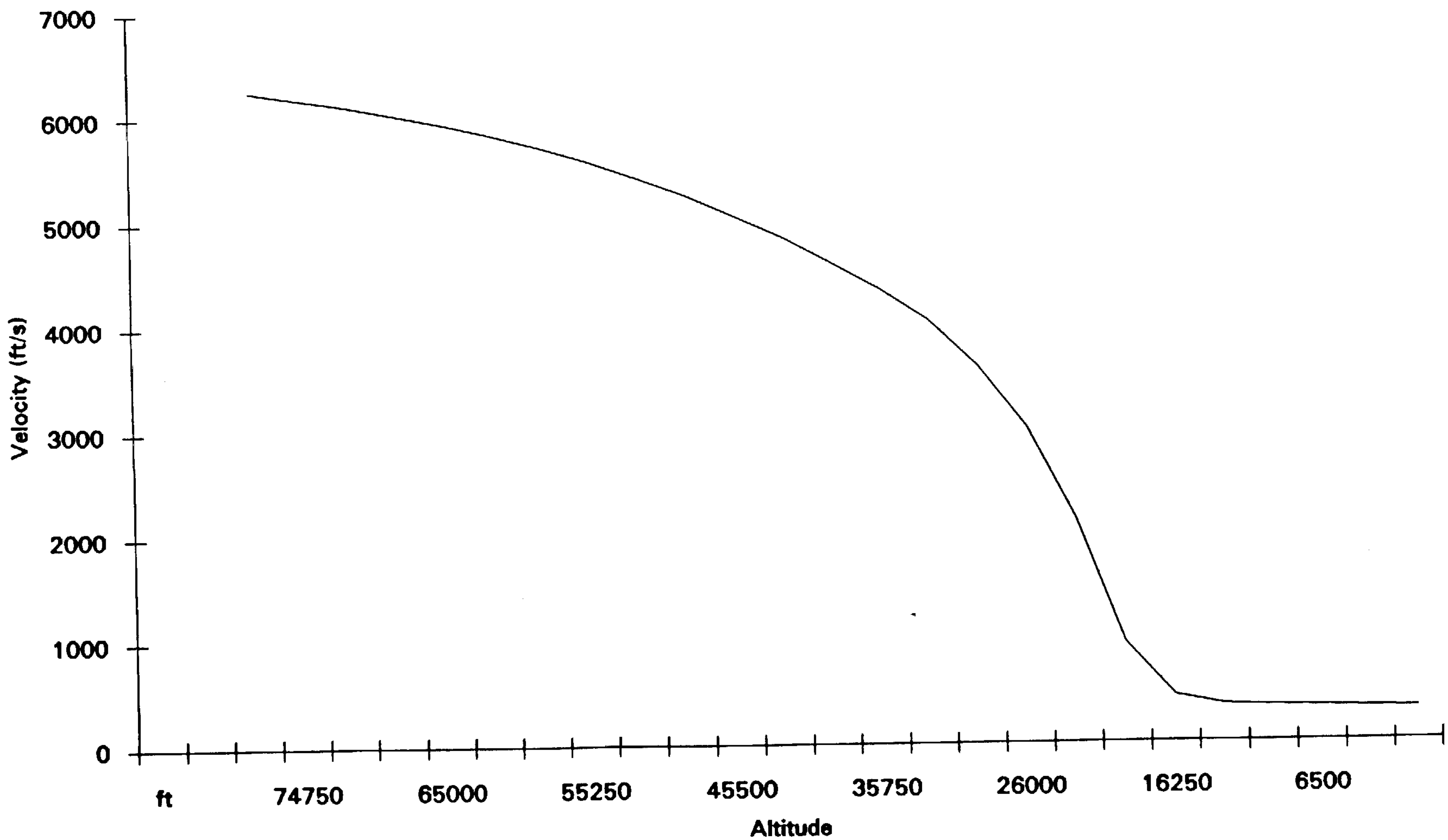



Figure B.4

Mission Results
Change in Velocity vsTime

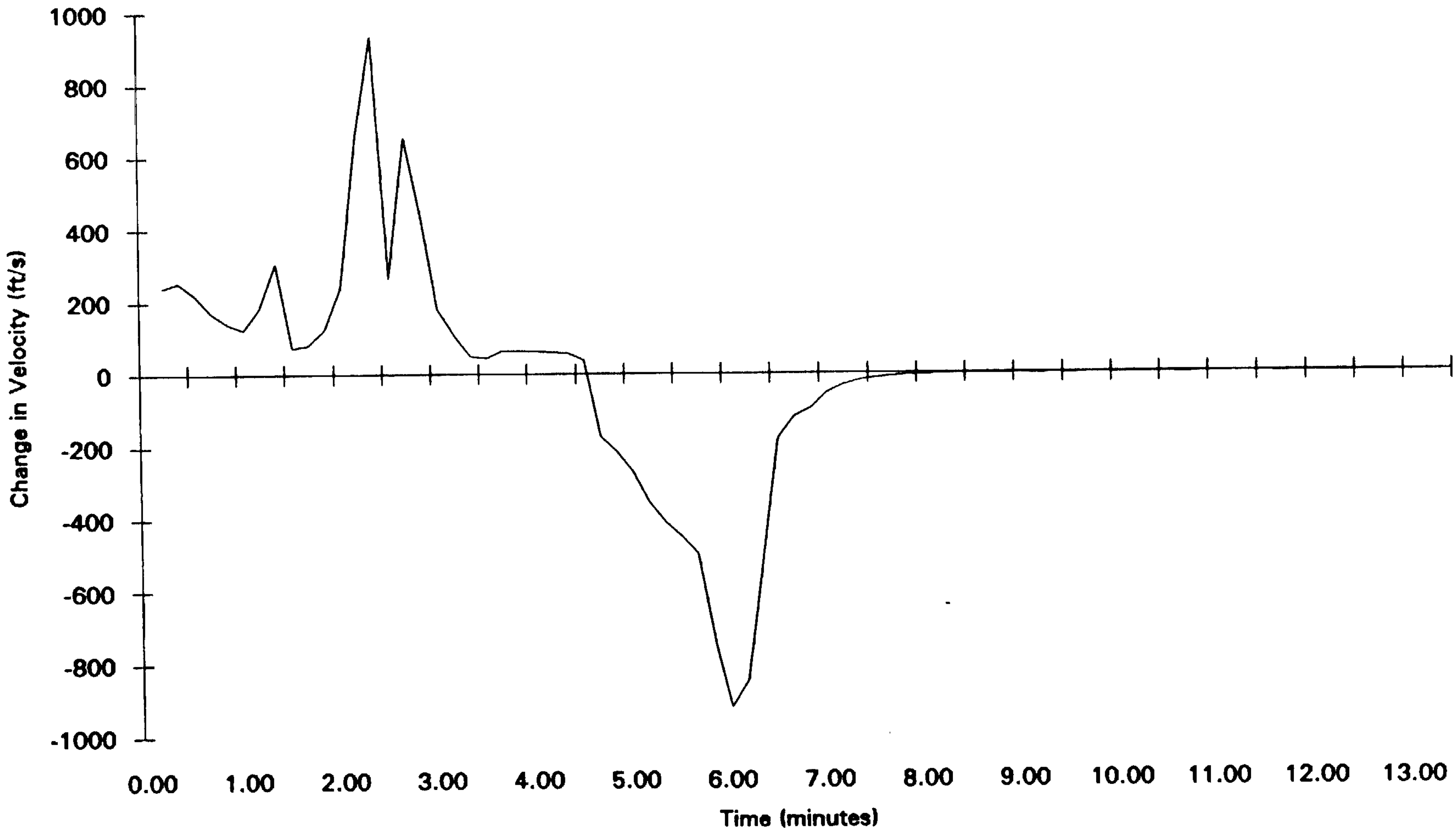



Figure B.5

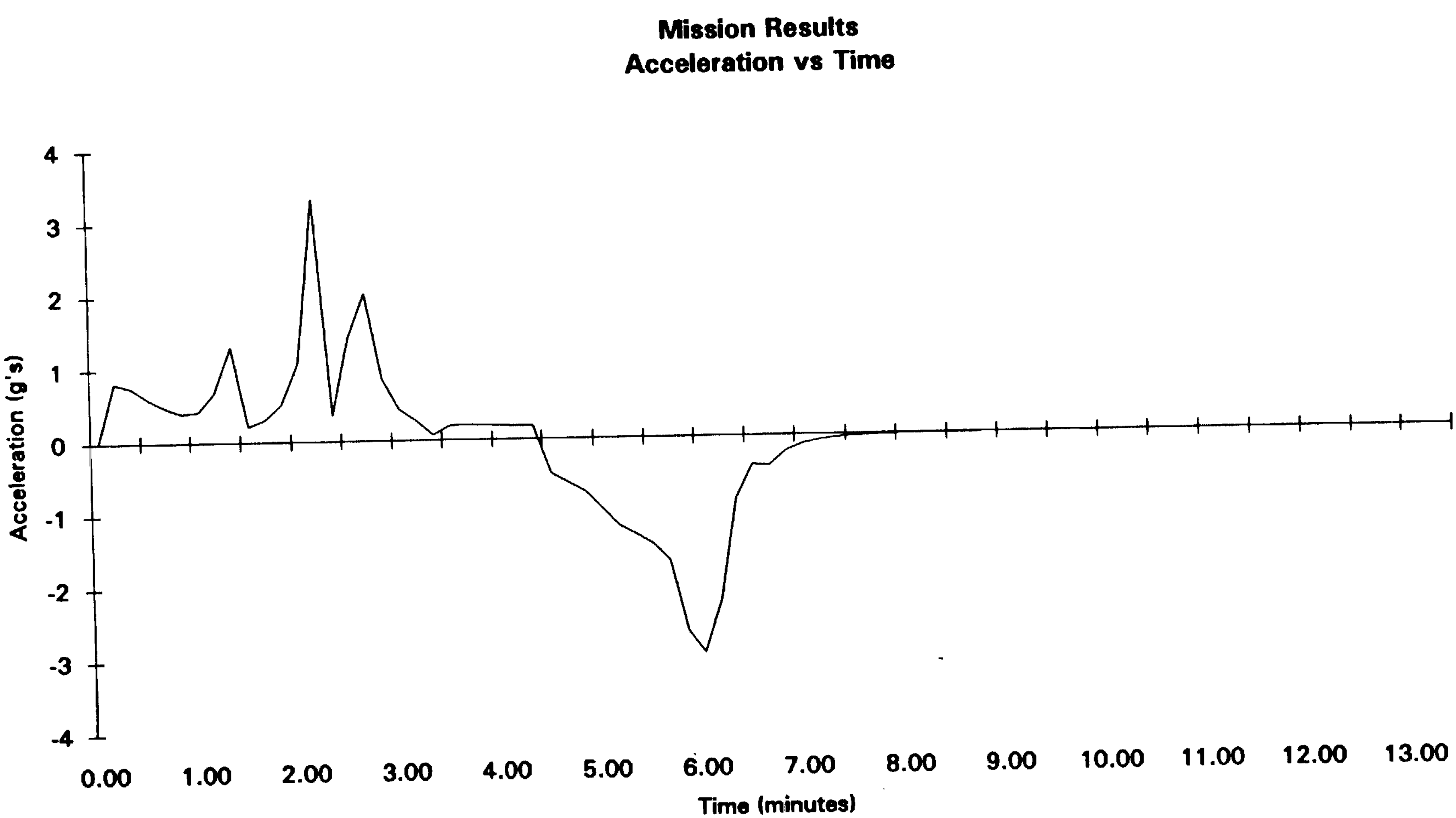

Mission Results
Acceleration vs Time
4
3
2
1
0
-1
-2
-3
-4
Acceleration (g's)
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
11.00
12.00
13.00
Time (minutes)

Figure B.6

Mated Vehicle Ascent

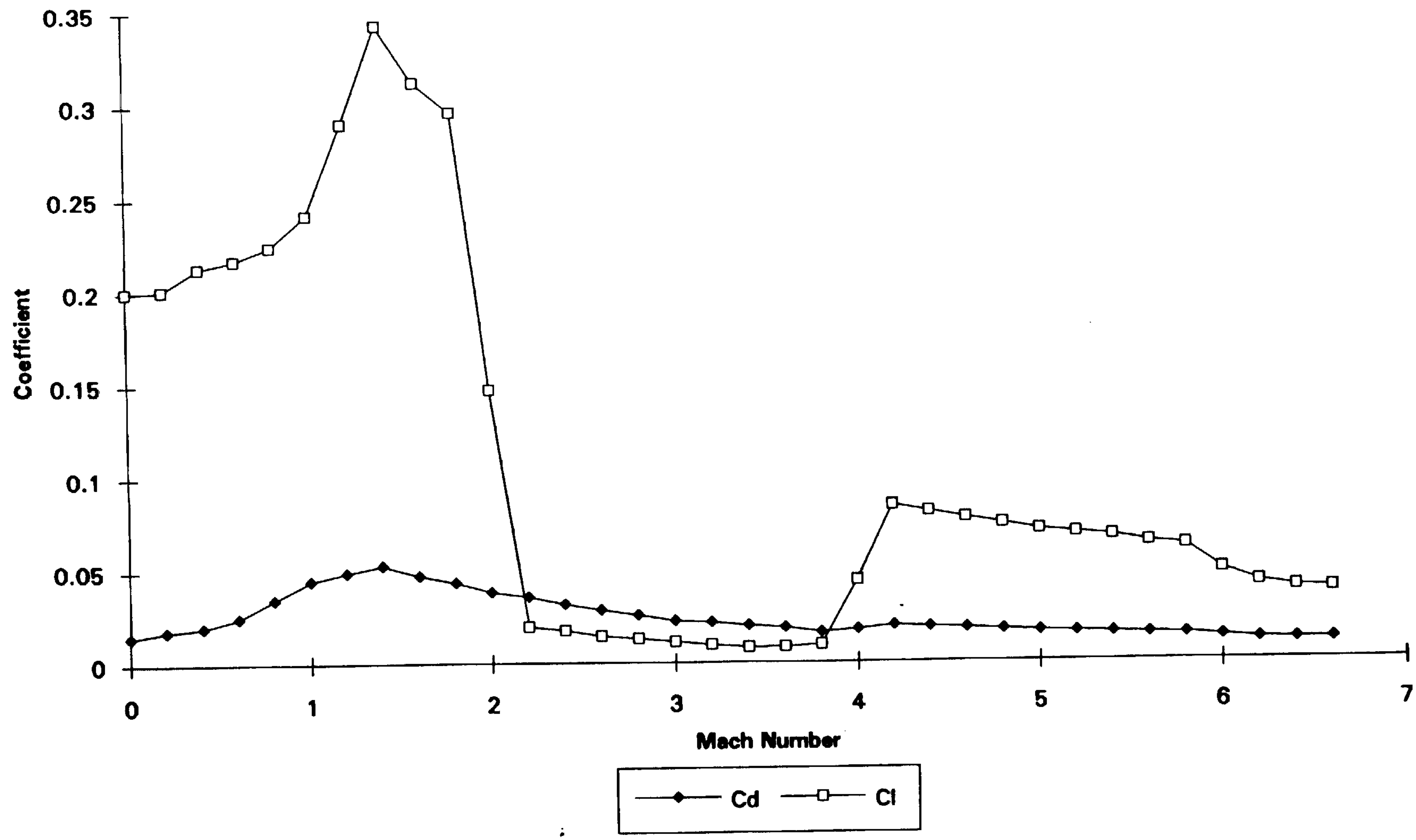



Figure B.7

Mated Vehicle Decent

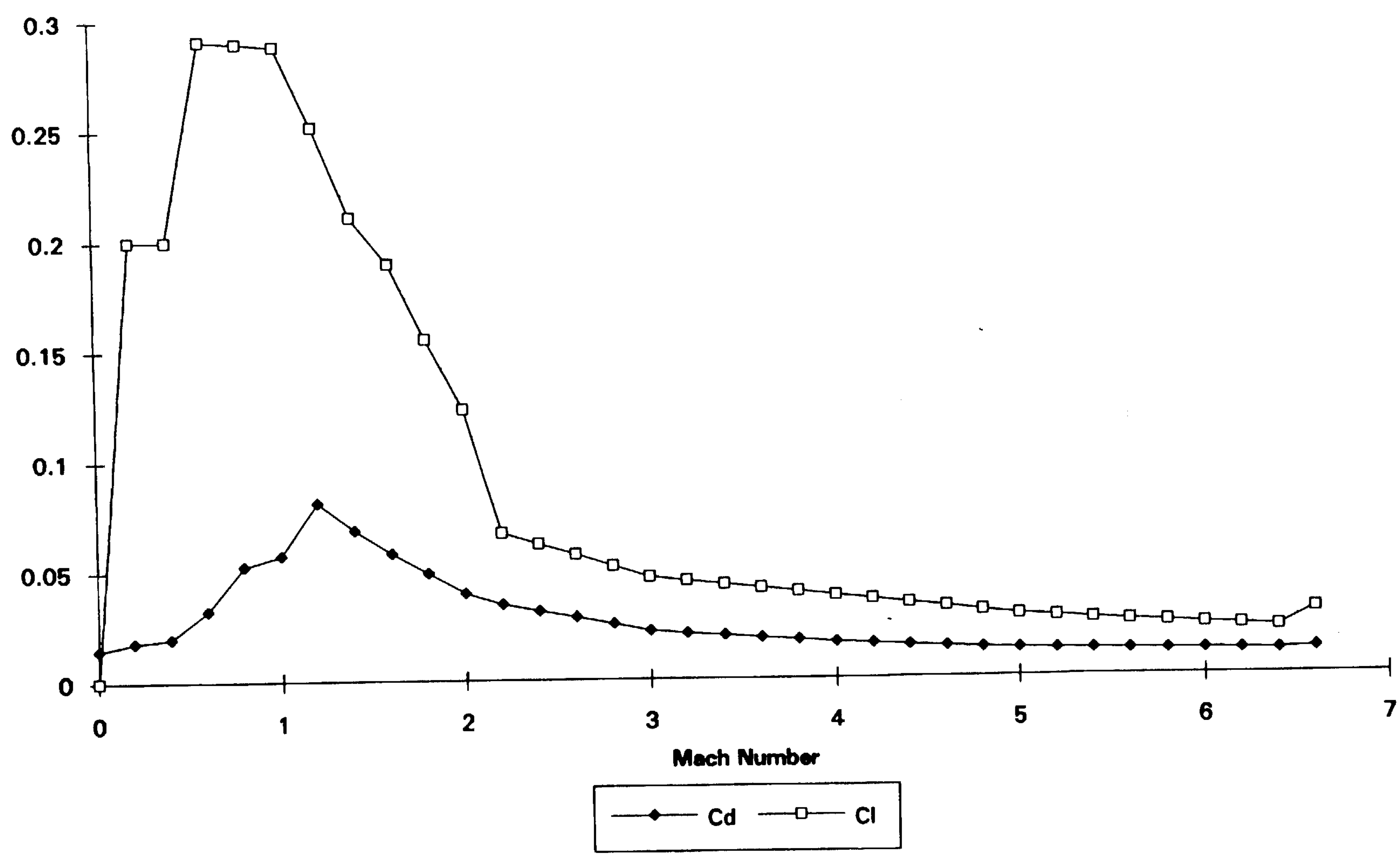



Figure B.8

## Booster Decent

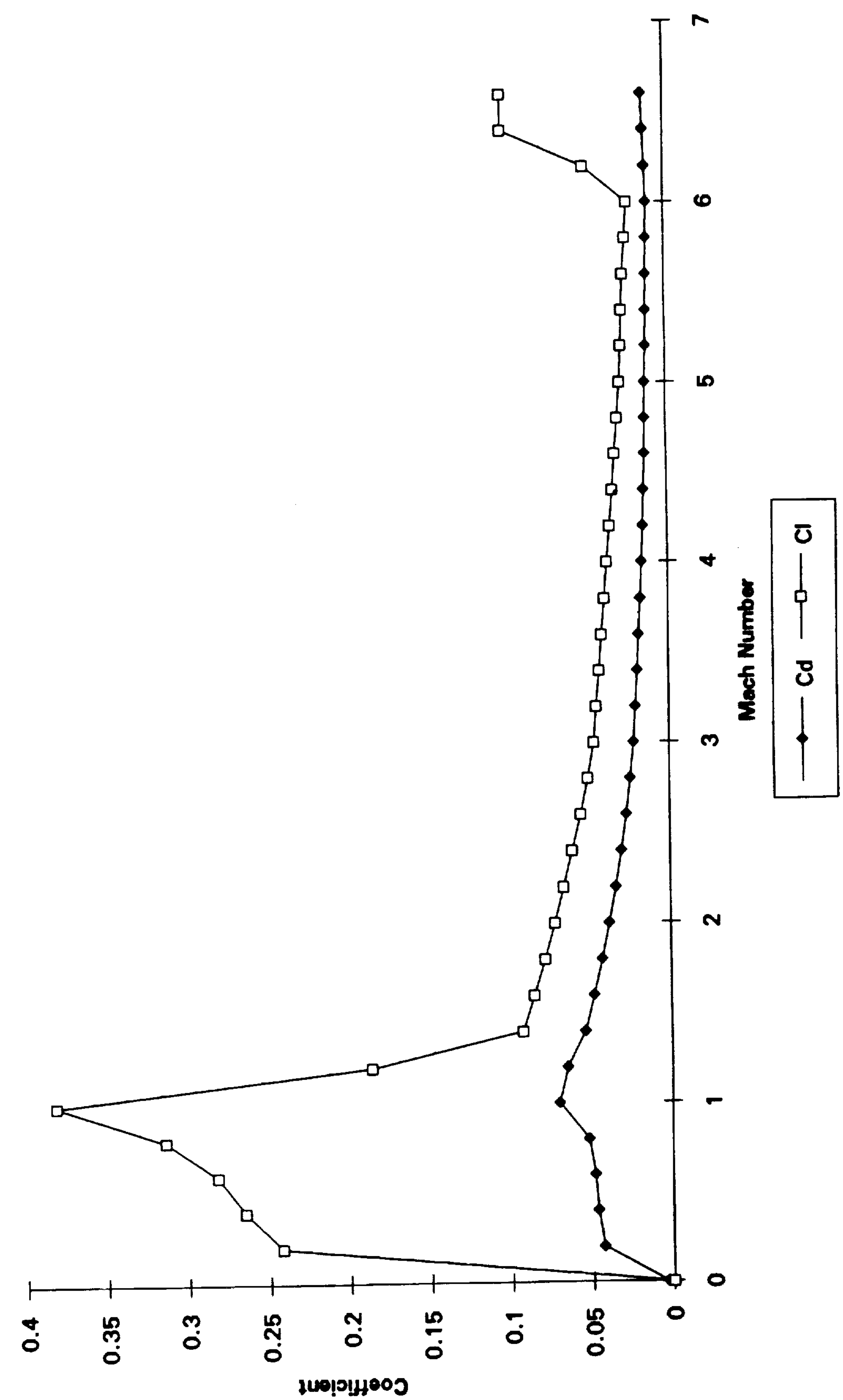
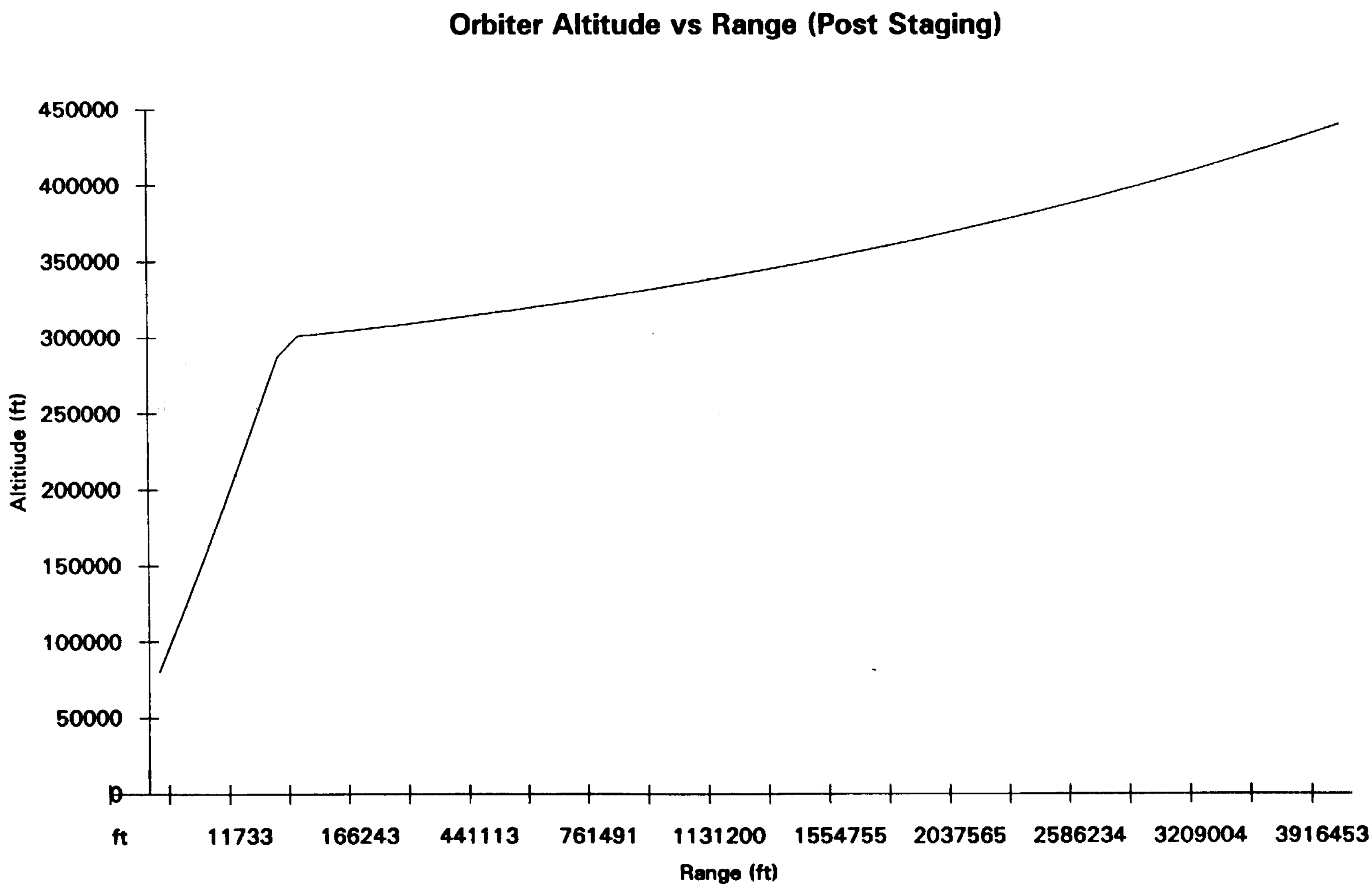



Figure B.9



Orbiter Altitude vs Range (Post Staging)
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
Altitude (ft)
ft
11733
166243
441113
761491
1131200
1554755
2037565
2586234
3209004
3916453
Range (ft)


Figure B.10

## Orbiter Velocity Change vs Time (Post Staging)

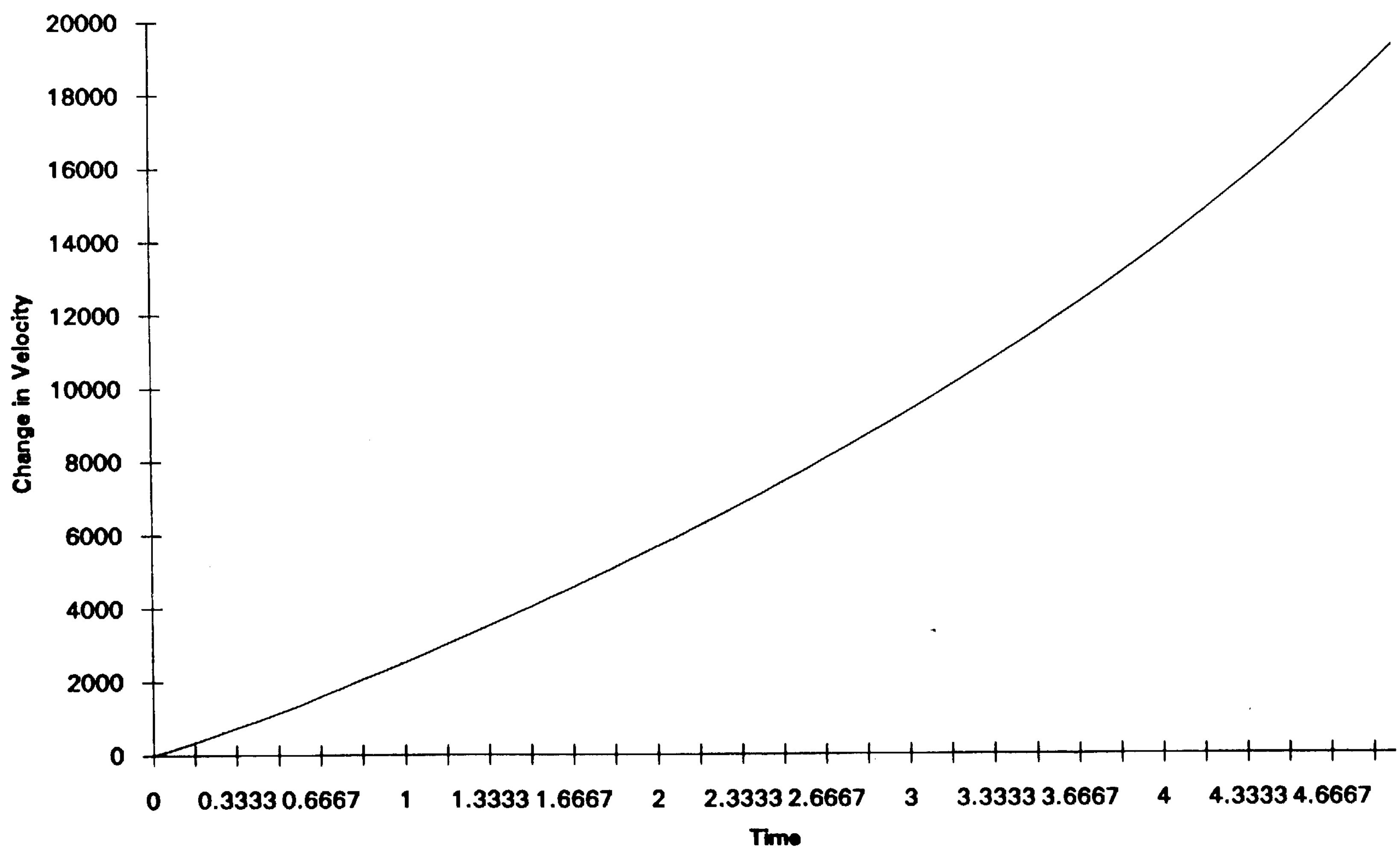



Figure B.11

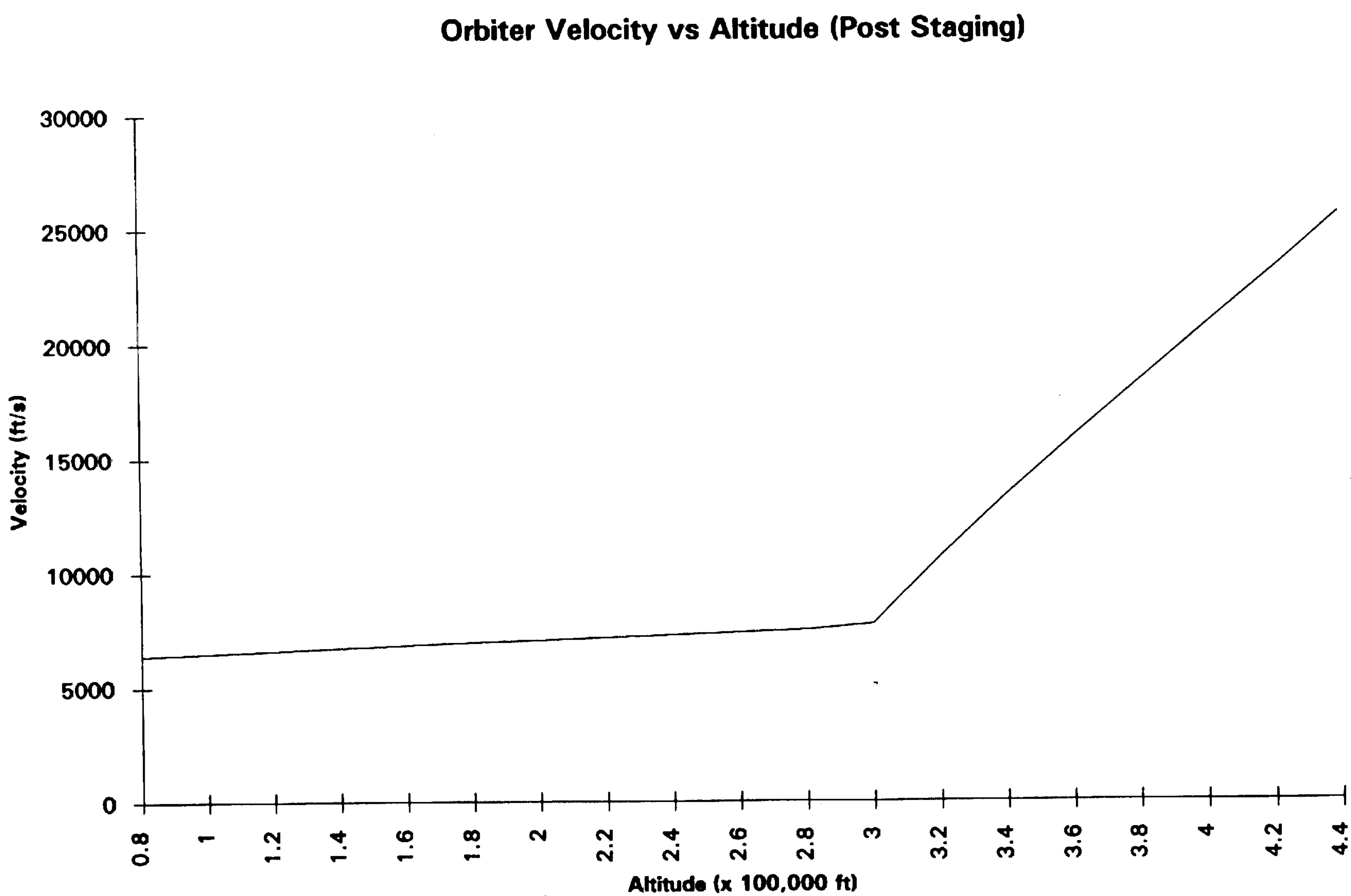

Orbiter Velocity vs Altitude (Post Staging)
Velocity (ft/s)
30000
25000
20000
15000
10000
5000
0
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
3.8
4
4.2
4.4
Altitude (x 100,000 ft)

Figure B.12

# APPENDIX C

# PERFORMANCE PROGRAM

## ALGORITHM FOR TSTO12.PAS

Initialize

- Assign and Initialize Output Files
- Print Headers to Output Files
- Initialize Global and Other Variables
- Initialize Flags and Counters

Print Initial Conditions to Output Files

- Calculate Output Variables
- Write Variables to Output Files

Main Iterative Loop

- Advance Loop Counter
- Calculate Runge-Kutta Variables
  - k11
    - Call change in velocity function
    - Calculate thrust
      - Call thrust function
        - Check for fuel
        - Calculate Mach number
          - Call Mach function

Double interpolate for thrust

Calculate drag

Call drag function

Calculate Mach number

Call Mach function

Interpolate for drag coef.

Interpolate for density

Determine planform area

Calculate drag

Calculate weight

Calculate change in velocity

k12

Call change in mass function

Calculate Mach number

Call Mach function

Interpolate specific thrust

Calculate thrust

Call thrust function

Check for fuel

Calculate Mach number

Call Mach function

Double interpolate for thrust

Calculate change in mass

k13

Calculate change in height

Call change in height function

Calculate change in height

k14

Calculate change in range

Call change in range function

Calculate change in range

k21

Repeat k11 with k1? values

k22

Repeat k12 with k1? values

k23

Repeat k13 with k1? values

k24

Repeat k14 with k1? values

k31

Repeat k11 with k2? values

k32

Repeat k12 with k2? values

k33

Repeat k13 with k2? values

k34

Repeat k14 with k2? values

k41

Repeat k11 with k3? values

k42

Repeat k12 with k3? values

k43

Repeat k13 with k3? values

k44

Repeat k14 with k3? values

Calculate overall interval changes

Adjust global variables

Examine new conditions for messages or major changes

If premature slowing then

Trip stop flag

If fuel exhausted then

Trip stop flag

If landing can occur then

Trip stop flag

If first leveling conditions are right then

Adjust flags

```
            Adjust global variables
        If resume ascent conditions are right then
            Adjust flags
            Adjust global variables
        If second leveling conditions are right then
            Adjust flags
            Adjust global variables
        If staging conditions are right then
            Adjust flags
            Adjust global variables
    If output conditions are right then
        Calculate output variables
        Write variables to output files
Repeat main loop until stop flag is tripped

Close output files and end program
```

## LIST OF SUPPORT FILES FOR TSTO12.PAS AND DESCRIPTIONS

| | |
|---|---|
| aero_g.dat | This is an output file of TSTO12. It contains the data in which the aerodynamics team would most likely be interested. In addition to altitude and Mach numbers, drag forces, lift forces, thrust forces, and weight are included. |
| alt.dat | This file contains the names of the files which contain the thrust values vs. their applicable altitude. The DoubleInterp function must have this information in order to perform correctly. These values originated from the engine specifications. |
| cd1_b.dat | This file contains Mach number vs. the coefficients of drag for mated vehicle ascent. These values originated from the aerodynamics analysis. |
| cd2_b.dat | This file contains Mach number vs. the coefficients of drag for lone booster descent. These values originated from the aerodynamics analysis. |
| cd2_abort.dat | This file contains Mach number vs. the coefficients of drag for a mated vehicle descent. These values originated from the aerodynamics analysis. |
| cl1_b.dat | This file contains Mach number vs. the coefficients of lift for a mated vehicle ascent. These values originated from the aerodynamics analysis. |

| | |
|---|---|
| cl2_b.dat | This file contains Mach number vs. the coefficients of lift for lone booster descent. These values originated from the aerodynamics analysis. |
| cl2_abrt.dat | This file contains Mach number vs. the coefficients of lift for a mated vehicle descent. These values originated from the aerodynamics analysis. |
| density.dat | This file contains altitude [ft] vs. the ratio of atmospheric density to sea level density. These values were extracted from a textbook. |
| glob_g.dat | This is an output file of TSTO12. It contains miscellaneous global variable data such as throttle settings, flight path angles, and total mass. |
| prop_g.dat | This is an output file of TSTO12. It contains the data in which the propulsion team would be interested. In addition to standards such as altitude and Mach number, thrust, specific thrust, and mass flow rate are included. |
| soundspd.dat | This file contains altitude [ft] vs. the ratio of the speed of sound to sea level speed of sound. These values were extracted from a textbook. |
| specthr.dat | This file contains the specific thrust [m/s] vs. the Mach number for one of the booster's engines. These values originated from the engine specifications. |
| thrxx.dat | This series of files contains the natural log of the thrust per |

unit intake area [ton/sq.m] vs. the Mach number. Each file contains the data for a different altitude. These values originated from the engine specifications.

tsto_g.dat — This is an output file from TSTO12. It contains a general sampling of the final design performance data. Some output values which it lists are altitude, Mach number, range, and velocity.

## LIST OF FUNCTIONS FOR TSTO12.PAS AND DESCRIPTIONS

DoubleInterp — This function is only used for the engine thrust data. The thrust is a function of two variables: Mach number and altitude. In order to calculate the thrust, DoubleInterp uses the Interpolate function twice and then interpolates that data once again to effectively double interpolate.

fDHDT — This function calculates the change in height per unit time from the velocity and flight path angle. The return value is in feet per second.

fDMDT — This function calculates the change in mass per unit time or the mass flow rate of the engines. To achieve this it divides the thrust by the specific thrust while juggling units to give slug/s.

fDrag — This function calculates the drag on the vehicle from the velocity and altitude. It access the proper drag coefficient file and uses the definition of drag to give a force in pounds. It also uses the Mach number to decide on the apparent planform area which can change due to flap extensions.

| | |
|---|---|
| fDRDT | This function calculates the change in range per unit time from the velocity and flight path angle. The return value is in feet per second. |
| fDVDT | This function calculates the change in velocity per unit time. It is an integral part of the analysis scheme in that it uses virtually every other function to wield the governing equation of motion. The return value is in feet per second squared. |
| fLift | This function calculates the lift produced by the vehicle from the velocity and altitude. It accesses the proper lift coefficient file and uses the definition of lift to give a force in pounds. It also uses the Mach number to decide on the apparent planform area which can change due to flap extensions. |
| fMach | This function calculates the Mach number given any velocity and altitude. It uses the altitude in order to get the speed of sound, then simply calculates the Mach number from its definition. |
| fThrust | This function calculates the thrust from the engines given any velocity, altitude, and throttle setting. It also uses vehicle constants such as intake area and number of engines. The thrust data is stored as the log of the thrust for ease of interpolation. Here exponents are taken to get actual values. The data is also stored in tonnes but converted to pounds. Before this function calculates any thrust, it checks for fuel! |

Interpolate

This function is essential to the input of data. First it reads an ASCII file made of two columns of data (arranged in a special format). When it has deciphered all of the values and has a true numerical representation of the table of data, it uses a given value of the first column and interpolates the data in the second column to match it. If a value falls out of range, it returns a value as close as it can get.

## LIST OF CONSTANTS FOR TSTO12.PAS AND DESCRIPTIONS

| | |
|---|---|
| AEROFILE | This constant is the name of the output file which will contain the aerodynamic team's output data. |
| ALTITUDESUBFILE | This constant is the name of the file which contains the altitudes for which thrust data is known and the names of the thrust files. |
| AltStaging | This constant is the altitude at which staging will occur. Units are feet. |
| AreaInt | This constant is the characteristic planform area with half of the flaps extended. |
| AreaIntake | This constant is the intake area for one booster engine. |
| AreaPlanform | This constant is the characteristic planform area for the booster. This value includes no flap extensions. |
| AreaTakeoff | This constant is the characteristic planform area with all flaps extended. |
| CDASCENTFILE | This constant is the name of the file which contains the coefficient of drag information for vehicle ascent to staging. |
| CDDESCENTFILE | This constant is the name of the file which contains the coefficient of drag information for vehicle descent from staging. |

| | |
|---|---|
| CLASCENTFILE | This constant is the name of the file which contains the coefficient of lift information for vehicle ascent to staging. |
| CLDESCENTFILE | This constant is the name of the file which contains the coefficient of lift information for vehicle descent from staging. |
| DATFILE | This constant is the name of the output file which will contain general output data. |
| DENSITYRATIO-FILE | This constant is the name of the file which contains the atmospheric density information. |
| g | This constant doubles as the acceleration due to gravity at the Earth's surface and as the conversion factor in the English set of units. |
| GammaDescent | This constant is the flight path angle for the booster from after staging until landing. Units are radian. |
| GammaLevel | This constant is the flight path angle for the booster for the first leveling out and during engine transition. Units are radian. |
| GammaResume | This constant is the flight path angle after engine transition is completed and the vehicle is resuming its ascent to staging altitude. Units are radian. |
| GammaStaging | This constant is the flight path angle during the second leveling out for staging. Units are radian. |

| | |
|---|---|
| GammaTakeoff | This constant is the flight path angle for the booster at the time of takeoff until the first leveling out. Units are radian. |
| GLOBFILE | This constant is the name of the output file which will contain miscellaneous global variable output data. |
| Interval | This constant is the time interval between each step of calculation. All global variables are calculated for the beginning and end of each interval. Units are seconds. |
| MachHalfFlaps | This constant is cut-off value for the characteristic planform area. Between the values MachHalfFlaps and MachZeroFlaps the characteristic planform area will be AreaInt. |
| MachLeveling | This constant is the Mach number at which the vehicle must level out to obtain a steady engine transition. |
| MachResume | This constant is the Mach number at which the vehicle can resume ascent to staging after the first leveling out. |
| MachStaging | This constant is the Mach number at which staging will occur. |
| MachZeroFlaps | This constant is the cut-off value for the use of any flaps. The characteristic planform area for Mach numbers beyond this value will be AreaPlanform. |
| MassBooster | This constant is the structural mass of the booster. This does not include fuel or the mass of the orbiter. Units are pounds. |
| MassFuel | This constant is the mass of the fuel for the booster. |

| | |
|---|---|
| MassOrbiter | This constant is the total mass of the orbiter. This is the booster's payload. |
| NumEngines | This constant is the number of engines which the booster has. |
| PROPFILE | This constant is the name of the output file which will contain the propulsion team's output data. |
| SLrho | This constant is the sea level density of the atmosphere. Units are slug per cubic meter. |
| SLSoundSpeed | This constant is the sea level speed of sound in the atmosphere. Units are feet per second. |
| SOUNDSPEED-RATIOFILE | This constant is the name of the file which contains the atmospheric speed of sound information. |
| SPECTHRUSTFILE | This constant is the name of the file which contains the engine specific thrust information. |
| Steps | This constant is the number of loop passes between each output time. This number times the interval will give the mission time between each output time. |
| ThrottlIdle | This constant is the throttle setting for the booster after staging has occurred until landing. |
| ThrottleInitial | This constant is the throttle setting at the time of takeoff until the first leveling out. |

| | |
|---|---|
| ThrottleLevel | This constant is the throttle setting during the first leveling out for engine transition. |
| ThrottleResume | This constant is the throttle setting from when the vehicle begins to resume ascent until the second leveling out. |
| ThrottleStaging | This constant is the throttle setting during the second leveling out for staging. |
| VelTakeoff | This constant is the takeoff velocity of the fully loaded booster. |

# LIST OF VARIABLES FOR TSTO12.PAS AND DESCRIPTIONS

| | |
|---|---|
| AdjThrustOutput | This variable is the adjusted-for-vehicle-parameters thrust value at output time. |
| AltitudeFlag | This variable is an on/off flag which trips when the vehicle has reached staging altitude. |
| AltitudeGlobal | This variable is the altitude of the vehicle at any time. Units are feet. |
| ChangeIn-AltitudeGlobal | This variable is the final change in the altitude for one interval. Units are feet. |
| ChangeIn-RangeGlobal | This variable is the final change in down range distance for one interval. Units are feet. |
| ChangeIn-TotalMass | This variable is the final change in total mass for one interval. Units are slug. |
| ChangeIn-VelocityGlobal | This variable is the final change in velocity for one interval. Units are feet per second. |
| Count | This variable is a loop counter which keeps track of how many times the program has gone through its main loop. This information is vital for a regular output pattern. |
| DRAGFILE | This variable is the name of the current file of drag coefficients being used. This is dependant on the leg of the mission and the vehicle configuration. |

| | |
|---|---|
| GammaGlobal | This variable is the flight path angle at any time. It is measured positive in the counter clockwise direction. Units are radian. |
| k11, k12, k13, k14 | These variables are the incremental changes for one interval in the velocity per unit time for the Runge-Kutta calculation scheme. |
| k21, k22, k23, k24 | These variables are the incremental changes for one interval in the total mass per unit time for the Runge-Kutta calculation scheme. |
| k31, k32, k33, k34 | These variables are the incremental changes for one interval in the height per unit time for the Runge-Kutta calculation scheme. |
| k41, k42, k43, k44 | These variables are the incremental changes for one interval in the down range distance per unit time for the Runge-Kutta calculation scheme. |
| LevelFlag | This variable is an on/off flag which trips the leveling out for engine transition. |
| LIFTFILE | This variable is the name of the current file of lift coefficients being used. This is dependant on the leg of the mission and the vehicle configuration. |
| MachOutput | This variable is the Mach number at output time. |
| MassFlowRate- | This variable in the mass flow rate of fuel exhausted at any |

| | |
|---|---|
| Global | time. It is also therefore the change in total mass of the vehicle. Units are slug per second. |
| OUTPUTFILE | This variable is the file which will contain the general output. |
| OUTPUTFILE2 | This variable is the file which will contain the aerodynamic team's output. |
| OUTPUTFILE3 | This variable is the file which will contain the propulsion team's output. |
| OUTPUTFILE4 | This variable is the file which will contain the miscellaneous global variable output. |
| PrintFlag | This variable is an on/off flag which trips the program to output the flight data when a change in flight legs has occurred. Otherwise the program will only output at certain intervals. |
| RangeGlobal | This variable is the down range distance that the vehicle has traveled at any time. Units are feet. |
| ResumeFlag | This variable is an on/off flag which trips when the end of engine transition has occurred and the vehicle is ready to resume ascent. |
| SpecThrOutput | This variable is the specific thrust value at output time. |
| StageFlag | This variable is an on/off flag which trips when staging has occurred. It assures that staging will not occur more than |

once.

StopFlag — This variable is an on/off flag which finally stops the looping procedure. A completed or aborted mission is the only trip for this flag.

StructuralMass — This variable is the total mass of the vehicle, whichever configuration it may be in, without the mass of the fuel. It is important for checking if any fuel remains. Units are slug.

ThrottleGlobal — This variable is the throttle setting for all engines at any time. Units are non-dimensional.

ThrustOutput — This variable is the unadjusted-for-vehicle-parameters thrust value at output time.

TotalMassGlobal — This variable is the total mass of the vehicle, whichever configuration it may be in, at any time. Units are slugs.

VelocityGlobal — This variable is the velocity in the direction of travel at any time. Units are feet per second.

## Program Listing of TSTO12.PAS

```
Program TST012(Input, Output);

{ Written by Glenn A Snow for TSTO-MQP-WPI}

uses Crt;                                   {needed to access TurboPascal library functions}

type
   string12 = string[12];                   {defined for interpolating function}

const

{ files }
                                            {file contents are indp. variable vs. dependant}
   DENSITYRATIOFILE     = 'density.dat';    {ratio of density to sea level density vs. alt}
   SOUNDSPEEDRATIOFILE  = 'soundspd.dat';   {ratio of speed of sound to sea level vs. alt}
   CDASCENTFILE         = 'cd1_b.dat';      {drag coef (mated ascent) vs. Mach}
   CLASCENTFILE         = 'cl1_b.dat';      {lift coef (mated ascent) vs. Mach}
   CDDESCENTFILE        = 'cd2_b.dat';      {drag coef (booster descent) vs. Mach}
   CLDESCENTFILE        = 'cl2_b.dat';      {lift coef (booster descent) vs. Mach}
   SPECTHRUSTFILE       = 'specthr.dat';    {engine specific thrust vs. Mach}
   ALTITUDESUBFILE      = 'alt.dat';        {altitude values vs. thrust file names}

   DATFILE              = 'tsto_g.dat';     {output file of general flight data}
   AEROFILE             = 'aero_g.dat';     {output file of aerodynamic forces}
   PROPFILE             = 'prop_g.dat';     {output file of propulsion data}
   GLOBFILE             = 'glob_g.dat';     {output file of misc. global values}

{ physical constants }

   SLSoundSpeed    = 1116.9;                {ft/s}
   SLrho           = 0.0023769;             {slug/ft^3}
   g               = 32.174;                {lbm-ft/(lbf-s^2)}

{ inputs (characteristic parameters / flight path constants)}

   MassBooster     = 280544;                {lb}
   MassFuel        = 160000;                {lb}
   MassOrbiter     = 388000;                {lb}

   NumEngines      = 8;
   AreaIntake      = 4.75;                  {sq m}

   AreaPlanform    = 10896;                 {sq ft}
   AreaInt         = 11400;                 {sq ft}
   AreaTakeoff     = 17000;                 {sq ft}
```

```
   MachZeroFlaps    = 1.5;               {ND}
   MachHalfFlaps    = 0.6;               {ND}

   VelTakeoff       = 441;               {ft/s}

   ThrottleInitial  = 1.00;              {ND}
   ThrottleIdle     = 0.05;              {ND}

   GammaTakeoff     =  0.18;             {rad}
   GammaDecent      = -0.13;             {rad}

   MachLeveling     = 2.0;               {ND}
   ThrottleLevel    = 0.55;              {ND}
   GammaLevel       = 0.00;              {rad}

   MachResume       = 4.0;               {ND}
   ThrottleResume   = 0.30;              {ND}
   GammaResume      = 0.18;              {rad}

   AltStaging       = 80000;             {ft}
   MachStaging      = 6.5;               {ND}
   ThrottleStaging  = 0.30;              {ND}
   GammaStaging     = 0.00;              {rad}

   Interval         =   0.4;             {s}
   Steps            =  25.0;             {Interval* Steps should equal 10 for printouts}


var

{ global }

   VelocityGlobal          : real;       {ft/s}
   AltitudeGlobal          : real;       {ft}
   ThrottleGlobal          : real;       {ND}
   TotalMassGlobal         : real;       {slug}
   GammaGlobal             : real;       {rad}
   MassFlowRateGlobal      : real;       {slug/s}
   RangeGlobal             : real;       {ft}

   StructuralMass          : real;       {slug}

{ Runge-Kutta variables }

   k11, k12, k13, k14      : real;
   k21, k22, k23, k24      : real;
   k31, k32, k33, k34      : real;
   k41, k42, k43, k44      : real;
```

```
{ final step changes }

  ChangeInVelocityGlobal  : real;
  ChangeInTotalMassGlobal : real;
  ChangeInAltitudeGlobal  : real;
  ChangeInRangeGlobal     : real;

{ flags and counters }

  StopFlag                : integer;
  PrintFlag               : integer;
  LevelFlag               : integer;
  ResumeFlag              : integer;
  AltitudeFlag            : integer;
  StageFlag               : integer;
  Count                   : integer;

{ files }

  DRAGFILE                : string12;
  LIFTFILE                : string12;
  OUTPUTFILE              : text;
  OUTPUTFILE2             : text;
  OUTPUTFILE3             : text;
  OUTPUTFILE4             : text;

{ output function values }

  ThrustOutput            : real;
  AdjThrustOutput         : real;
  SpecThrOutput           : real;
  MachOutput              : real;

{------------------------------------------------------------------------}
function Interpolate(FileName : string12; Value : real) : real;
{this function interpolates a dependant variable from a two column table}

var
   DataFile         : text;                         {DOS name of file}
   Data             : array [1..2, 1..85] of real;  {all the values}
   Row              : integer;                      {additive, becomes largest row number}
   Line             : array [1..85] of string[30];  {text line from file}
   EOFFlag          : integer;                      {end of file flag}
   One, Two         : string[10];                   {broken text line segments}
   CheckVal1        : integer;                      {error flag during conversion}
   CheckVal2        : integer;                      {error flag during conversion}
   Larger           : integer;                      {additive, becomes row number of value larger}
   NumberInQuestion : real;                         {manipulated before becoming Interpolate}
```

```
begin
   Assign(DataFile, FileName);                              {text file setup}
   Reset(DataFile);
   EOFFlag := 0;
   Row := 1;                                                {important intializer}
   while EOFFlag <> 1 do                                    {loop which reads and converts all
data in file}
      begin
         CheckVal1 := 0;
         CheckVal2 := 0;
         Readln(DataFile, Line[Row]);
         One := Copy(Line[Row], 1, 9);
         Two := Copy(Line[Row], 11, 10);
         Val(One, Data[1, Row], CheckVal1);                 {converted here}
         Val(Two, Data[2, Row], CheckVal2);
         if (CheckVal1 <> 0) or (CheckVal2 <> 0) then       {check for errors}
            begin
               Writeln('There has been an error converting some of the', FileName, ' text file');
               EOFFlag := 1;
            end;
         if Data[1, Row] = 10000000 then EOFFlag := 1;
         if Data[1, Row] = 10000000 then Row := Row- 1 else Row := Row + 1;
      end;
   Close(DataFile);
   Larger := 1;                                             {important intializer}
   while Data[1, Larger] < Value do Larger := Larger+ 1;    {loop to find Larger}
   if Larger = 1 then Interpolate := Data[2, 1]             {result of function depends on value
of Larger}
   else
      if Larger = (Row+ 1) then Interpolate := Data[2, Row]
      else
         Interpolate := (Value - Data[1, Larger- 1])*
         (Data[2, Larger]- Data[2, Larger- 1]) /
         (Data[1, Larger]- Data[1, Larger- 1]) + Data[2, Larger- 1];

end;  {function}

{--------------------------------------------------------------------------}
function DoubleInterp(Restric: string12; IndepR, Indep2: real): real;
{this function double interpolates from a system of two column files}

var
   LimitFile           : text;
   EOFFlag             : integer;
   Count               : integer;
   Line                : array [1..25] of string[25];
   CheckVal1           : integer;
   One                 : string[9];
   Two                 : array [1..25] of string12;
```

```
   Data                 : array [1..25] of real;
   Larger               : Integer;
   Bigger, Smaller      : real;

begin
   Assign(LimitFile, Restric);
   Reset(LimitFile);
   EOFFlag := 0;
   Count   := 0;
   while EOFFlag <> 1 do
      begin
         Count := Count+ 1;
         CheckVal1  := 0;
         readln(LimitFile, Line[Count]);
         One        := Copy(Line[Count], 1, 9);
         Two[Count] := Copy(Line[Count], 12, 9);
         Val(One, Data[Count], CheckVal1);
         if CheckVal1 <> 0 then writeln('There has been an error !');
         if Data[Count] = 10000000 then EOFFlag := 1;
      end;
   Count := Count- 1;
   Close(LimitFile);
   Larger := 1;
   while Data[Larger] < IndepR do Larger := Larger+ 1;
   if Larger = 1 then DoubleInterp := Interpolate(Two[1], Indep2)
   else
      if Larger = (Count+ 1) then DoubleInterp := Interpolate(Two[Count], Indep2)
      else
         begin
            Bigger := Interpolate(Two[Larger], Indep2);
            Smaller := Interpolate(Two[Larger- 1], Indep2);
            DoubleInterp := Bigger- (Bigger- Smaller)*
                            (Data[Larger]- IndepR)/
                            (Data[Larger]- Data[Larger- 1]);
         end;
end;

{--------------------------------------------------------------------------}
function fMach(Velocity, Altitude: real): real;
{this function calculates the Mach number from velocity and altitude}

begin
   fMach := Velocity/ (SLSoundSpeed* Interpolate(SOUNDSPEEDRATIOFILE, Altitude));
end;

{--------------------------------------------------------------------------}
function fThrust(Velocity, Altitude, Throttle: real): real;
{this function calculates the total thrust}
```

```
var
  Mach, T : real;

begin
  if TotalMassGlobal > StructuralMass then                        {checks to see if there is fuel}
    begin
      Mach  := fMach(Velocity, Altitude);
      T := exp(DoubleInterp(ALTITUDESUBFILE, Altitude, Mach)* ln(10))*
          AreaIntake* NumEngines* Throttle;                        {tonnes}
      T := T* 1000;                                                {kg}
      T := T* 9.807;                                               {N}
      fThrust := T* 2.2481E-01;                                    {lbf}
    end
    else fThrust := 0;                                             {no fuel, no thrust}
end;

{-------------------------------------------------------------------------}
function fDMDT(Velocity, Altitude, Throttle: real): real;
{this function calculates the change in mass per unit time}

var
  Mach, spthr, Thrust : real;

begin
  Mach   := fMach(Velocity, Altitude);
  spthr  := Interpolate(SPECTHRUSTFILE, Mach);                     {m/s}
  spthr  := spthr* 3.2808;                                         {ft/s}
  Thrust := fThrust(Velocity, Altitude, Throttle);                 {lbf}
  fDMDT  := Thrust/ spthr;                                         {slug/s}
end;

{-------------------------------------------------------------------------}
function fDrag(Velocity, Altitude: real): real;
{this function calculates the drag force from the velocity and altitude}

var
  Cd         : real;          {ND}                  {coefficient of drag for entire
vehicle}
  rho        : real;          {slug/cubic ft}       {density of atmosphere at altitude}
  SApparent  : real;          {sq.ft.}              {arrarent planform area depending on
Mach #}
  Mach       : real;

begin
  Mach := fMach(Velocity, Altitude);
  Cd   := Interpolate(DRAGFILE, Mach);
  rho  := SLrho* Interpolate(DENSITYRATIOFILE, Altitude);
  if Mach > MachZeroFlaps then SApparent := AreaPlanform else SApparent := AreaInt;
  if Mach < MachHalfFlaps then SApparent := AreaTakeoff;
```

```
   fDrag := 0.5* Cd* rho* Velocity* Velocity* SApparent;     {slug-ft/s^2 = lbf}
end;

{---------------------------------------------------------------------------}
function fDVDT(Velocity, Altitude, Throttle, TotalMass, Gamma, MassFlowRate: real): real;
{this function calculates the change in velocity per unit time}

var
   Thrust, Drag, Weight : real;

begin
   Thrust := fThrust(Velocity, Altitude, Throttle);                  {lbf}
   Drag   := fDrag(Velocity, Altitude);                              {lbf}
   Weight := TotalMass* g;                                           {lbf}
   fDVDT  := (Thrust- Drag- Weight* Sin(Gamma)- Velocity* MassFlowRate)/
                TotalMass;
end;

{---------------------------------------------------------------------------}
function fDHDT(Velocity, Gamma: real): real;
{this function calculates the change in hight per unit time}

begin
   fDHDT := Velocity* Sin(Gamma);
end;

{---------------------------------------------------------------------------}
function fDRDT(Velocity, Gamma: real): real;
{this function calculates the change in range per unit time}

begin
   fDRDT := Velocity* Cos(Gamma);
end;

{---------------------------------------------------------------------------}
function fLift(Velocity, Altitude: real): real;
{this function calculates the lift force}

var
   Cl          : real;          {ND}                  {coefficient of lift for entire
vehicle}
   rho         : real;          {slug/cubic ft}       {density of atmosphere at altitude}
   SApparent   : real;          {sq.ft.}              {arrarent planform area depending on
Mach #}
   Mach        : real;

begin
   Mach := fMach(Velocity, Altitude);
   Cl   := Interpolate(LIFTFILE, Mach);
```

```
   rho  := SLrho* Interpolate(DENSITYRATIOFILE, Altitude);
   if Mach > MachZeroFlaps then SApparent := AreaPlanform else SApparent := AreaInt;
   if Mach < MachHalfFlaps then SApparent := AreaTakeoff;

   fLift := 0.5* Cl* rho* Velocity* Velocity* SApparent;     {slug-ft/s^2 = lbf}
end;

(* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *)
begin {Program TSTO}

   ClrScr;                                                  {clear screen}

   DRAGFILE            := CDASCENTFILE;                     {initialize aerodynamic coeff}
   LIFTFILE            := CLASCENTFILE;

   Assign(OUTPUTFILE, DATFILE);                             {assign output files}
   Assign(OUTPUTFILE2, AEROFILE);
   Assign(OUTPUTFILE3, PROPFILE);
   Assign(OUTPUTFILE4, GLOBFILE);
   Rewrite(OUTPUTFILE);                                     {initialize output files}
   Rewrite(OUTPUTFILE2);
   Rewrite(OUTPUTFILE3);
   Rewrite(OUTPUTFILE4);
                                                            {print headers to output files}

   Writeln(OUTPUTFILE, 'Time':10, 'FuelMass':10, 'Accel':10, 'Velocity':10, 'Mach':10,
'Altitude':10, 'Range':10);
   Writeln(OUTPUTFILE, '(s)':10, '(lbs)':10, 'g''s':10, '(ft/s)':10, ' ':10, '(ft)':10, '(ft)':10);
   Writeln(OUTPUTFILE);

   Writeln(OUTPUTFILE2, 'Time':10, 'Altitude':10, 'Velocity':10, 'Mach':10, 'Lift':10, 'Drag':10,
'Thrust':10,
                      'Weight':10);
   Writeln(OUTPUTFILE2, '(s)':10, '(ft)':10, '(ft/s)':10, ' ':10, '(lbf)':10, '(lbf)':10,
'(lbf)':10, '(lbf)':10);
   Writeln(OUTPUTFILE2);

   Writeln(OUTPUTFILE3, 'Time':10, 'Altitude':10, 'Velocity':10, 'Mach':10, 'Thr/Eng':10,
'Thrust':10, 'SpecThr':10,
                      'FlowRate':10);
   Writeln(OUTPUTFILE3, '(s)':10, '(ft)':10, '(ft/s)':10, ' ':10, '(ton/m^2)':10, '(ton)':10,
'(m/s)':10, '(kg/s)':10);
   Writeln(OUTPUTFILE3);

   Writeln(OUTPUTFILE4, 'Time':10, 'Gamma':10, 'Throttle':10, 'TotalMass':10);
   Writeln(OUTPUTFILE4, '(s)':10, '(deg)':10, ' ':10, '(lbs)':10);
   Writeln(OUTPUTFILE4);

   StructuralMass       := (MassBooster+ MassOrbiter)/ g;          {define characteristic}
```

```
VelocityGlobal          := VelTakeoff;                              {initialize global variables}
AltitudeGlobal          := 0;
RangeGlobal             := 0;
ThrottleGlobal          := ThrottleInitial;
TotalMassGlobal         := (MassBooster+ MassFuel+ MassOrbiter)/ g;
GammaGlobal             := GammaTakeoff;
MassFlowrateGlobal      := fDMDT(VelocityGlobal, AltitudeGlobal, ThrottleGlobal);
ChangeInVelocityGlobal := 0;

                                                                    {initialize flags and counters}
StopFlag     := 0;
PrintFlag    := 0;
LevelFlag    := 0;
ResumeFlag   := 0;
AltitudeFlag := 0;
StageFlag    := 0;
Count        := 0;

{print initial conditions to output files}

     MachOutput      := fMach(VelocityGlobal, AltitudeGlobal);
     ThrustOutput    := exp(DoubleInterp(ALTITUDESUBFILE, AltitudeGlobal, MachOutput)* ln(10));
     AdjThrustOutput := ThrustOutput* AreaIntake* NumEngines* ThrottleGlobal;
     SpecThrOutput   := Interpolate(SPECTHRUSTFILE, MachOutput);

     Writeln(' .... ', Count* Interval:5:1);
     Writeln(OUTPUTFILE, Interval* Count:10:1,
                         ((TotalMassGlobal- StructuralMass)* g):10:0,
                         ChangeInVelocityGlobal/ Interval/ g:10:3,
                         VelocityGlobal:10:0,
                         MachOutput:10:1,
                         AltitudeGlobal:10:0,
                         RangeGlobal:10:0);
     Writeln(OUTPUTFILE2, Interval* Count:10:1,
                          AltitudeGlobal:10:1,
                          VelocityGlobal:10:1,
                          MachOutput:10:1,
                          fLift(VelocityGlobal, AltitudeGlobal):10:0,
                          fDrag(VelocityGlobal, AltitudeGlobal):10:0,
                          AdjThrustOutput* 2205.3861:10:0,
                          TotalMassGlobal* g:10:0);
     Writeln(OUTPUTFILE3, Interval* Count:10:1,
                          AltitudeGlobal:10:1,
                          VelocityGlobal:10:1,
                          MachOutput:10:1,
                          ThrustOutput:10:1,
                          AdjThrustOutput:10:1,
                          SpecThrOutput:10:1,
                          AdjThrustOutput* 1000* 9.807/ SpecThrOutput:10:1);
     Writeln(OUTPUTFILE4, Interval* Count:10:1,
```

```
                                    GammaGlobal* 180/ 3.14159:10:2,
                                    ThrottleGlobal:10:2,
                                    TotalMassGlobal* g:10:0);


while StopFlag = 0 do                                        {the main loop, can only be stopped
by flag}
   begin

     Count := Count+ 1;                                      {advance the counter}

     k11 := Interval* fDVDT(VelocityGlobal, AltitudeGlobal,     {calculate the Runge-Kutta
variables}
            ThrottleGlobal, TotalMassGlobal, GammaGlobal,
            MassFlowRateGlobal);
     k21 := Interval* fDMDT(VelocityGlobal, AltitudeGlobal,
            ThrottleGlobal);
     k31 := Interval* fDHDT(VelocityGlobal, GammaGlobal);
     k41 := Interval* fDRDT(VelocityGlobal, GammaGlobal);

     k12 := Interval* fDVDT(VelocityGlobal+ k11/ 2, AltitudeGlobal+ k31/ 2,
            ThrottleGlobal, TotalMassGlobal- k21/ 2, GammaGlobal,
            k21/ Interval);
     k22 := Interval* fDMDT(VelocityGlobal+ k11/ 2, AltitudeGlobal+ k31/ 2,
            ThrottleGlobal);
     k32 := Interval* fDHDT(VelocityGlobal+ k11/ 2, GammaGlobal);
     k42 := Interval* fDRDT(VelocityGlobal+ k11/ 2, GammaGlobal);

     k13 := Interval* fDVDT(VelocityGlobal+ k12/ 2, AltitudeGlobal+ k32/ 2,
            ThrottleGlobal, TotalMassGlobal- k22/ 2, GammaGlobal,
            k22/ Interval);
     k23 := Interval* fDMDT(VelocityGlobal+ k12/ 2, AltitudeGlobal+ k32/ 2,
            ThrottleGlobal);
     k33 := Interval* fDHDT(VelocityGlobal+ k12/ 2, GammaGlobal);
     k43 := Interval* fDRDT(VelocityGlobal+ k12/ 2, GammaGlobal);

     k14 := Interval* fDVDT(VelocityGlobal+ k13, AltitudeGlobal+ k33,
            ThrottleGlobal, TotalMassGlobal- k32, GammaGlobal,
            (k21+ 2* k22+ 2* k23)/ Interval/ 5);
     k24 := Interval* fDMDT(VelocityGlobal+ k13, Altitudeglobal+ k33,
            ThrottleGlobal);
     k34 := Interval* fDHDT(VelocityGlobal+ k13, GammaGlobal);
     k44 := Interval* fDRDT(VelocityGlobal+ k13, GammaGlobal);

     ChangeInVelocityGlobal  := (k11+ 2* k12+ 2* k13+ k14)/ 6;      {calculate the changes to the
global variables}
     ChangeInTotalMassGlobal := (k21+ 2* k22+ 2* k23+ k24)/ 6;
     ChangeInAltitudeGlobal  := (k31+ 2* k32+ 2* k33+ k34)/ 6;
     ChangeInRangeGlobal     := (k41+ 2* k42+ 2* k43+ k44)/ 6;
```

```
        VelocityGlobal  := VelocityGlobal+ ChangeInVelocityGlobal;      {adjust the global variables}
        TotalMassGlobal := TotalMassGlobal- ChangeInTotalMassGlobal;
        AltitudeGlobal  := AltitudeGlobal+ ChangeInAltitudeGlobal;
        RangeGlobal     := RangeGlobal+ ChangeInRangeGlobal;
        MassFlowrateGlobal := ChangeInTotalMassGlobal/ Interval;

    { examine the current flight conditions and adjust the parameters }

        if (ChangeInVelocityGlobal <= 0) and (StageFlag = 0) then      {premature slowing message}
          begin
            StopFlag := 1;
            Writeln;
            Writeln('Premature Slowing ... Aborting Mission ....');
            Writeln;
          end;

        if TotalMassGlobal <= StructuralMass then                      {fuel exhausted message}
          begin
            StopFlag := 1;
            Writeln;
            Writeln('Fuel Exhausted ... Aborting Mission ....');
            Writeln;
          end;

        if AltitudeGlobal <= 0 then                                    {landing message}
          begin
            StopFlag := 1;
            PrintFlag := 1;
            Writeln;
            Writeln('Landing ....');
            Writeln;
          end;

        if LevelFlag = 0 then                                          {level out and switch engine
    mode message}
          begin
            if (fMach(VelocityGlobal, AltitudeGlobal) >= MachLeveling) and
              (fMach(VelocityGlobal, AltitudeGlobal) <  MachResume) then
              begin
                Writeln;
                Writeln('Leveling Out ....');
                Writeln;
                PrintFlag      := 1;
                LevelFlag      := 1;
                ResumeFlag     := 1;
                ThrottleGlobal := ThrottleLevel;
                GammaGlobal    := GammaLevel;
              end;
          end;
```

```
if ResumeFlag = 1 then                                          {resume accent message}
   begin
      if (LevelFlag = 1) and
         (fMach(VelocityGlobal, AltitudeGlobal) >= MachResume) then
         begin
            Writeln;
            Writeln('Resuming Accent ....');
            Writeln;
            PrintFlag      := 1;
            ResumeFlag     := 0;
            ThrottleGlobal := ThrottleResume;
            GammaGlobal    := GammaResume;
         end;
   end;

if (AltitudeFlag = 0) and (AltitudeGlobal >= AltStaging) then   {level out for staging
message}
   begin
      Writeln;
      Writeln('Leveling Out at Staging Altitude ....');
      Writeln;
      PrintFlag      := 1;
      AltitudeFlag   := 1;
      ThrottleGlobal := ThrottleStaging;
      GammaGlobal    := GammaStaging;
   end;

if StageFlag = 0 then                                           {stage and begin decent
message}
   begin
      if (AltitudeFlag = 1) and
         (fMach(VelocityGlobal, AltitudeGlobal) >= MachStaging) then
         begin
            Writeln;
            Writeln('Staging ....');
            Writeln;
            PrintFlag      := 1;
            StageFlag      := 1;                          {make sure program can not come
back!}
            TotalMassGlobal := TotalMassGlobal- MassOrbiter/ g;
            StructuralMass  := MassBooster/ g;
            GammaGlobal     := GammaDecent;
            ThrottleGlobal  := ThrottleIdle;
            DRAGFILE        := CDDESCENTFILE;
            LIFTFILE        := CLDESCENTFILE;
         end;
   end;

if (Frac(Count/ Steps)= 0) or (PrintFlag = 1) then              {print to output files}
```

```
        begin

        MachOutput      := fMach(VelocityGlobal, AltitudeGlobal);
        ThrustOutput    := exp(DoubleInterp(ALTITUDESUBFILE, AltitudeGlobal, MachOutput)* ln(10));
        AdjThrustOutput := ThrustOutput* AreaIntake* NumEngines* ThrottleGlobal;
        SpecThrOutput   := Interpolate(SPECTHRUSTFILE, MachOutput);

        Writeln(' .... ', Count* Interval:5:1);
        Writeln(OUTPUTFILE, Interval* Count:10:1,
                            ((TotalMassGlobal- StructuralMass)* g):10:0,
                            ChangeInVelocityGlobal/ Interval/ g:10:3,
                            VelocityGlobal:10:0,
                            MachOutput:10:1,
                            AltitudeGlobal:10:0,
                            RangeGlobal:10:0);
        Writeln(OUTPUTFILE2, Interval* Count:10:1,
                             AltitudeGlobal:10:1,
                             VelocityGlobal:10:1,
                             MachOutput:10:1,
                             fLift(VelocityGlobal, AltitudeGlobal):10:0,
                             fDrag(VelocityGlobal, AltitudeGlobal):10:0,
                             AdjThrustOutput* 2205.3861:10:0,
                             TotalMassGlobal* g:10:0);
        Writeln(OUTPUTFILE3, Interval* Count:10:1,
                             AltitudeGlobal:10:1,
                             VelocityGlobal:10:1,
                             MachOutput:10:1,
                             ThrustOutput:10:1,
                             AdjThrustOutput:10:1,
                             SpecThrOutput:10:1,
                             AdjThrustOutput* 1000* 9.807/ SpecThrOutput:10:1);
        Writeln(OUTPUTFILE4, Interval* Count:10:1,
                             GammaGlobal* 180/ 3.14159:10:2,
                             ThrottleGlobal:10:2,
                             TotalMassGlobal* g:10:0);
        PrintFlag := 0;
        end; {output if}

    end;                                                    {end while loop}

  Close(OUTPUTFILE);                                        {close all open files}
  Close(OUTPUTFILE2);
  Close(OUTPUTFILE3);
  Close(OUTPUTFILE4);

  end. {TSTO program}
```

## ALGORITHM FOR ORB2.PAS

Initialize

    Assign and initialize output file

    Initialize flight variables

    Initialize global variables

    Initialize flags and counters

Print

    Print flight parameters to output file

    Print initial global variables to output file

Main iterative loop

    Calculate new masses

    Calculate Mach number

        Call Mach function

            Calculate Mach number

    Calculate drag coefficient

    Calculate drag force

    If second leg conditions are right then

        Adjust global variables

    Calculate gravitational acceleration

    Calculate change in velocity from governing equation

    Calculate change in altitude

    Calculate change in down range distance

    Adjust all global variables

```
        If output conditions are right then
             Write global variables to output file
        If fuel is exhausted then
             Trip stop flag
        If overall change in velocity is obtained then
             Trip stop flag
        Advance loop counter
   Repeat main iterative loop until stop flag is tripped


   Final output
        Write final global variable values to output file
        Write percent fuel reserve to output file
```

## LIST OF SUPPORTING FILES FOR ORB2.PAS AND DESCRIPTIONS

| | |
|---|---|
| density.dat | This file contains altitude [ft] vs. the ratio of atmospheric density to sea level density. These values were extracted from a textbook. |
| orbiter2.dat | This file is the program's only output file. It contains the important variables as well as the major flight parameters. |
| soundspd.dat | This file contains altitude [ft] vs. the ratio of the speed of sound to sea level speed of sound. These values were extracted from a textbook. |

## LIST OF FUNCTIONS OR ORB2.PAS AND DESCRIPTIONS

| | |
|---|---|
| fMach | This function calculates the Mach number given any velocity and altitude. It uses the altitude in order to get the speed of sound, then simply calculates the Mach number from its definition. |
| Interpolate | This function is essential to the input of data. First it reads an ASCII file made of two columns of data (arranged in a special format). When it has deciphered all of the values and has a true numerical representation of the table of data, it uses a given value of the first column and interpolates the data in the second column to match it. If a value falls out of range, it returns a value as close as it can get. |

## LIST OF CONSTANTS FOR ORB2.PAS AND DESCRIPTIONS

| | |
|---|---|
| C | This constant is the specific impulse of an engine. Units are pound seconds per slug. |
| CharArea | This constant is the characteristic area used for drag force calculations. Units are square feet. |
| DeltaVNeeded | This constant is the change in velocity which the orbiter must obtain in order to reach its intended orbit. Units are feet per second. |
| DestAltitude | This constant is the destination orbital altitude. It will be attained by a Hohmann transfer once the required velocity is attained. Units are feet. |
| FuelMass | This constant is the mass of fuel which the orbiter has at staging. Units are pounds. |
| g | This constant doubles as the acceleration due to gravity at the Earth's surface and as the conversion factor in the English set of units. |

| | |
|---|---|
| Interval | This constant is the time interval between each step of calculation. All global variables are calculated for the beginning and end of each interval. Units are seconds. |
| Mdot | This constant is the full throttle mass flow rate to an engine. Units are slug per second. |
| SLrho | This constant is the sea level density of the atmosphere. Units are slug per cubic meter. |
| SLSoundSpeed | This constant is the sea level speed of sound in the atmosphere. Units are feet per second. |
| StagingAltitude | This constant is the altitude of the orbiter at staging. Units are feet. |
| StagingMass | This constant is the mass of the orbiter at staging. Units are pounds. |
| StagingVelocity | This constant is the velocity of the orbiter at staging. Units are feet per |

second.

| | |
|---|---|
| Steps | This constant is the number of loop passes between each output time. This number times the interval will give the mission time between each output time. |
| Theta1 | This constant is the flight path angle for the first leg of the orbiter's journey. This value is measured from the vertical. Units are radian. |
| Theta2 | This constant is the flight path angle for the second leg of the orbiter's journey. This value is measured from the vertical. Units are radian. |

## LIST OF VARIABLES FOR ORB2.PAS AND DESCRIPTIONS

| | |
|---|---|
| AltitudeGlobal | This variable is the altitude of the vehicle at any time. Units are feet. |
| BigDeltaV | This variable is the total change in velocity since takeoff. Units are feet per second. |
| Cd | This variable is the coefficient of drag for each interval. |
| DeltaAltitude | This variable is the change in altitude for each interval. Units are feet. |
| DeltaRange | This variable is the change in down range distance for each interval. Units are feet. |
| Drag | This variable is the drag force on the orbiter at each pass of the loop. Units are pounds. |
| Gravitational-Acc | This variable is the acceleration due to gravity at each pass of the loop. This value diminishes with altitude. Units are |

feet per second squared.

| | |
|---|---|
| LittleDeltaV | This variable is the change in velocity for each interval. Units are feet per second. |
| LoopCount | This variable is the counter for the number of loop passes. |
| MachNumber | This variable is the Mach number at each pass of the loop. It is calculated from the fMach function. |
| MassFinal | This variable is the total mass of the orbiter at the end of each pass of the loop. Units are slugs. |
| MassGlobal | This variable is the total mass of the orbiter at any time. Units are slugs. |
| MassInitial | This variable is the total mass of the orbiter at the beginning of each pass of the loop. Units are slugs. |
| Panasonic | This variable is the file which will contain the output data. |

| | |
|---|---|
| RangeGlobal | This variable is the down range distance that the vehicle has traveled at any time. Units are feet. |
| StopFlag | This variable is an on/off flag which finally stops the looping procedure. A completed or aborted mission is the only trip for this flag. |
| StructuralMass | This variable is the mass of the orbiter's structures and does not include any fuel. Units are slugs. |
| Theta | This variable is the flight path angle of the orbiter and is dependant on the leg of the journey. Units are radian. |
| Throttle | This variable is the throttle setting for all engines at any time. It only controls the engine thrust though. |
| Throttle2 | This variable is the throttle setting for all engines at any time. It only controls the mass flow rate though. |
| VelocityGlobal | This variable is the velocity in the |

direction of travel at any time. Units are feet per second.

# Program Listing of ORB2.PAS

```
Program ORB2(Input, Output);

{written by Glenn A Snow with help from Kevin Horsely for TSTO-MQP-WPI}

uses Crt;

type
   string12 = string[12];

const

{ Physical Constants }

   g = 32.174;                   {lbm-ft/(lbf-s^2)}
   SLSoundSpeed = 1116.9;        {ft/s}
   SLrho = 0.002;                {slugs/cubic ft}

{ Vehicle Constants }

   Mdot = 43.90;                 {slug/s}
   C = 642000;                   {lbf-s/slugs}
   CharArea =  850;              {sq.ft}

{ Performance Restraints }

   StagingVelocity =  6397;      {ft/s}
   DeltaVNeeded    = 19854;      {ft/s}
   StagingAltitude =   80000;    {ft}
   DestAltitude    = 1336720;    {ft}
   StagingMass = 388000;         {lbs}
   FuelMass    = 296000;         {lbs}

{ Flight Path Constants }

   Theta1 = 0.087;               {rad}
   Theta2 = 1.536;               {rad}

{ Loop Constants }

   Interval = 0.01;              {s}
   Steps    = 500;

var

{ Output }

   Panasonic          : text;

{ Global }

   VelocityGlobal     : real;    {ft/s}
   AltitudeGlobal     : real;    {ft}
   RangeGlobal        : real;    {ft}
   MassGlobal         : real;    {slugs}
   BigDeltaV          : real;    {ft/s}

{ Loop Variables }

   StopFlag           : integer;
   LoopCount          : integer;
   MassInitial        : real;    {slugs}
   MassFinal          : real;    {slugs}
   MachNumber         : real;
   Drag               : real;    {lbf}
   GravitationalAcc   : real;    {ft/s^2}
```

```
{ Changes }

   LittleDeltaV       : real;   {ft/s}
   DeltaAltitude      : real;   {ft}
   DeltaRange         : real;   {ft}

{ Parameters }

   Cd                 : real;   {ND}
   Theta              : real;   {rad}
   Throttle           : real;   {ND}
   Throttle2          : real;   {ND}
   StructuralMass     : real;   {slugs}

{----------------------------------------------------------------------}
function Interpolate(FileName : string12; Value : real) : real;

var
   DataFile         : text;
   Data             : array [1..2, 1..85] of real;
   Row              : integer;
   Line             : array [1..85] of string[30];
   EOFFlag          : integer;
   One, Two         : string[10];
   CheckVal1        : integer;
   CheckVal2        : integer;
   Larger           : integer;
   NumberInQuestion : real;

begin
   Assign(DataFile, FileName);
   Reset(DataFile);
   EOFFlag := 0;
   Row := 1;
   while EOFFlag <> 1 do
      begin
         CheckVal1 := 0;
         CheckVal2 := 0;
         Readln(DataFile, Line[Row]);
         One := Copy(Line[Row], 1, 9);
         Two := Copy(Line[Row], 11, 10);
         Val(One, Data[1, Row], CheckVal1);
         Val(Two, Data[2, Row], CheckVal2);
         if (CheckVal1 <> 0) or (CheckVal2 <> 0) then
            begin
               Writeln('There has been an error converting some of the text file to numbers.');
               EOFFlag := 1;
            end;
         if Data[1, Row] = 10000000 then EOFFlag := 1;
         if Data[1, Row] = 10000000 then Row := Row- 1 else Row := Row + 1;
      end;
   Close(DataFile);
   Larger := 1;
   while Data[1, Larger] < Value do Larger := Larger+ 1;
   if Larger = 1 then Interpolate := Data[2, 1]
   else
      if Larger = (Row+ 1) then Interpolate := Data[2, Row]
      else
         Interpolate := (Value - Data[1, Larger- 1])*
         (Data[2, Larger]- Data[2, Larger- 1]) /
         (Data[1, Larger]- Data[1, Larger- 1]) + Data[2, Larger- 1];

end;

{----------------------------------------------------------------------}
function fMach(Velocity, Altitude: real): real;
{this function calculates the Mach number from its definition}

begin
   fMach := Velocity/ (SLSoundSpeed* Interpolate('soundspd.dat', Altitude));
end;

{----------------------------------------------------------------------}
```

```
begin

   ClrScr;
   Assign(Panasonic, 'orbiter2.dat');                          {initialize output file}
   Rewrite(Panasonic);

   BigDeltaV      := 0;                                        {initialize flight variables}
   Cd             := 0.02;
   Theta          := Theta1;
   Throttle       := 1.09;
   Throttle2      := 1.00;
   StructuralMass := (StagingMass- FuelMass)/ g;

   LittleDeltaV   := 0;
   VelocityGlobal := StagingVelocity;                          {initialize global variables}
   MassGlobal     := StagingMass/ g;
   AltitudeGlobal := StagingAltitude;
   RangeGlobal    := 0;

   Writeln(Panasonic, 'Mdot':10, Mdot:10:2, ' slug/s');        {print flight parameters to
output file}
   Writeln(Panasonic, 'T':10, C:10, ' lbf');
   Writeln(Panasonic, 'Area':10, CharArea:10, ' sq ft');
   Writeln(Panasonic, 'Stage Mass':10, StagingMass:10, ' lbs');
   Writeln(Panasonic, 'Fuel Mass':10, FuelMass:10, ' lbs');
   Writeln(Panasonic, 'Theta1':10, Theta1:10:4, ' rad', Theta1* 180/ 3.14159:10:2, ' deg');
   Writeln(Panasonic, 'Theta2':10, Theta2:10:4, ' rad', Theta2* 180/ 3.14159:10:2, ' deg');
   Writeln(Panasonic, 'Interval':10, Interval:10:2, ' sec');
   Writeln(Panasonic);
   Writeln(Panasonic, 'Time':10,
                      'FuelMass':10,
                      'Velocity':10,
                      'Mach #':10,
                      'Altitude':10,
                      'Range':10,
                      'Delta V':10,
                      'Acc':10);
   Writeln(Panasonic, '(s)':10,
                      '(slugs)':10,
                      '(ft/s)':10,
                      '  ':10,
                      '(ft)':10,
                      '(ft)':10,
                      '(ft/s)':10,
                      '(g''s)':10);
   Writeln(Panasonic);
   Writeln(Panasonic, '0.0':10,
                      (MassGlobal- StructuralMass):10:1,
                      VelocityGlobal:10:0,
                      fMach(VelocityGlobal, AltitudeGlobal):10:1,
                      AltitudeGlobal:10:0,
                      RangeGlobal:10:0,
                      BigDeltaV:10:0,
                      ' ':10);

   StopFlag  := 0;                                             {initialize loop variables}
   LoopCount := 1;

   while StopFlag = 0 do                                       {major interval loop}
      begin

         MassInitial := MassGlobal;                            {calculate new masses}
         MassFinal   := MassGlobal - Mdot* Throttle2* Interval;

         MachNumber := fMach(VelocityGlobal, AltitudeGlobal);

         if MachNumber > 20  then Cd := 0.0000 else            {calculate drag coefficient}
         if MachNumber > 16  then Cd := 0.0075 else
         if MachNumber > 12  then Cd := 0.0125 else
         if MachNumber > 6.5 then Cd := 0.0200;

         Drag := 0.5* SLrho* Interpolate('density.dat', AltitudeGlobal)* Sqr(VelocityGlobal)*
CharArea* Cd;
```

```
          if AltitudeGlobal > 300000 then                          {reset throttle values for
second leg}
             begin
                Theta     := Theta2;
                Throttle  := 0.76;
                Throttle2 := 0.55;
             end;

          GravitationalAcc := 1.040764E16/ Sqr(2.09256E7+ AltitudeGlobal);

          LittleDeltaV := C* Throttle* Interval/ MassInitial-       {governing equation}
                          Drag* Interval/ MassInitial-
                          GravitationalAcc* cos(Theta)* Interval;

          DeltaAltitude := VelocityGlobal* Interval* cos(Theta);    {calculate changes}

          DeltaRange := VelocityGlobal* Interval* sin(Theta);

          BigDeltaV      := BigDeltaV+ LittleDeltaV;                {adjust global variables}
          VelocityGlobal := VelocityGlobal+ LittleDeltaV;
          AltitudeGlobal := AltitudeGlobal+ DeltaAltitude;
          RangeGlobal    := RangeGlobal+ DeltaRange;
          MassGlobal     := MassFinal;

          if Frac(LoopCount/ Steps) = 0 then                        {output procedure}
             Writeln(Panasonic, LoopCount* Interval:10:1,
                                MassGlobal- StructuralMass:10:1,
                                VelocityGlobal:10:0,
                                MachNumber:10:1,
                                AltitudeGlobal:10:0,
                                RangeGlobal:10:0,
                                BigDeltaV:10:0,
                                (LittleDeltaV/ Interval/ g):10:1);

          if MassGlobal <= StructuralMass then                      {fuel exhausted contingency}
             begin
                StopFlag := 1;
                Writeln(Panasonic);
                Writeln(Panasonic, 'Fuel Exhausted !');
             end;

          if BigDeltaV >= DeltaVNeeded then                         {mission accomplished
contingency}
             begin
                StopFlag := 1;
             end;

          LoopCount := LoopCount+ 1;                                {advance counter}

       end;                                                         {end of major interval loop}

    Writeln(Panasonic, (LoopCount)* Interval:10:1,                  {final output sequence}
                       (MassGlobal- StructuralMass):10:1,
                       VelocityGlobal:10:0,
                       MachNumber:10:1,
                       AltitudeGlobal:10:0,
                       RangeGlobal:10:0,
                       BigDeltaV:10:0,
                       (LittleDeltaV/ Interval/ g):10:1);

     Writeln(Panasonic);
     Writeln(Panasonic, 'Percent fuel reserve: ', (MassGlobal- StructuralMass)* g* 100/
FuelMass:4:1);

    Close(Panasonic);

end.
```

CONTENTS OF **aero_g.dat:**

| Time (s) | Altitude (ft) | Velocity (ft/s) | Mach | Lift (lbf) | Drag (lbf) | Thrust (lbf) | Weight (lbf) |
|---|---|---|---|---|---|---|---|
| 0.0 | 0.0 | 441.0 | 0.4 | 835709 | 77624 | 879971 | 828544 |
| 10.0 | 1004.1 | 682.1 | 0.7 | 1339359 | 166292 | 999149 | 826280 |
| 20.0 | 2456.3 | 935.7 | 0.9 | 2530737 | 415572 | 1188939 | 823402 |
| 30.0 | 4336.0 | 1155.5 | 1.1 | 4085106 | 729849 | 1383219 | 819789 |
| 40.0 | 6564.0 | 1327.1 | 1.2 | 5767962 | 960792 | 1514276 | 815758 |
| 50.0 | 9068.6 | 1466.5 | 1.4 | 7380515 | 1147116 | 1635179 | 811355 |
| 60.0 | 11803.4 | 1590.7 | 1.5 | 7890266 | 1201538 | 1711801 | 806719 |
| 70.0 | 14804.6 | 1774.1 | 1.7 | 7907783 | 1181044 | 1904308 | 801793 |
| 80.0 | 18225.4 | 2081.3 | 2.0 | 4846465 | 1217495 | 2453422 | 796125 |
| 80.4 | 18375.1 | 2098.6 | 2.0 | 4514109 | 1221314 | 1368992 | 795871 |
| 90.0 | 18375.1 | 2154.6 | 2.1 | 3602404 | 1264346 | 1456608 | 792410 |
| 100.0 | 18375.1 | 2236.1 | 2.1 | 2068459 | 1325719 | 1594221 | 788560 |
| 110.0 | 18375.1 | 2360.9 | 2.3 | 773320 | 1398979 | 1830637 | 784317 |
| 120.0 | 18375.1 | 2601.2 | 2.5 | 795755 | 1494374 | 2388825 | 779278 |
| 130.0 | 18375.1 | 3260.6 | 3.1 | 799724 | 1705086 | 4372940 | 771564 |
| 138.4 | 18375.1 | 4179.6 | 4.0 | 5690569 | 2246136 | 2647640 | 761817 |
| 140.0 | 19574.3 | 4194.8 | 4.0 | 6641858 | 2227417 | 2732307 | 760657 |
| 150.0 | 27272.7 | 4461.4 | 4.4 | 8550551 | 1976236 | 3344172 | 751649 |
| 160.0 | 35808.6 | 5115.0 | 5.3 | 6967808 | 1560852 | 3354561 | 739056 |
| 170.0 | 45415.6 | 5555.5 | 5.7 | 4771546 | 1087829 | 1970433 | 728671 |
| 180.0 | 55542.5 | 5737.2 | 5.9 | 2692865 | 669784 | 1197104 | 722036 |
| 190.0 | 65918.1 | 5845.6 | 6.0 | 1503232 | 398755 | 782547 | 717581 |
| 200.0 | 76437.3 | 5895.1 | 6.1 | 891930 | 237663 | 449953 | 714730 |
| 203.6 | 80238.4 | 5899.4 | 6.1 | 743540 | 198176 | 368399 | 714025 |
| 210.0 | 80238.4 | 5939.4 | 6.1 | 730476 | 195452 | 368399 | 712882 |
| 220.0 | 80238.4 | 6003.2 | 6.2 | 708502 | 190846 | 368399 | 711046 |
| 230.0 | 80238.4 | 6066.9 | 6.3 | 707272 | 193483 | 368399 | 709146 |
| 240.0 | 80238.4 | 6128.7 | 6.3 | 706613 | 196378 | 368399 | 707171 |
| 250.0 | 80238.4 | 6188.4 | 6.4 | 705532 | 199175 | 368399 | 705114 |
| 260.0 | 80238.4 | 6246.1 | 6.4 | 711490 | 201962 | 368399 | 702971 |
| 269.2 | 80238.4 | 6297.4 | 6.5 | 1874848 | 241871 | 61400 | 312921 |
| 270.0 | 79585.9 | 6285.0 | 6.5 | 1926409 | 247226 | 63544 | 312890 |
| 280.0 | 71547.0 | 6110.7 | 6.3 | 2062947 | 318646 | 96995 | 312436 |
| 290.0 | 63760.8 | 5895.2 | 6.1 | 1241618 | 401808 | 142583 | 311829 |
| 300.0 | 56285.3 | 5624.8 | 5.8 | 1135508 | 527328 | 196895 | 311071 |
| 310.0 | 49215.3 | 5270.0 | 5.4 | 1527375 | 685688 | 285624 | 310104 |
| 320.0 | 42645.9 | 4858.9 | 5.0 | 1898499 | 849579 | 417988 | 308814 |
| 330.0 | 36633.5 | 4409.3 | 4.6 | 2384180 | 1013622 | 545102 | 307146 |
| 340.0 | 31235.6 | 3910.6 | 4.0 | 2704272 | 1161739 | 618463 | 305308 |
| 350.0 | 26612.4 | 3167.5 | 3.1 | 2501022 | 1166486 | 322145 | 304161 |
| 360.0 | 23088.6 | 2246.3 | 2.2 | 2078394 | 1066826 | 127637 | 303635 |
| 370.0 | 20752.9 | 1399.4 | 1.4 | 1561196 | 771222 | 49339 | 303418 |
| 380.0 | 19328.3 | 881.4 | 0.8 | 1898195 | 322594 | 28573 | 303319 |
| 390.0 | 18316.4 | 701.1 | 0.7 | 1102796 | 186149 | 26327 | 303247 |
| 400.0 | 17481.5 | 581.7 | 0.6 | 1103493 | 190278 | 26185 | 303180 |
| 410.0 | 16797.3 | 484.2 | 0.5 | 759634 | 132814 | 27533 | 303114 |
| 420.0 | 16207.3 | 431.0 | 0.4 | 603733 | 106396 | 29475 | 303044 |
| 430.0 | 15670.7 | 399.5 | 0.4 | 521381 | 92059 | 29868 | 302972 |
| 440.0 | 15166.4 | 380.0 | 0.4 | 475446 | 83982 | 30243 | 302899 |
| 450.0 | 14682.6 | 367.4 | 0.3 | 449050 | 79340 | 30607 | 302826 |
| 460.0 | 14212.1 | 359.0 | 0.3 | 433663 | 76636 | 30965 | 302752 |
| 470.0 | 13750.8 | 353.2 | 0.3 | 424860 | 75090 | 31320 | 302678 |
| 480.0 | 13295.8 | 348.9 | 0.3 | 420041 | 74245 | 31674 | 302603 |
| 490.0 | 12845.6 | 345.7 | 0.3 | 417685 | 73834 | 32029 | 302526 |
| 500.0 | 12399.2 | 343.2 | 0.3 | 416897 | 73700 | 32384 | 302449 |
| 510.0 | 11955.7 | 341.0 | 0.3 | 417050 | 73731 | 32741 | 302372 |
| 520.0 | 11514.9 | 339.1 | 0.3 | 417895 | 73884 | 33100 | 302293 |
| 530.0 | 11076.4 | 337.4 | 0.3 | 419070 | 74095 | 33460 | 302214 |
| 540.0 | 10640.0 | 335.8 | 0.3 | 420547 | 74359 | 33823 | 302133 |
| 550.0 | 10205.6 | 334.3 | 0.3 | 422145 | 74645 | 34188 | 302052 |
| 560.0 | 9773.1 | 332.9 | 0.3 | 423940 | 74965 | 34556 | 301970 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 570.0 | 9342.5 | 331.5 | 0.3 | 425823 | 75300 | 34926 | 301888 |
| 580.0 | 8913.7 | 330.1 | 0.3 | 427650 | 75625 | 35298 | 301804 |
| 590.0 | 8486.7 | 328.7 | 0.3 | 429391 | 75937 | 35672 | 301719 |
| 600.0 | 8061.4 | 327.4 | 0.3 | 431175 | 76256 | 36049 | 301634 |
| 610.0 | 7637.8 | 326.2 | 0.3 | 433179 | 76614 | 36429 | 301548 |
| 620.0 | 7215.8 | 324.9 | 0.3 | 435157 | 76966 | 36811 | 301461 |
| 630.0 | 6795.4 | 323.7 | 0.3 | 437162 | 77324 | 37195 | 301373 |
| 640.0 | 6376.5 | 322.5 | 0.3 | 439178 | 77683 | 37582 | 301284 |
| 650.0 | 5959.3 | 321.3 | 0.3 | 441173 | 78038 | 37972 | 301194 |
| 660.0 | 5543.6 | 320.1 | 0.3 | 443239 | 78407 | 38364 | 301103 |
| 670.0 | 5129.4 | 318.9 | 0.3 | 445265 | 78768 | 38759 | 301012 |
| 680.0 | 4716.7 | 317.8 | 0.3 | 447634 | 79186 | 39156 | 300919 |
| 690.0 | 4305.6 | 316.6 | 0.3 | 449978 | 79599 | 39556 | 300826 |
| 700.0 | 3896.0 | 315.3 | 0.3 | 452284 | 80005 | 39959 | 300731 |
| 710.0 | 3488.0 | 314.1 | 0.3 | 454690 | 80427 | 40364 | 300636 |
| 720.0 | 3081.7 | 312.8 | 0.3 | 456958 | 80824 | 40771 | 300539 |
| 730.0 | 2677.0 | 311.6 | 0.3 | 457826 | 80989 | 41181 | 300442 |
| 740.0 | 2273.6 | 310.7 | 0.3 | 459016 | 81213 | 41594 | 300344 |
| 750.0 | 1871.3 | 309.9 | 0.3 | 461494 | 81657 | 42010 | 300244 |
| 760.0 | 1470.2 | 308.9 | 0.3 | 465226 | 82306 | 42428 | 300144 |
| 770.0 | 1070.5 | 307.7 | 0.3 | 468318 | 82842 | 42850 | 300043 |
| 780.0 | 672.4 | 306.5 | 0.3 | 468990 | 82972 | 43273 | 299941 |
| 790.0 | 275.7 | 305.7 | 0.3 | 470065 | 83177 | 43700 | 299838 |
| 797.2 | -9.4 | 305.1 | 0.3 | 471105 | 83371 | 43999 | 299763 |

CONTENTS OF **alt.dat**:

Altitude [ft] vs. Thrust File Name

```
       0  THR00.DAT
   16404  THR16.DAT
   32808  THR32.DAT
   49212  THR49.DAT
   65617  THR65.DAT
   82021  THR82.DAT
   98425  THR98.DAT
10000000  0
```

CONTENTS OF **cd1_b.dat:**

Mach Number [ND] vs. Coefficient of Drag [ND]

| | |
|---|---|
| 0.0 | 0.014681 |
| 0.2 | 0.017925 |
| 0.4 | 0.019804 |
| 0.6 | 0.024602 |
| 0.8 | 0.034490 |
| 1.0 | 0.044540 |
| 1.2 | 0.048708 |
| 1.4 | 0.052472 |
| 1.6 | 0.047253 |
| 1.8 | 0.043264 |
| 2.0 | 0.038155 |
| 2.2 | 0.035620 |
| 2.4 | 0.031700 |
| 2.6 | 0.028610 |
| 2.8 | 0.025520 |
| 3.0 | 0.022430 |
| 3.2 | 0.021720 |
| 3.4 | 0.019900 |
| 3.6 | 0.018680 |
| 3.8 | 0.016240 |
| 4.0 | 0.017600 |
| 4.2 | 0.019510 |
| 4.4 | 0.018660 |
| 4.6 | 0.017820 |
| 4.8 | 0.016900 |
| 5.0 | 0.016130 |
| 5.2 | 0.015530 |
| 5.4 | 0.014910 |
| 5.6 | 0.014470 |
| 5.8 | 0.014170 |
| 6.0 | 0.012880 |
| 6.2 | 0.011290 |
| 6.4 | 0.011100 |
| 6.6 | 0.010930 |
| 10000000 | 0 |

CONTENTS OF **cd2_b.dat:**

Mach Number [ND] vs. Coefficient of Drag [ND]

| | |
|---|---|
| 0.0 | 0.003742 |
| 0.2 | 0.042900 |
| 0.4 | 0.046770 |
| 0.6 | 0.048320 |
| 0.8 | 0.051740 |
| 1.0 | 0.069980 |
| 1.2 | 0.064720 |
| 1.4 | 0.053364 |
| 1.6 | 0.047815 |
| 1.8 | 0.042780 |
| 2.0 | 0.037956 |
| 2.2 | 0.033890 |
| 2.4 | 0.030367 |
| 2.6 | 0.027119 |
| 2.8 | 0.024225 |
| 3.0 | 0.022092 |
| 3.2 | 0.020777 |
| 3.4 | 0.019532 |
| 3.6 | 0.018326 |
| 3.8 | 0.017238 |
| 4.0 | 0.016107 |
| 4.2 | 0.015213 |
| 4.4 | 0.014435 |
| 4.6 | 0.013696 |
| 4.8 | 0.013168 |
| 5.0 | 0.012797 |
| 5.2 | 0.012412 |
| 5.4 | 0.012064 |
| 5.6 | 0.011719 |
| 5.8 | 0.011365 |
| 6.0 | 0.010989 |
| 6.2 | 0.011592 |
| 6.4 | 0.012413 |
| 6.6 | 0.013637 |
| 10000000 | 0 |

CONTENTS OF **cd2_abrt.dat:**

Mach Number [ND] vs. Coefficient of Drag [ND]

| | |
|---|---|
| 0.0 | 0.014680 |
| 0.2 | 0.017925 |
| 0.4 | 0.019804 |
| 0.6 | 0.032190 |
| 0.8 | 0.052460 |
| 1.0 | 0.057010 |
| 1.2 | 0.080830 |
| 1.4 | 0.068430 |
| 1.6 | 0.057870 |
| 1.8 | 0.048810 |
| 2.0 | 0.039720 |
| 2.2 | 0.034430 |
| 2.4 | 0.031330 |
| 2.6 | 0.028260 |
| 2.8 | 0.025110 |
| 3.0 | 0.021990 |
| 3.2 | 0.020840 |
| 3.4 | 0.019700 |
| 3.6 | 0.018550 |
| 3.8 | 0.017400 |
| 4.0 | 0.016250 |
| 4.2 | 0.015470 |
| 4.4 | 0.014700 |
| 4.6 | 0.013920 |
| 4.8 | 0.013150 |
| 5.0 | 0.012670 |
| 5.2 | 0.012180 |
| 5.4 | 0.011850 |
| 5.6 | 0.011660 |
| 5.8 | 0.011480 |
| 6.0 | 0.011300 |
| 6.2 | 0.011110 |
| 6.4 | 0.011020 |
| 6.6 | 0.011670 |
| 10000000 | 0 |

CONTENTS OF **cl1_b.dat:**

Mach Number [ND] vs. Coefficient of Lift [ND]

| | |
|---|---|
| 0.0 | 0.2000 |
| 0.2 | 0.2010 |
| 0.4 | 0.2130 |
| 0.6 | 0.2170 |
| 0.8 | 0.2240 |
| 1.0 | 0.2410 |
| 1.2 | 0.2900 |
| 1.4 | 0.3430 |
| 1.6 | 0.3124 |
| 1.8 | 0.2962 |
| 2.0 | 0.1470 |
| 2.2 | 0.0197 |
| 2.4 | 0.0175 |
| 2.6 | 0.0145 |
| 2.8 | 0.0129 |
| 3.0 | 0.0113 |
| 3.2 | 0.0097 |
| 3.4 | 0.0082 |
| 3.6 | 0.0083 |
| 3.8 | 0.0096 |
| 4.0 | 0.0440 |
| 4.2 | 0.0841 |
| 4.4 | 0.0807 |
| 4.6 | 0.0773 |
| 4.8 | 0.0739 |
| 5.0 | 0.0705 |
| 5.2 | 0.0689 |
| 5.4 | 0.0673 |
| 5.6 | 0.0638 |
| 5.8 | 0.0620 |
| 6.0 | 0.0487 |
| 6.2 | 0.0419 |
| 6.4 | 0.0392 |
| 6.6 | 0.0382 |
| 10000000 | 0 |

CONTENTS OF cl2_b.dat:

Mach Number [ND] vs. Coefficient of Lift [ND]

```
    0.0   0.0000
    0.2   0.2420
    0.4   0.2650
    0.6   0.2820
    0.8   0.3142
    1.0   0.3816
    1.2   0.1857
    1.4   0.0921
    1.6   0.0850
    1.8   0.0781
    2.0   0.0720
    2.2   0.0661
    2.4   0.0606
    2.6   0.0551
    2.8   0.0506
    3.0   0.0466
    3.2   0.0449
    3.4   0.0431
    3.6   0.0413
    3.8   0.0395
    4.0   0.0377
    4.2   0.0358
    4.4   0.0340
    4.6   0.0322
    4.8   0.0304
    5.0   0.0286
    5.2   0.0277
    5.4   0.0269
    5.6   0.0260
    5.8   0.0245
    6.0   0.0230
    6.2   0.0500
    6.4   0.1010
    6.6   0.1010
10000000  0
```

CONTENTS OF cl2_abrt.dat:

Mach Number [ND] vs. Coefficient of Lift [ND]

| | |
|---|---|
| 0.0 | 0.00000 |
| 0.2 | 0.20000 |
| 0.4 | 0.20000 |
| 0.6 | 0.29070 |
| 0.8 | 0.28960 |
| 1.0 | 0.28810 |
| 1.2 | 0.25160 |
| 1.4 | 0.21060 |
| 1.6 | 0.18930 |
| 1.8 | 0.15500 |
| 2.0 | 0.12320 |
| 2.2 | 0.06697 |
| 2.4 | 0.06183 |
| 2.6 | 0.05668 |
| 2.8 | 0.05154 |
| 3.0 | 0.04639 |
| 3.2 | 0.04462 |
| 3.4 | 0.04284 |
| 3.6 | 0.04107 |
| 3.8 | 0.03929 |
| 4.0 | 0.03752 |
| 4.2 | 0.03566 |
| 4.4 | 0.03379 |
| 4.6 | 0.03193 |
| 4.8 | 0.03006 |
| 5.0 | 0.02820 |
| 5.2 | 0.02708 |
| 5.4 | 0.02596 |
| 5.6 | 0.02495 |
| 5.8 | 0.02405 |
| 6.0 | 0.02315 |
| 6.2 | 0.02250 |
| 6.4 | 0.02135 |
| 6.6 | 0.02962 |
| 10000000 | 0 |

CONTENTS OF **density.dat:**

Altitude [ft] vs. Ratio of Density to Sea Level [ND]

| | |
|---|---|
| 0 | 1.0 |
| 1000 | 0.9711 |
| 2000 | 0.9428 |
| 3000 | 0.9151 |
| 4000 | 0.8881 |
| 5000 | 0.8617 |
| 6000 | 0.8359 |
| 7000 | 0.8107 |
| 8000 | 0.7861 |
| 9000 | 0.7621 |
| 10000 | 0.7386 |
| 11000 | 0.7157 |
| 12000 | 0.6933 |
| 13000 | 0.6715 |
| 14000 | 0.6502 |
| 15000 | 0.6295 |
| 16000 | 0.6092 |
| 17000 | 0.5895 |
| 18000 | 0.5702 |
| 19000 | 0.5514 |
| 20000 | 0.5332 |
| 21000 | 0.5153 |
| 22000 | 0.4980 |
| 23000 | 0.4811 |
| 24000 | 0.4646 |
| 25000 | 0.4486 |
| 26000 | 0.4330 |
| 27000 | 0.4178 |
| 28000 | 0.4030 |
| 29000 | 0.3887 |
| 30000 | 0.3747 |
| 31000 | 0.3611 |
| 32000 | 0.3479 |
| 33000 | 0.3351 |
| 34000 | 0.3327 |
| 35000 | 0.3106 |
| 36000 | 0.2988 |
| 37000 | 0.2852 |
| 38000 | 0.2719 |
| 39000 | 0.2592 |
| 40000 | 0.2471 |
| 41000 | 0.2335 |
| 42000 | 0.2245 |
| 43000 | 0.2140 |
| 44000 | 0.2040 |

| | |
|---|---|
| 45000 | 0.1945 |
| 47000 | 0.1767 |
| 48000 | 0.1685 |
| 49000 | 0.1606 |
| 50000 | 0.1531 |
| 52000 | 0.1391 |
| 54000 | 0.1264 |
| 56000 | 0.1149 |
| 58000 | 0.1044 |
| 60000 | 0.09492 |
| 62000 | 0.08627 |
| 64000 | 0.07841 |
| 66000 | 0.07126 |
| 68000 | 0.06477 |
| 70000 | 0.05887 |
| 72000 | 0.05351 |
| 74000 | 0.04864 |
| 76000 | 0.04421 |
| 78000 | 0.04019 |
| 80000 | 0.03653 |
| 85000 | 0.02849 |
| 90000 | 0.02210 |
| 95000 | 0.01724 |
| 100000 | 0.01351 |
| 110000 | 0.008420 |
| 120000 | 0.005342 |
| 130000 | 0.003445 |
| 140000 | 0.002257 |
| 150000 | 0.001500 |
| 160000 | 0.001024 |
| 170000 | 0.0007122 |
| 180000 | 0.0005047 |
| 190000 | 0.0003614 |
| 200000 | 0.0002550 |
| 250000 | 0.0000323 |
| 300000 | 0 |
| 10000000 | 0 |

CONTENTS OF **glob_g.dat:**

| Time (s) | Gamma (deg) | Throttle | TotalMass (lbs) |
|---|---|---|---|
| 0.0 | 10.31 | 1.00 | 828544 |
| 10.0 | 10.31 | 1.00 | 826280 |
| 20.0 | 10.31 | 1.00 | 823402 |
| 30.0 | 10.31 | 1.00 | 819789 |
| 40.0 | 10.31 | 1.00 | 815758 |
| 50.0 | 10.31 | 1.00 | 811355 |
| 60.0 | 10.31 | 1.00 | 806719 |
| 70.0 | 10.31 | 1.00 | 801793 |
| 80.0 | 10.31 | 1.00 | 796125 |
| 80.4 | 0.00 | 0.55 | 795871 |
| 90.0 | 0.00 | 0.55 | 792410 |
| 100.0 | 0.00 | 0.55 | 788560 |
| 110.0 | 0.00 | 0.55 | 784317 |
| 120.0 | 0.00 | 0.55 | 779278 |
| 130.0 | 0.00 | 0.55 | 771564 |
| 138.4 | 10.31 | 0.30 | 761817 |
| 140.0 | 10.31 | 0.30 | 760657 |
| 150.0 | 10.31 | 0.30 | 751649 |
| 160.0 | 10.31 | 0.30 | 739056 |
| 170.0 | 10.31 | 0.30 | 728671 |
| 180.0 | 10.31 | 0.30 | 722036 |
| 190.0 | 10.31 | 0.30 | 717581 |
| 200.0 | 10.31 | 0.30 | 714730 |
| 203.6 | 0.00 | 0.30 | 714025 |
| 210.0 | 0.00 | 0.30 | 712882 |
| 220.0 | 0.00 | 0.30 | 711046 |
| 230.0 | 0.00 | 0.30 | 709146 |
| 240.0 | 0.00 | 0.30 | 707171 |
| 250.0 | 0.00 | 0.30 | 705114 |
| 260.0 | 0.00 | 0.30 | 702971 |
| 269.2 | -7.45 | 0.05 | 312921 |
| 270.0 | -7.45 | 0.05 | 312890 |
| 280.0 | -7.45 | 0.05 | 312436 |
| 290.0 | -7.45 | 0.05 | 311829 |
| 300.0 | -7.45 | 0.05 | 311071 |
| 310.0 | -7.45 | 0.05 | 310104 |
| 320.0 | -7.45 | 0.05 | 308814 |
| 330.0 | -7.45 | 0.05 | 307146 |
| 340.0 | -7.45 | 0.05 | 305308 |
| 350.0 | -7.45 | 0.05 | 304161 |
| 360.0 | -7.45 | 0.05 | 303635 |
| 370.0 | -7.45 | 0.05 | 303418 |
| 380.0 | -7.45 | 0.05 | 303319 |
| 390.0 | -7.45 | 0.05 | 303247 |
| 400.0 | -7.45 | 0.05 | 303180 |
| 410.0 | -7.45 | 0.05 | 303114 |
| 420.0 | -7.45 | 0.05 | 303044 |
| 430.0 | -7.45 | 0.05 | 302972 |
| 440.0 | -7.45 | 0.05 | 302899 |
| 450.0 | -7.45 | 0.05 | 302826 |
| 460.0 | -7.45 | 0.05 | 302752 |
| 470.0 | -7.45 | 0.05 | 302678 |
| 480.0 | -7.45 | 0.05 | 302603 |
| 490.0 | -7.45 | 0.05 | 302526 |
| 500.0 | -7.45 | 0.05 | 302449 |

| | | | |
|---|---|---|---|
| 510.0 | -7.45 | 0.05 | 302372 |
| 520.0 | -7.45 | 0.05 | 302293 |
| 530.0 | -7.45 | 0.05 | 302214 |
| 540.0 | -7.45 | 0.05 | 302133 |
| 550.0 | -7.45 | 0.05 | 302052 |
| 560.0 | -7.45 | 0.05 | 301970 |
| 570.0 | -7.45 | 0.05 | 301888 |
| 580.0 | -7.45 | 0.05 | 301804 |
| 590.0 | -7.45 | 0.05 | 301719 |
| 600.0 | -7.45 | 0.05 | 301634 |
| 610.0 | -7.45 | 0.05 | 301548 |
| 620.0 | -7.45 | 0.05 | 301461 |
| 630.0 | -7.45 | 0.05 | 301373 |
| 640.0 | -7.45 | 0.05 | 301284 |
| 650.0 | -7.45 | 0.05 | 301194 |
| 660.0 | -7.45 | 0.05 | 301103 |
| 670.0 | -7.45 | 0.05 | 301012 |
| 680.0 | -7.45 | 0.05 | 300919 |
| 690.0 | -7.45 | 0.05 | 300826 |
| 700.0 | -7.45 | 0.05 | 300731 |
| 710.0 | -7.45 | 0.05 | 300636 |
| 720.0 | -7.45 | 0.05 | 300539 |
| 730.0 | -7.45 | 0.05 | 300442 |
| 740.0 | -7.45 | 0.05 | 300344 |
| 750.0 | -7.45 | 0.05 | 300244 |
| 760.0 | -7.45 | 0.05 | 300144 |
| 770.0 | -7.45 | 0.05 | 300043 |
| 780.0 | -7.45 | 0.05 | 299941 |
| 790.0 | -7.45 | 0.05 | 299838 |
| 797.2 | -7.45 | 0.05 | 299763 |

CONTENTS OF **orbiter2.dat:**

| | | | |
|---|---|---|---|
| Mdot | 43.90 | slug/s | |
| T | 642000 | lbf | |
| Area | 850 | sq ft | |
| Stage Mass | 388000 | lbs | |
| Fuel Mass | 296000 | lbs | |
| Theta1 | 0.0870 | rad | 4.98 deg |
| Theta2 | 1.5360 | rad | 88.01 deg |
| Interval | 0.01 | sec | |

| Time (s) | FuelMass (slugs) | Velocity (ft/s) | Mach # | Altitude (ft) | Range (ft) | Delta V (ft/s) | Acc (g's) |
|---|---|---|---|---|---|---|---|
| 0.0 | 9200.0 | 6397 | 6.6 | 80000 | 0 | 0 | |
| 5.0 | 8980.5 | 6567 | 6.4 | 112281 | 2816 | 170 | 1.1 |
| 10.0 | 8761.0 | 6747 | 6.2 | 145436 | 5707 | 350 | 1.1 |
| 15.0 | 8541.5 | 6934 | 6.3 | 179506 | 8679 | 537 | 1.2 |
| 20.0 | 8322.0 | 7128 | 6.8 | 214524 | 11733 | 731 | 1.2 |
| 25.0 | 8102.5 | 7328 | 7.0 | 250523 | 14873 | 931 | 1.3 |
| 30.0 | 7883.0 | 7535 | 7.2 | 287535 | 18101 | 1138 | 1.3 |
| 35.0 | 7729.3 | 7756 | 7.4 | 300946 | 44829 | 1359 | 1.4 |
| 40.0 | 7608.5 | 7983 | 7.6 | 302315 | 84151 | 1586 | 1.4 |
| 45.0 | 7487.8 | 8214 | 7.8 | 303723 | 124618 | 1817 | 1.4 |
| 50.0 | 7367.1 | 8447 | 8.1 | 305172 | 166243 | 2050 | 1.5 |
| 55.0 | 7246.4 | 8683 | 8.3 | 306662 | 209039 | 2286 | 1.5 |
| 60.0 | 7125.6 | 8922 | 8.5 | 308193 | 253022 | 2525 | 1.5 |
| 65.0 | 7004.9 | 9164 | 8.7 | 309766 | 298206 | 2767 | 1.5 |
| 70.0 | 6884.2 | 9408 | 9.0 | 311381 | 344606 | 3011 | 1.5 |
| 75.0 | 6763.5 | 9656 | 9.2 | 313039 | 392236 | 3259 | 1.6 |
| 80.0 | 6642.7 | 9907 | 9.5 | 314741 | 441113 | 3510 | 1.6 |
| 85.0 | 6522.0 | 10162 | 9.7 | 316486 | 491254 | 3765 | 1.6 |
| 90.0 | 6401.3 | 10420 | 9.9 | 318276 | 542673 | 4023 | 1.6 |
| 95.0 | 6280.6 | 10681 | 10.2 | 320111 | 595389 | 4284 | 1.6 |
| 100.0 | 6159.8 | 10945 | 10.4 | 321992 | 649419 | 4548 | 1.7 |
| 105.0 | 6039.1 | 11214 | 10.7 | 323919 | 704780 | 4817 | 1.7 |
| 110.0 | 5918.4 | 11486 | 11.0 | 325893 | 761491 | 5089 | 1.7 |
| 115.0 | 5797.7 | 11762 | 11.2 | 327915 | 819571 | 5365 | 1.7 |
| 120.0 | 5676.9 | 12041 | 11.5 | 329985 | 879039 | 5644 | 1.8 |
| 125.0 | 5556.2 | 12325 | 11.8 | 332104 | 939916 | 5928 | 1.8 |
| 130.0 | 5435.5 | 12613 | 12.0 | 334273 | 1002220 | 6216 | 1.8 |
| 135.0 | 5314.8 | 12905 | 12.3 | 336492 | 1065975 | 6508 | 1.8 |
| 140.0 | 5194.0 | 13202 | 12.6 | 338763 | 1131200 | 6805 | 1.9 |
| 145.0 | 5073.3 | 13503 | 12.9 | 341085 | 1197920 | 7106 | 1.9 |
| 150.0 | 4952.6 | 13809 | 13.2 | 343461 | 1266156 | 7412 | 1.9 |
| 155.0 | 4831.9 | 14120 | 13.5 | 345890 | 1335933 | 7723 | 1.9 |
| 160.0 | 4711.1 | 14436 | 13.8 | 348373 | 1407274 | 8039 | 2.0 |
| 165.0 | 4590.4 | 14756 | 14.1 | 350912 | 1480206 | 8359 | 2.0 |
| 170.0 | 4469.7 | 15083 | 14.4 | 353507 | 1554755 | 8686 | 2.0 |
| 175.0 | 4349.0 | 15414 | 14.7 | 356159 | 1630946 | 9017 | 2.1 |
| 180.0 | 4228.2 | 15751 | 15.0 | 358870 | 1708809 | 9354 | 2.1 |
| 185.0 | 4107.5 | 16095 | 15.4 | 361639 | 1788372 | 9698 | 2.2 |
| 190.0 | 3986.8 | 16444 | 15.7 | 364469 | 1869665 | 10047 | 2.2 |
| 195.0 | 3866.1 | 16799 | 16.0 | 367360 | 1952719 | 10402 | 2.2 |
| 200.0 | 3745.3 | 17161 | 16.4 | 370314 | 2037565 | 10764 | 2.3 |
| 205.0 | 3624.6 | 17530 | 16.7 | 373331 | 2124237 | 11133 | 2.3 |
| 210.0 | 3503.9 | 17906 | 17.1 | 376413 | 2212769 | 11509 | 2.4 |
| 215.0 | 3383.2 | 18289 | 17.4 | 379560 | 2303197 | 11892 | 2.4 |
| 220.0 | 3262.4 | 18680 | 17.8 | 382775 | 2395558 | 12283 | 2.5 |
| 225.0 | 3141.7 | 19078 | 18.2 | 386059 | 2489890 | 12681 | 2.5 |
| 230.0 | 3021.0 | 19485 | 18.6 | 389413 | 2586234 | 13088 | 2.6 |
| 235.0 | 2900.3 | 19900 | 19.0 | 392838 | 2684631 | 13503 | 2.6 |
| 240.0 | 2779.5 | 20324 | 19.4 | 396336 | 2785125 | 13927 | 2.7 |
| 245.0 | 2658.8 | 20757 | 19.8 | 399909 | 2887761 | 14360 | 2.7 |
| 250.0 | 2538.1 | 21201 | 20.2 | 403558 | 2992586 | 14804 | 2.8 |
| 255.0 | 2417.4 | 21654 | 20.7 | 407285 | 3099650 | 15257 | 2.8 |
| 260.0 | 2296.6 | 22117 | 21.1 | 411092 | 3209004 | 15720 | 2.9 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 265.0 | 2175.9 | 22592 | 21.5 | 414980 | 3320703 | 16195 | 3.0 |
| 270.0 | 2055.2 | 23079 | 22.0 | 418952 | 3434804 | 16682 | 3.1 |
| 275.0 | 1934.5 | 23577 | 22.5 | 423010 | 3551364 | 17180 | 3.1 |
| 280.0 | 1813.7 | 24089 | 23.0 | 427155 | 3670449 | 17692 | 3.2 |
| 285.0 | 1693.0 | 24613 | 23.5 | 431390 | 3792122 | 18216 | 3.3 |
| 290.0 | 1572.3 | 25153 | 24.0 | 435718 | 3916453 | 18756 | 3.4 |
| 295.0 | 1451.6 | 25707 | 24.5 | 440142 | 4043515 | 19310 | 3.5 |
| 299.8 | 1336.1 | 26251 | 25.0 | 444461 | 4167611 | 19854 | 3.6 |

Percent fuel reserve: 14.5

CONTENTS OF **prop_g.dat:**

| Time (s) | Altitude (ft) | Velocity (ft/s) | Mach | Thr/Eng (ton/m^2) | Thrust (ton) | SpecThr (m/s) | FlowRate (kg/s) |
|---|---|---|---|---|---|---|---|
| 0.0 | 0.0 | 441.0 | 0.4 | 10.5 | 399.0 | 40473.9 | 96.7 |
| 10.0 | 1004.1 | 682.1 | 0.7 | 11.9 | 453.0 | 37852.5 | 117.4 |
| 20.0 | 2456.3 | 935.7 | 0.9 | 14.2 | 539.1 | 36101.6 | 146.4 |
| 30.0 | 4336.0 | 1155.5 | 1.1 | 16.5 | 627.2 | 35291.0 | 174.3 |
| 40.0 | 6564.0 | 1327.1 | 1.2 | 18.1 | 686.6 | 35033.0 | 192.2 |
| 50.0 | 9068.6 | 1466.5 | 1.4 | 19.5 | 741.4 | 35183.4 | 206.7 |
| 60.0 | 11803.4 | 1590.7 | 1.5 | 20.4 | 776.2 | 35418.4 | 214.9 |
| 70.0 | 14804.6 | 1774.1 | 1.7 | 22.7 | 863.5 | 36095.2 | 234.6 |
| 80.0 | 18225.4 | 2081.3 | 2.0 | 29.3 | 1112.5 | 38104.8 | 286.3 |
| 80.4 | 18375.1 | 2098.6 | 2.0 | 29.7 | 620.7 | 38202.3 | 159.4 |
| 90.0 | 18375.1 | 2154.6 | 2.1 | 31.6 | 660.5 | 38497.7 | 168.3 |
| 100.0 | 18375.1 | 2236.1 | 2.1 | 34.6 | 722.9 | 38947.3 | 182.0 |
| 110.0 | 18375.1 | 2360.9 | 2.3 | 39.7 | 830.1 | 39638.5 | 205.4 |
| 120.0 | 18375.1 | 2601.2 | 2.5 | 51.8 | 1083.2 | 40538.7 | 262.0 |
| 130.0 | 18375.1 | 3260.6 | 3.1 | 94.9 | 1982.8 | 41052.9 | 473.7 |
| 138.4 | 18375.1 | 4179.6 | 4.0 | 105.3 | 1200.5 | 36529.6 | 322.3 |
| 140.0 | 19574.3 | 4194.8 | 4.0 | 108.7 | 1238.9 | 36180.6 | 335.8 |
| 150.0 | 27272.7 | 4461.4 | 4.4 | 133.0 | 1516.4 | 29425.2 | 505.4 |
| 160.0 | 35808.6 | 5115.0 | 5.3 | 133.4 | 1521.1 | 26536.2 | 562.1 |
| 170.0 | 45415.6 | 5555.5 | 5.7 | 78.4 | 893.5 | 23253.3 | 376.8 |
| 180.0 | 55542.5 | 5737.2 | 5.9 | 47.6 | 542.8 | 21881.9 | 243.3 |
| 190.0 | 65918.1 | 5845.6 | 6.0 | 31.1 | 354.8 | 20964.4 | 166.0 |
| 200.0 | 76437.3 | 5895.1 | 6.1 | 17.9 | 204.0 | 20450.0 | 97.8 |
| 203.6 | 80238.4 | 5899.4 | 6.1 | 14.7 | 167.0 | 20420.8 | 80.2 |
| 210.0 | 80238.4 | 5939.4 | 6.1 | 14.7 | 167.0 | 20005.2 | 81.9 |
| 220.0 | 80238.4 | 6003.2 | 6.2 | 14.7 | 167.0 | 19342.9 | 84.7 |
| 230.0 | 80238.4 | 6066.9 | 6.3 | 14.7 | 167.0 | 18661.0 | 87.8 |
| 240.0 | 80238.4 | 6128.7 | 6.3 | 14.7 | 167.0 | 17921.4 | 91.4 |
| 250.0 | 80238.4 | 6188.4 | 6.4 | 14.7 | 167.0 | 17205.8 | 95.2 |
| 260.0 | 80238.4 | 6246.1 | 6.4 | 14.7 | 167.0 | 16514.4 | 99.2 |
| 269.2 | 80238.4 | 6297.4 | 6.5 | 14.7 | 27.8 | 15909.3 | 17.2 |
| 270.0 | 79585.9 | 6285.0 | 6.5 | 15.2 | 28.8 | 16029.0 | 17.6 |
| 280.0 | 71547.0 | 6110.7 | 6.3 | 23.1 | 44.0 | 18117.5 | 23.8 |
| 290.0 | 63760.8 | 5895.2 | 6.1 | 34.0 | 64.7 | 20448.6 | 31.0 |
| 300.0 | 56285.3 | 5624.8 | 5.8 | 47.0 | 89.3 | 22730.3 | 38.5 |
| 310.0 | 49215.3 | 5270.0 | 5.4 | 68.2 | 129.5 | 25408.9 | 50.0 |
| 320.0 | 42645.9 | 4858.9 | 5.0 | 99.8 | 189.5 | 27414.4 | 67.8 |
| 330.0 | 36633.5 | 4409.3 | 4.6 | 130.1 | 247.2 | 29010.0 | 83.6 |
| 340.0 | 31235.6 | 3910.6 | 4.0 | 147.6 | 280.4 | 36931.6 | 74.5 |
| 350.0 | 26612.4 | 3167.5 | 3.1 | 76.9 | 146.1 | 41027.8 | 34.9 |
| 360.0 | 23088.6 | 2246.3 | 2.2 | 30.5 | 57.9 | 39240.5 | 14.5 |
| 370.0 | 20752.9 | 1399.4 | 1.4 | 11.8 | 22.4 | 35169.3 | 6.2 |
| 380.0 | 19328.3 | 881.4 | 0.8 | 6.8 | 13.0 | 36174.9 | 3.5 |
| 390.0 | 18316.4 | 701.1 | 0.7 | 6.3 | 11.9 | 37619.9 | 3.1 |
| 400.0 | 17481.5 | 581.7 | 0.6 | 6.2 | 11.9 | 39001.4 | 3.0 |
| 410.0 | 16797.3 | 484.2 | 0.5 | 6.6 | 12.5 | 39961.8 | 3.1 |
| 420.0 | 16207.3 | 431.0 | 0.4 | 7.0 | 13.4 | 40361.1 | 3.2 |
| 430.0 | 15670.7 | 399.5 | 0.4 | 7.1 | 13.5 | 40598.2 | 3.3 |
| 440.0 | 15166.4 | 380.0 | 0.4 | 7.2 | 13.7 | 40745.7 | 3.3 |
| 450.0 | 14682.6 | 367.4 | 0.3 | 7.3 | 13.9 | 40842.0 | 3.3 |
| 460.0 | 14212.1 | 359.0 | 0.3 | 7.4 | 14.0 | 40907.6 | 3.4 |
| 470.0 | 13750.8 | 353.2 | 0.3 | 7.5 | 14.2 | 40954.2 | 3.4 |
| 480.0 | 13295.8 | 348.9 | 0.3 | 7.6 | 14.4 | 40989.0 | 3.4 |
| 490.0 | 12845.6 | 345.7 | 0.3 | 7.6 | 14.5 | 41016.3 | 3.5 |
| 500.0 | 12399.2 | 343.2 | 0.3 | 7.7 | 14.7 | 41038.9 | 3.5 |
| 510.0 | 11955.7 | 341.0 | 0.3 | 7.8 | 14.8 | 41058.5 | 3.5 |
| 520.0 | 11514.9 | 339.1 | 0.3 | 7.9 | 15.0 | 41076.0 | 3.6 |
| 530.0 | 11076.4 | 337.4 | 0.3 | 8.0 | 15.2 | 41092.2 | 3.6 |
| 540.0 | 10640.0 | 335.8 | 0.3 | 8.1 | 15.3 | 41107.4 | 3.7 |
| 550.0 | 10205.6 | 334.3 | 0.3 | 8.2 | 15.5 | 41121.9 | 3.7 |
| 560.0 | 9773.1 | 332.9 | 0.3 | 8.2 | 15.7 | 41133.2 | 3.7 |
| 570.0 | 9342.5 | 331.5 | 0.3 | 8.3 | 15.8 | 41141.9 | 3.8 |
| 580.0 | 8913.7 | 330.1 | 0.3 | 8.4 | 16.0 | 41152.5 | 3.8 |
| 590.0 | 8486.7 | 328.7 | 0.3 | 8.5 | 16.2 | 41170.9 | 3.9 |
| 600.0 | 8061.4 | 327.4 | 0.3 | 8.6 | 16.3 | 41188.9 | 3.9 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 610.0 | 7637.8 | 326.2 | 0.3 | 8.7 | 16.5 | 41202.1 | 3.9 |
| 620.0 | 7215.8 | 324.9 | 0.3 | 8.8 | 16.7 | 41214.4 | 4.0 |
| 630.0 | 6795.4 | 323.7 | 0.3 | 8.9 | 16.9 | 41226.5 | 4.0 |
| 640.0 | 6376.5 | 322.5 | 0.3 | 9.0 | 17.0 | 41238.5 | 4.1 |
| 650.0 | 5959.3 | 321.3 | 0.3 | 9.1 | 17.2 | 41250.3 | 4.1 |
| 660.0 | 5543.6 | 320.1 | 0.3 | 9.2 | 17.4 | 41261.9 | 4.1 |
| 670.0 | 5129.4 | 318.9 | 0.3 | 9.2 | 17.6 | 41273.4 | 4.2 |
| 680.0 | 4716.7 | 317.8 | 0.3 | 9.3 | 17.8 | 41271.9 | 4.2 |
| 690.0 | 4305.6 | 316.6 | 0.3 | 9.4 | 17.9 | 41264.8 | 4.3 |
| 700.0 | 3896.0 | 315.3 | 0.3 | 9.5 | 18.1 | 41255.4 | 4.3 |
| 710.0 | 3488.0 | 314.1 | 0.3 | 9.6 | 18.3 | 41238.7 | 4.4 |
| 720.0 | 3081.7 | 312.8 | 0.3 | 9.7 | 18.5 | 41221.9 | 4.4 |
| 730.0 | 2677.0 | 311.6 | 0.3 | 9.8 | 18.7 | 41269.0 | 4.4 |
| 740.0 | 2273.6 | 310.7 | 0.3 | 9.9 | 18.9 | 41327.9 | 4.5 |
| 750.0 | 1871.3 | 309.9 | 0.3 | 10.0 | 19.0 | 41350.9 | 4.5 |
| 760.0 | 1470.2 | 308.9 | 0.3 | 10.1 | 19.2 | 41304.5 | 4.6 |
| 770.0 | 1070.5 | 307.7 | 0.3 | 10.2 | 19.4 | 41257.3 | 4.6 |
| 780.0 | 672.4 | 306.5 | 0.3 | 10.3 | 19.6 | 41304.4 | 4.7 |
| 790.0 | 275.7 | 305.7 | 0.3 | 10.4 | 19.8 | 41366.8 | 4.7 |
| 797.2 | -9.4 | 305.1 | 0.3 | 10.5 | 20.0 | 41407.7 | 4.7 |

CONTENTS OF **soundspd.dat:**

Altitude [ft] vs. Ratio of Speed of Sound to Sea Level Speed [ND]

```
       0  1.0
    1000  0.9366
    2000  0.9966
    3000  0.9395
    4000  0.9662
    5000  0.9827
    6000  0.9792
    7000  0.9757
    8000  0.9722
    9000  0.9636
   10000  0.9650
   11000  0.9615
   12000  0.9579
   13000  0.9543
   14000  0.9507
   15000  0.9471
   16000  0.9434
   17000  0.9382
   18000  0.9361
   19000  0.9325
   20000  0.9238
   21000  0.9251
   22000  0.9214
   23000  0.9176
   24000  0.9139
   25000  0.9101
   26000  0.9063
   27000  0.9026
   28000  0.8987
   29000  0.8949
   30000  0.8911
   31000  0.8872
   32000  0.8834
   33000  0.8795
   34000  0.8758
   35000  0.8717
   36000  0.8677
   37000  0.8671
   80000  0.8671
   85000  0.8719
   90000  0.8809
   95000  0.8893
  100000  0.8986
  110000  0.9159
  120000  0.9329
  130000  0.9495
  140000  0.9659
  150000  0.9819
  160000  0.9904
  170000  0.9904
  180000  0.9808
  190000  0.9600
  200000  0.9386
10000000  0
```

CONTENTS OF **specthr.dat**:

Mach Number [ND] vs. Specific Thrust [m/s]

| | |
|---|---|
| 0.00 | 43505.22 |
| 0.50 | 39666.52 |
| 0.75 | 36680.87 |
| 1.00 | 35401.30 |
| 1.25 | 34974.78 |
| 1.48 | 35401.30 |
| 1.65 | 35913.13 |
| 1.85 | 37320.65 |
| 2.07 | 38531.97 |
| 2.34 | 40093.04 |
| 2.63 | 40946.09 |
| 2.97 | 41329.96 |
| 3.30 | 40732.83 |
| 3.77 | 38301.65 |
| 4.18 | 35188.04 |
| 4.28 | 29941.83 |
| 5.30 | 26444.35 |
| 6.00 | 21326.09 |
| 6.25 | 18809.61 |
| 6.50 | 15909.26 |
| 10000000 | 0 |

CONTENTS OF **thr00.dat**:

Mach Number [ND] vs. ln(Thrust [ton/sq.m]) [ND]

| | |
|---|---|
| 0.0 | 1.0212 |
| 0.5 | 1.0212 |
| 1.6 | 1.5000 |
| 10000000 | 0 |

CONTENTS OF **thr16.dat**:

Mach Number [ND] vs. ln(Thrust [ton/sq.m]) [ND]

| | |
|---|---|
| 0.0 | 0.8451 |
| 0.5 | 0.8451 |
| 1.6 | 1.3032 |
| 3.0 | 2.0000 |
| 10000000 | 0 |

CONTENTS OF **thr32.dat**:

Mach Number [ND] vs. ln(Thrust [ton/sq.m]) [ND]

| | |
|---|---|
| 0.5 | -0.301 |
| 1.6 | 01.000 |
| 3.0 | 01.750 |
| 3.9 | 02.187 |
| 10000000 | 0 |

CONTENTS OF **thr49.dat**:

Mach Number [ND] vs. ln(Thrust [ton/sq.m]) [ND]

| | |
|---|---|
| 1.6 | 0.6990 |
| 3.9 | 1.8750 |
| 5.0 | 1.8750 |
| 6.0 | 1.7813 |
| 10000000 | 0 |

CONTENTS OF **thr65.dat**:

Mach Number [ND] vs. ln(Thrust [ton/sq.m]) [ND]

| | |
|---|---|
| 1.6 | 0.2504 |
| 3.9 | 1.5624 |
| 5.0 | 1.5211 |
| 6.0 | 1.5000 |
| 10000000 | 0 |

CONTENTS OF **thr82.dat**:

Mach Number [ND] vs. ln(Thrust [ton/sq.m]) [ND]

| | |
|---|---|
| 2.3 | 0.3747 |
| 3.9 | 1.0626 |
| 5.0 | 1.1875 |
| 6.0 | 1.1252 |
| 10000000 | 0 |

CONTENTS OF **thr98.dat**:

Mach Number [ND] vs. ln(Thrust [ton/sq.m]) [ND]

| | |
|---|---|
| 2.5 | 0.2504 |
| 3.9 | 0.8751 |
| 5.0 | 0.8751 |
| 6.0 | 0.8195 |
| 10000000 | 0 |

CONTENTS OF tsto_g.dat:

| Time (s) | FuelMass (lbs) | Accel g's | Velocity (ft/s) | Mach | Altitude (ft) | Range (ft) |
|---|---|---|---|---|---|---|
| 0.0 | 160000 | 0.000 | 441 | 0.4 | 0 | 0 |
| 10.0 | 157736 | 0.821 | 682 | 0.7 | 1004 | 5518 |
| 20.0 | 154858 | 0.750 | 936 | 0.9 | 2456 | 13498 |
| 30.0 | 151245 | 0.604 | 1156 | 1.1 | 4336 | 23828 |
| 40.0 | 147214 | 0.480 | 1327 | 1.2 | 6564 | 36072 |
| 50.0 | 142811 | 0.399 | 1467 | 1.4 | 9069 | 49836 |
| 60.0 | 138175 | 0.422 | 1591 | 1.5 | 11803 | 64865 |
| 70.0 | 133249 | 0.681 | 1774 | 1.7 | 14805 | 81357 |
| 80.0 | 127581 | 1.302 | 2081 | 2.0 | 18225 | 100156 |
| 80.4 | 127327 | 1.344 | 2099 | 2.0 | 18375 | 100979 |
| 90.0 | 123866 | 0.209 | 2155 | 2.1 | 18375 | 121381 |
| 100.0 | 120016 | 0.302 | 2236 | 2.1 | 18375 | 143309 |
| 110.0 | 115773 | 0.501 | 2361 | 2.3 | 18375 | 166242 |
| 120.0 | 110734 | 1.068 | 2601 | 2.5 | 18375 | 190900 |
| 130.0 | 103020 | 3.325 | 3261 | 3.1 | 18375 | 219527 |
| 138.4 | 93273 | 3.253 | 4180 | 4.0 | 18375 | 250741 |
| 140.0 | 92113 | 0.346 | 4195 | 4.0 | 19574 | 257331 |
| 150.0 | 83105 | 1.409 | 4461 | 4.4 | 27273 | 299637 |
| 160.0 | 70512 | 2.013 | 5115 | 5.3 | 35809 | 346546 |
| 170.0 | 60127 | 0.854 | 5556 | 5.7 | 45416 | 399340 |
| 180.0 | 53492 | 0.423 | 5737 | 5.9 | 55543 | 454992 |
| 190.0 | 49037 | 0.268 | 5846 | 6.0 | 65918 | 512010 |
| 200.0 | 46186 | 0.066 | 5895 | 6.1 | 76437 | 569817 |
| 203.6 | 45481 | 0.017 | 5899 | 6.1 | 80238 | 590706 |
| 210.0 | 44338 | 0.196 | 5939 | 6.1 | 80238 | 628590 |
| 220.0 | 42502 | 0.200 | 6003 | 6.2 | 80238 | 688302 |
| 230.0 | 40602 | 0.195 | 6067 | 6.3 | 80238 | 748654 |
| 240.0 | 38627 | 0.189 | 6129 | 6.3 | 80238 | 809633 |
| 250.0 | 36570 | 0.183 | 6188 | 6.4 | 80238 | 871221 |
| 260.0 | 34427 | 0.176 | 6246 | 6.4 | 80238 | 933395 |
| 269.2 | 32377 | 0.170 | 6297 | 6.5 | 80238 | 991097 |
| 270.0 | 32346 | -0.475 | 6285 | 6.5 | 79586 | 996087 |
| 280.0 | 31892 | -0.605 | 6111 | 6.3 | 71547 | 1057577 |
| 290.0 | 31285 | -0.734 | 5895 | 6.1 | 63761 | 1117133 |
| 300.0 | 30527 | -0.970 | 5625 | 5.8 | 56285 | 1174312 |
| 310.0 | 29560 | -1.209 | 5270 | 5.4 | 49215 | 1228390 |
| 320.0 | 28270 | -1.333 | 4859 | 5.0 | 42646 | 1278639 |
| 330.0 | 26602 | -1.468 | 4409 | 4.6 | 36634 | 1324627 |
| 340.0 | 24764 | -1.695 | 3911 | 4.0 | 31236 | 1365915 |
| 350.0 | 23617 | -2.661 | 3167 | 3.1 | 26612 | 1401278 |
| 360.0 | 23091 | -2.972 | 2246 | 2.2 | 23089 | 1428232 |
| 370.0 | 22874 | -2.258 | 1399 | 1.4 | 20753 | 1446097 |
| 380.0 | 22775 | -0.861 | 881 | 0.8 | 19328 | 1456993 |
| 390.0 | 22703 | -0.402 | 701 | 0.7 | 18316 | 1464733 |
| 400.0 | 22636 | -0.417 | 582 | 0.6 | 17482 | 1471120 |
| 410.0 | 22570 | -0.221 | 484 | 0.5 | 16797 | 1476353 |
| 420.0 | 22500 | -0.126 | 431 | 0.4 | 16207 | 1480866 |
| 430.0 | 22428 | -0.077 | 399 | 0.4 | 15671 | 1484970 |
| 440.0 | 22355 | -0.048 | 380 | 0.4 | 15166 | 1488827 |
| 450.0 | 22282 | -0.032 | 367 | 0.3 | 14683 | 1492528 |
| 460.0 | 22208 | -0.022 | 359 | 0.3 | 14212 | 1496127 |
| 470.0 | 22134 | -0.015 | 353 | 0.3 | 13751 | 1499656 |
| 480.0 | 22059 | -0.011 | 349 | 0.3 | 13296 | 1503136 |
| 490.0 | 21982 | -0.009 | 346 | 0.3 | 12846 | 1506579 |
| 500.0 | 21905 | -0.007 | 343 | 0.3 | 12399 | 1509994 |
| 510.0 | 21828 | -0.006 | 341 | 0.3 | 11956 | 1513386 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 520.0 | 21749 | -0.006 | 339 | 0.3 | 11515 | 1516758 |
| 530.0 | 21670 | -0.005 | 337 | 0.3 | 11076 | 1520112 |
| 540.0 | 21589 | -0.005 | 336 | 0.3 | 10640 | 1523450 |
| 550.0 | 21508 | -0.005 | 334 | 0.3 | 10206 | 1526772 |
| 560.0 | 21426 | -0.004 | 333 | 0.3 | 9773 | 1530080 |
| 570.0 | 21344 | -0.004 | 331 | 0.3 | 9343 | 1533374 |
| 580.0 | 21260 | -0.004 | 330 | 0.3 | 8914 | 1536654 |
| 590.0 | 21175 | -0.004 | 329 | 0.3 | 8487 | 1539920 |
| 600.0 | 21090 | -0.004 | 327 | 0.3 | 8061 | 1543173 |
| 610.0 | 21004 | -0.004 | 326 | 0.3 | 7638 | 1546414 |
| 620.0 | 20917 | -0.004 | 325 | 0.3 | 7216 | 1549642 |
| 630.0 | 20829 | -0.004 | 324 | 0.3 | 6795 | 1552857 |
| 640.0 | 20740 | -0.004 | 322 | 0.3 | 6377 | 1556061 |
| 650.0 | 20650 | -0.004 | 321 | 0.3 | 5959 | 1559252 |
| 660.0 | 20559 | -0.004 | 320 | 0.3 | 5544 | 1562432 |
| 670.0 | 20468 | -0.004 | 319 | 0.3 | 5129 | 1565600 |
| 680.0 | 20375 | -0.004 | 318 | 0.3 | 4717 | 1568757 |
| 690.0 | 20282 | -0.004 | 317 | 0.3 | 4306 | 1571901 |
| 700.0 | 20187 | -0.004 | 315 | 0.3 | 3896 | 1575034 |
| 710.0 | 20092 | -0.004 | 314 | 0.3 | 3488 | 1578155 |
| 720.0 | 19995 | -0.004 | 313 | 0.3 | 3082 | 1581263 |
| 730.0 | 19898 | -0.003 | 312 | 0.3 | 2677 | 1584358 |
| 740.0 | 19800 | -0.003 | 311 | 0.3 | 2274 | 1587444 |
| 750.0 | 19700 | -0.003 | 310 | 0.3 | 1871 | 1590521 |
| 760.0 | 19600 | -0.004 | 309 | 0.3 | 1470 | 1593589 |
| 770.0 | 19499 | -0.004 | 308 | 0.3 | 1071 | 1596646 |
| 780.0 | 19397 | -0.003 | 307 | 0.3 | 672 | 1599691 |
| 790.0 | 19294 | -0.002 | 306 | 0.3 | 276 | 1602726 |
| 797.2 | 19219 | -0.002 | 305 | 0.3 | -9 | 1604906 |