NASA/TM—2005-213432 AIAA–2005–0611

Design and Fabrication of the ISTAR Direct-Connect Combustor Experiment at the NASA Hypersonic Tunnel Facility

Jinho Lee and Thomas M. Krivanek
Glenn Research Center, Cleveland, Ohio

February 2005

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.
- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***
- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA Access Help Desk at 301–621–0134
- Telephone the NASA Access Help Desk at 301–621–0390
- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076

NASA/TM—2005-213432 AIAA–2005–0611

Design and Fabrication of the ISTAR Direct-Connect Combustor Experiment at the NASA Hypersonic Tunnel Facility

Jinho Lee and Thomas M. Krivanek
Glenn Research Center, Cleveland, Ohio

Prepared for the
43rd Aerospace Sciences Meeting and Exhibit
sponsored by the American Institute of Aeronautics and Astronautics
Reno, Nevada, January 10–13, 2005

National Aeronautics and
Space Administration

Glenn Research Center

February 2005

Acknowledgments

The authors would like to acknowledge the support of our industry and NASA partners from all over the United States in addition to the financial support of the NASA NGLT program office.

This report contains preliminary findings, subject to revision as analysis proceeds.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov

Design and Fabrication of the ISTAR Direct-Connect Combustor Experiment at the NASA Hypersonic Tunnel Facility

Jinho Lee and Thomas M. Krivanek
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

The Integrated Systems Test of an Airbreathing Rocket (ISTAR) project was a flight demonstration project initiated to advance the state of the art in Rocket Based Combined Cycle (RBCC) propulsion development. The primary objective of the ISTAR project was to develop a reusable air breathing vehicle and enabling technologies. This concept incorporated a RBCC propulsion system to enable the vehicle to be air dropped at Mach 0.7 and accelerated up to Mach 7 flight culminating in a demonstration of hydrocarbon scramjet operation. A series of component experiments was planned to reduce the level of risk and to advance the technology base. This paper summarizes the status of a full scale direct connect combustor experiment with heated endothermic hydrocarbon fuels. This is the first use of the NASA GRC Hypersonic Tunnel facility to support a direct-connect test. The technical and mechanical challenges involved with adapting this facility, previously used only in the free-jet configuration, for use in direct connect mode will be also described.

I. Introduction

Reducing the cost of space access and improving safety are key elements of NASA's aerospace vision. Through the Next Generation Launch Technology (NGLT) program, significant investments were made to develop re-usable hypersonic vehicles and propulsion technologies in support of this vision.[1,2] This program focused on two-combined cycle propulsion demonstrators, one based on rocket engines and the other on turbine engines. The Integrated Systems Test of an Airbreathing Rocket (ISTAR) was the Rocket Based Combined Cycle (RBCC) demonstration project.[3] The Revolutionary Turbine Accelerator (RTA) was the Turbine Based Combined Cycle (TBCC) demonstration project.[4]

Hydrocarbon (HC) fuel is required to close the flight demonstration mission because of the volumetric advantage (energy density) of the HC fuel (compared to hydrogen). This proposed flight demonstration represented an important technical step towards the development of a hypersonic vehicle capable of orbital access.

II. RBCC Experiment

The ISTAR engine was being developed by a unique industry-government partnership and four NASA Centers working collectively to increase the system level understanding of hypersonic flight vehicles through design optimization studies coupled with critical experiments. Where possible, target goals have been driven by the system needs, and the focus has not been isolated into any single technical area.

There are many technical challenges involved with the combustor for this RBCC propulsion system. The tools available for combustor design lack the high level of technical confidence needed to accurately predict even routine applications, and the combustor must go through several distinctive modes of operation: Air-Augmented Rocket (ARR), Ramjet, and finally the Scramjet mode. Therefore, the combustion system must be designed to handle a wide range of local operating conditions in a very stable and reliable manner in order to maintain engine performance through the flight mission. The design cycle chosen incorporates a fixed combustor geometry which utilizes thermal choking versus a mechanically variable geometry to control the combustor operation. Where possible the ISTAR team made extensive use of both the National Aerospace Plane (NASP) database and the more recent Department of Defense/Air Force (DoD/AF) combustion database, obtained under the Hypersonic Technology (HyTech) program,[5] to assist in designing the engine flowpath. However, the differences in requirements for the ISTAR mission, such as lower Mach number mode transition, led to the need for the additional RBCC demonstrations such as the present direct connect experiment.

The X-43 class vehicle mission of flying a hypersonic X-vehicle from Mach 0.7 to a speed of Mach 7 drove the design of the ISTAR (designated X-43B) engine. The team arrived at the current engine design based on existing performance information after several engine configuration iterations. The final X-43B Flight Test Engine (FTE) configuration, shown in figure 1, consists of four engine modules with each containing three struts and two sidewalls to form the engine. The engine struts were used to integrate rocket thrusters and fuel injectors into the flowpath. Several assumed performance characteristics, such as isolator backpressure capability, flame stability limits, mixing efficiency, and overall combustion efficiency, required experimental validation.

Testing a full scale FTE is not possible because the facility needed to accommodate an engine this size is not currently available. Thus the decision was made to build a full scale direct connect combustor rig enabling combustor performance to be well characterized. Additional sub-scale and component performance testing would be conducted to compliment this experiment and to ultimately reach a high level of certainty in the engine performance.

In most cases, testing of sub-scale hardware coupled with analysis is used to assess the flight hardware engine performance for demonstrating next generation engines at a lower risk and cost. For some components, scaling down to smaller test hardware and inferring data to full scale hardware is the design practice. Reasonable understanding of the available sub-scale H_2-fueled engine performance data and its limitations can be obtained from Voland et al.[6] However, this level of design maturity does not extend to HC-fueled dual-mode combustors, where a large number of parameters reside outside of the current experience accumulated in databases. The variety of technical challenges in developing a HC-fueled dual-mode engine is summarized by Waltrup[7] and Tishkoff.[8]

The dual-mode Direct Connect Combustor (DCC) experiment is to be conducted at NASA's Hypersonic Tunnel Facility (HTF), located at Plum Brook Station, a satellite of GRC,[9] because of the available power infrastructure capable of handling large-scale experiments. This direct connect combustor experiment required numerous modifications to the HTF facility. These included the addition of a heated fuel supply and distribution system, updating the capabilities of the data acquisition system, and installing a gas sampling system. The major challenge was the task of designing the direct-connect test article and installation of hardware that will survive the high enthalpy test environment.

III. RBCC Combustor Research Objectives

The objective of the experiment is to demonstrate efficient and stable combustion of the endothermic HC fuel throughout the hypersonic accelerator trajectory while developing a parametric database over a range of off design test conditions so that a high level of confidence can be obtained for the hypersonic flight demonstration mission. Initially, the direct connect combustor experimental investigation will focus on the combustor performance issues and limitations at the Mach 3.5 flight condition. This will be followed by a similar experimental investigation at Mach 5 and 7 conditions to ensure that any candidate fueling configuration does not adversely impact the overall performance of the engine and stability at the higher flight speeds. A conceptual view of the required fuel staging at various flight engine modes is illustrated in figure 2.

For the Mach 3.5 flight condition, the combustor operation must be sufficiently stable to enable a smooth transition from AAR mode to the Ramjet operation. The design incorporates fuel staging, aided by a pilot flame, to tailor the burner for optimal and stable operations throughout the engine's mission profile. It is critical to obtain a quantitative understanding of the impact that the location of the injectors has on the flame stability, flame spread, backpressure characteristics, and thermal throat location for this fixed geometry combustor across the Mach number range.

The physical state of the fuel that is injected has also been a source of uncertainties[5,10] in past investigations because the injectors are usually designed with supercritical HC fuel characteristics and any deviation from that design state tends to cause significant performance losses. Figure 3 shows typical fuel penetration characteristics used in the design of this burner. This figure shows two sets of trends for fuel penetration; the upper curve is the gas-phase injector penetration, and the lower set is the penetration characteristics of liquid phase fuel.[11] A significant drop in fuel penetration may occur if the fuel state is changed from gas to liquid; such a change will have a negative performance impact. The lack of fundamental HC injection data is further illustrated in figure 4, which compares the currently needed data for the penetration and spreading with the currently available database.[12] The fuel penetration is essential because it affects the ability to propagate the flame from the front injectors to the secondary injectors in the aft portion of the combustor with enough heat addition to form a thermal throat within the combustor, which is critical to the engine operation. Maintaining a stable flame while the burner entry condition changes is a difficult problem and strongly tied to a particular flame holder configuration.[13,14] Two criteria of particular importance are the flame sensitivity to various environmental changes and the range of pilot fuel flow required to sustain the primary combustion in place. Therefore, a wide range of entry conditions, fuel temperatures, fuel splits, and wall temperature conditions, (beyond the baseline combustor environment conditions), will be carefully measured and studied. Once the cause and effects of the fueling parameters are well understood, a smooth fuel staging scheme needed to match burner entry variation can be developed and implemented.

It is also well known that the stability of a combustion system has sensitivities due to the chemical content of the test medium.[15,16] Brabbs et. al.,[17] showed that under ideal circumstances, vitiated contaminants can cause a change in ignition delay, leading to erroneous conclusions for the flight performance and operability in air. HTF is a non-vitiated facility where inherent trace species and water contaminates can be avoided. Therefore, this direct connect combustor experiment represents a unique opportunity to study flame stability limits of a burner configuration in synthetic air.

Precise understanding of non-premixed flame stability limits in open literature for hydrocarbon fuels, especially for JP7, is limited. Figure 5 shows the designed stability limit for this HC burner and is compared with a curve fit of the pre-mixed data as summarized by Ozawa.[14] Currently, HC burner operability predictions cannot be made with a high level of confidence due to the lack of credible high fidelity data for non-premixed situations. In addition, pilot flames have been shown in the past as an effective way of widening the flame stability range of various burner designs.[7] Therefore, the re-circulation region aft of the strut is fueled to create a pilot flame region. However, fuel to the pilot region typically contributes little to the overall propulsion system performance. From the current designer's view there is an incentive to minimize the amount of fuel into this region, which would take fuel away from the primary fuel injection locations. The quantity of the fuel needed to maintain stability is one of the key measurements needed to understand how to maximize combustor performance.

IV. Direct Connect Combustor

The direct connect combustor rig is presented in figures 6 and 7. This rig was designed with the mechanical flexibility and the thermal-structural margin needed to simulate dual-mode combustor operation at Mach numbers of 3.5, 5.0, and 7.0. These Mach numbers represent the points in the current mission profile at which a significant change in combustor flow physics must occur. The Mach 3.5 point is the transition from AAR to ramjet operation (lowest enthalpy) where the challenges of maintaining combustion and flame holding are the greatest. The Mach 5 point is where the combustor experiences maximum internal pressure and begins transition to scram operation, and the Mach 7 point is the highest enthalpy region associated with material thermal challenges and demonstration of scram operation.

The design trade study was driven by the critical impact that the burner thermal environment has on flame stability, and the requirement to match the essential thermal environment of the FTE combustor. There are various pros and cons to all choices of materials and rig configurations. This trade study concluded that while a cooled combustor rig using stainless steel construction would be more flexible in that it would provide a controlled environment suitable for this combustor, using a heated material would better fit our desire to ultimately simulate the actual Mach 7 burner environment. Therefore, the combustor rig was designed and fabricated using C18150 and CU107 type copper alloys. At the same time, issues relating to large heat losses in the various regions of the combustors were considered. Here, we relied on lessons learned by the DoD program to avoid or to minimize the difficulties of the past in translating the heat sink combustor- based performance data to an endothermically cooled 'hot' combustor environment.[10] The vision flight RBCC engine uses a fuel-cooled burner design, in which the injectors are designed using gas-phase data information and tools corrected for HC fuel. Hence, there is a direct impact on combustor performance if the desired condition of the fuel injected cannot be maintained. In addition, heat loss in various combustor regions, like the flame holding region; have been found to be important in the past. This type of heat loss was the major concern and the primary driver for the current DCC rig design. The fuel injectors (shown in fig. 8) are designed to be thermally isolated from the heat sink rig environment and are fabricated from Inconel to minimize any heat loss in the aft injectors. In addition, the flame holding strut base regions and the forward injector region are made of 347 stainless steel and are instrumented with TCs to quantitatively characterize the high temperature pilot region. The combustor walls are thermal barrier coated (TBC) to minimize heat loss and to provide a more accurate simulation of the FTE thermal environment, (i.e., wall temperature and boundary layer effects). In addition, a number of the key wall location temperatures will be measured to quantitatively characterize the actual wall heat flux and the resulting conductive heat loss. In order to characterize the overall engine performance the test article incorporates 350 static pressure taps and 67 thermal couple sites. Here the TCs are installed in triplets so that the transient copper wall temperatures measured can be used to infer the wall heat flux. Figure 9 shows typical characteristics of such analyses, done using a data set from a finite element model. This figure shows that even under ideal conditions the measured heat flux data may still be transient due to various factors, such as directional conduction however, they can still be used to characterize the thermal environment with some additional analytical effort. In order to study the pilot region closely, a set of un-cooled windows was added to the combustor rig for visual observations (shown in fig. 10). In addition, a set of thermal couples allows for the measurement of recirculation zone temperatures.

The test gas is provided to the combustor using new direct connect facility nozzles; designed using a method of characteristics technique, the Euler mode of the R+ solver.[18] Ultimately, the geometry was re-checked using WIND [19] analysis. A typical Euler solution and Navier-Stokes solution for the Mach 3.5 nozzle hardware is shown in figure 11, along with the hardware configuration for a visual reference. In order to quantitatively characterize and verify the inflow condition, the combustor rig has an instrumentation section where three core flow and two boundary layer pitot pressure rakes can be inserted. Figure 12 shows the details of the rakes and the installation of the rake in the combustor test article. These rakes can also be used to extract a sample and verify test gas composition using the gas sampling system shown in figure 13.

V. Combustor Rig, Facility Capability and Technical Goals

The primary goal of this combustor experiment is to provide quantitative data to address technology gaps and to enhance understanding of endothermic HC-fueled dual-mode combustors. While obtaining the overall combustion efficiency of the dual-mode burner is an important part of the proposed experimental study, it is just as critical to show that adequate flame holding behavior can be maintained throughout the mission. It is also essential that we gain a broad understanding of the burner combustion behavior in order to prevent an unexpected loss of combustor operation (i.e., flame out) resulting in mission failure.

Hence, the combustor performance shall be measured as a function of several parameters, such as fuel flows and splits, using two independent techniques with comparisons made for validation. These techniques include a gas sampling measurement for direct chemical-based combustion efficiency measurements (exit rakes shown in fig. 14) and extracted combustion efficiency data based on wall pressure measurements. Enhancement of the confidence of these measurements can be made through an analysis of the thermal environment of the burner. The large-scale combustor rig has been designed to avoid the inherent sub-scale combustion challenges, such as flame holding, or compromised testing at conditions that may not be characteristic of the expected combustor environment.

Initially, the experimental investigation will focus on the low flight enthalpy Mach 3.5 condition. Some of the key objectives of this experiment include determining: (a) the impact of injector locations and fuel splits on the burner pressure characteristics, injector configuration, associated isolator behavior, thermal throat location, and combustion efficiency; (b) the ability to hold a stable flame via piloted base regions and ranges for fuel flow needed; (c) the sensitivity of the flame in the combustor to entry condition perturbations and fuel state and (d) thermal environment of the burner under various flight conditions. [20] The combustor ignition is accomplished using silane (a mixture of 80 percent H_2 and 20 percent SiH_4 by volume) injected through separate injector ports added to the combustor rig.

The test matrix for the combustor experiment was developed around the planned fuel injector parametric where operational behaviors are largely unknown. In order to achieve desired combustor performance, three sets of injectors are used together to tailor the heat release required to generate the desired burner performance. The resulting data will aid in developing an optimal final fuel injector-staging configuration for the engine. In addition, the key fuel injector locations are instrumented with thermal couples (TC) for more accurate assessment of the fuel state at the injector. This will verify that the correct fuel injection temperature matching the flight conditions are obtained during a run.

As discussed earlier, high-resolution combustor wall pressure measurements will be used to infer the combustion efficiency from a local chemical equilibrium-based analytical performance analysis tool. A typical combustion efficiency prediction made with such a design tool, taken from Yungster et. al.,[21] is shown in figure 15. This figure shows that reasonable dual-mode performance can be achieved through fuel staging if the HC fuel can be thermally processed, injected, mixed, and burned as predicted by this model.

The backpressure characteristic of the burner will also be explored as a function of injector locations and fuel injector state. Once the back pressure characteristics have been determined, an optimal fueling configuration will be chosen to study the operability range of the pilot flame. Here, the stability data will be obtained as a function of quantitative information obtained from the heater, the rig, and the injectors, coupled with the visual observation obtained through the combustor window. The stability data will be used to compare with other premixed and non-premixed burners. Furthermore, the pilot region visual and thermocouple data will be compared with predictions obtained under Well Stirred Reactor (WSR) assumptions to determine the effectiveness of this pilot configuration. Once the preliminary understanding of the piloting capability is known, the combustor performance and operability limits will be mapped out. A similar study will also be conducted to map out the thermal throat control. The injector parametric will be used to place a thermal throat in various locations within the combustor.

This direct connect experimental configuration does not precisely simulate the flight engine isolator because the fore body boundary layer cannot be matched and the shock structure is not completely replicated. Therefore, some inlet correction[22] to the isolator data obtained may be needed to translate the results to the FTE environment. Nevertheless, the isolator-combustor interaction behavior can and will be studied by using a unique multiple passage engine isolator-facility isolator configuration. Here, issues such as the ultimate isolator limits,[23] isolator-to-isolator interactions and fuel injection tailoring will be the focus of the experiments proposed.

The database obtained from these experiments will serve as the basis for laying out flame holder-injector-combustion configurations for the future FTE that are both stable and optimal in terms of overall chemical combustion efficiency.

VI. Facility Features and Status

A. Current Facility Features

NASA's HTF uses a unique synthetic air system to provide the test medium for the experiment. A graphite storage heater is used to heat up compressed nitrogen (N_2) to a high temperature, after which it is passed through a mixing section where the proper amount of oxygen (O_2) to create 'synthetic' air is added to the main flow. The resulting test medium does not contain any of the chemical contaminates such as water or carbon dioxide associated with combustion heated (vitiated) hypersonic facilities. A steam ejector system is used to provide the altitude exhaust condition for the facility. Figure 16 shows a simple schematic of the HTF facility; further details of the free-jet HTF capability is summarized by Thomas.[9] The current HTF free-jet and combustor simulation capabilities are shown in figure 17, along with a typical air-breathing hypersonic flight corridor. Gas sampling is used to verify the test flow composition.

B. HTF-DCC Facility Modifications

Some of the facility's logic, control valve and flow meters were replaced in order to improve accuracy with the 'low' flow characteristic (< 50 lbm/s) of the Direct Connect combustor's flow field (compared to free-jet operation). Figure 18 shows the typical coriolis flow-meter which were added to both the N_2 and O_2 supply lines to accurately measure and control the flows for the combustor experiment. The updated digital HTF flow control system also allows for fine control and measurement of the flow over the full range of facility flow conditions. In addition, a new mixer extension was added upstream of the facility nozzle to allow for a sufficient mixing distance to assure a uniform test flow composition.

A new 96-channel dynamic data system was also installed and 406 Electronically Scanned Pressure (ESP) data channels are now available to allow for higher fidelity static pressure measurements. This resolution is required for an accurate internal force integration/engine thrust determination, and hence, a more accurate combustion efficiency calculation.

C. Fuel Heater

A new endothermic fuel heater system capable of conditioning the fuel in a manner that replicates the state of the fuel in the regeneratively fuel cooled flight engine heat exchanger (at flight condition) in both temperature and composition (level of cracking) was designed and built. There are four similar fuel heaters in the United States; at NASA LaRC, UTRC, ATK GASL, and AFRL. All use electrical power to cause an endothermic reaction of the HC fuel.[10] The heaters at UTRC and ATK GASL are very similar and were both built by UTRC. AFRL Cell-22 heater is based on the UTRC design but was built by AFRL. The NASA LaRC heater[24] is an identical copy of the heater at GASL and was built by GASL. The current GRC-HTF heater system was designed from the best features of all of these heaters and incorporated improvements from lessons learned from these systems. Furthermore, the new GRC heater is the largest in terms of fuel flow capability, and has incorporated a new fuel flow measurement system with improved accuracy and controllability. These two features lead to a unique capability to enable accurate assessment of combustor performance and stability, data that will be unique and essential. The final resulting design, shown in figure 19, is an optimized design for application in this experimental study of HC-fueled dual-mode combustors. It is expected that this design, with its accurate control system and valve system, can provide several steady-state data points within the available time window of any nominal combustor test.

D. HTF DCC Status and Integrated System Test (IST)

Currently, the coriolis N_2 and O_2 meters are completely installed, tested and ready to go. These flow meters and flow valves can control and supply up to 100 lbm/s of flow to the combustor with high precision. The new digital flow control system for the coriolis meters has also been installed and programmed. The Hypersonic Tunnel Facility's synthetic air system has been recertified for operation with improved accuracy to support the DCC test conditions. The fuel system and the secondary systems discussed previously are not completed; however all of the fuel heater system components have been procured, with the exception of the fuel scrap tank. Currently there is a programmatic uncertainty and funding has not been provided to complete this test. However, as outlined in this paper, the preparations have been made and the Mach 3.5 phase of this experiment is still expected to take place in the near future.

A separate set of (temporary) facility tunnel circuit components were built to accommodate the initial facility calibration and start up experiment. Figure 20 shows the configuration of this hardware installed at HTF. This installation features all of the inlet rake mounts so that it can be used for nozzle calibration tests without exposing the actual combustor test article during initial facility checkout, minimizing risk and additional test time on the test article. A facility Integrated Systems Test (IST) is scheduled for early next year to demonstrate and to validate the new facility capabilities. This IST will characterize the flow quality of the direct connect combustor rig nozzle and verify the test flow composition. Following this IST the DCC will be installed and the facility preparations completed for the Mach 3.5 test. Currently all test rig hardware has been designed and fabricated for this test.

VII. Summary

A brief summary of the full-scale direct connect combustor experimental capability developed at GRC-HTF has been presented, along with a discussion of the technical goal of the project and the mechanical challenges resulting from adopting a large scale free-jet facility for use as a direct connect combustor facility. An overview of the newly developed capabilities of the facility was given, and compared with the major technical challenges of the ISTAR project. Currently, we have completed the majority of test article/facility preparations and are awaiting the completion of support systems. This new facility capability and DCC experiment will provide a significant contribution to the existing HC hypersonic database. An extensive test matrix has been developed to explore the HC-fueled combustor operational map, including stability characteristics. This promises to be a unique and fruitful endeavor needed by the high-speed community. The HTF direct connect combustion rig is now a valuable asset for the hypersonic research community due to the large scale, clean flow, and the ability to provide heated hydrocarbon (HC) fuel to simulate the range of flight conditions and thermodynamic environments that the vehicle may encounter.

References

[1]Hueter U., and McClinton C.R., "NASA's Advanced Space Transportation Hypersonic Program," AIAA–2002–5175.

[2]McClinton C.R., et. al., "Airbreathing Hypersonic Technology Vision Vehicle and Development Dreams," AIAA–99–4978.

[3]Andreadis D., Drake A., Garrett J.L., Gettinger C.D., and Hoxie S.S., "Design Considerations of ISTAR Hydrocarbon Fueled Combustor Operating in Air Augmented Rocket, Ramjet and Scramjet Modes," 11th AIAA/AAF International Conference on Space Planes and Hypersonic Systems and Technologies, Orleans, France, September 29, 2002.

[4]Shafer D.G., and McNellis N., "Development of a Ground Based Mach 4+ Revolutionary Turbine Technology Demonstrator (RTATD) for Access to Space," ISOABE 2003.

[5]Mercier R.A., "Private communication"

[6]Voland R.T., and Rock K.E., "Concept Demonstration Engine and Sub-scale Parametric Engine Tests," AIAA–95–6055.

[7]Waltrup P., "Liquid Fueled Supersonic Combustion Ramjets: A Research Perspective of the Past, Present, and Future," AIAA–86–0158.

[8]Tishkoff J.M., Drummond J.P., Edwards T., and Nejad A.S., "Future Direction of Supersonic Combustion Research: Air Force/NASA Workshop on Supersonic Combustion," AIAA–97–1017.

[9]Thomas S.R., Woike M.R., and Pack W.D., "Mach-6 Integrated System Tests of the NASA Lewis Research Center Hypersonic Tunnel Facility," NASA/TM–107083.

[10]Norris R., and Boudreau A., "Lessons Learned from Free-jet Testing of the HyTech Ground Demonstration Engine No. 1," 51st JANNAF Propulsion meeting.

[11]Lin K.C., Kennedy P.J., and Jackson T.A., "Penetration Height of Liquid Jets in High Speed Cross Flows," AIAA–200–20873.

[12]Torrence M.G., "Effect of Injectant Molecular Weight on Mixing of a Normal Jet in a Mach 4 Airstream," NASA/TN–S–60 61.

[13]Gruber M.R., et. al., “Fundamental Study of Cavity-based Flame holder Concepts for Supersonic Combustors,” Journal of Propulsion and Power, Vol. 17, No. 1, 2001.
[14]Ozawa R.I., “Survey of Basic Data on Flame Stabilization and Propagation for High Speed Combustion Systems,” AFRL TR 70–81.
[15]Pellett G.L., Claudio B., and Chinitz W., “Review of Air Vitiation Effects on Scramjet Ignition and the Flame Holding Combustion Process,” AIAA–2002–3880.
[16]Cain T., and Walton C., “Review of Experiments on Ignition and Flame holding in Supersonic Flow,” AIAA–2002–3877.
[17]Brabbs T.A., Lezberg E.A., Bittker D.A., and Robertson T.F., “Hydrogen Oxidation Mechanism Application to (1) the Chaperon Efficiency of Carbon Dioxide and (2) Vitiated Air Testing,” NASA/TM–100186.
[18]Lee J., “Numerical Study of Mixing in Supersonic Combustors with Hypermixing Injectors,” Journal of Propulsion and Power, Vol. 10, No. 3, pp. 297–304.
[19]Engblom W.A., and Frate F.C., “Validation of WIND Code for Direct-Connect Flowpath Prediction,” AIAA–2005–1000.
[20]Heiser W.H., and Pratt D.T., Hypersonic Airbreathing Propulsion, AIAA Education Series 1994.
[21]Yungster S., Suresh A., Stewart M.E., and Lee J., “A Study of Ram Combustor Performance using 1–D and 3–D Numerical Simulations,” AIAA–2005–430.
[22]Frate F.C., Haas M., Van Dyke K.J., and Andreadis D., “Computational Analyses of Forebody, Inlet and Isolator Flowpath for an Airbreathing, Hydrocarbon-Fueled Engine System,” JANNAF 2003.
[23]Hawkins R.W., et. al., “Isolator Characteristics of the HySET engine,” 51st JANNAF Propulsion meeting.
[24]Capriotti D.P., et. al., “Experimental and Analytical Performance Characterization of the Aerojet Cascade Fuel Injector,” 51st JANNAF Propulsion meeting.

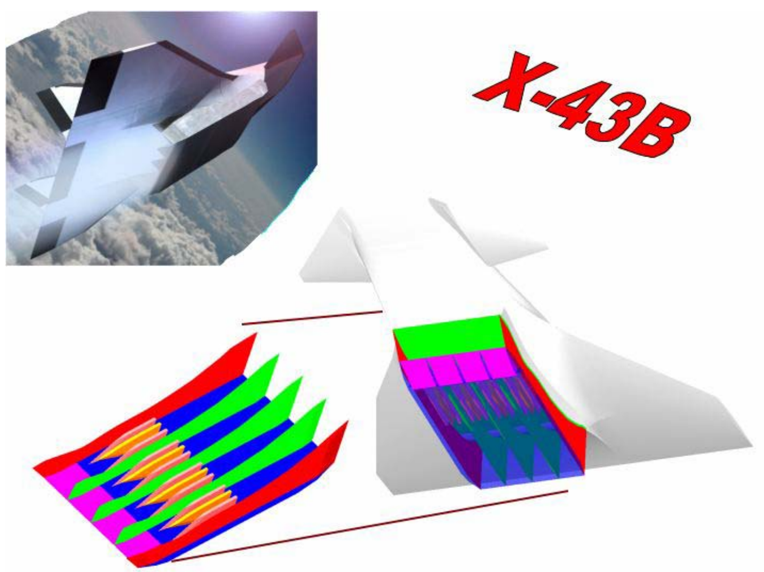

Figure 1.—Generic view of Flight Test Engine and X-43 class vehicle.

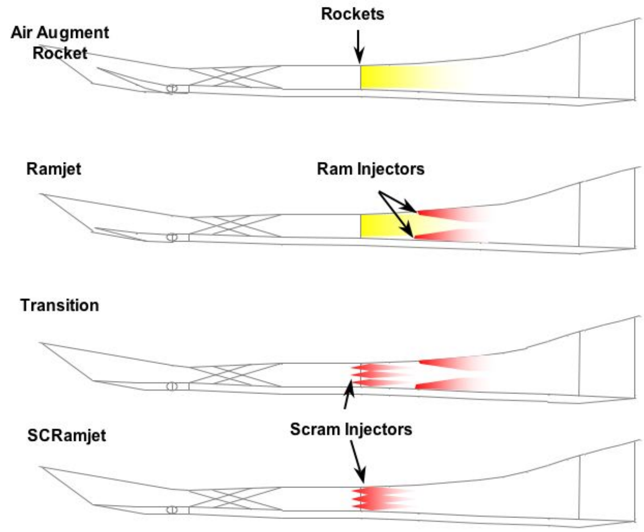

Figure 2.—RBCC engine burner modes required for the X-43B mission.

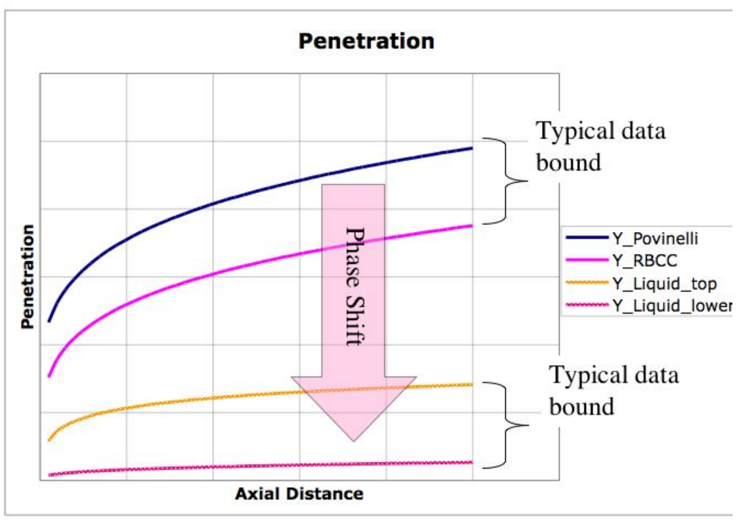

Figure 3.—Typical fuel penetration characteristic of gas-phase sonic injector compared with liquid injector.

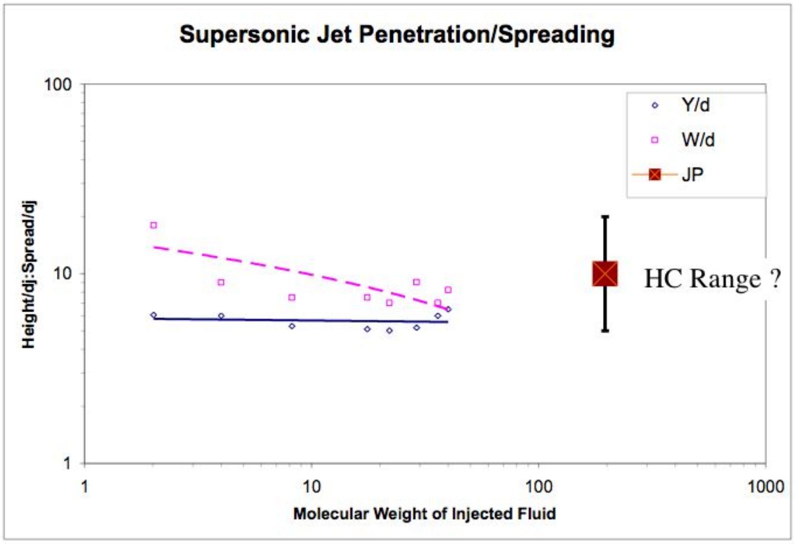

Figure 4.—Typical normalized penetration and spreading characteristics of supersonic gas injection as function of molecular weight.

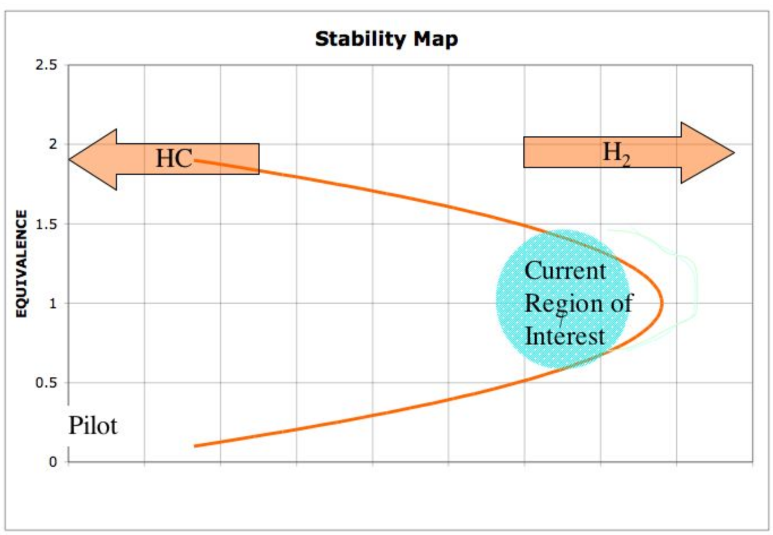

Figure 5.—Notional flame stability map of ISTAR burner compared with premixed data.

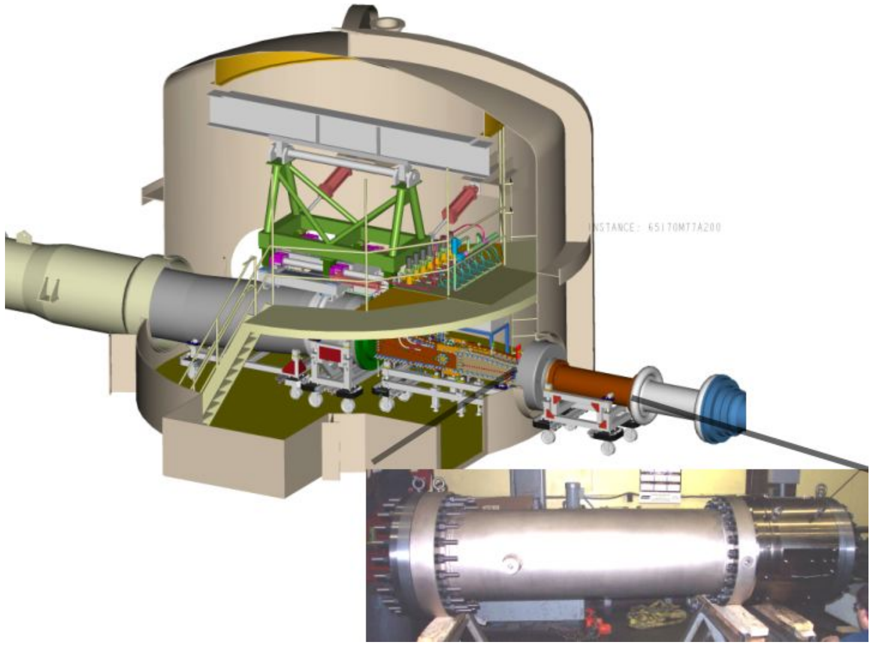

Figure 6.—Direct Connect Combustor (DCC) Rig, mixer extension, and facility nozzle installation.

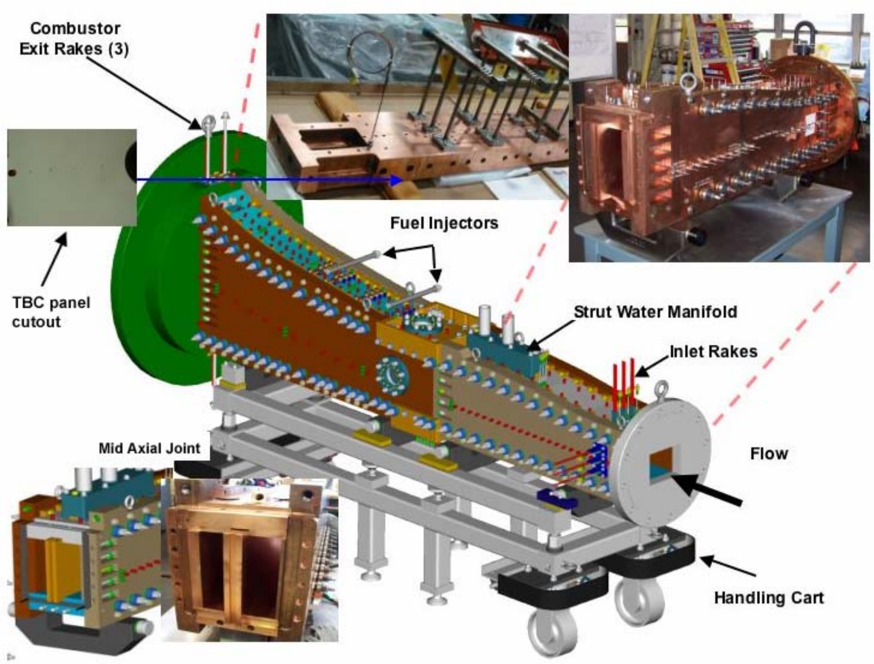

Figure 7.—Composite view of the combustor test rig and TBC’d pressure instrumentation panel.

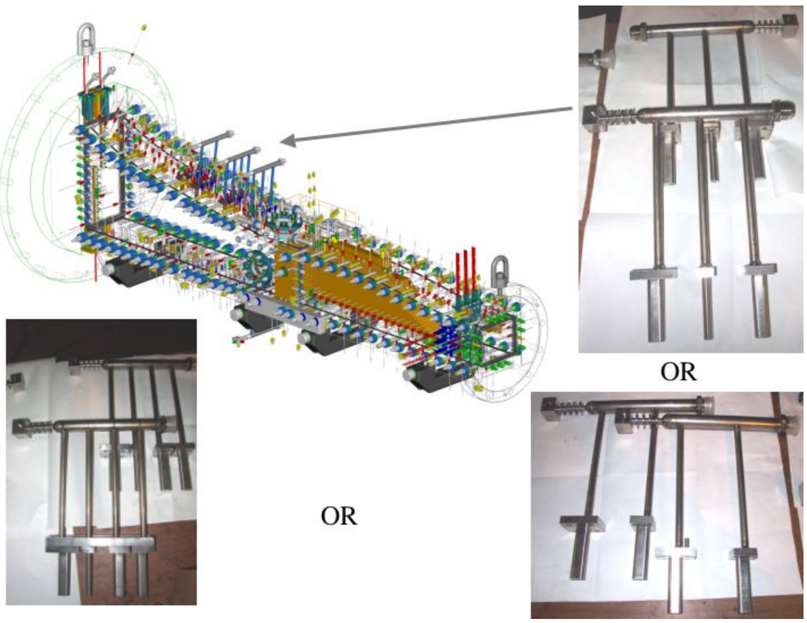

Figure 8.—Combustor instrumentation layout and various aft injector parametric capabilities.

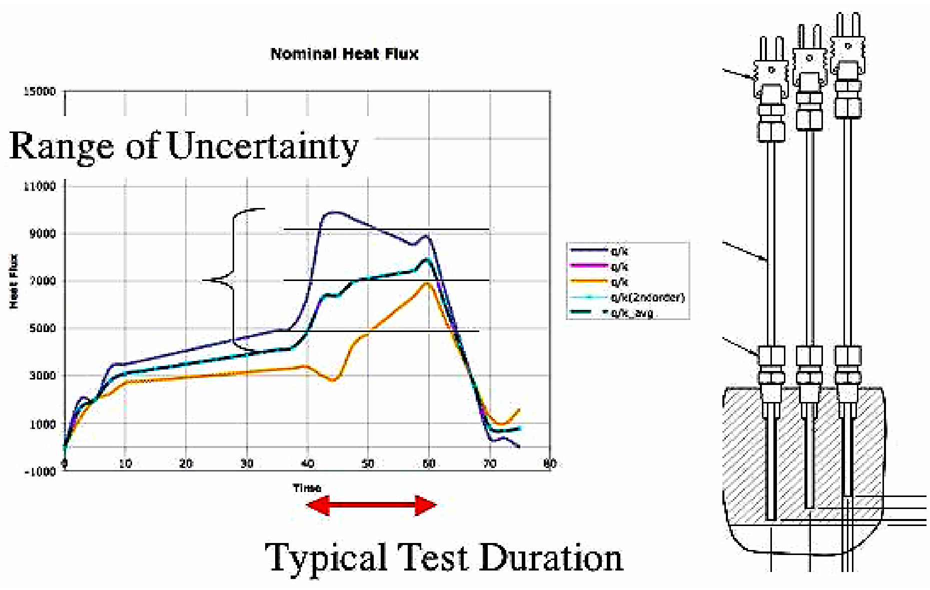

Figure 9.—Thermal couple(TC) triplet configuration and a typical heat flux computations using finite element model prediction.

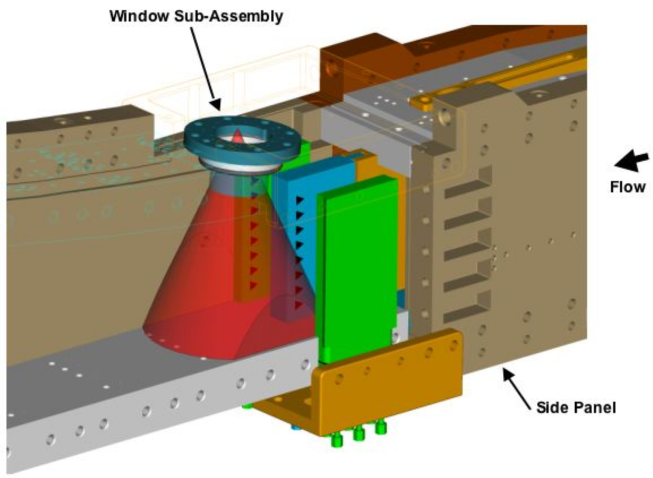

Figure 10.—Typical combustor window view factor.

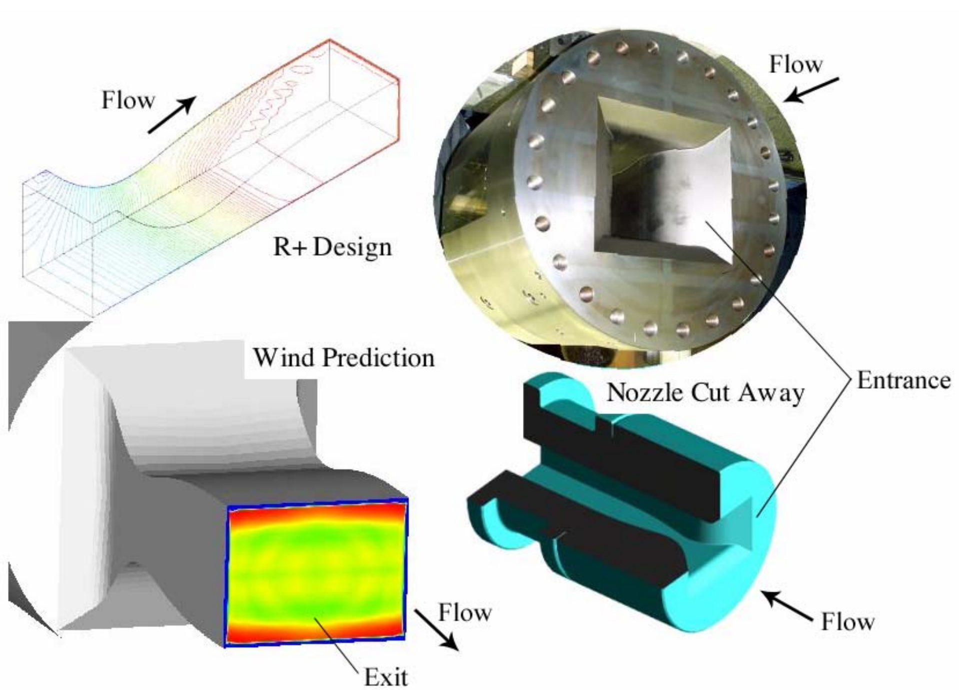

Figure 11.—Direct Connect Combustor nozzle design and hardware configuration.

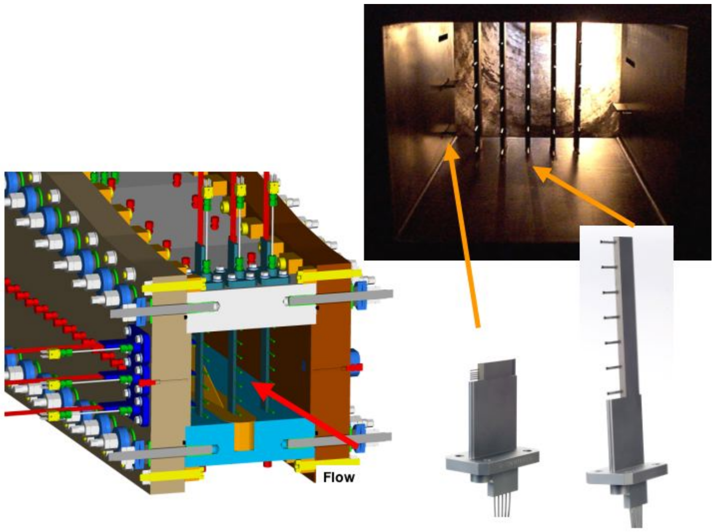

Figure 12.—Total pressure/gas sampling rakes
(two boundary layer rakes and five core rakes shown).

Figure 13.—Gas sample rack used in the chemical
combustion efficiency analysis.

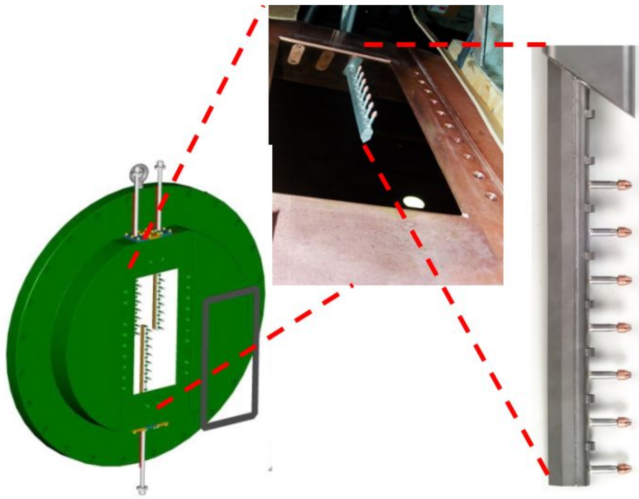

Figure 14.—Combustor exit rake configuration.

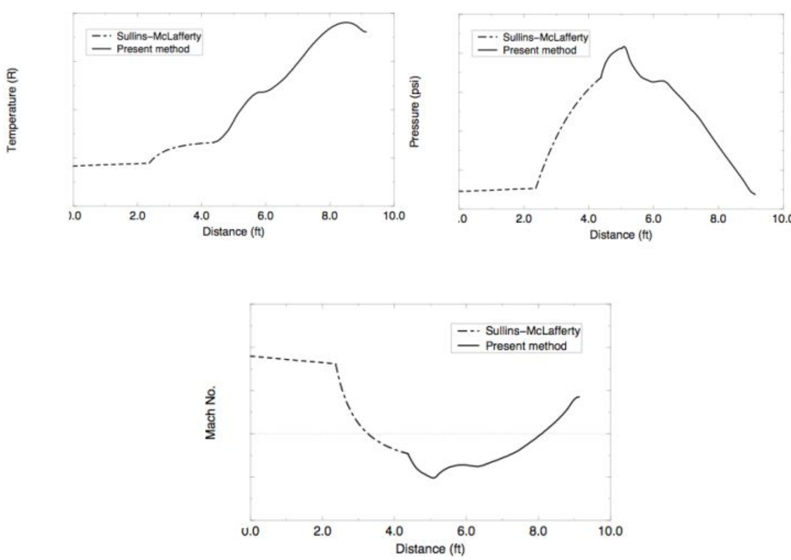

Figure 15.—One-dimensional performance characterization of the current combustor (Yungster).

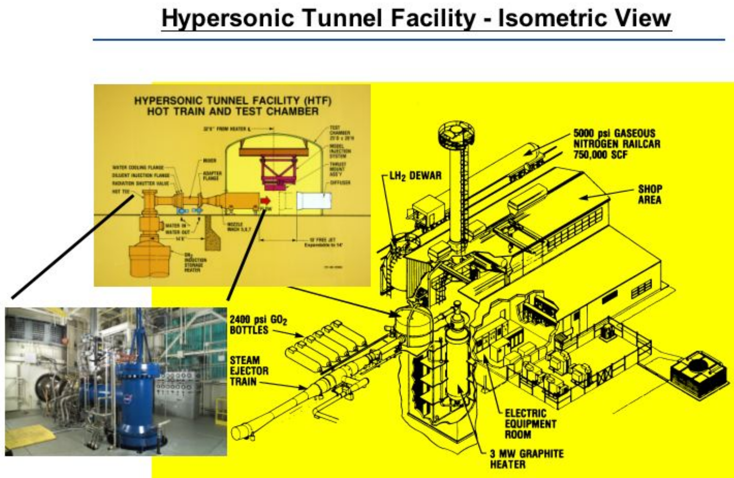

Figure 16.—View of the NASA Glenn Research Center's Hypersonic Tunnel Facility (HTF).

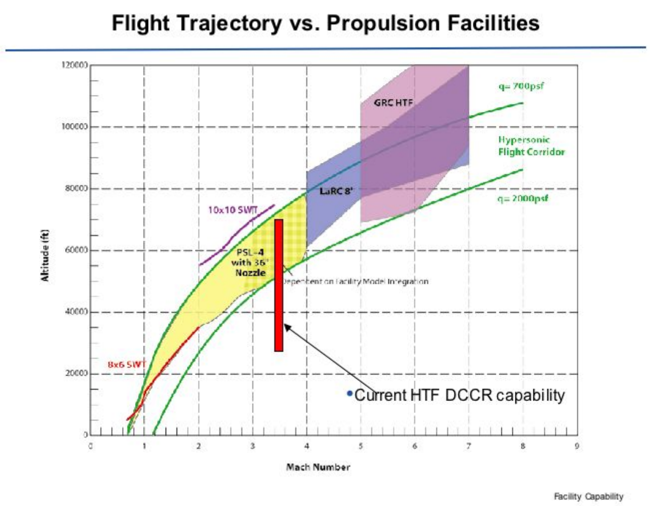

Figure 17.—Current HTF free-jet and direct connect combustor simulation capability.

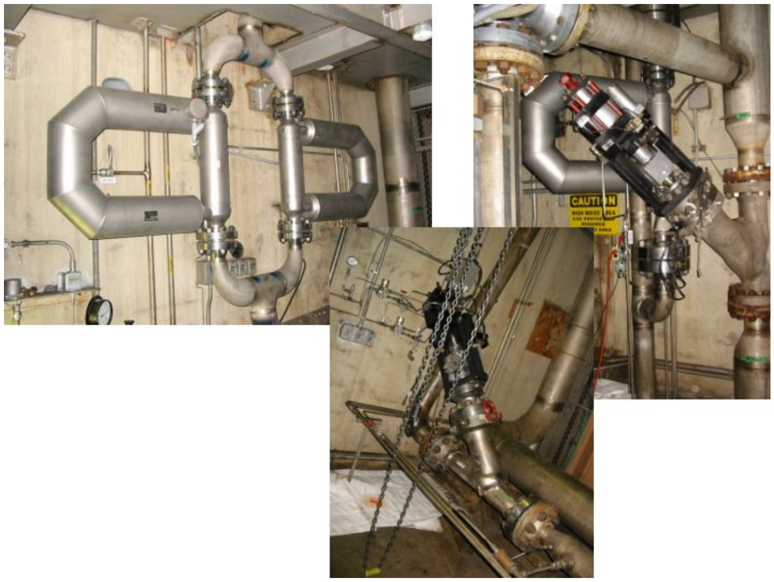

Figure 18.—New HTF N_2 and O_2 flow meters and control valves.

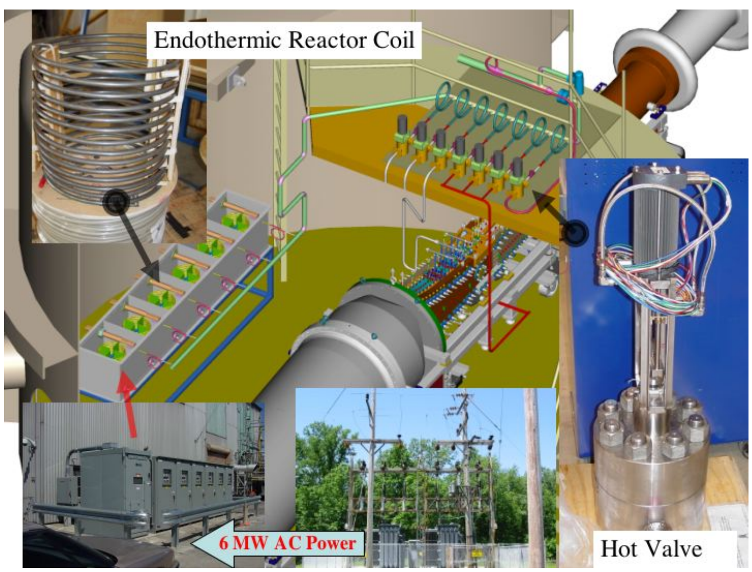

Figure 19.—Fuel Heater integration with the HTF Combustor experiment in the test cabin.

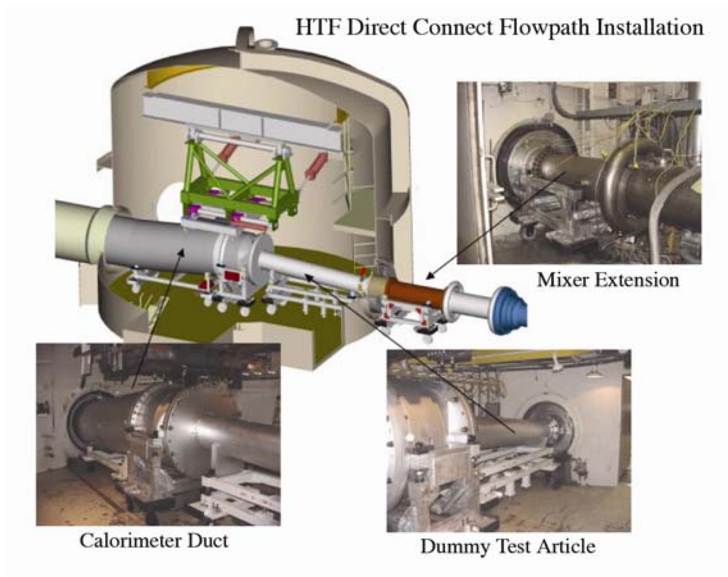

Figure 20.—Test Article used in facility nozzle calibration and IST.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	February 2005	Technical Memorandum

4. TITLE AND SUBTITLE

Design and Fabrication of the ISTAR Direct-Connect Combustor Experiment at the NASA Hypersonic Tunnel Facility

5. FUNDING NUMBERS

WBS–22–794–50–20

6. AUTHOR(S)

Jinho Lee and Thomas M. Krivanek

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–14966

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

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM—2005-213432
AIAA–2005–0611

11. SUPPLEMENTARY NOTES

Prepared for the 43rd Aerospace Sciences Meeting and Exhibit sponsored by the American Institute of Aeronautics and Astronautics, Reno, Nevada, January 10–13, 2005. Responsible person, Thomas M. Krivanek, organization code RTB, 216–433–2691.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category: 07 Distribution: Nonstandard

Available electronically at http://gltrs.grc.nasa.gov

This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

The Integrated Systems Test of an Airbreathing Rocket (ISTAR) project was a flight demonstration project initiated to advance the state of the art in Rocket Based Combined Cycle (RBCC) propulsion development. The primary objective of the ISTAR project was to develop a reusable air breathing vehicle and enabling technologies. This concept incorporated a RBCC propulsion system to enable the vehicle to be air dropped at Mach 0.7 and accelerated up to Mach 7 flight culminating in a demonstration of hydrocarbon scramjet operation. A series of component experiments was planned to reduce the level of risk and to advance the technology base. This paper summarizes the status of a full scale direct connect combustor experiment with heated endothermic hydrocarbon fuels. This is the first use of the NASA GRC Hypersonic Tunnel facility to support a direct-connect test. The technical and mechanical challenges involved with adapting this facility, previously used only in the free-jet configuration, for use in direct connect mode will be also described.

14. SUBJECT TERMS

Flame propagation; Supersonic combustion ramjet engines; Combustion physics; Hypersonic combustion; Hydrocarbon combustion; Combustion stability

15. NUMBER OF PAGES

23

16. PRICE CODE

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