NASA/TM—2013-218100

Lessons Learned During TBCC Design for the NASA-AFRL Joint System Study

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December 2013

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Prepared for the
58th Joint Army-Navy-NASA-Air Force (JANNAF) Propulsion Meeting
sponsored by the JANNAF Interagency Propulsion Committee
Arlington, Virginia, April 18–22, 2011

National Aeronautics and
Space Administration

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December 2013

Acknowledgments

The authors want to thank the Fundamental Aeronautics Program, Hypersonic management team for supporting this work and our efforts. The authors also wish to acknowledge the rest of the Boeing team: Marty Bradley, Dan Farrell, Matt Sexton, Josh Stengel, Deric Babcock for their contributions to this effort. The contracted part of this work was performed under NASA Contract no.: NNL08AA16B, Task Order no.: NNL08AB43T. The authors also extend our appreciation to David Witte (NASA Langley Research Center, the Technical Monitor for this contract) for his technical guidance and support, which allowed us to pursue some of the additional efforts that taught us so much.

This work was sponsored by the Fundamental Aeronautics Program
at the NASA Glenn Research Center.

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Abstract

NASA and the Air Force Research Laboratory are involved in a Joint System Study (JSS) on Two-Stage-to-Orbit (TSTO) vehicles. The JSS will examine the performance, operability and analysis uncertainty of unmanned, fully reusable, TSTO launch vehicle concepts. NASA is providing a vehicle concept using turbine-based combined cycle (TBCC) propulsion on the booster stage and an all-rocket orbiter. The variation in vehicle and mission requirements for different potential customers, combined with analysis uncertainties, make it problematic to define optimum vehicle types or concepts, but the study is being used by NASA for tool assessment and development, and to identify technology gaps. Preliminary analyses were performed on the entire TBCC booster concept; then higher-fidelity analyses were performed for particular areas to verify results or reduce analysis uncertainties. Preliminary TBCC system analyses indicated that there would be sufficient thrust margin over its mission portion. The higher fidelity analyses, which included inlet and nozzle performance corrections for significant area mismatches between TBCC propulsion requirements versus the vehicle design, resulted in significant performance penalties from the preliminary results. TBCC system design and vehicle operation assumptions were reviewed to identify items to mitigate these performance penalties. The most promising items were then applied and analyses rerun to update performance predictions. A study overview is given to orient the reader, quickly focusing upon the NASA TBCC booster and low speed propulsion system. Details for the TBCC concept and the analyses performed are described. Finally, a summary of "Lessons Learned" are discussed with suggestions to improve future study efforts.

Introduction

The Multi-Disciplinary, Analysis and Optimization (MDAO) discipline supporting the Hypersonics Project of the NASA Fundamental Aeronautics Program is tasked with identifying concepts and technologies that will enable safer, cheaper and more flexible access to space and high speed flight in the atmosphere. As part of that activity, MDAO must develop tools and techniques that analyze and assess these various concepts and technologies. Another integral function is defining different potential missions and vehicles that cover the solution space to best achieve the project goals. While exercising the various tools and techniques for vehicle and technology assessments, shortcomings in design methodologies and tools are exposed. Simultaneously, other potential mission, vehicle, and technology concepts are discovered. This process in not performed in a vacuum; working relationships are formed with industry, universities and other government agencies to share and advance our capabilities.

The Joint System Study (JSS) is a joint NASA/Air Force system study focused on Two-Stage-to-Orbit (TSTO) concepts. The Air Force supplied two vehicle concepts, both utilizing an all-rocket booster, one with a rocket orbiter, the other with a rocket-based combined-cycle (RBCC) orbiter. The NASA TSTO concept utilized a turbine-based combined-cycle (TBCC) booster and rocket orbiter. NASA and the Air Force agreed on common ground rules and assumptions, including developing a concept of

operations which would be used to assess development, refurbishment and life-cycle costs. Each group would perform an initial assessment of the other's concepts to highlight tool capabilities and limitations, and identify areas for joint efforts (tools, concept development, etc.). With the amount of uncertainty in technology assumptions and analysis capability, and with some understanding how that uncertainty can bias study results, NASA will not use this study to choose vehicle types or concepts. The overall focus for this exercise was tool assessment and development (including developing vehicle types and concepts) and identifying generic technology gaps.

This paper reports the work performed on the TBCC propulsion design, focusing on the low speed portion (up to Mach 3, where the air breathing propulsion transitions from gas turbine to ramjet/scramjet mode). Some background on the mission and NASA vehicle is given, quickly focusing on the low speed propulsion system. Initial assumptions used to develop baseline, uninstalled gas turbine engine performance and example engine performance are presented. Then the inlet and nozzle design concepts are introduced, leading to the higher fidelity analysis results. These analyses indicated a significant installation penalty from overexpansion losses on the low speed propulsion exhaust flow as well as the base drag from the single-expansion ramp nozzle (SERN) optimized for high speed performance. Under the given vehicle and propulsion constraints, various aspects of the low speed system design and high speed propulsion operation were reviewed to identify the most promising items to review further and possibly revise to mitigate installation penalties. That process led to some design and operational assumption changes; the higher fidelity tools were exercised again and these updated results are discussed. Finally, the "Lessons Learned" and "Summary" are presented to guide future efforts for better vehicle designs and operational concepts.

Results and Discussion

NASA TSTO Mission and Vehicle Concept

The NASA TSTO vehicle concept booster uses highly integrated air-breathing propulsion (with booster rocket assist as necessary) and an all-rocket orbiter. The baseline mission profile is shown in Figure 1. The launch vehicle concept is assumed to be unmanned, fully reusable and sized to deploy (or retrieve) a 20,000 lb payload to a 100×100 nmi., 28.5° inclination orbit.

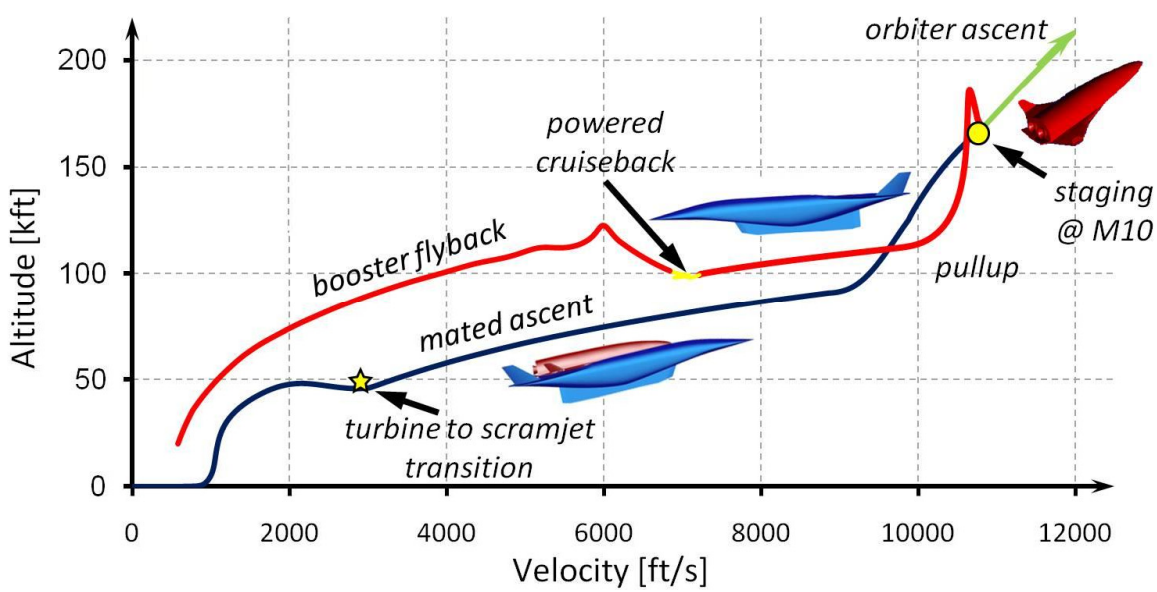

Figure 1.—NASA baseline TSTO mission profile.

Gas turbine engines are used for the mated ascent of the booster and orbiter, with booster rockets augmenting air breathing thrust for the takeoff and transonic push-through. At Mach 3, the air breathing propulsion system undergoes mode transition from gas turbine to ramjet/scramjet, which subsequently accelerates the vehicle to Mach 8. The booster rocket engines are then reignited for a pull-up maneuver to the staging point (to release the orbiter at its most advantageous state). The all-rocket orbiter proceeds to orbit. The booster makes a complex maneuver to recover from staging and returns to the launch site. The cruise-back is initially scramjet-powered with the final portion similar to the shuttle with a glide back to terminal area energy management and dead stick landing.

Figure 2 shows an image of the vehicle concept just after separation, noting that the upper surface of the booster vehicle is contoured for the orbiter shape to reduce drag effects while mated. Figure 3 is a top view of the booster, with some preliminary concepts for packaging of internal items. As shown in this figure, the booster volume is dominated by propellant. The low speed propulsion system is integrated above the high speed propulsion modules, which are located on the bottom of the booster vehicle.

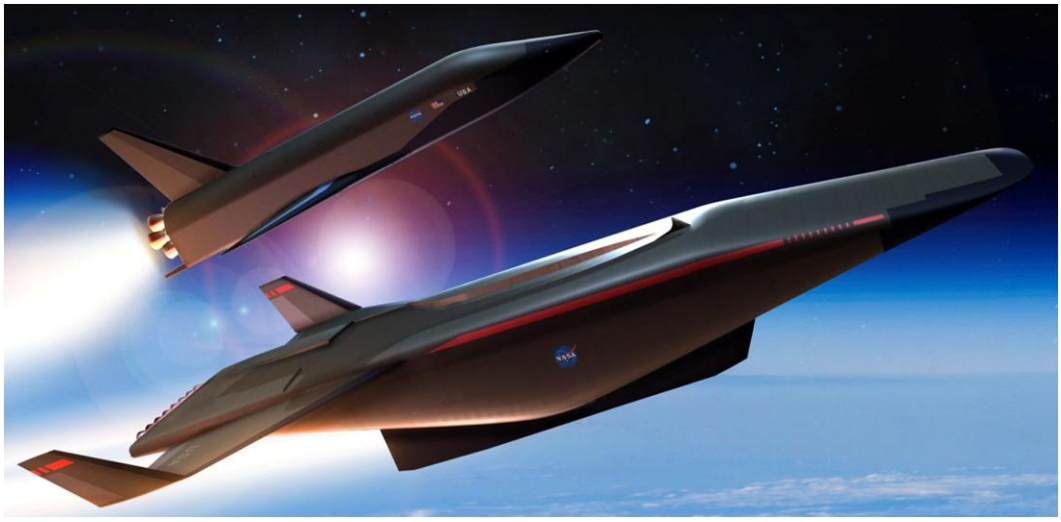

Figure 2.—NASA TSTO vehicle concept.

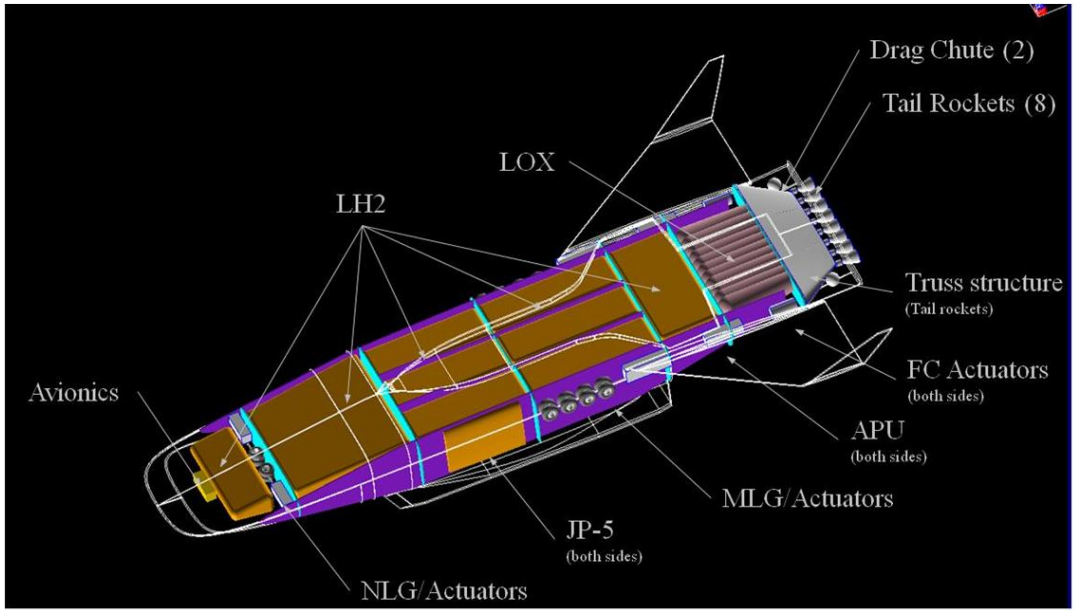

Figure 3.—Top view of booster.

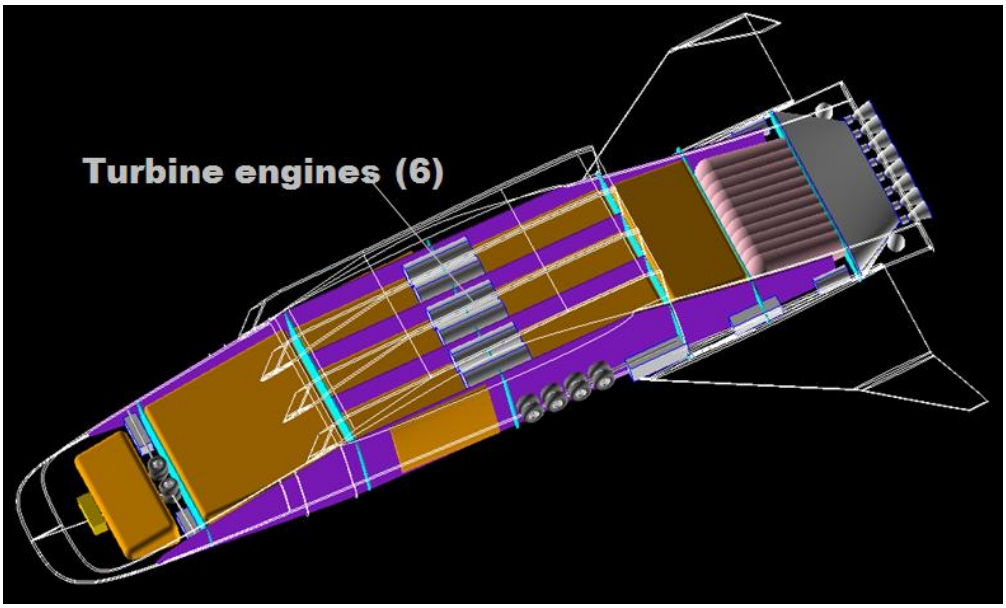

Figure 4.—Bottom view of booster.

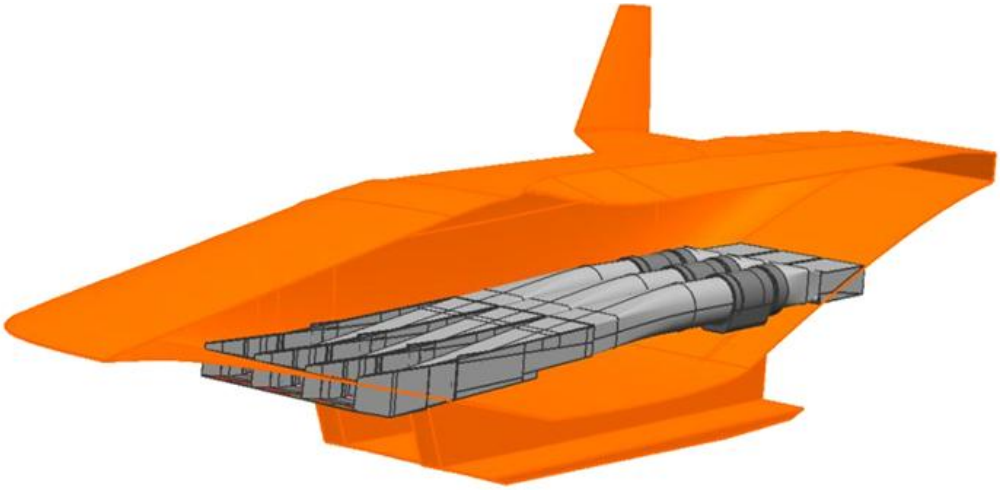

Figure 5.—Low speed propulsion conceptual design.

Figure 4 shows the booster from the bottom, indicating the ramjet/scramjet sidewalls of the high speed propulsion modules. These sidewalls extend into and partition the low speed propulsion area. Therefore the integration of the turbine engines includes constraining engine size to fit between the high speed module sidewalls and is covered later in this report. The overall air-breathing propulsion can be considered a variant of an over-under TBCC concept.

Low Speed Propulsion Concept

The major components of the low speed propulsion concept can be seen in Figure 5. The booster design was optimized for high speed propulsion performance where a significant portion of the first stage launch energy is supplied. The low speed system was then constrained on its booster location and size. The inlet concept incorporates mixed compression, variable geometry, and boundary layer bleed to provide efficient turbine airflow capture while maintaining operability margin. The inlet is highly integrated with the high-speed inlet and forebody. The nozzle concept also assumes variable geometry and is also highly integrated with the high-speed SERN.

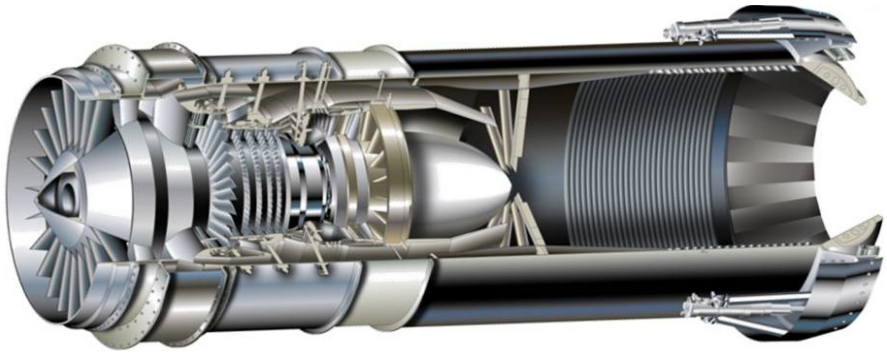

Figure 6.—Schematic of RTA-1 engine.

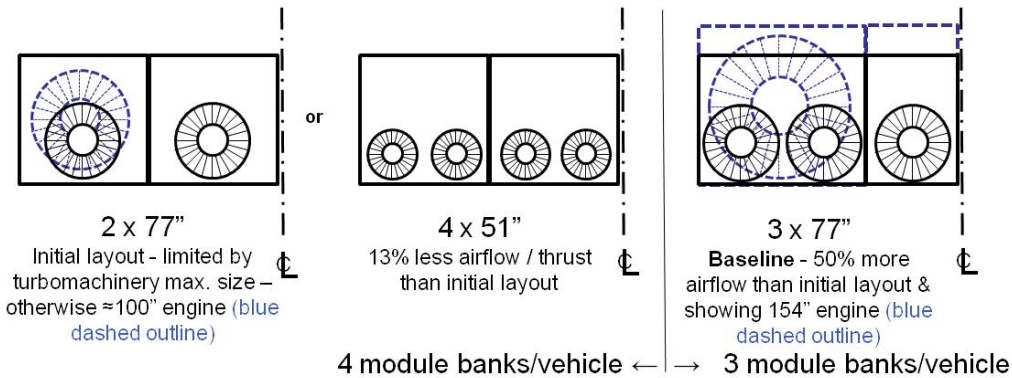

Figure 7.—Turbine engine packaging and sizing.

An advanced technology turbine engine was assumed, with the initial baseline engine being the Revolutionary Turbine Accelerator (RTA) (Ref. 1). A schematic of the RTA engine concept is shown in Figure 6. This is a high-thrust, high Mach-capable engine (versions of the RTA concept have good operating capabilities to Mach 4+). TBCC integration and sizing goals are (1) maximize TBCC thrust during the ascent/acceleration phase, (2) minimize booster rocket usage (while maintaining sufficient thrust and accelerations levels), and (3) meet vehicle packaging constraints (fit between the engine side walls for the high-speed ramjet/scramjet flow paths).

Initial Engine Packaging and Sizing

The gas turbine engine installation and sizing constraints were (1) the gas turbine engine had to fit between the high speed engine sidewalls, (2) turbine engine maximum diameter was limited to 80 in. (an assumed manufacturing size limitation), and (3) only a single row of turbine engines (could not have two rows of engines, to limit low speed flow path complexity and interactions). Various trades on engine size and packaging are shown in Figure 7. The initial booster propulsion design included four high speed propulsion modules per vehicle, which resulted in a total of four, 77 in. maximum diameter engines. Maximum available diameter of 80 in. results in a 77 in. engine to allow some minimal room for mounting and access. Trying to add two, smaller diameter engines, side by side in the duct, resulted in 14 percent less airflow. Conferring with the high speed propulsion designer, going from four to three high speed modules (across the bottom of the booster) was an acceptable design. This enabled the low speed system to include six, 77 in. maximum diameter gas turbines, a 50 percent increase in airflow and possibly thrust from the initial vehicle layout and was the baseline system. If turbine engine size limitations were relaxed, four, 100 in. diameter engines could be installed within the original booster concept that assumed four high speed propulsion modules. For the present study baseline booster with

three high speed propulsion modules, three 154 in. maximum diameter engines could be installed. The former increases airflow about 12 percent from the revised baseline. This is only a small gain, but potentially requires only a small improvement in turbomachinery technology. The latter option realizes a 100 percent increase in airflow from the revised baseline, but requires a much larger improvement in turbomachinery technology. These options were not pursued further during this study.

Initial Gas Turbine Engine Performance

Uninstalled turbine engine performance estimation is a combination of various factors, including inlet size and performance, engine cycle and size, and nozzle performance. It was assumed that the inlet design would be sized and operated to match engine airflow requirements. An additional inlet parameter for turbine engine performance is total pressure recovery (defined as the ratio of engine face total pressure to free stream total pressure). A modification to the inlet correlation from Billig (Ref. 2) was used, and is shown in Figure 8, with Mil Spec E-5007D as a reference. The recovery from the original correlation below Mach 1 was set to 0.95, based on experience with other inlet design efforts and previous study results for similar integrations.

Nozzle performance is highly dependent on its integration with the vehicle. For an initial estimate, nozzle velocity coefficient (ratio of actual to ideal nozzle exit velocity assuming expansion to ambient pressure) was derived from the work performed for a Mach 10 cruiser vehicle (Ref. 3) and is shown in Figure 9. The present booster concept is similar in shape to the Mach 10 cruiser.

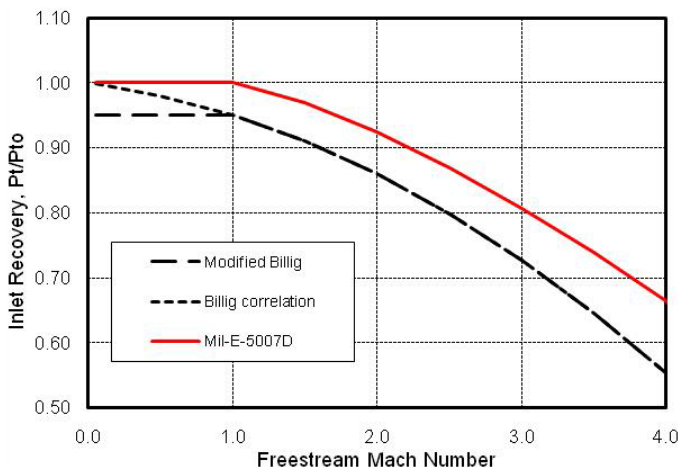

Figure 8.—Inlet recovery.

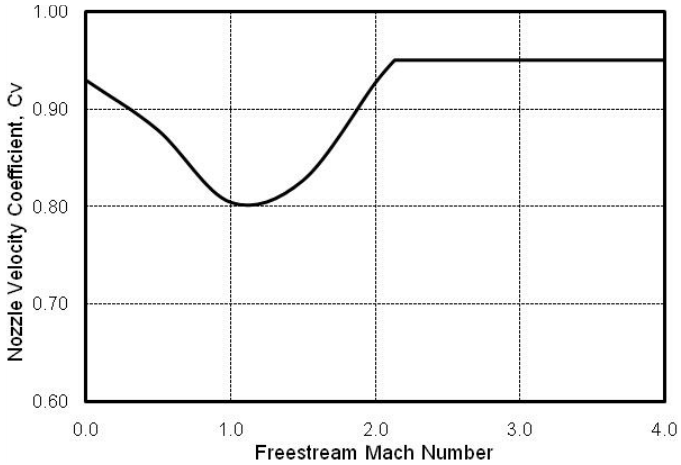

Figure 9.—Nozzle velocity coefficient.

The original plan was to generate engine performance for the RTA cycle using the model developed during the RTA project, but questions of proprietary data rights resulted in a generic, afterburning gas turbine model being generated from open data. The data from this model is representative of a RTA-class engine sized for this vehicle and can be shared by all. The generic model also enables modifications in some inlet, nozzle and engine parameters to be captured in the engine performance; but this model lacks capability to capture effects from additional parameters without further enhancement. Many external and internal engine parameters are available from this model. To illustrate the types of overall output at the baseline inlet and nozzle performance shown above, engine net thrust, net specific impulse and nozzle exit area per mass flow are shown in Figure 10, Figure 11, and Figure 12, respectively. These are plotted along lines of constant dynamic pressure (q, with units of pounds-force per foot (Ref. 2)). There are some expectations of reporting this model for more general use, but that is outside present project plans.

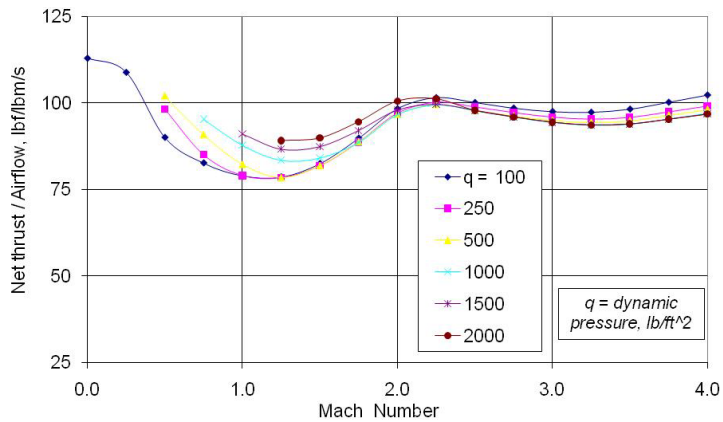

Figure 10.—Engine net thrust per airflow.

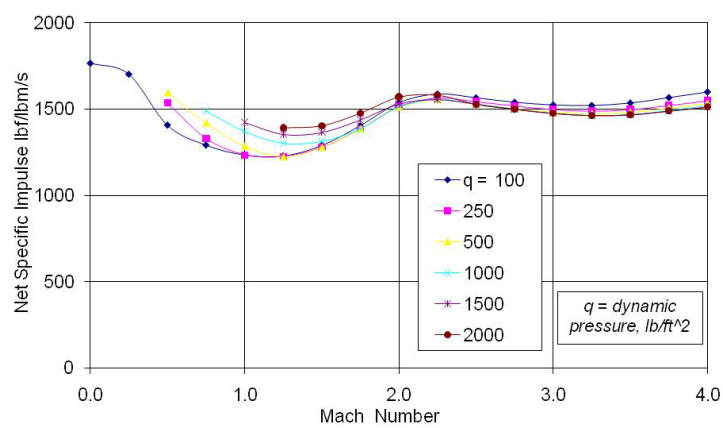

Figure 11.—Engine net specific impulse.

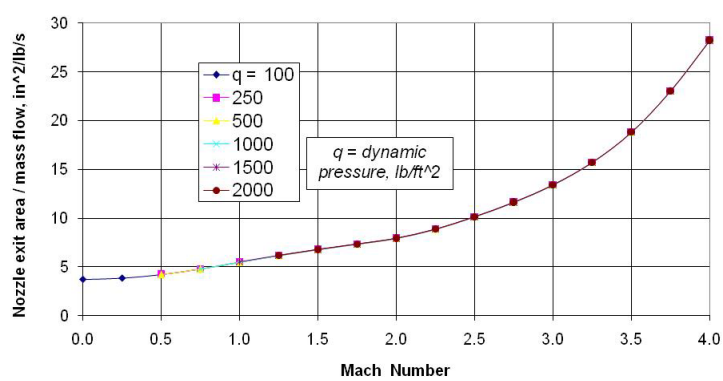

Figure 12.—Nozzle exit area per mass flow.

Current (2011) plans include developing an open, generic model for the RTA cycle that would be available for general distribution and integrated into the hypersonic analysis framework. The generic model will have the additional fidelity to enable engine component technology assessments and the inclusion of additional engine concepts.

Based on the initial booster vehicle size and geometry, low speed propulsion performance was generated and used for preliminary vehicle sizing and mission analyses. For this initial part of the study, in addition to thrust and drag forces from the low speed propulsion, it was assumed that adverse pressure fields on the booster lower surface would be minimal or could be easily mitigated (similar to results from the previous Mach 10 cruiser efforts). The booster rockets (essentially used to provide thrust for a pull-up maneuver and orient the orbiter for optimal separation conditions from the booster) were also used to provide some additional thrust from takeoff through transonic to maintain adequate thrust margin, as opposed to redesigning the low speed propulsion system. Based on initial performance assumptions, a "closed" vehicle design was achieved. Boeing Phantom Works was contracted to perform inlet and nozzle design, and provide higher fidelity analyses at particular flight points that would be used to calibrate lower fidelity analyses.

Inlet Design

The overall low speed inlet system is located internally above the high speed propulsion modules and their sub-systems. The low speed inlet door is highly integrated within the high speed forebody, to not adversely impact flow to the high speed propulsion modules when the low speed mode is not operating. The design and location of the low speed inlet includes many considerations and constraints. The higher and farther forward the inlet door is on the forebody, the greater the length, volume and weight required by the low speed propulsion system. But this also reduces the amount of flow turning and boundary layer growth for the flow captured by the low speed inlet, which reduces the amount of inlet bleed (and drag) and the amount of flow turning for turbine engine airflow (improving inlet performance, starting capability and operability). Conversely, positioning the low speed inlet door lower and farther aft on the forebody increases its interaction with the high speed inlet ramp, potentially disrupting the high speed propulsion airflow, especially during the critical propulsion mode transition from gas turbine to ramjet/scramjet. In addition, after the low speed inlet is closed, there are still heat loads and sealing requirements on the low speed inlet door. These requirements become more stringent as the low speed inlet door location is moved further aft on the booster forebody.

Boeing explored a few different inlet door concepts, including a traditional rotating flap design and a drawer concept (also called a translating scoop), as shown in Figure 13. The rotating flap concept was deemed impractical considering the required flap length to get a reasonable flow turning angle and minimizing the disruption of flow aft of the low speed inlet along the vehicle forebody and into the high speed system. The drawer concept was chosen for further design and analysis.

To provide the required capture, the drawer translates forward and down, as shown in Figure 14. This design maintains reasonable inlet turning angles and flow quality to the low speed inlet, while minimizing flow disruption aft of the low speed inlet. When closed, the drawer concept maintains the desired forebody shape and angles optimized for the high speed propulsion system.

Nozzle Design

The low speed nozzle design is highly integrated within the ramjet/scramjet SERN and is shown in Figure 15. Each turbine engine has its own individual nozzle, which starts with a circular to rectangular transition section. The upper nozzle surface is fixed and contoured such that the rotating lower body flap gives some variation for the nozzle throat; although throat area only varies by 30 percent over its expected Mach 0 to 3.5 speed range. The design is short and limits the amount of surface area subjected to the hot turbine exhaust flow, but there is still sufficient length to achieve good flow, variable geometry and performance qualities.

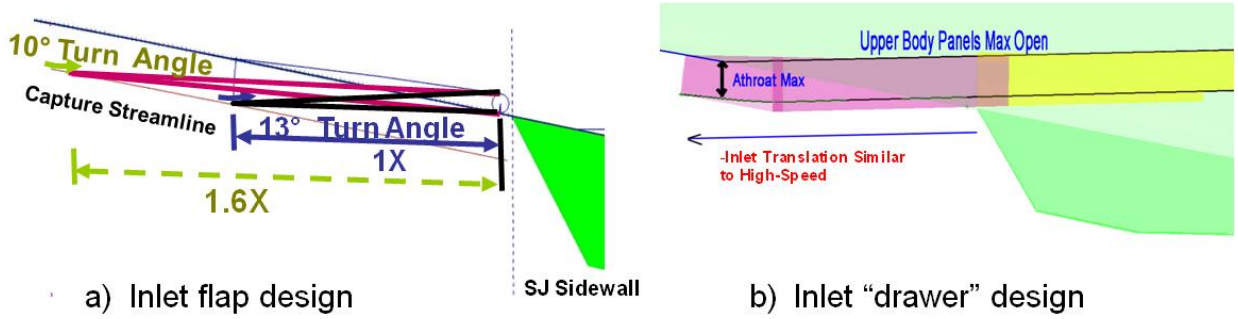

Figure 13.—Low speed inlet design concepts.

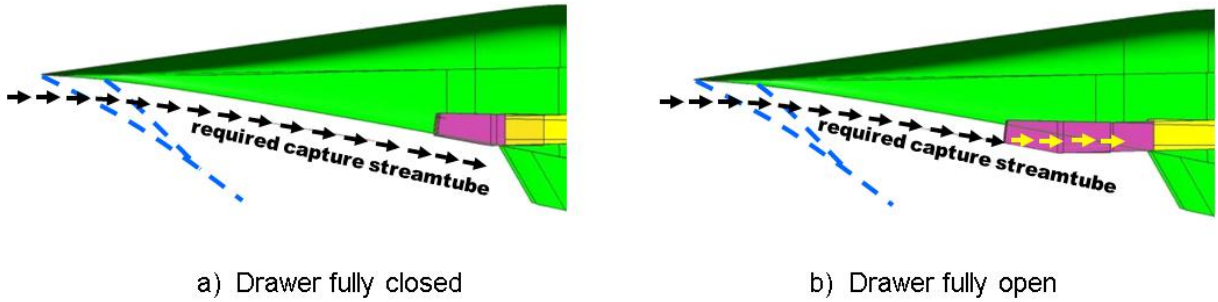

Figure 14.—Inlet drawer translation.

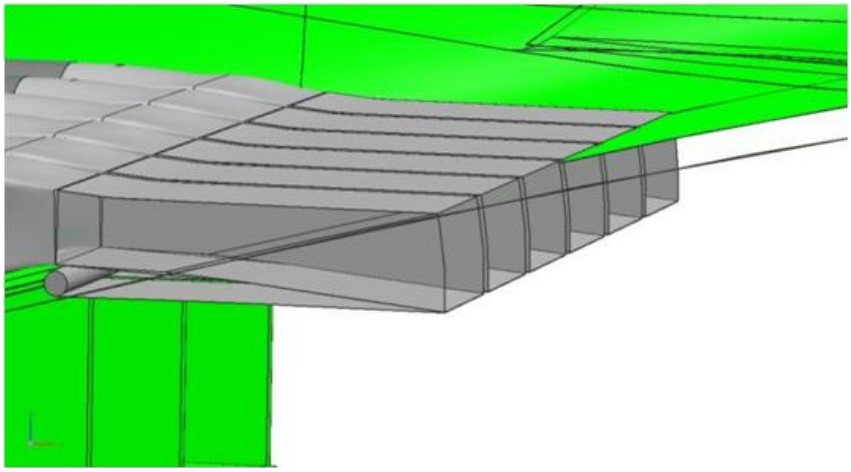

Figure 15.—Low speed nozzle schematic.

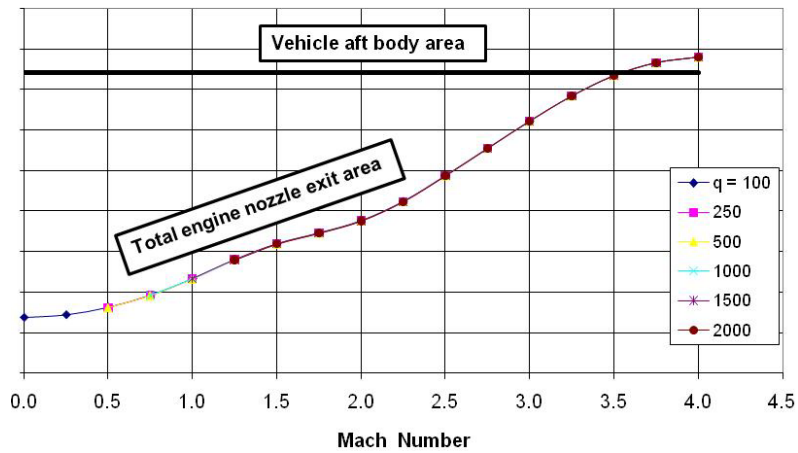

Figure 16.—Total engine nozzle area versus vehicle aft body.

Initial Higher Fidelity Analyses

As opposed to earlier study results for the Mach 10 cruiser, initial transonic CFD analyses for the booster showed significant overexpansion of the low speed propulsion exhaust flow. There was minimal flow separation or ambient flow expanding into the SERN that would alleviate large regions significantly below ambient pressure. These large, sub-ambient pressure regions result in significant drag forces and adverse vehicle moments during the low speed portion of the vehicle ascent. Much larger amounts of rocket assist were required during mission and sizing analyses to meet acceleration requirements than were initially assumed. This can be partially explained by the mismatch of low speed nozzle area required versus the SERN or vehicle aft body area, as shown in Figure 16. These effects can also be attributed to constraints put on the low speed propulsion design that were not realized during the preliminary, lower fidelity analyses. Since there was not time or resources for a major vehicle redesign, the design and operational assumptions were reviewed to identify potential solutions for this issue.

Engine Airflow Sizing

Review of the engine design found that it was based on using available engine components to build a test article for the RTA program. The engine face diameter (which determines airflow) was 57 in., but engine maximum diameter (which sets the limit for engine size) was 70 in. This is an engine face to maximum diameter ratio of 0.81. Previous study and actual engine designs suggests that internal rearrangement could reasonably enable an engine face to maximum diameter ratio up to 0.95. Such rearrangement would result in some small increase in engine length, but engine length was not limiting in this concept. Applying the 0.95 ratio of engine face to maximum diameter increases turbine engine airflow (and preliminary thrust capability) by 37 percent. Further increases in engine airflow capability were reviewed, but appeared to be at the limit of technology available within the study ground rules and assumptions. Vehicle operation was reviewed to determine if other options might be included to improve performance before the higher fidelity analyses were rerun with the increased airflow capability.

Operational Trades

Another potential option to improve performance is to configure the high speed flow path such that it mitigates some of the adverse pressure fields around the vehicle by filling some of the large SERN area, especially during transonic ascent. Previous studies (including Ref. 3) realized best vehicle performance by closing the high speed system until close to its operational regime; this was the baseline assumption for this study. This booster vehicle has a much smaller ratio of low to high speed propulsion system size and greater booster height than that study. The low speed exhaust is over-expanded for much of the low

TABLE 1.—DESIGN MATRIX OF HIGH SPEED INLET AND NOZZLE RAMP POSITIONS

Inlet ramp	Nozzle ramp	Result
Fully closed (baseline)	Fully open (baseline)	Baseline, large base drag.
Mid open	Fully open (baseline)	Insufficient inlet flow to fully pressurize upper nozzle ramp, nozzle ramp blocking some ambient flow that could help adverse pressure relief.
Mid open	Mid open	Realizes optimal improvement in forces and moments for cases and conditions considered.
Fully open	Fully open (baseline)	Insufficient internal flow area to pass all inlet flow captured. Large high speed inlet spillage can disrupt low speed inlet flow. Nozzle ramp blocking some ambient flow that could help adverse pressure relief.

speed propulsion operating region, filling only a portion of the aft surface, with the remainder at significantly less than ambient pressure. This results in a large adverse force and moment that is not captured with the initial, lower fidelity methods.

Table 1 includes the design matrix of high speed inlet and nozzle ramp positions that Boeing analyzed at the transonic condition with 2-D CFD to suggest ways to use the high speed inlet and nozzle ramps along with the rest of the high speed flow path to improve performance.

Opening the high speed inlet mid way introduces additional flow into the aft region which relieves some of the adverse pressure gradients on the aft surface as well as changes the amount and direction of the force on the high speed inlet ramp. But the high speed design has only limited internal flow capability and opening the high speed inlet further actually penalizes the forebody without significant aft body force and moment improvements. The baseline position of the high speed nozzle ramp (fully open) is blocking ambient flow from expanding into the aft region and mitigating some of the adverse forces and moments. Closing the nozzle ramp mid way would require additional actuation that is not in the baseline design, but should be straightforward to implement. The surrounding pressure fields tend to force the nozzle ramp toward closure when the low speed exhaust flow is over-expanded. Closing the high speed nozzle ramp further might direct flow further along the aft body, but would require additional actuation authority and would increase the adverse forces on the high speed nozzle ramp. The cases analyzed were not exhaustive, but suggest there is an optimum high speed system arrangement that could mitigate much of the adverse forces and moments noted if sufficient tools, methodologies and resources were available. These deficiencies are presently being addressed from multiple directions, but that will not be covered in this paper.

Low Speed System Location

The low speed inlet and nozzle locations were also reviewed for possible improvements to low speed system performance and volume. The low speed inlet was assumed further aft along the forebody, positioning the inlet lower and further back on the vehicle. The low speed nozzle was brought further forward along the SERN, positioning the low speed nozzle lower and further forward on the vehicle. This resulted in a significant reduction in low speed propulsion length. The preliminary review suggested minimal aerodynamic and performance improvements for the low speed propulsion from moving the low speed inlet and nozzle elements, but significantly lower flow quality for the high speed inlet when both where operating. Under some conditions, interactions from the high and low speed inlets would unstart both inlets. From a packaging perspective, the configuration change did reduce the volume required by the low speed propulsion system. However, the need to relocate various high speed propulsion subsystem components and hydrogen flow lines resulted in a net increase of total propulsion volume required in the booster and the access for servicing appeared to be significantly compromised. It was also unclear if such shortening of the internal inlet diffuser would allow enough length to mix out low speed inlet flow distortions for required turbine engine face airflow quality. As tools and methodologies improve and computational speeds increase, it will be beneficial to revisit these configuration changes to identify possible design improvements.

External Burning

Reference 4 suggests that external burning can also mitigate some of the adverse forces and moments during the critical transonic and low supersonic portion of the ascent. Boeing estimated the hydrogen flow required and performed CFD to verify the efficacy of external burning for adverse force alleviation and thrust improvement. These results suggest that overexpansion losses could be mitigated and the aft body pressures increased to near or even above ambient pressure levels with "reasonable" hydrogen flow rates. The biggest improvements are observed around transonic conditions, where the losses are most severe. During the external burning calculations, credit for aft body pressure rise was limited to ambient pressure, providing full mitigation of overexpansion losses. Not allowing pressure to rise above ambient (and therefore generating additional thrust) should be conservative. The simplified methods for external burning can easily be added to the lower fidelity analyses to remove the adverse forces and moments on the aft surface that are presently not included in the lower fidelity analyses. This would assume that hydrogen fuel is available and such an option is allowable by study ground rules. A limitation to such an approach is that it might replace design iterations or tool development that could lead to improved methodologies and, operational and vehicle design concepts.

Lessons Learned

Many lessons were learned by the JSS team during this study. Designing a hypersonic vehicle involves complex interactions among the many candidate designs, operational modes and components. Coordination of the low and high speed designs and their operational capabilities is important to achieve design study objectives. Lower fidelity methods may not capture interactions among these different components and their operational capabilities, which can lead to designs that have significant deficiencies and would have teams attempting to revise designs and assumptions to meet objectives with inadequate tools. Using previous study results for similar (but still different) hypersonic vehicles can lead the system designers astray, especially if they lead to ground rules or assumptions that might have been valid or useful before, but not as applicable to the new design and mission. Missed or forgotten, detailed component information can also lead the system analysts and designers to not fully realize the performance potential of critical subsystems. Higher fidelity CFD can reveal a lot of additional detail about how the systems actually perform and interact. These analyses can also show how some changes, including seemingly minor one, can achieve significant benefits. This is balanced by the significantly greater resources presently required to use high fidelity CFD tools to accurately capture these effects.

Summary and Conclusions

A joint system study between NASA and the Air Force is underway to review TSTO vehicle concepts. For NASA, this effort is focused on technology assessment and revealing gaps in technologies, methodologies and tools, not vehicle or concept selection. The baseline vehicle and mission concepts have been described, focusing on the booster and more specifically the low speed propulsion concept, its component attributes, design efforts, and performance. Initial, lower fidelity analyses indicated sufficient performance margins; however, subsequent higher fidelity analyses (including propulsion—vehicle interaction effects), resulted in performance shortfalls. Design and operational assumptions were reviewed and several items chosen for implementation and re-analysis which indicated pathways to mitigate the performance shortfalls. "Lessons Learned" during the study are presented here to educate the reader (and as a reference for the analysts) of details to include in future efforts, and moreover to avoid these same pitfalls.

This study notes that there is still a large analysis gap between the lower and higher fidelity tools. The lower fidelity tools enable system analysts to quickly perform a large number of iterations and screen potential concepts. The higher fidelity tools require significantly more detailed information (which takes time to gather and configure) and computational resources to run. For many systems, the interactions truly

are isolated and the lower fidelity analyses are sufficient to capture the most salient design features. However, for hypersonic, air-breathing systems, the interactions are crucial to the design and ways need to be found to include these interactions with greater fidelity earlier in the process. Efforts continue to integrate these different fidelity tools to facilitate the information transfer and to balance design complexity versus required design iterations (among other factors). This effort has indicated some areas where additional resources need to be applied.

Future Work

Further details and results for the JSS study are yet to be reported, as well as further details regarding some of the analyses included or referenced here. The generic turbine engine model is available for distribution and use, but it's limitations on applicability suggest it is only an interim solution. A government model for the RTA cycle is underway for incorporation this fiscal year within the hypersonic analysis framework, and will have increased capabilities for additional engine cycles, including more detail or analyses for the individual components. It is planned to include significant documentation on background and assumptions to guide users to apply it correctly, which is a concern for any tool or study. Part of NASA's focus on methodology and tool development is to be able to assess any technology or vehicle concept—which is truly a noble goal. There are various activities underway that will facilitate applying higher-fidelity analyses. These efforts include automated mesh and grid generation, improved inlet and nozzle methodologies and tools for the low speed portion, etc.; which are especially relevant as computing resources continue to evolve and improve.

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REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

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1. REPORT DATE *(DD-MM-YYYY)* 01-12-2013	**2. REPORT TYPE** Technical Memorandum	**3. DATES COVERED** *(From - To)*
4. TITLE AND SUBTITLE Lessons Learned During TBCC Design for the NASA-AFRL Joint System Study		**5a. CONTRACT NUMBER** **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S) Snyder, Christopher, A.; Espinosa, A.M., (Jose)		**5d. PROJECT NUMBER** **5e. TASK NUMBER** **5f. WORK UNIT NUMBER** WBS 599489.02.07.03.09.11.01
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191		**8. PERFORMING ORGANIZATION REPORT NUMBER** E-18815
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001		**10. SPONSORING/MONITOR'S ACRONYM(S)** NASA **11. SPONSORING/MONITORING REPORT NUMBER** NASA/TM-2013-218100

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category: 07
Available electronically at http://www.sti.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 443-757-5802

13. SUPPLEMENTARY NOTES

14. ABSTRACT

NASA and the Air Force Research Laboratory are involved in a Joint System Study (JSS) on Two-Stage-to-Orbit (TSTO) vehicles. The JSS will examine the performance, operability and analysis uncertainty of unmanned, fully reusable, TSTO launch vehicle concepts. NASA is providing a vehicle concept using turbine-based combined cycle (TBCC) propulsion on the booster stage and an all-rocket orbiter. The variation in vehicle and mission requirements for different potential customers, combined with analysis uncertainties, make it problematic to define optimum vehicle types or concepts, but the study is being used by NASA for tool assessment and development, and to identify technology gaps. Preliminary analyses were performed on the entire TBCC booster concept; then higher-fidelity analyses were performed for particular areas to verify results or reduce analysis uncertainties. Preliminary TBCC system analyses indicated that there would be sufficient thrust margin over its mission portion. The higher fidelity analyses, which included inlet and nozzle performance corrections for significant area mismatches between TBCC propulsion requirements versus the vehicle design, resulted in significant performance penalties from the preliminary results. TBCC system design and vehicle operation assumptions were reviewed to identify items to mitigate these performance penalties. The most promising items were then applied and analyses rerun to update performance predictions. A study overview is given to orient the reader, quickly focusing upon the NASA TBCC booster and low speed propulsion system. Details for the TBCC concept and the analyses performed are described. Finally, a summary of "Lessons Learned" are discussed with suggestions to improve future study efforts.

15. SUBJECT TERMS
Turbine engine; Systems analysis

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk (email:help@sti.nasa.gov)
U	U	U	UU	20	19b. TELEPHONE NUMBER *(include area code)* 443-757-5802