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Scott R. Thomas, Donald T. Palac, Charles J. Trefny, and Joseph M. Roche
Glenn Research Center, Cleveland, Ohio

July 2001

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# PERFORMANCE EVALUATION OF THE NASA GTX RBCC FLOWPATH

Scott R. Thomas, Donald T. Palac, Charles J. Trefny, and Joseph M. Roche
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

## Abstract

The NASA Glenn Research Center serves as NASA's lead center for aeropropulsion. Several programs are underway to explore revolutionary airbreathing propulsion systems in response to the challenge of reducing the cost of space transportation. Concepts being investigated include rocket-based combined cycle (RBCC), pulse detonation wave, and turbine-based combined cycle (TBCC) engines.

The GTX concept is a vertical launched, horizontal landing, single stage to orbit (SSTO) vehicle utilizing RBCC engines. The propulsion pod has a nearly half-axisymmetric flowpath that incorporates a rocket and ram-scramjet. The engine system operates from lift-off up to above Mach 10, at which point the airbreathing engine flowpath is closed off, and the rocket alone powers the vehicle to orbit.

The paper presents an overview of the research efforts supporting the development of this RBCC propulsion system. The experimental efforts of this program consist of a series of test rigs. Each rig is focused on development and optimization of the flowpath over a specific operating mode of the engine. These rigs collectively establish propulsion system performance over all modes of operation, therefore, covering the entire speed range.

Computational Fluid Mechanics (CFD) analysis is an important element of the GTX propulsion system development and validation. These efforts guide experiments and flowpath design, provide insight into experimental data, and extend results to conditions and scales not achievable in ground test facilities. Some examples of important CFD results are presented.

## Introduction

A primary NASA goal is to substantially reduce the cost of access to space. Hypersonic air-breathing propulsion promises to enable significant launch cost reductions by increasing the overall specific impulse of the propulsion system. The actual benefit of this approach will depend on vehicle robustness, weight margin, and design simplicity. The NASA GTX is a reusable, vertical launched, horizontal landing SSTO vehicle concept that seeks to lower launch costs through application of air-breathing propulsion. Figures 1 and 2 present the vehicle concept (shown is the 108,000 kg reference vehicle) and propulsion pod.

The GTX design philosophy focuses on minimizing vehicle weight and maximizing volumetric efficiency. Design features include a circular cross-sectional fuselage and semicircular propulsion pods. These features are intended to minimize the design complexity and maximize structural efficiency. The propulsion system utilizes a Rocket Based Combined Cycle (RBCC) concept. This is designed to combine the high thrust to weight of a rocket with the high specific impulse of a ram-scramjet in a single, integrated propulsion system; resulting in significantly reduced vehicle size, weight, and potentially cost. The program is focused on developing RBCC engine technology with an integrated vehicle concept to a point where commercial development can be initiated.

The propulsion pod (Fig. 2) has a nearly half-axisymmetric flowpath that incorporates a rocket and ram-scramjet. The engine system operates in four separate modes during the SSTO trajectory as illustrated in Fig. 3. First the engine functions with the rocket from lift-off through ~Mach 2.5 (Mode 1). The rocket is then ramped off and the flowpath is operated as a subsonic combustion ramjet (Mode 2). As the vehicle continues to accelerate, the airflow Mach number increases through the engine flowpath. Eventually the losses incurred due to forming the subsonic combustion region become unreasonable. Above this point (~Mach 6) significantly improved overall propulsion performance is gained by scheduling the fuel injection to operate the engine with supersonic combustion (i.e., scramjet; Mode 3). For the final ascent into orbit the air-breathing engine flowpath is closed off and the rocket is re-ignited; the rocket alone powers the vehicle to orbit (Mode 4).

The propulsion technology maturation of the GTX includes complementary experimental and computational efforts. Experiments include on-going proof-of-concept and component development tests. Flight-like propulsion system tests, and finally, flight demonstration of the reference vehicle would serve to validate performance and operability.

Details of the GTX program including vehicle conceptual design, rationale for the configuration choices, propulsion system configuration and thermodynamic cycles, and initial system performance results are presented in Refs. 1 and 2.

The purpose of this paper is to present an overview of the experimental and computational research efforts in support of the GTX RBCC propulsion system. This includes an outline of testing accomplished to date and on-going programs.

## GTX Experiments

A series of experiments will serve to mature the required technologies, and validate component weight and performance estimates of the GTX propulsion system. These experiments will collectively develop, optimize, and demonstrate the performance of the engine components as well as the integrated GTX flowpath for the four operating modes used over the entire flight trajectory. A roadmap showing the focus of the test rigs is presented in Fig. 4. An overview of each current rig is presented as follows:

### Direct-Connect Mixer/Combustor (Rig 1)

This experiment is a direct-connect mixer-combustor experiment. A gaseous $H_2$–$O_2$ rocket (developed in the rig 6 activity) is incorporated into this rig. A photograph of this experiment is presented in Fig. 5; this corresponds to a propulsion pod with a 28 cm cowl radius. The focus of this activity is to evaluate performance of the GTX flowpath with the rocket operating (Mode 1) and as a subsonic ramjet (Mode 2). Also, mode transition and the effect of combustor length on performance (including the mixing between the primary and secondary streams) will be studied. This experiment will be conducted in the NASA GRC Engine Components Research Laboratory[3] at conditions simulating sea level static (SLS) to Mach 3. Features include variable combustor length (63.5, 127, or 254 cm), and numerous fuel injection configurations (different stations, struts, etc.). The hardware fabrication is complete, installation is in the final stages, and testing is planned to commence in July 2001.

### Inlet Development and Validation (Rig 2)

This experiment has a 6.7 cm cowl lip radius, a translating centerbody to enable starting, and a cold-pipe/mass flow plug assembly mounted at the exit. Tests are conducted in the NASA Glenn Research Center 1×1 Supersonic Wind Tunnel.[4] A photograph of the model mounted in this facility is presented in Fig. 6. The 1×1 Supersonic Wind Tunnel is a continuous flow aerodynamic facility that is capable of producing discrete Mach numbers between 1.3 and 6.0. Mach number variation is achieved by replacing the nozzle section of the tunnel; a separate pair of nozzle blocks are used for each Mach number.

During testing the inlet centerbody is first positioned fully forward (full open) for starting; the centerbody is then translated aft in increments until unstart is observed. This establishes inlet operating range (maximum contraction ratio) at each Mach number. A series of backpressure sweeps are then accomplished. Once inlet starting is achieved the centerbody is positioned near maximum contraction, and the mass-flow plug is translated in small increments until the inlet unstarts due to backpressure.

To date, a model of the GTX inlet with a 12° spike was tested during two entries in the 1×1 SWT at Mach numbers from 2.8 to 6. The detailed results of inlet performance characteristics, predicted from CFD and subsequently measured experimentally, are presented in Refs. 5 and 6. Generally the maximum contraction ratio achieved was lower than that predicted by axisymmetric RANS calculations over the entire Mach number range tested. At Mach 6 the maximum contraction ratio achieved was ~8.

A modified GTX inlet design, which incorporates a 10° spike, is being fabricated and will be tested during calendar year 2001. CFD predictions have been carried out and show much improved flow uniformity, and significantly less flow separation. This inlet could include regions of boundary layer bleed if needed. The design calls for a nominal contraction ratio of 12 at Mach numbers above 5.

**Forebody-Inlet Integration (Rig 3)**

The forebody-inlet integration experiment is an aerodynamic model of the GTX air-breathing launch vehicle with 16.8 cm cowl lip radii. The objective of this test was to determine the effects of angle of attack on engine mass capture, inlet diverter effectiveness, and the flowfield at the cowl lip plane. Surface oil flow and temperature sensitive paint were used to obtain more detailed understanding of the flow development. Vehicle forebody and inlet interactions, including the severity of pod-to-pod interactions, were explored. These results also served to validate 3-D CFD calculations.

The first test of this rig was conducted in calendar year 2000 at the NASA Glenn Research Center 10×10 Supersonic Wind Tunnel[7] from Mach 2.0 to 3.5. Various angles of attack with and without boundary layer diversion were investigated. Measurements included flow profiles approaching the inlet and inlet mass capture. A photo of the installation is shown in Fig. 7. Detailed results of this experiment are presented in Ref. 8. With the diverter installed the mass flow rates were within 7 percent of theoretical predictions. At angles of attack between ±6°, the distortions at the cowl lip station for the top and side inlets were minimal. The data compared well to CFD predictions.

**Integrated Propulsion System Pod (Rig 4)**

The purpose of the rig 4 study is to develop and optimize the fuel injection (and piloting) schemes in the presence of realistic inlet flow distortions over the simulated flight Mach number range of 3.5 to 7. The rig 4 model is a variable geometry, heat sink design shown in the photograph of Fig. 8; it has a 13 cm cowl lip radius. The leading edges of the engine are water cooled; the remainder of the engine is uncooled and constructed largely from copper. The engine includes an actuated centerbody, multiple fuel injection stations, and is instrumented with ~120 static pressure taps.

The first tests of this model incorporated the 12° spike inlet and were completed in 1999. The details and performance results for this test program are presented in Ref. 9. These tests were conducted at the Propulsion Test Complex at GASL, Inc.[10] Performance data was obtained at simulated Mach numbers from 3.5 to 7. In all tests ambient gaseous hydrogen was the primary fuel; and a gaseous mixture of 80 percent hydrogen and 20 percent silane ($SiH_4$) was used as a pilot. The overall results were encouraging even though the inlet performance did not reach the anticipated levels; this was consistent with the rig 2 tests discussed previously. Engine performance was limited, particularly at higher equivalence ratios, due to this reduced inlet performance and contraction ratio. Engine thrust performance was quantified and generally performance results were comparable to referenced hypersonic propulsion data. The tests also helped to identify engine flowpath modifications that would lead to enhanced performance.

The GTX rig 4 model with flowpath modifications as identified, has been rebuilt and a second test phase is currently being conducted at the GASL, Inc., test leg No. 4. The model improvements are focused on improving inlet operating margin and increasing fuel/air mixing efficiency. The inlet incorporates a 10° spike angle, less inlet turning, and is designed to implement boundary layer bleed in various locations (if needed). Additional fuel injection stations were also added to more effectively schedule the fuel and maximize efficiency. Testing will be completed in calendar year 2001.

**Rocket Element Development (Rig 6)**

This task is an ongoing effort to develop rocket elements, both for use in testing, and ultimately to result in a flight-weight thrust chamber and nozzle. Tests are conducted in the NASA Glenn Research Center Rocket Combustion Laboratory Cell 32 where gaseous oxygen and hydrogen propellants are available at chamber pressures up to 14 MPa. The current effort includes the design, fabrication, and testing of the rocket for use in the Rig 1 experiment shown in Fig. 9.

**Rocket-In-A-Duct Code Validation (Rig 7)**

This experiment was a 110 N class rocket using gaseous hydrogen and oxygen, which operated at mixture ratio of 4 and a chamber pressure of 0.7 MPa. Tests were conducted in NASA Glenn Research Center Rocket Combustion Laboratory Cell 11. A photograph of the experiment is shown in Fig. 10. The testing was completed in calendar year 1999, and the results are published in Ref. 11. The performance of this rocket-in-a-duct was measured, and the results were used to validate axisymmetric FNS-CFD predictions. The CFD results were generated using design of experiments methods, and used to develop a parametric model of ducted rocket expansion efficiency.

**High Mach Performance Validation (Rig 9)**

The purpose of the rig 9 study is to determine scramjet performance of the GTX flowpath at simulated conditions between Mach 7 and 10. Testing was completed in calendar year 2001 in the GASL Hypulse facility[10] which is a reflected shock tunnel providing true temperature conditions for ~4 to 8 ms. The rig 9 is fixed geometry; although the centerbody can be manually positioned to various contraction ratios; a photograph of the model mounted in the Hypulse facility is presented in Fig. 11. The model has a 13 cm cowl lip radius. The engine is constructed primarily from aluminum; the leading edge regions and fuel manifolds, however, are stainless steel. The model was the first test of the modified engine design that incorporates flowpath changes including a 10° spike inlet. Inlet and fueled engine performance was validated at both the Mach 7 and 10 conditions. The inlet started and operated at the design contraction ratio of 12 for both test Mach numbers. Fueled engine performance was in line with pretest predictions.

## Computational and Structural Studies

A major strength of the program is the close coupling between the experimental and computational analysis. Both flowpath performance analysis, and structural research efforts are involved. An overview of the computational and analytical studies is presented as follows:

### Flowpath Performance Predictions

Significant computational and analytical efforts are on-going in support of the GTX program. Numerical solutions have been completed for the forebody, inlet, combustor, and nozzle of the propulsion system.[5,12–15] Figure 12 presents a 3-D PNS calculation for the flowfield along the forebody approaching the engine. These predictions help screen the effectiveness of candidate boundary layer diverter configurations. Figure 13 presents a representative solution of the flow through the inlet. These computations have characterized inlet performance and operability over the air-breathing Mach number range; and identified the extent of flow distortion in the corners. Figure 14 shows an axisymmetric finite-rate calculation of the flame propagation and thermal throat establishment in the ejector ramjet operating mode. Figure 15 shows a 3-D finite rate scramjet combustor calculation, which provides guidance for the design and implementation of the fuel injection scheme. Figure 16 presents a 3-D finite rate calculation of the nozzle flow for the rocket-only operating mode.

### Structural Architecture Development

The GTX "reference" vehicle is developed with close integration between the airframe and propulsion system. A cut-away view showing the GTX structure is presented in Fig. 17. The fuselage has an independent tank stack and an aeroshell.[16,17] This approach minimizes the thermal stress by allowing the cryogenic tank stack to contract while allowing the aeroshell to expand without straining the structure. The wings and tail are attached to the propulsion pod cowls, which are connected to the fuselage rings. This architecture is both structurally and aerodynamically efficient. A candidate structural architecture for the propulsion system is shown in Fig. 18. Thermal and structural analyses have been performed using the analytical tools outlined in Refs. 18 to 20. Material candidates with a potential for lightweight and simplicity have been selected from a set of near term technologies (5 to 10 years). The size of a closed vehicle depends on propulsion performance, structural efficiency, packaging efficiency, payload weight, and trajectory. The vehicle design and size changes as these parameters change. An analytical tool was developed in spreadsheet form to quickly evaluate the size of a closed vehicle, and for optimization studies.[16] Performance and structural analysis results are fed into this model to establish the vehicle size for the reference mission.

## Conclusions

The NASA GTX project is focused on determining the feasibility of using Rocket Based Combined Cycle propulsion to enable a reusable single stage to orbit vehicle. The project is focused on maturing the technology, using a 136 kg payload "reference vehicle" concept to guide the research. An objective of the project is to eventually manufacture and fly a subscale, suborbital X-vehicle in order to demonstrate SSTO feasibility, and potential for low cost access to space.

Significant experimental and computational research efforts are currently underway to mature the necessary technologies to move forward towards a flight demonstration program. The experimental activities serve to collectively validate propulsion system performance over the GTX trajectory and engine operating modes. Much test activity has occurred, is currently on-going, and is planned for the near future. The status of the test rigs was outlined in this paper. Detailed computational and analytical analysis has been completed which serves to complement the experimental efforts and assists interpretation of test results by providing more detailed understanding of the flow phenomenon. CFD is also an important tool to extrapolate results beyond where experiments are impractical (i.e., large scale). The GTX program, through the use of focused experimental efforts along with analytical tools, have made significant progress towards maturing and validating the required technologies, establishing and reducing component weights, and determining and optimizing propulsion performance.

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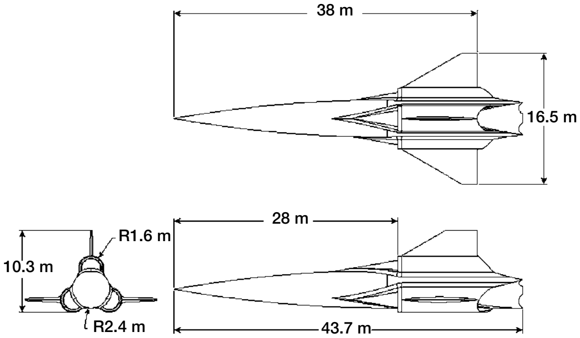



Figure 1.—NASA GTX vehicle concept.

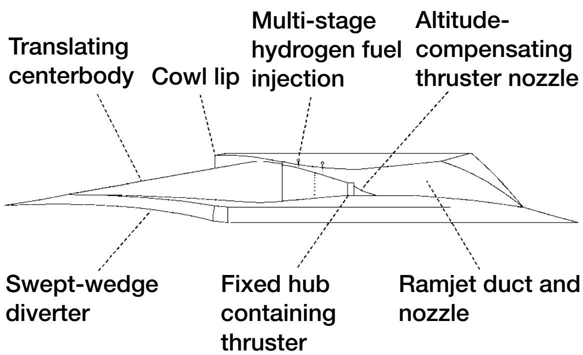



Figure 2.—Cut away of GTX propulsion pod.

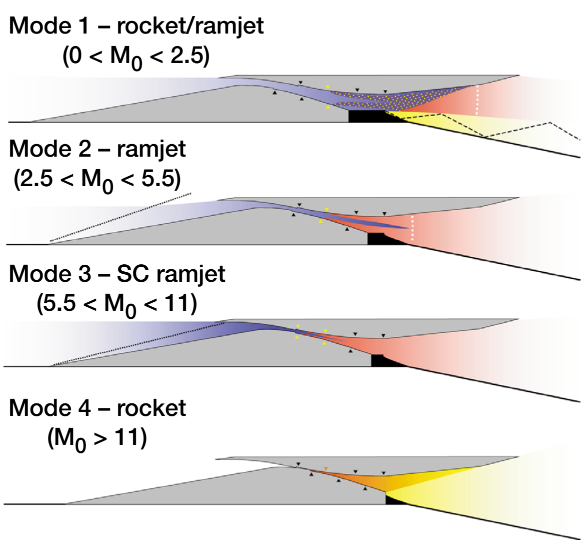
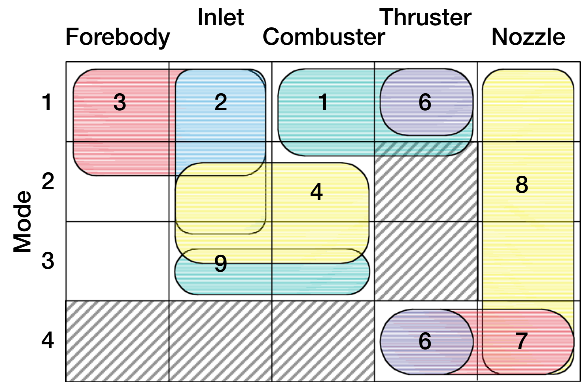



Figure 3.—GTX propulsion modes.




Shaded indicates component not used for this mode.

Figure 4.—Roadmap of GTX experiments.

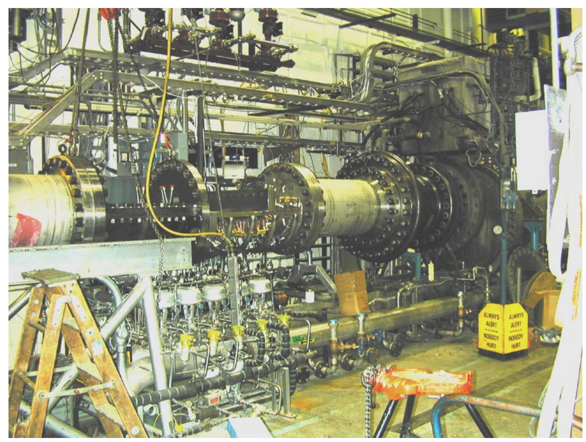


Figure 5.—Direct-connect mixer/combustor (rig 1).

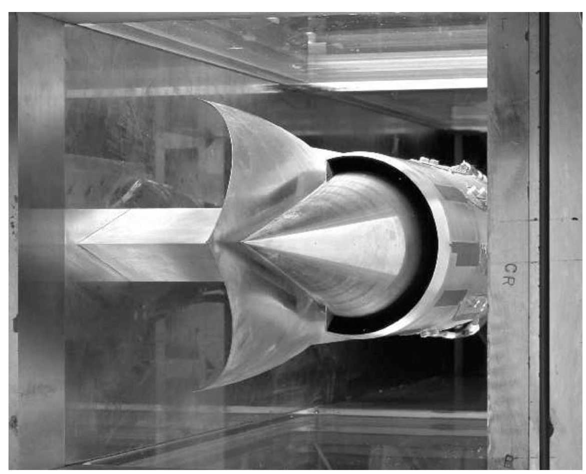


Figure 6.—Inlet development and validation (rig 2).

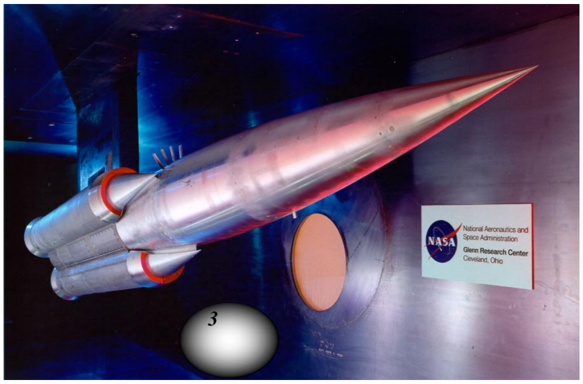


Figure 7.—Forebody-inlet integration (rig 3).

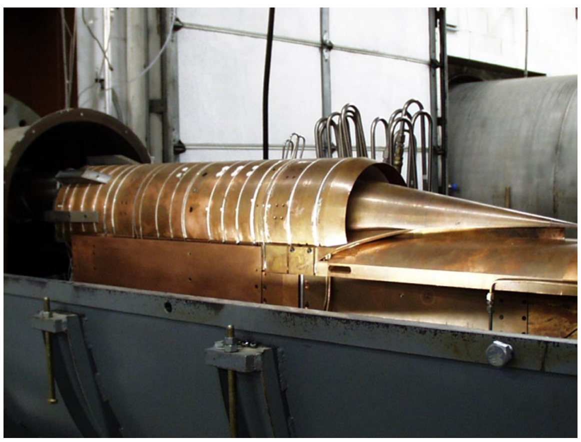


Figure 8.—Integrated propulsion system pod (rig 4).

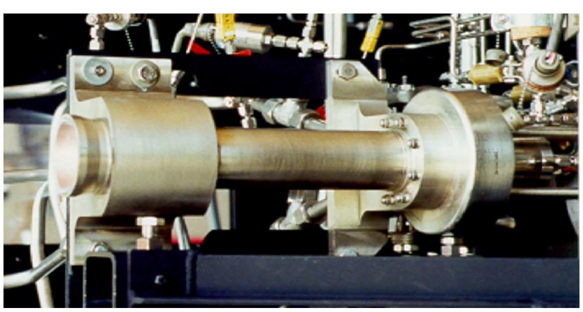


Figure 9.—Rocket element development (rig 6).

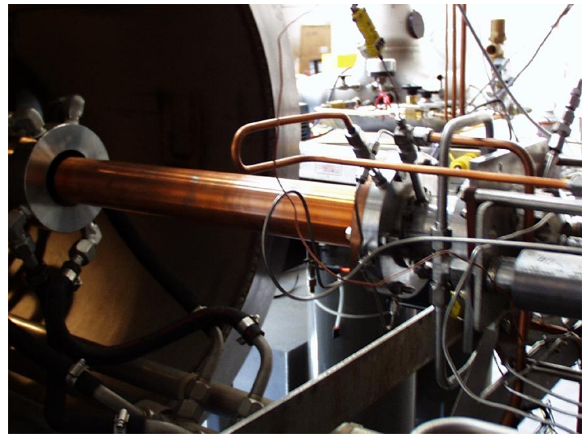


Figure 10.—Rocket in a duct code validation (rig 7).

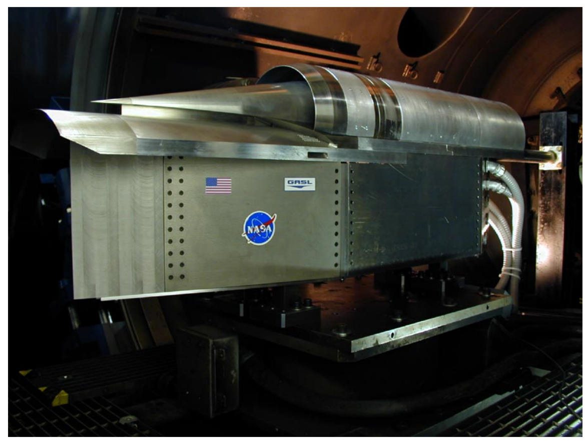
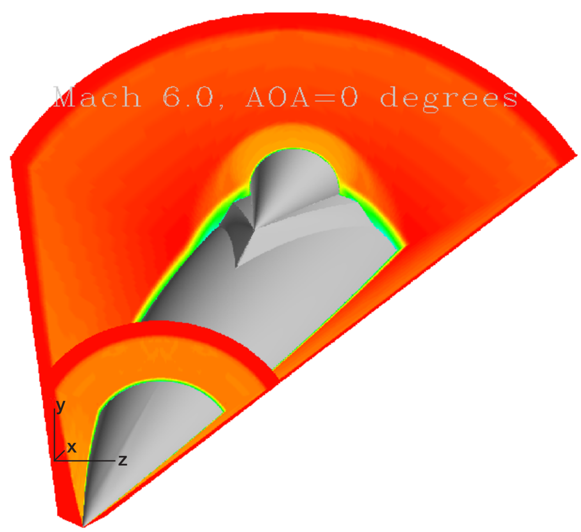
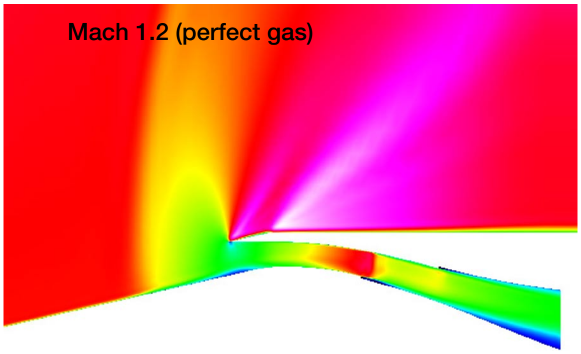


Figure 11.—High Mach number performance validation (rig 9).



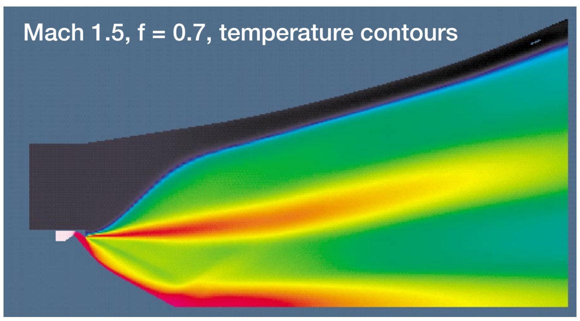

3-D PNS calculations for screening diverter configurations (Mach number contours).

Figure 12.—CFD for GTX forebody.



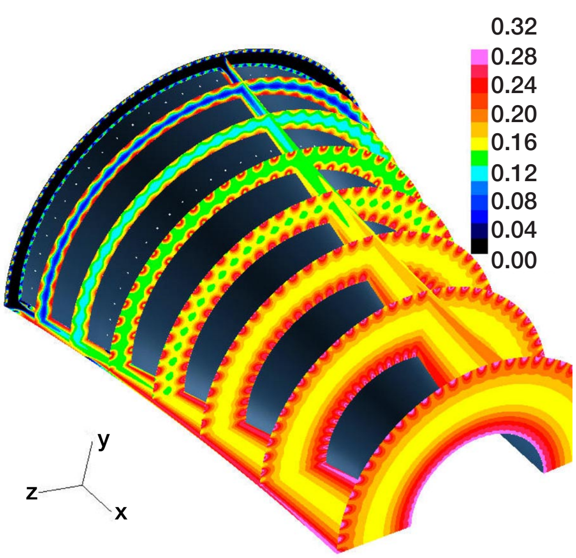

Axi-FNS for inlet performance map
(Mach number contours).

Figure 13.—CFD for GTX inlet.



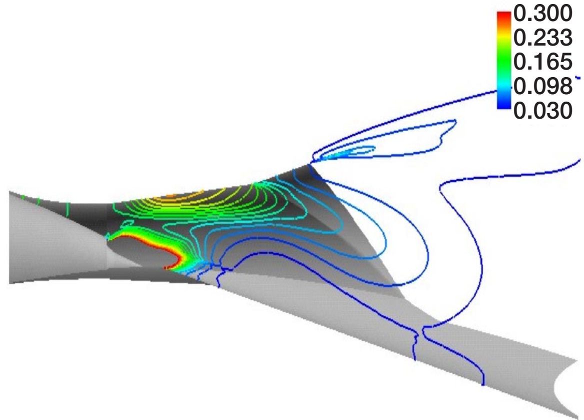

Axi finite-rate calculation of mode 1 flame propagation and thermal throat (static temperature contours).

Figure 14.—CFD for ejector ramjet operation.




3-D finite-rate scram calculation used to verify fuel injection scheme ($H_2O$ concentration).

Figure 15.—CFD for scramjet combustor.




3-D finite-rate mode 4 calculation used to guide nozzle design (static pressure contours, atm).

Figure 16.—CFD for GTX nozzle with rocket operation.

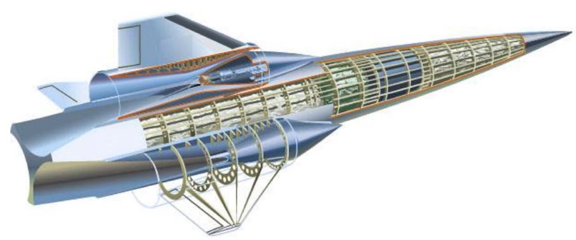


Figure 17.—Cut-away showing GTX structure.

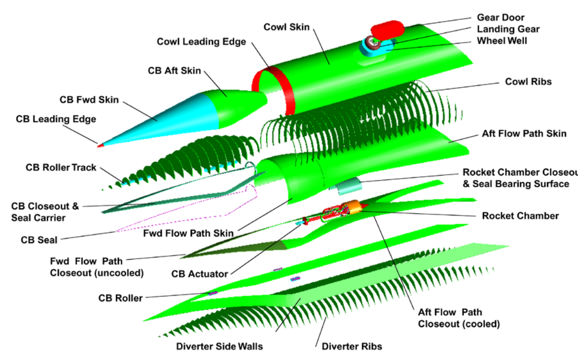



Figure 18.—Candidate structural architecture for GTX propulsion pod.

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Scott R. Thomas, Donald T. Palac, Charles J. Trefny, and Joseph M. Roche

**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

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**13. ABSTRACT** ***(Maximum 200 words)***
The NASA Glenn Research Center serves as NASA's lead center for aeropropulsion. Several programs are underway to explore revolutionary airbreathing propulsion systems in response to the challenge of reducing the cost of space transportation. Concepts being investigated include rocket-based combined cycle (RBCC), pulse detonation wave, and turbine-based combined cycle (TBCC) engines. The GTX concept is a vertical launched, horizontal landing, single stage to orbit (SSTO) vehicle utilizing RBCC engines. The propulsion pod has a nearly half-axisymmetric flowpath that incorporates a rocket and ram-scramjet. The engine system operates from lift-off up to above Mach 10, at which point the airbreathing engine flowpath is closed off, and the rocket alone powers the vehicle to orbit. The paper presents an overview of the research efforts supporting the development of this RBCC propulsion system. The experimental efforts of this program consist of a series of test rigs. Each rig is focused on development and optimization of the flowpath over a specific operating mode of the engine. These rigs collectively establish propulsion system performance over all modes of operation, therefore, covering the entire speed range. Computational Fluid Mechanics (CFD) analysis is an important element of the GTX propulsion system development and validation. These efforts guide experiments and flowpath design, provide insight into experimental data, and extend results to conditions and scales not achievable in ground test facilities. Some examples of important CFD results are presented.

**14. SUBJECT TERMS**
Combined cycle propulsion; Hypersonic propulsion; Ramjet; Scramjet; Air-breathing launch vehicle; Single stage to orbit

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