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Center-Loaded Duct Integral Rocket-to-Ramjet Transition Testing

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This paper describes the facility test equipment and techniques that have been developed for efficient integral rocket-to-ramjet transition testing. The facility and test procedures were demonstrated successfully with the use of representative advanced cruise missile test hardware and test conditions to establish the feasibility of the high-performance center-loaded duct propulsion concept. This concept requires the ramjet flameholder and fuel injectors to be stationed between two solid-propellant rocket grains. The transition test method was selected because it produces the true thermal/time history for both the test hardware and the environment. The test series included component checkout tests, ramburner firings to establish baseline performance, simulated transition tests to verify facility operation, and full rocket-to-ramjet transition firing for design verification.

Introduction

In an advanced cruise missile integral rocket/ramjet (IRR) propulsion system concept (Fig. 1), air is captured by a forward-mounted underslung chin inlet and is passed through an S-turn to a circular air transport duct that is concentric with the center of the fuel tank. The transport duct terminates with an interstage section containing fuel injectors and a flameholder at the entrance to a sudden-dump combustor. For the rocket design, rocket propellant is loaded in the circular transport duct section and in the ramjet combustion chamber. During rocket operation, the forward end of the air transport duct is closed off by a glass port cover, and an ejectable rocket nozzle is fixed inside the ramjet nozzle. When the missile transitions from rocket- to ramjet-powered flight, the rocket nozzle is ejected, the port cover is fragmented, and the ramjet fuel flow is initiated and ignited.

Use of the center-loaded duct concept introduced several technology issues. An area of major concern was the condition of the flameholder and fuel injectors after exposure to the rocket environment during rocket operation. The condition of the flameholder and fuel injectors could impact ramjet performance in the following ways: 1) increased blockage due to remaining insulation on the flameholder would increase dump pressure losses; 2) a marred flameholder configuration would decrease ramjet combustion performance (both efficiency and stability would be affected); and 3) damage to the fuel injectors would impact fuel distribution, thereby influencing ramburner lean blowout limits and combustion efficiency.

To determine the physical impact of the rocket environment on flameholders and fuel injectors and the corresponding impact on ramburner performance, a subscale rocket-to-ramjet transition test was conducted in a ramburner facility[1] where the test events were sequenced in accordance with Fig. 2. The severe thermal shock induced on the flameholder after it has first been exposed to the rocket environment (6500°R, 1200 psia, fuel rich) for approximately 6 s, immediately followed by the environment of the glass port cover fragments impingement and ramjet operation (1200°R, 40 psi, oxidizer rich) for 60 s or more, requires testing with realistic simulation both in environments and timeline of events. Therefore, the transition test method using test hardware modeled after advanced cruise missile configurations was selected. The ramburner facility performed many functions

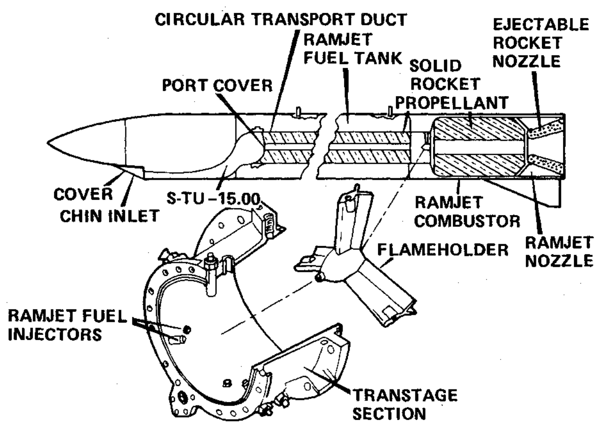

Fig. 1 Center-loaded duct configuration.

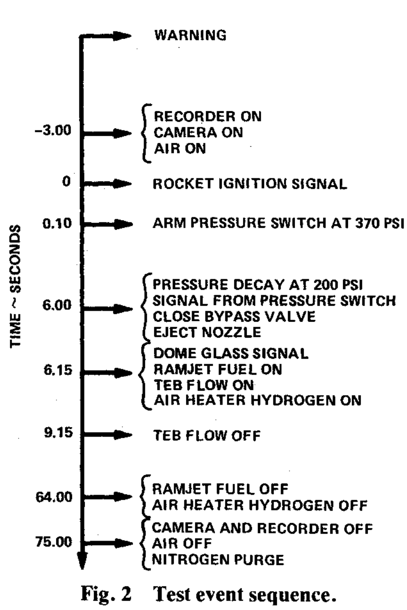

Fig. 2 Test event sequence.

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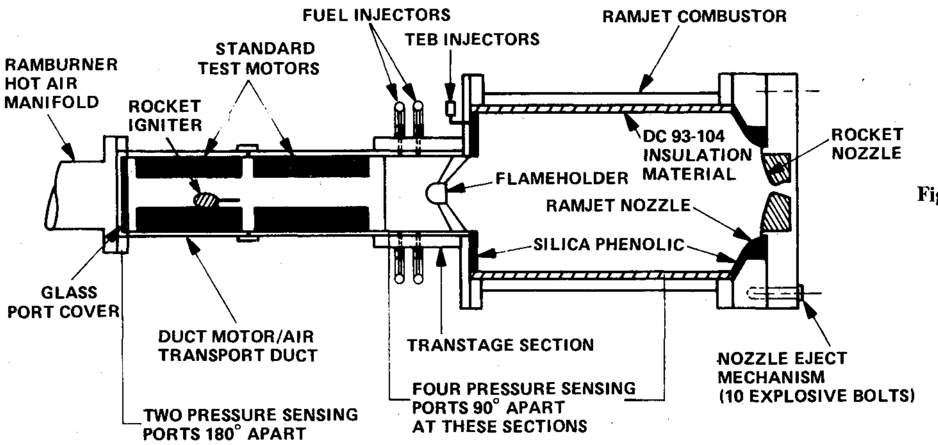


Fig. 3 Test hardware schematic.

Table 1 Facility function requirements

Sequence	Action
1	Pressurize facility air cavity for rocket burn cycle.
2	Initiate rocket burn.
3	Cover and seal forward end of test section air duct during rocket burn cycle.
4	Sense rocket motor burnout pressure.
5	Initiate rocket nozzle ejection at rocket burnout.
6	Open forward end of test section air duct at rocket burnout.
7	Direct air flow into air duct.
8	Heat air flow to air duct.
9	Regulate air flow rate.
10	Measure and record air flow rate and air duct temperature.
11	Initiate fuel flow to test ramjet injectors.
12	Ignite test ramjet.
13	Vary ramjet fuel flow rate during ramjet run cycle.
14	Measure and record ramjet fuel flow rate.
15	Measure and record thrust.
16	Measure and record test hardware pressures at inlet duct, transtage, and combustor section.
17	Measure and record hydrogen and ramjet fuel mass flow rates.

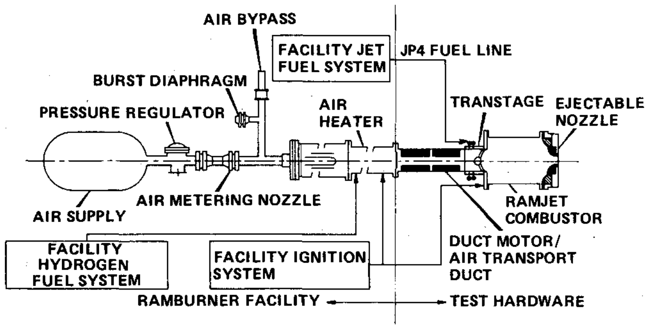


Fig. 4 Ramburner facility arrangement.

(see Table 1) critical to the operation of the integral rocket/ramjet model, as well as sequential control of all test actions. New facility equipment and techniques were developed for these tests.

Summary

A series of tests was conducted to demonstrate that advanced IRR cruise missile flameholder and fuel injector configurations could be designed to successfully withstand an integral rocket burning environment and then perform properly during the ramjet mode of operation. Subscale models of the flameholder and fuel injector components were fabricated and tested in environments similar to those projected for advanced cruise missile configurations and operations. Test results verified that the flameholder and fuel injector systems can be successfully protected against the severe rocket environment and then function during ramjet operation with minimal ramburner performance degradation.

The test program included fabrication of model hardware representative of baseline advanced cruise missile configurations. A schematic of the test hardware is shown in Fig. 3. A schematic of the ramburner hot air facility with the test hardware installation is shown in Fig. 4. The test series involved component checkout tests (such as fuel injector protective cap ejection and boost nozzle ejection demonstrations), ramburner firing to establish baseline ramjet performance, simulated transition tests to verify facility sequencing, and full rocket-to-ramjet transition firing for design validation. The only anomaly resulting from the rocket-to-ramjet transition test was the failure of the test article fuel injector thermal protection caps to fully clear the injector housings. This subsequently has been corrected by a redesign of the caps. All facility functional requirements (Table 1) were properly accomplished in this transition test.

Test Objectives

The primary objectives of the test program were to determine the effects of the rocket and transition environment on the flameholder geometry and its resulting performance operation, and to verify the thermal protection system and obtain data that could be used for full-scale testing. The objectives were achieved by subjecting instrumented model hardware to a rocket-to-ramjet transition test where the event timeline schedule shown in Fig. 2 was programmed and achieved. The ramburner pressure recoveries and gross thrust per pound of air flow were measured immediately after the system was exposed to the rocket environment. The measured data were then compared with pressure recovery and thrust data taken from tests in which a bare uninsulated flameholder system was used that was not subjected to a rocket firing. Visual inspection of the physical damage to the flameholder was also performed to assess the geometrical change resulting from exposure of the flameholder to the rocket environment.

A secondary objective of the test was to demonstrate the fuel injector protective cover concept. Both thermal protection during rocket operation and ejection of the caps during transition were to be demonstrated.

Program Plan and Facility Management

The test program called for an effort that included development of a test plan, procurement of rocket motors, design and fabrication of test hardware, critical reviews, verification of subsystems and components, full rocket-to-ramjet transition firings, and reduction and analysis of test data. Purchase orders were issued for the rocket motors,

Table 2 Test run matrix

Test	Remarks
Pyrophoric ignition system checkout	Conduct hydroproof, leak, and functional test prior to incorporation in facility.
Sequencer checkout	Verify output command signals and cycle reliability by multiple dry run cycling.
Hydroproof of test article hardware	Assemble all hardware, including port cover, and proof to 1.5 times the maximum expected operating pressure (MEOP).
Test article fuel injector protective cap ejection	Establish pop-off characteristics.
Air bypass valve checkout	Conduct cold flow testing with glass port cover fracturing to verify function.
Injector characterizing (arrangement A)	Vary fuel-to-air ratio (f/a) between 0.02 and 0.06.
Injector characterizing (arrangement B)	Vary f/a between 0.02 and 0.06.
Injector characterizing (arrangement C)	Vary f/a between 0.02 and 0.06.
Nozzle eject	Set facility flow conditions to provide 150 psia in combustor with no ramjet combustion.
Simulated transition	Check sequencing, break port cover, eject fuel caps, ignite ramjet, and vary f/a.
Rocket-to-ramjet transition	Conduct full transition sequence and vary f/a.

including chambers, propellant grains, ejectable rocket nozzles, and igniters. This was followed by a test plan describing the test conditions, instrumentation requirements, and hardware schematics.

Facility function requirements were then defined as shown in Table 1. The functional requirements provided the basis for establishing the facility modifications needed for the program tests. Design of the test hardware and the facility modifications were then initiated in parallel and fabrication was completed.

Technical reviewes were planned, including a hardware/test plan review, a preliminary facility/test procedure review, and a final test review held just prior to the rocket-to-ramjet transition firing. Pressure proof of the hardware and component checkout/verification tests were conducted, followed by the full-up rocket-to-ramjet transition test.

The test run matrix shown in Table 2 was arranged so that each critical component could be individually tested before being integrated with other systems. The facility modifications that were critical to the program were accomplished early for individual testing and for testing during the injector characterizing series and the simulated transition test series.

Because the existing facility spark plug ignition system would not survive a rocket motor environment, an alternative ignition system using a liquid pyrophoric was designed. The system delivers liquid pyrophoric fuel – triethylborane (TEB)—to the combustor. When the liquid is injected into air, it spontaneously burns, yielding heat energy to ignite the fuel/air mixture flowing through the combustor. During the transition tests, the ignition system had to simultaneously ignite the air heater and test article ramjet. Since simultaneous ignition had not been attempted before, ignition tests in this mode were incorporated into the simulated transition test series.

IRR transition was planned to be controlled by automatic timing equipment since the transition events must occur

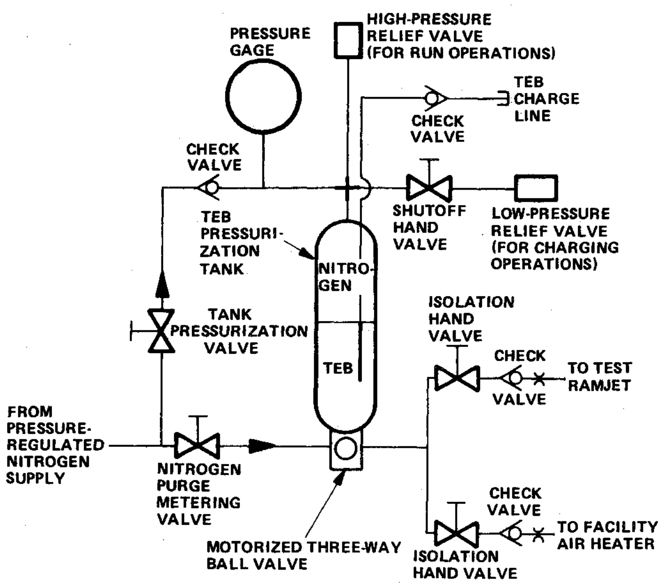


Fig. 5 Facility ignition system schematic.

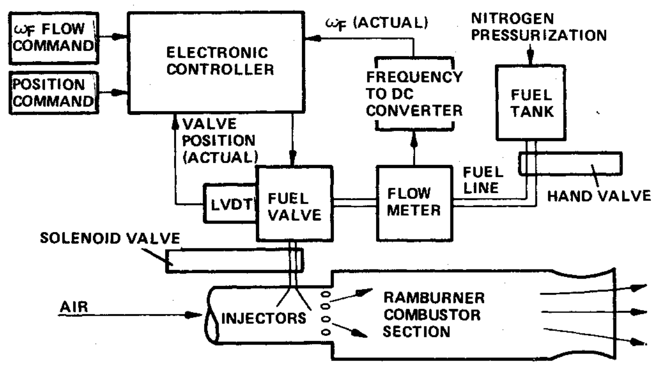


Fig. 6 Jet fuel control system.

rapidly and in the proper sequence (see Fig. 2). The facility automatic sequencer was modified for this purpose. After modification, sequencer performance was verified by cycling it and analyzing the recorded output electrical signals. Defective relays were detected and replaced in initial runs. After repetitive run cycle records showed no further malfunctions or anomalies, the sequencer was returned to service and was used in the subsystem checkout, injector characterizing, and simulated transition tests.

To pressurize the ramjet inlet section immediately upstream of the glass port cover, it was necessary to start the air flow several seconds ahead of the scheduled ramjet lightoff. The facility air bypass valve control logic was set up to regulate the inlet air pressure level during rocket operation and then close the bypass valve at transition to divert air flow into the ramjet inlet. To check out the air bypass valve, it was planned to test the valve initially with cold air flow runs. During the cold air flow runs, the valve functioned as a backpressure regulator to regulate air cavity pressure until a ramjet inlet glass port cover was fractured, at which time, the air bypass valve control logic closed the valve. Final checkout of the bypass valve was planned in the simulated transition tests.

Since the fuel flow rate can be varied with the facility fuel control system (Fig. 6), it was used to control the jet fuel flow to the ramjet model.

Hardware

The test hardware was designed to allow simulation of typical advanced cruise missile characteristics in key areas. Flow area distributions, flameholder configurations, solid propellant properties, and event sequencing were simulated to

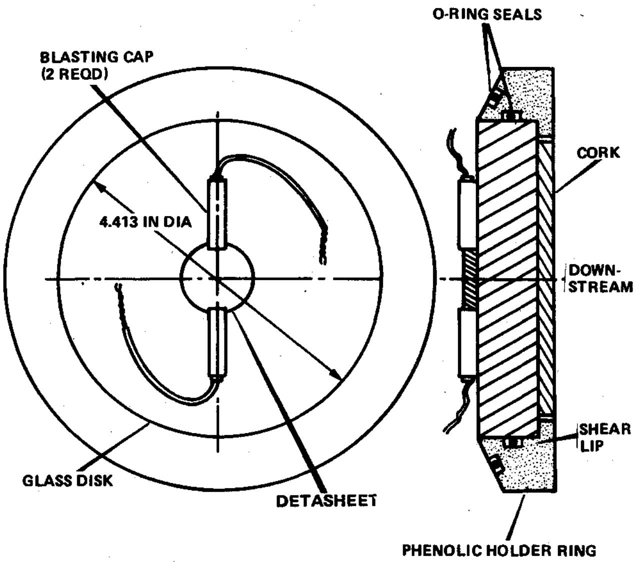


Fig. 7 Glass port cover assembly.

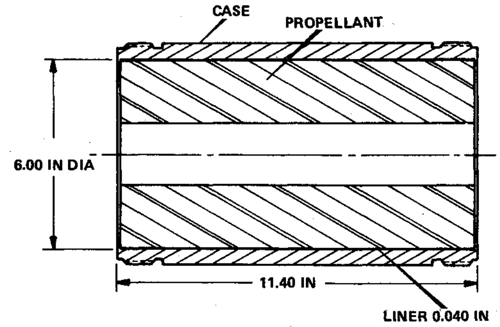


Fig. 8 Solid propellant grain segment.

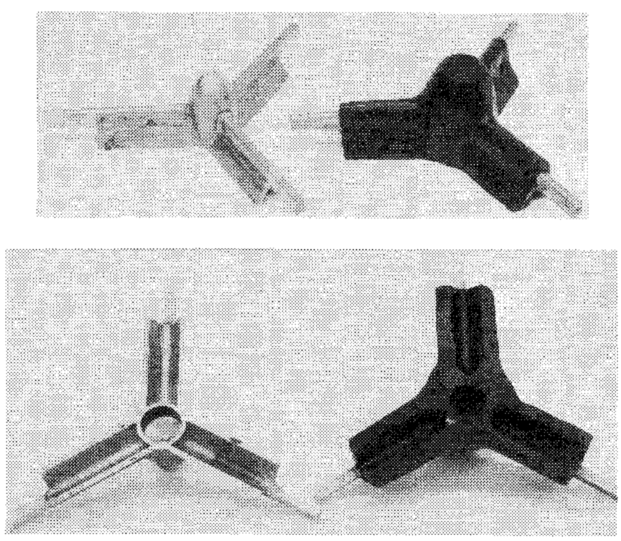


Fig. 9 Flameholder—bare and insulated.

provide representations of actual environments. The major subsystems are discussed individually in the following paragraphs.

The sequencer used in all facility operations incorporates cam timers and precision timing relays providing sequencing options for several activities. This sequencer was modified to arm and hold a pressure switch latching relay indicating that the rocket motor had ignited. Upon rocket motor pressure decay at burnout, the pressure switch signal caused the sequencer to signal the start of the transition events. The sequencer modifications allowed the transition events to be initiated from a pressure reference base rather than a timed base, allowing transition to start at motor burnout.

The facility ignition system designed for the program is shown schematically in Fig. 5. The system delivers TEB to the facility air heater and test article ramjet to ignite these systems. The system was designed to protect itself during the rocket burn by checking the back flow from the combustor. After the ignition cycle was complete, the system was set up to nitrogen purge the TEB from the ignition tubes.

The facility jet fuel control system (Fig. 6) was used to regulate the JP4 jet fuel to the test article ramjet. This is a closed-loop system that permits the operator to vary the fuel flow rate during the run. This feature was used to vary the fuel-to-air ratio during the component characterizing tests, the simulated transition tests, and the rocket-to-ramjet transition run.

The forward glass port cover (Fig. 7) was a glass disk with 0.15-in-thick cork insulation. The fragmentation charge for breaking the glass included 4 g of Datasheet C initiated by two blasting caps. A polyurethane foam insulator was placed on the upstream side of the glass to protect the fragmentation charge from the facility warm air. When the glass fractured, the phenolic lip (see Fig. 7) sheared off, releasing all the glass to flow downstream.

Each of the two solid propellant rocket grain segments (Fig. 8) was cast with 18 lb of solid propellant into a center perforated grain configuration that burns radially and from each end. The solid propellant was a carboxyl terminated polybutadiene (CTPB) formulation having 88% total solids and 20% aluminum. The two grains were coupled together with a threaded coupler to form a single rocket motor for the test. The rocket ignition system consisted of a single bag-type igniter with two squib initiators.

The transtage assembly, located between the rocket grains and the combustion chamber, housed six flush-mounted poppet-type fuel injectors and the Y-flameholder. The structural wall was protected by silica phenolic insulation. Each poppet fuel injector was threaded into an injector housing that was assembled to the transtage section. The injectors were protected during rocket operation by a carbon phenolic insulated steel cap.

The flameholder configuration (Fig. 9) was patterned from advanced cruise missile concepts and is defined as a Y with a V-gutter trailing edge along each leg. The three legs are joined in the center by an aerodynamically shaped body of revolution. The flameholder was constructed from Inconel 718 steel. Carbon phenolic insulation with varying thicknesses was applied to all outer surfaces of the flameholder. Radiographs of the insulated flameholder showed that the thickness of the leading edge material was 0.25 in. on the nose and 0.20 in. on the legs.

The combuster had an inside diameter of 11.0 in. and was 24 in. long. The insulation (DC 93-104) was 0.375 in. thick and was centrifugally spun cast in the chamber. The forward end of the chamber was insulated with silica phenolic. The sonic ramjet nozzle was insulated with tape-wrapped silica phenolic.

The ejectable rocket nozzle was constructed of carbon steel for the structural housing and high-density graphite for the throat. The ejection concept consisted of 10 explosive bolts through the rocket nozzle and threaded into the ramjet nozzle structure. The bolts were actuated during rocket motor burnout. The residual chamber pressure ejected the nozzle when the explosive bolts separated. To assure that all 10 explosive bolts would separate at the same time, each bolt required 20 A. A 300-A, 28 Vdc power supply was set up to provide the necessary current. Fast-closing relays were used so that separation would occur in time for the residual chamber pressure to eject the nozzle.

Hardware Checkout Test and Ramjet Characterization Tests

The test article hardware was initially hydroproofed to 1800 psi (1.5 times the rocket motor operating pressure). The first hydroproof test resulted in the glass port cover breaking during depressurization from 1800 psi after holding that pressure for 5 min. A failure analysis review was held and the findings were documented. Corrective action was taken to redesign the cover retaining flange and the hydroproof was repeated successfully.

Demonstration of the injector protective cap ejection was the first subsystem function test. Laboratory tests indicated that caps tested individually would eject at 30 psi pressure differential; however, concern over the simultaneous ejection of all six of the caps used in the fuel injector system, as well as all the caps passing by the flameholder blockage in the air transport duct, led to a successful test of the complete system dedicated to demonstrating the cap ejection system. During the first injector protective cap ejection tests, the caps were allowed to eject into the grass field in front of the teststand. Some of the caps were never recovered, and a method was therefore devised for capturing the protective caps. Two nylon mesh shrimp nets were secured over the exit of the combustor nozzle. When the protective caps were ejected by the cold airstream, the first net captured the caps and the second net captured the first net and its contents. This arrangement was successfully used for capturing the protective caps without damaging them and was used for the remainder of the cap ejection test series.

Following the injector protective cap ejection demonstration, test runs were conducted to check out the integration of the test article hardware with the facility and to establish ramburner reference performance and operating characteristics. Verification of the rocket nozzle ejection design was next demonstrated. This was followed by simulated transition tests, which incorporated the modified facility sequencer, ignition system, and air bypass system as well as the glass port cover into the system. During these tests, the sequencer was made to perform the transition sequencing of breaking the glass port cover, closing the facility bypass valve, engaging the ignition system, initiating facility air heater fuel, and turning on the ramjet fuel. This demonstration further verified injector cap ejection, simultaneous heater and ramburner ignition, and ramburner reference operating characteristics.

During the simulated transition tests, the first simultaneous lightoff of the facility air heater and test ramjet was attempted. During the attempt, the glass port cover ordnance did not function. As a result, the glass port did not fracture and no air could flow through the inlet. The test was aborted. The unfractured glass port cover was removed from the teststand for analysis. A failure analysis was then conducted by the ordnance and facility engineering staff members. It was determined, from recorded event signal data, that the sequencer voltage had been sent to the blasting cap, which failed to initiate a Datasheet explosive charge bonded to the glass port cover. The remaining glass port covers were retrofitted with a redundant blasting cap initiator arrangement and no further failures occurred. Simultaneous ignition of the air heater and ramjet engine was successfully achieved on the next simulated transition test run.

The all-up rocket-to-ramjet transition test was next conducted, incorporating all the subsystems. Since the rocket motors were based on existing heavyweight test motor designs previously demonstrated in numerous tests, they were not static fire tested during this program. However, propellant batch samples were taken to verify burning rate and mechanical properties. In addition, radiograph and visual inspections of the motors were made to certify motor compliance.

Test Arrangement

The tests were conducted in the ramburner hot air facility (Fig. 4). The facility provided the air flow and air temperature that advanced cruise missile configurations would experience in flight. The stored air was made by mixing 74% N_2 and 26% O_2 to account for vitiation from hydrogen combustion in the air heater. A combined air flow valve/pressure regulator in series with an air metering nozzle controlled and measured the air flow.

An air bypass valve was installed downstream of the metering nozzle. The valve allowed the air to bypass during rocket operation of the rocket-to-ramjet transition tests and also maintained pressure in the adapter section immediately upstream of the port cover. The valve was closed during transition and ramjet operation.

Warm air was generated by the combustion of hydrogen gas mixed with air flow through the air heater section. Additional oxygen was added to the stored air to maintain the correct oxygen content of the warm air delivered to the test hardware. Heater combustion was initiated by a TEB igniter and was terminated by hydrogen flow cutoff. The facility closed-loop fuel control system (Fig. 6) provided regulated JP4 fuel flow to the test ramjet.

Facility instrumentation monitored the flow regulator pressures, metering nozzle pressures and air temperature, hydrogen orifice flow pressure, and air heater pressure and temperature.

The test hardware was connected directly to the test facility by a short adapter section. The hardware consisted of the following items: a glass port cover separating the test hardware from the facility during rocket operation, solid propellant grains cast in the air transport duct section, a transtage assembly housing fuel injectors and a flameholder, six poppet-type variable orifice fuel injectors, an insulated Y-flameholder, TEB injectors, a ramjet combustion chamber and nozzle, and an ejectable rocket nozzle.

The test hardware instrumentation consisted of static pressures in the duct head end, four transtage static pressures spaced 90 deg around, four combustor static pressures spaced 90 deg around, and a load cell thrust measurement. Both quick-look oscillograph and FM tape recordings were used to record the test data.

Pressure transducers with a pressure measurement range between 0 and 200 psig and the capability of surviving overpressures up to 2000 psig were selected and used to sense pressures in the air transport duct, transtage, and ramjet combustor sections shown in Fig. 3. Transducers with a 0-2000 psig sensing range also sensed pressure in these sections. During high-pressure rocket burn, the high-pressure range transducers provided the primary and only pressure data. During low-pressure ramjet operation, the low-pressure range transducers were the primary pressure references, while the high-pressure transducers provided backup measurements.

A pressure arming/disarming switch was installed at the duct head end static pressure location. The switch was set to arm a facility timing sequencer when increasing pressure (at rocket ignition) passed through 400 psig. The switch triggered the sequencer to start transition functions when the rocket chamber pressure decayed to 200 psig during tailoff.

The facility sequencer was assembled to automatically command occurrence of the discrete transition functions at selected times (Fig. 2). The following discrete functions were controlled by the sequencer: eject rocket nozzle, close air bypass valve, break port cover, initiate hydrogen flow to air heater, turn on ramjet and air heater TEB, start ramjet fuel flow, and close off TEB.

Test Results

A successful rocket-to-ramjet transition test was conducted by use of the previously described hardware and test setup.

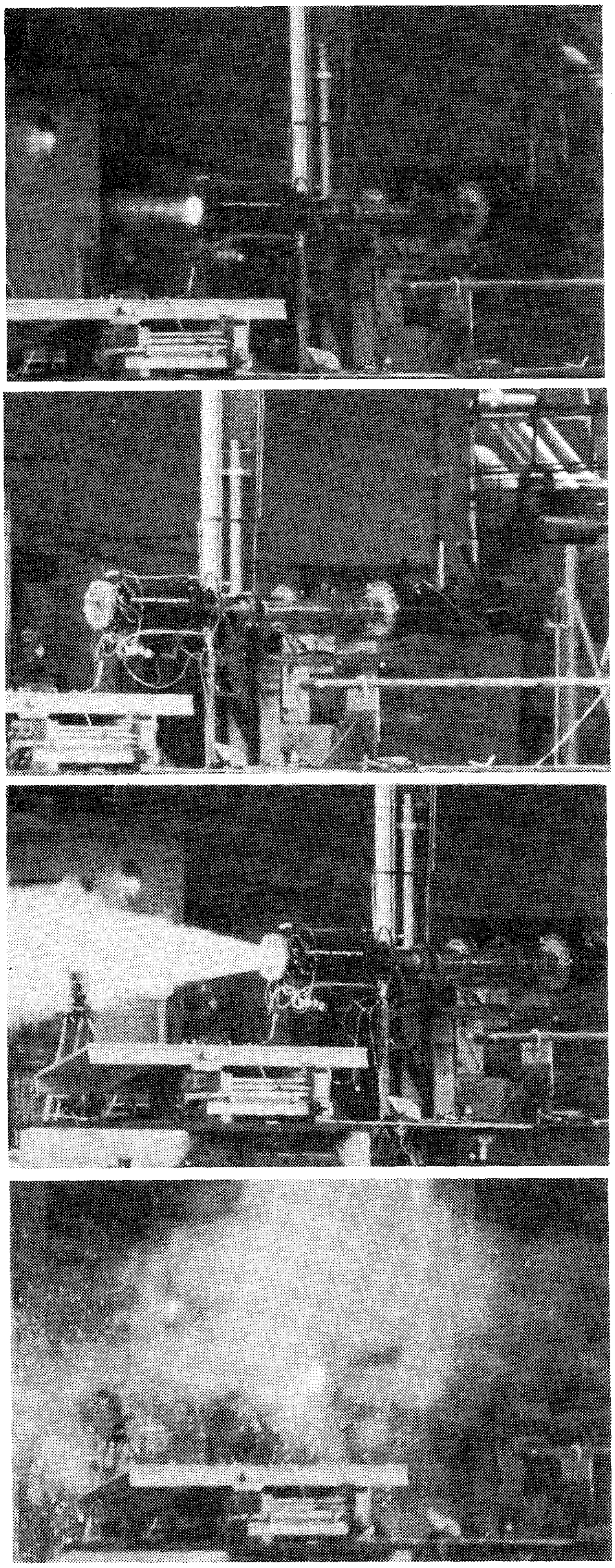


Fig. 10 Rocket-to-ramjet transition operation.

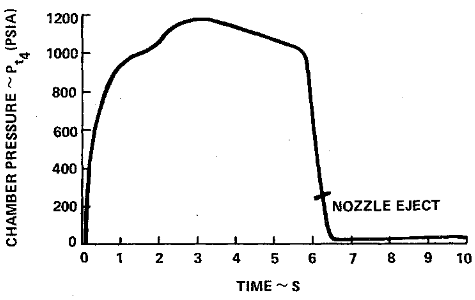


Fig. 11 Actual chamber pressure time history.

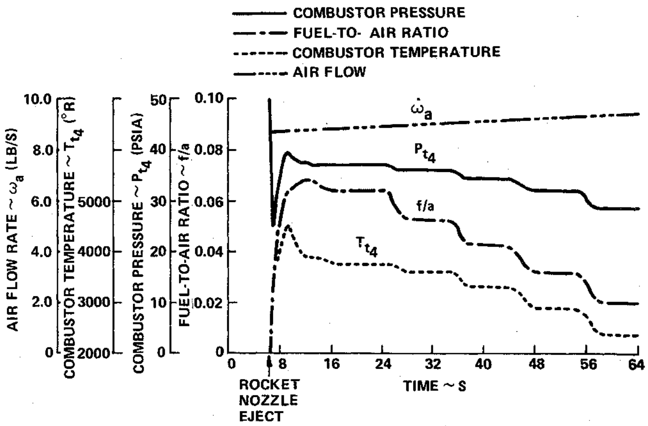


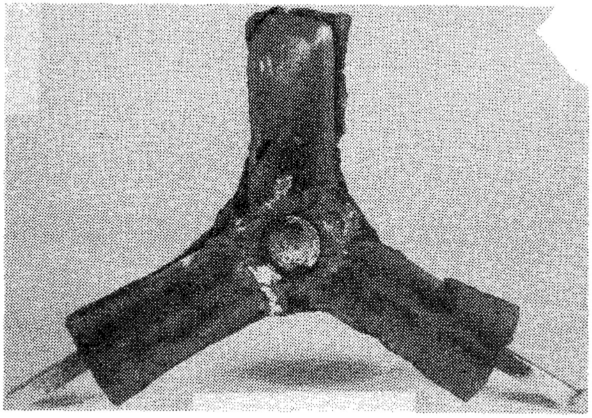
Fig. 12 Actual ramburner operating characteristics.

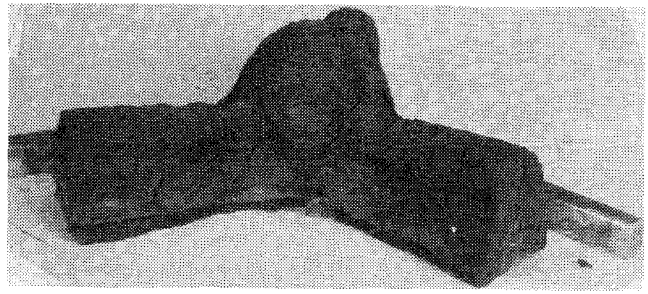
With one exception, all functions operated as designed. The exception was the fuel injection thermal protection caps, which did not completely clear the injector housings when the ramjet fuel flow began. This was caused by aluminum oxide from the solid propellant combustion products solidifying around the caps and effectively soldering the caps to the transtage wall. This has been corrected by a redesign of the caps which prevents the aluminum oxide from accumulating around the caps. The facility and test hardware rocket and ramburner performed satisfactorily and the test environment provided useful test data. Figure 10 shows the rocket firing, followed by the transition period and then normal ramburner operation.

A pressure/time history of the test is shown in Fig. 11. Rocket chamber pressure was approximately 1100 psi for 5.5 s. Transition time between nozzle eject and ramburner full thrust was 1.4 s and the ramburner ignition pressure was 40 psia. The majority of the transition time was in filling the nonflight length fuel lines from the on-off valve to the fuel injectors. Ramburner operating characteristics are shown in Fig 12. A 5% pressure overshoot was noted at ramburner ignition.

Ramburner combustion efficiency and burner pressure recovery from the rocket/ramjet test were measured. The resulting data were compared with data from previous ramburner tests of a bare flameholder tested under the same air flow and air temperature conditions and with the same transtage, combustor, and nozzle. The comparison shows a 2% drop in burner pressure recovery within the critical operating region as a result of increased blockage of the insulated flameholder. Insulation erosion profiles on the flameholder resulting from these type tests have been used subsequently to better predict insulation material thickness requirements which tend to reduce blockage. The difference in combustion efficiency can be attributed mainly to ejection failure of the fuel caps, whereby they remained partially on the housing and thus interfered with normal fuel spray operation.

Figure 13 shows the condition of the flameholder after the test. The center hub was in very good condition with less than 0.1 in. eroded. The three struts were in good condition except for one area where it appears that glass fragments from the port cover struck and caused removal of the carbon phenolic in that area. Also, the insulation was removed from the back side of one of the legs. The insulation was completely charred over the entire flameholder, and in most areas could be easily peeled from the metal surface.





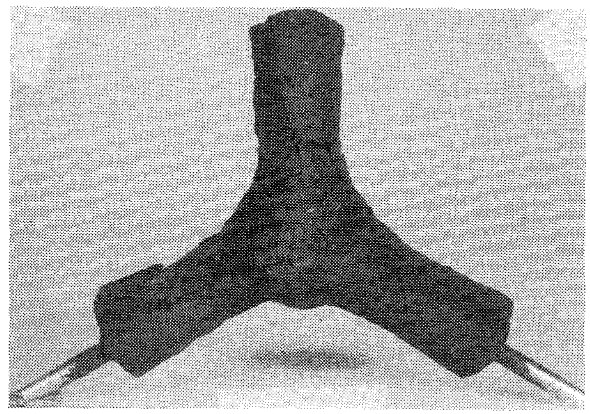


Fig. 13 Insulated flameholder after test.

Conclusions

The results of this experimental program have demonstrated that test equipment and techniques have been developed to allow efficient integral rocket-to-ramjet transition testing in the ramburner facility. This capability, coupled with other successfully completed test work, demonstrates that the facility is a versatile base for propulsion integration and freejet test work.

Following completion of this program, the facility was found to be in excellent condition and ready for other test activities. The new TEB ignition system developed for the program remains on line to permanently replace the retired spark plug ignition system. The sequencer modifications are permanent and suitable for future transition test work. The ramjet fuel system can be easily modified to adjust transition time between rocket burnout and ramjet ignition.

Acknowledgments

The authors wish to acknowledge R. Cronk, R. Greene, and B.F. Green for their outstanding efforts in contributing to the success of the program.

Reference

[1] Readey, H.J., Jr., "The Ramburner: A Versatile and Economical Facility Base for Thermal and Propulsion Experimental Work," *Proceedings AIAA/SA 13th Joint Propulsion Conference*, 1977.