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The GE-NASA RTA Hyperburner Design and Development

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Abstract

The Revolutionary Turbine Accelerator (RTA) project is a ground demonstration of a Mach 4 Turbine Based Combined Cycle engine. This new combined cycle engine developed for the ground-based demonstration will use a new type of augmentor called the hyperburner. The technical features of this new augmenter are introduced in this work. Some of the salient features include a new variable area bypass injector system and a new flame holder configuration. A summary of the hyperburner configuration and the supporting evidence obtained during the hyperburner rig experiments show that hyperburner is a viable burner concept capable of meeting the goals of the RTA ground engine demonstration project.

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] At the same time, the NGLT program is taking advantage of the significant series of advancements made over the past few years in developing fully re-usable air breathing hypersonic vehicles.[2] This program focused on two combined cycle propulsion demonstrators, one based on rocket engines and the other on turbine engines. The Revolutionary Turbine Accelerator (RTA) was the Turbine Based Combined Cycle (TBCC) demonstration project.[4] The Integrated Systems Test of an Airbreathing Rocket (ISTAR) was the Rocket Based Combined Cycle (RBCC) demonstration project.[3]

The primary objective of the RTA Turbine Engine Performance demonstration project was to design, develop, fabricate, and test a ground demonstration engine. Two of most the important objectives of this ground based engine experiments are: to demonstrate the mode transition from an augmented turbofan to a ramjet; and to demonstrate the Mach 4 thrust level required to accelerate a conceptual future X-vehicle to scramjet take over speed. Initially, ground-based testing will to be used to demonstrate a high level of thrust and Specific Impulse (Isp) at discrete notational trajectory points; at the same time, a database of relevant engine performance information will be obtained. It is envisioned that the technology and performance database developed from the ground demonstration experiments can be combined with other dual mode engine databases to develop a combination engine system for hypersonic aerospace vehicle applications.

Designated as the GE57 by the General Electric Aircraft Engine Company, the RTA engine represents a unique variable cycle engine where internal flowpath changes allow for high Isp throughout the flight trajectory for an accelerator vehicle. Figure 1 shows a cut away view of the RTA engine. Figure 1 also shows the GE YF120 turbofan engine and a state-of-the-art ramjet engine

Marquart RJ43-MA-3. These two engines have many of the technology features needed by the RTA engine. The RTA engine features a new augmentor called the hyperburner. From take-off to the region of transition to supersonic flight, this device will serve as a conventional augmentor boosting the turbine engine thrust. At high Mach numbers, the augmentor transitions to a ramjet, accelerating the vehicle to Mach 4. The primary goal of this paper is to summarize the technical characteristics of the new RTA ram burner. While this paper focuses on the ram burner, the RTA is a variable cycle turbine engine, and as such, all of the subsystems are essential to engine operation. A detailed description of the overall RTA engine system features can be found in Shafer[4,22] and Suder[5].

RTA-GE57 Engine Description

The RTA engine is very different from the famous Pratt and Whitney J58 (JT11D-12) engine[6] shown in figure 2 that powered the SR71/A12 series aircraft. The J58 engine utilized a unique bleed bypass system to match the core engine performance characteristics to its augmentor. This feature gave the J58 ramjet-like high Mach number thrust capability. In addition, as shown in figure 2, the J58 used an uncooled circumfrantial ring flame holder configuration in the augmentor. This type of flame holder configuration is similar to many of the turbojet engines developed during the 1950s and 1960s. In addition, endothermic JP7 fuel combined with a chemical lubrication additive was used to thermally close the engine and the airframe. While JP7 has excellent endothermic characteristics, it is a difficult fuel to ignite. Therefore, a pyrophoric ignition system based on triethylborane (TEB) was used in the J58 (see fig. 2). These were technically innovative features for the 1960’s time, but caused various durability and maintenance issues for this engine.

Like the J58, the RTA engine is a full variable cycle engine. Some of the durability and maintenance issues of J58 are eliminated through the use of conventional spark ignition, conventional JP8 fuel, an internally variable geometry and a fuel-cooled radial flame holder configuration. Furthermore, the RTA engine is designed and will be built according to the system-level recommendations of the high Mach turbine engine system studies, Air Force’s High-Speed Propulsion Assessment (HiSPA) and NASA’s High Mach Turbine Engine (HiMaTE) programs. The RTA engine uses several strategically located Variable Area Bypass Injectors (VABIs) in the turbine engine to maintain the optimal balance between the core turbo machinery and the burner components throughout the mission profile. VABIs are mechanical doors designed to divert airflow from various regions of the engine to another region. In some ways, the current RTA engine is similar in concept to various GE military turbofan engine products, such as the F110 and YF120 engines shown in figure 3. Nevertheless, the required RTA engine operating envelope includes operating points that are well beyond the current engine operating range. The current state-of-art high speed GE engines include the Mach 2.7 capable GE4 and the Mach 3 capable J93.[6,7] Therefore, a number of the technical challenges required careful attention during the RTA engine design process.

The hyperburner is a subsonic hydrocarbon fueled augmentor designed to meet the RTA mission requirements. A new hyperburner design and new augmentor hardware are required for the RTA engine because the operation of this burner is significantly different from a typical military augmentor. The hyperburner flow schedule is controlled through the use of variable area bypass injectors and a variable area axisymmetric nozzle. Figure 4 shows the fan bypass flowpath in the RTA engine controlled by the VABI doors. At takeoff, most of the air delivered to the hyperburner comes through the engine core; hence, the engine operates very much like a conventional augmented turbofan engine. Here, the maximum combustion efficiency for the overall engine is maintained by using a separate set of staged injectors to fuel and to burn the by-pass air and the core flow separately. At Mach 4, most of the air bypasses the core, coming through the outer region of the fan directly into the afterburner; here, the engine acts very much like a ramjet engine. A larger portion of the fuel is shifted from the core injectors to the by-pass injectors to accommodate this ramjet like engine operation. The combination of flow control and tailored fuel schedule enables this engine to make a smooth and stable burner transition from an afterburner to a ram burner. A conceptual fueling schedule trend needed to accomplish this transition is shown in figure 10. Figure 10 only shows the core and the bypass fueling trends are shown for simplicity. Several key issues like burner transient behavior and the burner thermal environment are also of utmost interest to the project because of their potential impact on the flight engine design.

In order to reduce financial and technical risk, an existing GE-YF120 asset, shown in figure 3, is used as the basis for the RTA variable cycle engine. Initially, the RTA program vision was to use the YF120 engine as-is in the ground demonstration engine. Therefore, much of the YF120 core engine was retained as-is including the main combustor. However, adopting the YF120 core engine for the RTA application required many more changes than originally envisioned; these changes became evident once the new fan and the expected operating temperature conditions were combined with the durability requirements. Some of the changes, like the enlargement of the engine casing size, required rework of the fuel system components to the main burner. Furthermore, slave cooling systems from the facility are used to thermally close the ground demonstration engine. This slave cooling is used to achieve thermal closure for a number of legacy secondary system components and the hyperburner. Limited availability of coolant at the higher Mach numbers is a major difficulity for this engine and the program. Currently, the slave cooling is also used to maintain thermal balance for the rear engine structure, majority of the hyperburner and axsymmetric nozzle. The use of slave cooling enables the RTA project to also maintain room temperature JP8 as the primary fuel for the engine, enabling the current RTA combustion system to be designed using proven aero-thermo-mechanical design practices and limitations. Therefore, it is important to note that additional combustion system analysis may be required to develop fully operational flight engines from the RTA database. The flight weight and self contained thermal closure requirement for these applications may require additional heat load into the JP fuel beyond the currently simulated range. The stability of the new hyperburner configuration was extensively rig tested and analyzed to ensure that the augmented turbofan to ramjet transition can occur without performance and operability risks.

Hyperburner: A New Kind of Ramjet

A new augmentor design with new flame holder and new fuel injector configuration is needed to meet the RTA project objective of sustained thrust and durability. At the same time, the goal of the proposed RTA ground demonstration experiment is to obtain a fan, hyperburner, and ground demonstration engine system operability and performance database. Therefore, highly instrumented, parametric-capable and mechanically flexible ground-based demonstration engine components are needed. A new hyperburner system with these features was designed for the RTA engine to meet these requirements. In addition, the current state-of-the-art information on screech, rumble, ignition, heat release, and flame spread were used to match this new afterburner to the core while the new engine components were being designed. Furthermore, some engine and burner parametric capability are needed because some of the required RTA engine operation exceeds the limitations of the current operability database. At these conditions, the parametric capability in the hyperburner can be used to ‘tune’ the system for optimal performance.

Mechanical flexibility was allowed in the design of this burner because thermal closure and flight weights were not requirements for this ground demonstration engine. This enabled the ground demonstration engine to use off-the-shelf fuel pumps, controllers, and mechanical parts. Furthermore, many of the core F110 augmentor parts, built from new material for thermal considerations, are directly adapted to the RTA engine. The adopted components include the integrated fuel injector flame holder configuration, some parts of the screech liner, and nozzle components. Figures 5 and 6 show the current hyperburner configuration along with GE F110 and P&W J58 augmentors for comparison. Figure 6 also shows the current GE F110 axisymmetric nozzle design, which is similar to the design adopted for RTA hyperburner application.

Baseline Hyperburner Design for GE57

Although, highly regarded, the F110-129 augmentor design, shown in figure 3, would not be simple to implement for the RTA application because of the fixed geometry mixing chutes used to combine the fan flow to the core flow. Therefore, the RTA hyperburner design is based on a more conservative and simpler concept of separate streams, where the core flow and the bypass flow are separately fueled and mixed over a conservative axial length. This design concept enabled the RTA engine to use a much more practical VABI door mechanical configuration, which was designed using the F110 asymmetric nozzle mechanical part designs with some unique modifications. In addition, the RTA ram burner was designed with a full range of modern afterburner features, such as high combustion efficiency, acoustic stability, low dry losses, and wide fuel-air modulation capability. A typical configuration of the RTA hyperburner cross section is shown in figure 6. Figure 6 shows the essential features of the current hyperburner design, such as the VABI door and the highly integrated radial fuel injector flame holder. The internal flame holder- fuel injector configuration is not shown in this figure because of the proprietary nature of the design. The VABI door, shown in figure 6, in combination with the dual VABI upstream (shown previously in figure 4), near the exit of the fan, is used to control the inflow condition to the hyperburner and vice-versa for the fan backpressure during high Mach number operation. The initial fuel injection and the control strategy were developed to maintain various design parameters, such as bulk velocity and static conditions, within the current base of experience. This strategy was used to limit any major performance and operability risks for the initial RTA engine demonstration. Even with these constraints, there are significant technical risks at the high Mach number operating point because the required operating environment exceeds the current base of experience. The conservative nature of the current ground demonstration engine design can be seen in figure 7, where the heat release rate characteristic of the hyperburner is compared with other highly successful augmentors. The heat release rate parameter is defined as the release of the energy content of the fuel per combustor volume and pressure. Therefore, lower value represents more conservative the burner design and a larger engine. Here, the variability in predictions shown in figure 7 represents the uncertainty in the performance information available in the open literature.[8,9,10] The Pratt and Whitney TF30 engine data was obtained from McAuly.9 The GE F110-129 engine data was obtained from Holzman.[8] In addition, a good sense of the J58 operating conditions were obtained from Reithmaier,[20] Conner[11] and Gunston.[10]

Using the F110 engine radial flame holder design eliminates the durability issues of the uncooled flame circumferential holders used in the engines like J58 and GE4. The final configuration of the hyperburner utilizes the advanced integrated fuel injector flame holder struts. This current configuration takes into consideration the latest combustor development ideas such as those proposed by Roquemore[12] among others. In addition, care was taken to avoid any aeromechanical designs that may cause pressure oscillations on the order of a couple hundreds of hertz and couple of thousand hertz, where it may lead to rumble and screech issues affecting the augmentor liner durability.[13,14] Liner durability of the F110 engines used in F-16 fighters has been a problem in the past and has been extensively studied at the Arnolds Engineering Development Center (AEDC)[15] by both GE and the US Air force.

The RTA hyperburner is a subsonic hydrocarbon fueled combustor and is not like other high-speed burners used in ramjet and scramjet engines. Here, variable geometry rather than the thermal choke is used to maintain the hyperburner at design conditions. Figures 8 through 10 show the expected trend of the average bulk average velocity, fuel splits, static pressure and temperatures as a function of flight Mach numbers. The trends in these figures show that fairly constant static conditions can be maintained up to Mach 3 flight conditions; beyond Mach 3, there is a rapid drop-off in combustor bulk velocity and a rapid rise in static pressure. Maintaining high performance while avoiding operability issues caused by flow transients and unloaded core at this region is a key challenge for this and future high Mach turbine engines. A conceptual hyperburner zonal fueling strategy verified through component test rig experiments is shown in figure 10. This conceptual fueling strategy clearly shows the current design intent of maintaining a separate core and bypass streams in the hyperburner.

Matching the hyperburner with these unique flow features and the core engine required a careful series of experimental work and supporting analysis to develop the level of confidence needed to develop a full-scale engine. The assumption that the room temperature JP8 is available throughout the accelerator mission profile directly leads to the conclusion that many of the hyperburner operation conditions are very similar to current augmentor operating conditions. Therefore, many of the legacy analytical model and mechanical design practices are directly applicable and were used to design the hyperburner. Furthermore, some of the aero-design assumptions and practices were verified using the latest Computational Fluid Dynamics (CFD) tools. Here, aerodynamic losses and flow separation issues, heat transfer issues, blockage effects, and flame holder lip velocity were checked using commercial and government developed CFD tools. Typical CFD solution obtained using the WIND code[16] to study the effect of flow separation on a generic benchmark augmenter configuration is shown in figure 11. Typical CFD and heat transfer prediction obtained using the GlennHT[17] code for a generic benchmark augmenter configuration is shown in figure 11. These predictions do not show any significant separation or significant heat transfer issues that may affect overall performance of the engine. However, these calculations do show that there is some risk of localized separations in various locations of the hyperburner, which may lead to local thermal difficulties.

In addition to the CFD analysis, a parametric experimental study was conducted to check the combustion efficiency of the current zonal fueling scheme, ignition characteristics, and the aero-thermal environment of the flame holder. In addition, the data obtained from the rig experiment was used to calibrate the thermal and fluid dynamic tools; some were later used in the design of the hyperburner. Several CFD predictions of the component test rig were made to gain insight into the component test flow physics. This analytical effort showed that the modeling complexity, modeling uncertainty and the computational cost made reacting flow calculation an impractical parametric tool for even this ‘simplified’ rig experiment. However, even though routine detailed predictions were not possible, useful physical insights into the flame holder flow physics were obtained from the calculations performed. Thus, both CFD calculations and the rig experiment were used to gain additional confidence and as sanity checks of the hyperburner design assumptions. Ebrahimi[20] using a structured flow solver called GPACT conducted the reacting flow CFD simulation in support of the component test rig study; a typical solution obtained is shown in figure 12.

Component test rig and experimental data.—A simple “partial-scale” combustor component rig experiment was extensively used to build confidence in the current flame holder configuration. This component test rig is a water-cooled two-dimensional rectangular test section and is capable of simulating the one atmosphere condition of the hyperburner. In addition, the rig test section has a window so that the flame can be characterized visually. The component test experiments were conducted in several stages; from cold flow linear flow calibration experiments to the demonstration of near complete combustion efficiency of the VABI separated zonal fuel strategy. A typical experiment conducted using the hyperburner component test rig is graphically shown in figure 12. Figure 12 shows the exit area of the experiment. The internal flame holder- fuel injector configuration is not shown in these figures because of the proprietary nature of the design. Most of the combustor rig experimental investigations were conducted to verify the hyperburner design assumptions. A step-by-step procedure was used to confirm that the combustion efficiency and wide range of stability required by the RTA mission could be obtained from the current hyperburner configuration. Here, various flight conditions from sea level static condition to Mach 4.0 thermal conditions were simulated. The flight conditions simulated in the component tests are compared with the required flight condition in figures 8 and 9. The stability experiments were conducted following a routine GE design practice; where separate fuel injectors and flame holders were used to simulate the integrated configuration to be used in the engine.

The experimental data obtained from these tests showed that this hyperburner configuration is able to achieve the wide stability range, high combustion efficiency, and acceptable pattern factor and igniter performance needed by the engine. However, the facility and the mechanical limitations prevented this component test rig from being used to obtain wider range of operability data on the effects of burner static pressure change and pressure transients. Furthermore, all tests were conducted using room temperature

JP8 and the impact of additional thermal stressing of the fuel that may occur in the engine system was not considered in the flame stability rig experiments conducted. Furthermore, the thermal chemical condition of the core flow was not matched to the flight engine conditions and all of the experiments stayed within the facility limitations. It is also known that inlet flow distortion into the ramjet combustor section can have significant impact on the achievable combustion efficiency. However, inlet distortion characteristic of the hyperburner has not yet been modeled nor simulated in rig experiments. Nevertheless, hyperburner flame holders, VABI flaps, and the turbine struts were carefully designed to minimize any direct wake interactions and seal difficulties for the engine.

Advanced flame stabilizer concept: A new flame holder configuration was developed for this engine. The RTA-GE57 flame holder configuration represents the latest technological evolution of the technologies used in other high speed engines. Furthermore, the new flame holder configuration promises to have better ignition and stability performance over the circumferential flame holders used in GE4s or earlier F110 engines and adds to the current high speed flame holder information base.[4] Shafer[22] summarized the new flame holder concept. Extensive rig testing was conducted on the new flame holder design to verify performance in terms of stability range, final configuration, igniter layout, and initial fuel injection strategy. Here, a three-dimensional non-reacting CFD analysis was valuable in gaining insight into the flow feature that gives this combustor configuration its unusual stability characteristics. The current RTA hyperburner flame holder configuration performance, as measured by combustion efficiency and stability, was verified through a component test rig experiment. The component test testing did not yield enough quantitative data to fully characterize the new hyperburner operation because of the differences between the engine and the rig, but was optimized enough to be included in the baseline hyperburner design.

Combustion efficiency: The chemical combustion efficiency obtained from some of the component test rig experiments is summarized in figure 10. In this figure, the chemical combustion efficiency trend is plotted as function of the flight Mach number. Additional lines are plotted to show the range and variation of the data obtained. This figure shows that high combustion efficiency is achievable with the current RTA flame holder configuration. It is also important to note that these experiments were conducted using a fixed geometry flame holder configuration along with a fixed geometry secondary flow system, which may need additional adjustments on the engine. Therefore, the secondary liner cooling and screech flows used by the engine's thermal closure must be carefully considered when the overall combustion efficiency of the engine is compared with these measurements. The RTA project vision is to reduce the overall impact of this thermal inefficiency through use of external cooling and thermal management system yet to be developed.

Flame stability: Characteristics: In addition to the combustion performance data, this rig and the current hyperburner flame holder configuration were used to obtain flame stability data. Figure 13 compares typical stability characteristics of the current hyperburner flame holder data to the data found in Ozawa[19] and data on other high-speed burners.[18] Figure 13 shows that this burner configuration does indeed provide a wider flame stability range than other more conventional burners. This comparison also shows that the current advanced combustor configuration can operate almost like a premixed hydrocarbon fueled burner in terms of stability. Here, both lean and rich sides of the stability limits were explored with and without the core flow present, and the data obtained showed that current staggered flame holder configuration is capable of obtaining the high combustion efficiency needed for the RTA engine system. It is also worthwhile to note that most of the dual mode (high Mach) burners are designed in a much narrower region located toward the center of the fuel-air ratio. Therefore, it may be possible to trade this stability with other engine design parameters to improve the overall packaging for future turbo-ramjet engine designs. A typical convective burner Mach number map of various burners used in hypersonic applications is summarized in figure 14.

During an injector screening experiment, some coking of the injectors was encountered when a set of the candidate fuel injector design did not atomize the JP8 as expected. This experience showed that fuel injector coking is a strong possibility if the injection pressure and or thermodynamic state of the fuel are pushed beyond the designed state. Therefore, the fuel-coking issue may need to be revisited when the thermal balance for a flight engine is considered. This is especially true if the heat load into the fuel is increased, since that can significantly elevate the fuel and fuel line temperatures. Furthermore, sensitivity to the actual mechanical configuration of the driver hole configurations was seen during rig testing. These sensitivities, however, were not quantified beyond the baseline points needed for the engine design. Furthermore, the importance of the proper thermal design was further reinforced to the design team when the VABI mechanism in the component test rig failed during testing due to a mismatch in component design conditions.

Summary

The technical features of a new augmenter design for the RTA program has been introduced. Some of the salient features and the design intent of this new burner, called the hyperburner, are the new variable area bypass injector (VABI) and the new flame holder configuration. All of supporting evidence obtained during the partial-scale component rig experiments and design analysis showed that the hyperburner is a viable burner concept capable of meeting the high performance goals of the RTA engine. Some of the supporting evidence includes wide stability limits and high chemical combustion efficiencies. The analysis presented shows that the current burner configuration should be able to achieve the RTA performance goals. Some work remains in addressing questions relating to the combustor performance as a function of thermal closure for the future flight engine.

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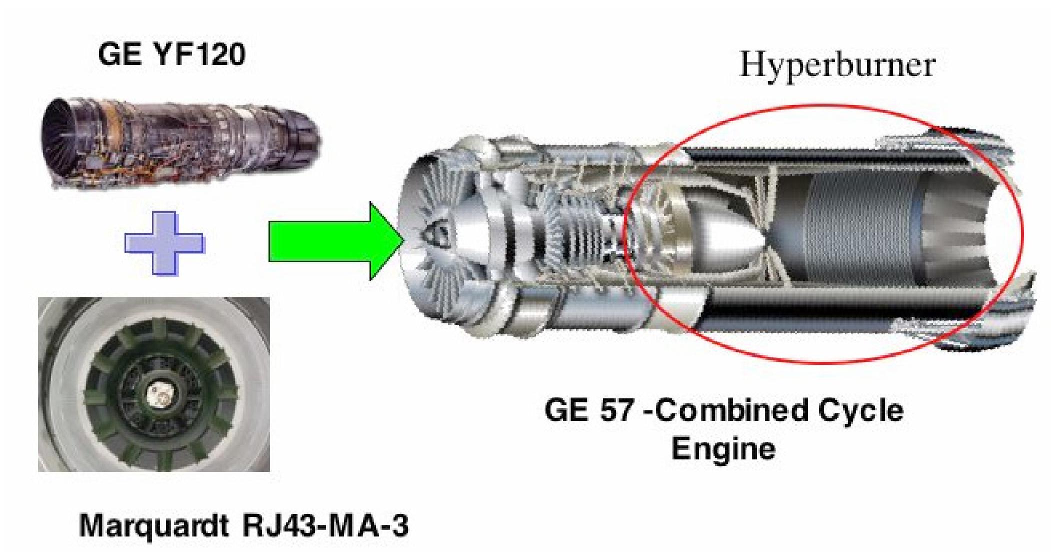

Figure 1.—RTA-GE 57 Ground Demonstration Engine.

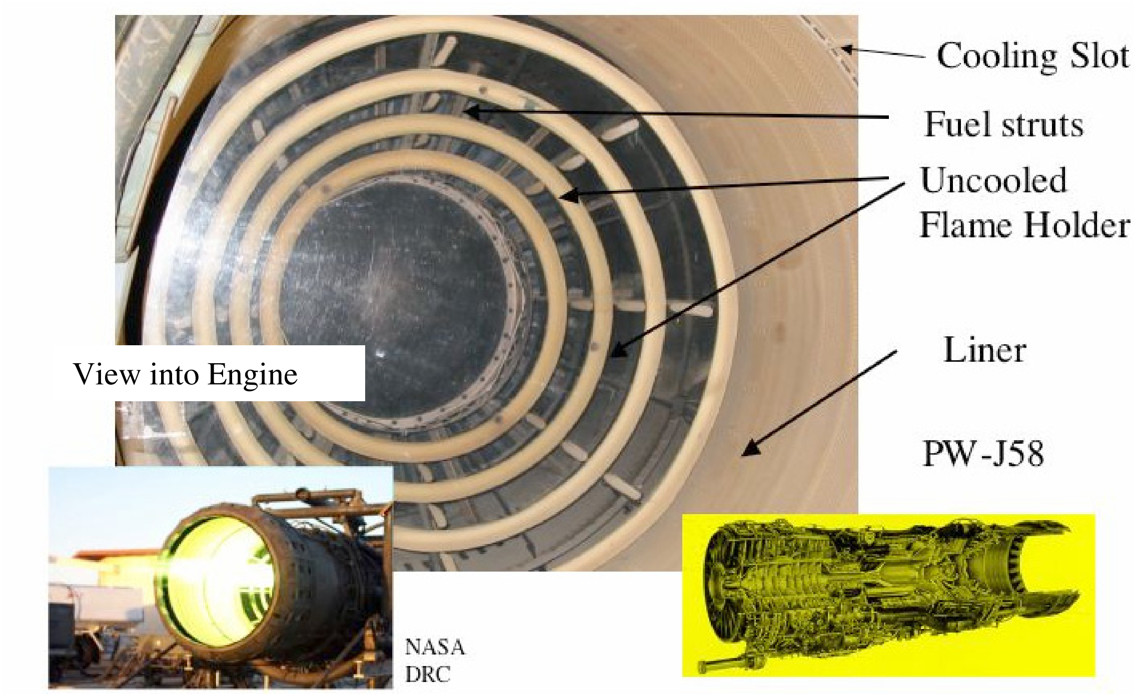

Figure 2.—PW J58 Engine and Flameholder Configuration.

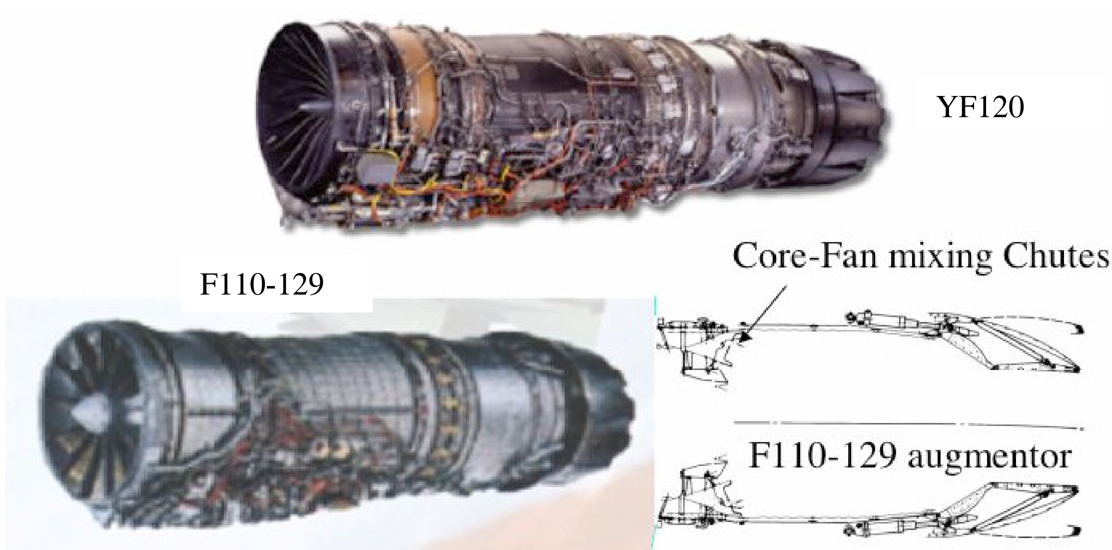

Figure 3.—GE YF120 and GE F 110 engine and F110 Augmentor Cross Section.

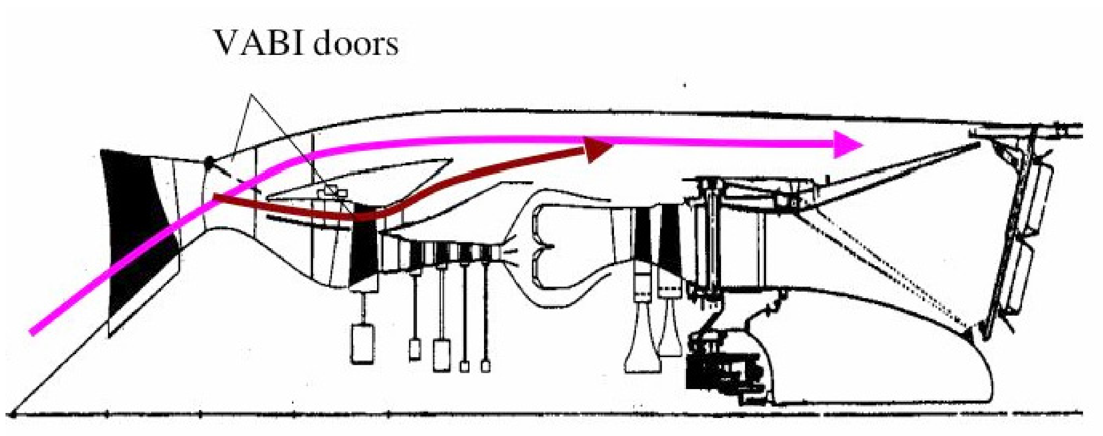

Figure 4.—Conceptual view of the RTA Fan bypass passage and front VABI configuration.

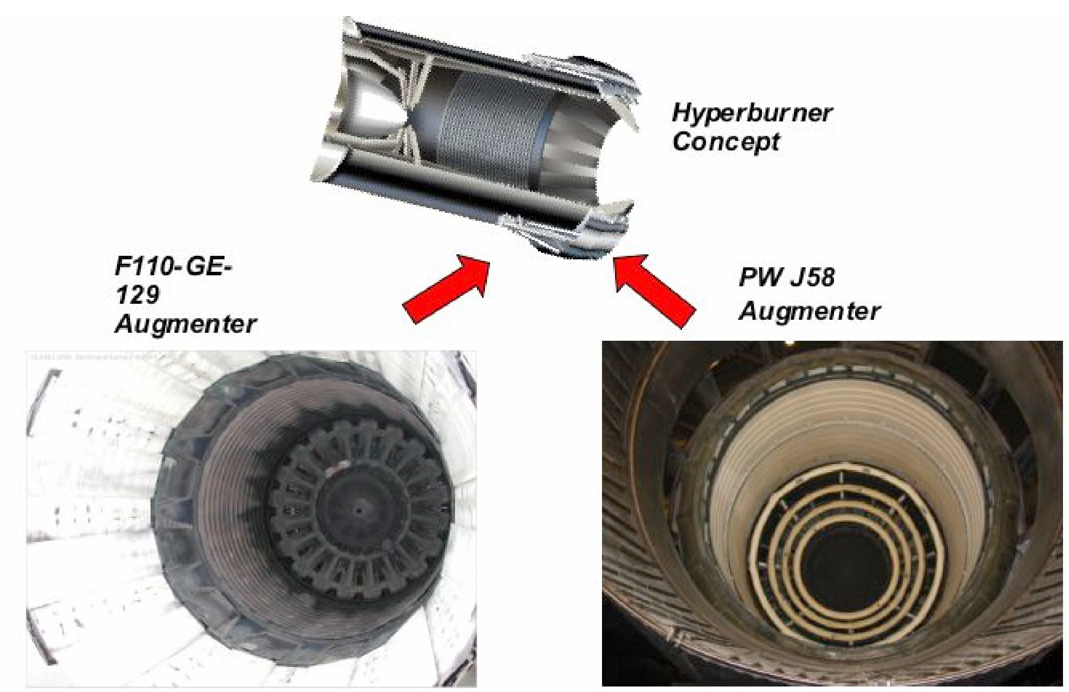

Figure 5.—Current RTA Hyperburner compared with F110 and J58 augmentor configurations.

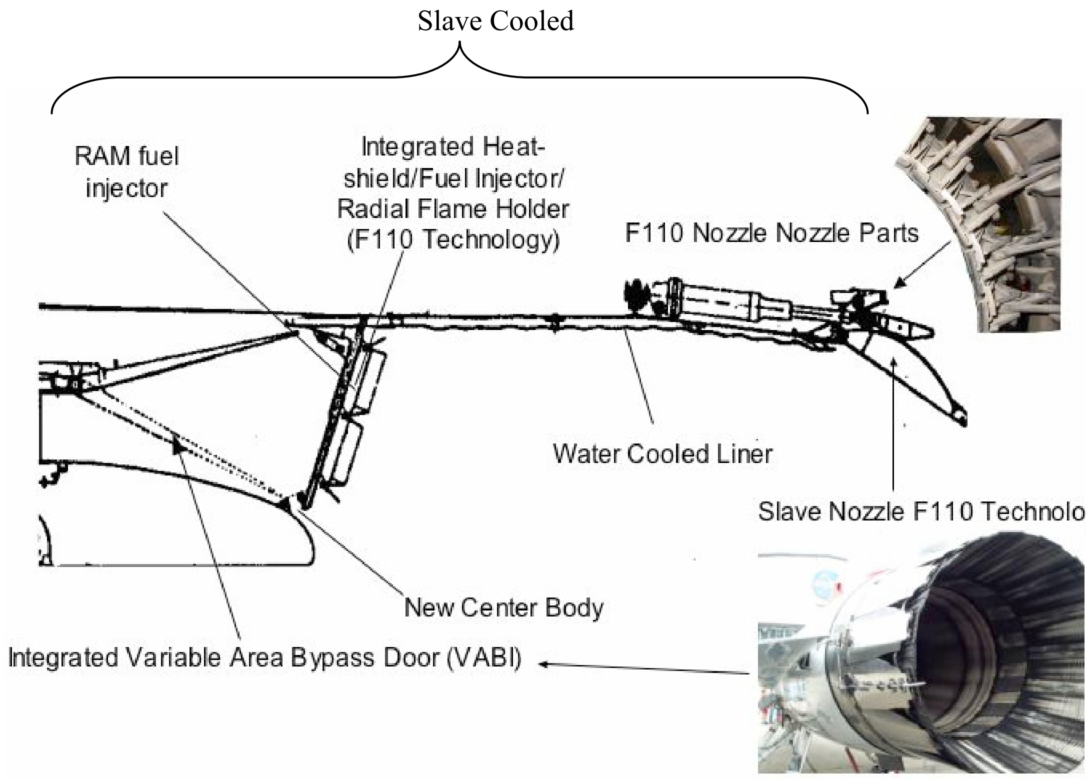

Figure 6.—Conceptual View of RTA Hyperburner and related engine hardware.

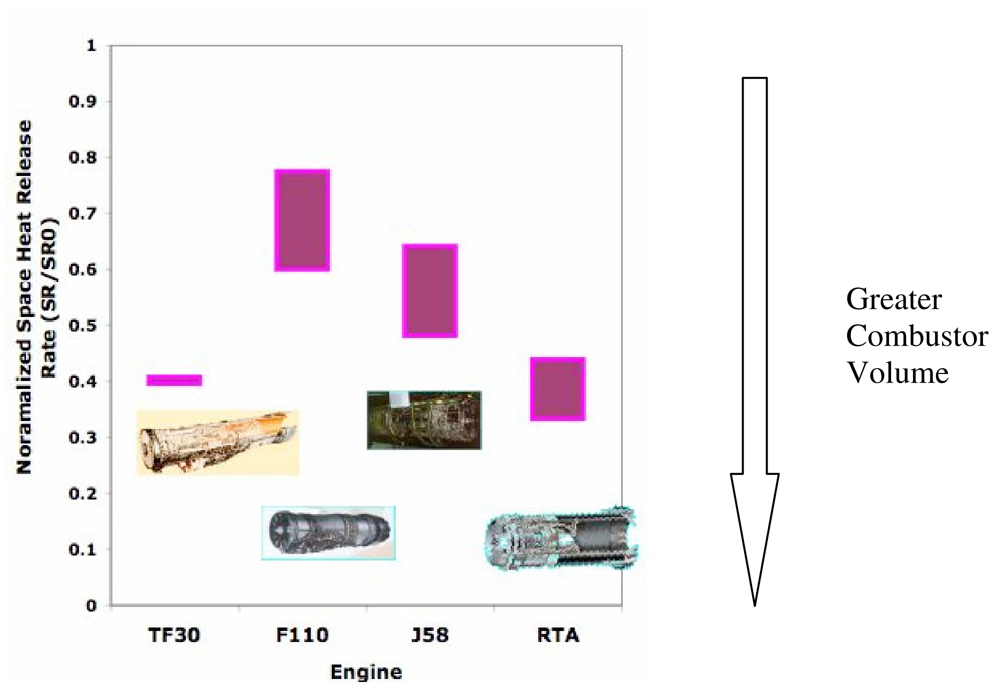

Figure 7.—Comparison of the normalized heat release rate of various engines.

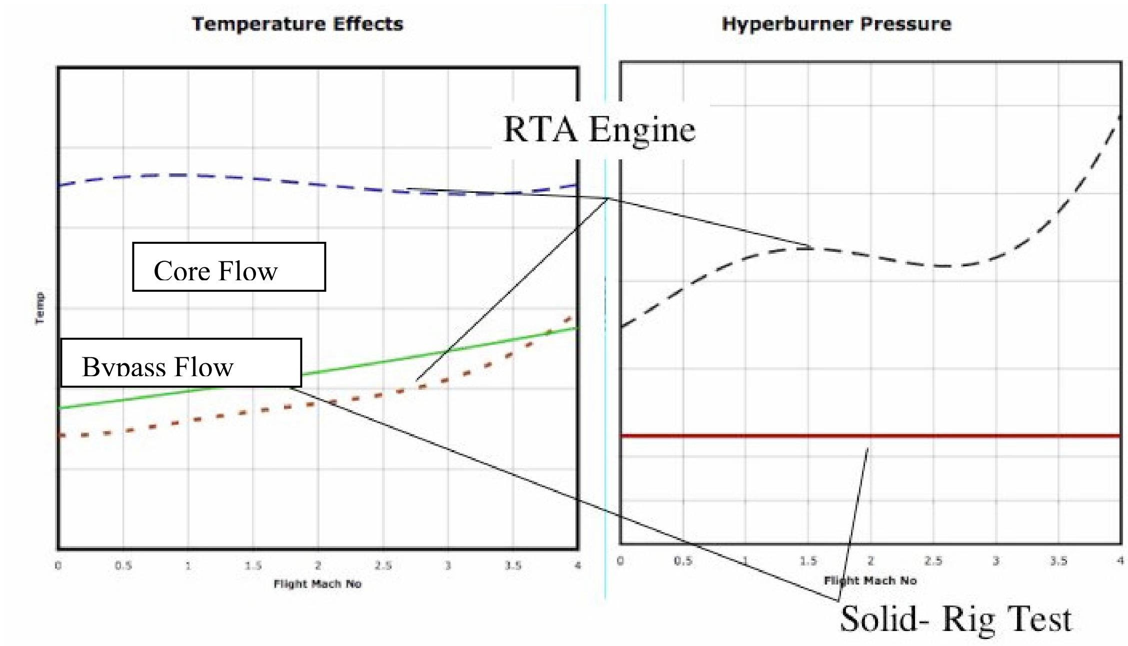

Figure 8.—Comparison of the Hyperburner operating conditions to rig simulated conditions.

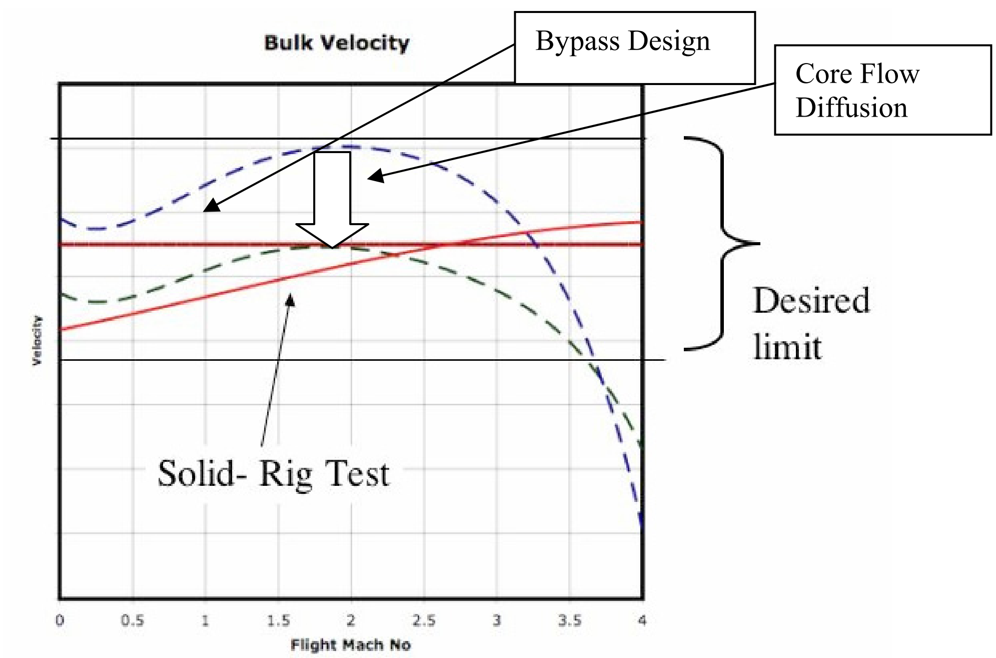

Figure 9.—Typical bulk velocity profiles through the flight envelope of the RTA engine.

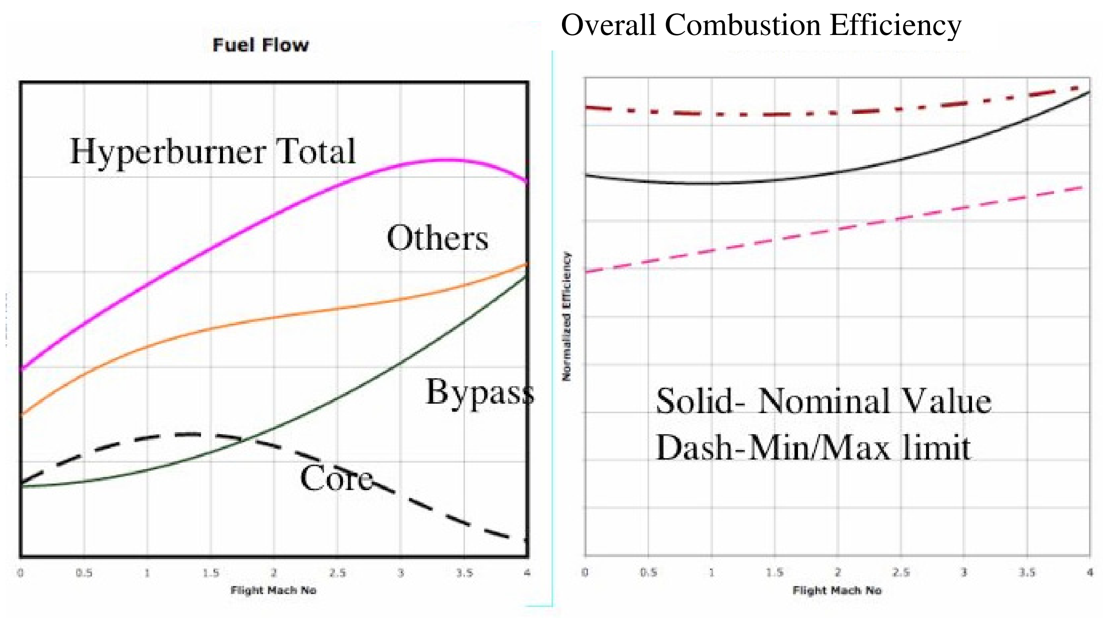

Figure 10.—Total Fuel flow for the Hyperburner as a function of the flow regions of interest and Chemical combustion efficiency obtained from the stability rig experiments shown as a function of the flight conditions simulated.

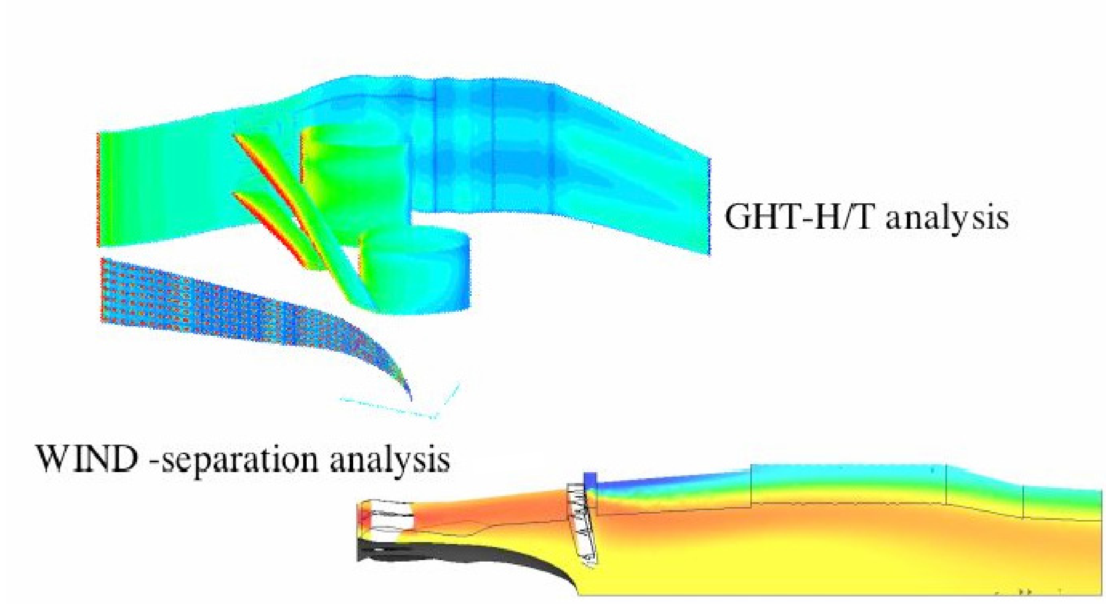

Figure 11.—Typical Hyperburner CFD solutions to a Benchmark problem similar to RTA.

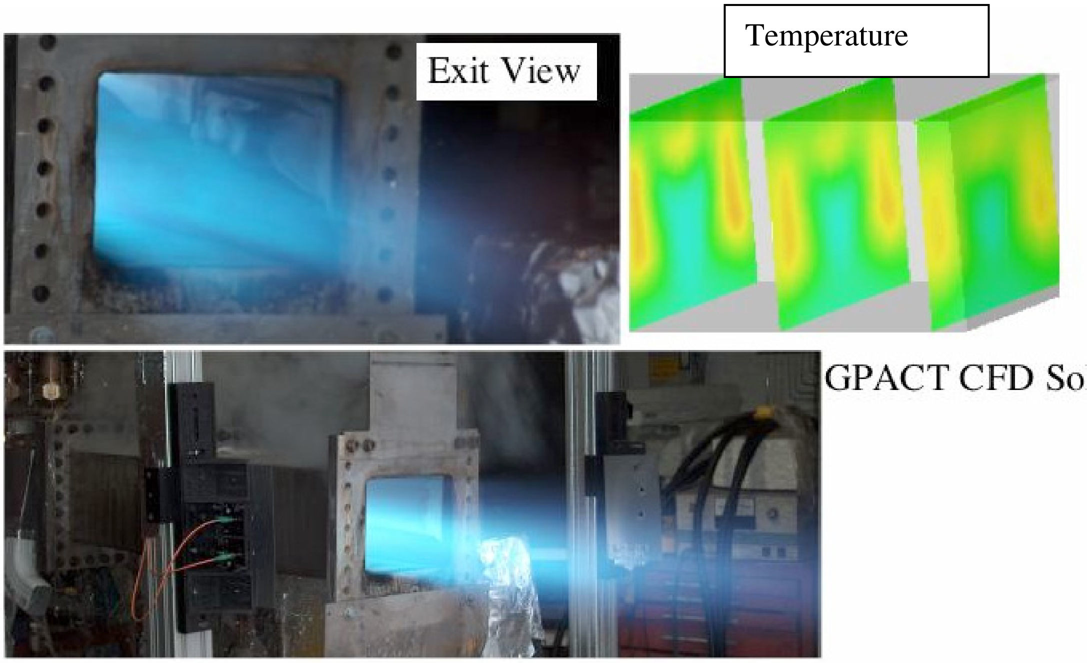

Figure 12.—Typical component test rig and a view of the experiment conducted in support of the hyperburner design.

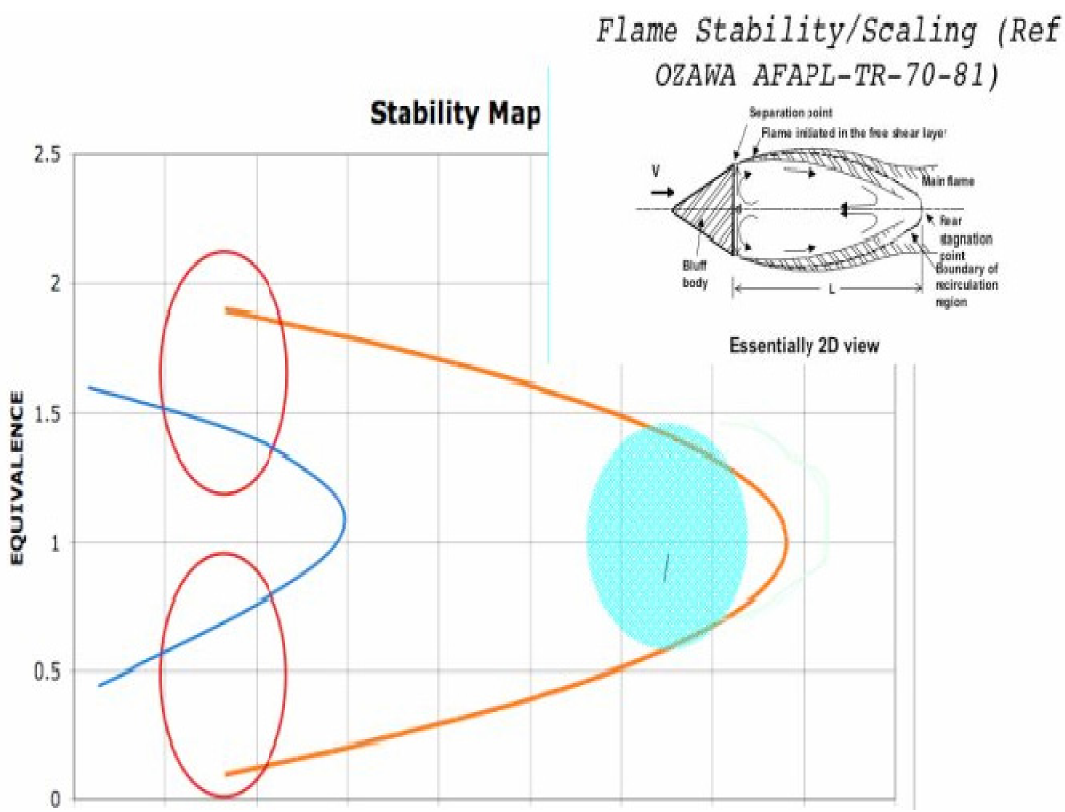

Figure 13.—Typical 2–D view of the Stability Model correlations and Summary of the stability data obtained through the stability rig experiments.

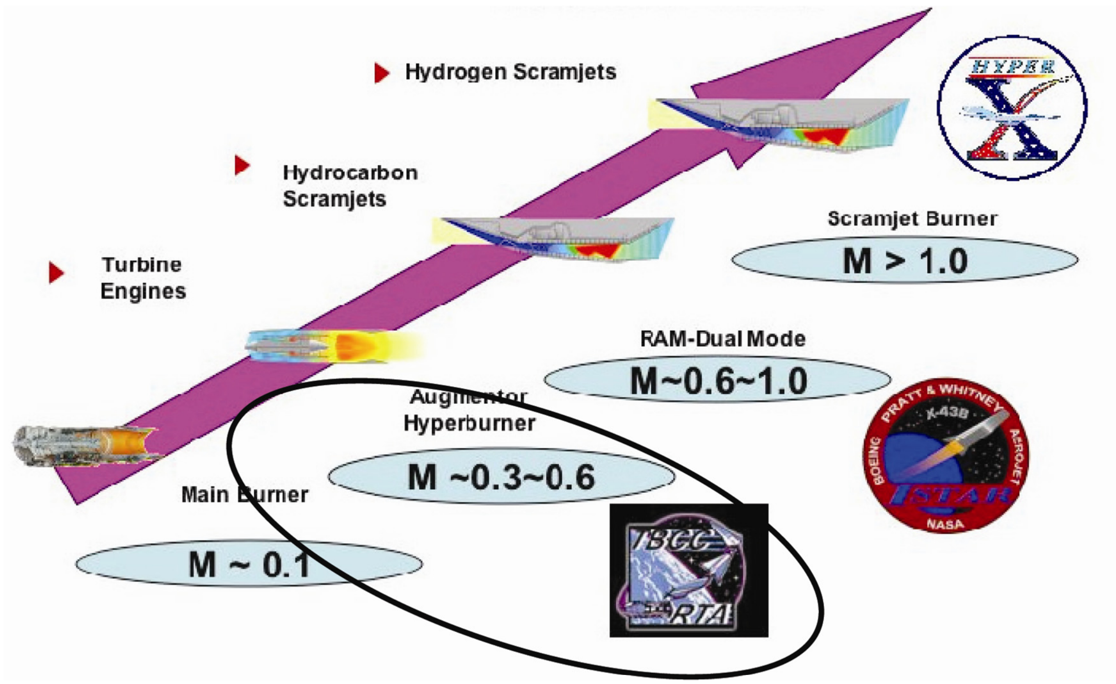

Figure 14.—A summary of the burner design conditions for hypersonic flight applications.

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

The Revolutionary Turbine Accelerator (RTA) project is a ground demonstration of a Mach 4 Turbine Based Combined Cycle engine. This new combined cycle engine developed for the ground-based demonstration will use a new type of augmentor called the hyperburner. The technical features of this new augmenter are introduced in this work. Some of the salient features include a new variable area bypass injector system and a new flame holder configuration. A summary of the hyperburner configuration and the supporting evidence obtained during the hyperburner rig experiments show that hyperburner is a viable burner concept capable of meeting the goals of the RTA ground engine demonstration project.

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