Rocket-Based Combined Cycle Engine Concept Development

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Abstract

The development of rocket-based combined cycle (RBCC) propulsion systems is part of a 12 year effort under both company funding and contract work. The concept is a fixed geometry integrated rocket, ramjet, scramjet, which is hydrogen fueled and uses hydrogen regenerative cooling. The baseline engine structural configuration uses an integral structure that eliminates panel seals, seal purge gas, and closeout side attachments. Engine A5 is the current configuration for NASA Marshall Space Flight Center (MSFC) for the ART program. Engine A5 models the complete flight engine flowpath of inlet, isolator, airbreathing combustor, and nozzle. High-performance rocket thrusters are integrated into the engine enabling both low speed air-augmente

rocket (AAR) and high speed pure rocket operation.

Engine A5 was tested in GASL's new Flight Acceleration Simulation Test (FAST) facility in all four operating modes, AAR, RAM, SCRAM and Rocket. Additionally, transition from AAR to ram amd RAM to SCRAM was also demonstrated. Measured performance demonstrated vision vehicle performance levels for Mach 3 AAR operation and ramjet operation from Mach 3 to 4. SCRAM and rocket mode performance was above predictions. For the first time, testing also demonstrated transition between operating modes..

Background

During the mid-1980s, it was recognized that the foundation for airbreathing high-speed systems was based on key rocket technologies and synergies with gas dynamic lasers in the areas of mixing and combustion. Besides basic technology, the experience gained through the operation of the world's only reusable space transportation engine [Space Shuttle Main Engine (SSME)] was equally important to any design. Additionally, NASP, provided the opportunity to identify and resolve many key risk issues inherent in designing, building, and operating a reusable hypersonic vehicle.

Besides the NASP configuration a broad variety of concepts have been evaluated. These ranged the gamut from large SSTO and two-stage-to-orbit (TSTO) launch systems to smaller unmanned cruise and accelerator vehicles and munitions. Systems evaluated have also included a range of low-cost flight demonstration options for RBCC engines, improvements of existing vehicles, and "clean sheet" designs. Included in this effort has been evaluation of diverse fuel candidates for hypersonic propulsion that include hydrogen, kerosenes, storable propellants and blends. Engine configurations considered have ranged from highly integrated 2- and 3-dimensional (2-D and 3-D) designs to axisymmetric approaches. The emphasis has consistently remained on propulsion for low-cost access to space and the need for near-term RBCC flight demonstration regardless of the concept investigated.

ART Program Emerges

Post NASP hypersonic technology development received renewed emphasis by establishing the NASA Advanced Space Transportation Program (ASTP) and from the results of the Highly Reusable Space Transportation (HRST) system studies in the mid-90s. Hypersonic, or to be more specific, RBCC propulsion systems were identified as prime candidates to foster space launch market elasticity and growth by meeting goal payload $/pound targets identified in the Commercial Space Transportation System (STS) studies.

One key element of the ASTP was the Advanced Reusable Transportation (ART) technology program, which provided substantive funding to continue RBCC maturation and development. Rocketdyne was one of four engine contractors initially participating under ART contracts awarded in 1996. The NASA MSFC ART program has enabled some of the most significant hypersonic propulsion maturation milestones and achievements since NASP.

Rocketdyne entered the ART program with five specific objectives:

1. Demonstration of engine performance and operability (AAR, rocket, and ramjet modes)
2. Demonstration of mode transition from AAR to ramjet

3. Evaluation of engine performance on trajectory
4. Compilation of design data for flightweight engine design and vision vehicle
5. Anchoring of existing design and analysis tools with test data.

The ART program fostered many significant accomplishments for the Rocketdyne RBCC engine including rocket single thruster design, fabrication and testing, CFD, cold flow testing, the creation and shakedown of a new trajectory simulation test capability–the GASL FAST facility, and multimode integrated engine freejet testing. Also, complementary discretionary and cooperative programs continued the structures and inlet development.

The ART program differed from NASP objectives by limiting airbreathing propulsion to the Mach 10-12 range. At this point, the vehicle will execute a rocket trajectory pull up (SSTO) or, alternatively, stage (Fig. 1). The ART approach focused on the use of existing materials rather than the NASP approach of developing high temperature materials. This decision produces a system which transitions from airbreathing to rocket mode in the Mach 10-12 range. For the flowpath, Rocketdyne has baselined a unique, lightweight, low-cost, metallic structures manufacturing process. This process brings simplicity and manufacturing scalability to help benchmark thrust/weight predictions. This approach is available today for use in flight demonstration systems.

Development of RBCC systems is being advanced by leveraging lessons learned on the STS, X-33/Reusable Launch Vehicle (RLV) program, and usable engine operations (SSME). Analogous to the RBCC, the aerospike system uses multiple thrust chambers. Relevant similar multithruster design and manufacturing issues are currently being resolved in an extensive development program. These synergies include ignition techniques, propellant feed, engine out resolution, turbomachinery development, and advanced material maturation for low-cost, lightweight ducts, pump housings, and actively cooled engine structures.

Flying a demonstration of an RBCC engine as soon as possible is a high priority. This flight demo will move the technology forward [using the NASA technical readiness level (TRL) scale] from a current level of TRL 5 to 6. TRL 6 is considered a demonstration threshold where new technologies are perceived as ready to transition into commercial product designs. This flight demo will allow a more accurate assessment of both performance and technical risk, as well as collection of required design data and, thus, is a key input for evaluating ultimate business viability. A near-term flight test will also help convince many possible users that the technology is ready for use in diverse potential applications and, hence, encourage their participation and investment in detailed system design and further technology maturation.

RBCC Concept

A combined cycle engine integrates different propulsive elements into a single flowpath. These elements are chosen to best meet system and mission requirements. Thus, by selecting different combinations of propulsion, combined cycle engines can be customized to fit the requirements for a specific application. For example, if long duration loiter is needed, the high specific impulse (Isp)/low specific fuel consumption (SFC) of a turbojet or turbofan may be included as a flowpath element. The Rocketdyne engine is an RBCC because it is capable of operating in rocket, AAR, ramjet, and scramjet modes. Fuel injection locations are varied to optimize performance in each mode. The historical (and current) challenge of these combined cycle engines is achieving a single flowpath that operates efficiently in all these modes while being actually producible, meeting reasonable cost and weight targets. Balancing both the thrust and Isp necessary to meet flight profile and mission requirements is also important.

To focus concept development on customer need, engine developers must make key philosophical and design approach decisions early in the process. Rocketdyne has selected a fixed geometry baseline approach that performs well across a broad mach range. This approach is driven by market needs for ultra-low-cost reusable space transportation, which dictate requirements for increased operability, decreased cost, simplicity, and decreased maintenance. A fixed geometry engine approach will minimize the need for actuation, moving structure, and complex, difficult high-temperature seals. The Rocketdyne fixed geometry baseline does not infer zero variable geometry (except as a system goal), but rather that variable geometry components must "buy" their way into the engine design. GASL testing has shown increased performance with variable geometry. However, for an application system variable geometry increases weight and complexity. System trade studies will determine whether the benefits for variable geoemtry exceed the cost

ART Simplifies Structural Approach

Figure 1 depicts the trajectory for an all-rocket system compared to that flown for a NASP-type system. The rocket trajectory lifts the system above the earth's atmosphere, then accelerates to orbital speeds. The NASP system accelerates within the atmosphere until scramjet performance decreases to rocket level, then transitions to rocket operation. The heat flux levels and corresponding wall temperatures within the engine continually increase throughout this trajectory (as seen in Fig. 1). The engine must either incorporate materials able to withstand the environment, or actively cool the system. Material challenges include development cost, schedule, and fabrication technology. The challenge with active cooling is the level required. It is inefficient to use more fuel for cooling than the amount of fuel that can be burned with the air flowing through the engine.

The ART program adopted a philosophy different from NASP. ART chose to transition to rocket in the Mach 10 to 12 range even though scramjet operation may be more efficient than rocket operation at this point. However, in so doing, conventional materials (i.e., existing) can be used and active cooling in excess of combustion requirements is avoided.

Final design data for RBCC application systems require flight testing of subscale systems. Use of existing materials enables flight testing now, followed by scale up to application systems using the same materials and fabrication methodology.

The engine system weight is comprised of the sum of the weights for the flowpath, subsystems, and ducts and attachments. The following sections discuss each structure separately and the overall impact on the system gross takeoff weight (GTOW).

Structural Concepts

The RBCC flowpath is basically a converging-diverging duct. However, the duct surface is not a simple piece of material, rather it is a heat exchanger attached to a support structure. The hot surface of the heat exchanger is the interior wall of the engine in contact with the air and combustion gases. It must withstand the required internal pressure of the coolant and the external pressure due to air compression and combustion. The internal channels are relatively small and allow high-pressure coolant to be contained with minimum thickness materials. Air and combustion pressures are only a fraction of the coolant pressure, but applied to the entire engine surface represent considerable force. The support structure maintains the integrity of the heat exchanger. It is sized by an area requirement, e.g., the cross-sectional area of the combustor cannot deviate from the no load geometry by more than a value determined by aerodynamic analysis for the highest pressure experienced along the flight trajectory. Two broad categories of structural concepts are non-integral and integral designs. Figure 2 depicts these concepts. In each case, the structure is composed of a heat exchanger and support structure.

The difference in the two structural concepts is the method for attaching the heat exchanger to the support structure. As shown in Fig. 2, the non-integral structure connects to the heat exchanger using pins and attachments. This allows the support structure to be thermally isolated from the heat exchanger and makes possible the use of lightweight high-strength materials that would be unusable if in direct contact with the heat exchanger. The disadvantage is the weight of the pins, attachments, and extra surface plate. Additionally, the heat exchanger panels require manifolds and seals, which also add weight to the system.

Integral structure attaches the support structure directly to the back surface of the heat exchanger. This eliminates the weight of the extra components present in the non-integral structure. However, a large thermal gradient develops through the structure, which, in turn, induces high thermal stresses. In this case, under high Mach operation, the thermally induced stresses result in an integral structure heavier than the non-integral structure. Systems designed for high Mach airbreathing operation generally accept the higher complexity of non-integral structures to achieve low weight.

The ART program approach of transition to rocket mode in the Mach 10 to 12 range enables use of integral structural concepts as the simplest, lowest weight design.

Engine Weight Reduction

At the start of the ART program, weight estimates were made for the engine system as part of the vision vehicle study. The engine evaluated in the initial study was based primarily on work prior to the start of the program. At that time, the Rocketdyne RBCC engine structural concept was non-integral using NARloy-Z heat exchanger panels. An engine module was comprised of two flowpaths driven by one set of fuel and oxidizer turbopumps.

Subsequent to the initial study, accounting for scram to rocket transition in the Mach 10 range has enabled the use of integral structure. This change, incorporating a metal matrix composite (MMC) support structure, produced a 17 percent reduction in weight per flowpath over the initial non-integral concept. This represents materials and manufacturing processes available today. In the future, with further development, additional weight reduction can be achieved by ceramic composites for the support structure. In this case, a 30 percent decrease in weight is obtained over the non-integral concept.

The engine propellant pump subsystems have been re-evaluated from both configuration and materials aspects. Past studies have shown a weight savings by increasing pump size and driving more flowpaths per pump set. Two configurations were evaluated: a dual pump and a single pump configuration. The dual pump system means one pump set drives half of the number of flowpaths, whereas the single pump configuration drives all the flowpaths. There is a 13 percent weight reduction for the dual pump configuration as compared to the modular system, and a 25 percent reduction for the single pump design.

Weight alone is not the determining factor in selecting a configuration for a given application. Man-rated systems may need multiple pumps for safety, whereas cargo-carrying systems may be acceptable as single pump systems. Operations and overall life cycle costs must be included as parameters in design trade studies to determine the best system.

Material substitution can also reduce subsystem weight. The use of MMCs were estimated to reduce pump and valve weight by 20 percent and fuel side ducting by 50 percent. Figure 3 summarizes these results. The single pump system using MMCs produces a 40 percent weight reduction as compared to the initial vision vehicle engine multipump, metal system.

Benefits of reduced engine weight

Rocketdyne worked with two business units of Boeing and a division of Lockheed-Martin to develop vision vehicles. Two vertical takeoff horizontal landing (VTHL) configurations and one horizontal takeoff horizontal landing (HTHL) configuration were evaluated. System parameters (e.g., forebody shape, external and internal contraction and expansion, number of engines, transition from scram to rocket) were developed through trade studies. System weights initially used were based on the non-integral engine structural concept with multiple pump sets. During the course of the ART program, these systems were re-evaluated first to reduce the number of pump sets, then the combination of changing the structural concept to integral structure and reduced pump sets. Both results are summarized in Table 1. The three vehicles used in this trade study were at different stages of optimization one compared to another and thus cannot be used to determine the best configuration. However, the effect on any configuration of material and subsystem changes is clearly seen.

The final entry in the table substitutes ceramic matrix composites (CMC) for MMC. This is based on material and fabrication processes being developed for the X-33 and RLV programs. As such, it represents technology available in the future, whereas the MMC system is existing technology and available now.

RBCC Engine and Test Facility

Configuration Description

The engine configuration starts with a 3-D side wall contraction inlet for ease of starting and operationally benign unstart and throttle restart capability. During unstart, a transient pressure pulse passes through the inlet where the peak pressure can be many times higher than the normal operating pressure within the inlet. This pulse can damage the inlet structure as well as adversely affect vehicle controllability. A benign unstart does none of these. In addition, throttle restart capability means engine restart can be accomplished without variable geometry. Following the inlet is a constant area, rectangular isolator section containing the pseudo-shock during ramjet operation. The individual rocket thrusters are installed in the isolator, distributed on two sides of the isolator for rapid mixing. The primary rocket thrusters exhaust into a step constant area combustor. The final section following the step constant area combustor is an expansion. The expansion section functions as a supersonic nozzle during the scramjet and rocket-only modes of operation. During low-speed operation, the expansion acts as a secondary combustor to allow full stoichiometric fuel combustion to be completed. Thermal choking is thereby controlled within the isolator pressure rise capability. The mode compatibility of the engine is the focus of the current study. Of particular interest is the transition between the AAR and the thermally choked ramjet mode.

The engine design philosophy is fixed geometry. However, variable geometry may be required. Since the level of variable geometry is unknown, the engine was designed to have a wide throttle and chamber pressure primary thruster capability to allow evaluation of these issues. The need for a dynamic real-time trajectory simulation was also built into the experimental program to fully investigate transition and determine variable geometry requirements.

The AAR mode is required from take off to ramjet operation, nominally Mach 3 flight conditions. Prior studies indicate that transition to scramjet operation is dependent on the combustor step expansion ratio and occurs in the Mach 5 to 7 regime. Scramjet operation was designed for speeds ranging from Mach 10 to 12, where pull-up and transition to full rocket mode occurs.

Hardware Description and Test Setup

The A5 experimental engine contains both actively and passively cooled sections. The inlet and nozzle are made of oxygen-free copper (OFC) copper and heat sink cooled. The hot section components, isolator, primary thrusters, and constant area combustor were all designed to be fuel cooled and flight type for aerothermal technology demonstration. The engine is operated using water coolant for expediency and facility compatibility.

The engine is fueled by three separate systems. One fuel system operates the primary thrusters on hydrogen and gaseous oxygen. The other two hydrogen systems are for the scramjet and ramjet modes. During the mode transition, the three systems are used simultaneously.

The engine is mounted at the exit of the facility nozzle in the GASL freejet test cell Leg 5, which is capable of flight enthalpy simulation to Mach 8. The engine is mounted on a 1 degree-of-freedom (DOF) force balance. The facility test cell is connected by a diffuser into large diameter ducts and a vacuum sphere.

FAST Facility

The Leg 5 test cell at GASL was specially constructed for the NASA ART program to simulate the dynamic conditions on an RBCC trajectory. The facility flow, total temperature, and nozzle angle are selected and computer-controlled for a given flight dynamic trajectory simulation. The facility permits the demonstration of mode transition and the economy of testing over a wide Mach number range in a single test. The FAST facility is shown in Fig. 4.

RBCC Engine A5 Development Testing

The Engine A5 experimental hardware performed very well in a series of hot-fire tests conducted over a 6-month period in the summer of 1999.

Testing was divided into the following categories:

- AAR
- Ramjet
- Trajectory
- Rocket

Approximately two-thirds of the testing was applied to the AAR and ramjet evaluations of the engine with the remainder of the testing split between trajectory and pure rocket tests. Subsequently, a successful series of SCRAM mode tests were carried out. Information from these tests is given in reference[1].

During the testing, over 400 ignitions of the rocket thrusters were achieved. The thrusters were operated with combustion pressure ranging from 200 to 1,000 psia to develop an understanding of the effect of rocket flowrate and thrust on engine AAR operation. Similarly, the thruster combustion mixture ratio was varied from 2 to 11 to determine the effects of fuel rich gases on the AAR operation. Tests were conducted at mixture ratios of 8 and above to measure AAR operation with no excess fuel in the thruster flow. By the end of the testing, over 4,700 seconds of operation were achieved by the Engine A5 thrusters.

Engine A5 in test in the GASL FAST facility is shown in Fig. 5. Shown in the figure is the exit of Engine A5 with the exhaust plume entering the facility diffuser. In this test, the rocket thrusters are firing and the engine is operating in the AAR mode.

AAR Testing

A typical AAR test is described in Fig. 6. The scales on this and the next few figures have been suppressed to comply with NASA requirements for publications in the open literature. This particular test was conducted at $M = 3.4$ freestream conditions. As shown, the freestream flow was initiated at approximately 18 seconds with steady-state conditions reached at 30 seconds. The measured thrust at this point represents the total engine drag at these conditions. The external geometry of Engine A5 was designed to be aerodynamically clean. However, due to the thickness of the engine walls, the external component of the engine drag was over half of the total drag. At $t = 30$ seconds, the rocket thrusters were ignited and AAR operation of the engine initiated with positive net thrust including the external engine drag. The increase in thrust with time was the result of increasing the rocket flow slowly during the test to provide parametric data evaluating the effects of rocket thrust on AAR performance.

A small decrease in engine thrust occurs at $t = 42$ seconds. This was the result of a partial inlet unstart at this level of rocket thruster flow. Due to the design of the sidewall compression inlet, the effect of an unstart on total thrust was small. Also, it was possible to continue to increase the thruster flow to generate total engine thrust levels above that of the fully started inlet. Addition of downstream fuel in the engine airbreathing combustor yielded the thrust increase at $t = 48$ seconds. Engine operation was terminated at $t = 54$ seconds.

The wall pressures shown in Fig. 7 indicate operation of Engine A5 during an AAR test. The pressures before rocket ignition indicate the compression in the inlet followed by expansion through the nozzle. As shown, the inlet compression is quite smooth. The difference between the inlet pressures and the nozzle pressures represents the internal compression drag of the engine. With rocket ignition and the beginning of AAR operation of the engine, the pressures in the nozzle increase substantially and continue to rise as rocket thrust is increased. The difference between these pressures and the inlet pressures represents the air-augmentation of the rocket thrust achieved by the engine operating in the AAR mode. The partial unstart discussed above is indicated by the final pressure profile shown in Fig. 7. In this case, pressures in the downstream part of the inlet have increased above the fully started values yielding increased compression drag and a net thrust reduction. Pressure levels in the front of the inlet remain low, limiting the reduced thrust effects of an inlet unstart.

A substantial quantity of AAR parametric data was measured in the AAR testing. The effects of rocket thrust, mixture ratio, and downstream fuel injection provide a comprehensive database for RBCC engine development. The engine performed quite well in the AAR operating mode in the freestream flow Mach range from 3 to 3.4. Thrust augmentation levels were significantly above 1 for the full range of rocket thrust levels evaluated. At $M = 0$ sea level static conditions, augmentation levels were reduced due to overexpansion losses in the high area ratio airbreathing nozzle. Variable geometry can be beneficial in minimizing these losses. Again, the overall system impact must be evaluated. Planned testing at this operating point will evaluate approaches, based on the test results to date, to reduce these losses.

Ramjet Operation

Operation of Engine A5 in the ramjet mode was similar to the AAR operation discussed previously. In this case, ram air compression was sufficient to isolate the airbreathing combustion process and the rocket thrusters were turned off. Elimination of the oxidizer required for AAR operation significantly increased the engine Isp.

A typical ramjet test is shown in Fig. 8. Engine thrust is indicated as well as downstream ramjet fuel injection pressure. As before, steady facility freestream conditions are reached at $t = 30$ seconds. Engine combustion is then initiated and the engine thrust is sufficient to offset the total engine drag at low fuel flowrates. At $t = 37$ seconds, the fuel scheduling is changed, resulting in significant engine net thrust. During the time from 39 to 50 seconds, upstream fuel flow is increased in steps as indicated by the incremental increases in engine thrust during this time period. At $t = 50$ seconds, the downstream fuel injection flow is increased gradually to $t = 54$ seconds. During this phase of the test, the net engine thrust increases by a factor of two. At $t = 52$ seconds, the combustion generated pressure rise in the engine is sufficient to again partially unstart the inlet and a decrease in net engine thrust occurs.

Engine internal wall pressure profiles during ramjet operation were similar to the AAR wall pressure profiles shown in Fig. 7. In this case, the nozzle wall pressures increased with increasing ramjet fuel flow until partial inlet unstarts occurred as discussed previously. In ramjet operation, maximum engine thrust was achieved with the inlet fully started.

Transition Demonstrated

One key achievement of the Engine A5 development tests was the demonstration of AAR to ramjet transition. This transition was demonstrated on an actual simulated trajectory using the unique features of the GASL FAST facility. During the test, both the aerodynamic and the enthalpy Mach number were increased from Mach 3 to 4. Transition was scheduled to occur at M = 3.4 in the middle of the test with the facility nozzle at the nominal horizontal position. Engine operation during the transition is shown in Fig. 9. During the initial AAR operation of the engine, the rocket thrusters were throttled to reduce engine thrust prior to transition to ramjet operation. This was done as a first step in developing a smooth transition in thrust through the change of operating modes. As shown in Fig. 9, during the time the rocket thrusters were throttled and the engine experienced a simulated acceleration from M = 3 to 3.4, the engine Isp gradually increased. This was a result of an increasing fraction of the thrust being generated by the airbreathing components of the engine. When the engine reached simulated conditions just above M = 3.4, the downstream ram fuel flow was increased significantly. The initial effect of this increase can be observed in the increase in thrust at this point just before the rocket thrusters are shut down. At this point, the engine thrust decreases before stabilizing at approximately constant ramjet thrust for the remainder of the simulated acceleration to M = 3.9 conditions. During this period, engine Isp is much higher, which is indicative of the advantages of ramjet operation with no on-board oxidizer required.

Rocket Mode Testing

Engine A5 was tested as a pure rocket at near-vacuum conditions by closing off the inlet with a simulated door in a low ambient pressure environment. In these tests, the engine rocket thrusters were operated over a range of combustion pressures and varying levels of hydrogen bleed flow were injected into the base region formed by the simulated door. Operation of multiple rocket thrusters during a typical rocket mode test is shown in Fig. 10. Following thruster ignition, the thrusters were operated at a chamber pressure of 1,000 psia for 15 seconds in this test. As stated above the thrusters were fired over 400 times with the uniform steady operation. shown in Figure 10.

RBCC engine rocket mode thrust at vacuum conditions is significantly greater than the thrust of the rocket thrusters alone. This is achieved by generating positive thrust on the close-off door and the airbreathing engine nozzle walls. Base pressures measured in the region of the close-off door are shown in Fig. 11 for increasing levels of base bleed flow. The results are also compared to the predicted levels based on linear aerospike cold flow experimental data. Results are in good agreement with analytical predictions, again demonstrating synergy with pure rocket technology.

High rocket mode performance was measured in the Engine A5 tests. The measured performance levels were within the values predicted based on analysis and cold flow test results. The experimental performance levels were scaled to an operational vision vehicle by accounting for the effects of cryogenic propellants with regenerative cooling and adjusting the combustion efficiency to demonstrated full-scale values. Also, the thrust gained by expanding the rocket exhaust over the aftbody of the vehicle was added to the engine thrust. The resulting Engine A5 scaled performance levels were above the values used in earlier vision vehicle studies.

Performance Summary

A summary of Engine A5 measured AAR and ramjet performance levels scaled and compared to values used in the earlier vision vehicle studies is shown in Fig. 12. The rocket mode performance discussed previously is also included. AAR performance in the Mach 3 range was close to, but slightly below, the vision value. Ramjet performance in the Mach 3.4 to 4.2 range was very close to the levels used in the vision vehicle study. Testing currently in progress is expected to fill in the comparison for $M = 0$ sea level static and $M = 6$ to 8 scramjet performance.

Conclusion

Rocketdyne and NASA have made significant progress toward demonstrating that a single integrated RBCC engine can perform effectively as an AAR, a ramjet, a scramjet, and a pure rocket. With planned demonstrations to benchmark simple lightweight structures and producibility, a near-term low-cost RBCC flight demonstration is the next logical step.

Reference

1. Hannigan, R. J., Space Flight in the Era of Aero-space Planes. Krieger Publishing, 1994

Fig. 1. RBCC Trajectories Reduce Thermal Protection and Structural Requirements

Fig. 2. Comparison of Non-Integral and Integral Structures

Fig. 3. Weight Reduction due to Material and Subsystem Changes

Fig. 4. Innovative GASL Test Approach Simulates Airbreathing Flight Trajectory

Fig. 5. Engine A5 Test in GASL FAST Facility

Fig. 6. Engine A5 AAR Test Evaluating the Effects of Increasing Rocket Thrust at M = 3.4 Conditions

Fig. 7. Engine A5 AAR Operation at M = 3.4

Fig. 8. Typical Engine A5 Ramjet Test

Fig. 9. Engine A5 Transition from AAR to Ramjet Operation

Fig. 10. Engine A5 Rocket Mode Thruster Combustion Pressure

Fig. 11. Engine A5 Rocket Mode Base Pressure

Fig. 12. Engine A5 Tests Verify Vision Vehicle Performance Levels

Table 1. Ratio of Vehicle GTOW to GTOW of Initial Configurations

Vehicle	A	B	C
Initial Configuration	1.00	1.00	1.00
Integral + Dual	0.88	0.82	0.72
Integral + Single	0.86	0.74	0.67
Integral + Single + CMC	0.83	0.70	0.57

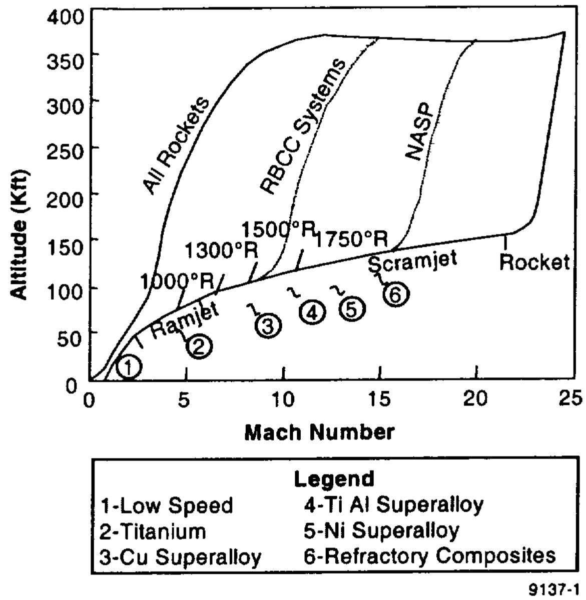

Figure 1. RBCC Trajectories Reduce Thermal Protection and Structural Requirements

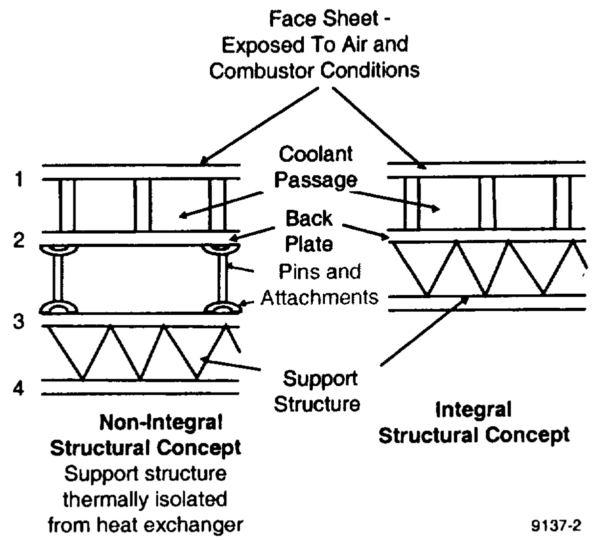

Figure 2. Comparison of Non-Integral and Integral Structures

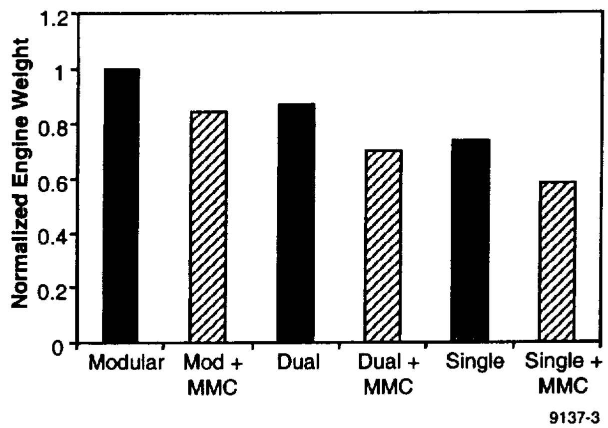

Figure 3. Weight Reduction due to

Material and Subsystem Changes

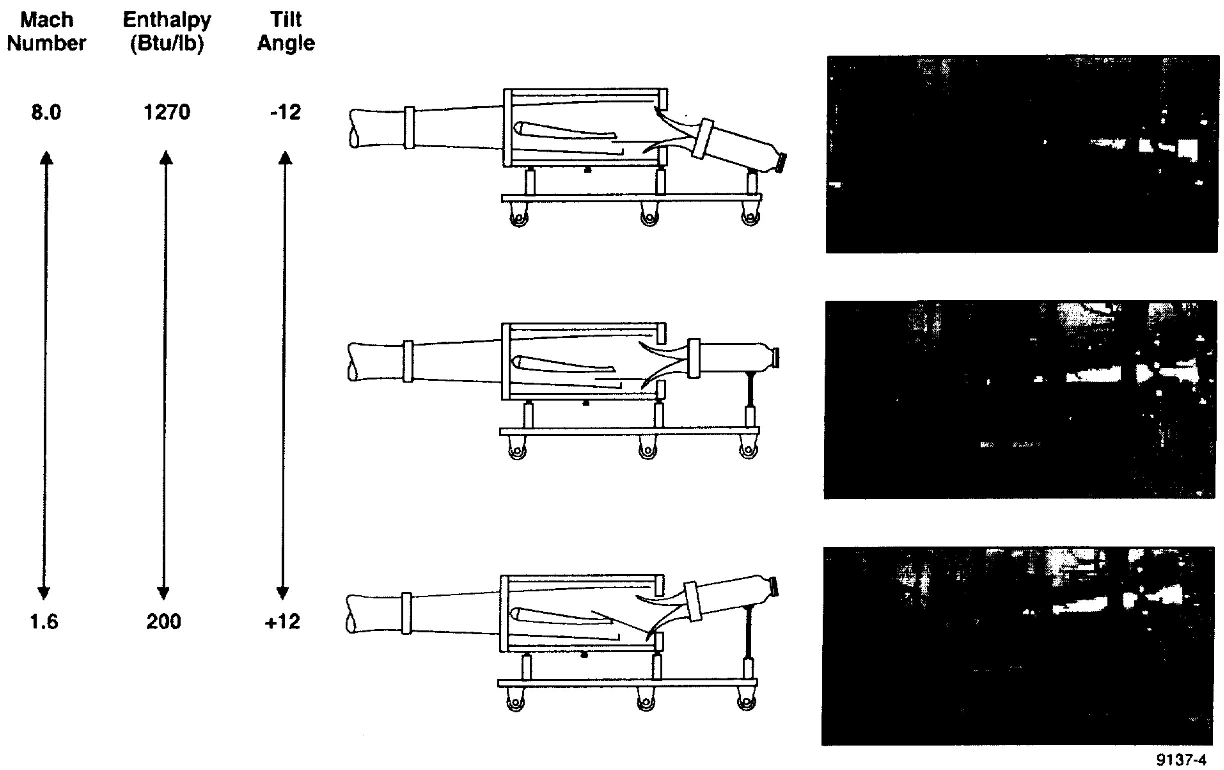

Figure 4. Innovative GASL Test Approach Simulates Airbreathing Flight Trajectory

Figure 5. Engine A5 Test in

GASL FAST Facility

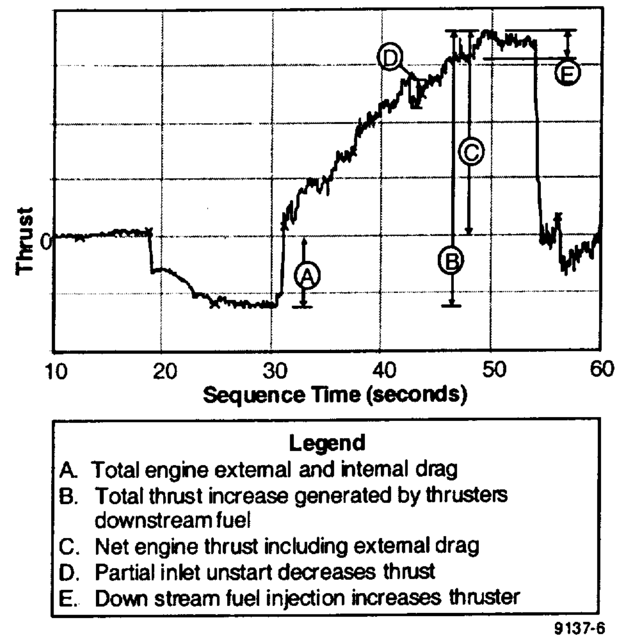

Figure 6. Engine A5 AAR Test Evaluating the Effects of Increasing Rocket Thrust at M = 3.4 Conditions

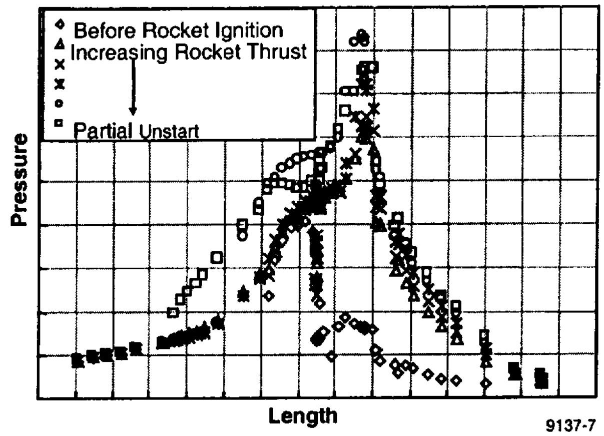

Figure 7. Engine A5 AAR Operation

at M = 3.4

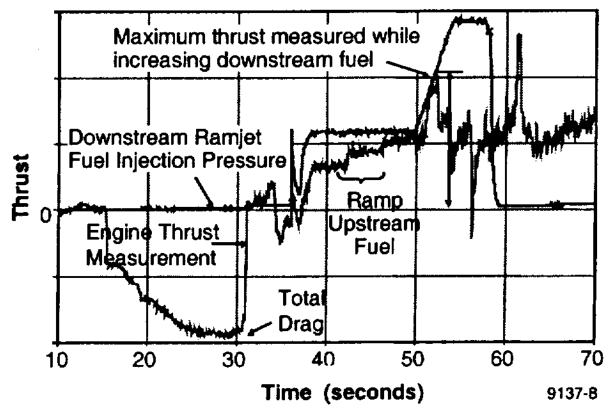

Figure 8. Typical Engine A5 Ramjet Test

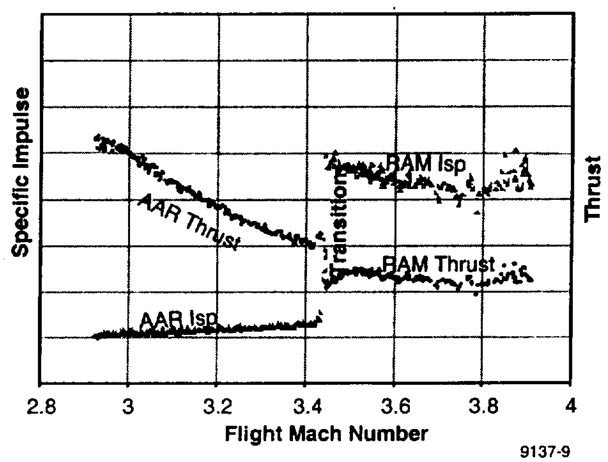

Figure 9. Engine A5 Transition from AAR

to Ramjet Operation

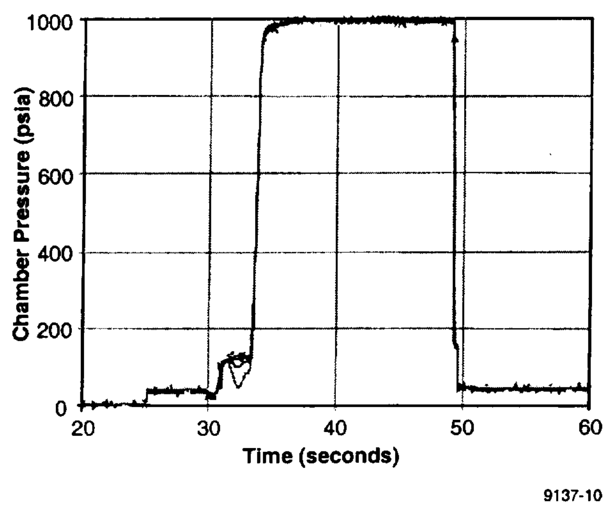

Figure 10. Engine A5 Rocket Mode

Thruster Combustion Pressure

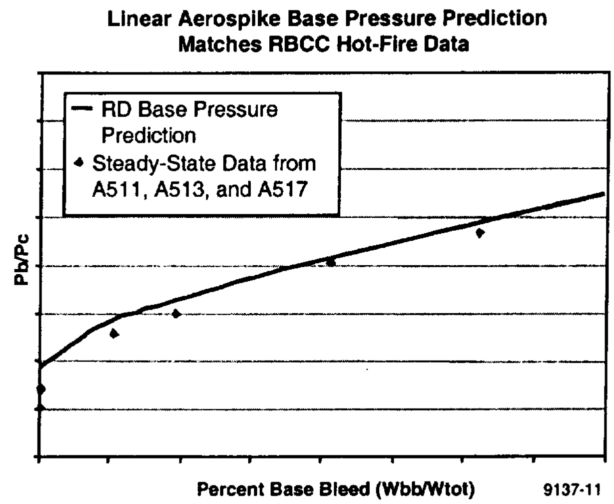

Figure 11. Engine A5 Rocket Mode

Base Pressure

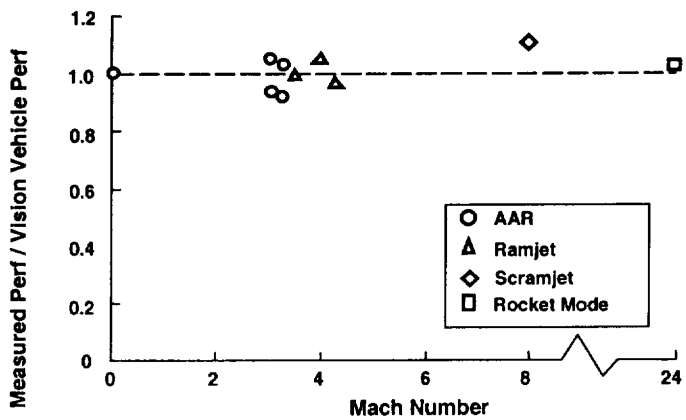

Figure 12. Engine A5 Tests Verify Vision Vehicle Performance Levels