NASA-TM-106,418

NASA Technical Memorandum 106418

NASA-TM-106418 19940017286

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December 1993

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Options For thrust Augmentation For The BETA II Two-Stage To Orbit Launch Vehicle

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ABSTRACT

A study to improve the performance of the NASA two-stage-to-orbit vehicle was undertaken. The NASA concept, a horizontal takeoff and landing, fully reusable, two-stage to orbit vehicle will be capable of launching and returning a 10,000 pound payload to a 100 nmi polar orbit. The vehicle, Beta II, is a derivative of the USAF/Boeing Beta vehicle which was designed to deliver a 50,000 pound payload to a similar orbit. Beta II stages at Mach 6.5 and about 100,000 feet altitude. The propulsion system for the booster is an over/under turbine engine/ramjet configuration. In this paper a study was performed for one of the candidate engines, the variable cycle engine, to assess its potential to meet the required performance needs of the Beta II vehicle. Several options for thrust augmentation were studied in order to improve the performance of the engine where there was a critical need. The methodology, constraints, propulsion performance and mission study results are presented.

INTRODUCTION

This paper is the result of the NASA Lewis Research Center's (LeRC) on-going study of propulsion systems for low risk replacements for the Space Shuttle. The purpose of this present study was to predict the improved vehicle performance due to the enhancements made to the booster propulsion system.

The vehicle used for this study, Beta II, is a Two-Stage-To-Orbit (TSTO) vehicle derived from the USAF/Boeing Beta vehicle (ref. 1 & 2). Beta II, a horizontal takeoff and landing vehicle, was downsized from the original Beta to deliver 10,000 pounds to a 100 nmi polar orbit. The vehicle configuration is shown in Figure 1. Beta II was designed to be fully reusable, using low risk and near term technology. The total takeoff weight of Beta II (booster and orbiter) was 1 million pounds (ref. 3). The Beta II configuration studied in this paper had four High Speed Civil Transport (HSCT) derived turbine engines on top and one conventional ramjet at the bottom per nacelle (see Figure 2). JP fuel was used in both the main burner and the afterburner of the HSCT engines and they operated from takeoff to Mach 3 or 3.5. The ramjet used hydrogen fuel and became operational around Mach 1.0 and continued until separation occurred. Also, included in this configuration was a variable capture area inlet for better inlet/engine airflow matching throughout the flight path.

The booster of the Beta II is fully airbreathing from takeoff to separation at Mach 6.5 and 100,000 feet altitude. After separation the booster returned to its landing site. The orbiter, similar to the Space Shuttle, was bottom loaded within the booster. The orbiter was propelled by one Space Shuttle Main Engine (SSME). The orbiter propulsion system operated from booster/orbiter separation to orbit.

The options looked at in this study included turbine engine aerodynamic overspeeding and water injection in the transonic region as well as water injection at high speed to enhance the engine performance. The results of these studies are outlined below.

ENGINE DESCRIPTIONS

The engine chosen for this study was the Variable Cycle Engine (VCE) (ref. 4). The VCE is a very complex cycle but offers a lot of flexibility for alternative missions. The VCE is a derivative cycle of a conventional two-spool turbofan with some notable features. The VCE has two bypass ducts instead of one. The first bypass duct (outer duct) acts as a valve that can be controlled to maximize thrust (figure 3). At takeoff the outer bypass is closed (turbofan configuration) and at high Mach number the outer bypass duct is opened allowing higher engine airflow and increasing thrust. The second bypass (inner duct) is positioned after the Core-Driven-Fan (CDF) rather than behind the front fan as it is done for a conventional turbofan. The placement of the inner duct behind the CDF helps maintain an almost constant bypass ratio in it throughout the engine flight regime because the front fan is allowed to pass only as much airflow as the CDF can handle. The VCE was designed for a Mach number of 2.4 and 60,000 feet altitude. The Overall Pressure Ratio (OPR) was 21.3 at Sea Level Static (SLS) condition and a corrected airflow of 790 lb/s. The inner bypass ratio was held at 0.3 (ref. 4); the outer bypass ratio was negligible at sea level but increased up to 0.53 at the turbomachinery shut down point.

ENGINE CONSTRAINTS & OPERATION

Since only four turbine engines designed for 610 lb/s. corrected airflow at sea level static condition could fit inside each nacelle, all performance data was ratioed to 610 lb/s. corrected airflow at SLS for the turbine engine. The engine was limited to a maximum burner temperature of 3560 R and a maximum compressor exit temperature of 1810 R.

The turbine engine was fully afterburned throughout the flight path to maximize thrust. A common inlet was used for both turbine and ramjet engines. During turbine engine operation, airflow not required for the VCE was used for the ramjet.

RAMJET

The ramjet sizing was done in a previous study (ref. 5) to determine the Mach number and altitude limits for the Beta II vehicle. A maximum burner cross-sectional area of 111.3 square feet was used. The ramjet was hydrogen fueled and the fuel-to-air ratio was chosen to maximize thrust. The maximum fuel-to-air ratio was 0.95 of the stoichiometric value because 5% of the ramjet airflow was used for ramjet cooling.

METHOD OF ANALYSIS

Several codes were used in performing the Beta II vehicle propulsion analysis. The NASA Engine Performance Program (NEPP) (ref. 6), was used to carry out the turbine engine performance analysis. NEPP performs a one-dimensional, steady-state thermodynamic analysis and includes chemical equilibrium effects. The fan, compressor and turbine aerodynamics maps used are similar in technology and performance to those being used in current High Speed Research Studies.

The ramjet performance was calculated using RAMSCRAM (ref. 7). RAMSCRAM is a one-dimensional, steady-state code which includes chemical equilibrium effects for a ramjet or scramjet duct. A constant area burner was assumed. The program determines the loss in momentum due to the heat release in the combustor.

The performance data used for the nozzle was from previous Beta II studies using SEAGULL (ref. 8). SEAGULL is a steady-state, inviscid, two-dimensional performance code which uses a finite difference method. The inlet performance data was obtained using the Inlet Performance Analysis Code (IPAC) (ref. 9). IPAC makes use of the oblique shock and Prandtl-Meyer expansion theory for the prediction of inlet performance. The inlet performance data used for this study is given in (ref. 2 & 9). Since the performance data generated for the turbine engine was uninstalled data, the INSTALL (ref. 10) code was used to take into account the installation effects of the propulsion system. The INSTALL code was designed to calculate net installed propulsion performance at various flight conditions based on uninstalled engine data, inlet and nozzle data.

The mission analysis was performed using the Optimal Trajectories by Implicit Simulation program (OTIS) (ref. 11). OTIS was used to find optimal trajectories while satisfying maximum dynamic pressure, staging mach number and engine operating points constraints. OTIS simulates and optimizes point mass trajectories with provisions made for free and fixed end constraints, specified way points and path constraints.

DISCUSSION AND RESULTS

For this study three options were assessed as a means to increase the overall performance of the Beta II vehicle: (1) Overspeeding the turbine engine in the transonic region in order to alleviate the transonic thrust pinch; (2) Water injection in the transonic region at different locations in the turbine engine for the same purpose mentioned above; (3) Water injection at the engine face in order to extend the Mach number range of the turbomachinery from Mach number 2.4 up to Mach number 3.5. Uninstalled performance for the turbine engine using these options will be presented and discussed followed by the mission analysis. Uninstalled thrust was corrected for altitude effects along the flight trajectory using the ratio of engine face total pressure to standard pressure and is presented per propulsion module which consists of four VCE engines. For the configurations where water injection was investigated, turbine engine specific fuel consumption represents total propellant used, i.e, both JP fuel and water. Similarly, corrected airflow consists of both air and water.

OVERSPEED: TRANSONIC

Aerodynamic overspeeding of the VCE fan in the transonic region was studied to assess its thrust augmentation capability because the performance of the Beta II vehicle in the transonic region is very marginal. Aerodynamic overspeeding is done sometimes for short periods to improve engines performance when it is necessary. The penalty is a weight increase of the rotating component since it has to be designed to withstand the added stress associated with the overspeeding, if not, the engine life will be reduced. Since the Beta II booster is an acceleration vehicle with short duty cycles, overspeeding would not have any significant impact on the vehicle in terms of weight increase. Therefore, aerodynamic overspeeding of 7 and 10 percent of the fan were investigated to improve Beta II performance in the transonic region.

Figures 4 and 5 show that overspeeding the fan transonically increases the thrust up to 4 percent with almost no change, except at the higher transonic Mach numbers, in specific fuel consumption. As shown in figure 6, 7 percent overspeeding increases airflow by 1 percent while 10 percent overspeeding increases it by 3 percent. The bypass ratio for the outer duct decreases at the low transonic Mach number to allow more airflow through the core, but increases at the higher transonic Mach number (fig. 7). Since both the 7 and 10 percent overspeed cases were run at the same maximum level of afterburner (same exit fuel-to-air-ratio), the higher airflow of the 10 percent overspeed case yields a higher increase in thrust at no additional cost in specific fuel consumption. The fan pressure ratio for 10 percent overspeed was 7 percent lower than that with 7 percent overspeeding . That is why the airflow for the 10 percent overspeeding is about 2 percent higher than the 7 percent overspeed case.

As the Mach number and fan entrance temperature increases for both the 7 and 10 percent overspeed cases, the turbine engine reduces the fan pressure ratio, to reduce fan power requirements. As a result, the increase in thrust with airflow is lower at the higher transonic Mach number.

WATER INJECTION: TRANSONIC

Water injection was studied to determine its thrust enhancement potential in the transonic region to help alleviate the thrust pinch for the Beta II vehicle. Water injection was done for the VCE at the fan and the high pressure compressor (HPC) faces as well as in the main burner and the afterburner. The amount of water injected at the fan and the HPC faces was limited by the vapor saturation limit. Any additional water added past that limit would have caused a decrease in compressor blades performance due to the water droplets impinging on the blades. Water consumption was the limiting factor (at the point where the specific fuel consumption became unrealistic) for the main burner and the afterburner. Therefore, a limit of 8.5 percent ratio of water to airflow was chosen for the main burner and the afterburner cases for this study. As seen in figure 8, water injection, in terms of thrust augmentation, improves the engine performance in the transonic region substantially. Water injection in the fan shows the best gain in thrust compared to the other cases investigated. The difference in thrust increase for water injection in the HPC, the main burner and the afterburner was not significant. However, when compared with the baseline case, the increase in thrust for these three cases was substantial.

Because the increase in thrust tells only half of the story, it must be emphasized that the amount of water injected to obtain a certain level of thrust augmentation must be considered. Both main and afterburner results were obtained with 8.5 percent of water injection whereas the fan and the HPC were not able to sustain that much. Even less water was injected in the HPC compared to the amount injected in the fan because convergence for the HPC was very sensitive to the amount of water injected. The amount of water injection possible for the HPC with cycle convergence ranged from 0.1 percent at Mach 0.9 to 0.6 percent at Mach 1.5 while for the fan it ranged from 0 percent water at Mach 0.9 to 2.3 percent at Mach 1.3. Thus, when the thrust increase was compared with the amount of water added, it could well be argued that the best place for the water injection, in the transonic region, is at the HPC face since the specific fuel consumption for the HPC was lower than the other cases. This is clearly shown in figure 9.

The trend for the fuel consumption for the main and afterburner was as expected; water injection in the main burner increased specific fuel consumption (SFC) by a factor of 1.5 over the baseline case and by a factor of 2 for the afterburner case. The only exception occurred at Mach 1.5 where cycle convergence limited the amount of water injected into the afterburner to 0.7 percent. That explains why the SFC at that Mach number is almost equal the baseline case (fig. 9).

Except for the burner case (fig. 10), the variable bypass was not much affected by the water injection in the transonic region because not much water was added at the fan or at the compressor face to make a significant difference. Because the turbine was choked, the cycle had to bypass some airflow to account for the water being injected in the main burner. Figure 11 shows that the corrected airflow curves remained almost unaffected by the water injection. When water was injected at the fan or compressor face, only a small amount of water could be added due to the low engine entrance temperature in the transonic region. In the case of water injection in the main burner, the same total airflow was maintained by increasing the bypass ratio. Since a variable throat area nozzle was assumed, water injection in the afterburner had no effect on airflow or bypass ratio.

WATER INJECTION: HIGH SPEED

Water injection was also used at the engine face as a way to maintain the Mach 2.4 (design Mach number) engine entrance temperature constraint past Mach 2.4 up to Mach 3.5. Since the VCE engine had to spool down above Mach 2.1 to remain within the compressor exit temperature constraint of 1810 R, water injection at the fan seemed to be a viable option compared to using more expensive, exotic materials capable of withstanding the high temperatures.

Figure 12 shows that the addition of water allows the airflow to be kept much higher than the baseline case, thus, increasing the corrected thrust significantly in the high Mach number region. Water injection was turned on at Mach 2.5 at which point the amount required to simulate the design point conditions for the VCE was minimal (0.7 percent). Thus, there was no significant gain in terms of thrust at Mach 2.5, but past that point thrust increases significantly as the amount of water injected increases (fig. 13). However, the increase in thrust was not free. Figure 14 shows a considerable increase in specific fuel consumption compared to the baseline case.

As can be seen from figure 15, water injection at high Mach number affects the variable bypass ratio. That is because the engine did not have to spool down since the engine entrance temperature was kept at Mach 2.4 conditions. Thus, the amount of bypass airflow stayed constant. Figure 16 shows that modest amount of water would be required to keep the engine entrance temperatures within the Mach 2.4 design limit if the turbomachinery operation had to be extended up to Mach 3.5. The water decreases engine entrance temperature which helps keep corrected airflow up. However, as stated earlier, there is a significant increase in specific fuel consumption by the time Mach 3.5 is reached (fig. 14).

MISSION ANALYSIS

Several missions were run using the same vehicle but different VCE engine configurations. The vehicle take-off gross weight was kept constant at 1 million pounds while running the different configurations. The following VCE configurations were investigated: (1) 7 and 10 percent overspeed in the transonic region; (2) Water injection in the transonic region at the fan and the compressor faces as well as in the main burner and the afterburner; (3) Water injection at the fan face to maintain a Mach 2.4 engine entrance temperature constraint up to Mach number 3 or 3.5; (4) Extending the turbine engine operation up to Mach 3 or 3.5 without using water.

For the cases where turbofan operation was extended to Mach 3 and 3.5 without water injection, the compressor exit temperature limit (1810 R) was maintained, but the fan entrance temperature limit was exceeded. Such operation would require substituting higher temperature materials in the fan..

When the turbomachinery operation was extended past Mach 2.4, the overall performance of the propulsion system (both turbine engines and ramjet) decreased. That was even more so for the cases where water injection was used to prevent the turbine engine from spooling down. That is because at the high speed, the turbine engine is taking away needed airflow from the ramjet (Mach 2.4-3.5). Since less airflow was available to the ramjet, the overall performance in terms of total thrust for the vehicle was down. The same trend was observed but to a lesser degree for the cases where the extension of the Mach number was investigated with no water added at the fan face to maintain the engine entrance temperature condition (Mach 2.4). The reason is because, without water injection, the turbine engine spooled down significantly as Mach number increased past the design point in order to maintain the high pressure compressor exit temperature constraint (even though the fan entrance temperature was exceeded). As a result, more airflow was available to the ramjet . Therefore, overall propulsion performance was better than the cases with water injection.

The vehicle relative staging weight, Ws, for the VCE engine was obtained by subtracting the vehicle staging weight for the baseline case from the staging weight of each configuration studied. Thus, from figure 17, any configuration on the upper part of the graph indicates an improvement over the baseline case since it represents an increase in staging weight for that particular configuration. The increase in staging weight over the baseline indicates that less propellant is used for that configuration to reach the staging Mach number from takeoff. Conversely, any configuration on the lower part indicates the reverse trend.

Figure 17 shows that overspeeding the VCE by 10 percent in the transonic region increased the vehicle staging weight by 0.11 percent. Water injection at the High Pressure Compressor (HPC) face increased the vehicle staging weight by 0.73 percent followed by water injection at the fan face in the transonic region. On the other hand, overspeeding the VCE by 7 percent decreased the vehicle staging weight slightly compared to the baseline case. This is due to an increase in specific fuel consumption at the high Mach number in the transonic region. Water injection in the main burner decreased the staging weight by 1.7 percent followed by the afterburner with a decrease of 1.36 percent. Water injection at the engine face to extend the Mach number up to 3.5 decreased the staging weight as well. For the case where water was not used while extending the Mach number up to 3.5, the staging weight decreased but to a lesser degree than that of the water injection case.

For the cases of water injection and overspeeding in the transonic region significant change occurred in the flight path of the VCE when compared with the baseline. The overspeed cases executed the transonic dive at a slightly higher altitude (fig. 18). Water injection in the HPC pushed the vehicle flight path in the transonic region significantly higher than the baseline (fig. 19). For the fan, the same trend was observed but the change in altitude was to a lesser degree than that of the HPC. From an environmental point of view (in the case of flying over land) it would be preferable to have the sonic boom at a much higher altitude than the baseline case. Both the main burner and the afterburner cases started the transonic dive at approximately the same altitude that the baseline did but bottomed out at a slightly higher altitude.

The injection of water at the engine face to keep the design 2.4 conditions, but operating the turbomachinery up to Mach 3.5, did not change the VCE flight path at the high Mach number (fig. 20). The reason was due to the fact that the OTIS mission code was run with a dynamic pressure constraint and was optimized to minimize mission fuel consumption.

SUMMARY

This study addressed the issue of improving the performance of the VCE engine in the transonic region as well as at the high Mach number in order to improve the performance of the Beta II vehicle. Two methods were studied : (1) Engine overspeeding in the transonic region; (2) Water injection at different locations in the VCE engine.

Overspeeding in the transonic region showed modest gain in thrust. The thrust increase was essentially cost free since the specific fuel consumption (SFC) was negligible.

Water injection in the transonic region at different locations in the turbine engine increased the thrust substantially. When the water was injected at the main burner or the afterburner the thrust gains were at the cost of very high specific fuel consumption. Water injection at the fan entrance and the HPC entrance were effective in increasing staging weight but the amount of water that could be added was small so the gain in vehicle staging weight was small (0.73 percent for the HPC case).

Water injection at the engine face to extend the Mach number to 3 or 3.5 showed considerable thrust increase at the higher Mach numbers since the turbine engine did not have to spool down to maintain the temperature constraint at the compressor exit. But the cost of obtaining it was high due to the high specific fuel consumption. Staging weight increased only slightly in the Mach 3 case while it decreased in the Mach 3.5 case.

Water injection at the HPC face in the transonic region resulted in the best performance gain (minimum propellant usage for the mission) compared to the other thrust augmentation options studied. However, the gain was small and may be offset by the additional water injection hardware needed. Therefore, the use of water injection in the transonic region or at high speed for thrust enhancement may cost more in SFC than the net gain in thrust for the type of vehicle configuration investigated in this study. However, the increase in airflow and thrust augmentation obtained from the options studied may prove very effective in extending the turbine Mach number range for a propulsion system without a ramjet.

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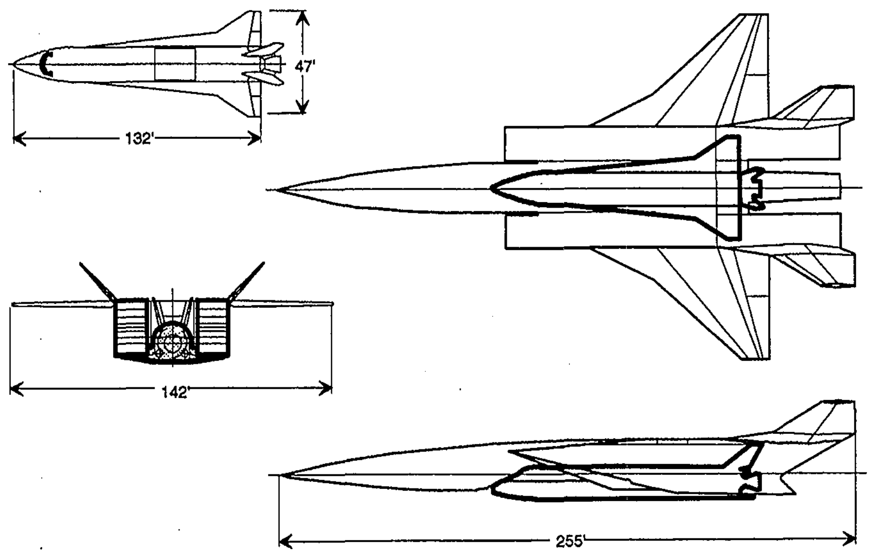

Figure 1. Beta II Configuration.

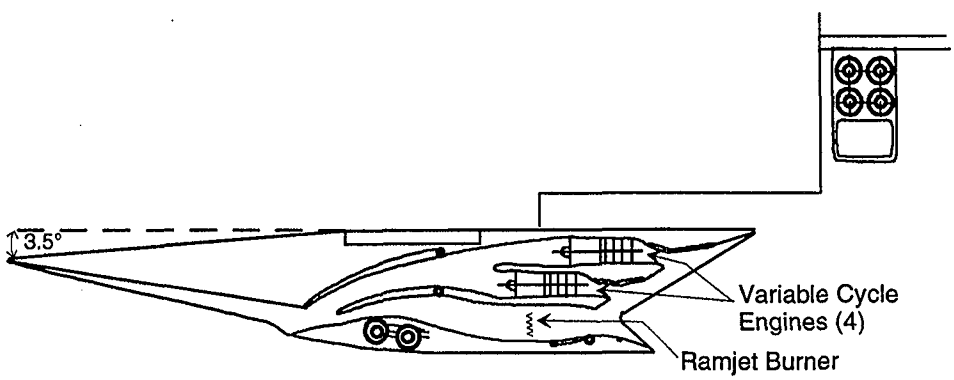

Figure 2. Beta II Nacelle Configuration.

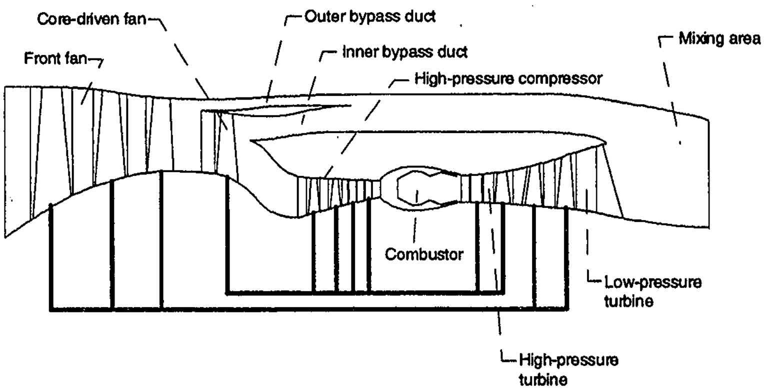

Figure 3. Variable Bypass Engine Flowpath.

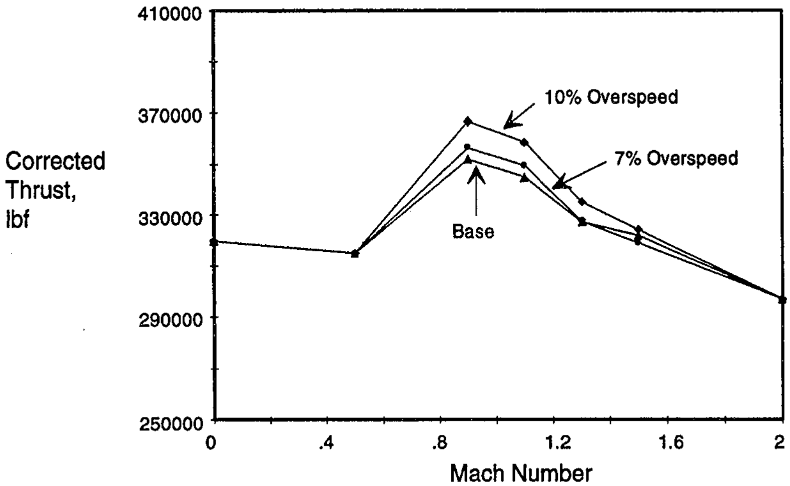

Figure 4. Effect of Transonic Overspeed on Thrust.

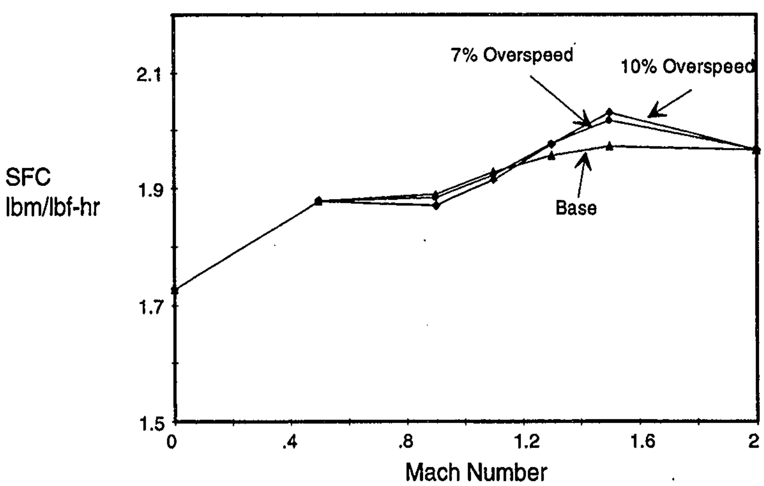

Figure 5. Effect of Transonic Overspeed on Specific Fuel Consumption.

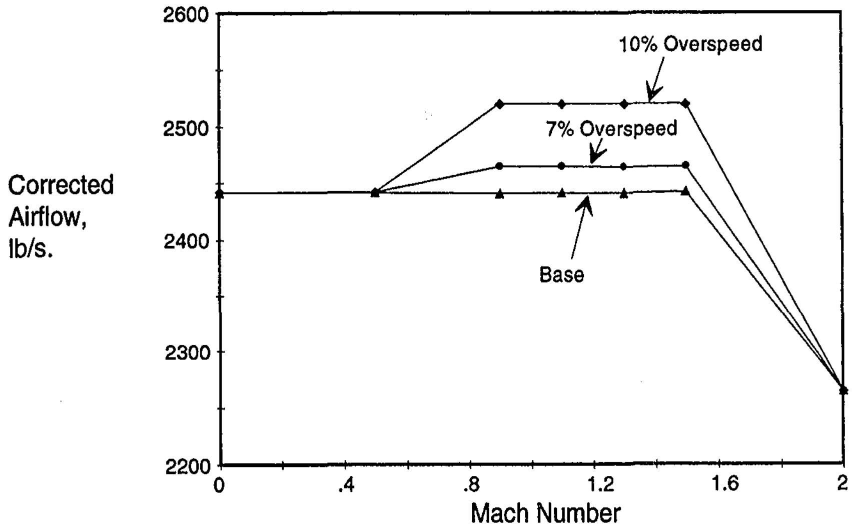

Figure 6. Effect of Transonic Overspeed on Airflow.

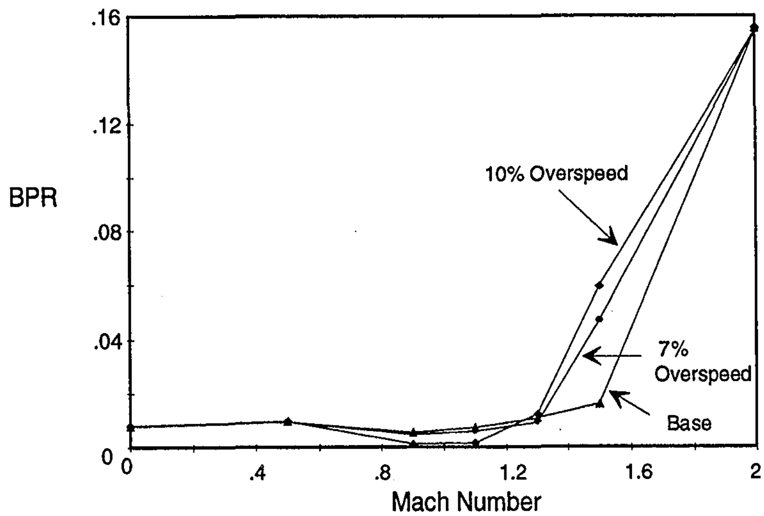

Figure 7. Effect of Transonic Overspeed on the Variable Bypass Ratio.

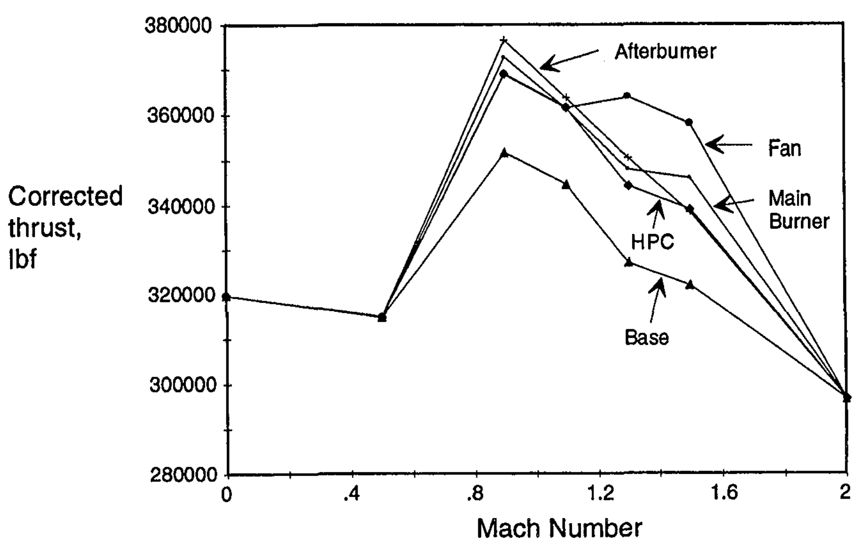

Figure 8. Effect of Water Injection in the Transonic on Thrust.

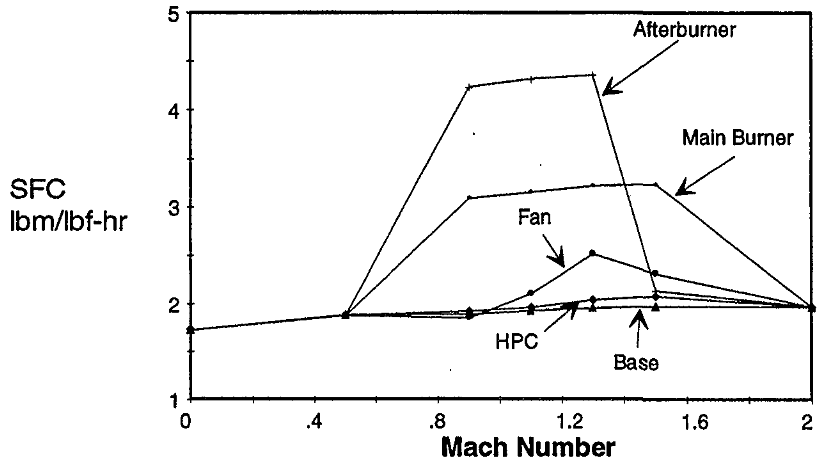

Figure 9. Effect of Water Injection in the Transonic on Specific Fuel Consumption.

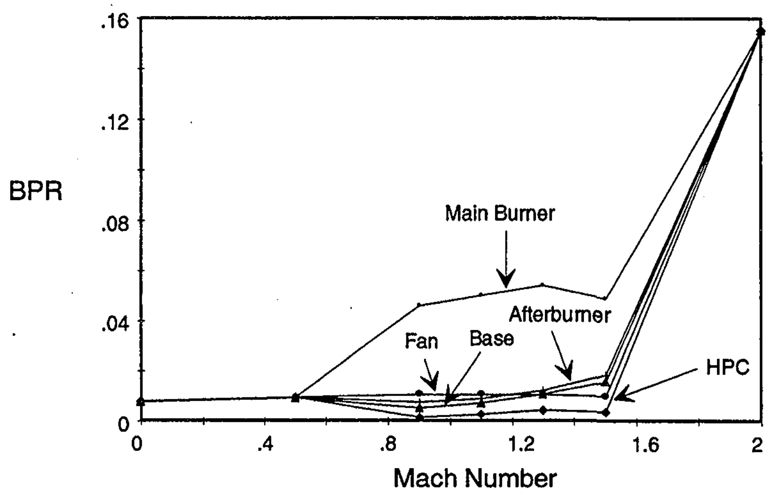

Figure 10. Effect of Water Injection in the Transonic on the Variable Bypass Ratio.

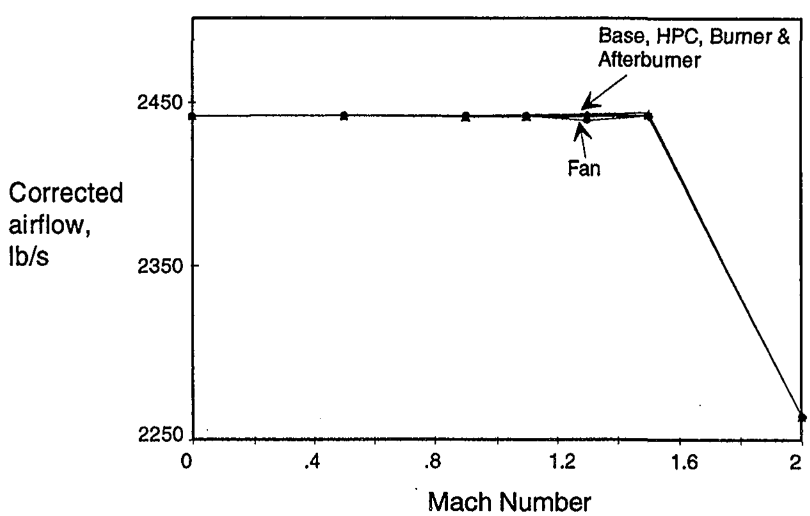

Figure 11. Effect of Water Injection in the Transonic on Airflow.

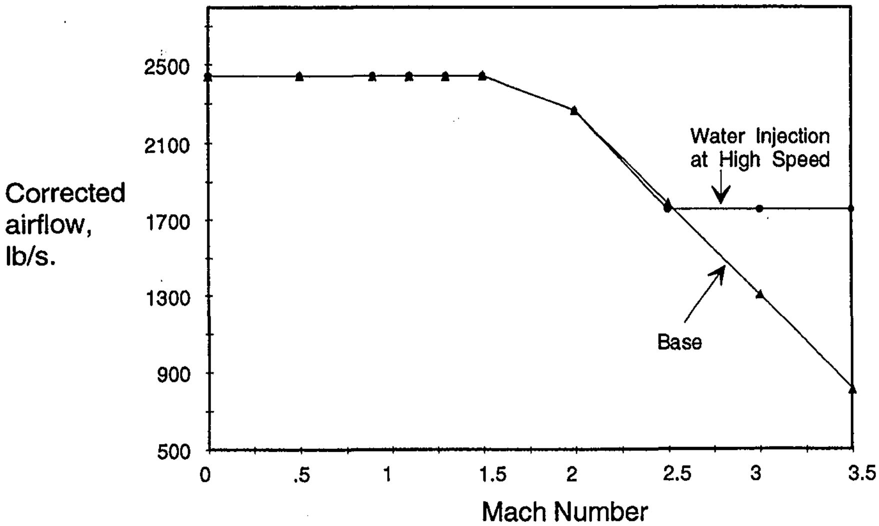

Figure 12. Effect of Water Injection on Airflow at High Mach Numbers to Keep Mach 2.4 Conditions.

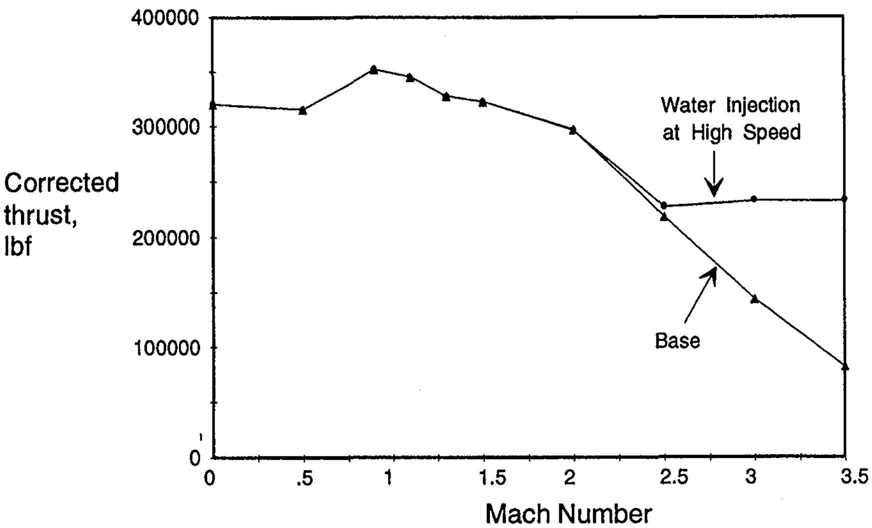

Figure 13. Effect of Water Injection on Thrust at High Mach Numbers to Keep Mach 2.4 Conditions.

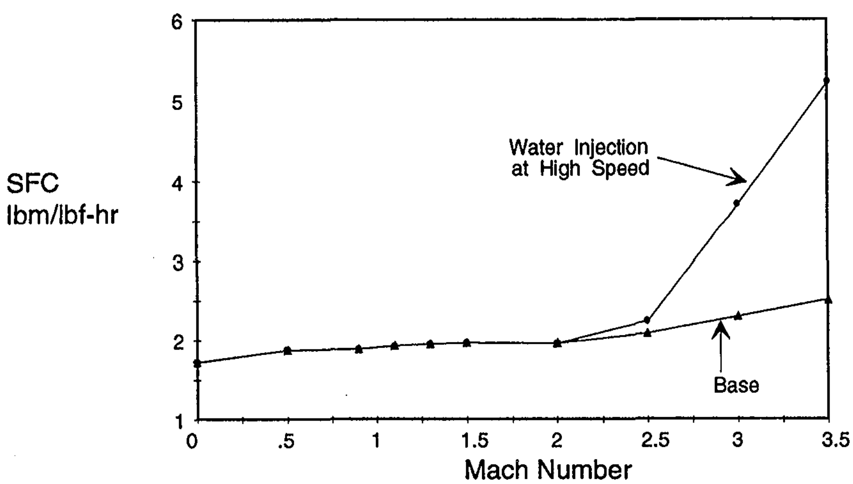

Figure 14. Effect of Water Injection at High Mach Numbers on SFC to Keep Mach 2.4 Conditions.

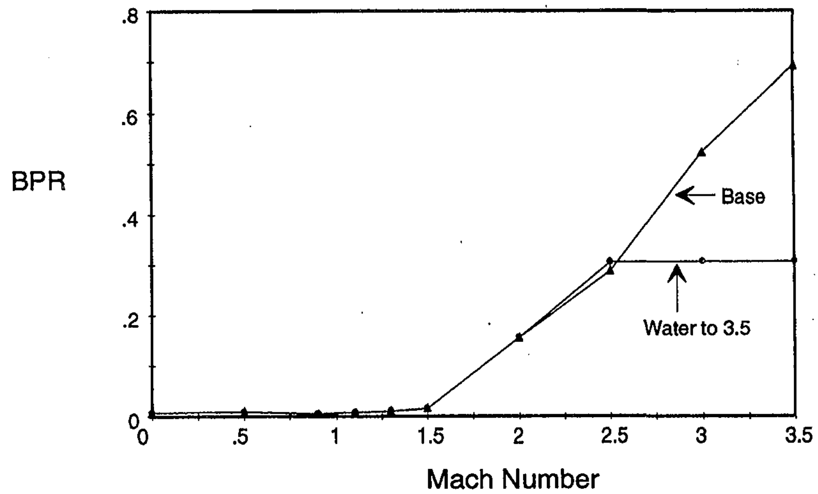

Figure 15. Effect of Water Injection at High Mach Number on the Variable Bypass Ratio to Keep Mach 2.4 Conditions.

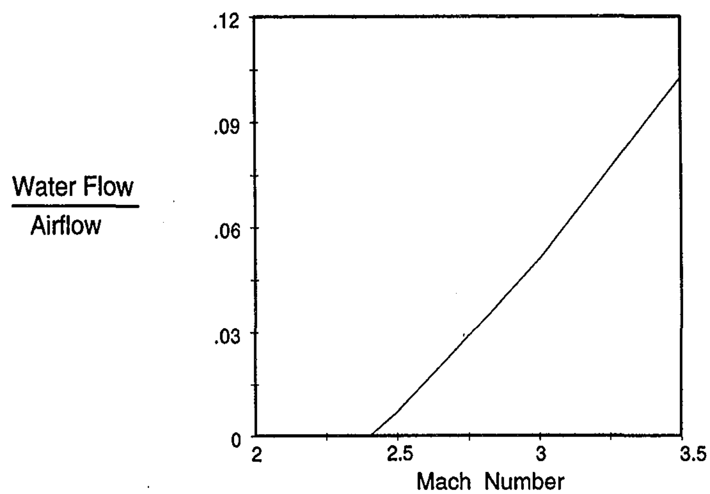

Figure 16. Amount of Water Required to Keep Mach 2.4 Temperatures at High Mach Numbers.

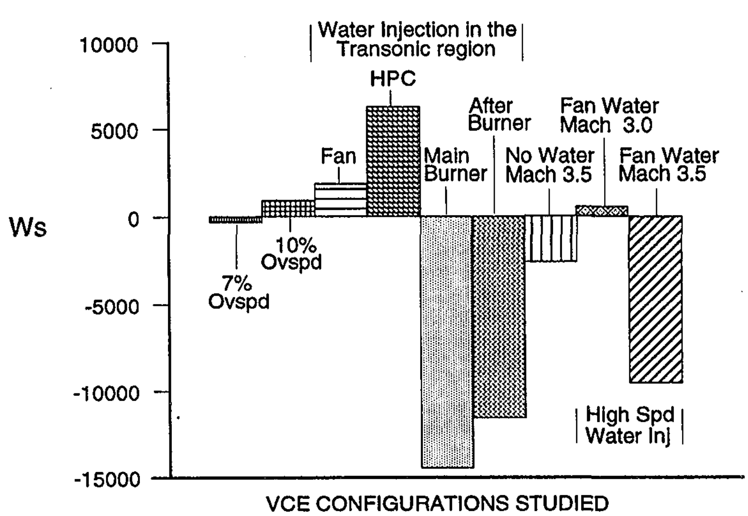

Figure 17. Change in Vehicle Staging Weight Relative to the Baseline Case for Each Configuration Studied.

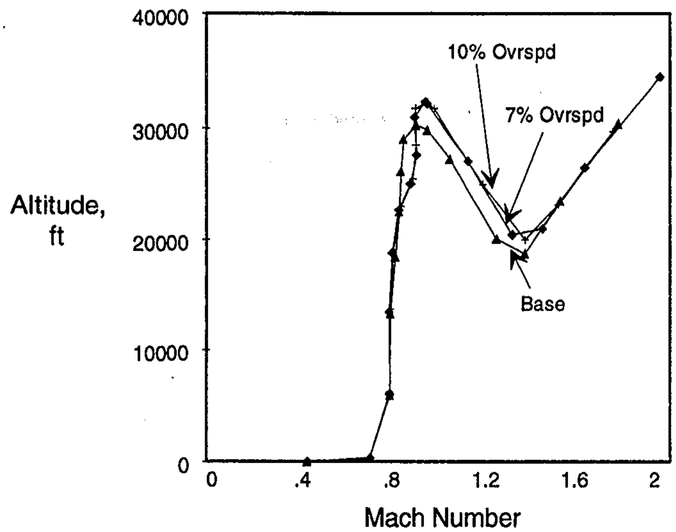

Figure 18. Flight Trajectory for Baseline and Overspeed Cases in the Transonic.

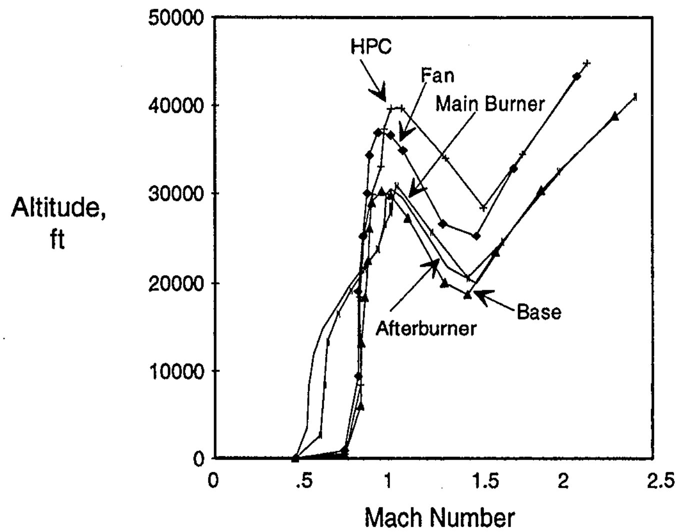

Figure 19. Flight Trajectory for Baseline and Water injection Cases in the Transonic.

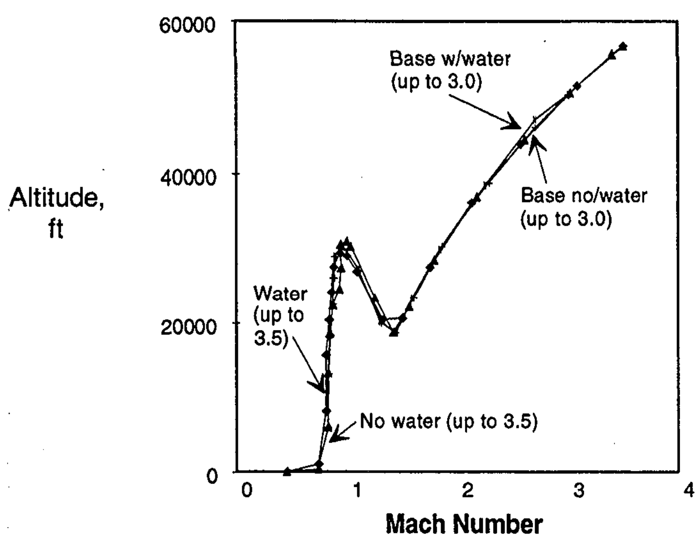

Figure 20. Flight Trajectory for Baseline and Water Injection Cases to Keep Mach 2.4 Conditions at High Speeds.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 1993	Technical Memorandum

4. TITLE AND SUBTITLE

Options for Thrust Augmentation for the Beta II Two-Stage-To-Orbit Launch Vehicle

5. FUNDING NUMBERS

WU-505-70-00

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
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8. PERFORMING ORGANIZATION REPORT NUMBER

E-8255

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM-106418

11. SUPPLEMENTARY NOTES

Responsible person, Kenol Jules, (216) 433-7016.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category 07

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A study to improve the performance of the NASA two-stage-to-orbit vehicle was undertaken. The NASA concept, a horizontal takeoff and landing, fully reusable, two-stage to orbit vehicle will be capable of launching and returning a 10,000 pound payload to a 100 nmi polar orbit. The vehicle, Beta II, is a derivative of the USAF/Boeing Beta vehicle which was designed to deliver a 50,000 pound payload to a similar orbit. Beta II stages at Mach 6.5 and about 100,000 feet altitude. The propulsion system for the booster is an over/under turbine engine/ramjet configuration. In this paper a study was performed for one of the candidate engines, the variable cycle engine, to assess its potential to meet the required performance needs of the Beta II vehicle. Several options for thrust augmentation were studied in order to improve the performance of the engine where there was a critical need. The methodology, constraints, propulsion performance and mission study results are presented.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Turbomachinery; Romjet; Airbreathing; Booster; Gas turbine engines; Mach number	15
	16. PRICE CODE
	A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

National Aeronautics and
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