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Innovative Airbreathing Propulsion Concepts for Access to Space

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Glenn Research Center, Cleveland, Ohio

October 2001

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Abstract

The National Aeronautics and Space Administration (NASA) Glenn Research Center (GRC) is actively involved in the research of new air-breathing propulsion systems for access to space. The rationale for using air-breathing propulsion is discussed. Several categories of propulsion systems are described, including rocket-based and turbine-based combined cycles. Current research in these areas at GRC is highlighted.

Introduction

The current cost to launch payloads to low earth orbit (LEO) is approximately 10000 U.S. dollars ($) per pound ($22000 per kilogram). This high cost limits our ability to pursue space science and hinders the development of new markets and a productive space enterprise. This enterprise includes NASA's space launch needs and those of industry, universities, the military, and other U.S. government agencies. NASA's Advanced Space Transportation Program (ASTP) proposes a vision of the future[1] where space travel is as routine as in today's commercial air transportation systems. Dramatically lower launch costs will be required to make this vision a reality. In order to provide more affordable access to space, NASA has established new goals in its Aeronautics and Space Transportation plan. These goals target a reduction in the cost of launching payloads to LEO to $1000 per pound ($2200 per kilogram) by 2007 and to $100's per pound by 2025[2] while increasing safety by orders of magnitude.

Several programs within NASA are addressing innovative propulsion systems that offer potential for reducing launch costs. Various air-breathing propulsion systems currently are being investigated under these programs. The NASA Aerospace Propulsion and Power Base Research and Technology Program supports long-term fundamental research and is managed at GRC. Currently funded areas relevant to space transportation include hybrid hyperspeed propulsion (HHP) and pulse detonation engine (PDE) research. The HHP Program currently is addressing rocket-based combined cycle and turbine-based combined cycle systems. The PDE research program has the goal of demonstrating the feasibility of PDE-based hybrid-cycle and combined cycle propulsion systems that meet NASA's aviation and access-to-space goals.

The ASTP also is part of the Base Research and Technology Program and is managed at the Marshall Space Flight Center. As technologies developed under the Aerospace Propulsion and Power Base Research and Technology Program mature, they are incorporated into ASTP. One example of this is rocket-based combined cycle systems that are being considered as part of ASTP.

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The NASA Ultra Efficient Engine Technology (UEET) Program has the goal of developing propulsion system component technology that is relevant to a wide range of vehicle missions. In addition to subsonic and supersonic speed regimes, it includes the hypersonic speed regime. More specifically, component technologies for turbine-based combined cycle engines are being developed as part of UEET.

Airbreathing Propulsion for Launch Vehicles

The use of air-breathing propulsion for launch vehicles can result in significant weight savings. This is due to the fact that oxygen from the atmosphere is utilized to reduce the amount of oxidizer that the vehicle must carry. The oxidizer weight savings then can be reinvested in a more robust vehicle structure and increased payload capacity. It should be emphasized that the propulsion system itself should be as robust as possible, since reusability is a key requirement for reducing space transportation costs.

Figure 1 shows the performances of various propulsion systems as a function of Mach number. The performance parameter is specific impulse, which is defined as the propellant weight flow specific thrust. Note that air-breathing propulsion systems (i.e., turbojet, ramjet, scramjet) generally perform better than pure rocket systems.

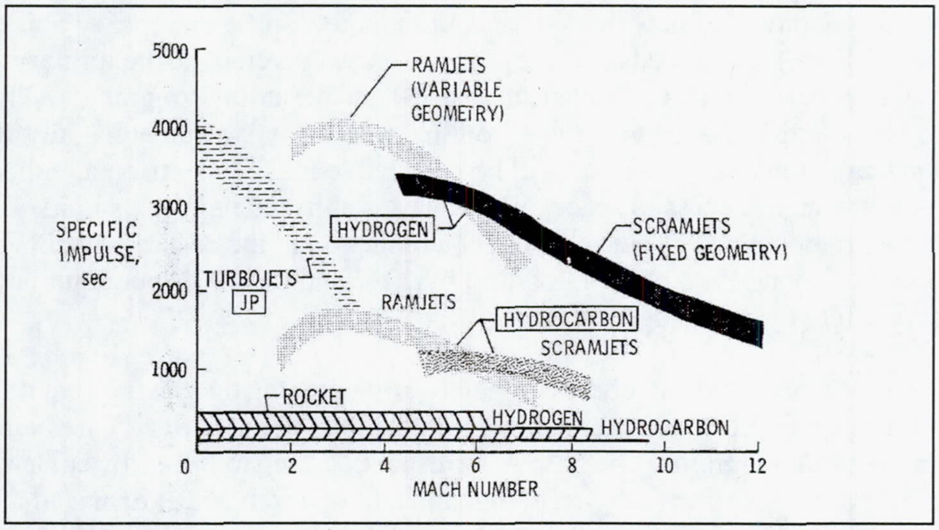


Figure 1. Performance vs. mach number for various propulsion systems.

The Orbital Sciences Corporation already is using an air-breathing propulsion system in its Pegasus launch vehicle. The Pegasus is a winged, three-stage, solid rocket booster that is deployed from a L-1011 jetliner. Thus, the jet engines of the L-1011 provide air-breathing propulsion for the first part of the Pegasus trajectory (about Mach 0.8 and 39,000 feet). It would be more efficient, however, if the airbreathing propulsion system were more closely integrated with the launch vehicle. A highly integrated airframe-propulsion system also is required if the air-breathing propulsion system is utilized at higher Mach numbers.

There are many airbreathing propulsion cycles that can be considered for a reusable launch vehicle. Extensive system studies have been performed by NASA Langley to evaluate several candidates.[3] The design and evaluation of a particular cycle must be done in conjunction with the airframe design, and an iterative design and analysis process is required as shown in Figure 2. The process starts from the left with a preliminary vehicle and propulsion definition that is based on the mission requirements. Various analysis steps follow, including a full evaluation of performance over the complete flight trajectory. Analysis then is followed by a series of component and system experiments to validate the design. Based on the experimental results, modifications are made, and the cycle is repeated. The intent of the concentric circles in Figure 2 is to indicate that as the number of design and analysis iterations increase, the fidelity increases as well.

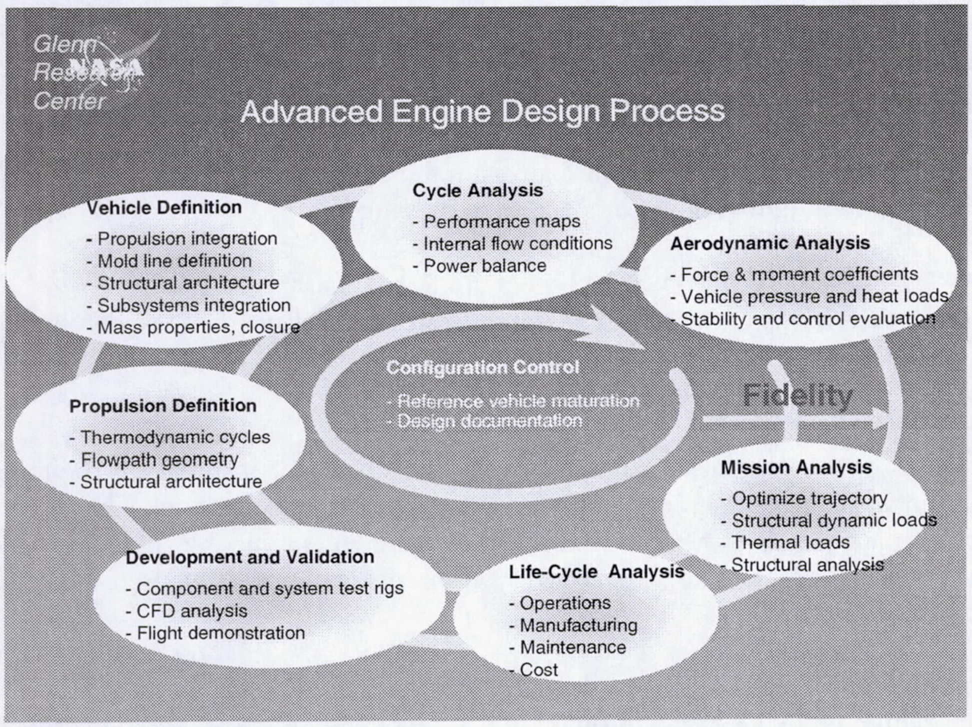


Figure 2. Propulsion system design process.

Combined Cycles

Two of the leading concepts for airbreathing launch vehicles are the rocket-based combined cycle (RBCC) and turbine-based combined cycle (TBCC) propulsion systems. Combined cycle systems utilize several propulsion cycles integrated in a common flowpath. Typically, a scramjet and/or ramjet system is combined with a low speed accelerator. A rocket engine usually is included to propel the vehicle when the atmospheric oxygen levels become inadequate for air-breathing propulsion.

Rocket-Based Systems

In a RBCC system, a rocket engine provides the low-speed accelerator and final propulsion modes. In between these modes, ramjet/scramjet propulsion is used. At low speeds, air enters the flowpath through an inlet and is mixed with the primary rocket flow stream. This mode of operation is referred to as ejector ramjet. In some versions of RBCC engines, fuel is injected into the flowpath either upstream or downstream of the rocket engine. In other versions, the air is mixed with a fuel-rich rocket exhaust. At speeds near Mach 3, there is sufficient ram compression that the transition can be made from ejector ramjet to ramjet mode. Gradually, the rocket engine is shut down and full ramjet operation occurs. Ramjet mode is continued until speeds reach Mach 5-6, where performance and materials limitations require transition to supersonic combustion, or scramjet mode. At some point, the benefits of air-breathing propulsion are diminished and transition to rocket only mode occurs. The Mach number at which this mode transition occurs is approximately 10 or above. Note that the transition Mach number for each of the four operating modes are design parameters for the propulsion system.

There are various possible modifications to the basic RBCC system described above. Some RBCC engine concepts include a fan to augment the low-speed performance. A major challenge with this configuration is stowing of the fan during the high-speed portions of the vehicle trajectory. Another thermodynamic cycle that can improve the performance of an RBCC engine is the addition of a liquid air cycle (LACE). Here, the extremely low temperature of the liquid hydrogen fuel is exploited to produce liquid air from the atmosphere. The major issue with LACE is the design of a lightweight, compact heat exchanger.

Turbine-Based Engines

Some commonly used terms to describe the general categories of turbine-based systems are briefly presented below.

Turboramjet

The first category of these engines is known as turboramjets, that consist of a turbojet or turbofan engine integrated with a subsonic combustion ramjet or dual-mode scramjet. The turbojet/turbofan capability can be provided by an existing jet engine (e.g., J-85) or may require development of an entirely new turbomachinery system design (e.g., Air Core Enhanced Turboramjet, AceTR).

Air Turboramjet

In the air turboramjet (ATR), a conventional fan is integrated with a rocket type combustor and turbine. This decouples the turbine drive gas from the fan airstream. The "classical" ATR requires fuel and oxidizer to be carried on the vehicle. An "expander" ATR uses heated fuel as the energy source to drive the turbine. A "precooled regenerative" ATR uses a heat exchanger located upstream of the fan to precool the inlet air. This concept can be taken one step further by using the heat exchanger to liquefy some of the incoming air. The liquefied air then can be stored for use by the rocket engine.

Variable Cycle Turbofan Ramjet

Originally studied in the mid 1970's, the variable cycle turbofan ramjet uses double bypass and variable cycle engine features. This enables efficient hypersonic cruise capabilities and very good part-power subsonic cruise and loiter capabilities. In addition, these features allow smooth mode transitions, but at the expense of system complexity.

Turbine Bypass Cycle

The turbine bypass cycle redirects part of the compressor exit flow around the combustor and turbine of a single spool engine. This offers the potential to operate at a lower compressor exit temperature while maintaining approximately the same level of thrust and specific fuel consumption. An example of this kind of engine is the J58 engine found in the SR-71.

NASA Glenn RBCC and TBCC concepts

GTX Rocket-based combined cycle

The GTX program[4] has the objective of demonstrating the feasibility of RBCC propulsion for a single-stage-to-orbit (SSTO) reusable launch vehicle. The interest in RBCC is driven by its potential to decrease the propellant fraction required (PFR). The reduction is the result of using oxygen in the atmosphere during part of the trajectory. This is illustrated in Figure 3, which shows PFR as a function of equivalent effective specific impulse.

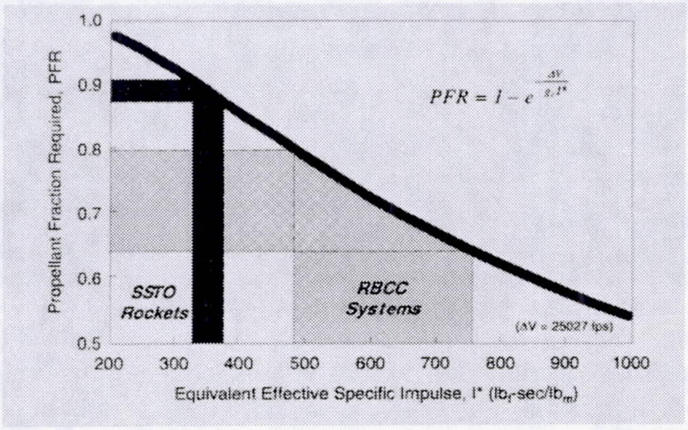


Figure 3. Effect of I* on propellant mass fraction for SSTO.

This latter measure of propulsion performance requires further explanation. The effective specific impulse (I_{eff}) is defined as the sum of all forces in the direction of flight due to propulsion, aerodynamics, and gravity, divided by the propellant flow rate. Since I_{eff} for an air-breathing launch vehicle can vary significantly during ascent, it cannot be used directly in the rocket equation

$$PFR = 1 - e^{\Delta V / g_c I_{eff}}$$

Rather, I^* is used, which is defined as the constant, equivalent value of I_{eff} that, when used in the rocket equation, results in the correct mass ratio.

From Figure 3, it is evident that RBCC systems offer the potential for reduced PFR over SSTO rockets. These savings can be reinvested in robust structure, increased payload, or reduced vehicle size. Research is required to determine if the savings in PFR will be overcome by other factors associated with the use of air-breathing propulsion. These include the weight and complexity of airbreathing components, as well as increased heating, drag, and structural loading due to flight through the atmosphere.

The SSTO problem is to design a vehicle, with an accompanying propulsion system, that provides the appropriate I^* for a desired payload, with sufficient robustness as to be highly reusable. The robustness should not come at so high a cost that it reduces the desired payload fraction. Figure 4 illustrates this design problem. In the figure, inert mass fraction is plotted versus I^*. Note that the vector sum shown must tend towards increased structural margin if there is to be a benefit from RBCC propulsion.

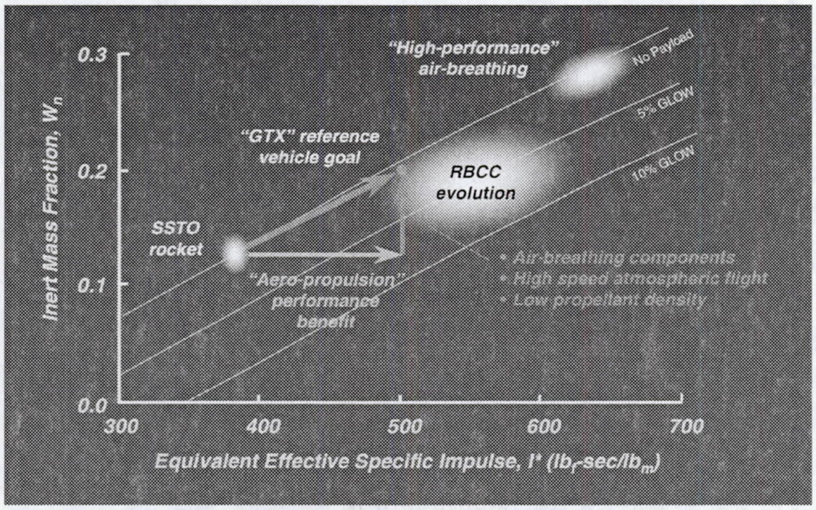


Figure 4. SSTO launch vehicle design space.

In order to address the issues raised above, NASA Glenn is developing an RBCC propulsion system for a modest initial mission. The GTX "reference" vehicle is being designed to place a 300-pound payload into low-Earth orbit. This mission will reduce the scale and cost of the RBCC demonstration.

Vehicle and Propulsion System Description
The GTX vehicle configuration is shown in Figure 5.

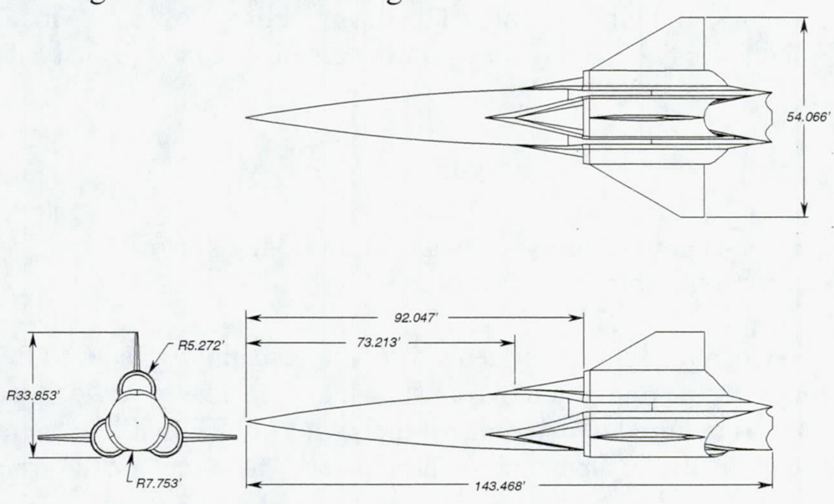


Figure 5. GTX reference vehicle geometry.

The most striking visual aspect of the vehicle is its strong resemblance to a traditional rocket. This is because the geometry is selected for features such as structural efficiency and simplicity. The vehicle is intended to take off vertically and land horizontally. This minimizes wing structure and reliance on low-speed aerodynamics, which can lead to non-optimum shapes and increased weight. There are three semi-circular propulsion pods mounted symmetrically on the aft part of the vehicle. Note that the forebody of the vehicle does not appear to provide inlet precompression. Analysis has shown, however, that significant precompression does exist. The aft-facing projected area of the vehicle is used for nozzle expansion, as is typical for a hypersonic vehicle. A more detailed view of the propulsion pod is shown in Figure 6.

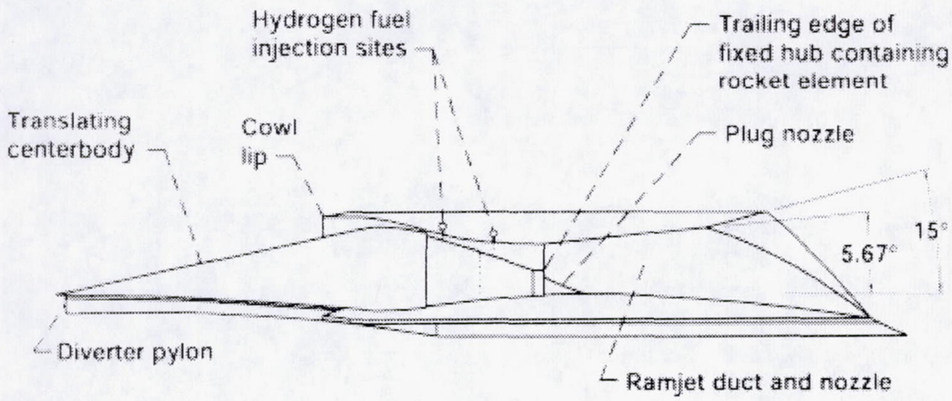


Figure 6. GTX propulsion pod detail.

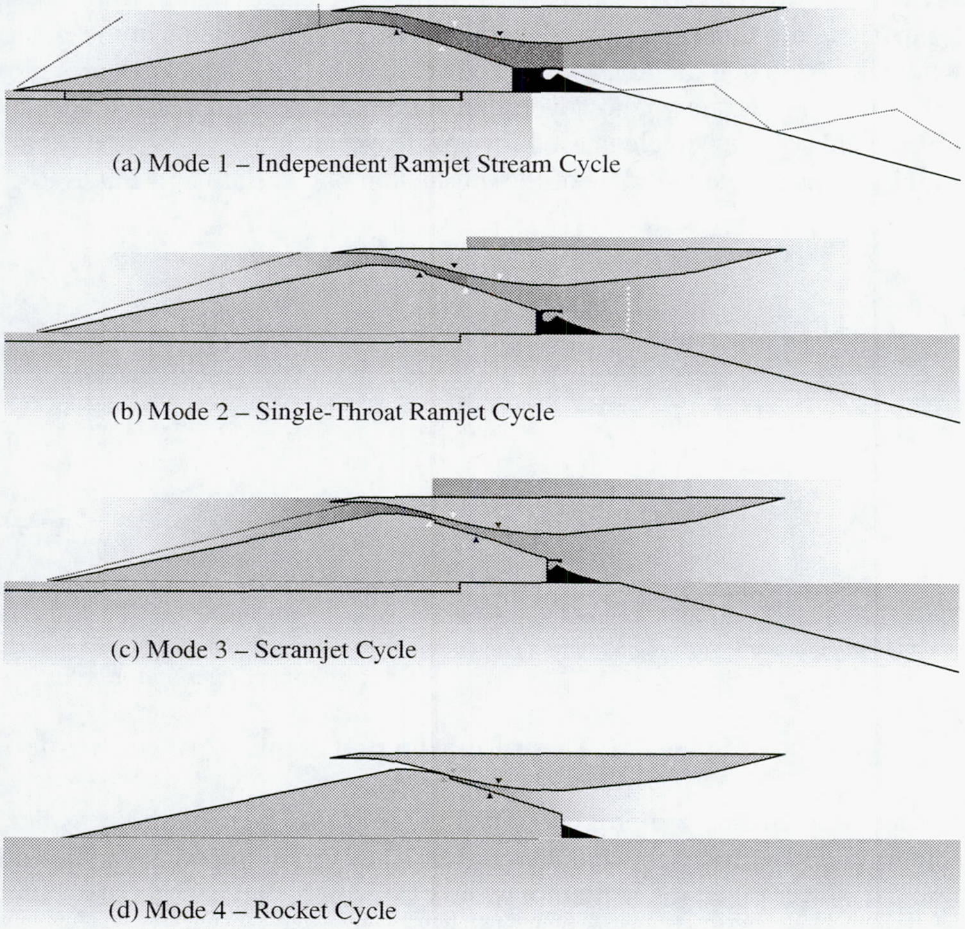
A translating-centerbody, mixed-compression type inlet is used. The centerbody "spike" is offset from the vehicle forebody to divert the boundary layer. The current inlet design does not incorporate boundary-layer bleed in an attempt to save on weight and complexity. Future testing and analysis will determine if this savings is achievable.

A single rocket element is located in a semi-circular hub that is fixed within the propulsion pod, and the centerbody translates over the hub. Ramjet duct and nozzle expansion regions follow the rocket element. The ramjet duct length must be designed to allow sufficient completion of the combustion process. This is a major design issue and has prompted the conception of a new propulsion mode that is described in the next section.

The final nozzle expansion "cone" intersects the body of the vehicle, giving its aft region a unique shape. Since in ramjet mode the combustion is subsonic, one would normally expect a converging-diverging nozzle to be accommodated by some type of variable geometry. GTX avoids the added weight of variable nozzle geometry through the use of a "thermal throat."

Propulsion system operating modes

The four operating modes for the GTX propulsion system are shown in Figure 7.



(a) Mode 1 – Independent Ramjet Stream Cycle

(b) Mode 2 – Single-Throat Ramjet Cycle

(c) Mode 3 – Scramjet Cycle

(d) Mode 4 – Rocket Cycle

Figure 7. GTX propulsion system operating modes.

The first mode, the independent ramjet stream cycle, is shown in Figure 7(a). In this mode, the engine provides the thrust required for vertical lift off. It differs from the other low speed cycles that have been proposed and/or demonstrated in RBCC engines. Where other RBCC cycles depend on a high degree of mixing of the primary (rocket) and secondary (ejector) flow streams, the independent ramjet stream (IRS) cycle does not. At liftoff, the inlet centerbody is fully extended, and the rocket operates at maximum chamber pressure. The secondary stream is fueled with hydrogen when the vehicle gains sufficient speed, and is burned to provide thrust in addition to the rocket. Eventually, the rocket chamber pressure can be reduced to optimize $I_{eff.}$ The IRS cycle allows for a shorter overall flowpath length, resulting in significant weight savings.

When the ramjet thrust reaches a sufficient level, the rocket can be shut down. This begins the single-throat ramjet cycle (mode 2) that is shown in Figure 7(b). This mode (as well as part of the first mode) requires a thermal throat to be established in the nozzle region. The thermal throat acts much like a mechanical throat, accelerating the flow to supersonic speeds. Control of the thermal throat is a critical design issue. In the GTX propulsion system, it is anticipated that the radial distribution of fuel in the inlet diffuser region based on inlet pressure measurements can be used to control the thermal throat location.

When sufficient velocity is reached, between Mach 5 and 6, transition to supersonic combustion is beneficial. Fuel is injected further upstream from a step located in the centerbody. This step provides flameholding and inlet isolation. Thermal choking is no longer required. The scramjet cycle (mode 3), shown in Figure 7(c), is continued until I_{eff} approaches that of the rocket's vacuum specific impulse. At this point, the vehicle pitches up, the centerbody is translated aft to close off the inlet, and the rocket is re-ignited. This rocket cycle (mode 4) is shown in Figure 7(d). Since the rocket now is essentially in a duct, a properly designed expansion process is critical to performance.

Technical Challenges and Current Status

Design challenges of the GTX propulsion system are described in this section. The overall systems problem of optimizing performance and weight over dramatically varying flight conditions is a monumental task. Since there is little test data available (and no flight data) on RBCC engines, traditional design and analysis techniques that rely on empiricism cannot be used. Critical technologies must be developed through an iterative process of experimentation coupled with analytical guidance.

Efficient cycle concepts in modes one and four must be developed. The IRS cycle proposed for mode one in the GTX propulsion system was demonstrated through one-dimensional analysis.[5] Two-dimensional analysis is in progress and experimental demonstration is planned for early 2001. A parametric study of ducted rocket performance[6] was completed and used to guide the GTX mode-four design.

GTX mode 2 and 3 performance currently is undergoing experimental testing utilizing the flowpath model shown in Figure 8. To date, 38 successful tests of the flowpath have been completed at Mach numbers ranging from 3.5 to 7. Of these tests, 22 were fueled. The data from these tests show that the engine thrust performance was consistent with other current hypersonic propulsion test data.

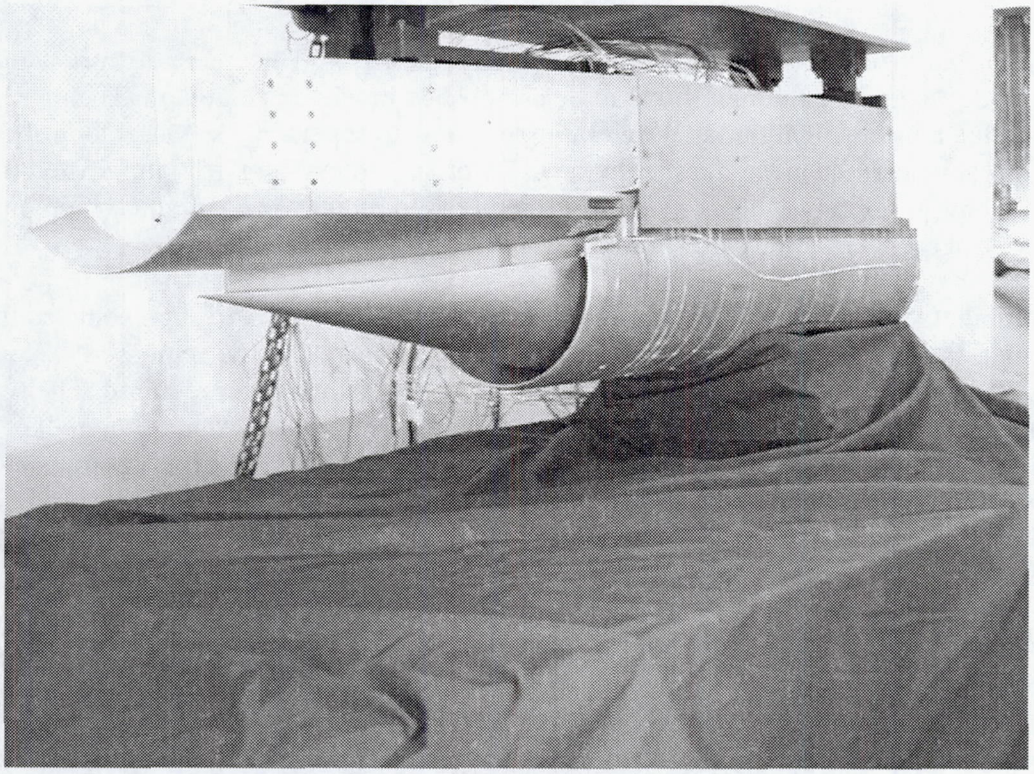


Figure 8. GTX flowpath model.

The model is made of heavy, water-cooled copper because of its heat conduction capability. This obviously is not optimal from a weight perspective. The development of actively cooled, flight-weight structures is crucial to demonstrating performance and a high degree of reusability. Highly efficient, lightweight inlet and nozzle technologies are also important. The materials, structures, and cooling issues currently are being addressed in collaboration with Pratt & Whitney.

Turbine-Based Combined Cycle Research

NASA Glenn also is investigating the potential for utilizing turbine-based combined cycles (TBCC) for access to space. Turbine-based systems may apply to single and two-stage-to-orbit (TSTO) launch vehicle concepts. However, TSTO may be the more likely option due to the low thrust-to-weight for current and proposed TBCC propulsion systems.

To demonstrate the potential for TBCC systems, a near-term, low-risk TBCC propulsion system demonstrator was defined based on the integration of an existing turbojet (J85) with a single-throat ramjet. In conjunction with the engine, Lockheed-Martin initiated a conceptual vehicle design. The proposed vehicle, shown in Figure 9, is 40 foot long, has a gross lift-off weight of 10,000 pounds, and is powered by two TBCC engines. The intent of the engine/vehicle design was to serve as a TBCC demonstrator to expand the experimental database on these systems.

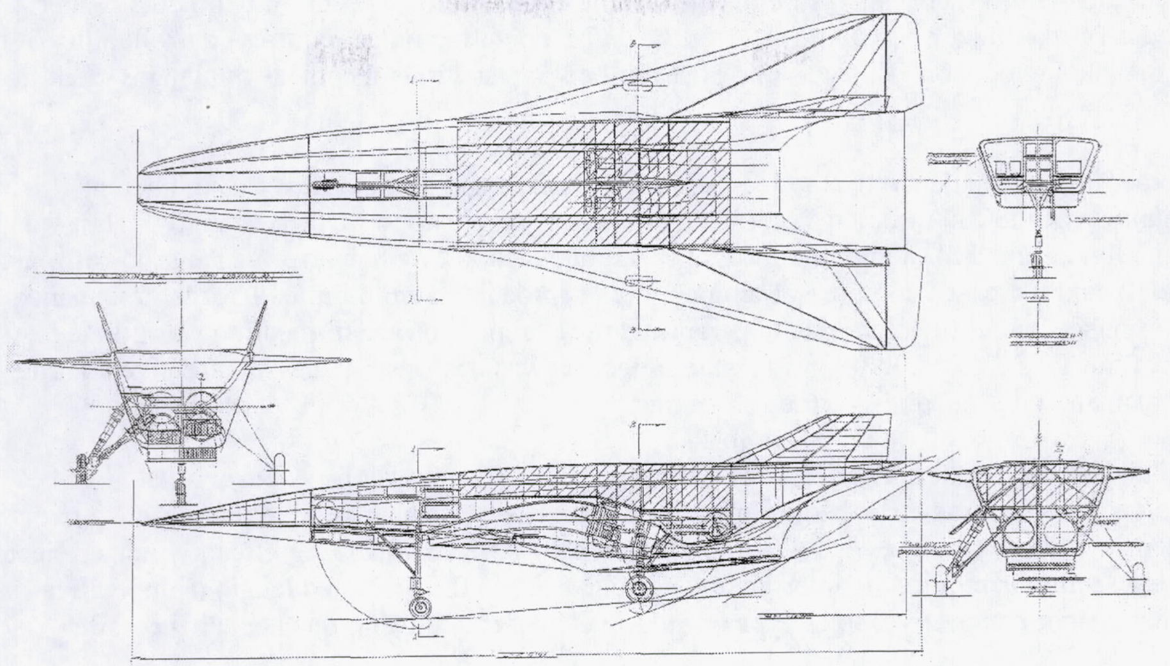


Figure 9. TBCC-powered demonstrator vehicle.

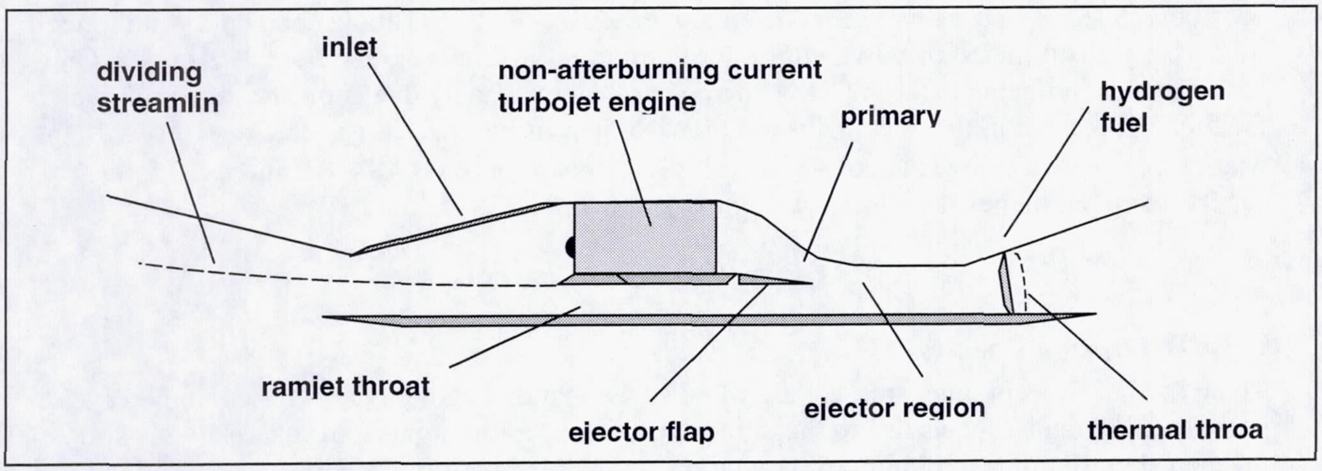


Figure 10. Turbine-based combined cycle concept.

The main features of the TBCC concept are shown in Figure 10. The turbojet engine operates from takeoff to speeds near Mach 3. At takeoff, the ejector flap is down, closing off the ramjet duct. Hydrogen fuel is injected in the nozzle region, which acts as an afterburner. Soon after takeoff, the ejector flap is raised to reduce inlet spillage drag by allowing air to pass through the ramjet duct. Near Mach 3, the transition from turbojet operation to full ramjet occurs. The turbojet engine is effectively “cocooned” by lowering the inlet flap and raising the ejector flap. During subsonic and supersonic flight, a thermal throat is established by the hydrogen spraybar to provide the proper backpressure for the turbine engine at low speeds and ramjet at higher speeds. To maximize specific thrust over the entire operating range requires controllability of the thermal choke location. This was one of several engine and inlet technical challenges identified for this concept.

Another unique challenge for the J85-based TBCC demonstrator pertains to the inherent limitations of the J85 turbojet. The J85 engine must operate up to Mach 3, even though it was originally designed for a maximum flight speed of Mach 2. Engine performance drops off past Mach 2, and increased compressor temperatures approach material limits. In order to enhance performance and allow high Mach operability, pre-compressor water injection was utilized. As part of the TBCC research program, water injection was demonstrated as an effective cooling mechanism in a ground test of the J85 engine.[7]

In addition to the water injection demonstration, a TBCC propulsion system simulator was developed,[8] and parametric studies of the TBCC ejector performance were done using a two-dimensional Navier-Stokes code.[9] Preliminary results revealed that a significantly longer ejector mixing section is required than originally designed. Since the predicted length is impractical from a weight perspective, some type of mixing enhancement technique appears necessary.

NASA Glenn also is collaborating with the Japanese Institute of Space and Astronautical Science (ISAS) in the testing of inlet components for an expander cycle air turbo ramjet engine (ATREX).[10] Inlet tests from Mach 2-6 for the variable geometry, mixed-compression inlet have been completed. The tests were conducted in the NASA Glenn 1×1 foot supersonic wind tunnel. Centerbody position and bleed schedules for optimum pressure recovery were determined. One of the key technologies in the ATREX engine is a heat exchanger that cools the air coming into the fan. It is located in the inlet diffuser region. Requirements for a large-scale inlet test with the heat exchanger are being studied. These tests are planned for the NASA Glenn 10×10 foot supersonic wind tunnel subject to final agreement with ISAS.

Other Propulsion Concepts

Pulse Detonation Engines

There has been recent interest in the use of pulse detonation engines (PDE) for combined cycle propulsion systems. This is due to the promise of high specific impulse from a relatively simple mechanism utilizing a minimum of moving parts. The high performance makes the PDE attractive for the low speed accelerator in a combined cycle. The low number of moving parts offers low maintenance cost.

To place the PDE in perspective with other engine cycles, a one-dimensional analysis was performed. The analysis compared a PDE cycle with Brayton and Humphrey cycles. Results show that over a range of cycle static temperature ratios (T_3/T_0), the PDE and Humphrey cycles have a higher thermal efficiency than the Brayton cycle. These results assume that inlet, combustor, and nozzle efficiencies are equivalent to those achievable with current gas turbine engines. Thus, the effects of PDE generated unsteadiness on engine component performance must be understood.

NASA Glenn has initiated a Pulse Detonation Engine Technology program to address the above issue, as well as others. Numerical and experimental studies will be conducted in order to understand inlet and nozzle performance in a PDE. Combined cycles utilizing PDE in pulsed ejector configurations will be investigated. Thermal fatigue life for candidate combustor liner materials will be evaluated utilizing an existing laser thermal fatigue facility. Fundamental work related to understanding and addressing noise and emissions in PDE's will also be supported.

Exoskeletal Engine

The exoskeletal engine concept (Figure 11) represents a paradigm shift in turbomachinery design. This concept utilizes a drum-type rotor design for the turbomachinery, where the blades are attached to inner and outer rings. As a result, the blades primarily are in radial compression as opposed to radial tension. Bearings are located between the outer ring and the engine shell. For large engines, one of the major challenges is in bearing design. Magnetic bearings have been suggested as a possible solution to this problem. The drum rotor design allows the turbomachinery to be designed using ceramic matrix composite materials. These materials can operate at higher temperatures than the metal alloys that are typically used in turbomachinery components. This is a beneficial feature for a hypersonic propulsion system, where the high stagnation temperatures can exceed the limits of traditional turbomachinery materials.

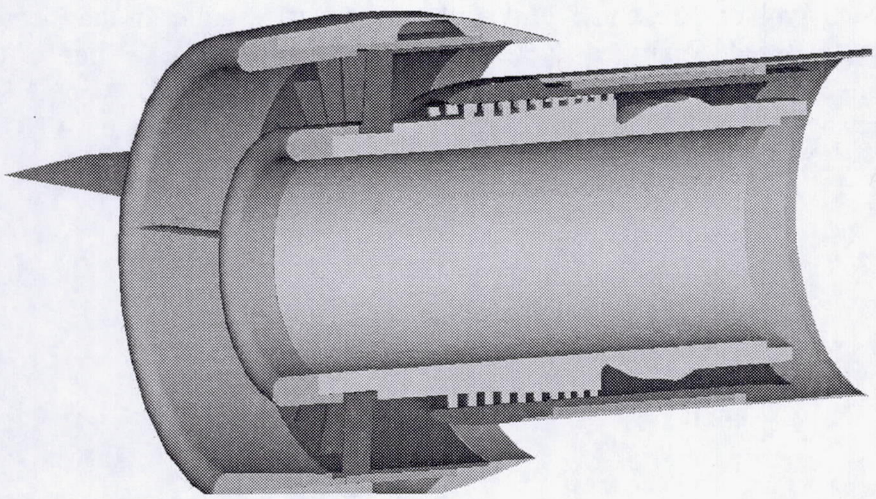


Figure 11. Exoskeletal engine concept.

Concluding Remarks

The National Aeronautics and Space Administration has set some challenging goals for reducing the cost of launching payloads into low-Earth orbit. This includes reducing the cost by nearly two orders of magnitude within the next 25 years. Innovative research programs have been established to meet those goals, and airbreathing propulsion concepts offer much promise for lowering launch costs. Various airbreathing propulsion system concepts were presented in this paper. The technical challenges associated with the concepts were identified, and significant progress has been made in theoretical and experimental studies.

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

This paper will present technologies and concepts for novel aeropropulsion systems. These technologies will enhance the safety of operations, reduce life cycle costs, and contribute to reduced costs of air travel and access to space. One of the goals of the NASA program is to reduce the carbon-dioxide emissions of aircraft engines. Engine concepts that use highly efficient fuel cell/electric drive technologies in hydrogen-fueled engines will be presented in the proposed paper. Carbon-dioxide emissions will be eliminated by replacing hydrocarbon fuel with hydrogen, and reduce NOx emissions through better combustion process control. A revolutionary exoskeletal engine concept, in which the engine drum is rotated, will be shown. This concept has the potential to allow a propulsion system that can be used for subsonic through hypersonic flight. Dual fan concepts that have ultra-high bypass ratios, low noise, and low drag will be presented. Flow-controlled turbofans and control-configured turbofans also will be discussed. To increase efficiency, a system of microengines distributed along lifting surfaces and on the fuselage is being investigated. This concept will be presented in the paper. Small propulsion systems for affordable, safe personal transportation vehicles will be discussed. These low-oil/oilless systems use technologies that enable significant cost and weight reductions. Pulse detonation engine-based hybrid-cycle and combined-cycle propulsion systems for aviation and space access will be presented.

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