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Testing of the NASA Hypersonics Project's Combined Cycle Engine Large Scale Inlet Mode Transition Experiment (CCE LIMX)

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Abstract

The NASA Fundamental Aeronautics Hypersonics project is focused on technologies for combined cycle, air-breathing propulsions systems to enable highly reliable reusable launch systems for access to space. Turbine Based Combined Cycle (TBCC) propulsion systems offer specific impulse (I_{sp}) improvements over rocket-based propulsion systems in the subsonic takeoff and return mission segments and offer improved safety. The potential to realize more aircraft-like operations with expanded launch site availability and reduced system maintenance are additional benefits.

Among the most critical TBCC enabling technologies as identified in the National Aeronautics Institute (NAI) study were: 1) mode transition from the low speed propulsion system to the high speed propulsion system, 2) high Mach turbine engine development and 3) innovative turbine based combined cycle integration.

To address these key TBCC challenges, NASA's Hypersonics project (TBCC Discipline) initiated an experimental mode transition task that includes an analytic research endeavor to assess the state-of-the-art of propulsion system performance and design codes. This initiative includes inlet fluid and turbine performance codes and engineering-level algorithms. This effort has been focused on the Combined-Cycle Engine Large Scale Inlet Mode Transition Experiment (CCE LIMX) which is a fully integrated TBCC propulsion system with flow path sizing consistent with previous NASA and DoD proposed Hypersonic experimental flight test plans. This experiment is being tested in the NASA Glenn Research Center 10- by 10-ft Supersonic Wind Tunnel (SWT) Facility. The goal of this activity is to address key hypersonic combined-cycle engine issues: (1) dual integrated inlet operability and performance issues—unstart constraints, distortion constraints, bleed requirements, controls, and operability margins, (2) mode-transition sequence elements caused by the switch between the turbine and the ramjet/scramjet flow paths (imposed variable geometry requirements), (3) turbine engine transients (and associated time scales) during transition. The model will be tested in four test phases to develop a unique TBCC database to validate design and analysis tools and address operability, integration, and interaction issues for this class of advanced propulsion systems. The test article installation and facility build-up/preparation was completed and the inlet performance and operability characterization testing commenced on March 7, 2011. The major upcoming events of this activity include:

- Phase I: Parametric inlet characterization testing completed—2nd QTR 2011
- Phase II: Inlet system identification tests completed—3rd QTR 2011
- Phase III: Controlled mode transition with simulated engines demonstrated—3rd QTR 2012
- Phase IV: Controlled mode transition with turbine engine demonstrated—3rd QTR 2013

In this paper we will discuss the following: 1) research objectives addressing TBCC enabling technologies, 2) features of the CCE hardware design which provide a unique TBCC mode transition data

base, 3) experimental procedures and test plans including a discussion of the facility and instrumentation, and 4) a status of the parametric inlet characterization testing.

Introduction

The “National Aeronautics Research and Development Policy” (Ref. 1) document, issued by the National Science and Technology Council in December 2006, stated that one (among several) of the guiding objectives of the federal aeronautics research and development endeavors shall be stable and long-term foundational research efforts. Nearly concurrently, the National Academies issued a more technically focused aeronautics blueprint, entitled: the “Decadal Survey of Civil Aeronautics—Foundations for the Future” (Ref. 2). Taken together these documents outline the principles of an aeronautics maturation plan. Thus, in response to these overarching inputs (and others), the National Aeronautics and Space Administration (NASA) organized the Fundamental Aeronautics Program (FAP), a program within the NASA Aeronautics Research Mission Directorate (ARMD). The FAP initiated foundational research and technology development tasks to enable the capability of future vehicles that operate across a broad range of Mach numbers, inclusive of the subsonic, supersonic, and hypersonic flight regimes.

The FAP Hypersonics Project concentrates on two hypersonic missions: (1) Air-breathing Access to Space (AAS) and (2) the (Planetary Atmospheric) Entry, Decent, and Landing (EDL). The AAS mission focuses on Two-Stage-To-Orbit (TSTO) systems using “air-breathing” combined-cycle-engine propulsion; whereas, the EDL mission focuses on the challenges associated with delivering large payloads to (and from) Mars. So, the FAP Hypersonic Project investments are aligned to achieve mastery and intellectual stewardship of the core competencies in the hypersonic-flight regime, which ultimately will be required for practical systems with highly integrated aerodynamic/vehicle and propulsion/engine technologies. Within the FAP Hypersonics, the technology management is further divided into disciplines including one targeting Turbine-Based Combine-Cycle (TBCC) propulsion. Additionally, to obtain expertise and support from outside (including industry and academia) the hypersonic uses both NASA Research Announcements (NRA’s) and a jointly sponsored, Air Force Office of Scientific Research and NASA, National Hypersonic Science Center that are focused on propulsion research. Finally, these two disciplines use selected external partnership agreements with both governmental agencies and industrial entities.

The TBCC discipline is comprised of analytic and experimental tasks, and is structured into the following two research topic areas: (1) TBCC Integrated Flowpath Technologies, and (2) TBCC Component Technologies. These tasks will provide experimental data to support design and analysis tool development and validation that will enable advances in TBCC technology.

Benefits of TBCC Propulsion

NASA’s Fundamental Aeronautics Program is investigating turbine-based propulsion systems for access to space. TBCC propulsion provides the potential for aircraft-like, space-launch operations that may significantly reduce launch costs and improve safety due to their following characteristics:

1. Turbine-based propulsion systems exhibit significant specific impulse (I_{sp}) improvements over rocket-based propulsion systems in the subsonic takeoff and return mission segments, see Figure 1.
2. Turbine-based systems can mitigate mission risk by providing operational flexibility for all-weather launch, take-off and landing cross-range, powered landing and abort scenarios.
3. Turbine engines afford dual-use capability, adequately serving low speed accelerator missions as well as long range cruise missions.
4. Performance growth margin for TBCCs can be inherently designed for the system, yielding a robust propulsion package that is able to change with mission requirements.

TBCC propulsion for hypersonic applications requires high Mach turbine engines to accelerate the vehicle to scramjet takeover speeds. Major challenges are to develop a turbine accelerator with near Mach 4 capabilities and develop a scramjet with a low ignition speed ($M < 4$) to enable transition from the low speed to high speed propulsion system. A long term challenge is to understand and design to minimize propulsion system dry weight which can counterbalance the predicted I_{sp} (wet weight) benefit.

TBCC Enabling Technologies

The most critical TBCC enabling technologies as identified in the National Institute of Aerospace study (Ref. 3) were: 1) mode transition from the low speed propulsion system to the high-speed propulsion system, 2) high-Mach turbine engine development, 3) transonic aero-propulsion performance, 4) low-Mach-number dual-mode scramjet operation, 5) Innovative three dimensional flowpath concepts and 6) Innovative turbine-based combined-cycle integration. A further breakout of these TBCC enabling technology challenges are identified in Figure 2.

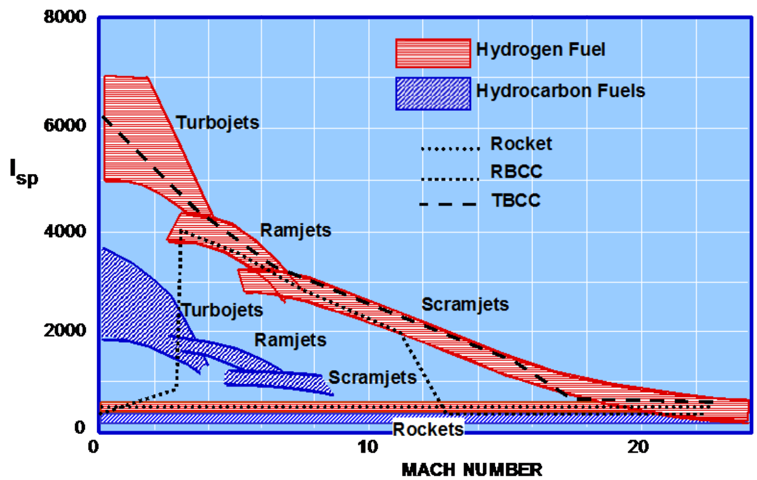


Figure 1.—Comparison of specific impulse for turbine-based and rocket-based propulsion systems.

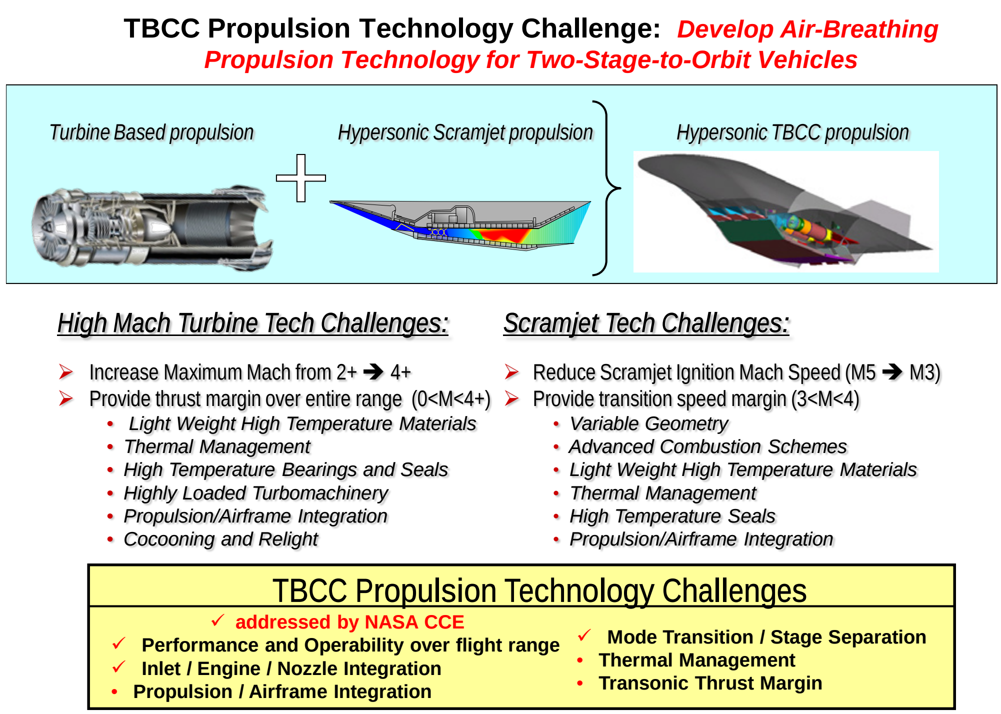
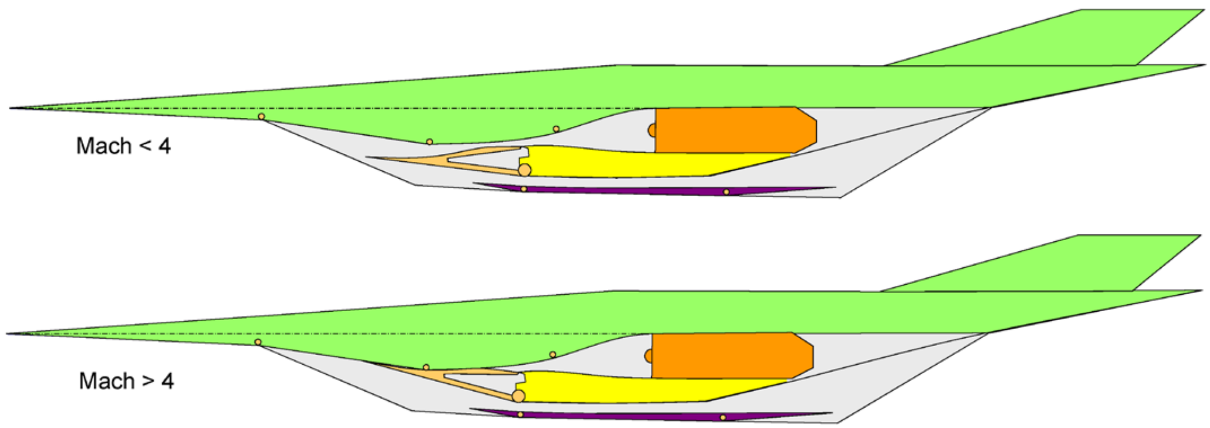
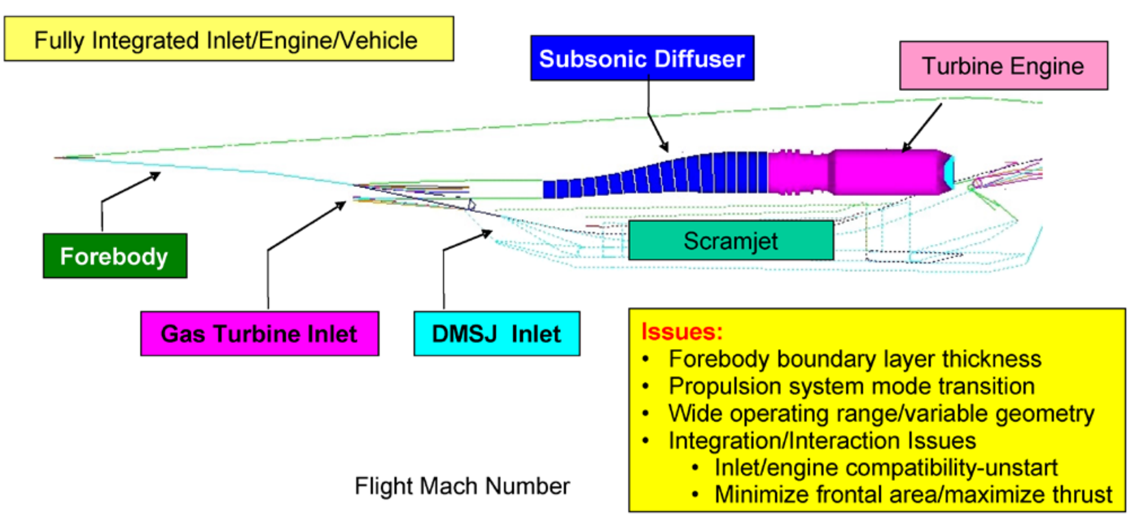


Figure 2.—Technologies to enable TBCC propulsion for access to space vehicles.

Based on the Next Generation Launch Technology (NGLT) studies (Ref. 4), an over-under TBCC system (turbine engine over ram/scramjet) was selected as the reference vehicle configuration for a TBCC TSTO space access by the NASA FAP Hypersonics MDAO (Multidisciplinary Design and Analysis Optimization) discipline. The over-under TBCC configuration and challenges associated with this configuration are illustrated in Figure 3. This present study investigates a two-dimensional inlet concept designed (Ref. 5) with a mode transition Mach number of 4 and a top end Mach number of 7. The goals of the activity are to address key hypersonic combine-cycle engine issues: (1) the operating constraints of a high-temperature turbine and a dual mode scramjet engine (specific to the TBCC), (2) dual integrated inlet operability and performance issues including unstart constraints, inlet flow distortion effects, bleed requirements and controls characterization, and operability margins, and (3) mode-transition constraints imposed by the turbine and the ramjet/scramjet flow paths (imposed variable geometry requirements). The near term emphasis is to understand, demonstrate, and control the mode transition between the low speed turbine engine and the dual-mode ram/scramjet engine for a relevant TBCC over/under propulsion configuration. This requires a comprehensive understanding of the integrated inlet characteristics and the inlet/engine/nozzle interactions to model and predict the behavior of the TBCC propulsion system. In the subsequent sections we will summarize the specific TBCC research objectives/questions related to integrated flowpath technology, inlet/engine integration, and mode transition between the turbine and dual mode ram/scramjet engines.



(a)



(b)

Figure 3.—Over-under configuration serves as NASA's TBCC TSTO reference vehicle for MDAO. (a) Operating configuration before and after mode transition. (b) Features of the propulsion system.

Integrated Inlet Technology

Military Specification (Mil-spec) inlet performance, as measured by total pressure recovery, can be achieved for an inlet carefully designed for single point operation. However for a TBCC system, the inlet must operate over a wide range of flight conditions and distribute the flow with acceptable distortion and unsteadiness to both the turbine engine as well as the dual mode ram/scramjet engine. Common practice is to use variable geometry and designed bleed configurations to enable a wide range of inlet operability and meet performance requirements including maximizing pressure recovery and minimizing flow spillage. However, this added complexity to achieve high performance and operability results in additional weight, complex vehicle integration, and an increase in drag. Figure 4 illustrates that the inlet pressure recovery can vary by a factor of 4X (assuming Mil-spec can be achieved over the Mach flight range) depending on the inlet complexity. Component performance levels (such as total pressure recovery) are used in system trade studies for each vehicle configuration and mission such as air-breathing access to space (AAS). To this end, NASA is focusing on the development of validated design and analysis tools as well as parametric databases which are required to perform these system trade studies.

Specific questions related to integrated inlet technology addressed by the inlet performance and characteristic (Phase I) testing of the Combined Cycle Engine Large Scale Inlet Mode Transition Experiment (CCE LIMX) include:

- Is Mil-Spec performance achievable over the wide operating range that is required for TBCC space access?
- Can design and analysis tools reliably predict inlet performance and operability?
- What is the trade-off between bleed and inlet performance/operability?
- Can design and analysis tools adequately predict operability limits both with and without bleed?
- Can these tools predict low/high speed inlet interaction effects due to varying inlet backpressures and low/high speed inlet cowl positions?

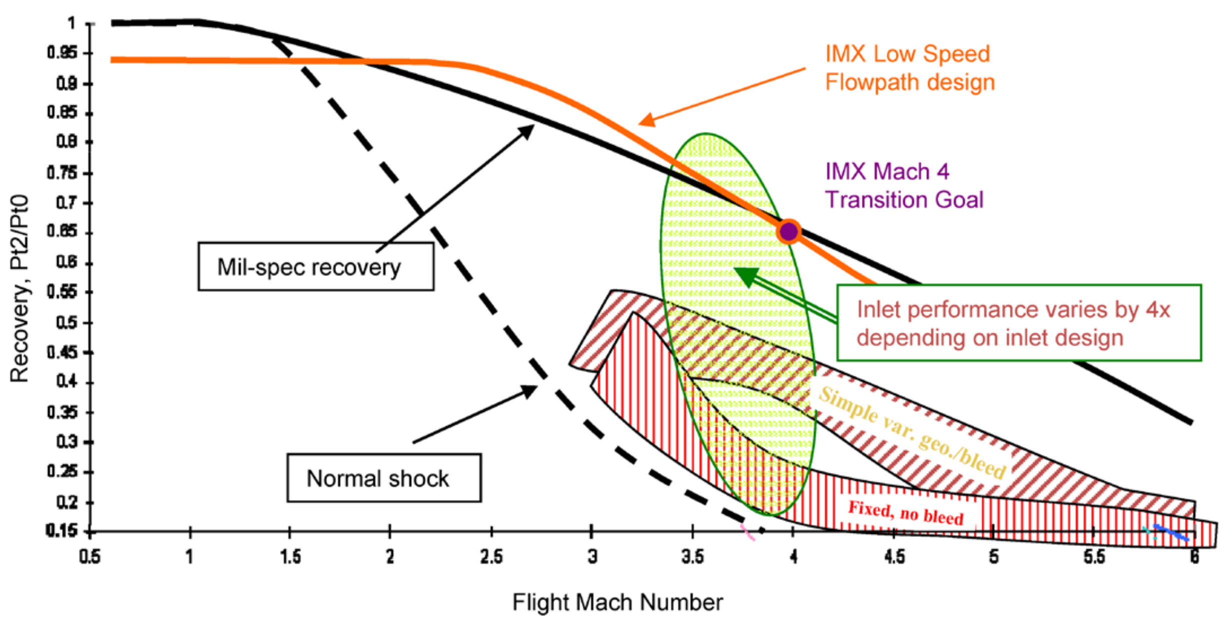


Figure 4.—Potential Inlet Total Pressure Recovery for TBCC inlets.

Inlet/Engine Interactions

In order to maintain propulsion system performance through mode transition, the inlet/engine as well as the low speed/high speed engine interactions must be controlled to avoid inlet unstarts and engine stalls while maintaining the proper airflow quality and splits as the low speed turbine engine is spooled down and the dual mode ramjet takes over. Specific questions with regard to inlet/engine interaction:

- What impact does engine inlet distortion have on performance and operability?
- Can design and analysis tools predict distortion into engine both with and without bleed?
- Can these tools predict the impact of distortion on engine performance and operability?
- What is the trade-off between bleed and inlet exit profile? Are vortex generators required?

Propulsion Mode Transition

Validated design and analysis tools are necessary to model the TBCC propulsion system characteristics over the wide flight range and during mode transition. This requires addressing specific questions with regard to understanding and demonstrating mode transition:

- What is the process for safe and optimum mode transition?
- Can design and analysis tools properly model components adequately to perform a controlled mode transition?
- Are these predictions of sufficiently high fidelity to guide the testing and avoid inlet unstart and/or engine stall?
- Can these design tools be effectively used to extrapolate the experimental data in order to optimize the propulsion system configuration?

Throughout the CCE LIMX testing, this model will be used as a testbed to assess the state-of-the-art of performance and design codes/tools, inclusive of fluid and turbine performance codes and engineering-level algorithms. During this activity integrated system design and analysis tools, as well as dynamic models, are being developed and validated to support the controls design and demonstration of mode transition of an over-under TBCC propulsion system.

CCE LIMX—Testbed for Mode Transition Testing

The CCE LIMX is a dual integrated inlet flowpath designed for mode transition testing, including controls and integrated inlet and engine testing. The unique features of the CCE LIMX that are being used to develop databases and assess state-of-the-art (SOA) tools are shown in Figure 5.

There are four phases in the test activity that span approximately 3 years: Phase I: inlet performance and operability characterization in which cold pipe and mass flow plugs are used to simulate engine backpressures for both the low-speed and high-speed flow paths. Open loop control mode transition sequences will also be demonstrated. Phase II: unsteady Inlet dynamic system identification experiments using the cold pipe and mass flow plugs installed in both flowpaths. This test phase will provide the data needed to develop the closed loop propulsion system controller. Phase III: demonstrate closed loop mode transition control strategies using the cold pipe and mass flow plugs installed in both flowpaths. Phase IV: demonstrate closed loop controlled mode transition strategies with a candidate turbine engine and single expansion ramp nozzle (SERN) system incorporated into the low-speed flowpath (see Appendix). As currently planned the high-speed flowpath uses the cold pipe and mass flow plugs to simulate the ram/scramjet for all four phases.

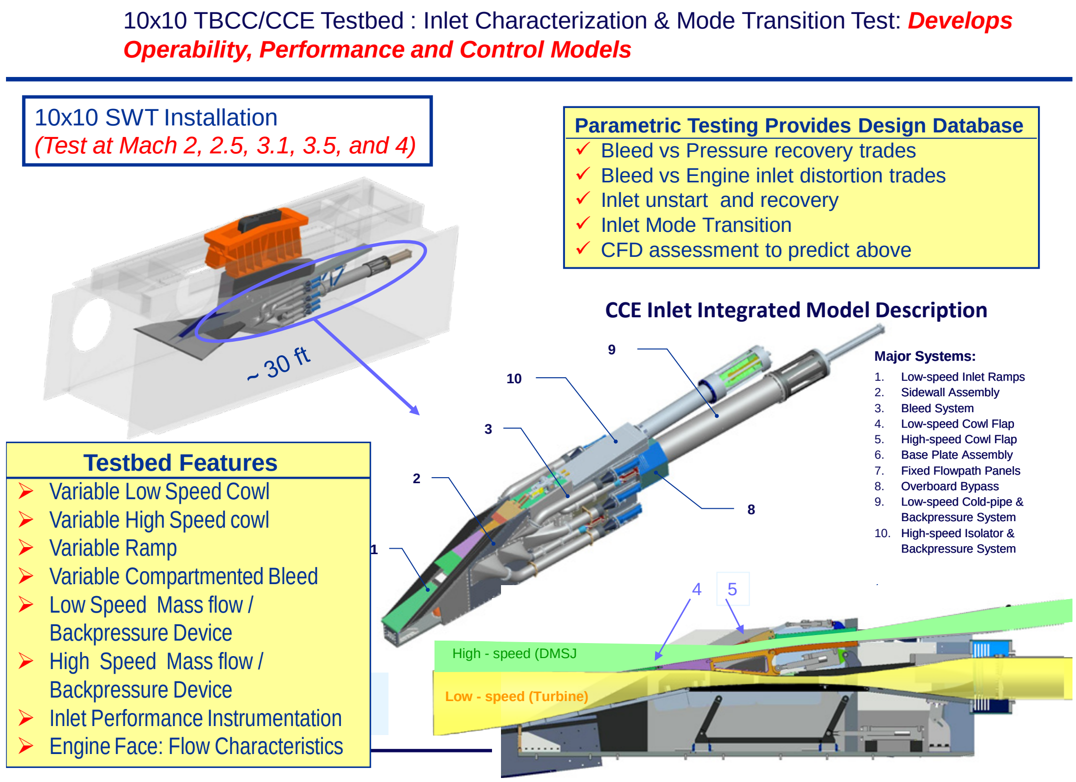


Figure 5.—Unique features of the CCE LIMX to develop databases and assess SOA tools.

The CCE LIMX has substantial parametric capability; it has a reconfigurable bleed system, variable-geometry flow paths, and accommodates a nominally 12-in. diameter turbine. There are a total of 13 bleed locations (controlled by 15 cold pipe/mass flow plug assemblies) in the low speed flowpath: five on the ramp, three on each of the sidewalls, and two on the cowl. Cold pipe and mass flow plug assemblies are used on the low speed and high speed flow paths to measure flowrate and to backpressure the inlet. The mass flow plugs and cold pipes integrated with the CCE LIMX model are shown in Figure 6. Additionally, due to the large scale, the inlet model is highly instrumented; therefore, spatially resolved distributions and high fidelity data can be obtained.

The CCE research objectives include:

1. Proof of concept of an over/under split flow inlet for a TBCC propulsion system.
    a. Develop an integrated performance and operability database
    b. Demonstrate mode transition at large scale.
2. Validate inlet computational fluid dynamic (CFD) code predictions of performance and operability for the low-speed and high speed flowpaths.
3. Develop realistic distortion characteristics throughout the mode transition Mach number range and assess the impact of this distortion on the turbine engine performance and operability.
4. Use this hardware as a testbed for future mode transition controls research and integrated inlet/engine propulsion system studies.

The 10- by 10-ft SWT can operate over a Mach number range of 2 to 3.5 (Ref. 6). The CCE LIMX is mounted to the facility strut and the angle of attack can be varied between –15° and 5° by rotating the strut about its pivot pin which has a 3 in diameter. By operating the facility at Mach 3.5 and positioning the CCE LIMX model at an angle of about –7°, as shown in Figure 7, a Mach 4 test condition is provided (which is the design condition); some off-design testing at other Mach numbers will also be conducted.

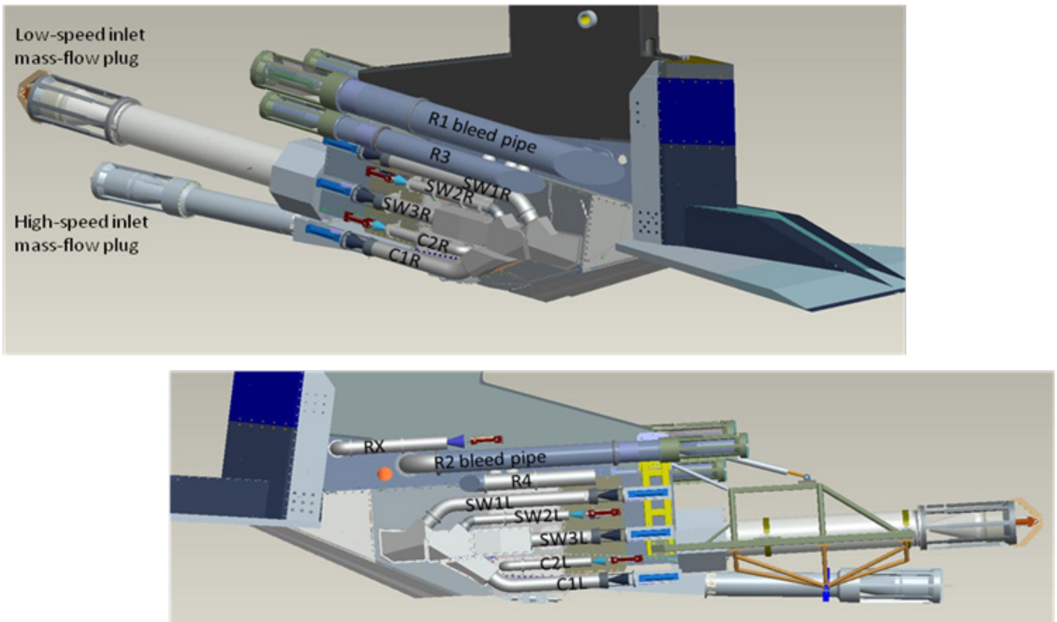


Figure 6.—CCE LIMX mass-flow plug and cold pipe locations.

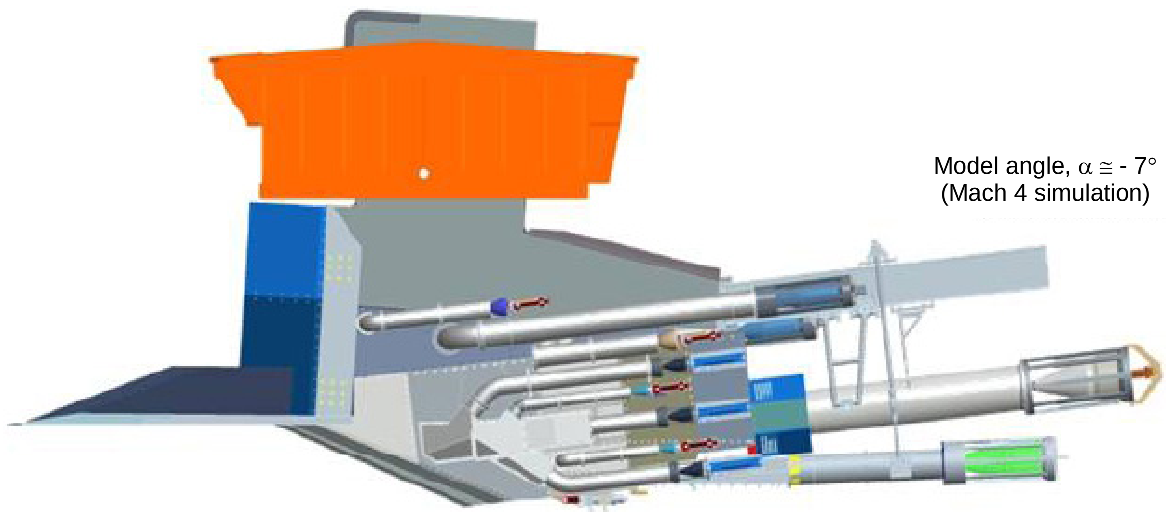


Figure 7.—CCE LIMX Model orientation in the 10- by 10-ft SWT.

The CCE LIMX development was led by NASA with many partners playing an integral role in the design and development. Techland Research, Inc. was the primary contractor for the inlet aerodynamic flowpath design (Ref. 5). Alliant Techsystems, Inc. (ATK) had the primary responsibility for the mechanical design and integration of the inlet hardware and also provided a candidate scramjet design which was carried through detailed design. Arctic Slope Regional Corporation (ASRC) also helped with mechanical design and were responsible for much of the design and fabrication of the facility hardware including the strong back. Metalex, Inc. fabricated the majority of the inlet test rig hardware. Williams International is providing the (high Mach) turbine engine via an interagency agreement between NASA and the Air Force Research Lab (AFRL) to develop high speed turbine engines. The integrated turbine engine nozzle was designed and fabricated by Spiritech, Inc. Boeing, Inc. contributed with CFD simulations which helped with test preparations. The collage shown in Figure 8 illustrates the contributions of the CCE testbed hardware team.

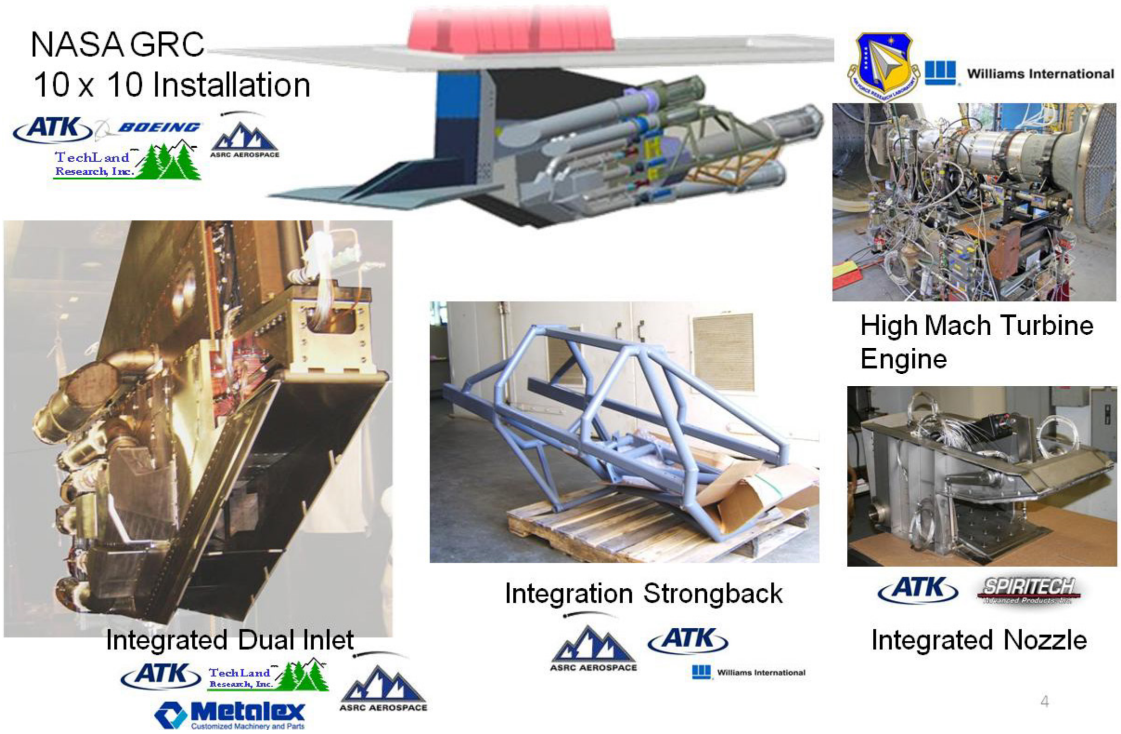


Figure 8.—CCE Testbed and Mode Transition Team.

Facility Preparation and CCE LIMX Model Installation

CCE LIMX preparations have been underway for over 3 years. Installation of the test article and all facility preparations were completed, and Phase I testing commenced March 7, 2011.

Due to the large scale of the test article, its complexity, and the extent of instrumentation, the process of carefully installing this test article took place through most of calendar year 2010. The test team took the time and care during installation to make certain the flowpath was configured as designed. The inlet model was delivered to the 10- by 10-ft SWT facility in January 2010 and mounted into the tunnel by February 2010 (Fig. 9(a)). Upon receipt and installation of the hardware, a need to re-work many of the seals and make some modifications to the hardware was determined. This subsequently required substantial disassembly, rework, and reassembly. During re-work, the model was disassembled, leak paths were sealed, and the instrumentation routing was completed. Between March and September 2010 the model was reassembled, which included the installation of all cold pipe and mass flow plug assemblies as shown in Figure 9(b). The forebody pre-compression plate, which is the trapezoidal shaped surface shown in Figure 9(c), was then installed onto the facility strut and aligned with the inlet model. Final instrumentation end-to-end checks, calibration of all moving systems (17 mass flow plugs, two cowls, ramp, and strut angle) were conducted. The overall integrated systems testing, pre-test checkouts, and all required safety and test readiness reviews were completed October 2010 through February 2011; testing commenced on March 7, 2011.

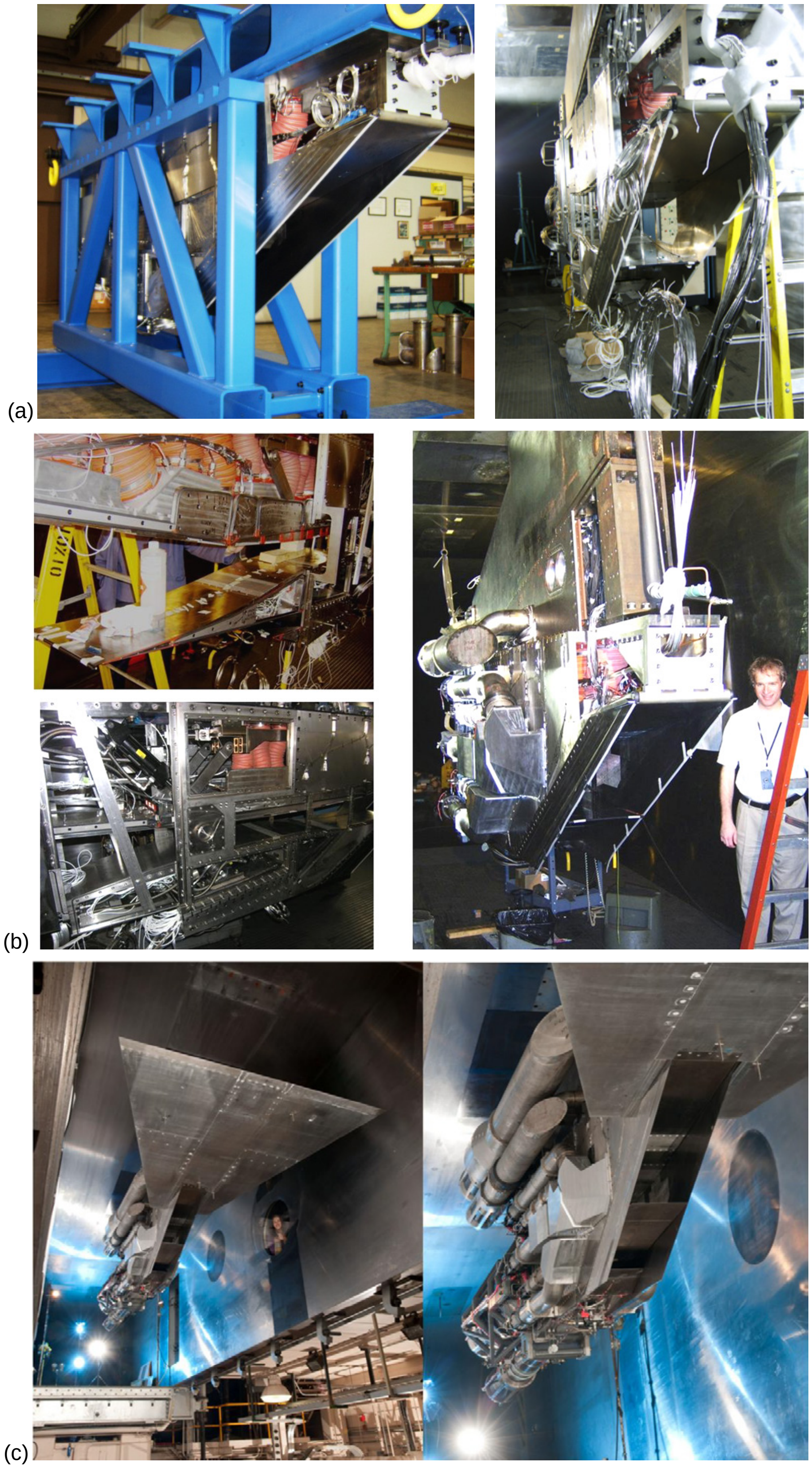


Figure 9.—(a) Model as delivered and subsequently mounted in the facility (Jan. to Feb. 2010). (b) Model partly disassembled to work seals and hardware interfaces, instrumentation routing, checked out, and inlet model re-assembled (Mar. to Sep. 2010). (c) CCE LIMX installed in the 10- by 10-ft SWT ready for test.

CCE LIMX Testing

Four test phases to address the technical challenges and questions discussed previously are planned over the next 3 years. Phase I commenced on March 7, 2011, and is expected to conclude by the end of May 2011. Previous studies were used to mitigate risk and guide preparations for these experiments (Ref. 7). These efforts included CFD analysis (Ref. 8) as well as smaller scale screening tests (Ref. 9) in the NASA Glenn 1- by 1-ft supersonic wind tunnel. The small scale test results and the CFD analysis were used to set initial bleed schedules, assess sensitivity to performance and operability with variable geometry (both cowls, and low speed ramp), identify necessary control models (Ref. 10), and to help develop the test plan. The CCE LIMX has substantially more parametric capability than the small scale test model and is more highly instrumented to provide improved fidelity of results. By using the small scale test and computational results, an initial test plan for the Phase I experiment was developed as shown in Table I.

TABLE I.—TEST MATRIX FOR THE CCE LIMX INLET CHARACTERIZATION (PHASE I)

Test series	Bleed pattern	Vortex generator configuration	Simulated Mach numbers	Notes	Planned data points
1	A7	Basic	4	Facility and model checkout run	7
2	A7	Basic	4	Configuration a7, testing at lower pressure	165
3	A7	Basic	4	Configuration a7, start of standard testing	204
4	A8	Basic	4	Alternate bleed configuration, a8	204
5	A9	Basic	4	Alternate bleed configuration, a9	204
6	Selected	Basic	4	Alternate cowl lip al	204
7	Selected	Vg1	4	Alternate vortex generator pattern	204
8	Selected	Selected	4	Performance and mode transition	661
9	Selected, reduced bleed	Selected	4	Reduced bleed	204
10	Selected	Selected	3	Lower (off design) mach number tests	661
11	Selected, reduced bleed	Selected	3	Lower (off design) mach number tests	204
12	Selected	Selected	3.5	Lower (off design) mach number tests	223
13	Selected	Selected	2.5	Lower (off design) mach number tests	223
14	Selected	Selected	2	Lower (off design) mach number tests	223

Due to high electrical power usage, testing of the 10- by 10-ft SWT occurs on third shift. At the time of the writing of this report 10 nights of testing have been conducted. The 10- by 10-ft SWT is a continuous flow facility and substantial data can be obtained in a test period. For any supersonic tunnel, model size is a concern due to blockage, or the ability to 'pass the [tunnel normal] shock' and start the tunnel. Initial testing has first shown that the supersonic tunnel was able to start and operate nominally with this large model installed (Refs. 6 and 11). During the second test period a hard facility shutdown (or tunnel unstart) was observed, which produced a high pressure load over the model. Because the hardware was structurally designed to handle this event, the tunnel unstart did not result in any facility or model damage.

With this experience complete, testing is progressing with substantial research testing has been achieved to date. Several hundred data points have been taken and are being analyzed; the first configurations for the low speed and the high speed flowpaths have been initially characterized and the performance assessed. Access to this data can be obtained through the authors and will be reported out in detail in the near future. The results are being compared to pre-test computational solutions and to the small scale inlet mode transition experiment (IMX) results previously obtained in 1- by 1-ft SWT. Phase I and II testing are planned to be completed during 2011 (expected to conclude August 2011); Phase III in 2012, and Phase IV in 2013.

Summary and Concluding Remarks

One of the missions of the NASA Aeronautics Research Directorate (ARMD) Fundamental Aeronautics Program (FAP) Hypersonics project is to develop air-breathing propulsion technology for air-breathing access to space (AAS). The focus of this effort is in developing a two stage to orbit (TSTO) turbine based combined cycle (TBCC) propulsion system.

There are many technical challenges involved with the development of a TBCC propulsion system and these were discussed in this paper. The TBCC Discipline of the Hypersonics project is pursuing the Combined Cycle Engine Large Scale Inlet Mode Transition Experiment (CCE LIMX) to work towards answering these questions. This very complex experimental activity will take place over the next three years and will be accomplished through 4 distinct phases of testing. Phases I through III use the initial test article configuration, which is presently being tested in the NASA Glenn 10- by 10-ft SWT, and includes mass flow plug and cold pipe assemblies in both the low speed and high speed flowpaths. For Phase IV, a high Mach capable turbine engine and single expansion ramp nozzle (SERN) will be incorporated into the low-speed flowpath. This engine and nozzle have also been developed as a part of the TBCC discipline activity.

Over the past 3 years the CCE LIMX hardware has been developed, designed, fabricated, installed, checked out, and is now being tested in the 10- by 10-ft SWT. Testing commenced on March 7, 2011, and to date 10 nights of testing have been conducted. Initial testing has shown that the supersonic tunnel was able to easily start and operate nominally with this large model installed, and a hard facility shutdown was experienced without any resultant facility or model damage. Already several hundred data points have been obtained, since this is a continuous flow facility, and these are being analyzed. Access to the data can be obtained through the authors and will be reported out in detail in the near future.

Overall this test activity is providing a highly accurate, refined database on this TBCC design and will serve to demonstrate the controlled mode transition which is required by an advanced air-breathing propulsion system to enable hypersonic flight. Beyond the four phases of this current study the CCE LIMX test hardware/TBCC testbed will be continue to remain available to address future national needs in combined cycle propulsion.

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Appendix—Mach 3 Capable Turbine Development

The CCE LIMX Phase IV task includes removing the cold pipe and mass flow plug assembly from the low-speed flowpath and installing a Mach 3 capable turbine engine in its place. In preparation for this test a William International WJ38 Turbine Engine has been modified as required for Mach 3 operation. The engine is currently available and has undergone sea level static (SLS) checkout tests. A final series of checkout/acceptance testing is planned with an afterburner and integrated nozzle installed. Figure 10 shows a photo of the WI turbine and the integrated nozzle assembly; this hardware will be delivered to NASA at the conclusion of the checkout testing (expected April 2011).

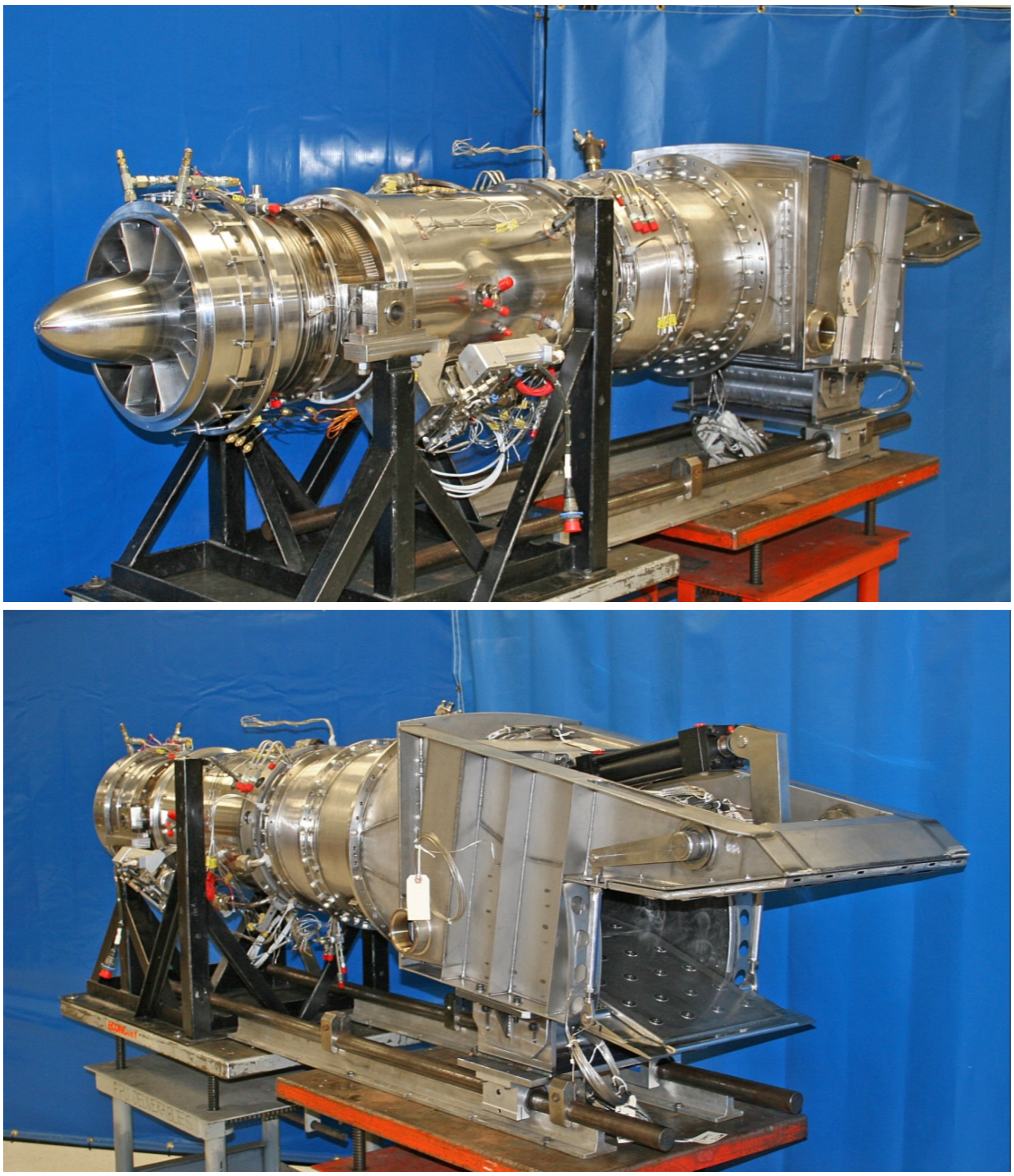

Figure 10.—Williams International High Mach WJ38 turbine engine and integrated nozzle assembly.

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14. ABSTRACT Status on an effort to develop Turbine Based Combined Cycle (TBCC) propulsion is described. This propulsion technology can enable reliable and reusable space launch systems. TBCC propulsion offers improved performance and safety over rocket propulsion. The potential to realize aircraft-like operations and reduced maintenance are additional benefits. Among most the critical TBCC enabling technologies are: 1) mode transition from turbine to scramjet propulsion, 2) high Mach turbine engines and 3) TBCC integration. To address these TBCC challenges, the effort is centered on a propulsion mode transition experiment and includes analytical research. The test program, the Combined-Cycle Engine Large Scale Inlet Mode Transition Experiment (CCE LIMX), was conceived to integrate TBCC propulsion with proposed hypersonic vehicles. The goals address: (1) dual inlet operability and performance, (2) mode-transition sequences enabling a switch between turbine and scramjet flow paths, and (3) turbine engine transients during transition. Four test phases are planned from which a database can be used to both validate design and analysis codes and characterize operability and integration issues for TBCC propulsion. In this paper we discuss the research objectives, features of the CCE hardware and test plans, and status of the parametric inlet characterization testing which began in 2011. This effort is sponsored by the NASA Fundamental Aeronautics Hypersonics project.					
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