FINAL REPORT

for

NASA – Langley Grant NCC1-229

IMPROVING CONCEPTUAL DESIGN FOR LAUNCH VEHICLES

Covering the Period September 23, 1996 to September 22, 1999

Year 3 Topic

THE BIMESE CONCEPT: A STUDY OF MISSION AND ECONOMIC OPTIONS

Submitted By

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Date Submitted

December 22, 1999

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December 22, 1999

Dr. Ted Talay
Chief, Vehicle Analysis Branch
Mail Code 365
NASA Langley Research Center
Hampton. VA 23681-2199

Dear Dr. Talay,

Attached are the final report materials for NASA Cooperative Agreement NCC1-229 entitled "Improving Conceptual Design for Launch Vehicles" that was conducted by the Space Systems Design Laboratory (SSDL) at the Georgia Institute of Technology during the period September 23, 1996 to September 22, 1999. The most recent year of this cooperative agreement focused on the economic viability of a Bimese reusable launch vehicle when servicing future intercontinental fast package delivery missions. Several alternative configurations were considered and the results are summarized in the attached report. In addition, a summary of funded activities and a set of presentation-style charts from this project are also included.

This report concludes the nominal period of performance of the three-year NCC1-229 activity. During this overall project, the SSDL students and researchers developed a new cost and business assessment model for estimating the economics of reusable launch systems. This tool is called CABAM, and it has since been made available to a number of advanced design organizations. In year 2 of this project, our efforts focused on computational frameworks for supporting multidisciplinary design environments. For this task, we created a web-based demonstration environment that integrated four disciplines for designing an RBCC SSTO spaceplane. Our most recent activities have focused on the assessment of a Bimese RLV for intercontinental fast-package delivery markets.

I would like to thank you for your continued support of our research and educational activities in advanced space transportation system design. Partly with the support of this cooperative agreement, SSDL has grown from only 2 graduate students in 1996 to a more fully developed and capable research lab of 18 graduate students and 4 undergraduate students in 1999. We look forward to working with you and your organization on future projects.

Sincerely,

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Final Summary of Cooperative Agreement Activities

Improving Conceptual Design for Launch Vehicles

Cooperative Agreement NCC1-229, NASA – Langley Research Center

Total Period of Performance: September 22, 1996 – September 23, 1999
Current Period of Performance: September 23, 1998 - September 22, 1999

Project Background:

This report summarizes key activities conducted in the third and final year of the cooperative agreement NCC1-229 entitled "Improving Conceptual Design for Launch Vehicles." This project has been funded by the Vehicle Analysis Branch at NASA's Langley Research Center in Hampton, VA. Work has been performed by the Space Systems Design Lab (SSDL) at the Georgia Institute of Technology, Atlanta, GA.

Accomplishments during the first and second years of this project have been previously reported in annual progress reports. This report will focus on the third and final year of the three year activity.

Summary of Project Accomplishments:

From September 23, 1998 to September 22, 1999 this project focused on the assessment of the economics of a Bimese reusable launch vehicle when configured to support a intercontinental fast-package (fast cargo) delivery business. Several configurations were examined including a single Bimese RLV element, a single element with extra internal tanks in the payload bay, a single element with strap-on solid rocket boosters, and a single element with extra tanks <u>and</u> strap-on solid rocket boosters. For each configuration, the payload performance was calculated as a function of launch azimuth from Kennedy Space Center, Florida. A parametric business market was created to assess the economic viability of a Bimese vehicle operating as a fast-package delivery vehicle. The study results are summarized in the attached report and the accompanying presentation charts.

A secondary (and less tangible) goal of the three-year project was to encourage and support the development of a research laboratory at Georgia Tech focused on the study of advanced space transportation. Toward that end, the project was also quite successful. With the support of government funding, the Space Systems Design Laboratory at Georgia Tech has grown from only

2 graduate students in 1996 to 18 graduate students and 4 undergraduate students in 1999. During this time, the lab has graduated 10 students with advanced degrees, developed several new tools and techniques applicable to the design of conceptual launch vehicles, and has published a number of technical papers documenting these accomplishments.

Graduate Students Supported:

For the current period of this project (year 3), two Georgia Tech graduate students were directly supported by funds derived from this cooperative agreement. These graduate students were awarded graduate research assistantships (GRAs) and received monthly stipends and tuition reimbursement.

1) Jeffery Tooley (graduate student, GRA supported from 9/98 – 9/99)

2) Brad St. Germain (graduate student, GRA, supported from 7/99 – 8/99)

Jeff Tooley was supported during the entire third year of the project and is responsible for most of the work on the Bimese study. Brad St. Germain was supported for a summer period that he spent working as a summer intern in the Vehicle Analysis Branch at NASA Langley. While at VAB, Mr. St. Germain worked on KLIN-cycle propulsion concepts under the supervision of NASA's Roger Lepsch.

Degrees Awarded:

Two advanced degrees were awarded based partially on research work performed during this period of the project.

1) Jeffrey Tooley, Master of Science in Aerospace Engineering, December 1999.

2) Brad St. Germain, Master of Science, December 1999.

Jeff Tooley completed his M.S. A. E. degree in the fall of 1999 and has entered the aerospace workforce. Brad St. Germain (who was supported by Georgia state funds during the academic year) earned an M. S. degree in the fall of 1999 and is continuing his education in the Ph.D. program at Georgia Tech.

Travel & Summer Activities:

The following travel was taken in support of activities related to this project.

1) Brad St. Germain spent 7 weeks in the summer of 1999 as a summer intern in the Vehicle Analysis Branch at NASA - Langley. Mr. St. Germain's travel expenses were partially offset by funds from the cooperative agreement.

2) Dr. John Olds and Jeff Tooley visited NASA Langley on August 9 - 11 to discuss preliminary results of the Bimese project. Dr. Ted Talay provided some input and advise regarding the project.

3) Dr. John Olds visited NASA Langley on November 3 and 4 in conjunction with the AIAA Spaceplanes and Hypersonic Technologies Conference in Norfolk, VA. Dr. Olds and several SSDL graduate students met with Dr. Ted Talay, Roger Lepsch, Doug Morris, Prasun Desai, and other NASA researchers.

Plans for Continuing This Cooperative Agreement:

A proposal for a continuation of this cooperative agreement has been submitted to NASA Langley and is currently in evaluation. If accepted, this continuation will investigate markets, design criteria, and vehicle concepts for economically successful Space Tourism ventures. This topic is of mutual interest to NASA and SSDL.

Final Report Attachments

Improving Conceptual Design for Launch Vehicles

NCC1-229

(Year 3 Activities)

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NOMENCLATURE

AATe	Architecture Assessment Tool enhanced
CABAM	Cost And Business Analysis Module
CSTS	Commercial Space Transportation Study
DDT&E	design, development, testing and evaluation
GEM	graphite epoxy motor
IRR	internal rate of return
KSC	Kennedy Space Center
LEO	low Earth orbit
LH2	liquid hydrogen
LOX	liquid oxygen
NASA	National Aeronautics and Space Administration
OMS	orbital maneuvering system
POST	Program to Optimize Simulated Trajectories
T/W	thrust-to-weight
TFU	theoretical first unit cost
SRB	solid rocket booster
SRM	solid rocket motors

I. INTRODUCTION

The Bimese architecture for low cost access to space is based on a philosophy of maximum commonality between reusable flight elements. This strategy is thought to lead to reduced development cost, fleet production cost, and operations cost. As envisioned by researchers at NASA Langley (Talay, et al), the nominal Bimese configuration consists of two identical autonomous LOX/LH2 rocket-powered wing-body RLVs mated together into a vertical liftoff TSTO configuration. In this nominal or "mated" configuration, the system is designed to deliver 60 klb of payload to low earth orbit from a launch site at NASA Kennedy Space Center. The "booster" RLV crossfeeds propellant into the "orbiter" RLV until the staging point at which the empty booster separates and performs an unpowered return to the launch site. The fully loaded "orbiter" continues on to orbit with the payload. In fact, the "booster" and "orbiter" in the mated configuration are identical rocket vehicles and can be interchanged from flight to flight. While this results in some non-optimal compromises in the design of the Bimese RLV (e.g. ordinarily, the booster of a TSTO system wouldn't need a payload bay), the life cycle costs are expected to benefit from the high degree of commonality between the systems (e.g. same engines, same construction methods, same maintenance routines). In addition, the TSTO approach results in a smaller and less technologically risky development program relative to a SSTO configuration with similar technology levels.

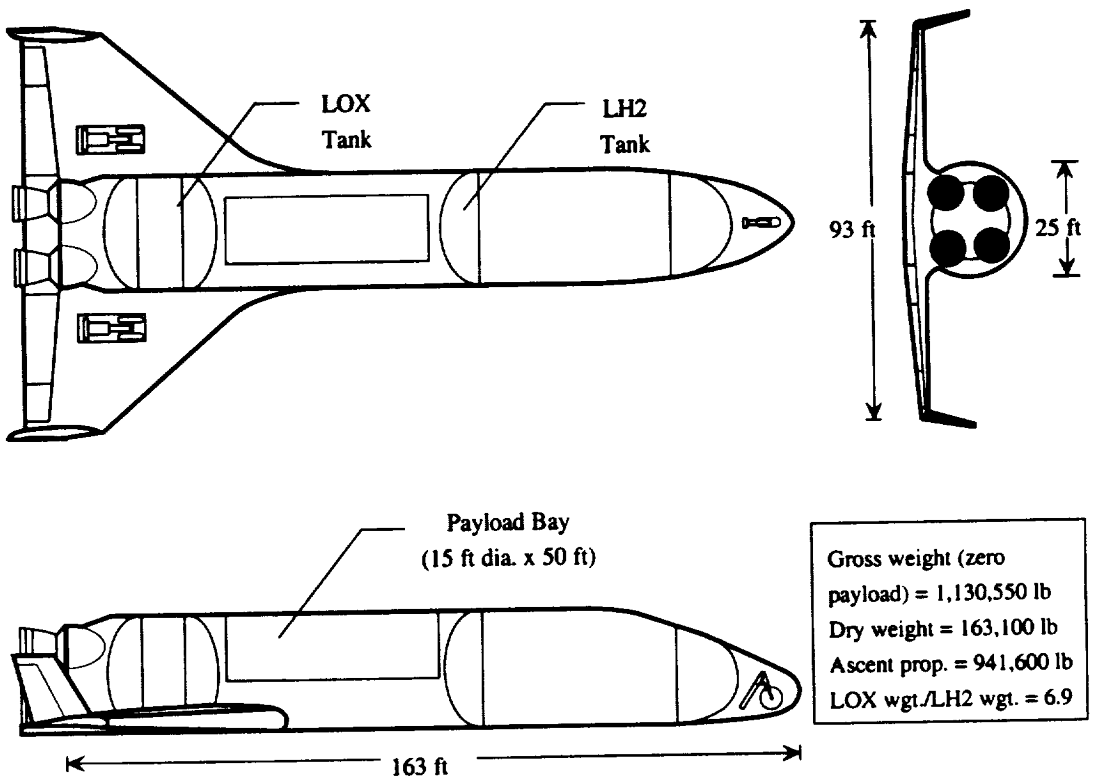
In addition to the nominal mated configuration, a number of complementary Bimese configurations have been considered to widen the payload delivery range of the architecture and increase payload delivery flexibility. That is, a large family of configurations (all using a single or multiple Bimese RLV flight elements in some way) could capture medium payload delivery missions (20 – 40 klb), heavy payload delivery missions (40 - 60 klb), very heavy payload delivery missions (>100 klb), and crew and cargo rotation missions to the International Space Station. Strap–on boosters, large expendable liquid core stages, and propellant drop tanks can be added to the basic Bimese flight vehicle to create these alternate configurations.

The goal of the research outlined in this report is to consider the possibility of using elements of the Bimese architecture to capture part of the market in ultra-fast intercontinental package delivery. That is, can a single Bimese RLV (augmented or unaugmented) be used to fly a fast, suborbital trajectory to deliver high priority payloads from the United States (nominally KSC) to fictitious spaceports in European or Asian cities? If so, can a positive economic business case be made for this fast "point-to-point" market using a Bimese RLV? How much payload can be carried per flight? What type of annual flight rates are necessary to make an attractive economic case?

This study was completed by researchers in the Space Systems Design Laboratory in the School of Aerospace Engineering at Georgia Institute of Technology between 1998 and 1999.

II. THE BIMESE LAUNCH VEHICLE

The Bimese is a conceptual design for a fully reusable wing-body launch vehicle. It is the vehicle that will be used as the base element for all architectural development in the Bimese space transportation system, hence the name. In Figure II.1 the Bimese is pictured in a three-view along with vehicle specifications. Although all of the given specifications are for a fully fueled vehicle with zero payload, not all configurations will use these parameters (e.g. in the case of ascent propellant off-load). Designed by NASA Langley Research Center, it was sized to deliver 60 klb of payload when launched from Kennedy Space Center (KSC) to a 100 nmi x 50 nmi at 28.5° inclination orbit in what is called the mated (Bimese) TSTO configuration (discussed in Section III.5).



Gross weight (zero payload) = 1,130,550 lb
Dry weight = 163,100 lb
Ascent prop. = 941,600 lb
LOX wgt./LH2 wgt. = 6.9

Figure II.1 – Bimese Three-view

With four conceptual liquid oxygen (LOX)/liquid hydrogen (LH2) engines the Bimese relies on the development of a new propulsion system with the parameters listed in Table II.1.

Table II.1 – Conceptual LOX/LH2 Engine Parameters

Sea level thrust (lb)	384,000
Vacuum I_{sp} (s)	443
Sea level T/W	74.6
Engine throttle	30%
Mixture ratio	6.9
Lifetime (flights)	250

Other design parameters that are important for the analysis of the vehicle are listed in Table II.2.

Table II.2 – Design Constraints

Acceleration limit (g)	3
Maximum wing normal force (lb)	379,000
Maximum dynamic pressure (lb/ft^2)	1,000

III. MISSION AND PAYLOAD OPTIONS

The mission options of the Bimese transportation system will be analyzed in terms of trying to fill NASA and the commercial markets' demand for a wide variety of payload capabilities with minimum architectural development. In this study there are five varieties of the Bimese element being explored: single element, fuel-augmented, thrust-augmented, fuel/thrust-augmented, and the mated (Bimese) configurations. These five varieties are shown in Figure III.1. Other variants that exist, but are not being investigated, are the heavy lift concepts that are characterized by the addition of a large second or third expendable stage to any of the previous configurations. Quantifying the performance of each configuration will be done in terms of two parameters: due east point-to-point range capability for 1 klb from 28.5° latitude (KSC); and low Earth orbit (LEO) payload delivered to a 100 nmi x 50 nmi at 28.5° inclination orbit. For the LEO case there is enough orbital maneuvering system (OMS) propellant on the Bimese to circularize to 100 nmi x 100 nmi at 28.5° inclination orbit.

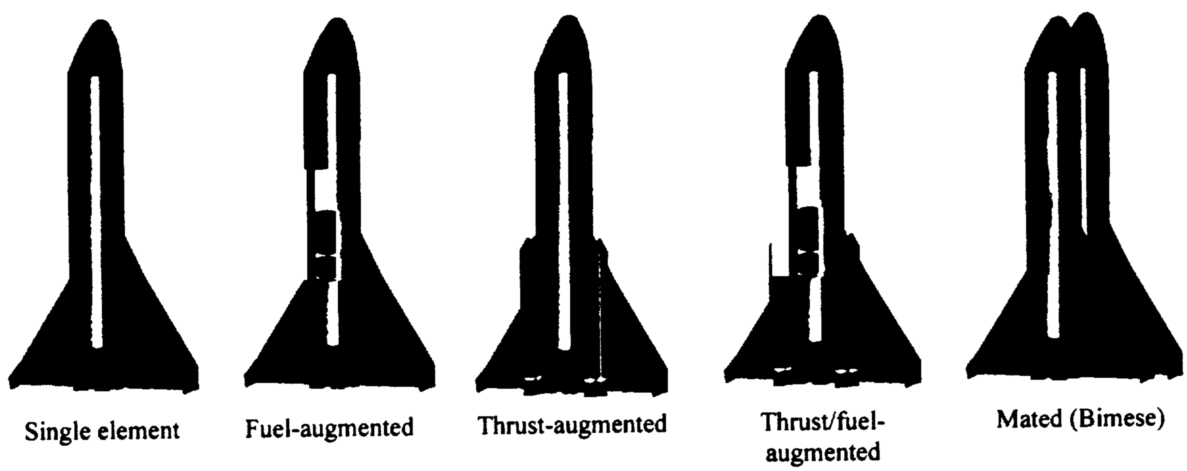


Figure III.1 – Bimese Space Transportation System Mission Options

For these missions all of the trajectory analysis is done using three degree-of-freedom Program to Optimize Simulated Trajectories (POST). For the LEO missions POST is used to optimize the controls for maximum burnout weight. For point-to-point missions POST simulates a ballistic boost-glide trajectory, while optimizing alpha (limited to 40 degrees) for maximum range. For fuel and thrust augmentation new component weights are analyzed using mass estimating relationships. More on the specifics of the vehicle trajectory and component weights will be introduced as each configuration is studied. The POST input and aerodynamic files are in Appendix A.

III.1. SINGLE ELEMENT BIMESE

The single element configuration consists of the Bimese flown without any other components.

III.1.1. Single Element Bimese: LEO

It is determined that the single element configuration <u>cannot make it to LEO</u> before burning out of ascent propellant. In the simulation the single Bimese must use about 40,000 lb of non-propellant mass to make it to orbit.

III.1.2. Single Element Bimese: Point-to-Point

For the single element point-to-point configuration 6,200 lb of propellant is off-loaded which corresponds to the OMS fuel needed to circularize and de-orbit. The single element point-to-point simulation shows that the Bimese can transport 1 klb of payload to 28.5° latitude with a range of 3,900 nmi. A ground track of the trajectory is shown in Figure III.2. Also shown in this figure are the approximate landing locations for launches in all directions and the single element ranges loaded with 60 klb of payload. The figure depicts that the added payload weight reduces the range by about 30% and launching in a westerly direction (as compared to an easterly one) reduces the range by approximately 30%.

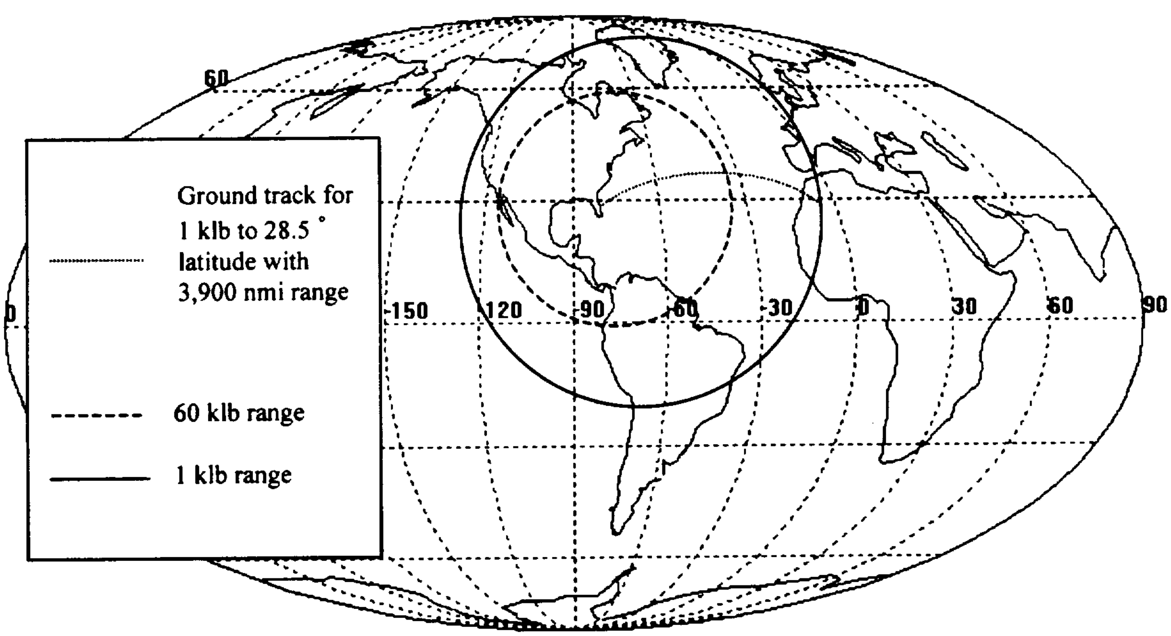


Figure III.2 – Ranging and Ground Track for Single Element Bimese

Five plots of the reference point-to-point trajectory are seen in Figure III.3a through III.3e. The plots show, in order, a time history of the vehicle's altitude, range, angle of attack, acceleration, and velocity. Figure III.3a shows that the trajectory stops at an altitude of 50,000 ft; once the vehicle has reached this altitude and a Mach number of about 1 the trajectory is assumed to be an automated loiter and landing phase that is not simulated. Another feature of this plot is the skipping trajectory; by skipping across the upper atmosphere the vehicle can obtain maximum range. As can be seen from the range plot most of the ranging is done during this skipping phase. Unfortunately this skipping also corresponds to high aerodynamic heating. Also note that the vehicle travels 3,900 nmi in 37 minutes, which gives an average speed of 8,000 miles per hour. This high average flight speed is important for applications of the point-to-point trajectories and will be discussed in more detail later.

III.1.3 Single Element Bimese Conclusions

The single element Bimese has no LEO capability, but it does have a marginal trans-Atlantic point-to-point range with small payloads (under 1 klb). Trans-continental service between the coasts of the United States is also a possibility, setting aside the obvious problems associated with land overflight (noise, safety, and regulatory issues), but the performance of a single element Bimese falls short of enabling trans-Pacific service. <u>To support a more ambitious , long range fast package delivery service, the single element Bimese would have to be sized up by roughly 25% - 35%.</u>

Given its small payload and range capability, the single element Bimese configuration might best be used to offer "charter style" trans-Atlantic service for extremely high value, but lightweight cargoes on an as-needed basis (see the economic analysis in Section IV). In addition, the suborbital trans-Atlantic trajectory flown by the simple Bimese would be excellent for testing a Bimese prototype, putting it through many of the extremes that an orbital vehicle would encounter.

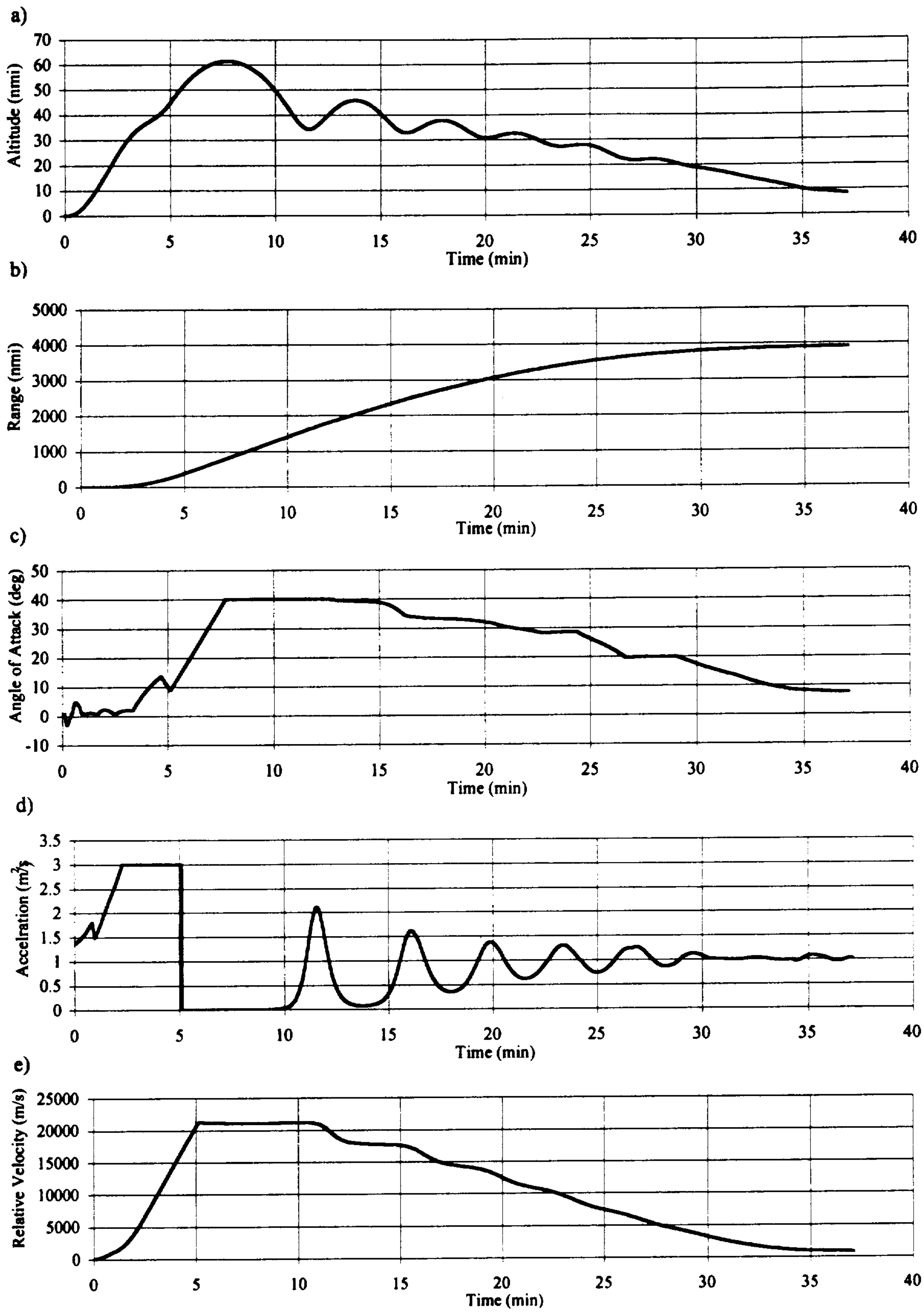


Figure III.3a-e – Time History Plots for Single Element Bimese Point-to-Point

III.2. FUEL-AUGMENTED BIMESE

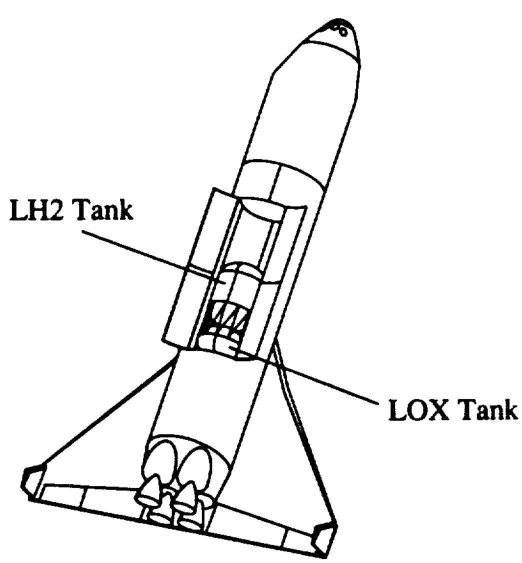
The fuel-augmented Bimese configuration consists of a single element with an extra LOX and LH2 tank in its payload bay. The payload bay is a cylinder, 50 ft long with a 15 ft diameter. If it is fully loaded with propellant, it could hold about 200,000 lb of LOX/LH2.

III.2.1. Fuel-Augmented Bimese: LEO

The fuel-augmented Bimese for the LEO mission for still cannot get any payload to orbit. Although the increased fuel added velocity increment capability, the fact that no additional thrust is added causes the overall thrust-to-weight at liftoff (T/W) to decrease as propellant is added. Even assuming that a liftoff T/W of 1.05 provides adequate liftoff margin, the fuel-augmented Bimese must burn about 20,000 lb of non-propellant mass to get to orbit.

III.2.2. Fuel-Augmented Bimese: Point-to-Point

Simulation of point-to-point fuel-augmented trajectories show that even a payload bay stuffed full of fuel only increases the point-to-point range by about 400 nmi. Combine this with the fact that for minimum architectural developments, the same payload tanks will be used for the fuel/thrust-augmented vehicle (which is expected to have a capability of about 20,000 lb to LEO) leads to the choice of filling three-fifths of the payload bay with tanks. This leaves room for about 20,000 lb of payload and adds only 200 nmi in range to the fuel-augmented point-to-point trajectory. A line drawing of the fuel-augmented Bimese along with payload tank specifications is shown in Figure III.4. The fuel-augmented point-to-point range for 1 klb to 28.5° latitude is 4,100 nmi, no plots will be shown for this because they are very similar to the single element plots.



Payload Tank Parameters	
LOX fuel (lb)	87,300
LOX tank weight (lb)	590
LH2 fuel (lb)	12,600
LH2 tank weight (lb)	890
Structure/feeds (lb)	1,000
Total weight (lb)	104,480
Length of Apparatus (ft)	30

Figure III.4 – Fuel-Augmented Bimese with Payload Tank Parameters

III.2.3. Fuel-Augmented Bimese Conclusions

With the assumptions made on available fuel load, the fuel-augmented Bimese offers little advantage over the single element Bimese. It has no LEO capability and the point-to-point range is only increased by a few hundred nautical miles. In addition it has the operational disadvantage of having to install, fill, and purge during ascent the payload bay tanks.

III.3. THRUST-AUGMENTED BIMESE

The thrust-augmented Bimese configuration consists of a single element with Solid Rocket Motors (SRMs) strapped to the side of the Bimese. A new motor will need to be designed to fill this piece of the transportation system. Keeping the design realistic the new motor is modeled as a derivative of the Graphite Epoxy Motor (GEM), which is currently used on the Delta II 7925. The GEM is chosen because of its good performance and lightweight structure, which are shown in Table III.1.

Table III.1 – Reference GEM Performance and Design Parameters (Delta)

Propellant mass (klb)	25.8
Gross mass (klb)	28.6
Sea level thrust (klb)	99
Sea level I_{sp} (s)	265
Burn time (s)	63.0
Expansion ratio	10.7
Overall length (ft)	42
Core diameter (ft)	3

Scaling the GEM involves the use of <u>simple scaling equations</u>. To increase the burn time of the GEM more propellant is added, while the dry weight is scaled linearly with the fuel weight (dry weight is calculated to be ~10% of the propellant weight). Linearly increasing the nozzle exit area and fuel flow rate while keeping a constant expansion ratio scales thrust. Specific impulse remains a constant for all of the scaling.

A few changes are made to the single element trajectory for the simulations with SRMs. First a 10% drag rise is included while the motors are attached to capture some of the aerodynamic effects of the SRMs. Also because the SRMs provide added T/W the Bimese accelerates much faster resulting in violation of the dynamic pressure constraint listed in Table II.2. To alleviate this problem the main engines are throttled to a constant value while the SRMs are thrusting; this throttle value is optimized within the trajectory simulation.

III.3.1. Thrust-Augmented Bimese: LEO

With thrust augmentation the single Bimese <u>can finally make it to orbit</u>. In order to investigate the ability of the thrust-augmented Bimese to ferry payload to LEO, a design of experiments analysis is performed. Both SRM burn time and total SRM sea level thrust are varied and LEO payload is observed. Based on initial simulation experimental ranges of 75 to 125 sec. for burn time and 1,500 to 2,000 klb for total SRM sea level thrust are chosen. The lower limits are set by zero payload capability. The upper limits are set by throttle limit violation when trying to meet the dynamic pressure constraint. Table III.2 shows the results of the design of experiment (a negative payload indicates the vehicle cannot make it to orbit). A response surface with a mean square of 0.999 is generated and plotted in Figure III.5.

Table III.2 – Experimental Design for Thrust-Augmented Bimese

SRM burn time (s)	Total SRM Sea Level Thrust (klb)	Payload to LEO (lb)
75	1,500	-7,896
100	1,500	-1,727
125	1,500	1,123
75	1,750	-1,553
100	1,750	5,742
125	1,750	8,712
75	2,000	3,651
100	2,000	11,939
125	2,000	17,077

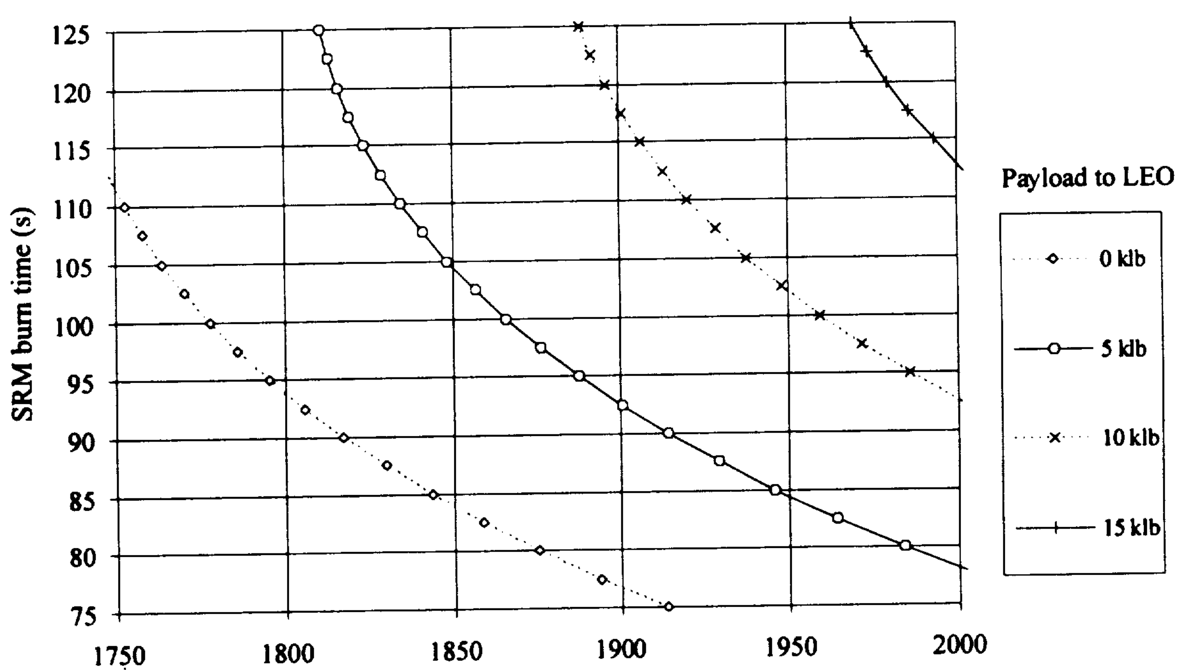


Figure III.5 – LEO Payload to Orbit for Thrust-Augmented Bimese

This figure illustrates that the thrust-augmented single Bimese can get anywhere between 1 and 20 klb to LEO. It also shows that many SRM designs can fill a single payload requirement to LEO. That is, the solution for a given payload capability is a non-unique combination of total SRB sea-level thrust and burn time. To determine which SRM design is best (here, lowest SRB gross weight) for each payload capability, a plot of SRM gross weight for the 5 and 10 klb payload thrust-augmented Bimese is introduced in Figure III.6.

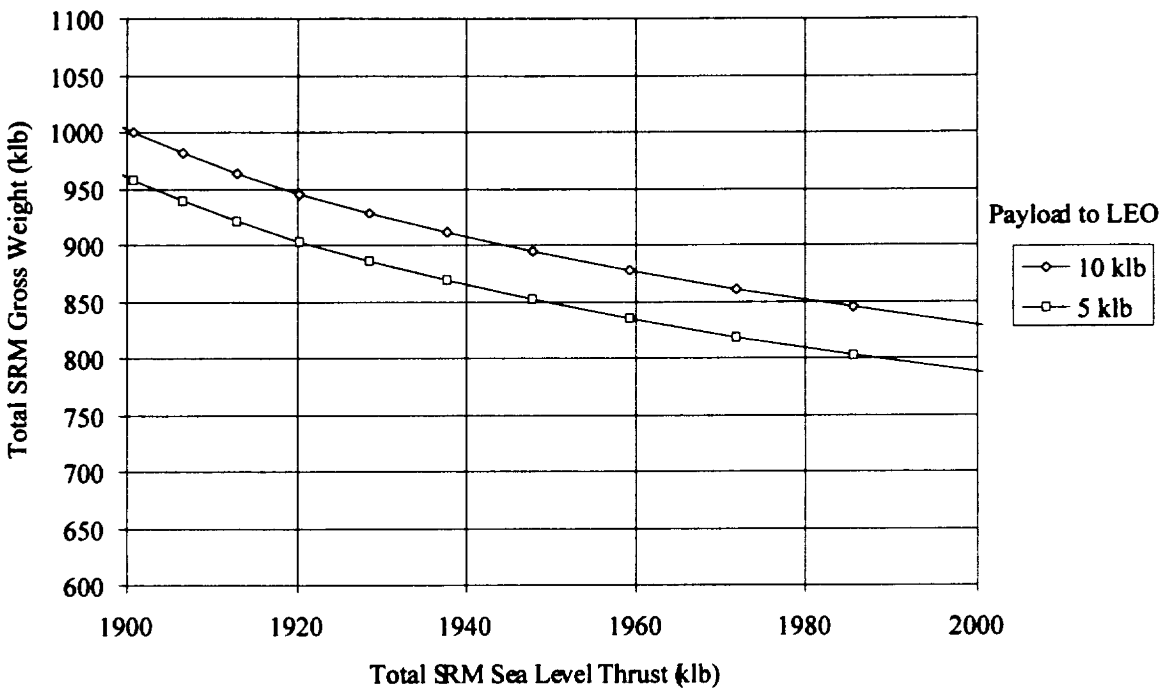
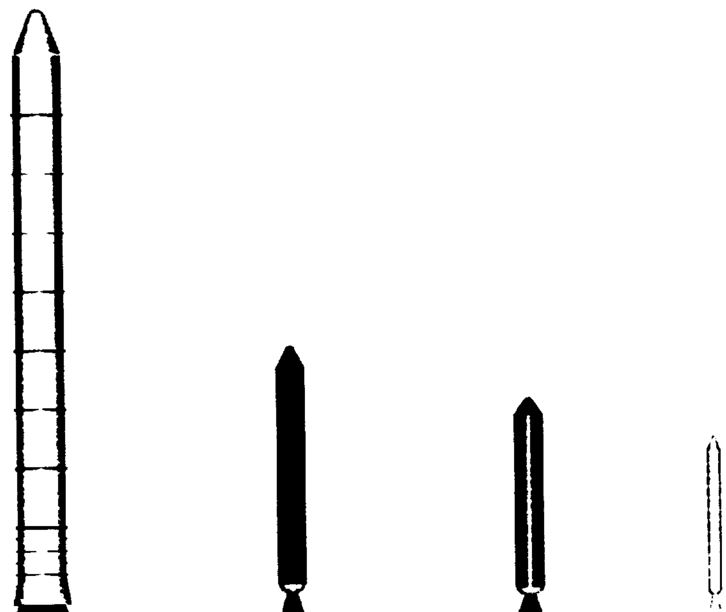


Figure III.6 – SRM Gross Weight Change for Constant Payload to LEO

For a constant payload, the minimum SRB weight occurs with maximum allowable thrust. Therefore the maximum thrust value that is within the ranges of the experimental design will be used for thrust augmentation. That is, the total sea-level SRB thrust is set to 2,000,000 lb. in subsequent analysis and SRB burn time is varied to get the desired payload capability.

The number of individual of SRB's for the 5 and 10 klb payload cases was chosen to be 4 to yield a symmetric configuration and a reasonable SRB size (500 klb thrust at sea-level per SRB). Figure III.7 shows the GEM derivatives and the resultant burn times for each payload capacity (GEM-10 for the 10 klb payload case and GEM-5 for the 5 klb payload case). The figure also compares the Bimese GEMs with the Shuttle SRB and the reference GEM from the Delta 7925.



SRM name	Shuttle SRB	GEM-10	GEM-5	GEM
Vehicle use	Two on the Space Shuttle	Four on 10 klb to LEO thrust-augmented Bimese	Four on 5 klb to LEO thrust-augmented Bimese	Nine on Delta 7925
Propellant mass (klb)	1,107	190	155	25.8
Gross mass (klb)	1,300	210	175	28.6
Sea level thrust (klb)	2,650	500	500	98.9
Sea level I_{sp} (s)	267	274	274	274
Burn time (s)	124	92.8	78.2	63.0
Expansion ratio	7.5	10.7	10.7	10.7
Overall length (ft)	150	60	50	43
Core diameter (ft)	12	6	6	3

Figure III.7 – SRM Size and Performance Comparison Chart

The Bimese with four GEM-10s, seen in Figure III.8, will be used as the reference thrust-augmented Bimese.

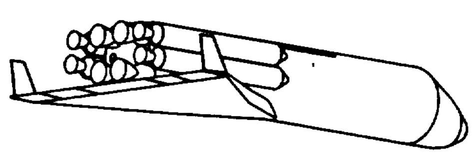


Figure III.8 – Thrust-Augmented Bimese with Four GEM-10s

A verification run was performed to obtain the actual payload (instead of the regressed payload) obtained when four GEM-10s with the parameters in Figure III.7. For the verification run, the thrust-augmented single Bimese was found to insert 9,740 lb of payload into LEO.

Altitude, throttle setting, dynamic pressure, and acceleration of the simulated ascent trajectory are seen in Figures III.9a through d. In Figure III.9b notice the throttle setting for the main engines is set to a constant value at twenty seconds up until the solids are dropped. Also notice in Figure III.9d the high liftoff T/W of about 1.75; this is what causes the dynamic pressure violation and the need for throttling.

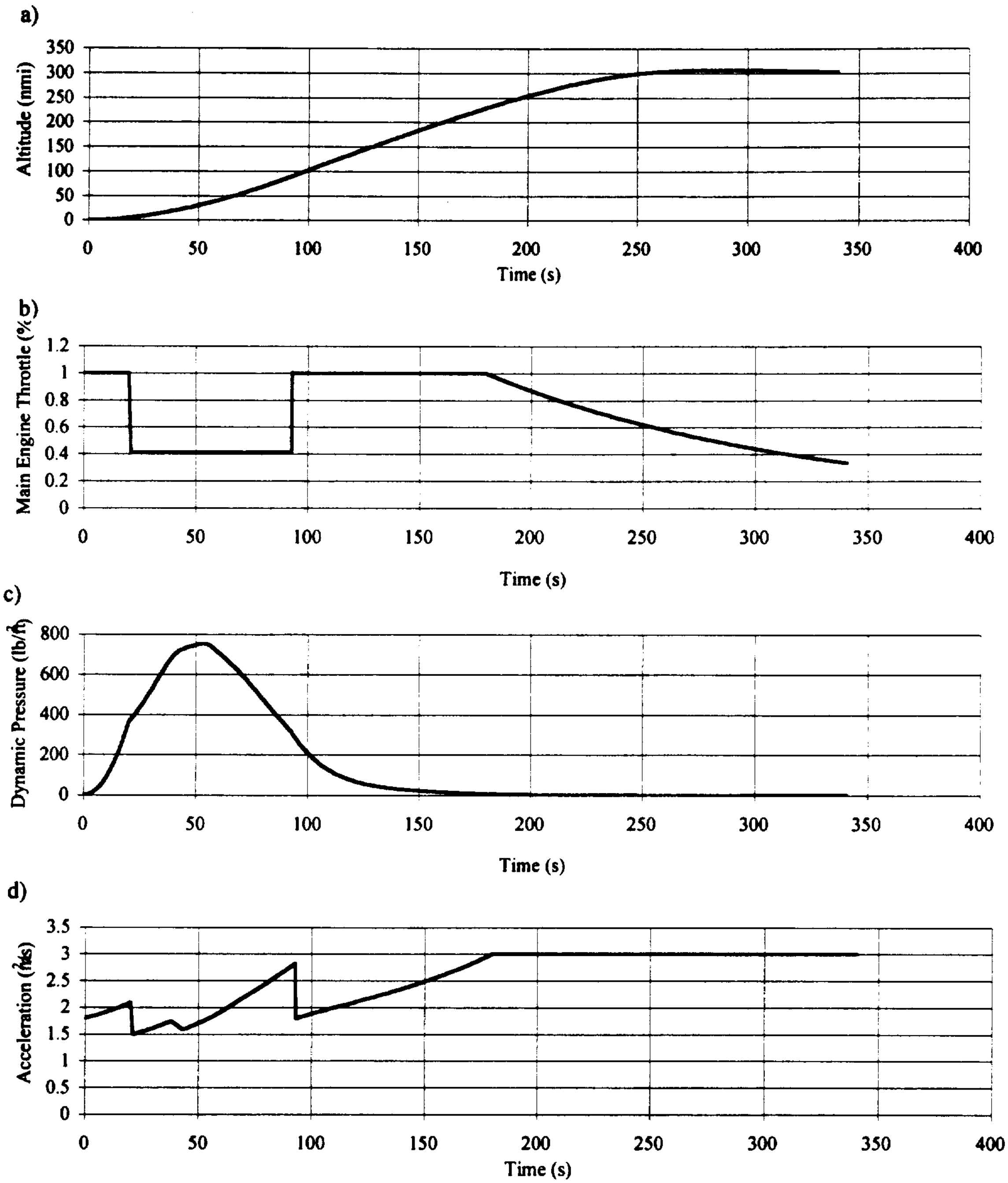


Figure III.9a-d – Time History Plots for Thrust-Augmented Bimese to LEO

III.3.2. Thrust-Augmented Bimese: Point-to-Point

The thrust-augmented Bimese with four GEM-10s cannot fly a ballistic point-to-point trajectory while meeting all of the constraints listed in Table III.2. Therefore the point-to-point trajectory is simulated with two GEM-10s. For the point-to-point configuration, 6,200 lb of propellant is off-loaded from the orbital configuration which corresponds to the OMS fuel needed to circularize and de-orbit. The single element point-to-point simulation shows that the thrust-augmented Bimese can transport 1 klb of payload to 28.5° latitude with a range of 6,050 nmi. A ground track of the trajectory is shown in Figure III.10. Also shown in this figure are the approximate landing locations for launches in all directions. The same graphic has range capabilities for the thrust-augmented Bimese with 60 klb of payload. The thrust-augmented Bimese is easily capable of delivering 1 klb or more to a variety of spots in Europe, but still falls short of trans-Pacific range. From the figure, carrying 60 klb of payload weight with the thrust-augmented single Bimese results in a range similar to that of the 1 klb single element Bimese point-to-point range (i.e. marginal trans-Atlantic range).

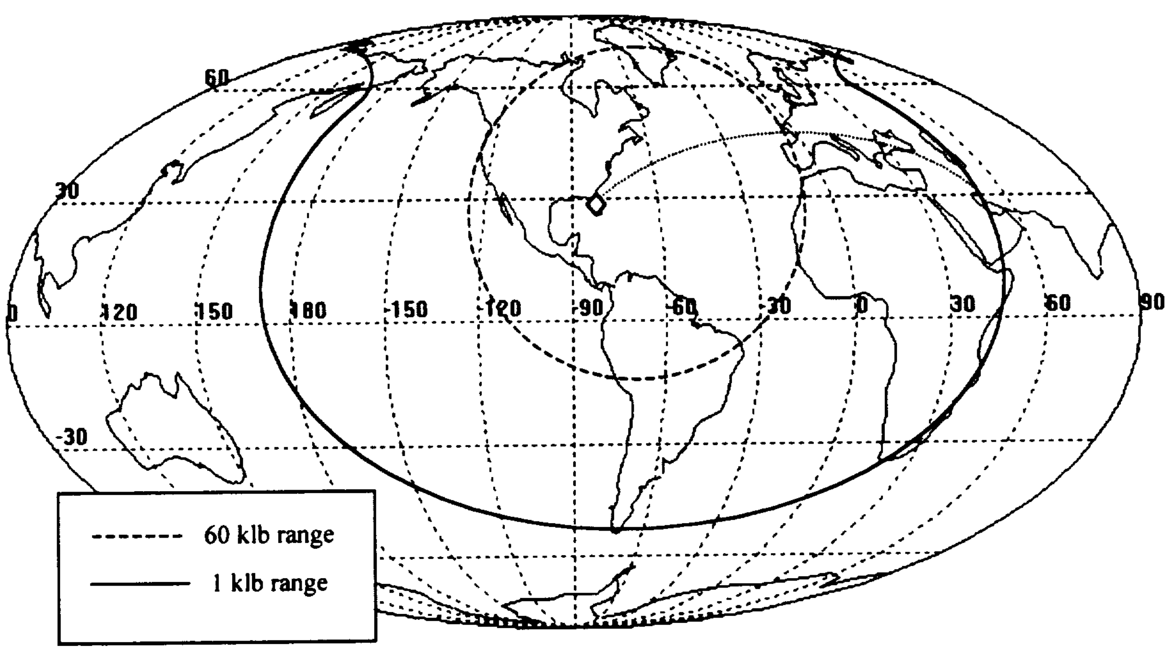


Figure III.10 – Ranging and Ground Track for Thrust-Augmented Bimese

Four plots of the point-to-point trajectory are seen in Figure III.3a through III.3e. The plots show in order a time history of the vehicle's altitude, acceleration, angle of attack, and velocity profile. Another feature of the trajectory is the extreme altitude (80 km) to which the vehicle ascends. The trajectory takes about 45 minutes. There are abrupt peaks in the velocity profile (Figure II.11d) which would indicate severe heating loads. Because the vehicle appears to be at the limit (or perhaps even beyond in the case of aeroheating) of many of its trajectory constraints, no higher thrust configurations will be examined for longer range point-to-point missions.

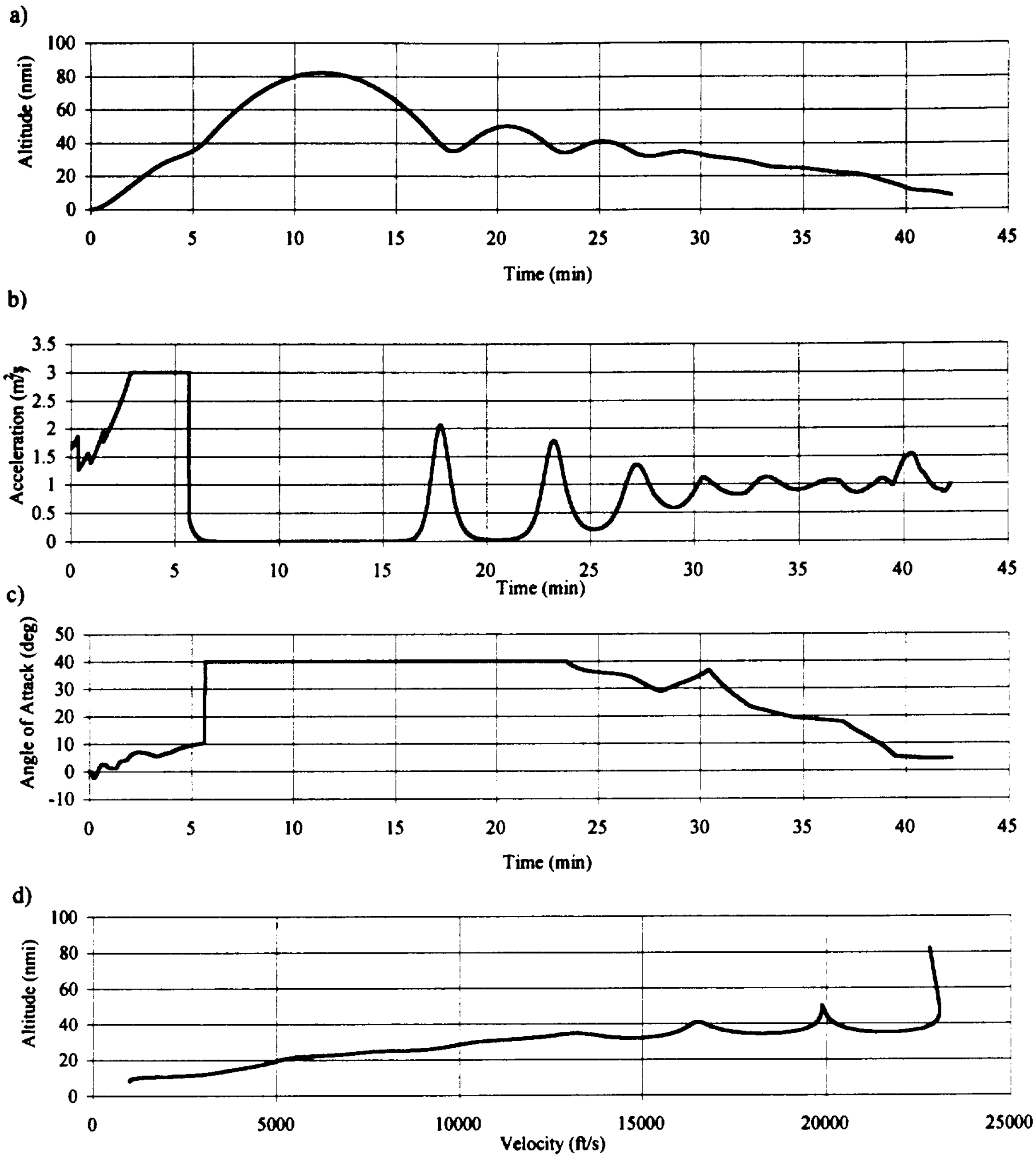


Figure III.11a-d – Time History Plots for Thrust-Augmented Bimese to PTP

III.3.3. Thrust-Augmented Bimese Conclusions

The thrust-augmented Bimese is a success both in terms of LEO payload and point-to-point range. With four GEM-10 SRBs, the vehicle can deliver almost 10,000 lb to LEO. The point-to-point ability has significant range and payload with the ability to boost to such places as western Europe and the tip of South America from KSC in under an hour. Its drawback is the requirement of the use of large solids that will need to be purchased and integrated for every flight.

III.4. FUEL/THRUST-AUGMENTED BIMESE

The fuel/thrust-augmented Bimese configuration consists of a single element Bimese with fuel tanks in the payload bay and SRMs strapped to the side. The same designs for the fuel-augmented Bimese payload tanks (99,900 lb. of propellant per Figure III.4) and thrust-augmented Bimese SRMs are used on this vehicle for the LEO mission. As mentioned earlier, this configuration was not examined for point-to-point range since it would easily exceed the trajectory constraints on a programmed suborbital mission. Since this configuration can easily make low earth orbit, one might think of it (and the four SRB thrust-augmented Bimese in the previous section) as a global range fast-package delivery vehicle with a point-to-point payload equal to its orbital payload capability.

III.4.1. Fuel/Thrust-Augmented Bimese: LEO

Similar to that performed for the thrust-augmented Bimese, a design of experiments analysis is performed on the thrust/fuel-augmented Bimese to test its LEO capability. The same range of 75 to 125 sec. for burn time and 1,500 to 2,000 klb for total SRM sea level thrust are chosen. Table III.3 shows the results of the design of experiments matrix (a negative payload indicates the vehicle cannot make it to orbit). A response surface with a mean square of 0.985 is generated and plotted in Figure III.12.

Table III.3 – Experimental Design for Fuel/Thrust-Augmented Bimese

SRM burn time (s)	Total SRM Sea Level Thrust (klb)	Payload to LEO (lb)
75	1,500	-1,751
100	1,500	4,507
125	1,500	7,774
75	1,750	3,562
100	1,750	10,179
125	2,000	15,566
75	2,000	9,960
100	2,000	19,672
125	2,000	22,323

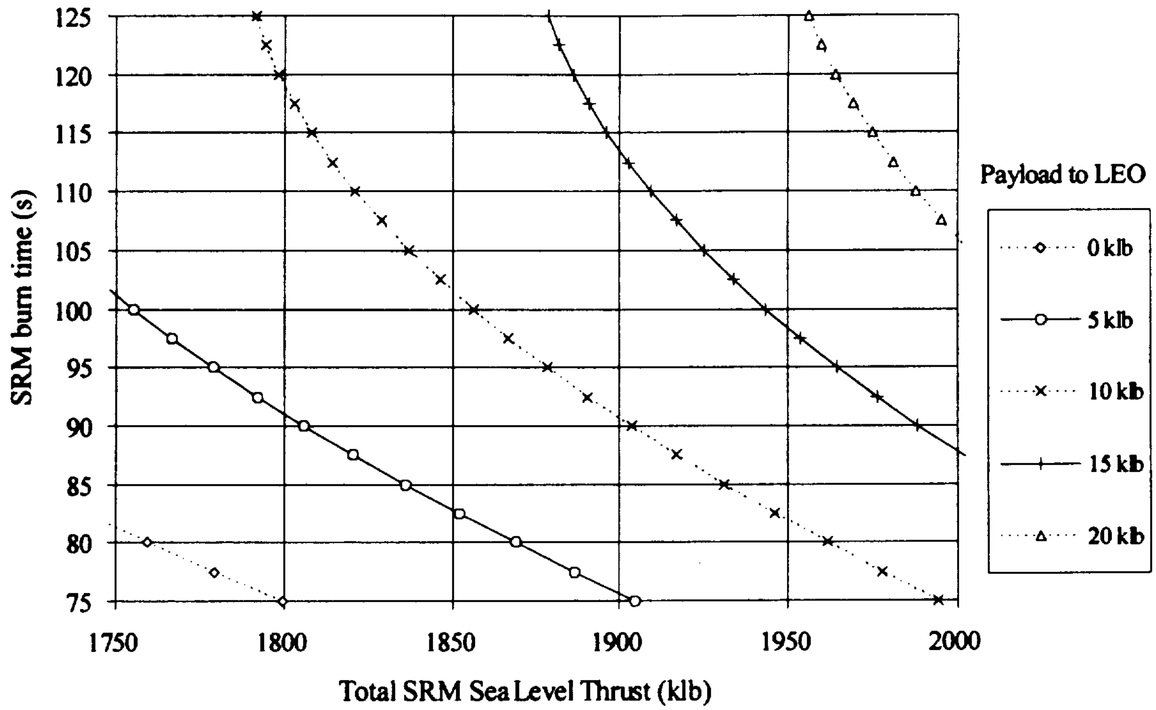


Figure III.12 – LEO Payload to Orbit for Fuel/Thrust-Augmented Bimese

This figure illustrates that the fuel/thrust-augmented Bimese can get anywhere between 1 and 25 klb to LEO. For similar sized SRMs, it can deliver about five thousand more pounds of payload over the thrust-augmented Bimese without additional tanks in the payload bay. For commonality with the thrust-augmented Bimese, the fuel/thrust-augmented design will use four previously sized GEM-10s (500 klb sea level thrust each with a 92.8 sec. burn time, from Figure III.7). Verifying the response surface prediction with an actual trajectory simulation with these SRMs gives a payload of 15,900 lb. A picture of this Bimese configuration is shown in Figure III.13.

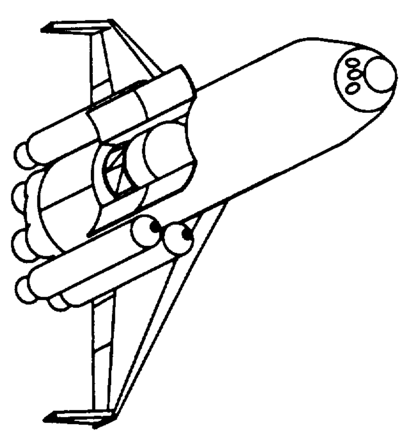


Figure III.13 – Fuel/Thrust-Augmented Bimese

Although there are tanks in the payload bay, there is still a 20 ft long 15 ft diameter space in the bay, which is enough room for the reference payload. Time history plots of the ascent trajectory are not shown because they are very similar to the thrust-augmented Bimese plots.

III.4.2. Fuel/Thrust-Augmented Bimese Conclusions

Fuel augmentation increases the payload of thrust augmentation by about 5,000 lb, which is attractive considering the only added costs are fuel tanks, operational complexity, and fitting the Bimese with proper payload feed lines. If a global range fast package delivery is desired, this configuration could delivery 15,900 lb. to orbit, and then deliver it to nearly any location on the globe. However, the four SRB's and the internal fuel tanks make this configuration more expensive to operate than any of the previous concepts considered.

III.5. MATED BIMESE

For completeness, the nominal mated Bimese configuration was examined. The mated Bimese configuration consists of two single elements attached to each other. Pictured in Figure III.14 the mated Bimese has the following characteristics: propellant cross-feed, un-powered fly back, and commonality between booster and orbiter.

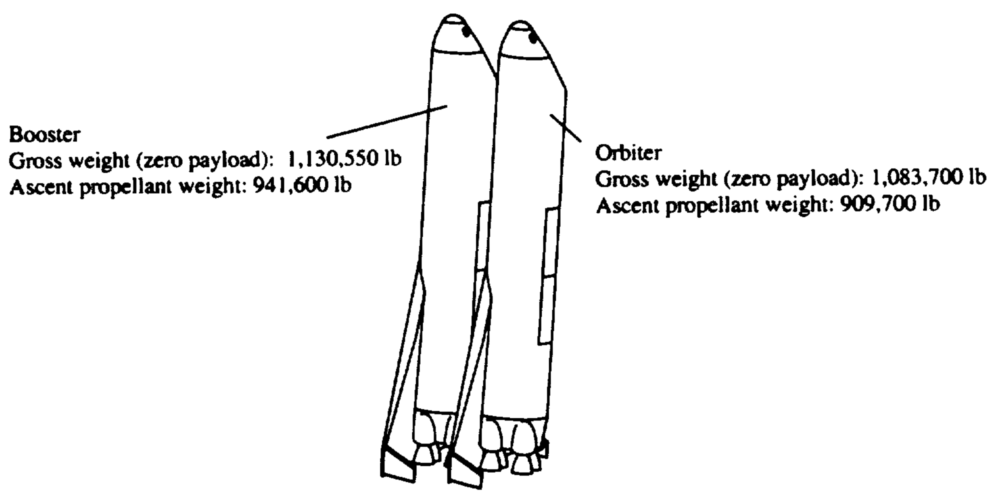


Figure III.14 – Mated Bimese

III.5.1. Mated Bimese: LEO

The Bimese was designed so that the mated configuration could lift 60 klb to LEO. Upon launch fuel is cross-fed from the booster Bimese to the orbiter Bimese, while all eight engines are ignited. The booster stages at Mach 3.2 (propellant must be off-loaded to do this) and then performs a hypersonic turn and glides back to the launch site. From here the orbiter ascends to orbit, with the benefit of a Mach 3.2 boost. Plots of the ascent trajectory are seen in Figure III.15a-c.

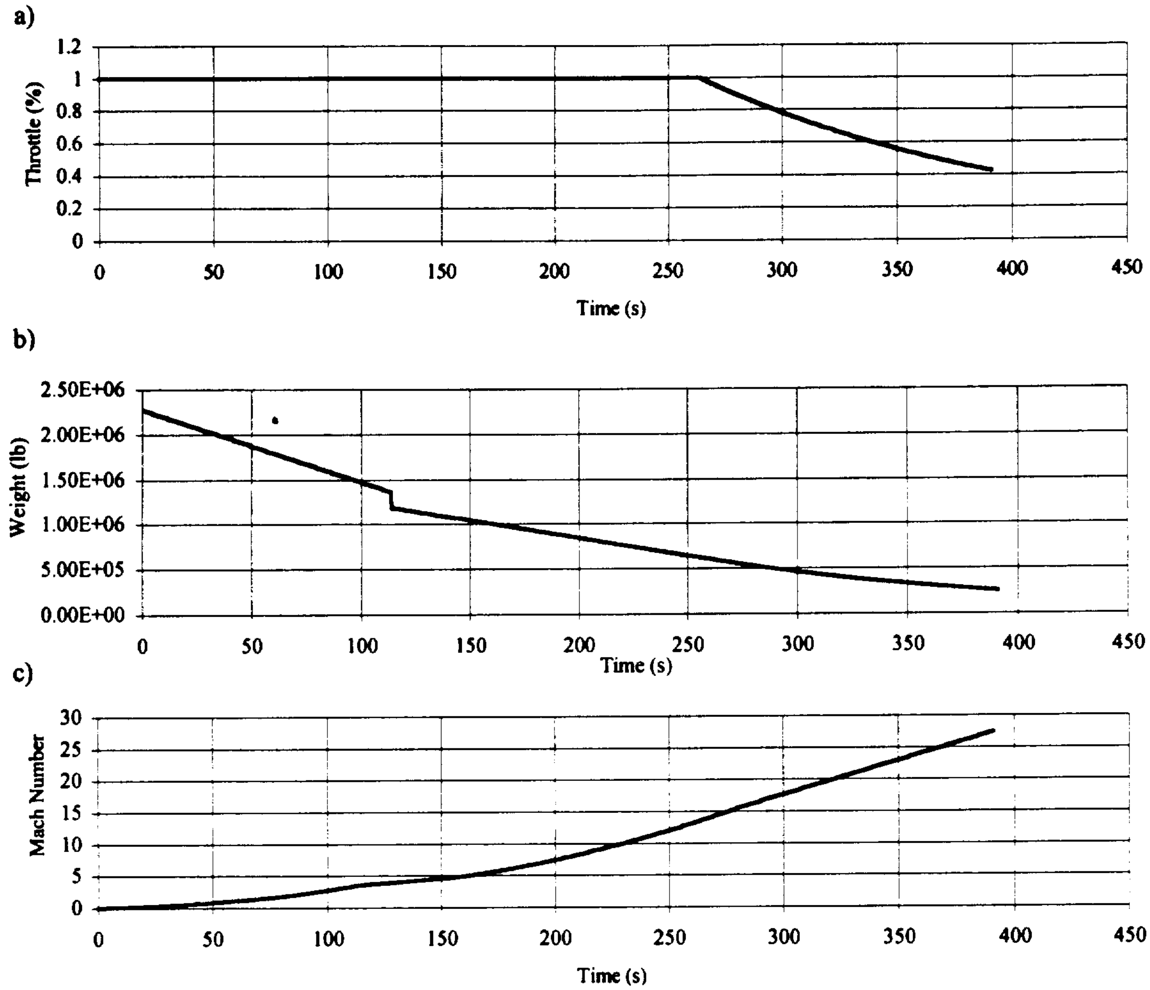


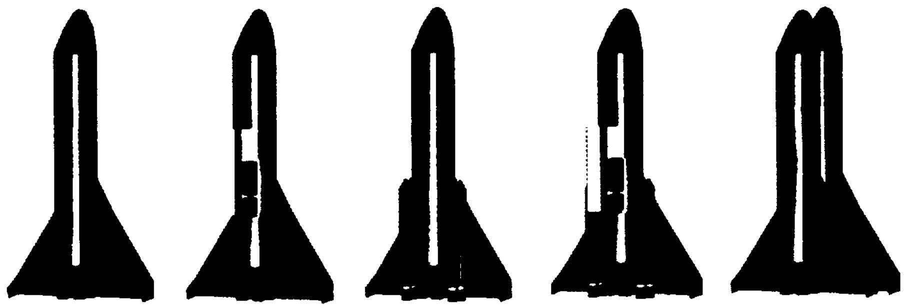
Figure III.15a-c – Time History Plots for Fuel/Thrust-Augmented to LEO

III.5.2. Mated Bimese Conclusions

The large payload capability of the mated Bimese makes it a candidate for NASA missions to the space station or heavy lift missions such as the deployment of a large space telescope. The commercially market for this size payload is unproven, but it is possible it could be used for multiple manifesting or geo-stationary payload delivery.

III.6. SUMMARY OF MISSION OPTIONS

A fleet of vehicles has now been established that can deliver a wide range of payloads to orbit from Kennedy Space Center and (at least from a performance perspective) can deliver cargoes to terrestrial spaceports in support of a ultra-fast package delivery service. Except for the fuel-augmented Bimese each of the vehicle seems to have a niche where it could be used to enter the commercial or government launch market. The vehicles are shown in Figure III.16 along with the capabilities.



Mission	Single element	Fuel-augmented	Thrust-augmented # GEM-10s 2	Thrust-augmented # GEM-10s 4	Thrust/fuel-augmented (4 GEM-10s)	Mated (Bimese)
LEO Capability (lb)**	0	0	0	9,750	15,900	60,000
Point-to-point capability (nmi)*	3,900	4,100	6,050	†	†	†

*** LEO payload delivered to a 100 nmi x 100 nmi at 28.5° inclination*

** Point-to-point range capability for 1 klb to 28.5° latitude*

† These vehicles have essentially global range with a point-to-point cargo equal to their LEO payload

Figure III.16 – Bimese Payload and Mission Options Summary

For global range fast-package delivery, any of the configurations with orbital capability would meet the requirements. The thrust-augmented configuration with 2 GEMs provided the longest range and highest payload capacity in a suborbital configuration (although still short of trans-Pacific). The simplest and cheapest configuration, the single element Bimese, is too small to provide more than lightweight cargo delivery (< 1klb) to extreme western Europe from KSC.

IV. ECONOMIC ANALYSIS

One of the goals of this study is to investigate the economic prospects for a profitable ultra-fast package delivery business using components of the Bimese architecture. All of the following economic analyses will assume the creation of a startup fast-package delivery company named Bimese PTP, Inc. Four economic scenarios will be considered with assumptions ranging from conservative to very optimistic. The success of each scenario will be quantified in terms of an Internal Rate of Return (IRR) that is calculated from an internal cash flow analysis (revenues - expenses and taxes). In the aerospace sector, a business venture is ordinarily considered to be economically attractive if the IRR is greater than about 25%. Note that for most of the point-to-point scenarios considered, any operating synergies between Bimese PTP, Inc. and companies using Bimese elements in the LEO crew/cargo delivery market are ignored. That is, the Bimese PTP, Inc. company is considered a separate company and does not share personnel or flight vehicles with LEO missions. However, three of the four scenarios examined assume some reusable element production and design cost synergy with an unnamed LEO company.

IV.1. THE POINT-TO-POINT FAST PACKAGE MARKET

For the emerging, intercontinental ultra-fast package delivery market, the advantage for using rocket over aircraft delivery lies in the former's speed of flight. The time for checkout, truck delivery, and port delay for the two modes are the same. Therefore to see any real advantage over aircraft, the Bimese must ship goods fast and far to places where there is a large difference between aircraft trip times and boost-glide trip times. Table IV.3 shows the advantage rocket delivery has over airplane delivery in terms of trip time for selected trans-Atlantic and KSC - South American city pairs. Representative prices from the current aircraft-based fast package market are also given (about \$10/lb for a 2 lb. package).

Table IV.1 – Time of Flight of Aircraft versus Bimese

From	To	Approximate flight time (hr)		FedEx next day air cost
		Aircraft	Bimese	(\$/lb)
KSC	Madrid	8	~ 0.7	10
KSC	Los Angeles	3	~ 0.5	7
KSC	London	8	~ 0.7	10
KSC	Rio De Janeiro	10	~ 0.7	12
KSC	Paris	9	~ 0.7	13

From Table IV.1, a rocket-based system can reduce the flight time for package delivery by over 90% in some cases (longer ranges show better reductions). While this does not necessarily translate to significant door-to-door time reductions, it is clearly an advantage for rocket systems. Of course the Bimese has many disadvantages compared to aircraft systems including: no existing spaceports for vertical launch, high turn around times, high startup costs, land overflight issues at lower altitudes, uncertain reliability, and the use of an unproven vehicle concept. Economically these disadvantages will be hard to overcome for Bimese PTP, Inc.

IV.1.1. The Size of the Ultra-Fast Package Delivery Market

The basic assumption in this analysis is that shippers will pay a premium for speed. Just as companies such as Federal Express and Emory World Wide became economically successful by offering next-day service within the U.S. and Europe, many believe that there is a market for next-day (or even same-day) service between long range city pairs. The size of this market will depend on the price offered to shippers. That is, the ultra-fast package is assumed to be price elastic. Unfortunately, no universally accepted data exists for the ultra-fast package delivery market

For the purposes of this study, the fast-package delivery data from NASA's Commercial Space Transportation Study (CSTS) will be used for order of magnitude analysis. In general, the CSTS data can be summarized by Figure IV.1. Note that this figure uses a log-log scale. Here one can see the upper and lower bounds of the CSTS predicted markets.

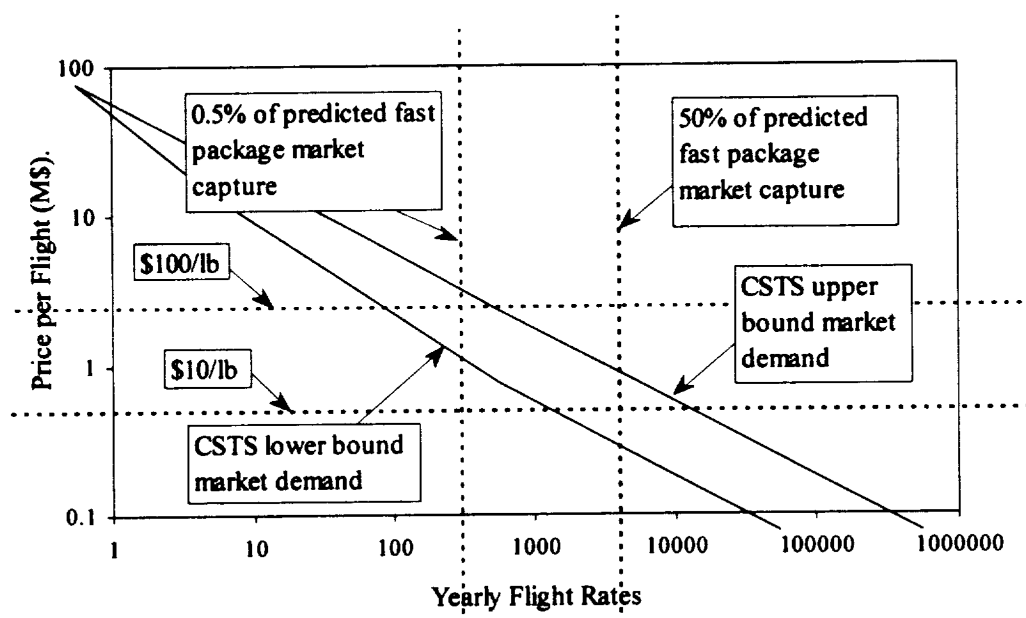


Figure IV.1 – Point-to-Point Market Summary

If we assume that the average configuration used by Bimese PTP, Inc. will ship an average of 5,000 lb. per flight and set the lower limit on average package price at $10/lb. (current aircraft system prices) and the upper limit one order of magnitude higher ($100/lb), then a region of the CSTS data can be bounded within the CSTS data. Note that the CSTS data for this market consists of an upper limit and a lower limit. The bounded region corresponds to a revenue of between $0.5 M and $5 M per flight and a total number of annual flights of the system (all routes) of between 200 and 8000 flights per year or about 0.5% to 50% of the current aircraft-based fast package delivery market.

Higher package prices (higher premiums over today's prices) result in very low traffic rates and seem unlikely to justify the required investment to create Bimese PTP, Inc. Offering lower package prices might be considered a less risky way to enter new market. That is, it is more reasonable to expect current shippers to pay a premium of 25% - 100% for faster speed (say, up to $20/lb.) than it is to expect shippers to pay prices a factor of 10 higher than current prices. The former is more of an incremental market expansion, while the later approach would depend almost exclusively on enticing new, previously unserviced, shippers to enter the market (e.g. shipment of biological specimens, volatile pharmaceuticals, or other priority freight). However, it is unlikely that Bimese PTP, Inc. could offer prices close to or lower than that offered by today's aircraft given the extra expenses of operating a rocket relative to an aircraft.

Based on these qualitative arguments, the ideal "sweet spot" of the CSTS fast-package market for a rocket system would seem to lie in the middle to lower right of the box indicated in Figure IV.1 — roughly 2000 flights per year at a revenue of $1M per flight. Whether the system is actually profitable in that range will be determined in a subsequent section of this report.

IV.1.2. The "Ideal" Service Scenario

Before directly considering the economics of Bimese PTP, Inc., an "ideal" service scenario was envisioned based on the point-to-point payload performance of the Bimese configurations previously examined.

In order to be successful, Bimese PTP, Inc. will likely need to offer regular scheduled service between selected city pairs or spaceports between economically developed parts of the world. Daily weekday service each way between two spaceports would yield about 500 flights per year. Four routes would be needed to serve the 2000 flight per market estimated for the CSTS sweet spot above.

Based on performance, Bimese PTP, Inc. would prefer to offer a range of flight configurations. The longest range and heavy cargo route(s) would be serviced by the thrust-augmented single element Bimese with four GEM-10 SRB's. This vehicle would in fact provide global range with up to almost 10,000 lb. of payload. The intermediate route(s) would be served by the thrust-augmented single element Bimese with only two GEM-10 SRBs. This configuration provides a sufficient range to reach mid-Europe from KSC with payloads up to 40 klb. - 60 klb. (and could marginally reach the Pacific-rim from the west coast of the U.S. with small payloads up to 1 klb.). Relative to the four GEM-10 option, the two GEM-10 configuration is expected to be cheaper to operate and is therefore the preferred workhorse (for a performance point of view). The mated Bimese configuration requires two flight elements per mission and is thought to be too "overkill" for servicing the point-to-point market.

Given its limited range, the single element Bimese by itself is undersized for use on a regularly scheduled service route. Therefore, it is more likely to be used in limited role. A standby "charter" mode for very high priority, but lightweight cargoes is envisioned.

From the east coast of the U.S., the single element Bimese might be used to fly cargoes up to 1 klb to extreme western Europe or to South America. No more than 50 or so of these charter flights are expected per year (once per week).

While this "ideal" service scenario would provide the requisite level of service to enable the ultra-fast package delivery market, it remains to be seen whether it results in a economically attractive scenario for Bimese PTP, Inc.

IV.2. BIMESE PTP, INC. COST AND OPERATIONS

To estimate IRR for a business scenario, the cost and revenue cash flows must be predicted as a function of flight rate. Bimese PTP, Inc. will incur both non-recurring (start-up) costs and recurring costs (variable costs). Non-recurring costs typically consist of facilities construction costs, flight vehicle DDT&E costs (design, development, testing, and evaluation), and reusable flight vehicle procurement costs (related to TFU, theoretical first unit cost, and required fleet size). Recurring costs include procurement of expendable hardware, ground labor costs, maintenance hardware costs, propellant costs, and insurance costs. Financing costs (interest on debt) are also accounted for in the cash flow analysis.

IV.2.1. Economic Assumptions

Bimese PTP, Inc. is assumed to begin to develop the Bimese launch vehicle with government help in 2007; the entire Bimese program ends in 2037. The transportation system created is one full generation beyond the Shuttle Transportation System in terms of the technologies utilized (Gen2 RLV). Production and operations learning curves of 85% have been assumed. All of the cost and business analysis is forecasted using Cost And Business Analysis Module (CABAM) developed at Georgia Tech's SSDL and all of the operations modeling is performed using Architecture Assessment Tool-enhanced (AATe) v1.0 developed by NASA KSC. Monetary units will be given in terms of constant year 1998 United States dollars.

The TFU and DDT&E for the Bimese launch vehicle were estimated using component-level weight-based NASA Air Force COst Model (NAFCOM) equations stored in CABAM. The results obtained for the Bimese airframe and engine are listed in Table IV.2. The values shown are prior to taking a deduction for government contribution and include a 20% cost margin for conservatism. The TFU listed for the Bimese liquid engine is for a single engine, not for a complete flight set of 4. The engines are assumed to have a lifetime of 250 flights before they need to be replaced and each airframe has a life of 1,000 flights before it needs to be replaced. For all business cases it will be assumed that, at the very least, the government pays for 20% of the airframe DDT&E and 100% of the engine DDT&E. For the mission option with payload tanks, the tanks are assumed to be reusable, and the DDT&E and TFU for these tanks are also listed in Table IV.2.

Table IV.2 - Bimese Launch Vehicle Costs

Component	DDT&E (M$)	TFU (M$)
Airframe	$ 6,950	$ 1,431
Main engine	$ 450	$ 109
Payload tanks	$ 95	$ 20

It is assumed that a separate company makes the GEM-10s and charges Bimese PTP Inc. a fixed price for the SRB motors. The current GEM on the Delta has a fixed price of about $1.2M. Taking into account an expected price benefit from volume production and also the fact that the GEM-10 is scaled up by a factor of about five in terms of mass and thrust, the GEM-10's will be assumed to cost $2M each. As will be shown, this estimate has a significant effect on the economics of the thrust-augmented single element Bimese options.

Using AATe (Architecture Assessment Tool from NASA KSC), the turnaround times between flights of the various Bimese configurations are estimated and listed in Table IV.3. AATe is grounded in Space Shuttle data and estimates the ground processing time of advanced space vehicle concepts based on system-by-system order-of-magnitude comparisons between the current concept and the Space Shuttle. The single element Bimese is the simplest of the configurations examined and is estimated to have an average turnaround time of just under two-weeks (leading to an annual flight of about 31 flights per airframe per year). By comparison, a shuttle orbiter requires about 12 - 16 weeks of processing between flights. For the Bimese configurations, there is a slight increase in turnaround time, as the integration becomes more complex. It is assumed for the mated Bimese that the preparations before launch and after landing can be done on the two elements simultaneously. Note that while a two week turnaround time is good compared to the current space shuttle, it is no where near the turnaround time of a typical long range aircraft (which can be measured in hours). This variable has a significant effect on required fleet size for Bimese PTP, Inc. To support the "ideal" scenario of 2000 flights per year , the required fleet size would be about 70 airframes!

Table IV.3. – Turnaround Times for Bimese Configurations

Architectural Configuration	Turn around time (days)	Yearly flight rate
Single element	12	31
Thrust-augmented	13	28
Fuel-augmented	13	28
Thrust/fuel-augmented	14	26
Mated	16	23

Non-recurring construction of facilities cost are assumed to be paid for by a local or national government investing in a spaceport for possible economic benefits to a region. That is, the spaceport is assumed to be a comparable fixed infrastructure to a regional airport and Bimese PTP, Inc. is analogous to an airline operating from a government-owned spaceport. Operating from this spaceport, Bimese PTP Inc. is assumed to account for 15% of the total flights and pays a nominal "fee" of $50k - $100k per flight to use the facilities, launch pads, and runways of the spaceport.

IV.2.2. Recurring Cost Results and Comparisons

Expendable GEM-10 cost, ground personnel labor costs, maintenance hardware cost, propellant cost, stage integration, and insurance costs sum up to total recurring costs per flight. Economies of scale are assumed to benefit recurring costs slightly. Figure IV.2 shows the estimated magnitude of these variable costs for each of the five Bimese configurations examined.

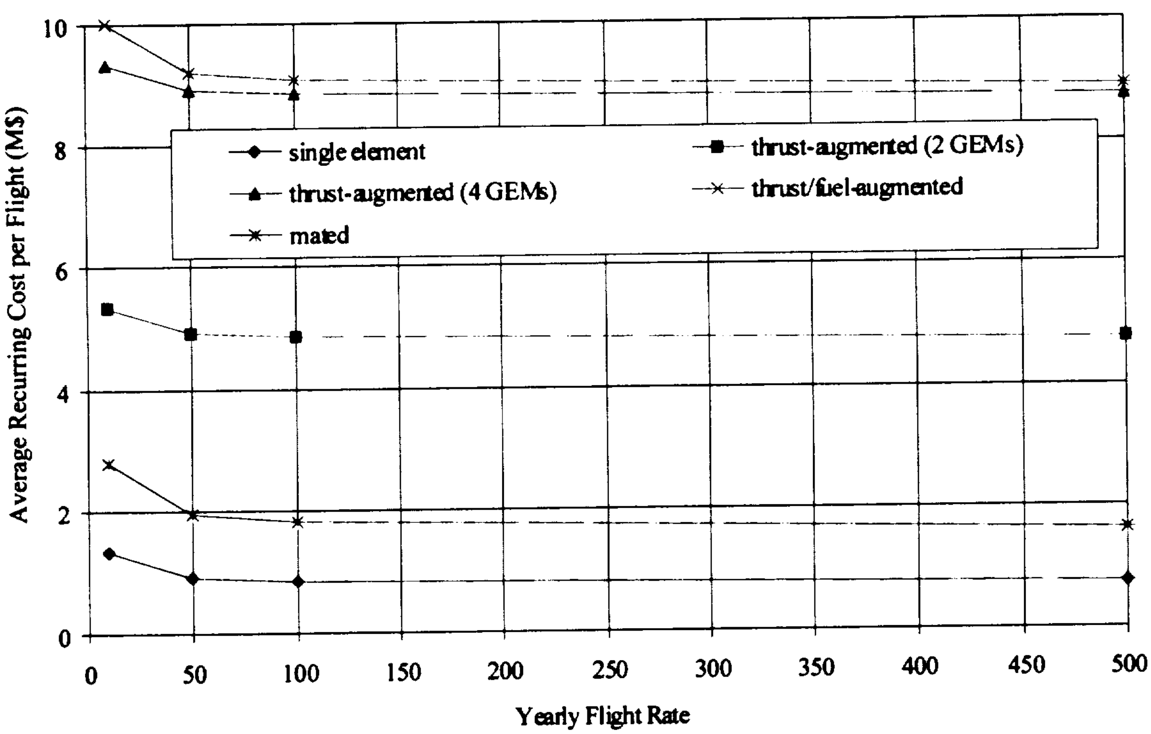


Figure IV.2 – Average Recurring Costs for Multiple Configurations

It is quite clear the major effect on the recurring cost is the purchase cost of the GEM-10 SRBs at $2M each. Given that the <u>total revenue</u> goal from section IV.1.1 is only on the order of $1M per flight, any configuration with the <u>recurring cost</u> over $1M is economically infeasible (before amortization of non-recurring costs are even considered). The fully reusable single element and mated Bimese configurations pass this first-order cost filter, but all configurations with expendable SRB's do not. This requires a major rework of the "ideal" service scenario of section IV.1.2.

IV.2.3 The "Realistic" Service Scenario

The discussions above create a dilemma for Bimese PTP, Inc. Due to range and payload requirements, a full global range fast-package service with regularly scheduled routes requires a thrust-augmented Bimese configuration. The expected ultra-fast package market only reaches appreciable size when package prices are around $20/lb. so revenue is limited to under $1M/flight. However, because the thrust-augmented Bimese configurations use expendable SRB's, their cost quickly exceeds the expected revenues.

Assuming that the single element Bimese design cannot be sized up to carry more payload or achieve a longer range and further assuming that the use of the mated configuration for fast package delivery will not be competitive since the fleet size will essentially be doubled at each site (doubling the non-recurring costs that must be amortized each flight), the following scenario is established. Bimese PTP, Inc. will offer only "charter-style" service on single element Bimese vehicles from KSC to points within its 3,900 nmi range. Payload will be limited to the 1 klb. capacity of this configuration. Note that the fuel-augmented version of the Bimese could be used where necessary to extend the range slightly. This option is not modeled explicitly, but the results would not be expected to change the "realistic" service economic analysis results significantly.

Bimese PTP Inc.'s realistic service scenario is to offer <u>chartered flights of the single element Bimese across the Atlantic Ocean</u>. To begin the Bimese PTP, Inc. will operate from four launch sites and as the years go buy ramp up building sites inland on the two continents. Figure IV.3 shows a representative scenario for the Bimese fast package delivery system.

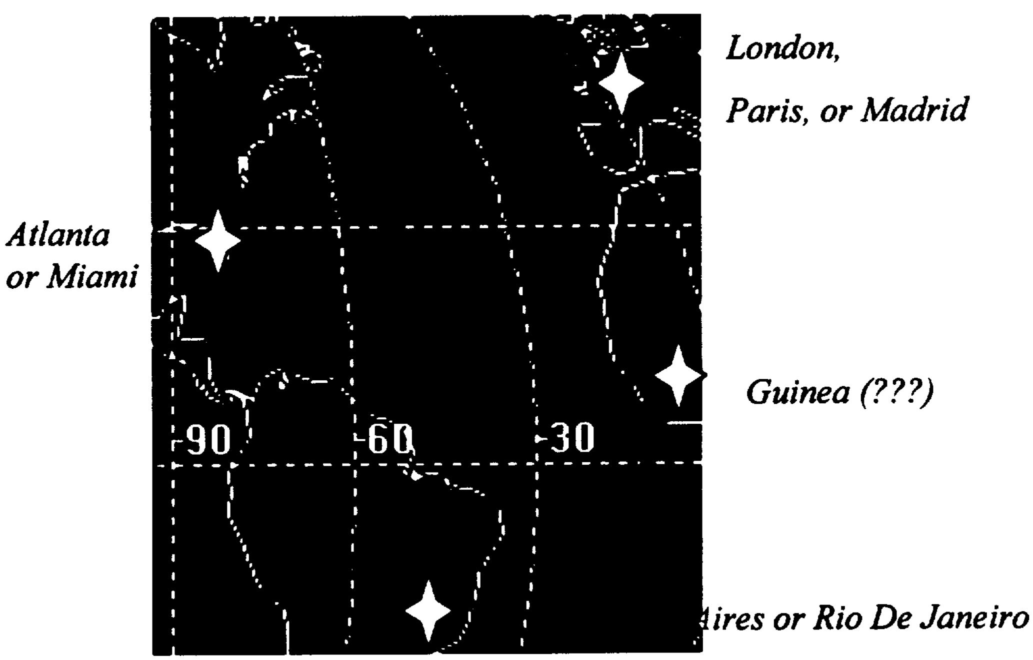


Figure IV.3 – Possible Initial Routes for Bimese PTP, Inc. Fast Package Delivery

IV.3. POINT-TO-POINT BUSINESS ANALYSIS RESULTS

When degrading the level of service from the regularly scheduled "ideal" case to the trans-Atlantic chartered flight scenario forced by performance and cost considerations, the CSTS price elasticity curves used in section IV.1.1 can no longer be relied upon to estimate the number of flights for a given package price. That is, the number of chartered trans-Atlantic fast-package flights for the single element Bimese is expected to be <u>significantly less than the global fast-package market in the CSTS model</u>. However, the CSTS market demand can serve as an upper bound sanity check for further analysis.

Given the uncertainty in the market size vs. package price, the following economic analyses treated the market elasticity parametrically. The package delivery price and the flight rate are varied to determine what they need to be to result in a positive economic result for the realistic Bimese PTP, Inc. operating scenario. The requirements are then compared to the traffic levels predicted for global service from the CSTS model.

For estimating the cash flow and internal rate of return of Bimese PTP, Inc, four different scenario assumptions were considered ranging from conservative to very optimistic. Recall that the vehicle turnaround time has a major impact on fleet size. Non-recurring costs (DDT&E and reusable hardware production, related to TFU) must be recouped over all flights in the model and can be a significant contributor to total cost per flight. For example, a $25 B non-recurring investment for a system that flies 2000 flights per year for 30 years would contribute over $400,000 to the per flight cost of a fast-package delivery flight (not even counting the interest cost associated with the debt!). With these contributors in mind, the following four scenarios are examined:

1. standard non-recurring cost, standard turnaround time (baseline)
2. reduced turnaround time case
3. reduced non-recurring cost and reduced turnaround time
4. zero non-recurring cost

IV.3.1. Baseline Case Economic Results

The economic results for the baseline case are shown parametrically in Figure IV.4. Here, the baseline assumptions that the government contributes 20% of airframe DDT&E and 100% of engine DDT&E are used. The AATe prediction of turnaround time of 12 days for each single element Bimese is also used. Finally, the variable costs from Figure IV.2 are used for the recurring cost estimates.

Recall that an acceptable IRR is around 25%. Figure IV.4 shows that for the baseline case, Bimese PTP Inc. requires about $7M per flight of revenue to achieve this goal when having a flight rate of about 5,000 per year (the highest flight rate considered in this analysis). At this high price ($7000/lb.), the CSTS market for the entire <u>global</u> fast package market predicts a demand of no more than 20 - 30 flights per year! Clearly, the baseline assumptions will not result in a positive business case.

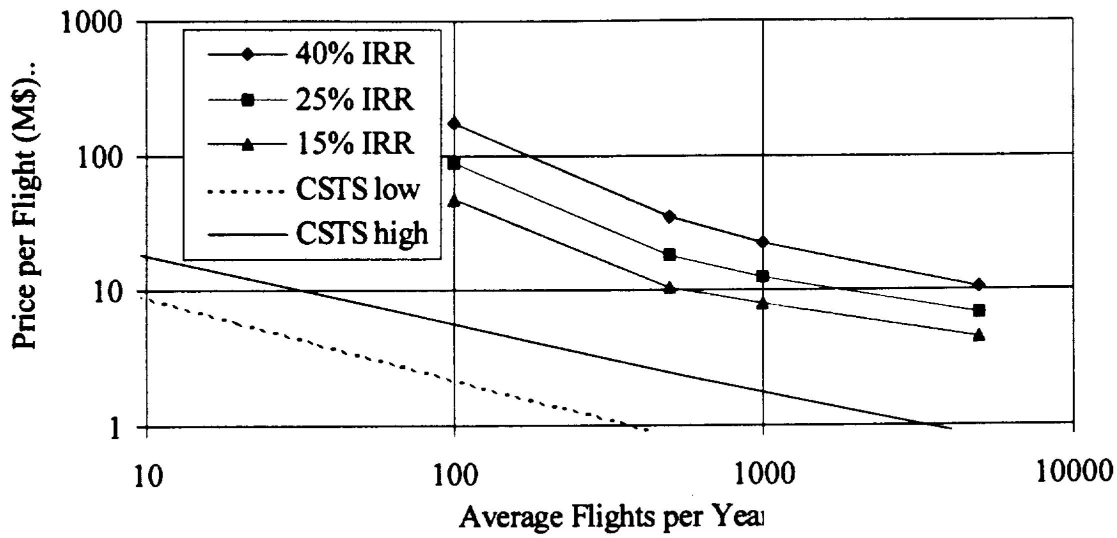


Figure IV.4 – IRR for Bimese Inc. Baseline Case

One problem with the baseline assumptions is the slow turnaround time. To support 5,000 flights per year over the entire scenario, extra Bimese RLV's must be purchased at each site to fill in for vehicles that are being processed for return to flight. For the baseline scenario, 171 single element Bimese RLVs would be required to be purchased. This leads to a fleet acquisition cost of $154 B! Even if the economic return on investment was attract, this startup cost is well out of the realm of feasibility for a private startup business venture.

IV.3.2. Reduced Turnaround Time Scenario

As a sensitivity, the second case analyzed assumes that <u>the turnaround time of a single element Bimese RLV can be reduced significantly to only one day</u>. This is comparable to assuming "aircraft-like" operations for a reusable launch vehicle. In this case, required fleet size is no longer governed by the length of time it takes to ready a flight vehicle for another flight (the processing queue), but rather by the life of the airframe. The life of the airframe was earlier assumed to be 1,000 flights before replacement (still low by aircraft standards, but an order of magnitude longer than the Space Shuttle).

The IRR sensitivity for this scenario is shown in Figure IV.5. Again, the desire to obtain the lowest package price drives the flight rate up significantly. At 5,000 flights/year (the highest flight rate considered), the price associated with 25% IRR is $6M per flight. Again, 5,000 flights/year is well outside for the number of flights predicted by the global market for this price.

At 5,000 flights/year, the assumption of a 1 day turnaround time reduces the fleet size to 144 airframes for the nearly 30 year mission model (with a ramp up to full operating capacity between 2011 and 2012). Compared to the baseline case, the fleet acquisition cost is lowered by $51 B, but the total cost is still well out the range of what can be expected from a private venture.

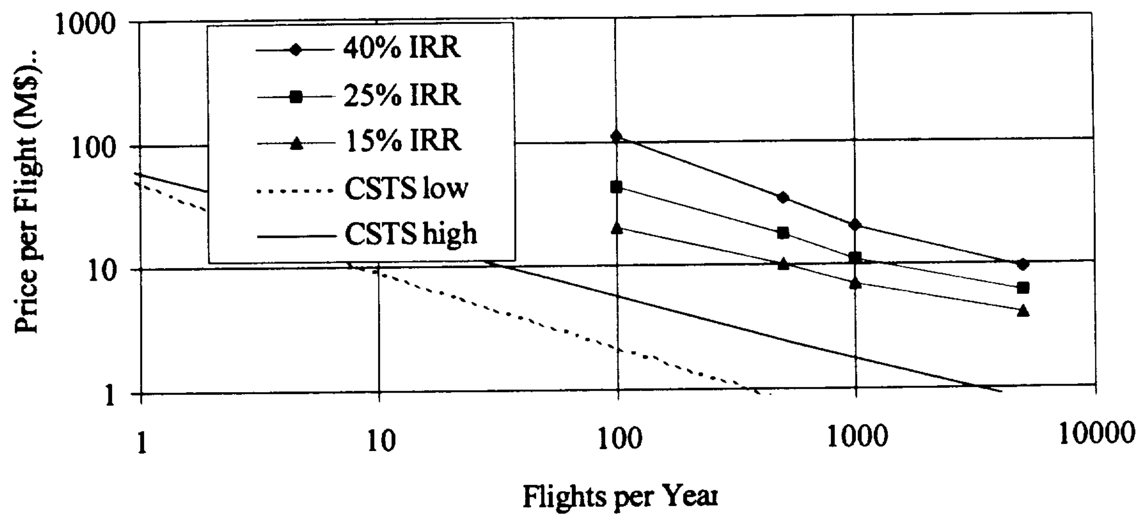


Figure IV.5 – IRR for Bimese Inc. with Reduced Turnaround Time

In Figure IV.5, the benefits of fast turnaround time are more evident at low flight rates where turnaround time determines fleet size rather than airframe life. Lower flight rats will reduce overall program costs, and if they can be made economically attractive, are a preferred solution for Bimese PTP, Inc. However, at low flight rates, the DDT&E and other non-recurring costs become more of a contributor to the economic success. That is, DDT&E is a more significant component of life cycle cost at low flight rates.

IV.3.3. Reduced Non-Recurring Cost and Turnaround Time Scenario

As a third scenario of assumptions assumptions, the earlier predicted values of TFU and DDT&E are reduced. Bimese PTP Inc. now has 100% of airframe DDT&E paid by the government (or other entity) and TFU is assumed to have been reduced by 20%. These changes might be thought of as the result of a <u>synergy between the single element Bimese used for fast-package delivery and a government configuration used for an orbital mission (the mated Bimese).</u> For example, if the government pays for the development of the Bimese RLV to service the International Space Station, then Bimese PTP, Inc. might make use of the design work for free. Further, the government could pay a third-party company to create a production line for manufacturing Bimese RLVs for the government's mated configuration. Bimese PTP, Inc. could then purchase their single element Bimese vehicles from the third party at a discount.

The results for this scenario are show in Figure IV.6. From this chart it is seen that the economics are becoming more reasonable, but the prices still do not match the demand. Here, charging a price per flight of $6M with only 250 fleet flights per year returns an IRR of 25%. The fleet size for this scenario is only 8 airframes and the fleet procurement cost falls to $15 M (DDT&E is zero to Bimese PTP, Inc.). Unfortunately, the predicted market size for the <u>global</u> market at a price of $6M ($6000/lb) is nearly an order of magnitude lower than 250 trans-Atlantic flights per year required to make this scenario successful.

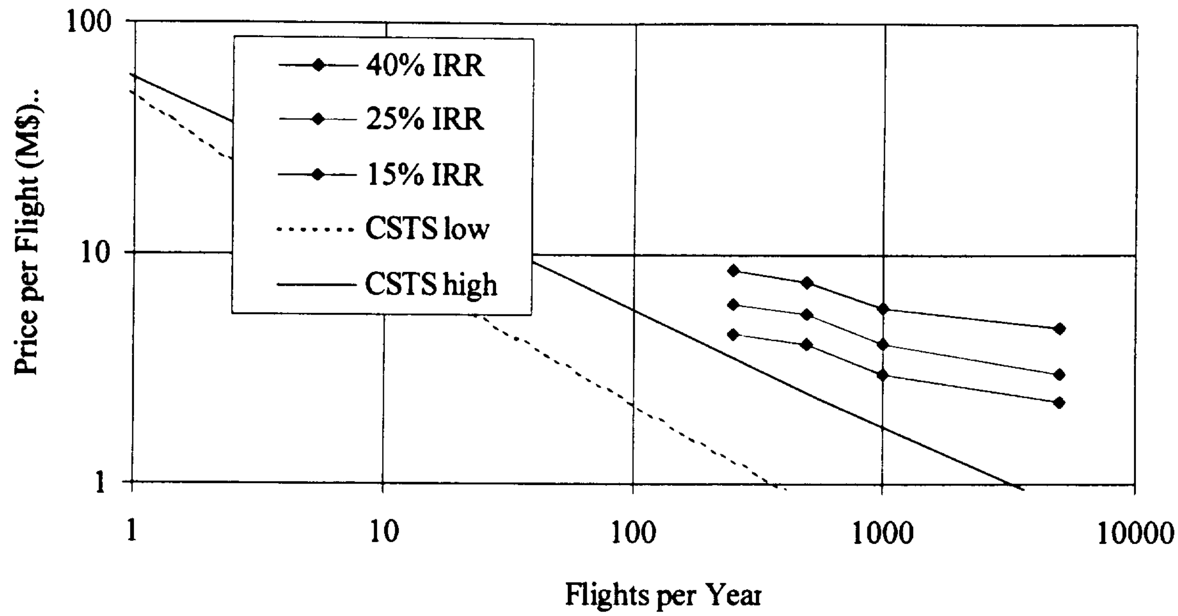


Figure IV.6 – IRR for Bimese Inc. with Reduced DDT&E and TFU

IV.3.4. Zero Non-Recurring Cost

One final case is looked at with the extremely optimistic assumption of zero non-recurring cost. The government (or some other entity) was assumed to bear the entire DDT&E cost for the single element Bimese and pay the production cost to have them produced for Bimese PTP, Inc. The one day turnaround time assumption was also retained. In this scenario, Bimese PTP, Inc. pays only the direct recurring cost of operating the single element Bimese RLV on the trans-Atlantic charter flights.

A plot of the IRR sensitivity for this assumption is seen in Figure IV.7. The return on investment curve is relatively flat for this case (more closely related to the recurring cost curves) and reveals that a 25% return on investment can be obtained by charging about \$800,000 per trans-Atlantic charter flight and flying 500 times per year or charging about \$1M per flight and flying about 100 flights per year. The IRR = 25% curve actually crosses the CSTS curve for global demand for fast package services, but recall that the demand for charter-style trans-Atlantic flights is likely a tenth or less of the global CSTS market. In addition, the low payload capacity of the single element Bimese (1 klb) results in a package price of approximately \$1000/lb. — a factor of 100 premium above current prices. Note that our previous "sweet spot" analysis of the CSTS market had assumed that the average Bimese configuration would carry 5,000 lb cargo globally, therefore \$1M per flight would have been only \$200/lb. The need to avoid the expensive SRB configurations forced the selection of the less capable single element Bimese for the point-to-point missions. Unfortunately, <u>the recurring cost alone are still to expensive to make even the trans-Atlantic fast package market economically attractive for Bimese PTP, Inc.</u>

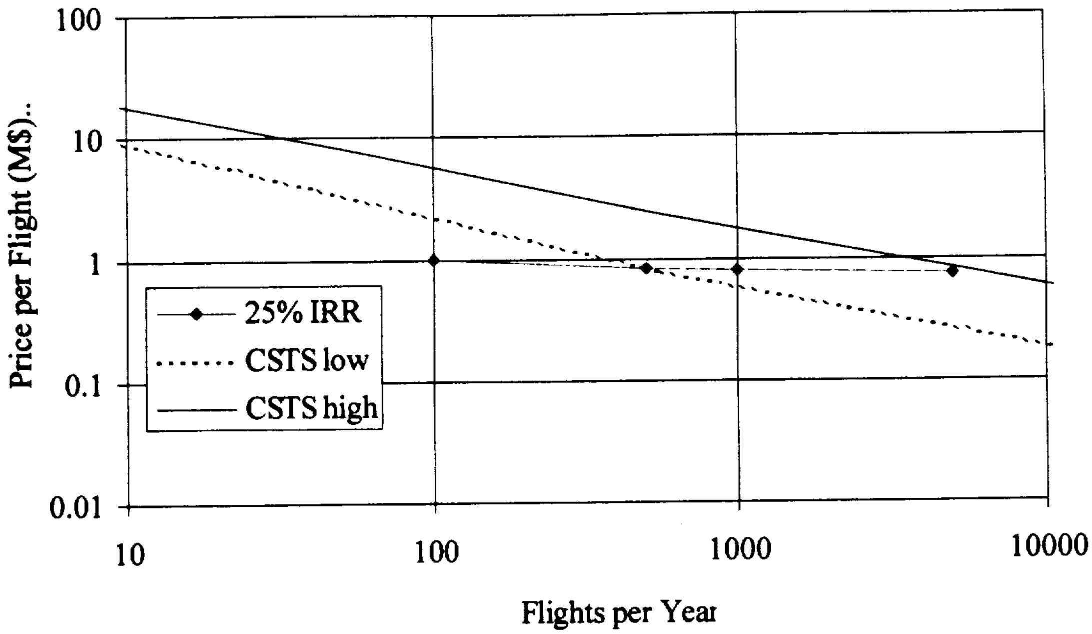


Figure IV.7 – IRR for Bimese Inc. with Recurring Cost Only

IV.3.5. Economic Analysis Summary

A more detailed breakdown of the economics of the four economic scenarios considered is given below in Table IV.4. Even with government contributions of $7.4 B and zero fleet acquisition costs, the price and annual flight rates that Bimese PTP, Inc. requires to make a 25% IRR clearly exceeds the number of flights estimated to be available at that price.

Table IV.4 – Economic Indicators for Four Cases

	Baseline	Reduced turn around time	Reduced DDT&E, TFU, and turn around time	Recurring Cost Only
Required Flights/year	5,000	5,000	250	100
Price/flight (M$)	$7	$6	$6	$1.0
Approximate trans-Atlantic flights avail.	<10	<15	<15	<25
IRR	~25%	~25%	~25%	~25%
Fleet size	171	144	8	4
Fleet acquisition (B$)	$154	$103	$ 15	$0
Turn around time (days)	12	1	1	1
DDT&E Government Contribution (M$)	$1,850	$1,850	$7,400	$7,400
TFU (M$)	$1,900	$1,900	$1,500	$0

In the most optimistic case, the recurring costs alone prove to be too great for the predicted trans-Atlantic market. Here, a package price of $100/lb (a factor of 10 premium over today's prices) would generate a revenue of only $100,000 per trip. For the single-element Bimese, direct recurring costs alone contribute over $400,000 of cost per trip. Paying the launch site fee of $100,000 and adding enough profit to pay taxes, interest, and still return a 25% IRR raises the required price to over $900,000 per flight. It does not appear that the Bimese will lead to a successful economic business case given the assumptions used in the study.

V. CONCLUSIONS

This study performed an assessment of the Bimese launch vehicle architecture for use as a vehicle for intercontinental, ultra-fast package delivery. Specifically, the point-to-point payload performance of several configurations of the rocket-powered Bimese RLV element were assessed. Then an economic assessment was made to determine the revenues, costs, and internal rate of return (IRR) for a fictitious Bimese PTP, Inc. company created to provide the ultra-fast package delivery service. Unfortunately, the study was unable to identify any attractive business scenario for a Bimese-derived fast-package service.

The performance analysis examined the point-to-point range capability of a single element Bimese RLV, a fuel-augmented Bimese RLV, a thrust-augmented Bimese RLV(augmented with 2 or 4 expendable GEM SRBs), a thrust and fuel-augmented Bimese RLV, and the nominal "mated" Bimese configuration. Of these configurations, the single element Bimese was found to have about a 3,900 nmi. range with a 1 klb payload — marginally sufficient to reach western Europe from KSC, but insufficient to reach the Pacific rim from the continental U.S. The configuration augmented with two GEM-10 SRB's can carry significant payload on trans-Atlantic routes and might even be capable of trans-Pacific service from the west cost of the U.S. This two SRB configuration was preferred from a suborbital performance point-of-view. The larger configurations were all capable of making orbit, and therefore could be used to support long/global range or heavy cargo routes.

A subsequent economic analysis of the expected ultra-fast package delivery market identified a "sweet spot" at a revenue per flight of around \$1M per flight for a vehicle capable of carrying an average of 5,000 lb. per flight in a 2,000 flight per year global market. This price point represents a premium of about 100% above today's (aircraft system) fast package prices and would result in a service that could cut 90% of the flight time required for long routes. Unfortunately, the preferred mix of Bimese configurations relied heavily on GEM SRB thrust-augmentation to achieve the required payloads and ranges. At an estimated price of \$2M per booster, the cost of any SRB augmented configurations was well above the target price of \$1M per flight. A case was made for using the single element Bimese RLV in a limited "charter-style" trans-Atlantic service, but even with the assumption that Bimese PTP, Inc. paid only the recurring costs of operating the Bimese on this route, no economically attractive solution was found. Given the more limited range and payload of the single element Bimese, available revenue would be reduced to only about \$100,000 per flight and even the fully reusable single element Bimese proves more expensive to operate than the available revenues. Therefore it was concluded that no attractive economic scenario exists for the assumptions of this study.

Several key parameters in the current study are responsible for this negative conclusion. The following observations are offered as potential areas of improvement:

1. Reduce Direct Recurring Costs of Rocket Vehicles. The direct recurring cost (labor, propellant, hardware spares, insurance, and site fee) of a flight vehicle form the ultimate "price bottom" for any fast package system. Rocket systems are expected to be more expensive than aircraft to operate on these routes due to higher loads, higher complexity, smaller margins, etc. While the direct cost of a single element Bimese RLV at approximately $400,000/flight is already very optimistic by rocket standards, if rockets are to be competitive in future ultra-fast package delivery missions, recurring costs must be reduced by an order of magnitude over the already aggressive assumptions used in this analysis.

2. Increase Size and Range of Single Element Bimese RLV. It was shown that expendable SRBs could not be used for thrust-augmentation and still meet the stringent ultra-fast package economic goals. A fully reusable element was the only attractive solution. Unfortunately, the current single element Bimese (sized for the mated TSTO mission) is too small in both range and payload capacity for servicing a global ultra-fast package market. A larger, almost single-stage capable, vehicle with 5,000 lb. of global range payload capacity would be more optimum for this mission.

3. Reduce or Share Initial Non-Recurring Costs. The economic scenarios examined highlight the critical importance of low non-recurring cost to the economic success of an ultra-fast package delivery market. A company such as Bimese PTP, Inc. has little chance of economic success if its startup costs (including vehicle DDT&E, facilities costs, and fleet procurement) are excessive. For a new rocket-based system, this can easily be 10's or even 100's of billions of dollars for ambitious global flight rates. If the government can provide a mechanism for reducing this non-recurring cost (perhaps by a synergistic development of a version of the point-to-point flight vehicle for civil or military orbital missions) then the chance of economic success is greatly increased. Toward this end, the highly flexible Bimese architecture is an excellent concept for a synergistic development program. State or federal development of common spaceport infrastructures (analogous to regional airports) is also important.

4. Streamline Rocket Vehicle Ground Operations. The economic scenarios examined highlighted the need to have very low processing times between flights of a point-to-point ultra-fast package vehicle. Even using optimistic assumptions, current models predict turnaround times of around two weeks for rocket-style point-to-point vehicles. However, to keep fleet sizes low and make maximum use of reusable assets to support a regular flight schedule, "aircraft-like" turnaround times on the order of a single day are required.

APPENDICES

APPENDIX A. POST DECKS

A.1. BIMESE AERODYNAMICS

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5,-0.051882,
10,-0.0619,
15,-0.0619,
20,-0.0619,
25,-0.0619,
30,-0.0619,
35,-0.0619,
1.1,
-10,-0.056865,
-5,-0.056865,
0,-0.056865,
5,-0.056865,
10,-0.0676,
15,-0.0676,
20,-0.0676,
```

```
25,-0.0676,
30,-0.0676,
35,-0.0676,
2,
-20,-0.027384,
-10,-0.028784,
0,-0.029284,
10,-0.028784,
20,-0.0302,
30,-0.0278,
40,-0.0246,
50,-0.0207,
60,-0.0161,
70,-0.011,
3,
-20,-0.019262,
-10,-0.019962,
0,-0.020162,
10,-0.019962,
20,-0.0147,
30,-0.0135,
40,-0.0119,
50,-0.01,
60,-0.0078,
70,-0.0054,
4,
-20,-0.011751,
-10,-0.012051,
0,-0.012251,
10,-0.012051,
20,-0.0085,
30,-0.0077,
40,-0.0069,
50,-0.0058,
60,-0.0045,
70,-0.0031,
6,
-20,-0.006393,
-10,-0.006593,
0,-0.006593,
10,-0.006593,
20,-0.0038,
30,-0.0034,
40,-0.003,
50,-0.0026,
60,-0.002,
70,-0.0014,
8,
-20,-0.002,
-10,-0.0022,
0,-0.0022,
10,-0.0022,
20,-0.0021,
30,-0.0019,
40,-0.0017,
50,-0.0014,
60,-0.0011,
70,-0.0008,
10,
-20,-0.0013,
-10,-0.0014,
0,-0.0015,
10,-0.0014,
20,-0.0012,
30,-0.0011,
40,-0.0009,
50,-0.0008,
60,-0.0007,
70,-0.0005,
12,
-20,-0.0007,
-10,-0.001,
0,-0.001,
10,-0.001,
20,-0.0008,
30,-0.0006,
40,-0.0005,
50,-0.0005,
60,-0.0004,
70,-0.0003,
15,
-20,-0.0008,
-10,-0.0006,
0,-0.0006,
10,-0.0006,
20,-0.0008,
30,-0.0001,
40,-0.0001,
50,-0.0002,
60,-0.0002,
70,-0.0002,
20,
-20,-0.0002,
-10,0.0001,
0,0.0002,
10,0.0002,
20,-0.0002,
30,-0.0003,
40,-0.0003,
50,-0.0002,
60,0,
70,-0.0001,
25,
-20,0,
-10,0,
0,0,
10,0,
20,0,
30,0,
40,0,
50,0,
60,0,
70,0,
```

A.2. SINGLE ELEMENT BIMESE: LEO

```
P$SEARCH
C****************************************************
C  LOX/LH2 SINGLE BIMESE W/RS2100 Engine (revised 1/1/99)
C  WB-003-C Bimese 0 Klb to 100 nmi
C  28.5 DEGREES INCLINATION
C  LATEST WB-001 AERO ADDED 5/6/97
C****************************************************
C
 SRCHM = 4, / PROJECTED GRADIENT METHOD
c IPRO = -1, / PRINT FINAL TRAJECTORY ONLY
 IOFLAG = 0, / ENGLISH IN - ENGLISH OUT
 CONEPS(1) = 89.9, / CONVERGENCE TOLERANCE
 CONEPS(2) = .00001, / MIN ALLOWED PERCENTAGE CHANGE
 CONEPS(3) = .00001, /
 CONEPS(4) = .00001, /
 CONEPS(5) = .00001, /
 PCTCC=.001, /
 IDEB=0, / No Detail
C
C****************************************************
C           OPTIMIZATION VARIABLE
C****************************************************
C
 OPTVAR = 6HWEIGHT, / MAXIMIZE FINAL BURNOUT WEIGHT
 OPT = 1, / MAXIMIZATION FLAG
 OPTPH = 500, / PHASE AT WHICH WEIGHT IS MAXIMIZED
 WOPT = .000003, / OPTIMIZATION VARIABLE WEIGHTING
 MAXITR =40, / MAXIMUM ITERATIONS ALLOWED
C
C****************************************************
C
C           CONSTRAINT VARIABLES
C
C****************************************************
C
 NDEPV = 6, / NUMBER OF DEPENDENT VARIABLES USED AS
CONTROLS
 DEPVR = 5hgdalt, 6HGAMMAI, 3HINC, 5HXMAX1, 5HXMAX2, 5HXMIN2,
/ INSERTION ORBIT CONDITIONS + CONSTRAINTS
 DEPVAL = 303805.0, 0.0, 28.5, 1000., 379165., -379165., / INSERTION
ORBIT VALUES + CONSTRAINTS
 DEPTL = 500, .1, .1, 1., 100, 100, / DESIRED ACCURACIES
 DEPPH = 500, 500, 500, 500, 500, 500, / EVENTS
 IDEPVR = 0, 0, 0, 1, 1, -1,
C
C****************************************************
C
C
C           CONTROL VARIABLES
C
C****************************************************
C
  nindv  = 16,
  indvr  = 15*6hpitpc2,3hazl,
  indph  = 15,18,20,30,40,60,65,70,75,80,85,90,95,100,105,10,
  u= -1.112110516660E+00, 9.596061841384E-02, 2.405720312012E-02, -
8.647860715809E-01, -8.524468987230E-01,
 -7.365135456373E-01, -6.185493375131E-02, -1.780915656336E-01, -
2.827569253803E-01, -2.117153231269E-01,
 -1.977722599479E-03, -6.981303256862E-02, -1.949655878951E-02, -
3.901753314859E-01, -1.333034849750E-01,
 8.621963895029E+01,
 u= -9.631146612932E-01, 1.206853378424E-01, 3.371722786330E-02,
   -8.335495035323E-01, -4.798149007642E-01,
   -4.000001681097E-01, -4.348020053465E-02, -1.415419515140E-01,
   -4.036245017758E-01, -9.915998643712E-02,
   -1.851298896717E-03, -6.981303256862E-02, -1.949655878951E-02,
-3.901753314859E-01, -1.333034849750E-01,
   8.621963895029E+01,
 u= -2.043034871238E+00, 1.225369241872E-01, 2.129087327276E-02, -
2.688018798002E-01, -8.078862072536E-01,
 -6.011886894844E-01, -7.606668313577E-02, -2.236506111735E-01, -
4.402526852204E-01, -1.406015654871E-01,
 -1.878724563661E-03, -1.073245500135E-01, -2.122784772197E-02, -
3.484124575335E-01, -1.235092248124E-01,
 8.627362883464E+01,
 u= -2.048482830768E+00, 1.270951672930E-01, 1.952917063025E-02, -
2.808866024197E-01, -8.902962326908E-01,
 -7.600675483939E-01, -1.057582836078E-01, -2.674372552951E-01, -
3.188541758559E-01, -1.783906646563E-01,
 -1.895282842109E-03, -1.396042300682E-01, -2.200578107558E-02, -
3.734017639366E-01, -1.230747709286E-01,
 8.627366205750E+01,
 u= -1.925681152711E+00, 1.275911554941E-01, 1.952723724261E-02, -
2.791245629003E-01, -8.701005542814E-01,
 -7.197987859824E-01, -1.036802444856E-01, -2.656831800408E-01, -
3.293637048943E-01, -1.871700580567E-01,
 -1.896853573847E-03, -1.468066280418E-01, -2.220930232417E-02, -
4.361270765231E-01, -1.328583934429E-01,
 8.625266261937E+01,
 u= -1.897293827039E+00, 1.277775518953E-01, 1.952811760879E-02, -
2.775129774345E-01, -8.517441085340E-01,
 -7.045014431499E-01, -1.037184763853E-01, -2.674115124193E-01, -
3.358224514068E-01, -1.900500823104E-01,
 -1.897188763099E-03, -1.480803180235E-01, -2.223470725970E-02, -
4.437324044731E-01, -1.336372477044E-01,
 8.624400839367E+01,
 u= -1.877073987231E+00, 1.279360175615E-01, 1.953283442428E-02, -
2.757516305779E-01, -8.349255442527E-01,
 -6.872640468140E-01, -1.034497473644E-01, -2.679953020693E-01, -
3.399318594345E-01, -1.921090903175E-01,
 -1.897429992035E-03, -1.490770425276E-01, -2.225582901147E-02, -
4.510385562812E-01, -1.344942922373E-01,
 8.623542756604E+01,
 PERT = 16*1.0E-4, / PERTURB
 $
C****************************************************
C
C           TRAJECTORY SIMULATION INPUTS
C
C****************************************************
P$GENDAT
 TITLE = 0H* LOX/LH2 BIMESE 28.5 deg delivering 60 Klb *,
 EVENT = 10, / FIRST EVENT
  WGTSG = 1390000., / INITAL LIFTOFF WEIGHT with ADDED FLUIDS
  FESN = 500, / FINAL EVENT NUMBER
  MAXTIM = 1000., / MAXIMUM TIME
  ALTMAX = 10000000., / MAXIMUM ALTITUDE ALLOWED
  ALTMIN = -5000., / MINIMUM ALTITUDE ALLOWED
  PRNC = 0, /setup plot file
  MONX = 4HDYNP, 4HFAZB, / MONITOR Q & NORMAL FORCE
  PRNT(97) = 5HXMAX1, 5HXMAX2, 5HXMIN2, 6HALTITO, 4HMACH,
4HDYNP,
  4HAMYB, 5HTTMYB, 5HPSTOP, /
 IGUID(1) = 1, / INERTIAL EULER ANGLE OPTION
 IGUID(2) = 0, / SAME STEERING OPTION FOR ALL CHANNELS
 IGUID(4) = 1, / CUBIC POLY WITH CONSTANT TERM SET BY INPUT
  PITPC(1) = 0., / INITIAL PITCH RATE
  YAWPC(1) = 0., / INITIAL YAW RATE
  ROLPC(1) = 0., / INITIAL ROLL RATE
 NPC(1) = 2, / PRINT CONIC BLOCK AT EACH PHASE CHANGE
  PINC = 20, / PRINT INTERVAL EVERY 20 SECONDS
 NPC(2) = 1, / FOURTH ORDER RUNGE KUTTA
  DT = 1, / INTEGRATION STEP SIZE
 NPC(3) = 4, / PLANET RELATIVE INPUT ON VELOCITY VECTOR
  VELR = .1, / INITIAL VELOCITY AT LAUNCH PAD
  GAMMAR = 90., / INITIAL PLANET RELATIVE FLIGHT PATH ANGLE
  AZVELR = 0., / INITIAL AZIMUTH ANGLE OF VELR
  azl  = 90,
 NPC(4) = 2, / PLANET RELATIVE INPUT ON ALTITUDE VECTOR
  ALTITO = 0., / INITIAL ALTITUDE
  GDALT = 0., / INITIAL ALTITUDE
  GDLAT = 28.5, / LATITUDE OF LAUNCH SITE
  LONG = 280.0, / LONGITUDE OF LAUNCH SITE
  LONGI = 280.0, / LONGITUDE EAST OF PRIME MERIDIAN
 NPC(5) = 5, / 1976 US STANDARD ATMOSPHERE
 NPC(6) = 0, / NO WINDS
 NPC(7) = 1, / ACCELERATION LIMIT SET
  ASMAX = 3.0, / LIMIT ACCELERATION THROUGHOUT TRAJECTORY
  LREF = 162.6, /BODY LENGTH FROM NOSE TO BASE
  SREF = 3500.7, /REFERENCE AREA FOR ORBITER ONLY
 NPC(8) = 2, / CL, CD & CM TABLE INPUTS
 NPC(9) = 1, / ROCKET ENGINE WITH THRUST TABLE AND ISPVAC
 NPC(10) = 0, / STATIC TRIM IN PITCH
 GXP(1) = 160.2, /X-LOCATION OF ENGINE GIMBAL MEASURED FROM
NOSE
 ITRIM = 1, / TRIM WITH ENGINE DEFLECTIONS ONLY
 IENGT = 1, / CALCULATE ENGINE INCIDENCE ANGLES FROM STATIC
TRIM EQUATIONS
 NPC(11) = 0, / NO FUNCTIONAL INEQUALITY CONSTRAINTS
 NPC(12) = 3, / CALCULATE CROSSRANGE AND DOWNRANGE BASED
ON ORBIT
  ALTREF = 100.0, / 100 NMI CIRCULAR MILE REFERENCE ORBIT
  AZREF = 0., / AZIMUTH REFERENCE
 NPC(13) = 0, / DO NOT JETTISON PROPELLANT
 NPC(14) = 0, / NO HOLDDOWN BEFORE LIFTOFF
 NPC(15) = 0, / DO NOT CALCULATE AEROHEATING
 NPC(16) = 0, / USE OBLATE EARTH GRAVITY MODEL
c NPC(17) = 2, / JETTISON BOOSTER
 NPC(18) = 0, / DO NOT TERMINATE TRAJECTORY
C NPC(19) = 0, / DO NOT PRINT INPUT CONDITION SUMMARIES
 NPC(20) = 0, / DO NOT USE ANY SPECIAL DT CALCULATION
 NPC(21) = 0, / DO NOT CALCULATE FUEL AND OXIDIZER WEIGHTS
AND VOLUMES
 NPC(22) = 0, / DO NOT CALCULATE THROTTLING
 NPC(23) = 0, / DO NOT COMPUTE VELOCITY MARGINS
 NPC(24) = 0, / DO NOT COMPUTE ANY PARAMETER INTEGRALS
```

```
 NPC(25) = 3, / COMPUTE VELOCITY LOSSES AND PRINT AT EACH
TIME
 NPC(26) = 0, / NO SPECIAL AEROHEATING CALCULATIONS
 NPC(27) = 0, / DO NOT INTEGRATE ENGINE FLOWRATES
  IWPF(1) = 1, / INTEGRATE BOOSTER FLOW RATES
 NPC(28) = 0, / TRACKING STATION OPTION NOT USED
 NPC(29) = 0, / DO NOT COMPUTE VACUUM IMPACT POINTS
 NPC(30) = 0, / USE N-STAGE VEHICLE WEIGHT MODEL
  IENGA(1) = 1, / THROTTLE ORBITER
  IENGMF(1) = 1, / ORBITER ROCKETS ARE ON
  IWDF(1) = 1, / CALCULATE ORBITER FLOW RATES AS A TABLE
LOOKUP
  NENG = 1, / THE NUMBER OF THRUSTING ENGINES
 NPC(31) = 0, / NO VERNAL EQUINOX, SUN SHADOW, SUN ANGLE
CALCULATIONS
 NPC(32) = 0, / NO PARACHUTE DRAG
 NPC(33) = 0, / NO ARC LENGTH CALCULATIONS
 NPC(34) = 0, / NO KEPLERIAN STATE CALCULATIONS
 NPC(35) = 0, / NO SENSED VELOCITY INCREMENT CALCULATIONS
 NPC(36) = 0, / DO NOT ACTIVATE SUNLIGHT OPTIONS
 NPC(37) = 0, / DO NOT ACTIVATE DATE OPTION
 NPC(38) = 0, / NO ATMOSPHERIC TURBULENCE
 NPC(39) = 0, / NO ATMOSPHERIC GUSTS
 NPC(40) = 1, /
 $
$TBLMLT
 TVC1M = 3.3351, / Thrust multiplier for Orbiter
 WD1M = 3.3351, / Flow rate multiplier for Orbiter
 AE1M = 3.3351, / Exit area multiplier for Orbiter
 $
$TAB
 TABLE = 5HTVC1T, 0,531500., / VACUUM THRUST OF Orbiter engine
 $
$TAB
 TABLE = 4HWD1T,0,1199.77, / FLOW RATE OF Orbiter engine
 $
$TAB
 TABLE = 4HAE1T, 0,33.558, / EXIT AREA OF Orbiter engine
 $
$TAB TABLE = 4HXCGT,1,6HWEIGHT,2,1,-1,1,
  2006450,123.51,134870,115.50,
 $
$TAB TABLE=5HXREFT,0,109.90,
 $
$TAB TABLE=5HZREFT,0,0,
 $
*include '/home/asdl1/jtooley/post/BIMESE/bimese.aero'
 ENDPHS = 1,
 $
l$gendat
 event=15,critr=4htime,value=07,endphs=1,
 iguid(4)=0,
 $
l$gendat
 event=18,critr=4htime,value=17,endphs=1,
 $
l$gendat
 event=20,critr=4htime,value=30,endphs=1,
 $
l$gendat
 event=30,critr=4htime,value=40,endphs=1,
 $
l$gendat
 event=40,critr=4htime,value=60,endphs=1,
 $
l$gendat
 event=60,critr=4htime,value=80,endphs=1,
 $
l$gendat
 event=65,critr=4htime,value=110,endphs=1,
 $
l$gendat
 event=70,critr=4htime,value=150,endphs=1,
 $
l$gendat
 event=75,critr=4htime,value=170,endphs=1,
 $
l$gendat
 event=80,critr=4htime,value=200,endphs=1,
 $
l$gendat
 event=85,critr=4htime,value=230,endphs=1,
 $
l$gendat
 event=90,critr=4htime,value=260,endphs=1,
 $
l$gendat
 event=95,critr=4htime,value=280,endphs=1,
 $
l$gendat
 event=100,critr=4htime,value=300,endphs=1,
 $
l$gendat
event=105,critr=4htime,value=320,endphs=1,
$
l$gendat
c this event marks injection into orbit
event=500,critr=4hveli,value=25855.000,
ENDPHS = 1,
ENDJOB = 1,
ENDPRB = 1,
$
```

A.3. THRUST-AUGMENTED BIMESE: LEO

```
pSeearch
c**************************************************
c  LOX/LH2 Single Bimese w/solids
c  wb-003-c bimese
c  latest wb-001 aero added 5/6/97
c**************************************************
c
c  Ascent of:
c  Single Bimese w/solids to a 100 nmi x 50 nmi x 28.5 degrees inclination
c  Jeffrey Tooley, Sept. 1999
c
c Optimization Variables
c ----------------------------------------
 srchm = 4, / projected gradient method
 ioflag = 0, / english in - english out
 optvar = 6hweight, / maximize final burnout weight
 opt = 1, / maximization flag
 optph = 500, / phase at which weight is maximized
 wopt = .000003, / optimization variable weighting
 maxitr = 40, / maximum iterations allowed
 coneps(1) = 89.9, / convergence tolerance
 coneps(2) = .00001, / min allowed percentage change
 coneps(3) = .00001, /
 coneps(4) = .00001, /
 coneps(5) = .00001, /
 pctcc=.001, /
 ideb=0, / no detail
c ----------------------------------------
c
c  Dependent Variables (constraints)
c ----------------------------------------
 ndepv = 11, / number of dependent variables
 depvr = 5hgdalt, 6hgammai, 3hinc, 5hxmax1, 5hxmax2, 5hxmin2, 5hveli ,
5hxmax4, 5hxmax5, 5hxmin5,5hxmin6,
 depval = 303805,    0.0, 28.5, 1000., 379165, -379165, 25855, 3, 1.0001,
0.19999, 0.19999,
 deptl = 500, .1, .1, 1., 100, 100, 100, .1, .001, .001, .001,/ desired accuracies
 depph = 500, 500, 500, 500, 500, 500, 500, 500, -14, 500, 500,/ events
 idepvr = 0, 0, 0, 1, 1, -1, 0, 1, 1, -1, -1,
c ----------------------------------------
c
c  Independent Variables
c ----------------------------------------
 nindv = 15,
 indvr = 12*6hpitpc2,3hazl,6hwstpd2,6hetapc1,
 indph = 15,16,20,30,40,60,65,70,75,80,85,90,10,10,14,
 pert = 15*1.0e-4, / perturb
c ----------------------------------------
c
c  initial guesses for independent variables (last set only)
c ----------------------------------------
/za gem motor
/
/us for T = 1250000 and tb = 50
u= -1.016611483083E+00, -8.734921040992E-01, -7.298162085384E-01, -
1.837842834798E-01, -1.200160273233E-01,
-2.709352765022E-01, -1.056161813457E-01, -3.899892128789E-01, -
1.663152629391E-01, -1.156000206226E-01,
-9.118640989624E-05, -8.100390628086E-03, 8.630873927719E+01,
1.174842158622E+06, 7.752838032258E-01,
/
/us for T = 1250000 and tb = 75
u= -1.016487161331E+00, -7.661696981753E-01, -9.308445422486E-01, -
1.812502263332E-01, -1.161504035642E-01,
-2.554738962328E-01, -1.012784101591E-01, -3.420689885571E-01, -
1.580161341920E-01, -1.114993191605E-01,
-9.118453042250E-05, -8.035460118865E-03, 8.632002467650E+01,
1.184216263756E+06, 9.090036980025E-01,
/
/us for T = 1250000 and tb = 100
u= -1.013127114102E+00, -7.621387946283E-01, -9.336093040501E-01, -
1.822677980694E-01, -1.170677279692E-01,
-2.615008560714E-01, -1.025580027732E-01, -3.569933474143E-01, -
1.590316364633E-01, -1.119607963055E-01,
-9.118482452200E-05, -8.043631635838E-03, 8.632301112353E+01,
1.188248485805E+06, 9.415103497269E-01,
/
/us for T = 1250000 and tb = 125
u= -1.230533904197E+00, -5.740527778979E-01, -7.399842061065E-01, -
5.312274701219E-01, -1.495510895919E-01,
-1.720920461344E-01, -1.996011203752E-01, -2.384473650279E-01, -
1.599005371693E-01, -9.867868958230E-02,
-9.117146890710E-05, -7.617017970988E-03, 8.632095046949E+01,
1.191119712313E+06, 9.984378032358E-01,
/
/us for T = 1500000 and tb = 50
u= -1.021634553664E+00, -8.952249285219E-01, -7.088016202825E-01, -
1.813018381815E-01, -1.188169964731E-01,
-2.668948103490E-01, -1.052673956727E-01, -3.884585607856E-01, -
1.660365592192E-01, -1.154965926578E-01,
-9.118623132244E-05, -8.091639257352E-03, 8.630856302853E+01,
1.179513611878E+06, 6.723180739283E-01,
/
/us for T = 1500000 and tb = 75
u= -1.024092069128E+00, -7.444211046506E-01, -9.751303063896E-01, -
1.759285777821E-01, -1.138439419397E-01,
-2.451072795132E-01, -9.971374051328E-02, -3.285167753522E-01, -
1.569657170385E-01, -1.109599670444E-01,
-9.118416294708E-05, -8.024678635726E-03, 8.632000337253E+01,
1.189412235105E+06, 8.454451783891E-01,
/
/us for T = 1500000 and tb = 100
u= -1.077524926498E+00, -6.494411690905E-01, -1.030007471972E+00, -
2.539062986169E-01, -1.541083409887E-01,
-1.481429480179E-01, -1.871145333546E-01, -2.487804493937E-01, -
1.985658661540E-01, -1.001712559494E-01,
-9.117326948552E-05, -7.673542691382E-03, 8.632905609778E+01,
1.195670608738E+06, 9.808437135977E-01,
/
/us for T = 1500000 and tb = 125
u= -1.083483704817E+00, -6.299342591120E-01, -7.579326683569E-01, -
4.348036006134E-01, -1.557763536568E-01,
-1.792066806223E-01, -2.257504916082E-01, -2.637245432764E-01, -
1.981213733257E-01, -9.972717688620E-02,
-9.117219021412E-05, -7.639170094409E-03, 8.631032487455E+01,
1.198937405551E+06, 8.690272270267E-01,
/
/us for T = 1750000 and tb = 50
u= -1.030890331152E+00, -8.819237775802E-01, -6.041527647271E-01, -
3.058207695465E-01, -1.088142498372E-01,
-1.712496699280E-01, -2.441458892383E-01, -3.102574400097E-01, -
1.837601913347E-01, -1.376444393257E-01,
-9.118454331076E-05, -8.100338608611E-03, 8.630230586672E+01,
1.183879192962E+06, 4.753223116481E-01,
/
/us for T = 1750000 and tb = 75
u= -1.012561089280E+00, -8.109375803400E-01, -6.883514888500E-01, -
3.082536426446E-01, -1.074713990997E-01,
-1.695877916238E-01, -2.414612908123E-01, -3.066562163292E-01, -
1.770676798990E-01, -1.385942045407E-01,
-9.118512509890E-05, -8.133636325475E-03, 8.629974593443E+01,
1.194725675189E+06, 5.686873842838E-01,
/
/us for T = 1750000 and tb = 100
u= -1.119644404139E+00, -7.299256742014E-01, -6.290610811593E-01, -
2.998262279759E-01, -1.089327620667E-01,
-1.715299868060E-01, -2.672650478202E-01, -3.620041714477E-01, -
1.939629147078E-01, -1.493602508291E-01,
-9.118639508832E-05, -8.221682262731E-03, 8.628254920542E+01,
1.201342294671E+06, 5.338831737613E-01,
/
/us for T = 1750000 and tb = 125
u= -1.034490621985E+00, -6.296869070388E-01, -7.476293309793E-01, -
3.866599777706E-01, -1.520678057466E-01,
-1.799567320494E-01, -2.431396118968E-01, -2.890750153747E-01, -
2.582313830897E-01, -1.045033211370E-01,
-9.117250966781E-05, -7.642675498768E-03, 8.629577478565E+01,
1.206729464637E+06, 7.224136914808E-01,
/
/us for T = 2000000 and tb = 50
u= -1.041700574636E+00, -9.113060589251E-01, -6.081748427955E-01, -
3.004653560676E-01, -1.074458353958E-01,
-1.663580530485E-01, -2.331437685358E-01, -2.920105955044E-01, -
1.812598477304E-01, -1.362782328997E-01,
-9.118401607201E-05, -8.083587670384E-03, 8.630657520541E+01,
1.188357998283E+06, 4.579755706971E-01,
/
/us for T = 2000000 and tb = 75
u= -9.938943556588E-01, -7.196945397596E-01, -8.383322964457E-01, -
3.516069785664E-01, -1.393093086263E-01,
-1.526158531641E-01, -1.891147042851E-01, -2.250814302084E-01, -
2.423031024078E-01, -1.014088816368E-01,
-9.117107480505E-05, -7.611121038006E-03, 8.630657120469E+01,
1.201122540204E+06, 5.877265285799E-01,
/
/us for T = 2000000 and tb = 100
u= -1.025359806951E+00, -6.636492519973E-01, -8.188552501225E-01, -
3.676142214755E-01, -1.440107219982E-01,
-1.603895421557E-01, -2.117895648724E-01, -2.492677779574E-01, -
2.472158313723E-01, -1.022128484684E-01,
-9.117167445845E-05, -7.626472284749E-03, 8.630347099111E+01,
1.210835111653E+06, 6.429308137273E-01,
/
/us for T = 2000000 and tb = 125
u= -1.024464713350E+00, -6.311563424471E-01, -7.698687883663E-01, -
3.836667359859E-01, -1.503173629751E-01,
```

```
-1.772889669686E-01, -2.362454461379E-01, -2.827078427946E-01, -
2.546884812394E-01, -1.032405112280E-01,
-9.117231686169E-05, -7.634991337489E-03, 8.629733183355E+01,
1.214971202342E+06, 7.023825295125E-01,
/
/us for T = 2000000 and tb = 100
u= -1.083483704817E+00, -6.299342591120E-01, -7.579326683569E-01, -
4.348036006134E-01, -1.557763536568E-01,
-1.792066806223E-01, -2.257504916082E-01, -2.637245432764E-01, -
1.981213733257E-01, -9.972717688620E-02,
-9.117219021412E-05, -7.639170094409E-03, 8.631032487455E+01,
1.198937405551E+06, 8.690272270267E-01,
$
c
c
c BEGIN EVENT LISTING - trajectory simulation inputs
c
p$gendat
 title = 0h* LOX/LH2 Bimese 28.5 deg delivering 60 klb *,
 event = 10, / first event
c
c output setup
c ------------------------------------------------
  npc(11) = 0, / no functional inequality constraints
   fesn  = 500, / final event number
   npc(1) = 2, / print conic block at each phase change
    pinc = 2, / print interval every 20 seconds
   npc(2) = 1, / fourth order runge kutta
    dt = 1, / integration step size
   npc(20) = 0, / do not use any special dt calculation
   npc(25) = 3, / compute velocity losses and print at each time
   maxtim = 1000., / maximum time
   altmax = 10000000., / maximum altitude allowed
   altmin = -5000 , / minimum altitude allowed
   prnc  = 0, /setup plot file
   monx  = 4hdynp, 4hfazb, 5halpha, 4hasmg, 4heta , 4hetal./ monitor q &
normal force
   prnt(97) = 5hxmax1, 5hxmax2, 5hxmin2, 6haltito, 4hmach, 4hdynp, 3hwd1,
3hwd2,
   prnt(105)= 5hwprp1, 5hwprp2, 4hamyb, 5httmyb, 5hxmax5, 5hxmin5,
5hxmin6./
c ------------------------------------------------
c
c Guidance setup
c ------------------------------------------------
  iguid(1)  = 1, / inertial euler angle option
  iguid(2)  = 0, / same steering option for all channels
  iguid(4)  = 1, / cubic poly with constant term set by input
   pitpc(1) = 0., / initial pitch rate
   yawpc(1) = 0., / initial yaw rate
   rolpc(1) = 0., / initial roll rate
c ------------------------------------------------
c
c Earth relative Components
c ------------------------------------------------
  npc(3) = 4, / planet relative input on velocity vector
   velr = .1, / initial velocity at launch pad
   gammar = 90., / initial planet relative flight path angle
   azvelr = 0., / initial azimuth angle of velr
   azl  = 90.,
  npc(12) = 3, / calculate crossrange and downrange based on orbit
   altref = 100.0, / 100 nmi circular mile reference orbit
   azref = 0., / azimuth reference
c ------------------------------------------------
c
c Earth Launch Site
c ------------------------------------------------
  npc(4) = 2, / planet relative input on altitude vector
   altito = 0., / initial altitude
   gdalt = 0., / initial altitude
   gdlat = 28.5, / latitude of launch site
   long = 280.0, / longitude of launch site
   longi = 280.0, / longitude east of prime meridian
c ------------------------------------------------
c
c Earth atmosphere inputs
c ------------------------------------------------
  npc(5) = 5, / 1976 us standard atmosphere
  npc(6) = 0, / no winds
c ------------------------------------------------
c
c Earth Gravity
c ------------------------------------------------
  npc(16) = 0, / use oblate earth gravity model
c ------------------------------------------------
c
c Limit acceleration
c ------------------------------------------------
  npc(7) = 1, / do not limit acceleration
   asmax = 3.0, / limit acceleration throughout trajectory
c ------------------------------------------------
c
c Aerodynamic and Trim Data (Tables down below)
c ------------------------------------------------
npc(8)  = 2, / cl, cd & cm table inputs
 lref  = 162.6, /body length from nose to base
 sref  = 3500.7, /reference area for orbiter only
npc(10)  = 0, / static trim in pitch
gxp(1)  = 160.2, /x-location of engine gimbal measured from nose
itrim  = 1, / trim with engine deflections only
npc(15)  = 0, / do not calculate aeroheating
npc(26)  = 0, / no special aeroheating calculations
npc(38)  = 0, / no atmospheric turbulence
npc(39)  = 0, / no atmospheric gusts
npc(40)  = 1, /
c ------------------------------------------------
c
c Propulsive Data
c ------------------------------------------------
npc(9) = 1, / rocket engine with thrust table and ispvac
iengt = 1, / calculate engine incidence angles from static trim equations
npc(13) = 0, / do not jettison propellant
npc(22) = 2, / set eta to value inputted by etapc
 etapc(1) = 1.0, / throttle value
npc(27) = 0, / do not integrate engine flowrates
 iwpf(1) = 1,1, / integrate booster and strap flow rates
/the throttling is kind of complicated
/the engine can be throttled to meet dynamic pressure and wing loading
/constraints during ascent, but the solid motors cannot be throttled
/once the vehicle gets to 3g's the post is instructed to limit the acc. to 3.
 ienga(1) = -1,0, / throttle orbiter using input eta, but not strap ons
 iengmf(1) = 1,1, / orbiter and strap rockets are on
  iwdf   =    1,1,  /use isp vac
  nengl  =    1,
  nengh  =    2,  /highest number of engines
  mentnk  =    1,2,  /map each engine to a specific tank
  wprp(1)  =    7.5295e5, /weight of srb propellent
  menstp  =    1,2,
c ------------------------------------------------
c
c Weight model
c ------------------------------------------------
 npc(17) = 2, / jettison booster
 npc(30) = 3, / use n-stage vehicle weight model
  wstpd(1) =   .75295e5, /dry weight of srb
  wstpd(2) =   1218283./grossweight of orbiter
c ------------------------------------------------
c
c Random Stuff
c ------------------------------------------------
 npc(14) = 0, / no holddown before liftoff
 npc(18) = 0, / do not terminate trajectory
 npc(21) = 0, / do not calculate fuel and oxidizer weights and volumes
 npc(23) = 0, / do not compute velocity margins
 npc(24) = 0, / do not compute any parameter integrals
 npc(28) = 0, / tracking station option not used
 npc(29) = 0, / do not compute vacuum impact points
 npc(31) = 0, / no vernal equinox, sun shadow, sun angle calculations
 npc(32) = 0, / no parachute drag
 npc(33) = 0, / no arc length calculations
 npc(34) = 0, / no keplerian state calculations
 npc(35) = 0, / no sensed velocity increment calculations
 npc(36) = 0, / do not activate sunlight options
 npc(37) = 0, / do not activate date option
c ------------------------------------------------
c
c Tables
c ------------------------------------------------
$
p$tblmlt
 cdm = 1.1,
 tvc2m = 3.3351, / thrust multiplier for orbiter
 wd2m = 3.3351, / flow rate multiplier for orbiter
 ae2m = 3.3351, / exit area multiplier for orbiter
$
p$tab
 table = 5htvc2t, 0,531500., / vacuum thrust of orbiter engine
$
p$tab
 table = 5htvc1t, 0,2.2406e6, / vacuum thrust of strap-ons engine
$
p$tab
 table = 4hwd2t,0,1199.77, / flow rate of orbiter engine
$
p$tab
 table = 4hwd1t,0,8140, / flow rate of strap-ons engine
$
p$tab
 table = 4hae2t, 0,33.558, / exit area of orbiter engine
$
p$tab
 table = 4hae1t, 0,113.73, / exit area of strap-ons engine
$
p$tab table = 4hxcgt,1,6hweight,2,1,-1,1,
  2006450,123.51,134870,115.50,
$
```

```
p$tab table=5hxrefl,0,109.90,
$
p$tab table=5hzrefl,0,0,
$
*include '/home/asdl1/jtooley/post/BIMESE/bimese aero'
 endphs = 1,
c -----------------------------------------------
$
l$gendat
 event=14,1,critr = 5htime ,
 value = 20,  /change throttle to acceleration limiting
 xmax(5) = 0,  /reset throttle so can make sure etapc(1) isn't set to above one
  etapc(1) = .5,
 endphs    = 1,
$
l$gendat
 event=15,critr=4htime,value=07,endphs=1,
 iguid(4)=0,
$
l$gendat
 event=16,critr=4htime,value=20,endphs=1,
$
l$gendat
 event=18,1,critr=4hasmg,
 value = 2.999,  /change throttle to acceleration limiting
 iguid(4)=2,
 npc(7) = 1, / limit acceleration
   asmax = 3.0, / limit acceleration to 3 g's
 npc(22) = 2,
 ienga(1) = 0,1, / throttle orbiter using acc. limit, but not strap ons
 etapc(1) = 1,
 endphs   = 1,
$
l$gendat
 event=19,1,critr=5hwprp1,value=0,
 value     = 0,  /turn on new engine when 1st stage fuel is empty
 nstpl    = 2,
 iengmf(1)  = 0,  /strap ons off
 npc(7) = 1, /  limit acceleration
   asmax = 3.0, / limit acceleration to 3 g's
 npc(22) = 2,
 ienga(1) = 0,1, / throttle orbiter using acc. limit
 etapc(1) = 1,
$
p$tblmlt
 cdm = 1.0,
$
p$tab
 table = 5htvc2t, 0,531500., / vacuum thrust of orbiter engine
 endphs    = 1,
$
l$gendat
 event=20,critr=4htime,value=51,endphs=1,
$
l$gendat
 event=30,critr=4htime,value=80,endphs=1,
$
l$gendat
 event=40,critr=4htime,value=110,endphs=1,
$
l$gendat
 event=60,critr=4htime,value=140,endphs=1,
$
l$gendat
 event=65,critr=4htime,value=170,endphs=1,
$
l$gendat
 event=70,critr=4htime,value=200,endphs=1,
$
l$gendat
 event=75,critr=4htime,value=230,endphs=1,
$
l$gendat
 event=80,critr=4htime,value=240,endphs=1,
$
l$gendat
 event=85,critr=4htime,value=250,endphs=1,
$
l$gendat
 event=90,critr=4htime,value=260,endphs=1,
$
l$gendat
c this event marks injection into orbit
 event=500,critr=5hwprop,value=-999733,
 endphs = 1,
 endjob = 1,
 endprb = 1,
$
```

A.4. MATED BIMESE: LEO

```
P$SEARCH
C*************************************************
C  LOX/LH2 BIMESE W/RS2100 Engine (revised 1/1/99)
C  WB-003-C Bimese 60 Klb to 100 nmi
C  28.5 DEGREES INCLINATION
C  LATEST WB-001 AERO ADDED 5/6/97
C*************************************************
C
 SRCHM = 4, / PROJECTED GRADIENT METHOD
C IPRO = -1, / PRINT FINAL TRAJECTORY ONLY
 IOFLAG = 0, / ENGLISH IN - ENGLISH OUT
 CONEPS(1) = 89.9, / CONVERGENCE TOLERANCE
 CONEPS(2) = .00001, / MIN ALLOWED PERCENTAGE CHANGE
 CONEPS(3) = .00001, /
 CONEPS(4) = .00001, /
 CONEPS(5) = .00001, /
 PCTCC= 001, /
 IDEB=0, / No Detail
C
C*************************************************
C          OPTIMIZATION VARIABLE
C*************************************************
C
 OPTVAR = 6HWEIGHT, / MAXIMIZE FINAL BURNOUT WEIGHT
 OPT = 1, / MAXIMIZATION FLAG
 OPTPH = 500, / PHASE AT WHICH WEIGHT IS MAXIMIZED
 WOPT = .000003, / OPTIMIZATION VARIABLE WEIGHTING
 MAXITR = -1, / MAXIMUM ITERATIONS ALLOWED
C
C*************************************************
C
C          CONSTRAINT VARIABLES
C
C*************************************************
C
 NDEPV = 6, / NUMBER OF DEPENDENT VARIABLES USED AS
CONTROLS
 DEPVR = 5HGDALT, 6HGAMMAI, 3HINC, 5HXMAX1, 5HXMAX2,
5HXMIN2, / INSERTION ORBIT CONDITIONS + CONSTRAINTS
 DEPVAL = 303805.0, 0.0, 28.5, 1000., 379165., -379165., / INSERTION
ORBIT VALUES + CONSTRAINTS
 DEPTL = 300.0, .1, .1, 1., 100, 100, / DESIRED ACCURACIES
 DEPPH = 500, 500, 500, 500, 500, 500, / EVENTS
 IDEPVR = 0, 0, 0, 1, 1, -1,
C
C*************************************************
C
C          CONTROL VARIABLES
C
C*************************************************
C
 nindv = 16,
 indvr = 15*6hpitpc2,3hazl,
 indph = 15,18,20,30,40,60,65,70,75,80,85,90,95,100,105,10,
 u= -9.631146612932E-01, 1.206853378424E-01, 3.371722786330E-02,
   -8.335495035323E-01, -4.798149007642E-01,
   -4.000001681097E-01, -4.348020053465E-02, -1.415419515140E-01,
   -4.036245017758E-01, -9.915998643712E-02,
   -1.851298896717E-03, -3.262486724374E-02, -2.648031155382E-02,
   -4.657733088827E-01, -1.312917301909E-01,
   0.0,
 u= -1.112110516660E+00, 9.596061841384E-02, 2.405720312012E-02, -
8.647860715809E-01, -8.524468987230E-01,
-7.365135456373E-01, -6.185493375131E-02, -1.780915656336E-01, -
2.827569253803E-01, -2.617153231269E-01,
-1.977722599479E-03, -7.981303256862E-02, -3.949655878951E-02, -
5.901753314859E-01, -1.333034849750E-01,
 8.621963895029E+01,
 PERT = 16*1.0E-4, / PERTURB
 $
C*************************************************
C
C          TRAJECTORY SIMULATION INPUTS
C
C*************************************************
P$GENDAT
 TITLE = 0H* LOX/LH2 BIMESE 28.5 deg delivering 60 Klb *,
 EVENT = 10, / FIRST EVENT
  WGTSG = 2274254., / INITAL LIFTOFF WEIGHT with ADDED FLUIDS
  FESN = 500, / FINAL EVENT NUMBER
  MAXTIM = 1000., / MAXIMUM TIME
  ALTMAX = 10000000., / MAXIMUM ALTITUDE ALLOWED
  ALTMIN = -5000., / MINIMUM ALTITUDE ALLOWED
  PRNC = 0, /setup plot file
  MONX = 4HDYNP, 4HFAZB, / MONITOR Q & NORMAL FORCE
  PRNT(97) = 5HXMAX1, 5HXMAX2, 5HXMIN2, 6HALTITO, 4HMACH,
4HDYNP,6HNETISP,
  4HAMYB, 5HTTMYB, 5HPSTOP, /
 IGUID(1) = 1, / INERTIAL EULER ANGLE OPTION
IGUID(2) = 0, / SAME STEERING OPTION FOR ALL CHANNELS
IGUID(4) = 1, / CUBIC POLY WITH CONSTANT TERM SET BY INPUT
 PITPC(1) = 0., / INITIAL PITCH RATE
 YAWPC(1) = 0., / INITIAL YAW RATE
 ROLPC(1) = 0., / INITIAL ROLL RATE
NPC(1) = 2, / PRINT CONIC BLOCK AT EACH PHASE CHANGE
 PINC = 20, / PRINT INTERVAL EVERY 20 SECONDS
NPC(2) = 1, / FOURTH ORDER RUNGE KUTTA
 DT = 1, / INTEGRATION STEP SIZE
NPC(3) = 4, / PLANET RELATIVE INPUT ON VELOCITY VECTOR
 VELR = .1, / INITIAL VELOCITY AT LAUNCH PAD
 GAMMAR = 90., / INITIAL PLANET RELATIVE FLIGHT PATH ANGLE
 AZVELR = 90., / INITIAL AZIMUTH ANGLE OF VELR
NPC(4) = 2, / PLANET RELATIVE INPUT ON ALTITUDE VECTOR
 ALTITO = 0., / INITIAL ALTITUDE
 GDALT = 0., / INITIAL ALTITUDE
 GDLAT = 28.5, / LATITUDE OF LAUNCH SITE
 LONG = 280.0, / LONGITUDE OF LAUNCH SITE
 LONGI = 280.0, / LONGITUDE EAST OF PRIME MERIDIAN
NPC(5) = 5, / 1976 US STANDARD ATMOSPHERE
NPC(6) = 0, / NO WINDS
NPC(7) = 1, / ACCELERATION LIMIT SET
 ASMAX = 3.0, / LIMIT ACCELERATION THROUGHOUT TRAJECTORY
 LREF = 162.6, /BODY LENGTH FROM NOSE TO BASE
 SREF = 7001.4, /REFERENCE AREA
NPC(8) = 2, / CL, CD & CM TABLE INPUTS
NPC(9) = 1, / ROCKET ENGINE WITH THRUST TABLE AND ISPVAC
NPC(10) = 0, / STATIC TRIM IN PITCH
GXP(1) = 160.2, /X-LOCATION OF ENGINE GIMBAL MEASURED FROM
NOSE
ITRIM = 1, / TRIM WITH ENGINE DEFLECTIONS ONLY
IENGT = 1, / CALCULATE ENGINE INCIDENCE ANGLES FROM STATIC
TRIM EQUATIONS
NPC(11) = 0, / NO FUNCTIONAL INEQUALITY CONSTRAINTS
NPC(12) = 3, / CALCULATE CROSSRANGE AND DOWNRANGE BASED
ON ORBIT
 ALTREF = 100.0, / 100 NMI CIRCULAR MILE REFERENCE ORBIT
 AZREF = 0., / AZIMUTH REFERENCE
NPC(13) = 0, / DO NOT JETTISON PROPELLANT
NPC(14) = 0, / NO HOLDDOWN BEFORE LIFTOFF
NPC(15) = 0, / DO NOT CALCULATE AEROHEATING
NPC(16) = 0, / USE OBLATE EARTH GRAVITY MODEL
NPC(17) = 2, / JETTISON BOOSTER
NPC(18) = 0, / DO NOT TERMINATE TRAJECTORY
C NPC(19) = 0, / DO NOT PRINT INPUT CONDITION SUMMARIES
NPC(20) = 0, / DO NOT USE ANY SPECIAL DT CALCULATION
NPC(21) = 0, / DO NOT CALCULATE FUEL AND OXIDIZER WEIGHTS
AND VOLUMES
NPC(22) = 0, / DO NOT CALCULATE THROTTLING
NPC(23) = 0, / DO NOT COMPUTE VELOCITY MARGINS
NPC(24) = 0, / DO NOT COMPUTE ANY PARAMETER INTEGRALS
NPC(25) = 3, / COMPUTE VELOCITY LOSSES AND PRINT AT EACH
TIME
NPC(26) = 0, / NO SPECIAL AEROHEATING CALCULATIONS
NPC(27) = 0, / DO NOT INTEGRATE ENGINE FLOWRATES
 IWPF(1) = 0, / DO NOT INTEGRATE MAIN ENGINES
 IWPF(2) = 1, / INTEGRATE BOOSTER FLOW RATES
NPC(28) = 0, / TRACKING STATION OPTION NOT USED
NPC(29) = 0, / DO NOT COMPUTE VACUUM IMPACT POINTS
NPC(30) = 0, / USE N-STAGE VEHICLE WEIGHT MODEL
 IENGA(1) = 1, / CALCULATE BOOSTER THROTTLE NECESSARY TO
LIMIT ACCELERATION
 IENGA(2) = 1, / THROTTLE ORBITER
 IENGMF(1) = 1, / BOOSTER ENGINES ARE ON
 IENGMF(2) = 1, / ORBITER ROCKETS ARE ON
 IWDF(1) = 1, / CALCULATE BOOSTER FLOW RATES AS A TABLE
LOOKUP
 IWDF(2) = 1, / CALCULATE ORBITER FLOW RATES AS A TABLE
LOOKUP
 NENG = 2, / THE NUMBER OF THRUSTING ENGINES
NPC(31) = 0, / NO VERNAL EQUINOX, SUN SHADOW, SUN ANGLE
CALCULATIONS
NPC(32) = 0, / NO PARACHUTE DRAG
NPC(33) = 0, / NO ARC LENGTH CALCULATIONS
NPC(34) = 0, / NO KEPLERIAN STATE CALCULATIONS
NPC(35) = 0, / NO SENSED VELOCITY INCREMENT CALCULATIONS
NPC(36) = 0, / DO NOT ACTIVATE SUNLIGHT OPTIONS
NPC(37) = 0, / DO NOT ACTIVATE DATE OPTION
NPC(38) = 0, / NO ATMOSPHERIC TURBULENCE
NPC(39) = 0, / NO ATMOSPHERIC GUSTS
NPC(40) = 1, /
$
P$TBLMLT
 TVC1M = 3.3351, / THRUST MULTIPLIER FOR BOOSTER
 WD1M = 3.3351, / FLOW RATE MULTIPLIER FOR BOOSTER
 AE1M = 3.3351, / EXIT AREA MULTIPLIER FOR BOOSTER
 TVC2M = 3.3351, / Thrust multiplier for Orbiter
 WD2M = 3.3351, / Flow rate multiplier for Orbiter
 AE2M = 3.3351, / Exit area multiplier for Orbiter
```

```
$
PSTAB
 TABLE = 5HTVC1T,0,531500., / VACUUM THRUST
$
PSTAB
 TABLE = 5HTVC2T, 0,531500., / VACUUM THRUST OF Orbiter engine
$
PSTAB
 TABLE = 4HWD1T,0,1199.77, / FLOW RATE
$
PSTAB
 TABLE = 4HWD2T,0,1199.77, / FLOW RATE OF Orbiter engine
$
PSTAB
 TABLE = 4HAE1T,0,33.558, / EXIT AREA
$
PSTAB
 TABLE = 4HAE2T, 0,33.558, / EXIT AREA OF Orbiter engine
$
PSTAB TABLE = 4HXCGT,1,6HWEIGHT,2,1,-1,1,
  2006450,123.51,134870,115.50,
$
PSTAB TABLE=5HXREFT,0,109.90,
$
PSTAB TABLE=5HZREFT,0,0,
$
*include '/home/asdl1/jtooley/post/BIMESE/bimese.aero'
 ENDPHS = 1,
$
l$gendat
 event=15,critr=4htime,value=07,endphs=1,
 iguid(4)=0,
$
l$gendat
 event=18,critr=4htime,value=17,endphs=1,
$
l$gendat
 event=20,critr=4htime,value=30,endphs=1,
$
l$gendat
 event=30,critr=4htime,value=40,endphs=1,
$
l$gendat
 event=40,critr=4htime,value=60,endphs=1,
$
l$gendat
 event=60,critr=4htime,value=80,endphs=1,
$
l$gendat
 event=65,critr=4htime,value=100,endphs=1,
$
l$GENDAT
 EVENT = 35, CRITR = 6HWEICON, VALUE =909679.,
 WJETT = 174031., / JETTISON DRY Booster
 IENGMF(1) = 0, / TURN Booster OFF
 IENGMF(2) = 1, / TURN Orbiter ON
 IWDF(1) = 0, / FLOW RATES OFF
 IWDF(2) = 1, / FLOW RATES ON
 IENGA(1) = 0, /
 IENGA(2) = 1, /
 IWDF(1) = 0, /
 IWDF(2) = 1, /
 LREF = 162.6, /Orbiter
 SREF = 3500.7, /Orbiter alone
 ENDPHS = 1,
$
l$gendat
 event=70,critr=4htime,value=145,endphs=1,
$
l$gendat
 event=75,critr=4htime,value=185,endphs=1,
$
l$gendat
 event=80,critr=4htime,value=220,endphs=1,
$
l$gendat
 event=85,critr=4htime,value=255,endphs=1,
$
l$gendat
 event=90,critr=4htime,value=290,endphs=1,
$
l$gendat
 event=95,critr=4htime,value=330,endphs=1,
$
l$gendat
 event=100,critr=4htime,value=360,endphs=1,
$
l$gendat
 event=105,critr=4htime,value=390,endphs=1,
$
l$gendat
c this event marks injection into orbit
 event=500,critr=4hveli,value=25855.000,
 ENDPHS = 1,
 ENDJOB = 1,
 ENDPRB = 1,
$
```

A.5. SINGLE ELEMENT: POINT-TO-POINT

```
P$SEARCH
C*******************************************************
C  LOX/LH2 BIMESE W/RS2100 Engine (revised 1/1/99)
C  WB-003-C Bimese point to point
C  single Orbiter cannot make it to orbit
C  Goal is to maximize crossrange of orbiter
C  Simulates the ascent (but not to orbit) and reentry
C  The Gliding entry phase is simulated down to 80,000 ft and a rel vel of 2500
ft/s
C  At this point energy management phase would take over, but it is not
simulated
C  Energy management phase usually results in a 100 nmi crossrange
C  LATEST WB-001 AERO ADDED 5/6/97
C*******************************************************
C
 SRCHM = 4, / PROJECTED GRADIENT METHOD
c IPRO = -1, / PRINT FINAL TRAJECTORY ONLY
 IOFLAG = 0, / ENGLISH IN - ENGLISH OUT
 CONEPS(1) = 89.9, / CONVERGENCE TOLERANCE
 CONEPS(2) = .00001, / MIN ALLOWED PERCENTAGE CHANGE
 CONEPS(3) = .00001, /
 CONEPS(4) = .00001, /
 CONEPS(5) = .00001, /
 PCTCC=.001, /
 IDEB=0,  / No Detail
C
C*******************************************************
C             OPTIMIZATION VARIABLE
C*******************************************************
C
 OPTVAR = 6HDPRNG1, / MAXIMIZE DISTANCE TRAVELED
 OPT = 1, / MAXIMIZATION FLAG
 OPTPH = 500, / PHASE AT WHICH WEIGHT IS MAXIMIZED
 WOPT = .000003, / OPTIMIZATION VARIABLE WEIGHTING
 MAXITR = -1, / MAXIMUM ITERATIONS ALLOWED
C
C*******************************************************
C
C             CONSTRAINT VARIABLES
C
C*******************************************************
C
 NDEPV = 5, / NUMBER OF DEPENDENT VARIABLES USED AS
CONTROLS
 DEPVR =  5HXMAX3,5HXMAX1, 5HXMAX2, 5HXMIN2, 5HXMAX4,
 DEPVAL =  4, 1000., 379165., -379165.,40, / INSERTION ORBIT VALUES +
CONSTRAINTS
 DEPTL =  .1,   1,    100,     100, 1, / DESIRED ACCURACIES
 DEPPH =   500,500,500,500,500,/ EVENTS
 IDEPVR =  1, 1, 1, -1, 1,
C*******************************************************
C
C
C             CONTROL VARIABLES
C
C*******************************************************
C
 tabl(1) =4hpitt,4hpitt,4hpitt,4hpitt,4hpitt,4hpitt,4hpitt,4hpitt,
 tabl(9)
=6halphat,6halphat,6halphat,6halphat,6halphat,6halphat,6halphat,6halphat,
 tably(1)=1,2,3,4,5,6,7,8,
 tably(9)=3,4,5,6,7,8,9,10,
 nindv  = 16,  /In this deck banking angles are not needed to meet constraints
 indvr  = 5htabl1,5htabl2,5htabl3,5htabl4,5htabl5,5htabl6,5htabl7,5htabl8,
 indvr(9)
=5htabl9,6htabl10,6htabl11,6htabl12,6htabl13,6htabl14,6htabl15,6htabl16,
 indph  = 15,15,15,15,15,15,15,15,
 indph(9) = 20,20,20,20,20,20,20,20,
 PERT = 16*1.0E-4,1,  / PERTURB
 u= -8.274111864380E-03,-2.133260052939E+01,-2.397666974775E+01,
   -5.626555826370E+01,-7.361997959382E+01,-8.622227418861E+01,
   -9.336816957698E+01,-9.873961518200E+01, 8.627310476026E+01,
 u= -8.274245165569E-03,-2.139110649241E+01,-2.420824304951E+01,
   -5.618058820848E+01,-7.346516014114E+01,-8.171782513255E+01,
   -9.367542853691E+01,-9.860263846201E+01, 8.627300997425E+01,
 /u's that result in opt guidance with only alpha control violates normal force
const
 u= -8.274217413973E-03,-2.121879899720E+01,-2.413003298457E+01,
   -5.462767091147E+01,-8.475214444848E+01,-8.152759020379E+01,
   -9.279218168809E+01,-9.860263846201E+01, 8.651244888145E+01,
    40,5.951168900506E+01, 4.140549137941E+01, 1.065461141837E+01,
    5.929888736206E+00, 5.058832037600E+00, 1.327631524231E-02,-
60,60,60,-40,-40,20,
 u= -8.274217413973E-03,-2.121879899720E+01,-2.413003298457E+01,
   -5.462767091147E+01,-8.475214444848E+01,-8.152759020379E+01,
   -9.279218168809E+01,-9.860263846201E+01, 8.651244888145E+01,
    40,5.951168900506E+01, 4.140549137941E+01, 1.065461141837E+01,
   5.929888736206E+00, 5.058832037600E+00, 1.327631524231E-02,-10,-10,-
10,-10,-10,-10,
 /converged solution without constraining final velocity
 u= -8.274217413973E-03,-2.121879899720E+01,-2.413003298457E+01,
   -5.462767091147E+01,-8.475214444848E+01,-8.152759020379E+01,
   -9.279218168809E+01,-9.860263846201E+01, 7.176385530439E+01,
   4.000008502815E+01, 6.101418902565E+01, 4.258546163130E+01,
   1.063685205035E+01, 5.913129650736E+00, 5.045232193202E+00,
   1.327631425463E-02, 0.999774520459E+00, 0.984773751125E+00,
   0.976526577165E+00, 0.995185582387E+00, 0.000005876146E+01,
   0.000000000000E+01,
 /converged with velocity constraint
 u= -8.274218664838E-03,-2.122348549737E+01,-2.415495329997E+01,
   -5.532985169107E+01,-8.484468181437E+01,-8.149072879458E+01,
   -9.225087779792E+01,-9.849049546882E+01,
   4.072197186392E+01, 4.046499248601E+00, 4.098270640091E+00,
   4.027990176507E+01,
3.027990176507E+01,2.327990176507E+01,2.327990176507E+01,2.327990176
507E+01,
 /use u's for 1,000 lb payload
 u= -8.274279039759E-03,-2.142081663503E+01,-2.361182370361E+01,
   -5.618851516036E+01,-9.697944809427E+01,-6.839258291462E+01,
   -9.366037176118E+01,-9.990424738464E+01, 4.000013311904E+01,
   4.000000031147E+01, 3.091193896437E+01, 3.047280667995E+01,
   2.047418722764E+01, 2.320844011004E+01, 1.315381826792E+01,
   0.317517262700E+01,
 /use u's for 1,000 lb payload
 u= -8.274285458116E-03,-2.144825875449E+01,-2.359079011735E+01,
   -5.519649718889E+01,-9.249077673248E+01,-7.116956274567E+01,
   -9.258437443429E+01,-9.990424738464E+01, 3.910694125902E+01,
   3.927560866427E+01, 3.048172604214E+01, 3.015810000807E+01,
   2.035214171299E+01, 2.309694617097E+01, 1.317472828524E+01,
   3.176752890923E+00,
 u=  -8.274285001159E-03, -2.133740974347E+01, -2.372382620481E+01, -
5.502854357052E+01, -9.204608000024E+01,
 -7.127449378298E+01, -9.260171928367E+01, -9.990424738464E+01,
3.910694125902E+01,  3.927560866427E+01,
  3.048172604214E+01,  3.015810000807E+01,  2.035214171299E+01,
2.009694617097E+01,  1.317472828524E+01,
  3.176752890923E+00,
 u=  -8.274284650071E-03, -2.427521889897E+01, -2.574404360316E+01, -
5.500979194040E+01, -9.202426147050E+01,
 -7.128267284684E+01, -9.260263474492E+01, -9.990424738464E+01,
3.910694125902E+01,  3.927560866427E+01,
  3.048172604214E+01,  3.015810000807E+01,  2.035214171299E+01,
2.009694617097E+01,  1.317472828524E+01,
  3.176752890923E+00,
 u=  -8.274277405352E-03, -2.203465552405E+01, -2.646959148998E+01, -
5.486751359144E+01, -9.155510109285E+01,
 -7.130735674352E+01, -9.211244742081E+01, -9.990424738464E+01,
3.904698297619E+01,  3.914151458512E+01,
  3.039242625757E+01,  3.009199393551E+01,  2.032308900060E+01,
2.007854985308E+01,  1.317695197695E+01,
  3.176930789416E+00,
 u=  -8.274292444634E-03, -2.213526273097E+01, -2.655677633584E+01, -
5.520896242270E+01, -8.704952345146E+01,
 -7.487853389145E+01, -8.694521837372E+01, -9.990424738464E+01,
3.794469689704E+01,  3.618706367882E+01,
  2.926431136015E+01,  2.942776111155E+01,  1.992022902436E+01,
1.991268210402E+01,  1.321554806599E+01,
  3.180024775060E+00,
 u=  -8.274302609566E-03, -2.198109731806E+01, -2.687452357529E+01, -
5.545321538596E+01, -8.475943112996E+01,
 -7.365226913249E+01, -8.586190138421E+01, -9.990424738464E+01,
3.683948762582E+01,  3.333347120303E+01,
  2.847403324808E+01,  2.890967570875E+01,  1.973721712864E+01,
1.988779251295E+01,  1.325399446711E+01,
  3.183062499091E+00,
 u=  -8.274300530916E-03, -2.193239408865E+01, -2.666928433839E+01, -
5.972409437765E+01, -8.570534750554E+01,
 -8.215147334882E+01, -7.889139786174E+01, -9.267465301832E+01,
3.490164234376E+01,  3.222910009984E+01,
  2.821906569241E+01,  2.871116523180E+01,  1.967036825028E+01,
1.987834137037E+01,  1.330195534512E+01,
  3.186489413846E+00,
 u=  -8.274286253070E-03, -2.186160679832E+01, -2.669959867244E+01, -
5.722351248990E+01, -8.730825579231E+01,
 -7.564352400382E+01, -8.335736962521E+01, -9.693565430695E+01,
3.491010638185E+01,  3.223600706208E+01,
  2.822052945986E+01,  2.871237714334E+01,  1.967077580437E+01,
1.987840475437E+01,  1.330172986096E+01,
  3.186473085384E+00,
 u=  -8.274300530916E-03, -2.193239408865E+01, -2.666928433839E+01, -
5.972409437765E+01, -8.570534750554E+01,
 -8.215147334882E+01, -7.889139786174E+01, -9.267465301832E+01,
3.490164234376E+01,  3.222910009984E+01,
  2.821906569241E+01,  2.871116523180E+01,  1.967036825028E+01,
1.987834137037E+01,  1.330195534512E+01,
```

```
3.186489413846E+00,
u= -8.274300807638E-03, -2.193378482791E+01, -2.666884420787E+01, -
5.980620048027E+01, -8.584646483286E+01,
-8.239188743511E+01, -7.890618137000E+01, -9.258617718327E+01,
3.490164234376E+01, 3.222910009984E+01,
2.821906569241E+01, 2.871116523180E+01, 1.967036825028E+01,
1.987834137037E+01, 1.330195534512E+01,
3.186489413846E+00,
u= -8.274301427914E-03, -2.193677671608E+01, -2.665854637207E+01, -
5.954695994818E+01, -8.518115781198E+01,
-8.228939751839E+01, -7.898719381359E+01, -9.261476261244E+01,
3.486356778167E+01, 3.219810154606E+01,
2.821252839576E+01, 2.870574049722E+01, 1.966858499644E+01,
1.987805852482E+01, 1.330297094262E+01,
3.186562801210E+00,
u= -8.274329468128E-03, -2.207572164824E+01, -2.648082538327E+01, -
6.124029854938E+01, -7.949261935183E+01,
-8.654086891647E+01, -7.857401453515E+01, -8.818307319575E+01,
3.469786133216E+01, 3.206410790120E+01,
2.818501554105E+01, 2.868246733162E+01, 1.966084040721E+01,
1.987688374684E+01, 1.330730628828E+01,
3.186876237782E+00,
u= -8.274333080081E-03, -2.208893325119E+01, -2.643193837210E+01, -
6.097657119546E+01, -7.868071872061E+01,
-8.660725274903E+01, -7.992194878060E+01, -8.838011470419E+01,
3.427335034189E+01, 3.172440837729E+01,
2.811822072577E+01, 2.862380238584E+01, 1.964171632818E+01,
1.987402867145E+01, 1.331822394620E+01,
3.187664051246E+00,
u= -8.274329468128E-03, -2.207572164824E+01, -2.648082538327E+01, -
6.124029854938E+01, -7.949261935183E+01,
-8.654086891647E+01, -7.857401453515E+01, -8.818307319575E+01,
3.469786133216E+01, 3.206410790120E+01,
2.818501554105E+01, 2.868246733162E+01, 1.966084040721E+01,
1.987688374684E+01, 1.330730628828E+01,
3.186876237782E+00,
/63s chump
u= -8.274333080081E-03, -2.208893325119E+01, -2.643193837210E+01, -
6.097657119546E+01, -7.868071872061E+01,
-8.660725274903E+01, -7.992194878060E+01, -8.838011470419E+01,
3.427335034189E+01, 3.172440837729E+01,
2.811822072577E+01, 2.862380238584E+01, 1.964171632818E+01,
1.987402867145E+01, 1.331822394620E+01,
3.187664051246E+00,
u= -8.274333613270E-03, -2.202585497121E+01, -2.645259999024E+01, -
6.063376525407E+01, -7.804844460816E+01,
-8.623598730071E+01, -8.007198328577E+01, -8.838011470419E+01,
3.419581771260E+01, 3.164212737107E+01,
2.810181328856E+01, 2.860985929624E+01, 1.963703285971E+01,
1.987333933870E+01, 1.332049929277E+01,
3.187822044937E+00,
u= -8.274333080081E-03, -2.208893325119E+01, -2.643193837210E+01, -
6.097657119546E+01, -7.868071872061E+01,
-8.660725274903E+01, -7.992194878060E+01, -8.838011470419E+01,
3.427335034189E+01, 3.172440837729E+01,
2.811822072577E+01, 2.862380238584E+01, 1.964171632818E+01,
1.987402867145E+01, 1.331822394620E+01,
3.187664051246E+00,
$
C**************************************************
C
C          TRAJECTORY SIMULATION INPUTS
C
C**************************************************
P$GENDAT
 TITLE = 0H* LOX/LH2 BIMESE 28.5 deg delivering 60 Klb *,
 EVENT = 10, / FIRST EVENT
  WGTSG  =  1122050,
  FESN = 500, / FINAL EVENT NUMBER
  MAXTIM = 3000., / MAXIMUM TIME
  ALTMAX = 10000000., / MAXIMUM ALTITUDE ALLOWED
  ALTMIN = -5000., / MINIMUM ALTITUDE ALLOWED
  PRNC = 0, /setup plot file
c  PRNCA = 0, /setup delimited plot file
  MONX = 4HDYNP, 4HFAZB, 4HASMG, 5HALPHA, 6HGAMMAI, /
MONITOR Q & NORMAL FORCE
  PRNT(97) = 5HXMAX1, 5HXMAX2, 5HXMIN2, 6HALTITO, 4HMACH,
4HDYNP,5HXMAX5,
  4HAMYB, 5HTTMYB, 4hfazb, /
 IGUID(1) = 1, / INERTIAL EULER ANGLE OPTION
 IGUID(2) = 0, / SAME STEERING OPTION FOR ALL CHANNELS
 IGUID(4) = 1, / CUBIC POLY WITH CONSTANT TERM SET BY INPUT
  PITPC(1) = 0., / INITIAL PITCH RATE
  YAWPC(1) = 0., / INITIAL YAW RATE
  ROLPC(1) = 0., / INITIAL ROLL RATE
 NPC(1) = 2, / PRINT CONIC BLOCK AT EACH PHASE CHANGE
  PINC = 20, / PRINT INTERVAL EVERY 20 SECONDS
 NPC(2) = 1, / FOURTH ORDER RUNGE KUTTA
  DT = 1, / INTEGRATION STEP SIZE
 NPC(3) = 4, / PLANET RELATIVE INPUT ON VELOCITY VECTOR
  VELR = .1, / INITIAL VELOCITY AT LAUNCH PAD
  GAMMAR = 90., / INITIAL PLANET RELATIVE FLIGHT PATH ANGLE
  AZVELR = 0., / INITIAL AZIMUTH ANGLE OF VELR
  azl = 63,
 NPC(4) = 2, / PLANET RELATIVE INPUT ON ALTITUDE VECTOR
  ALTITO = 0., / INITIAL ALTITUDE
  GDALT = 0., / INITIAL ALTITUDE
  GDLAT = 28.5, / LATITUDE OF LAUNCH SITE
  LONG = 280.0, / LONGITUDE OF LAUNCH SITE
  LONGI = 280.0, / LONGITUDE EAST OF PRIME MERIDIAN
 NPC(5) = 5, / 1976 US STANDARD ATMOSPHERE
 NPC(6) = 0, / NO WINDS
 NPC(7) = 1, / ACCELERATION LIMIT SET
  ASMAX = 3.0, / LIMIT ACCELERATION THROUGHOUT TRAJECTORY
  LREF = 162.6, /BODY LENGTH FROM NOSE TO BASE
  SREF = 3500.7, /REFERENCE AREA FOR ORBITER ONLY
 NPC(8) = 2, / CL, CD & CM TABLE INPUTS
 NPC(9) = 1, / ROCKET ENGINE WITH THRUST TABLE AND ISPVAC
 NPC(10) = 0, / STATIC TRIM IN PITCH
 GXP(1) = 160.2, /X-LOCATION OF ENGINE GIMBAL MEASURED FROM
NOSE
 ITRIM = 1, / TRIM WITH ENGINE DEFLECTIONS ONLY
 IENGT = 1, / CALCULATE ENGINE INCIDENCE ANGLES FROM STATIC
TRIM EQUATIONS
 NPC(11) = 0, / NO FUNCTIONAL INEQUALITY CONSTRAINTS
 NPC(12) = 3, / CALCULATE CROSSRANGE AND DOWNRANGE BASED
ON ORBIT
  ALTREF = 100.0, / 100 NMI CIRCULAR MILE REFERENCE ORBIT
  AZREF = 0., / AZIMUTH REFERENCE
 NPC(13) = 0, / DO NOT JETTISON PROPELLANT
 NPC(14) = 0, / NO HOLDDOWN BEFORE LIFTOFF
 NPC(15) = 0, / DO NOT CALCULATE AEROHEATING
 NPC(16) = 0, / USE OBLATE EARTH GRAVITY MODEL
c NPC(17) = 2, / JETTISON BOOSTER
 NPC(18) = 0, / DO NOT TERMINATE TRAJECTORY
C NPC(19) = 0, / DO NOT PRINT INPUT CONDITION SUMMARIES
 NPC(20) = 0, / DO NOT USE ANY SPECIAL DT CALCULATION
 NPC(21) = 0, / DO NOT CALCULATE FUEL AND OXIDIZER WEIGHTS
AND VOLUMES
 NPC(22) = 0, / DO NOT CALCULATE THROTTLING
 NPC(23) = 0, / DO NOT COMPUTE VELOCITY MARGINS
 NPC(24) = 0, / DO NOT COMPUTE ANY PARAMETER INTEGRALS
 NPC(25) = 3, / COMPUTE VELOCITY LOSSES AND PRINT AT EACH
TIME
 NPC(26) = 0, / NO SPECIAL AEROHEATING CALCULATIONS
 NPC(27) = 0, / DO NOT INTEGRATE ENGINE FLOWRATES
  IWPF(1) = 1, / INTEGRATE BOOSTER FLOW RATES
 NPC(28) = 0, / TRACKING STATION OPTION NOT USED
 NPC(29) = 0, / DO NOT COMPUTE VACUUM IMPACT POINTS
 NPC(30) = 0, / USE N-STAGE VEHICLE WEIGHT MODEL
  IENGA(1) = 1, / THROTTLE ORBITER
  IENGMF(1) = 1, / ORBITER ROCKETS ARE ON
  IWDF(1) = 1, / CALCULATE ORBITER FLOW RATES AS A TABLE
LOOKUP
  NENG = 1, / THE NUMBER OF THRUSTING ENGINES
 NPC(31) = 0, / NO VERNAL EQUINOX, SUN SHADOW, SUN ANGLE
CALCULATIONS
 NPC(32) = 0, / NO PARACHUTE DRAG
 NPC(33) = 0, / NO ARC LENGTH CALCULATIONS
 NPC(34) = 0, / NO KEPLERIAN STATE CALCULATIONS
 NPC(35) = 0, / NO SENSED VELOCITY INCREMENT CALCULATIONS
 NPC(36) = 0, / DO NOT ACTIVATE SUNLIGHT OPTIONS
 NPC(37) = 0, / DO NOT ACTIVATE DATE OPTION
 NPC(38) = 0, / NO ATMOSPHERIC TURBULENCE
 NPC(39) = 0, / NO ATMOSPHERIC GUSTS
 NPC(40) = 1, /
$
P$TBLMLT
 TVC1M = 3.3351, / Thrust multiplier for Orbiter
 WD1M = 3.3351, / Flow rate multiplier for Orbiter
 AE1M = 3.3351, / Exit area multiplier for Orbiter
$
P$TAB
 TABLE = 5HTVC1T, 0,531500., / VACUUM THRUST OF Orbiter engine
$
P$TAB
 TABLE = 4HWD1T,0,1199.77, / FLOW RATE OF Orbiter engine
$
P$TAB
 TABLE = 4HAE1T, 0,33.558, / EXIT AREA OF Orbiter engine
$
P$TAB TABLE = 4HXCGT,1,6HWEIGHT,2,1,-1,1,
 2006450,123.51,134870,115.50,
$
P$TAB TABLE=5HXREFT,0,109.90,
$
P$TAB TABLE=5HZREFT,0,0,
*include '/home/asdl1/jtooley/post/BIMESE/PT2PT/bimese.aero'
 ENDPHS = 1,
$
l$gendat
event=15,critr=4htime,value=07,
iguid(4)=2,
$
l$tblmlt
$
```

```
l$tab table=4hpitt,1,6htime ,8,1,1,1,
 10, 90, /all inertial pitch angles are ind. vars.
 30, 90,
 50, 90,
 100, 90,
 150, 90,
 200, 90,
 280, 90,
 320, 90,
 endphs=1,
 $
l$gendat
 title = 0h*Ramp up alpha*,
 event=18, critr=5hwprop, value=-941600, /Maximum allowable propellant
 iengmf(1)=0,   /turn all engines off
 iguid=0,0,3,   /use aero angles with dalpha set in next phase
 dalpha = 40,   /independent variable
 endphs = 1,
 $
l$gendat
 title = 0h*alpha reaches specified value*,
 event=19,critr=6hgammai,value=0,
 npc(17)=2,         / weight jettison option
 wjett=4925,        / vent residuals
 endphs = 1,
 $
l$gendat
 title = 0h*Begin Descent*,
 event=20,critr=6hgammai,value=0,
 dt =4, /increase step size during long descent
 iguid=0,0,2, /use aero angle tables
 npc(17)=2,         / weight jettison option
 wjett=4295,         / vent residuals
 xmax(5)=0,        / reset max gamma monitor
 $
l$tblmlt
 $
l$tab table=6halphat,1,4hvelr,10,1,-1,1,
 25000,  40,
 18000,  40, /Hypersonic trim at 40 degrees
 16000,  0, /control imparted to optimizer
 12000,  0,
 10000,  0,
 8000,   0,
 6000,   0,
 4000,   0,
 2000,   0,
 0,      0,
 endphs=1,
 $
l$gendat
 title = 0h*Destination acheived*,
 event=500,critr=5hgdalt,value=50000,
 ENDPHS = 1,
 ENDJOB = 1,
 ENDPRB = 1,
 $
```

A.6. FUEL-AUGMENTED BIMESE: POINT-TO-POINT

```
P$SEARCH
C**************************************************
C  LOX/LH2 BIMESE with fuel augmentation W/RS2100 Engine (revised
1/1/99)
C  WB-003-C Bimese point to point
C  single Orbiter cannot make it to orbit
C  Goal is to maximize crossrange of orbiter
C  Simulates the ascent (but not to orbit) and reentry
C  The Gliding entry phase is simulated down to 80,000 ft and a rel vel of 2500
ft/s
C  At this point energy management phase would take over, but it is not
simulated
C  Energy management phase usually results in a 100 nmi crossrange
C  LATEST WB-001 AERO ADDED 5/6/97
C**************************************************
C
 SRCHM = 4, / PROJECTED GRADIENT METHOD
c IPRO = -1, / PRINT FINAL TRAJECTORY ONLY
 IOFLAG = 0, / ENGLISH IN - ENGLISH OUT
 CONEPS(1) = 89.9, / CONVERGENCE TOLERANCE
 CONEPS(2) = .00001, / MIN ALLOWED PERCENTAGE CHANGE
 CONEPS(3) = .00001, /
 CONEPS(4) = .00001, /
 CONEPS(5) = .00001, /
 PCTCC=.001, /
 IDEB=0, / No Detail
C
C**************************************************
C           OPTIMIZATION VARIABLE
C**************************************************
C
 OPTVAR = 6HDPRNG1, / MAXIMIZE DISTANCE TRAVELED
 OPT = 1, / MAXIMIZATION FLAG
 OPTPH = 500, / PHASE AT WHICH WEIGHT IS MAXIMIZED
 WOPT = .000003, / OPTIMIZATION VARIABLE WEIGHTING
 MAXITR =40, / MAXIMUM ITERATIONS ALLOWED
C
C**************************************************
C
C           CONSTRAINT VARIABLES
C
C**************************************************
C
 NDEPV = 5, / NUMBER OF DEPENDENT VARIABLES USED AS
CONTROLS
 DEPVR =  5HXMAX3,5HXMAX1, 5HXMAX2, 5HXMIN2, 5HXMAX4,
 DEPVAL =  4, 1000., 379165., -379165.,40, / INSERTION ORBIT VALUES +
CONSTRAINTS
 DEPTL =  1,  1,   100,    100, 1, / DESIRED ACCURACIES
 DEPPH =  500,500,500,500,500,/ EVENTS
 IDEPVR = 1, 1, 1, -1, 1,
C**************************************************
C
C
C           CONTROL VARIABLES
C
C**************************************************
C
 tabl(1) =4hpitt,4hpitt,4hpitt,4hpitt,4hpitt,4hpitt,4hpitt,4hpitt,
 tabl(9)
=6halphat,6halphat,6halphat,6halphat,6halphat,6halphat,6halphat,6halphat,
 tably(1)=1,2,3,4,5,6,7,8,
 tably(9)=3,4,5,6,7,8,9,10,
 nindv  = 16, /In this deck banking angles are not needed to meet constraints
 indvr  = 5htabl1,5htabl2,5htabl3,5htabl4,5htabl5,5htabl6,5htabl7,5htabl8,
 indvr(9)
=5htabl9,6htabl10,6htabl11,6htabl12,6htabl13,6htabl14,6htabl15,6htabl16,
 indph  = 15,15,15,15,15,15,15,15,
 indph(9) = 20,20,20,20,20,20,20,20,
 PERT = 16*1.0E-4,1,  / PERTURB
u= -8.274111864380E-03,-2.133260052939E+01,-2.397666974775E+01,
  -5.626555826370E+01,-7.361997959382E+01,-8.622227418861E+01,
  -9.336816957698E+01,-9.873961518200E+01, 8.627310476026E+01,
u= -8.274245165569E-03,-2.139110649241E+01,-2.420824304951E+01,
  -5.618058820848E+01,-7.346516014114E+01,-8.171782513255E+01,
  -9.367542853691E+01,-9.860263846201E+01, 8.627300997425E+01,
 /u's that result in opt guidance with only alpha control violates normal force
const.
u= -8.274217413973E-03,-2.121879899720E+01,-2.413003298457E+01,
  -5.462767091147E+01,-8.475214444848E+01,-8.152759020379E+01,
  -9.279218168809E+01,-9.860263846201E+01, 8.651244888145E+01,
   40,5.951168900506E+01, 4.140549137941E+01, 1.065461141837E+01,
   5.929888736206E+00, 5.058832037600E+00, 1.327631524231E-02,-
60,60,60,-40,-40,20,
 u= -8.274217413973E-03,-2.121879899720E+01,-2.413003298457E+01,
  -5.462767091147E+01,-8.475214444848E+01,-8.152759020379E+01,
  -9.279218168809E+01,-9.860263846201E+01, 8.651244888145E+01,
   40,5.951168900506E+01, 4.140549137941E+01, 1.065461141837E+01,
   5.929888736206E+00, 5.058832037600E+00, 1.327631524231E-02,-10,-10,-
10,-10,-10,-10,
 /converged solution without constraining final velocity
 u= -8.274217413973E-03,-2.121879899720E+01,-2.413003298457E+01,
  -5.462767091147E+01,-8.475214444848E+01,-8.152759020379E+01,
  -9.279218168809E+01,-9.860263846201E+01, 7.176385530439E+01,
   4.000008502815E+01, 6.101418902565E+01, 4.258546163130E+01,
   1.063685205035E+01, 5.913129650736E+00, 5.045232193202E+00,
   1.327631425463E-02, 0.999774520459E+00, 0.984773751125E+00,
   0.976526577165E+00, 0.995185582387E+00, 0.000005876146E+01,
   0.000000000000E+01,
 /converged with velocity constraint
 u= -8.274218664838E-03,-2.122348549737E+01,-2.415495329997E+01,
  -5.532985169107E+01,-8.484468181437E+01,-8.149072879458E+01,
  -9.225087779792E+01,-9.849049546882E+01,
   4.072197186392E+01, 4.046499248601E+00, 4.098270640 91E+00,
   4.027990176507E+01,
3.027990176507E+01,2.327990176507E+01,2.327990176507E+01,2.327990176
507E+01,
 /use u's for 1,000 lb payload
 u= -8.274279039759E-03,-2.142081663503E+01,-2.361182370361E+01,
  -5.618851516036E+01,-9.697944809427E+01,-6.839258291462E+01,
  -9.366037176118E+01,-9.990424738464E+01, 4.000013311904E+01,
   4.000000031147E+01, 3.091193896437E+01, 3.047280667995E+01,
   2.047418722764E+01, 2.320844011004E+01, 1.315381826792E+01,
   0.317517262700E+01,
 /use u's for 1,000 lb payload
 u= -8.274285458116E-03,-2.144825875449E+01,-2.359079011735E+01,
  -5.519649718889E+01,-9.249077673248E+01,-7.116956274567E+01,
  -9.258437443429E+01,-9.990424738464E+01, 3.910694125902E+01,
   3.927560866427E+01, 3.048172604214E+01, 3.015810000807E+01,
   2.035214171299E+01, 2.309694617097E+01, 1.317472828524E+01,
   3.176752890923E+00,
 u=  -8.274285001159E-03, -2.133740974347E+01, -2.372382620481E+01, -
5.502854357052E+01, -9.204608000024E+01,
 -7.127449378298E+01, -9.260171928367E+01, -9.990424738464E+01,
3.910694125902E+01,  3.927560866427E+01,
 3.048172604214E+01,  3.015810000807E+01,  2.035214171299E+01,
2.009694617097E+01,  1.317472828524E+01,
 3.176752890923E+00,
 u=  -8.274284650071E-03, -2.427521889897E+01, -2.574404360316E+01, -
5.500979194040E+01, -9.202426147050E+01,
 -7.128267284684E+01, -9.260263474492E+01, -9.990424738464E+01,
3.910694125902E+01,  3.927560866427E+01,
 3.048172604214E+01,  3.015810000807E+01,  2.035214171299E+01,
2.009694617097E+01,  1.317472828524E+01,
 3.176752890923E+00,
 u=  -8.274277405352E-03, -2.203465552405E+01, -2.646959148998E+01, -
5.486751359144E+01, -9.155510109285E+01,
 -7.130735674352E+01, -9.211244742081E+01, -9.990424738464E+01,
3.904698297619E+01,  3.914151458512E+01,
 3.039242625757E+01,  3.009199393551E+01,  2.032308900060E+01,
2.007854985308E+01,  1.317695197695E+01,
 3.176930789416E+00,
 u=  -8.274292444634E-03, -2.213526273097E+01, -2.655677633584E+01, -
5.520896242270E+01, -8.704952345146E+01,
 -7.487853389145E+01, -8.694521837372E+01, -9.990424738464E+01,
3.794469689704E+01,  3.618706367882E+01,
 2.926431136015E+01,  2.942776111155E+01,  1.992022902436E+01,
1.991268210402E+01,  1.321554806599E+01,
 3.180024775060E+00,
 u=  -8.274302609566E-03, -2.198109731806E+01, -2.687452357529E+01, -
5.545321538596E+01, -8.475943112996E+01,
 -7.365226913249E+01, -8.586190138421E+01, -9.990424738464E+01,
3.683948762582E+01,  3.333347120303E+01,
 2.847403324808E+01,  2.890967570875E+01,  1.973721712864E+01,
1.988779251295E+01,  1.325399446711E+01,
 3.183062499091E+00,
 u=  -8.274300530916E-03, -2.193239408865E+01, -2.666928433839E+01, -
5.972409437765E+01, -8.570534750554E+01,
 -8.215147334882E+01, -7.889139786174E+01, -9.267465301832E+01,
3.490164234376E+01,  3.222910009984E+01,
 2.821906569241E+01,  2.871116523180E+01,  1.967036825028E+01,
1.987834137037E+01,  1.330195534512E+01,
 3.186489413846E+00,
 u=  -8.274286253070E-03, -2.186160679832E+01, -2.669959867244E+01, -
5.722351248990E+01, -8.730825579231E+01,
 -7.564352400382E+01, -8.335736962521E+01, -9.693565430695E+01,
3.491010638185E+01,  3.223600706208E+01,
 2.822052945986E+01,  2.871237714334E+01,  1.967077580437E+01,
1.987840475437E+01,  1.330172986096E+01,
 3.186473085384E+00,
 u=  -8.274300530916E-03, -2.193239408865E+01, -2.666928433839E+01, -
5.972409437765E+01, -8.570534750554E+01,
 -8.215147334882E+01, -7.889139786174E+01, -9.267465301832E+01,
3.490164234376E+01,  3.222910009984E+01,
 2.821906569241E+01,  2.871116523180E+01,  1.967036825028E+01,
1.987834137037E+01,  1.330195534512E+01,
 3.186489413846E+00,
```

```
u= -8.274300807638E-03, -2.193378482791E+01, -2.666884420787E+01, -
5.980620048027E+01, -8.584646483286E+01,
-8.239188743511E+01, -7.890618137000E+01, -9.258617718327E+01,
3.490164234376E+01, 3.222910009984E+01,
 2.821906569241E+01, 2.871116523180E+01, 1.967036825028E+01,
1.987834137037E+01, 1.330195534512E+01,
 3.186489413846E+00,
u= -8.274301427914E-03, -2.193677671608E+01, -2.665854637207E+01, -
5.954695994818E+01, -8.518115781198E+01,
-8.228939751839E+01, -7.898719381359E+01, -9.261476261244E+01,
3.486356778167E+01, 3.219810154606E+01,
 2.821252839576E+01, 2.870574049722E+01, 1.966858499644E+01,
1.987805852482E+01, 1.330297094262E+01,
 3.186562801210E+00,
u= -8.274329468128E-03, -2.207572164824E+01, -2.648082538327E+01, -
6.124029854938E+01, -7.949261935183E+01,
-8.654086891647E+01, -7.857401453515E+01, -8.818307319575E+01,
3.469786133216E+01, 3.206410790120E+01,
 2.818501554105E+01, 2.868246733162E+01, 1.966084040721E+01,
1.987688374684E+01, 1.330730628828E+01,
 3.186876237782E+00,
u= -8.274333080081E-03, -2.208893325119E+01, -2.643193837210E+01, -
6.097657119546E+01, -7.868071872061E+01,
-8.660725274903E+01, -7.992194878060E+01, -8.838011470419E+01,
3.427335034189E+01, 3.172440837729E+01,
 2.811822072577E+01, 2.862380238584E+01, 1.964171632818E+01,
1.987402867145E+01, 1.331822394620E+01,
 3.187664051246E+00,
u= -8.274329468128E-03, -2.207572164824E+01, -2.648082538327E+01, -
6.124029854938E+01, -7.949261935183E+01,
-8.654086891647E+01, -7.857401453515E+01, -8.818307319575E+01,
3.469786133216E+01, 3.206410790120E+01,
 2.818501554105E+01, 2.868246733162E+01, 1.966084040721E+01,
1.987688374684E+01, 1.330730628828E+01,
 3.186876237782E+00,
/63s chump
u= -8.274333080081E-03, -2.208893325119E+01, -2.643193837210E+01, -
6.097657119546E+01, -7.868071872061E+01,
-8.660725274903E+01, -7.992194878060E+01, -8.838011470419E+01,
3.427335034189E+01, 3.172440837729E+01,
 2.811822072577E+01, 2.862380238584E+01, 1.964171632818E+01,
1.987402867145E+01, 1.331822394620E+01,
 3.187664051246E+00,
u= -8.274336613270E-03, -2.202585497121E+01, -2.645259999024E+01, -
6.063376525407E+01, -7.804844460816E+01,
-8.623598730071E+01, -8.007198328577E+01, -8.838011470419E+01,
3.419581771260E+01, 3.164212737107E+01,
 2.810181328856E+01, 2.860985929624E+01, 1.963703285971E+01,
1.987333933870E+01, 1.332049929277E+01,
 3.187822044937E+00,
u= -8.274333080081E-03, -2.208893325119E+01, -2.643193837210E+01, -
6.097657119546E+01, -7.868071872061E+01,
-8.660725274903E+01, -7.992194878060E+01, -8.838011470419E+01,
3.427335034189E+01, 3.172440837729E+01,
 2.811822072577E+01, 2.862380238584E+01, 1.964171632818E+01,
1.987402867145E+01, 1.331822394620E+01,
 3.187664051246E+00,
u= -8.274336613270E-03, -2.202585497121E+01, -2.645259999024E+01, -
6.063376525407E+01, -7.804844460816E+01,
-8.623598730071E+01, -8.007198328577E+01, -8.838011470419E+01,
3.419581771260E+01, 3.164212737107E+01,
 2.810181328856E+01, 2.860985929624E+01, 1.963703285971E+01,
1.987333933870E+01, 1.332049929277E+01,
 3.187822044937E+00,
/3640 nmi
u= -8.274336613270E-03, -2.202585497121E+01, -2.645259999024E+01, -
6.063376525407E+01, -7.804844460816E+01,
-8.623598730071E+01, -8.007198328577E+01, -8.838011470419E+01,
3.419581771260E+01, 3.164212737107E+01,
 2.821252839576E+01, 2.870574049722E+01, 2.966858499644E+01,
2.987805852482E+01, 2.330297094262E+01,
 3.186562801210E+00,
u= -8.274329468128E-03, -2.207572164824E+01, -2.648082538327E+01, -
6.124029854938E+01, -7.949261935183E+01,
-8.654086891647E+01, -7.857401453515E+01, -8.818307319575E+01,
3.469786133216E+01, 3.206410790120E+01,
 2.818501554105E+01, 2.868246733162E+01, 1.966084040721E+01,
1.987688374684E+01, 1.330730628828E+01,
 3.186876237782E+00,
u= -8.274315061533E-03, -2.083199291760E+01, -2.670226024393E+01, -
6.040374503005E+01, -7.667961117423E+01,
-8.412923823129E+01, -7.997500051937E+01, -8.866659594450E+01,
3.469786133216E+01, 3.206410790120E+01,
 2.818501554105E+01, 2.868246733162E+01, 1.966084040721E+01,
1.987688374684E+01, 1.330730628828E+01,
 3.186876237782E+00,
/best yet
u= -8.274306536628E-03, -2.019618275164E+01, -2.681577801909E+01, -
6.011972982534E+01, -7.609800789898E+01,
-8.386786285560E+01, -7.997954289628E+01, -8.866229545215E+01,
3.468526422358E+01, 3.205394268403E+01,
 2.818293957303E+01, 2.868071018069E+01, 1.966025287625E+01,
1.987679537281E+01, 1.330757147006E+01,
 3.186895964765E+00,
/best yet
u= -8.274309637309E-03, -2.000579704613 4E+01, -2.676679725598E+01, -
6.022313281598E+01, -7.444962467778E+01,
-8.421749631901E+01, -8.004018814016E+01, -8.869629766147E+01,
3.469786133216E+01, 3.306410790120E+01,
 2.818501554105E+01, 2.868246733162E+01, 1.766084040721E+01,
1.987688374684E+01, 1.330730628828E+01,
 3.186876237782E+00,
/best yet
u= -8.274309861218E-03, -2.007213940000E+01, -2.676680228124E+01, -
6.018145869216E+01, -7.432252760012E+01,
-8.399011537991E+01, -7.987723313527E+01, -8.860452272171E+01,
3.468987198199E+01, 3.305758391144E+01,
 2.818356164077E+01, 2.868129459871E+01, 2.066066004205E+01,
1.987682515094E+01, 1.330747760206E+01,
 3.186889963287E+00,
/best yet
u= -8.274320997854E-03, -2.007694435983E+01, -2.675706581402E+01, -
5.859331017995E+01, -7.216723574025E+01,
-8.312579688950E+01, -8.120456859472E+01, -8.789938887512E+01,
3.431539389942E+01, 3.275264592107E+01,
 2.811744139113E+01, 2.863021528797E+01, 2.061248469139E+01,
1.985550239908E+01, 1.331536987233E+01,
 3.187476745181E+00,
 $
C***********************************************************
C
C            TRAJECTORY SIMULATION INPUTS
C
C***********************************************************
P$GENDAT
 TITLE = 0H* LOX/LH2 BIMESE 28.5 deg delivering 60 Klb *,
 EVENT = 10, / FIRST EVENT
  WGTSG  =  1362398,
  FESN = 500, / FINAL EVENT NUMBER
  MAXTIM = 3000., / MAXIMUM TIME
  ALTMAX = 10000000., / MAXIMUM ALTITUDE ALLOWED
  ALTMIN = -5000., / MINIMUM ALTITUDE ALLOWED
  PRNC = 0, /setup plot file
c   PRNCA = 0, /setup delimited plot file
  MONX = 4HDYNP, 4HFAZB, 4HASMG, 5HALPHA, 6HGAMMAI, /
MONITOR Q & NORMAL FORCE
  PRNT(97) = 5HXMAX1, 5HXMAX2, 5HXMIN2, 6HALTITO, 4HMACH,
4HDYNP,5HXMAX5,
  4HAMYB, 5HTTMYB, 4hfazb, /
 IGUID(1) = 1, / INERTIAL EULER ANGLE OPTION
 IGUID(2) = 0, / SAME STEERING OPTION FOR ALL CHANNELS
 IGUID(4) = 1, / CUBIC POLY WITH CONSTANT TERM SET BY INPUT
  PITPC(1) = 0., / INITIAL PITCH RATE
  YAWPC(1) = 0., / INITIAL YAW RATE
  ROLPC(1) = 0., / INITIAL ROLL RATE
 NPC(1) = 2, / PRINT CONIC BLOCK AT EACH PHASE CHANGE
  PINC = 20, / PRINT INTERVAL EVERY 20 SECONDS
 NPC(2) = 1, / FOURTH ORDER RUNGE KUTTA
  DT = 1, / INTEGRATION STEP SIZE
 NPC(3) = 4, / PLANET RELATIVE INPUT ON VELOCITY VECTOR
  VELR = .1, / INITIAL VELOCITY AT LAUNCH PAD
  GAMMAR = 90., / INITIAL PLANET RELATIVE FLIGHT PATH ANGLE
  AZVELR = 0., / INITIAL AZIMUTH ANGLE OF VELR
  azl  = 67,
 NPC(4) = 2, / PLANET RELATIVE INPUT ON ALTITUDE VECTOR
  ALTITO = 0., / INITIAL ALTITUDE
  GDALT = 0., / INITIAL ALTITUDE
  GDLAT = 28.5, / LATITUDE OF LAUNCH SITE
  LONG = 280.0, / LONGITUDE OF LAUNCH SITE
  LONGI = 280.0, / LONGITUDE EAST OF PRIME MERIDIAN
 NPC(5) = 5, / 1976 US STANDARD ATMOSPHERE
 NPC(6) = 0, / NO WINDS
 NPC(7) = 1, / ACCELERATION LIMIT SET
  ASMAX = 3.0, / LIMIT ACCELERATION THROUGHOUT TRAJECTORY
  LREF = 162.6, /BODY LENGTH FROM NOSE TO BASE
  SREF = 3500.7, /REFERENCE AREA FOR ORBITER ONLY
 NPC(8) = 2, / CL, CD & CM TABLE INPUTS
 NPC(9) = 1, / ROCKET ENGINE WITH THRUST TABLE AND ISPVAC
 NPC(10) = 0, / STATIC TRIM IN PITCH
 GXP(1) = 160.2, /X-LOCATION OF ENGINE GIMBAL MEASURED FROM
NOSE
 ITRIM = 1, / TRIM WITH ENGINE DEFLECTIONS ONLY
 IENGT = 1, / CALCULATE ENGINE INCIDENCE ANGLES FROM STATIC
TRIM EQUATIONS
 NPC(11) = 0, / NO FUNCTIONAL INEQUALITY CONSTRAINTS
 NPC(12) = 3, / CALCULATE CROSSRANGE AND DOWNRANGE BASED
ON ORBIT
  ALTREF = 100.0, / 100 NMI CIRCULAR MILE REFERENCE ORBIT
  AZREF = 0., / AZIMUTH REFERENCE
 NPC(13) = 0, / DO NOT JETTISON PROPELLANT
 NPC(14) = 0, / NO HOLDDOWN BEFORE LIFTOFF
 NPC(15) = 0, / DO NOT CALCULATE AEROHEATING
 NPC(16) = 0, / USE OBLATE EARTH GRAVITY MODEL
c NPC(17) = 2, / JETTISON BOOSTER
 NPC(18) = 0, / DO NOT TERMINATE TRAJECTORY
C NPC(19) = 0, / DO NOT PRINT INPUT CONDITION SUMMARIES
```

```
 NPC(20) = 0, / DO NOT USE ANY SPECIAL DT CALCULATION
 NPC(21) = 0, / DO NOT CALCULATE FUEL AND OXIDIZER WEIGHTS
AND VOLUMES
 NPC(22) = 0, / DO NOT CALCULATE THROTTLING
 NPC(23) = 0, / DO NOT COMPUTE VELOCITY MARGINS
 NPC(24) = 0, / DO NOT COMPUTE ANY PARAMETER INTEGRALS
 NPC(25) = 3, / COMPUTE VELOCITY LOSSES AND PRINT AT EACH
TIME
 NPC(26) = 0, / NO SPECIAL AEROHEATING CALCULATIONS
 NPC(27) = 0, / DO NOT INTEGRATE ENGINE FLOWRATES
  IWPF(1) = 1, / INTEGRATE BOOSTER FLOW RATES
 NPC(28) = 0, / TRACKING STATION OPTION NOT USED
 NPC(29) = 0, / DO NOT COMPUTE VACUUM IMPACT POINTS
 NPC(30) = 0, / USE N-STAGE VEHICLE WEIGHT MODEL
  IENGA(1) = 1, / THROTTLE ORBITER
  IENGMF(1) = 1, / ORBITER ROCKETS ARE ON
  IWDF(1) = 1, / CALCULATE ORBITER FLOW RATES AS A TABLE
LOOKUP
  NENG = 1, / THE NUMBER OF THRUSTING ENGINES
 NPC(31) = 0, / NO VERNAL EQUINOX, SUN SHADOW, SUN ANGLE
CALCULATIONS
 NPC(32) = 0, / NO PARACHUTE DRAG
 NPC(33) = 0, / NO ARC LENGTH CALCULATIONS
 NPC(34) = 0, / NO KEPLERIAN STATE CALCULATIONS
 NPC(35) = 0, / NO SENSED VELOCITY INCREMENT CALCULATIONS
 NPC(36) = 0, / DO NOT ACTIVATE SUNLIGHT OPTIONS
 NPC(37) = 0, / DO NOT ACTIVATE DATE OPTION
 NPC(38) = 0, / NO ATMOSPHERIC TURBULENCE
 NPC(39) = 0, / NO ATMOSPHERIC GUSTS
 NPC(40) = 1, /
$
P$TBLMLT
 TVC1M = 3.3351, / Thrust multiplier for Orbiter
 WD1M = 3.3351, / Flow rate multiplier for Orbiter
 AE1M = 3.3351, / Exit area multiplier for Orbiter
 $
P$TAB
 TABLE = 5HTVC1T, 0,531500., / VACUUM THRUST OF Orbiter engine
 $
P$TAB
 TABLE = 4HWD1T,0,1199.77, / FLOW RATE OF Orbiter engine
 $
P$TAB
 TABLE = 4HAE1T, 0,33.558, / EXIT AREA OF Orbiter engine
 $
P$TAB TABLE = 4HXCGT,1,6HWEIGHT,2,1,-1,1,
  2006450,123.51,134870,115.50,
 $
P$TAB TABLE=5HXREFT,0,109.90,
 $
P$TAB TABLE=5HZREFT,0,0,
*include '/home/asdl1/jtooley/post/BIMESE/PT2PT/bimese.aero'
 ENDPHS = 1,
 $
l$gendat
 event=15,critr=4htime,value=07,
 iguid(4)=2,
 $
l$tblmlt
 $
l$tab table=4hpitt,1,6htime ,8,1,1,1,
 10, 90, /all inertial pitch angles are ind. vars
 30, 90,
 50, 90,
 100, 90,
 150, 90,
 200, 90,
 280, 90,
 320, 90,
 endphs=1,
 $
l$gendat
title = 0h*Ramp up alpha*,
event=18, critr=5hwprop, value=-1166600, /Maximum allowable propellant
iengmf(1)=0,   /turn all engines off
iguid=0,0,3,   /use aero angles with dalpha set in next phase
dalpha = 40,   /independent variable
endphs = 1,
$
l$gendat
title = 0h*alpha reaches specified value*,
event=19,critr=6hgammai,value=0,
npc(17)=2,        / weight jettison option
wjett=4925,       / vent residuals
endphs = 1,
$
l$gendat
title = 0h*Begin Descent*,
event=20,critr=6hgammai,value=0,
dt =4, /increase step size during long descent
iguid=0,0,2, /use aero angle tables
npc(17)=2,        / weight jettison option
wjett=4295,         / vent residuals
xmax(5)=0,      / reset max gamma monitor
$
l$tblmlt
$
l$tab table=6halphat,1,4hvelr,10,1,-1,1,
25000, 40,
18000, 40, /Hypersonic trim at 40 degrees
16000, 0, /control imparted to optimizer
12000, 0,
10000, 0,
8000, 0,
6000, 0,
4000, 0,
2000, 0,
0,   0,
endphs=1,
$
l$gendat
title = 0h*Destination acheived*,
event=500,critr=5hgdalt,value=50000,
ENDPHS = 1,
ENDJOB = 1,
ENDPRB = 1,
$
```

A.7. THRUST-AUGMENTED BIMESE: POINT-TO-POINT

```
P$SEARCH
C****************************************************
C  LOX/LH2 BIMESE W/RS2100 Engine (revised 2/1/99)
C  WB-003-C Bimese
C  T/W=1.5 / strap on burn time=80s
C  to 100 nmi
C  28.5 DEGREES INCLINATION
C  LATEST WB-001 AERO ADDED 5/6/97
C****************************************************
C
 SRCHM = 4, / PROJECTED GRADIENT METHOD
c IPRO = -1, / PRINT FINAL TRAJECTORY ONLY
 IOFLAG = 0, / ENGLISH IN - ENGLISH OUT
 CONEPS(1) = 89.9, / CONVERGENCE TOLERANCE
 CONEPS(2) = .00001, / MIN ALLOWED PERCENTAGE CHANGE
 CONEPS(3) = .00001, /
 CONEPS(4) = .00001, /
 CONEPS(5) = .00001, /
 PCTCC=.001, /
 IDEB=0, / No Detail
C
C****************************************************
C            OPTIMIZATION VARIABLE
C****************************************************
C
 OPTVAR = 6HDPRNG1, / MAXIMIZE FINAL BURNOUT WEIGHT
 OPT = 1, / MAXIMIZATION FLAG
 OPTPH = 500, / PHASE AT WHICH WEIGHT IS MAXIMIZED
 WOPT = .000003, / OPTIMIZATION VARIABLE WEIGHTING
 MAXITR = 10, / MAXIMUM ITERATIONS ALLOWED
C
C****************************************************
C
C
C            CONSTRAINT VARIABLES
C
C****************************************************
C
 NDEPV = 5, / NUMBER OF DEPENDENT VARIABLES USED AS
CONTROLS
 DEPVR = 5HXMAX3,5HXMAX1, 5HXMAX2, 5HXMIN2, 5HXMAX4,
 DEPVAL = 4, 1000., 379165., -379165.,40, / INSERTION ORBIT VALUES +
CONSTRAINTS
 DEPTL = .1, 1, 100, 100, 3, / DESIRED ACCURACIES
 DEPPH = 500,500,500,500,500,/ EVENTS
 IDEPVR = 1, 1, 1, -1, 1,
C
C****************************************************
C
C
C            CONTROL VARIABLES
C
C****************************************************
C
 tabl(1) =4hpitt,4hpitt,4hpitt,4hpitt,4hpitt,4hpitt,4hpitt,4hpitt,4hpitt,
 tabl(10)
=6halphat,6halphat,6halphat,6halphat,6halphat,6halphat,6halphat,6halphat,
 tably(1)=1,2,3,4,4,5,6,7,8,
 tably(10)=3,4,5,6,7,8,9,10,
 nindv  = 20, /In this deck banking angles are not needed to meet constraints
 indvr  =
5htabl1,5htabl2,5htabl3,5htabl4,5htabl5,5htabl6,5htabl7,5htabl8,5htabl9,
 indvr(10)
=6htabl10,6htabl11,6htabl12,6htabl13,6htabl14,6htabl15,6htabl16,6htabl17,6heta
pc1,
 indvr(19) = 6hpitpc2,6hpitpc2,
 indph  = 15,15,15,15,19,19,19,19,19,
 indph(10) = 200,200,200,200,200,200,200,200,14,15,16,
 u= -1.842705717869E+00, -4.552324033711E-01, -2.705219506659E-01, -
7.014759690989E-01, -2.315063553074E-01,
 -2.170624414801E-01, -1.038046299574E-01, -1.722008909834E-01, -
1.217485835263E-01, -1.850085860485E-01,
 -1.909381515345E-03, -1.655436587730E-01,  8.629812269404E+01,
 u= -1.486110012522E+00, -3.736172917025E-01, -3.288992151857E-01, -
7.294698349305E-01, -2 701815735483E-01,
 -2.393359404878E-01, -1.098713129975E-01, -1.870812088176E-01, -
1.282566472966E-01, -1.982704408308E-01,
 -1 910365335931E-03, -1.719945392416E-01,  8.627488501636E+01,
 u= -1.379859497480E+00, -5.721289749266E-01, -4.280546033644E-01, -
7.203025804504E-01, -2.297368985200E-01,
 -1.934959071753E-01, -9.819963822808E-02, -1.508943760030E-01, -
1.122159644621E-01, -1.671565598504E-01,
 -1.909074297634E-03, -1.657085165387E-01,  8.631048929058E+01,
 u= -1.563060261283E+00, -4.204227379936E-01, -4.880118729701E-01, -
6.322100315856E-01, -2.179633167876E-01,
 -2.038609612770E-01, -1.064910783472E-01, -1.744110516730E-01, -
1.268493922201E-01, -2.012714659367E-01,
 -1.912442257678E-03, -1.839198474348E-01,  8.629175054744E+01,
 u= -1.598115087083E+00, -3.966502586373E-01, -7.444247193000E-01, -
5.048125113924E-01, -1.709662457655E-01,
 -1.835908154233E-01, -1.064996810070E-01, -1.763159979488E-01, -
1.247919411693E-01, -1.951570735172E-01,
 -1.911633824151E-03, -1.733406327892E-01,  8.630846599866E+01,
 u= -1.379859497480E+00, -5.721289749266E-01, -4.280546033644E-01,
-7.203025804504E-01, -2.297368985200E-01,
 -1.934959071753E-01, -9.819963822808E-02, -1.508943760030E-01, -
1.122159644621E-01,
-1.671565598504E-01,
 -1.909074297634E-03, -1.657085165387E-01,    4.072197186392E+01,
4.046499248601E+00, 4.09827064091E+00,
   4.027990176507E+01,
3.027990176507E+01,2.327990176507E+01,2.327990176507E+01,2.327990176
507E+01,
 u= 9.242808759185E-01,-1.379529174790E+00,-5.552979221554E-01,
   3.701639152958E-01,-2.234290686519E-01,-1.843221353295E-01,
  -9.061212975613E-02,-1.238895620693E-01,-9.260317938731E-02,
   1.923200834122E-01,-1.904298597594E-03,-1.251615655156E-01,
   4.043547255215E+01, 5.805144858214E-02, 1.081939710556E+01,
   4.070377031501E+01, 2.799017650700E-01, 2.327990176507E+01,
   2.327990176507E+01, 2.327990176507E+01,
 u= 4.487158363725E-01,-9.204245813696E-01,-8.071037724968E-01,
   3.177994383543E-01,-2.203605593222E-01,-1.885358421199E-01,
  -9.984943222223E-02,-2.208186101885E-01,-9.976252446377E-02,
   2.470738892865E-01,-1.903692370377E-03,-1.245706914681E-01,
    3.910694125902E+01,
   3.927560866427E+01, 3.948172604214E+01, 3.715810000807E+01,
   3.035214171299E+01, 2.509694617097E+01, 1.017472828524E+01,
   5.176752890923E+00,
 u= 4.251147856104E-01,-9.533370436527E-01,-8.438372137148E-01,
   -3 132763765653E-01,-2.531469336858E-01,-2 410741277909E-01,
  -2.006457875451E-01,-2.230104448959E-01,-2.003398252286E-01,
   2.456209939822E-01,-1.903790332027E-03,-1.246720847156E-01,
   7.375410999323E+01, 5.572916737096E+01, 5.762317541649E+01,
   3.715810000807E+01, 3.035214171299E+01, 2.509694617097E+01,
   1.017472828524E+01, 5.176752890923E+00,
 u= 4.253716364780E-01,-9.501708282094E-01,-8.415512693240E-01,
  -3.929743645432E-01,-2.729771963870E-01,-2.709495812873E-01,
  -2.805810930008E-01,-2.929898528250E-01,-2.903138205567E-01,
  -2.956346808950E-01,-2.903789321139E-03,-1.246711359153E-03,
   7.374426557195E+01, 5.572916737096E+01, 5.762317541649E+01,
   3.715810000807E+01, 3.035214171299E+01, 2.509694617097E+01,
   1.017472828524E+01, 5.176752890923E+00,
 u= 4.230314408879E-01,-9.776833296223E-01,-8.622998505297E-01,
  -3.969774412886E-01,-2.743828542664E-01,-2.718929104372E-01,
  -2.812004636382E-01,-2.931387442514E-01,-2.905117098237E-01,
  -2.956974209105E-01,-2.903795616494E-03,-1.246711557671E-03,
   7.346781025037E+01, 5.572916737096E+01, 5.762317541649E+01,
   3.715810000807E+01, 3.035214171299E+01, 2.509694617097E+01,
   1.017472828524E+01, 5.176752890923E+00,
 u= -0.1,-9.795743774426E-02,-8.636911066030E-02,
  -3.972476949904E-01,-2 744808149175E-01,-2.719589950960E-01,
  -2.812442497406E-01,-2.931492673359E-01,-2 905259208340E-01,
  -2.957019763132E-01,-2.903796080943E-03,-2.246711572568E-03,
   3.545768112036E+01, 4.072916737096E+01, 3.062317541649E+01,
   3.715810000807E+01, 3.035214171299E+01, 2 509694617097E+01,
   1.017472828524E+01, 5.176752890923E+00,
 u= -1.687815136588E-01,-1.783863328443E-01,-2.623375026312E-01,
   2.142877002568E-01, 2.333280001883E-02,-2.131926223861E-01,
  -5.229069222661E-01,-5.804218800240E-01,-7 201377173098E-01,
  -4.526098954050E-01,-2.923294513265E-03,-2.248851770800E-03,
   4.052064130713E+02, 3.958862723683E+01, 3.737126630163E+01,
   3.715810000437E+01, 3.035214171299E+01, 2.509694617097E+01,
   1.017472828524E+01, 5.176752890923E+00,
 u= -8.274285458116E-03,-2.144825875449E+01,-2.359079011735E+01,-
2.359079011735E+01,
  -5.519649718889E+01,-9.249077673248E+01,-6.916956274567E+01,
  -9.258437443429E+01,-9.990424738464E+01, 3.910694125902E+01,
   3.927560866427E+01, 3.048172604214E+01, 3.015810000807E+01,
   2.035214171299E+01, 2.309694617097E+01, 1.317472828524E+01,
   3.176752890923E+00,
 u= -8.274279039759E-03,-2.242081663503E+01,-2.961182370361E+01,-
2.961182370361E+01,
  -5.318851516036E+01,-8.997944809427E+01,-9.039258291462E+01,
  -9.166037176118E+01,-9.990424738464E+01, 4.000013311904E+01,
   4.000000031147E+01, 3.091193896437E+01, 3.047280667995E+01,
   2.047418722764E+01, 2.320844011004E+01, 1.315381826792E+01,
   0.317517262700E+01,
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  -5.898633542759E+01,-5.914625019722E+01,-8.540636263795E+01,
  -9.399519892613E+01,-9.753162536695E+01,-9.890424738464E+01,
   3.702351988527E+01, 3.883591302614E+01, 3.004680231522E+01,
   2.988121307979E+01, 2.023405938248E+01, 2.299103797495E+01,
   1.318842807970E+01, 3.177860591864E+00,
 u= -8.274072572495E-03, -2.516641508994E+01, -3.347018111551E+01, -
6.837325262484E+01, -6.251257785392E+01,
 -9.640984403435E+01, -9.243020684862E+01, -8.521473158277E+01, -
9.881868167316E+01, 3.701363843799E+01,
 3.883039588934E+01, 3.004256333184E+01, 2.987940487552E+01,
2.023272349809E+01, 2.298990539951E+01,
 1.318830959560E+01, 3.177859559009E+00,
```

```
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9.883930715438E+01, 3.702343628918E+01,
 3.883586650997E+01, 3.004676545896E+01, 2.988119751687E+01,
2.023404774361E+01, 2.299102806393E+01,
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 -9.758672125897E+01, -8.619576645333E+01, -8.005462949859E+01, -
9.882670811828E+01, 3.714636055494E+01,
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2.089786522557E+01, 2.237834366289E+01,
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2.089062163853E+01, 2.237249534300E+01,
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7.301232341105E+01, -6.418824838908E+01,
 -1.013325675975E+02, -8.449960098214E+01, -7.688616776559E+01, -
9.876270635844E+01, 3.700872500876E+01,
 3.740874535957E+01, 3.074447078595E+01, 2.864564604748E+01,
2.088563378577E+01, 2.236853046228E+01,
 1.317945280912E+01, 3.177780918805E+00,0.5,-1.083483704817E+00, -
6.299342591120E-01,
 PERT = 13*1.0E-4, / PERTURB
 $
C****************************************************
C
C          TRAJECTORY SIMULATION INPUTS
C
C****************************************************
P$GENDAT
 TITLE = 0H* LOX/LH2 BIMESE 28.5 deg delivering 60 Klb *,
 EVENT = 10, / FIRST EVENT
  FESN = 500, / FINAL EVENT NUMBER
  MAXTIM = 5000., / MAXIMUM TIME
  ALTMAX = 10000000., / MAXIMUM ALTITUDE ALLOWED
  ALTMIN = -5000., / MINIMUM ALTITUDE ALLOWED
  PRNC = 0, /setup plot file
  PRNC = 0, /setup plot file
  PRNCA = 0, /setup delimited plot file
  MONX = 4HDYNP, 4HFAZB, 4HASMG, 5HALPHA, 6HGAMMAI, /
MONITOR Q & NORMAL FORCE
  PRNT(97) = 5HXMAX1, 5HXMAX2, 5HXMIN2, 6HALTITO, 4HMACH,
4HDYNP,3HWD1,3HWD2,5hwprp1,5hwprp2,
  4HAMYB, 5HTTMYB, 5HPSTOP, /
 IGUID(1) = 1, / INERTIAL EULER ANGLE OPTION
 IGUID(2) = 0, / SAME STEERING OPTION FOR ALL CHANNELS
 IGUID(4) = 1, / CUBIC POLY WITH CONSTANT TERM SET BY INPUT
  PITPC(1) = 0., / INITIAL PITCH RATE
  YAWPC(1) = 0., / INITIAL YAW RATE
  ROLPC(1) = 0., / INITIAL ROLL RATE
 NPC(1) = 2, / PRINT CONIC BLOCK AT EACH PHASE CHANGE
  PINC = 20, / PRINT INTERVAL EVERY 20 SECONDS
 NPC(2) = 1, / FOURTH ORDER RUNGE KUTTA
  DT = 1, / INTEGRATION STEP SIZE
 NPC(3) = 4, / PLANET RELATIVE INPUT ON VELOCITY VECTOR
  VELR = .1, / INITIAL VELOCITY AT LAUNCH PAD
  GAMMAR = 90., / INITIAL PLANET RELATIVE FLIGHT PATH ANGLE
  AZVELR = 0., / INITIAL AZIMUTH ANGLE OF VELR
  azl = 90,
 NPC(4) = 2, / PLANET RELATIVE INPUT ON ALTITUDE VECTOR
  ALTITO = 0., / INITIAL ALTITUDE
  GDALT = 0., / INITIAL ALTITUDE
  GDLAT = 28.5, / LATITUDE OF LAUNCH SITE
  LONG = 280.0, / LONGITUDE OF LAUNCH SITE
  LONGI = 280.0, / LONGITUDE EAST OF PRIME MERIDIAN
 NPC(5) = 5, / 1976 US STANDARD ATMOSPHERE
 NPC(6) = 0, / NO WINDS
 NPC(7) = 1, / ACCELERATION LIMIT SET
  ASMAX = 3.0, / LIMIT ACCELERATION THROUGHOUT TRAJECTORY
  LREF = 162.6, /BODY LENGTH FROM NOSE TO BASE
  SREF = 3500.7, /REFERENCE AREA FOR ORBITER ONLY
 NPC(8) = 2, / CL, CD & CM TABLE INPUTS
 NPC(9) = 1, / ROCKET ENGINE WITH THRUST TABLE AND ISPVAC
 NPC(10) = 0, / STATIC TRIM IN PITCH
 GXP(1) = 160.2, /X-LOCATION OF ENGINE GIMBAL MEASURED FROM
NOSE
 ITRIM = 1, / TRIM WITH ENGINE DEFLECTIONS ONLY
 IENGT = 1, / CALCULATE ENGINE INCIDENCE ANGLES FROM STATIC
TRIM EQUATIONS
 NPC(11) = 0, / NO FUNCTIONAL INEQUALITY CONSTRAINTS
 NPC(12) = 3, / CALCULATE CROSSRANGE AND DOWNRANGE BASED
ON ORBIT
  ALTREF = 100.0, / 100 NMI CIRCULAR MILE REFERENCE ORBIT
  AZREF = 0., / AZIMUTH REFERENCE
 NPC(13) = 0, / DO NOT JETTISON PROPELLANT
 NPC(14) = 0, / NO HOLDDOWN BEFORE LIFTOFF
 NPC(15) = 0, / DO NOT CALCULATE AEROHEATING
 NPC(16) = 0, / USE OBLATE EARTH GRAVITY MODEL
 NPC(17) = 2, / JETTISON BOOSTER
 NPC(18) = 0, / DO NOT TERMINATE TRAJECTORY
C NPC(19) = 0, / DO NOT PRINT INPUT CONDITION SUMMARIES
 NPC(20) = 0, / DO NOT USE ANY SPECIAL DT CALCULATION
 NPC(21) = 0, / DO NOT CALCULATE FUEL AND OXIDIZER WEIGHTS
AND VOLUMES
 NPC(22) = 0, / DO NOT CALCULATE THROTTLING
 NPC(23) = 0, / DO NOT COMPUTE VELOCITY MARGINS
 NPC(24) = 0, / DO NOT COMPUTE ANY PARAMETER INTEGRALS
 NPC(25) = 3, / COMPUTE VELOCITY LOSSES AND PRINT AT EACH
TIME
 NPC(26) = 0, / NO SPECIAL AEROHEATING CALCULATIONS
 NPC(27) = 0, / DO NOT INTEGRATE ENGINE FLOWRATES
  IWPF(1) = 1,1, / INTEGRATE BOOSTER AND STRAP FLOW RATES
 NPC(28) = 0, / TRACKING STATION OPTION NOT USED
 NPC(29) = 0, / DO NOT COMPUTE VACUUM IMPACT POINTS
 NPC(30) = 3, / USE N-STAGE VEHICLE WEIGHT MODEL
  IENGA(1) = 0,1, / THROTTLE ORBITER, BUT NOT STRAP ONS
  IENGMF(1) = 1,1, / ORBITER AND STRAP ROCKETS ARE ON
   iwdf    =     1,1,  /use Isp vac
   nengl   =     1,
   nengh   =     2,   /highest number of engines
   mentnk  =      1,2,    /map each engine to a specific tank
   wprp(1) =      37648,   /weight of SRB propellent
   wstpd(1) =     376480,   /dry weight of SRB
  wstpd(2) =  1181050,
   menstp  =      1,2,
 NPC(31) = 0, / NO VERNAL EQUINOX, SUN SHADOW, SUN ANGLE
CALCULATIONS
 NPC(32) = 0, / NO PARACHUTE DRAG
 NPC(33) = 0, / NO ARC LENGTH CALCULATIONS
 NPC(34) = 0, / NO KEPLERIAN STATE CALCULATIONS
 NPC(35) = 0, / NO SENSED VELOCITY INCREMENT CALCULATIONS
 NPC(36) = 0, / DO NOT ACTIVATE SUNLIGHT OPTIONS
 NPC(37) = 0, / DO NOT ACTIVATE DATE OPTION
 NPC(38) = 0, / NO ATMOSPHERIC TURBULENCE
 NPC(39) = 0, / NO ATMOSPHERIC GUSTS
 NPC(40) = 1, /
 $
P$TBLMLT
 TVC2M = 3.3351, / Thrust multiplier for Orbiter
 WD2M = 3.3351, / Flow rate multiplier for Orbiter
 AE2M = 3.3351, / Exit area multiplier for Orbiter
 CDM  = 1.2,  /Table multiplier for drag becuase of strapons
 $
P$TAB
 TABLE = 5HTVC2T, 0,531500., / VACUUM THRUST OF Orbiter engine
 $
P$TAB
 TABLE = 5HTVC1T, 0,1120300., / VACUUM THRUST OF strap-ons engine
 $
P$TAB
 TABLE = 4HWD2T,0,1199.77, / FLOW RATE OF Orbiter engine
 $
P$TAB
 TABLE = 4HWD1T,0,4070, / FLOW RATE OF strap-ons engine
 $
P$TAB
 TABLE = 4HAE2T, 0,33.558, / EXIT AREA OF Orbiter engine
 $
P$TAB
 TABLE = 4HAE1T, 0,56.869, / EXIT AREA OF strap-ons engine
 $
```

```
PSTAB TABLE = 4HXCGT,1,6HWEIGHT,2,1,-1,1,
  2006450,123.51,134870,115.50,
 $
PSTAB TABLE=5HXREFT,0,109.90,
 $
PSTAB TABLE=5HZREFT,0,0,
*include '/home/asdl1/jtooley/post/BIMESE/PT2PT/bimese aero'
 ENDPHS = 1,
 $
l$gendat
 event=14,1,critr = 5htime ,
 value = 20, /change throttle to acceleration limiting
 xmax(5) = 0, /reset throttle so can make sure etapc(1) isn't set to above one
  etapc(1) = .5,
 endphs     = 1,
 $
l$gendat
 event=15,critr=4htime,value=07,endphs=1,
 iguid(4)=0,
 $
l$gendat
 event=16,critr=4htime,value=20,endphs=1,
 $
l$gendat
 event=18,1,critr=4hasmg,
 value = 2.999, /change throttle to acceleration limiting
  npc(7) = 1, / limit acceleration
   asmax = 3.0, / limit acceleration to 3 g's
  npc(22) = 2,
  ienga(1) = 0,1, / throttle orbiter using acc. limit, but not strap ons
  etapc(1) = 1,
  endphs     = 1,
 $
l$gendat
 event=19,1,critr=5hwprp1,value=0,
 value     = 0, /turn on new engine when 1st stage fuel is empty
 nstpl     = 2,
 iengmf(1)  = 0, /strap ons off
  npc(7) = 1, / limit acceleration
   asmax = 3.0, / limit acceleration to 3 g's
  npc(22) = 2,
  ienga(1) = 0,1, / throttle orbiter using acc. limit
  etapc(1) = 1,
 $
p$tblmlt
 cdm = 1.0,
 $
l$tab table=4hpitt,1,6htime ,8,1,1,1,
 10, 90, /all inertial pitch angles are ind. vars
 30, 90,
 50, 90,
 115, 90,
 150, 90,
 200, 90,
 280, 90,
 320, 90,
 endphs=1,
 $
l$gendat
 title = 0h*Ramp up alpha*,
 event=100, critr=5hwprp2, value=-909679, /Maximum allowable propellant
 iengmf(1)=0,0, /turn all engines off
 iguid=0,0,3, /use aero angles with dalpha set in next phase
 dalpha = 40, /independent variable
 endphs = 1,
 $
l$gendat
 title = 0h*alpha reaches specified value*,
 event=150,critr=6hgammai,value=0,mdl = 9,
 npc(17)=2,        / weight jettison option
 wjett=4925,       / vent residuals
 endphs = 1,
 $
l$gendat
 title = 0h*Begin Descent*,
 event=200,critr=6hgammai,value=0,
 dt =4, /increase step size during long descent
 iguid=0,0,2, /use aero angle tables
 npc(17)=2,        / weight jettison option
 wjett=4295,        / vent residuals
 xmax(5)=0,      / reset max gamma monitor
 $
l$tblmlt
 $
l$tab table=6halphat,1,4hvelr,10,1,-1,1,
 25000, 40,
 18000, 40, /Hypersonic trim at 40 degrees
 14000, 0, /control imparted to optimizer
 12000, 0,
 10000, 0,
 8000, 0,
 6000, 0,
 4000, 0,
 2000, 0,
 0,    0,
 endphs=1,
 $
l$gendat
 title = 0h*Destination acheived*,
 event=500,critr=5hgdalt,value=50000,
 ENDPHS = 1,
 ENDJOB = 1,
 ENDPRB = 1,
 $
```

ACKNOWLEDGEMENTS

The authors would like to thank the following people for the help in the completion of this project: Ashraf Charania and Rebecca Cutri-Kohart for their help in the analysis of the Bimese launch vehicle; the students of the Space Systems Design Lab for general support; and Dr. Ted Talay who proposed the Bimese concept as a project.

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The Bimese Concept: A Study of Mission and Economic Options

Final Presentation for NASA LaRC NCC1-229

Dr. John R. Olds and Jeffrey Tooley

Space Systems Design Lab

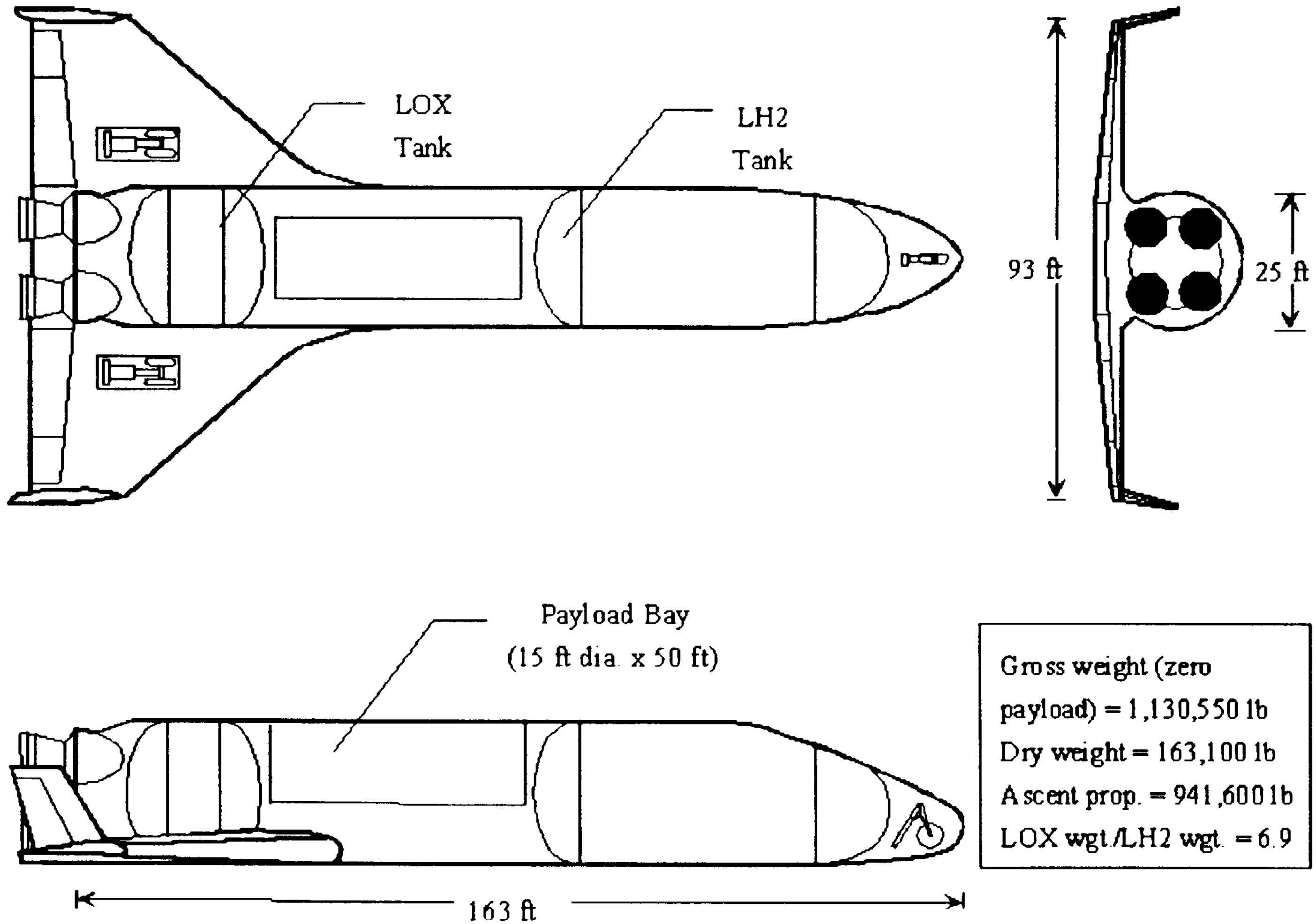
Georgia Institute of Technology

Georgia Tech Project Goals

Assess the point-to-point payload potential of several Bimese RLV configurations and assess the economic attractiveness of using the Bimese to support a future ultra-fast package delivery business

- Missions and Configurations Assessed:
  - single element Bimese
  - fuel-augmented Bimese
  - thrust-augmented Bimese
  - thrust/fuel-augmented Bimese
  - mated Bimese
- Economic Models Assessed:
  - point-to-point fast package delivery

Single Bimese Launch Vehicle

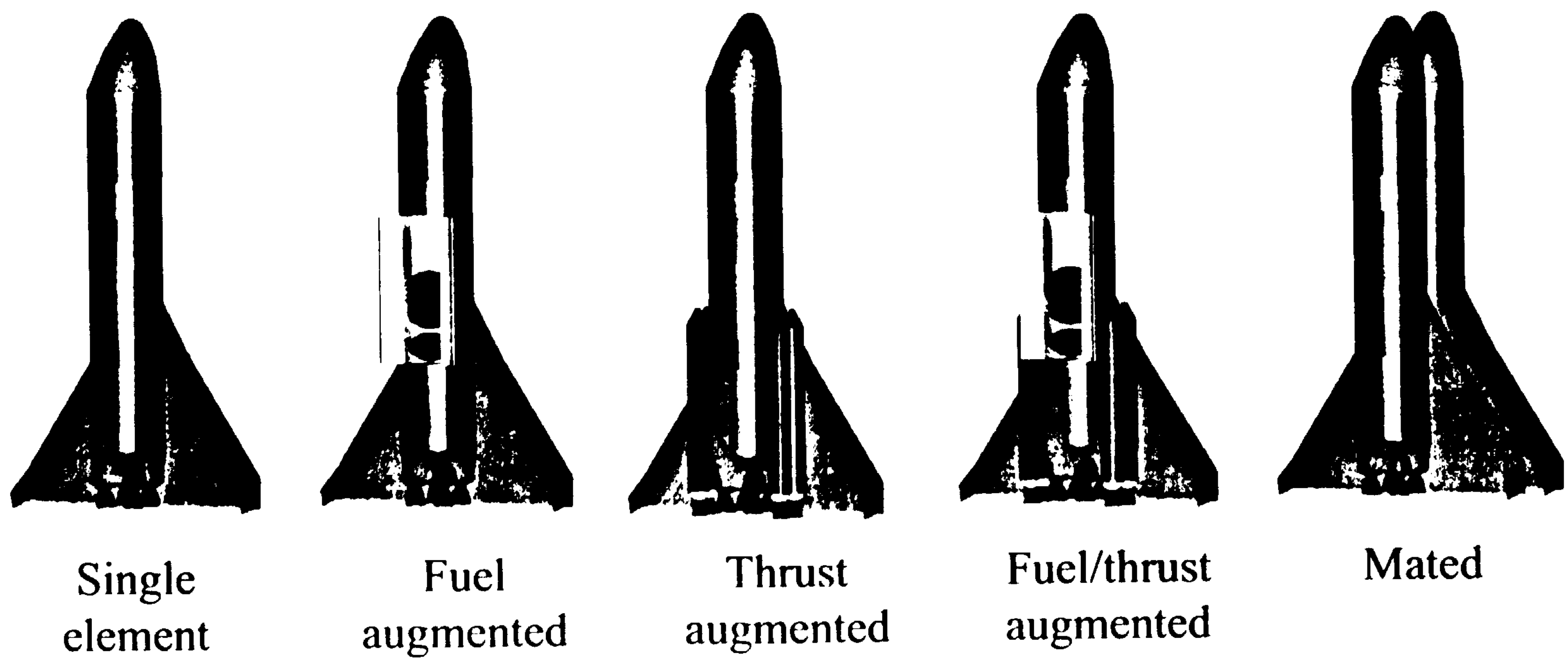


Gross weight (zero payload) = 1,130,550 lb
Dry weight = 163,100 lb
Ascent prop. = 941,600 lb
LOX wgt./LH2 wgt. = 6.9

Configuration Options

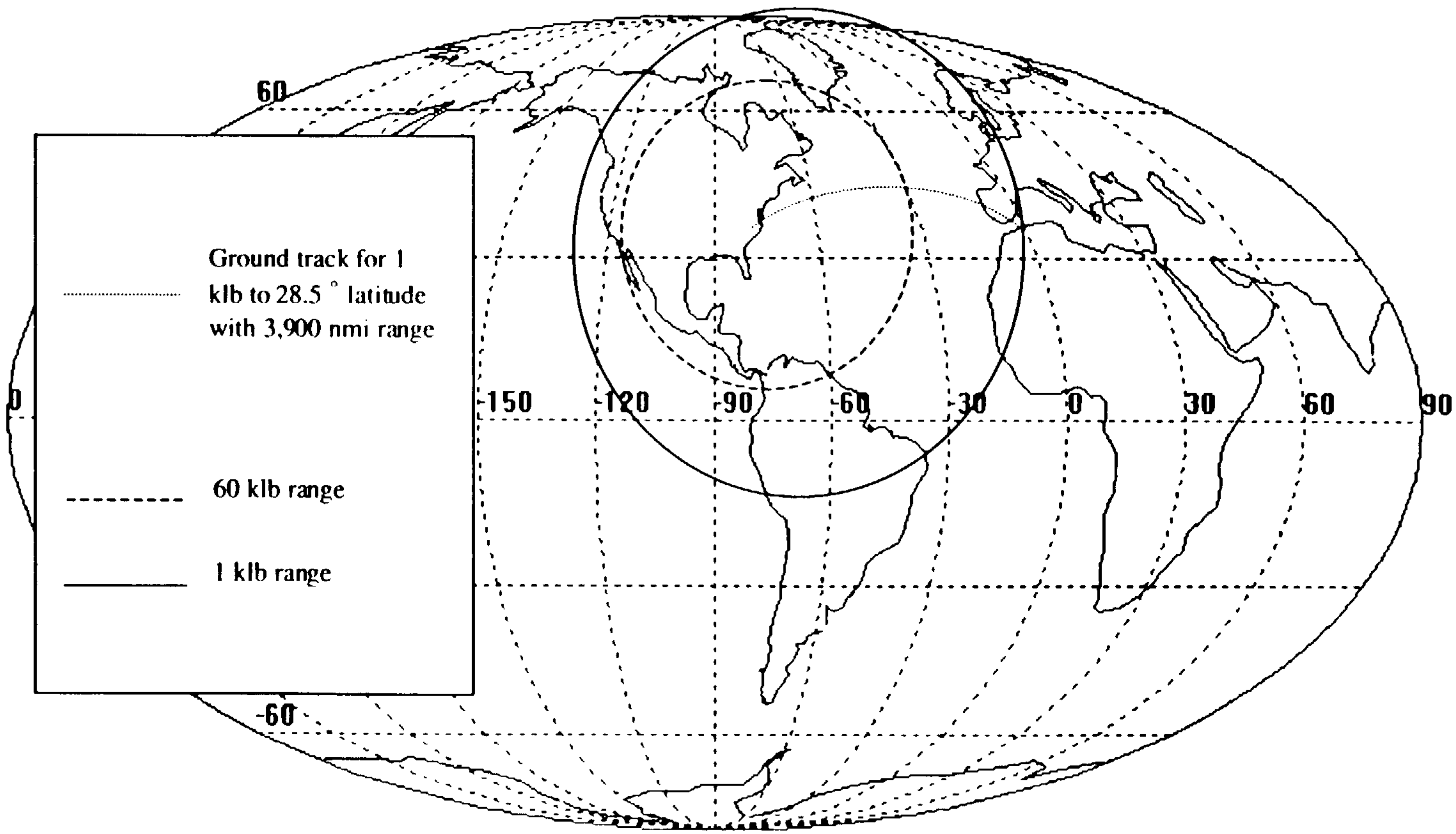
Options are analyzed in terms of:

- point-to-point range from the KSC spaceport
- LEO payload capability to 100 nmi x 100 nmi x 28.5 degree inclination



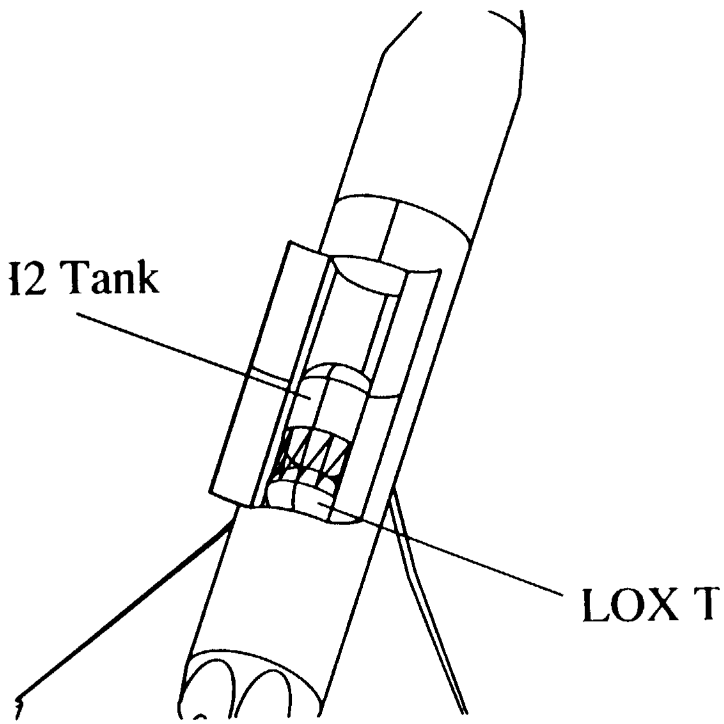
Bimese Single Element Results

- No LEO capability
- PTP payload of 1 klb delivered to a 3,900 nmi range (east)



Fuel-Augmented Bimese

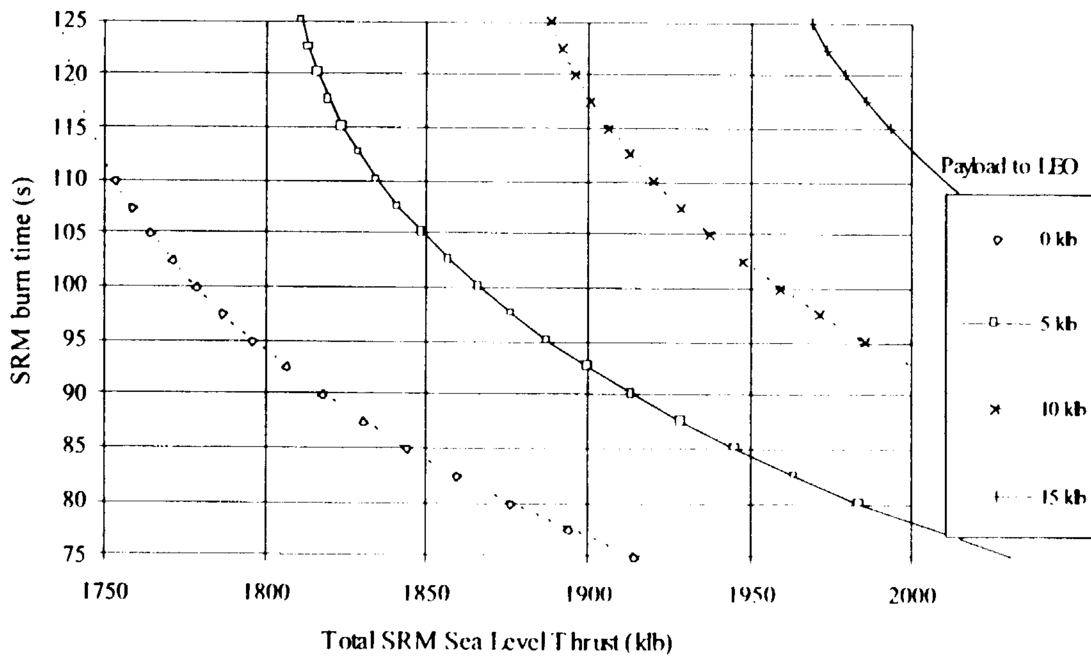
- No LEO capability
  - tanks add ΔV, but loss of T/W prevents the Bimese from ascending to orbit
- PTP payload of 1 klb delivered to a 4,100 nmi range (east)

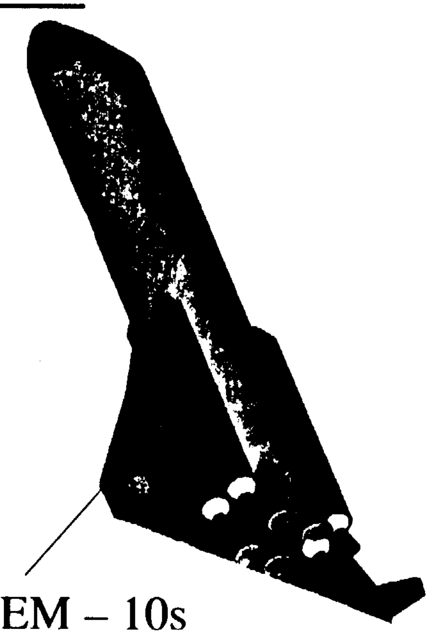


Payload Tank Parameters	
LOX fuel (lb)	87,300
LOX tank weight (lb)	590
LH2 fuel (lb)	12,600
LH2 tank weight (lb)	890
Structure/feeds (lb)	1,000
Total weight (lb)	104,480
Length of Apparatus (ft)	30

Thrust-Augmented Bimese

- Solids modeled after Delta GEM (Graphite Epoxy Motor)
- Design of experiments study optimized thrust and burn time
- 4 parametric "GEM-10s" sized to deliver <u>10 klb to LEO</u>





<u>GEM – 10s</u>

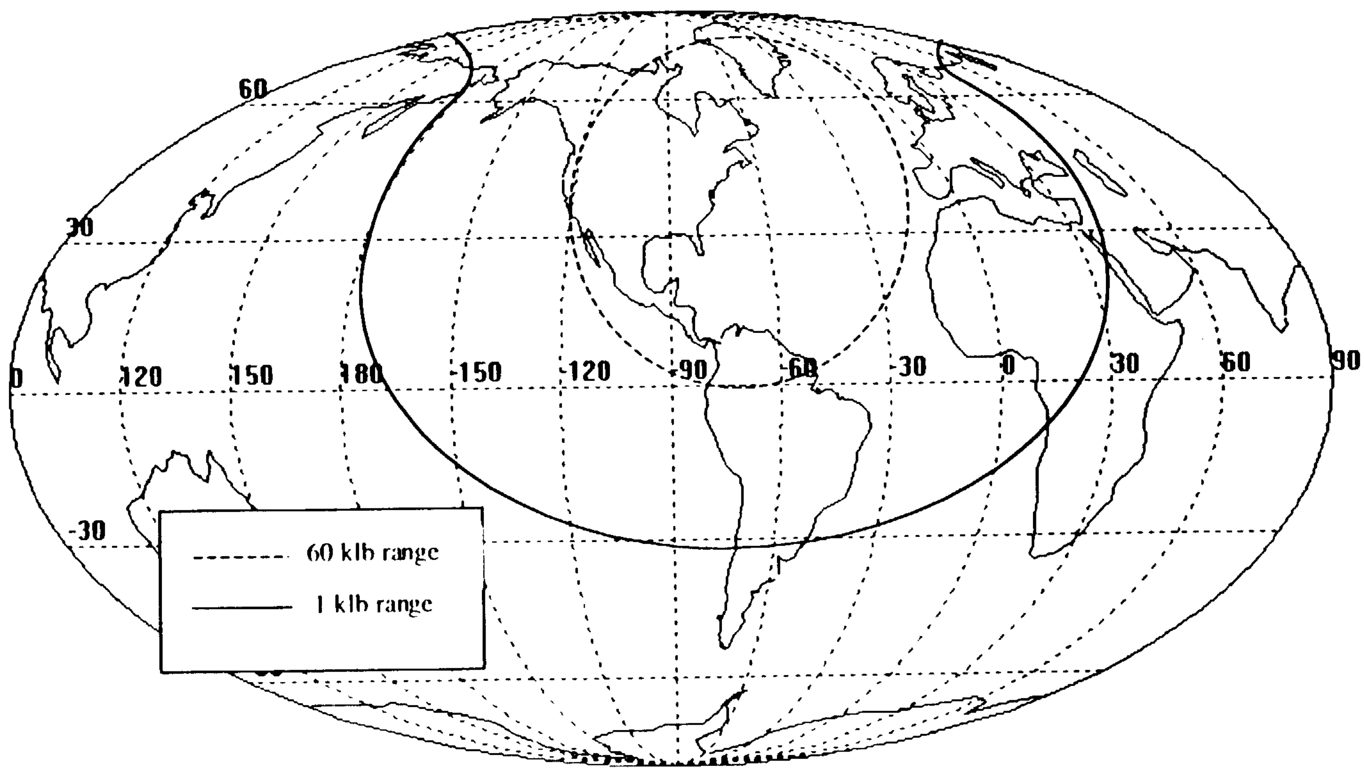
s.l. thrust: 500 klb ea.

I_{sp}: 274 s

gross weight: 210 klb

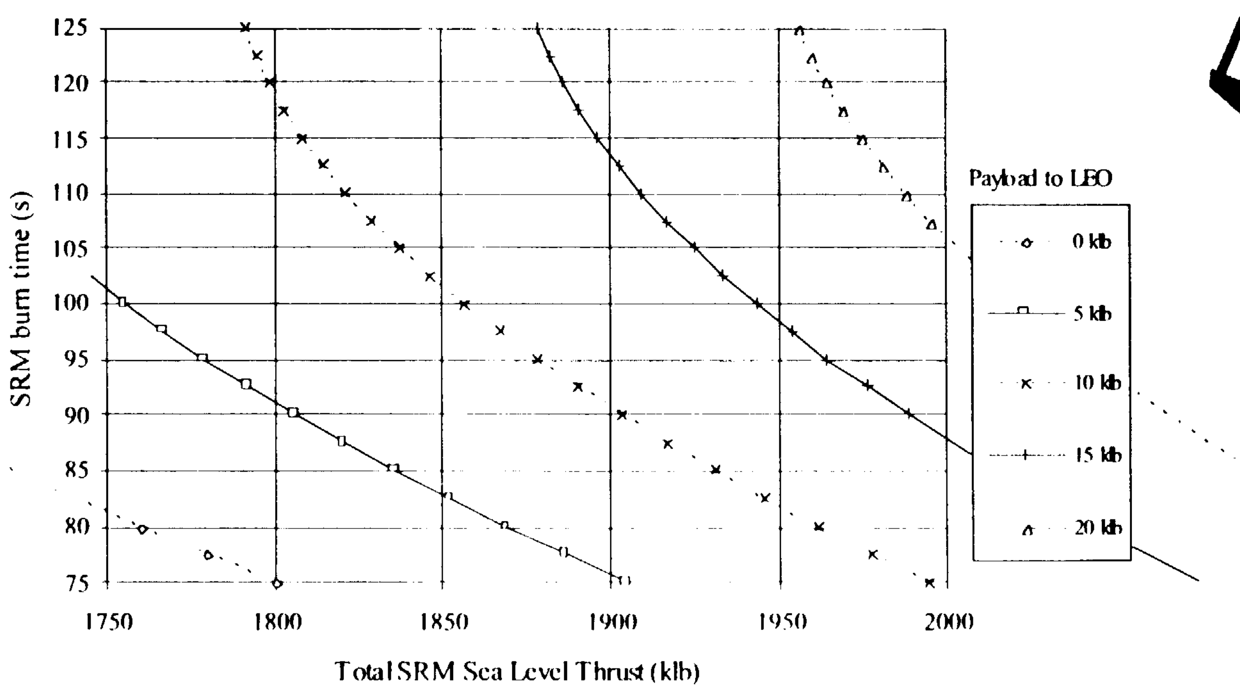
Point-to-point Bimese with SRM

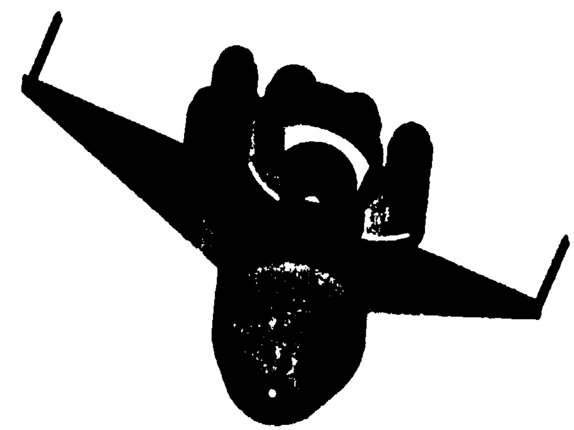
- 2 GEM-10s are used for thrust-augmented point-to-point trajectory
- PTP payload of 1 klb delivered to a 6,900 nmi range (east, 2 SRB)



Fuel/Thrust Augmented Bimese

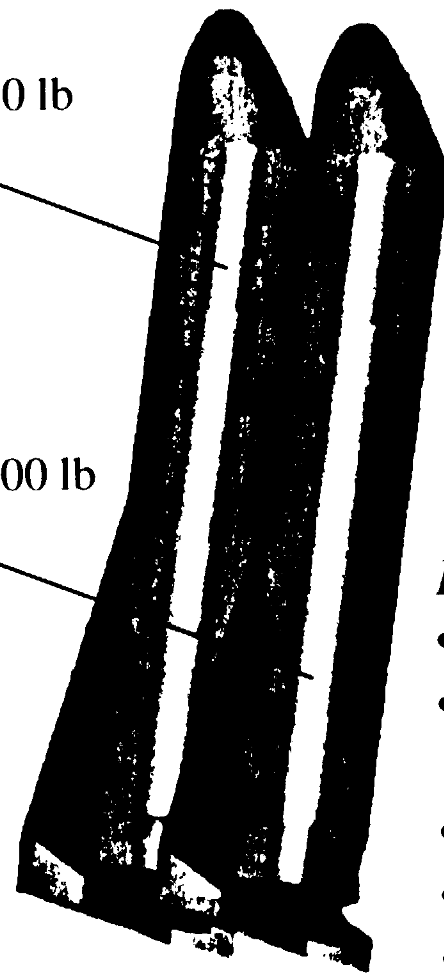
- Contains both extra internal tanks and solid rocket motors
- DoE study optimized thrust and burn time for GEM SRBs
- With 4 GEM-10s (commonality), capability of 15,900 lb to LEO





Mated Bimese

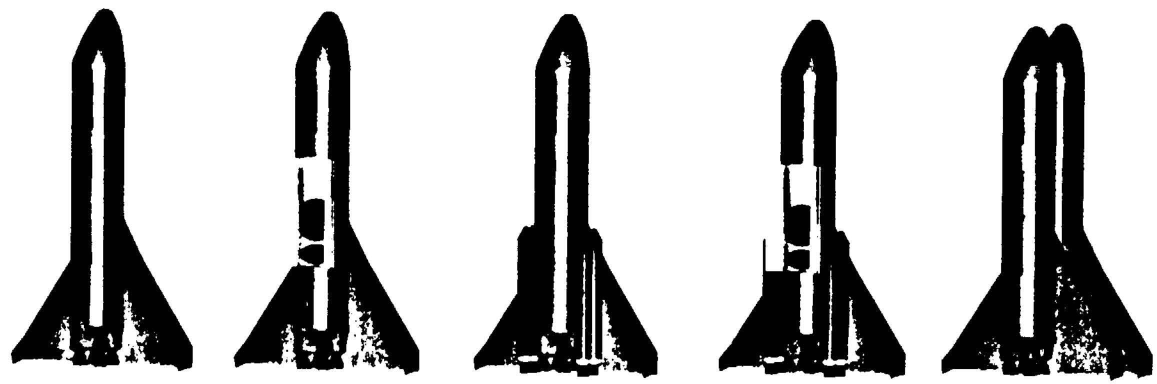
<u>Booster</u>
Gross weight (zero payload) :1,130,550 lb
Ascent propellant: 941,600 lb



<u>Orbiter</u>
Gross weight (zero payload) :1,083,700 lb
Ascent propellant: 909,700 lb

Features Include:
- 4 LOX/LH2 engines each
- propellant cross feed from booster to orbiter
- Mach 3.2 staging
- glide-back booster
- payload 60 klb to LEO

Summary of Missions



Mission	Single element	Fuel augmented	Thrust augmented		Thrust/fuel augmented	Mated (Bimese)
			# GEM-10s			
			2	4		
LEO Capability (lb)*	0	0	0	9,740	15,900	60,000
Point-to-point capability (nmi)**	3,900	4,100	6,050	0	0	0

** LEO payload delivered to a 100 nmi x 100 nmi at 28.5° inclination*
*** Point-to-point range capability for 1 klb due east from 28.5° latitude*

Augmented 4 GEM configuration (and larger) has global PTP range. Single element Bimese has trans-Atlantic range.

Business Analysis

Business analysis task is intended to explore possible scenarios for a point-to-point fast package delivery company.

Fast Package Delivery by Bimese PTP, Inc.

Analysis Tools Include:

Operations Modeling - AAT Release Version 1

Vehicle Costing - CABAM

Business Modeling - CABAM

Fast Package Advantage

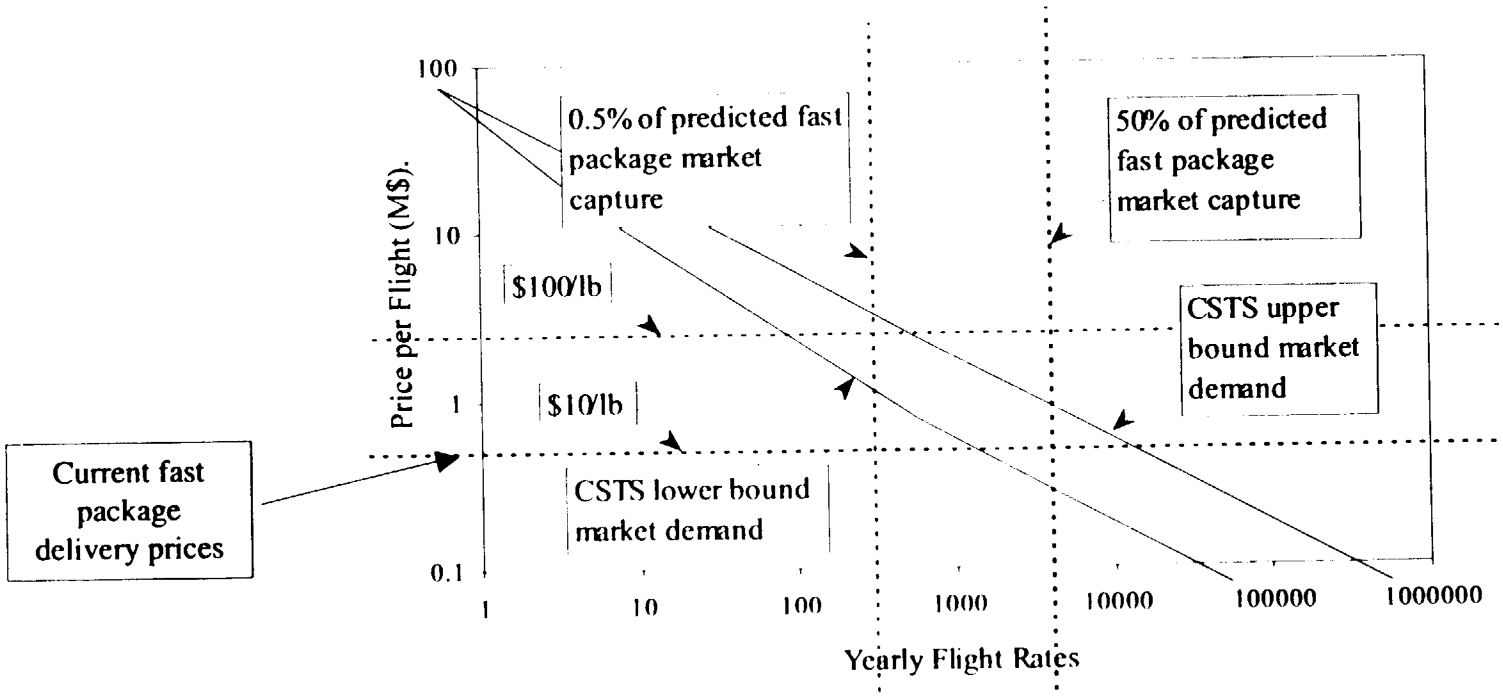
Where does the advantage lie in rocket-based delivery?

- Advantage lies in faster transit time, aircraft flight time is on the order of hours larger than rocket delivery.
- The further the destination, the greater the time advantage.

From	To	Approximate Flight Time		FedEx
		Jet	Bimese	Cost
KSC	Madrid	10 hr	~40 min	10 $/lb
KSC	LA	7 hr	~30 min	7 $/lb
KSC	London	10 hr	~40 min	10 $/lb
KSC	Rio De Janiero	12 hr	~40 min	12$/lb
KSC	Paris	11 hr	~40 min	10 $/lb

Estimated Market Elasticity

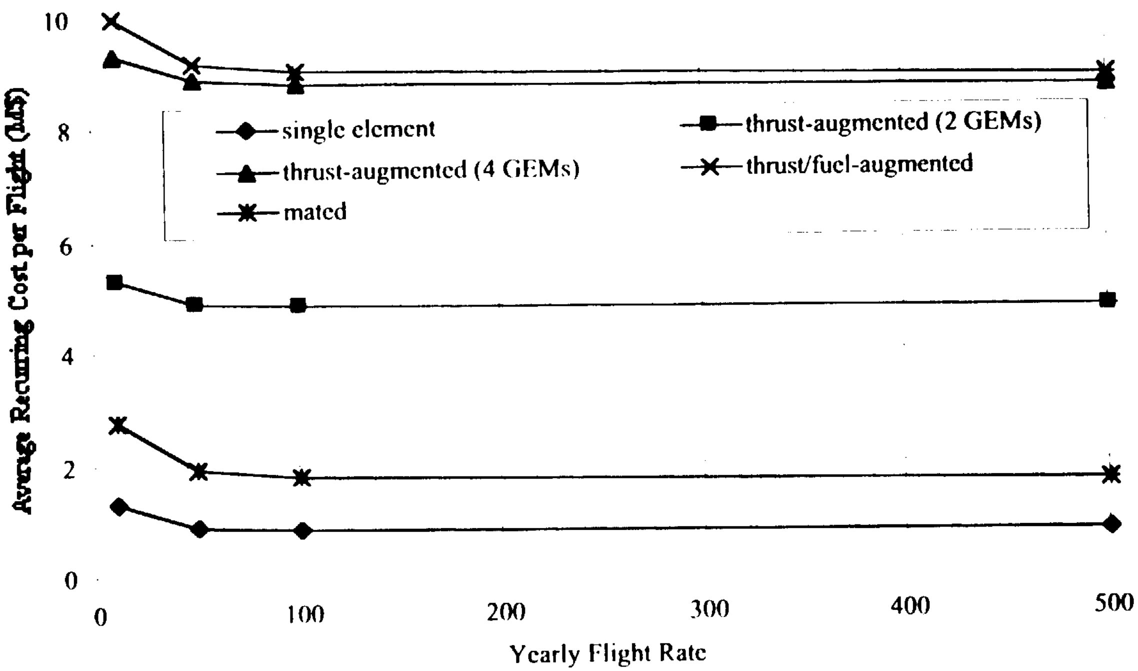
CSTS ultra-fast package market predicts a "sweet spot" at $1M price per flight and about 2000 flights per year globally @ 5,000 lb. of payload/flight (equiv. to daily service along four routes).



Cost Analysis Assumptions

- Bimese PTP, Inc. Program Years
  - Initial operational capability in 2011 (full by year 2012)
  - Program termination in 2039
  - All analyses maintain constant debt-to-equity ratio of 3.0
- Baseline Government Cost Contributions
  - Airframe: DDT&E: 20%; TFU: 0%
  - Propulsion: DDT&E: 100%; TFU: 0%
  - Construction of Ground Facilities: 100%
- 4 engines per airframe
  - Airframe lifetime of 1000 flights, engine lifetime of 250 flights
  - Vehicle turnaround/processing time of 12 - 16 days
- Expendable GEM-10 SRBs purchased from separate supplier @$2M each
- All cost figures in 1999 dollars unless otherwise noted
- Learning Curves
  - Recurring Cost: 85%
  - Production: 90%

Recurring Cost Prediction



Accounting only for recurring costs, it is clear that the configurations with strap-on SRB thrust-augmentation cannot meet the $1M/flight price target

Realistic Business Scenario

- "Ideal" case would use multiple Bimese configurations to service a global fast-package market
  - Unfortunately, long range thrust-augmented vehicles are too expensive to provide an acceptable package price for the market
- "Realistic" case might use the fully reusable single element Bimese on "charter-style" trans-Atlantic flights
  - Recurring cost at least passes first-order filter (less than target price of $1M per flight)
  - Payload and range are limited (too small to support global market)
  - Unfortunately, trans-Atlantic charter market will be only a fraction of the full CSTS market prediction

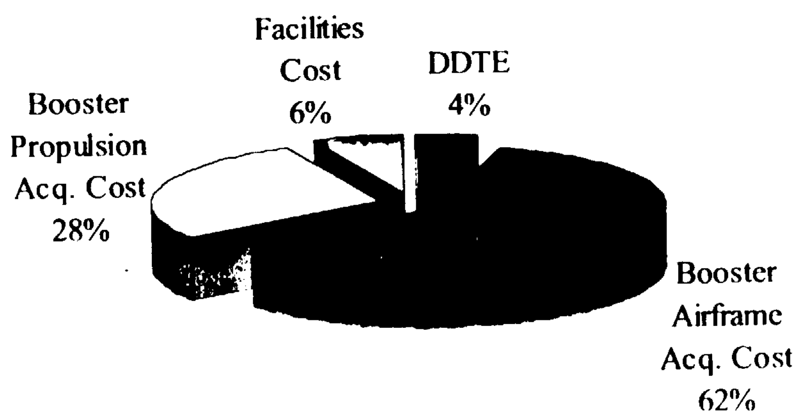
Non-Recurring Cost Summary

DDTE Total	$7,495 M
TFU Total	$1,887 M

First flight unit cost

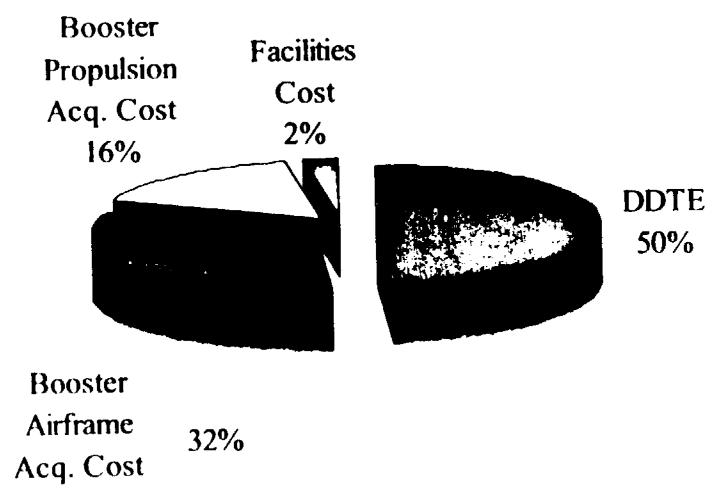
5000 flights/year

Non-recurring Cost Breakdown



100 flights/year

Non-recurring Cost Breakdown



Amortized non-recurring cost can add significant per flight $

Four Business Scenarios

Four separate business scenarios for the single element Bimese trans-Atlantic market were examined with assumptions ranging from conservative to very optimistic.

1. Baseline Economic and Operations Assumptions
   - Bimese PTP, Inc. pays 80% of airframe DDT&E and all production costs
   - baseline 12 day turnaround time from AATe (drives fleet size)
2. Reduced Turnaround Time
   - aircraft-like 1 day turnaround time for PTP missions
3. Reduced Non-Recurring Cost (and reduced turnaround time)
   - synergy with gov't orbital config. pays <u>all of DDT&E</u> and reduces production costs by 20%
   - 1 day turnaround time
4. Recurring Cost-only Case!
   - Bimese PTP, Inc. pays only recurring costs and launch site fee, no non-recurring costs!
   - 1 day turnaround time

Four Business Case Results

	Baseline	Reduced turn around time	Reduced DDT&E, TFU, and turn around time	Recurring Cost Only
Required Flights/year	5,000	5,000	250	100
Price/flight (M$)	$7	$6	$6	$1.0
Approximate trans-Atlantic flights avail.	<10	<15	<15	<25
IRR	~ 25%	~ 25%	~ 25%	~ 25%
Fleet size	171	144	8	4
Fleet acquisition (B$)	$154	$103	$ 15	$0
Turn around time (days)	12	1	1	1
DDT&E Government Contribution (M$)	$1,850	$1,850	$7,400	$7,400
TFU (M$)	$1,900	$1,900	$1,500	$0

In order to produce a 25% IRR for Bimese PTP, Inc., required flight rates (and prices) exceed the available trans-Atlantic flights in all cases. <u>No business cases close for this market.</u>

Economic Conclusions

Even in the most optimistic scenario, recurring cost only, the single element Bimese <u>fails to produce an attractive business scenario.</u>

- At only 1 klb of payload and assuming $100/lb package, expected trans-Atlantic PTP revenues are only $100,000 per flight
- Direct operating expenses alone amount to about $400,000 per flight (labor, propellants, maintenance hardware, insurance) and the spaceport site fee adds about $100,000
- To pay taxes and still yield a 25% return on investment, Bimese PTP, Inc. would need revenues of over $900,000 per flight. Adding a requirement to amortize non-recurring costs such as DDT&E and fleet procurement will only make the problem worse.

Study Recommendations

While the study failed to identify an attractive ultra-fast package business scenario for the Bimese architecture, clear directions of improvement were established.

1. Reduce the Direct Recurring Cost of Rocket Vehicles. To enable an ultra-fast package delivery market, the recurring costs of rocket-based solutions must be reduced by another order of magnitude from the costs used in this study (two orders of magnitude lower than the space shuttle).

2. Increase the Size and Range of the Single Element Bimese RLV. The study showed that expendable thrust-augmentation boosters are too expensive to be used in the ultra-fast package market, but longer range (global) and higher payload (5 klb) are necessary to enable the global market. A larger (almost single-stage) fully reusable rocket vehicle is more optimum (unfortunately, this is a mismatch for the mated TSTO)

Study Recommendations (2)

3. Reduce or Share Initial Non-Recurring Costs. Having to recoup non-recurring costs has a significant impact on the price that a new business can offer. Amortized non-recurring costs can easily be several times higher than the direct recurring costs. Here, the Bimese strategy is an attractive option since the DDT&E of the concept might be absorbed by the government as it develops the concept for for orbital missions. Similarly, shared a production line with government vehicles might reduce the fleet procurement costs for a rocket-based fast package business.

4. Streamline Rocket Vehicle Group Operations. To compete with aircraft in a fast-package market, rocket vehicles will have to have aircraft-like turnaround times, no more than 1 day to support daily service on routes. This represents an order of magnitude reduction from the original turnaround time calculated for the single element Bimese and two orders of magnitude reduction from the space shuttle.