Propulsion Options for the Hypersonic Research Airplane

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A critical factor in the design of a research airplane capable of obtaining full-scale data in the Mach 4-10 range, is the propulsion system and propellant required for acceleration and for maintaining steady-state test conditions. Typical flight trajectories, test times, and propellant requirements are shown for existing test ranges. A vehicle configuration capable of carrying the boost and sustaining propellant and various experiment systems within the constraints of the B52 carrier aircraft, is illustrated. The limitations for testing turboramjet and other large diameter airbreathing propulsion systems are discussed.

Introduction

THE propulsion systems discussed in this paper are based on the requirements of a Hypersonic Research Airplane (HRA) configuration developed by Rockwell International's in-house studies, performed at its Space Division with supporting assistance from the Los Angeles Aircraft Division. Considerable prior and concurrent work in the field of hypersonic research aircraft has been done by personnel at the NASA Langley Research Center.[1-9] The McDonnell Douglas Company also has been studying similar concepts under contract with the Air Force Flight Dynamics Laboratory.[10] The long range objective of these studies is the definition of design requirements and techniques for future high-speed military aircraft, transports, and the next generation launch vehicles. It became apparent that for obtaining much of the hypersonic technical data, a flight research vehicle would yield the most useful data. However, it was obvious that the cost of such a vehicle could be prohibitive unless maximum utilization could be made of existing components, materials, and fabrication techniques.

A major factor in the performance capability and the cost of any flight vehicle is the propulsion system, which includes the boost engines to accelerate the vehicle to test conditions, the sustaining engine to maintain steady state conditions, and the propellant tankage which greatly influences vehicle size. Before discussing in more detail the propulsion requirements and alternatives, it is necessary to discuss the overall Hypersonic Research Airplane design requirements, constraints, and technology research objectives.

Hypersonic Research Airplane Configuration

The HRA is required to be of a modular configuration which can incorporate a wide variety of research experiments with minimum modification. Major research packages include those pertinent to advanced airbreathing propulsion, aerodynamics, thermodynamics, structures and materials, guidance, and flight control systems, and military stores release. During the analysis of technology capabilities and requirements, it became apparent that capability would not be limited to advanced space Shuttle launch systems, but would also be applicable to supersonic-hypersonic military aircraft and advanced hypersonic transport systems.

The requirement for low vehicle and overall program costs was the primary factor in the determination of vehicle size and configuration. The low cost requirement generated the design to cost approach through use of: a) X-15 Research Airplane experience and design philosphy, b) existing B52 for air launch, c) presently available test range and ground tracking facilities, d) design toward low empty weight consistent with use of nonexotic materials; also through e) minimized use of high temperature materials with their expensive fabrication requirements; use of f) off-the-shelf components and subsystems from Shuttle, YF-12, and others, g) boost rocket engines already developed and qualified, h) tradeoff test requirements with cost; through i) elimination of sybsystems not absolutely required, and j) acceptance of reasonable risks.

The requirement for the HRA to be air launched from the B52 was the primary aircraft sizing factor. The ground clearance and span restrictions are illustrated in Fig. 1. Also, the weight is limited to approximately 90,000 lb gross. Realistic scramjet propulsion system testing dictated the fuselage bottom contours for integration of engine and airframe inlet compression and exhaust expansion surfaces. Figure 2 shows the resulting Rockwell International basepoint configuration with sufficient propellant for boost (assuming three Agena engines), and 1440 lb of liquid hydrogen for experimental scramjet propulsion and structural cooling research.

The HRA basepoint design is compatible with the B52 in a manner similar to the X-15 Research Airplane observing wing span and ground clearance constraints. The vehicle launches at 56,000 lb with 32,500 lb of propellant in the general tankage arrangement, shown in Fig. 2. Figure 3 illustrates the modular design which facilitates modifications for various experiments and research. This configuration is being used as a basepoint definition around which design trades are being made. Using this basic configuration, the boost engine trades and alternatives can be evaluated.

Boost Engine Trades and Choices

For obvious economic reasons, only existing rocket engines were investigated for the boost propulsion required to accelerate the HRA from B52 launch conditions (45,000 ft, 0.8 Mach) to the hypersonic test conditions. At test conditions a small (15K-20K) variable output from the rocket propulsion system will be required to match the aircraft drag. Output

Presented as Paper 74-990 at the AIAA 6th Aircraft Design, Flight Test, and Operating Meeting, Los Angeles, Calif., August 12-14, 1974; submitted September 6, 1974; revision received November 11, 1974. This work was done under independent research and development effort by the Space Systems and Applications Department, Space Division, Rockwell International, Downey, Calif.

Index categories: Airbreathing Propulsion, Hypersonic; Aircraft Testing (Including Component Wind Tunnel Testing); Liquid Rocket Engines.

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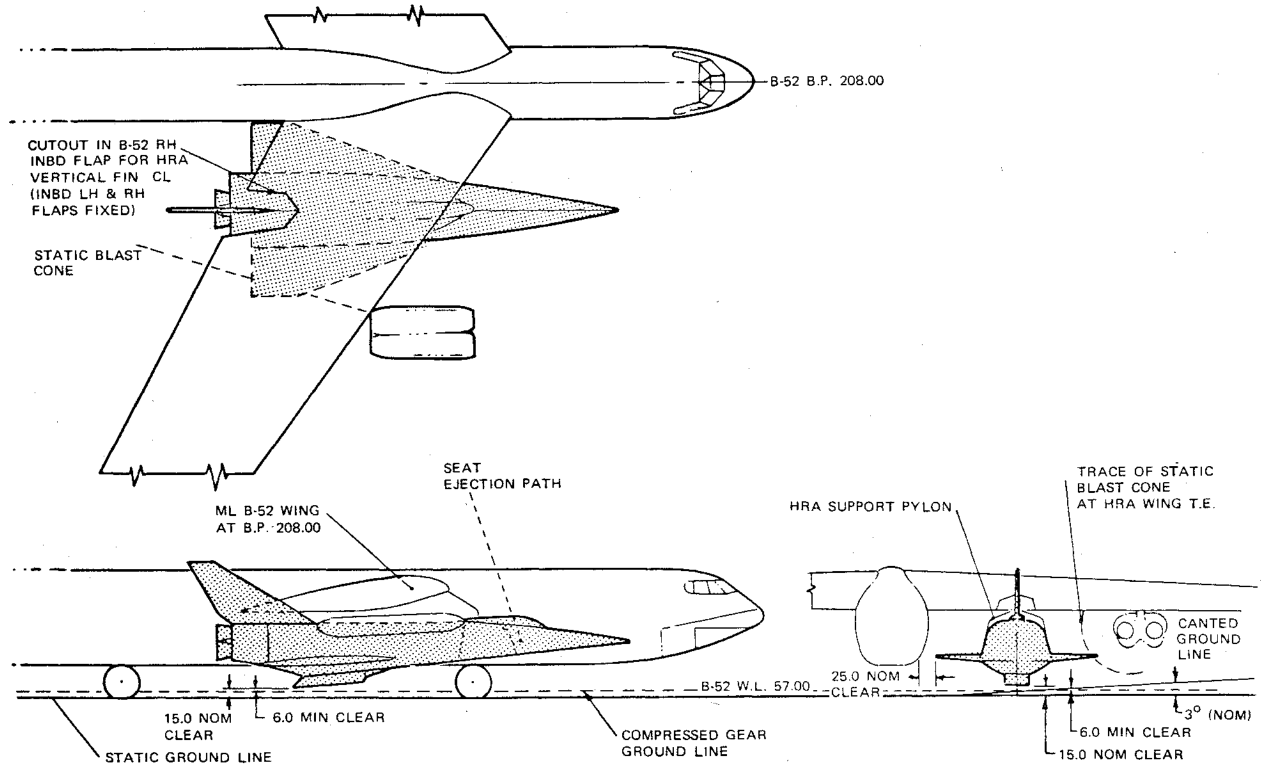

Fig. 1 B52 Carrier constraints; wing span, fus height, vert tail "notch," and pilot ejection path.

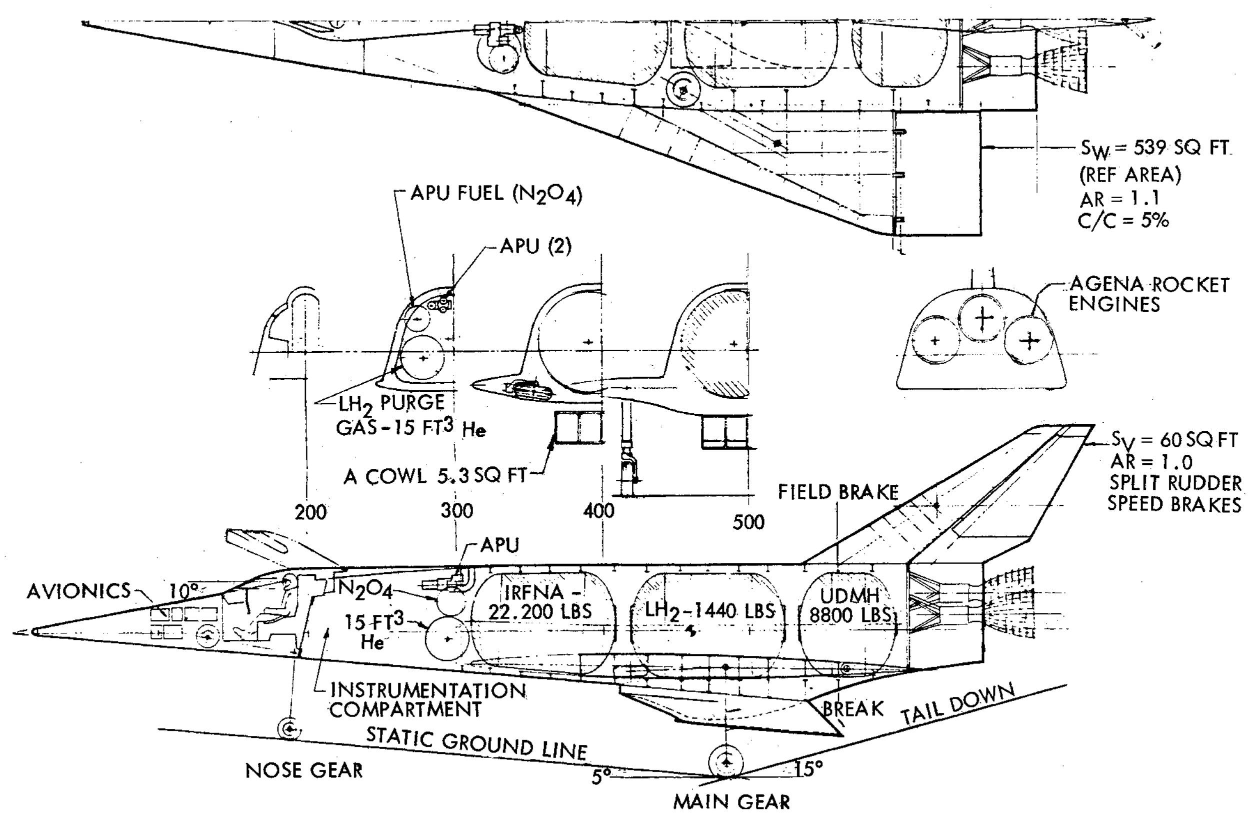

Fig. 2 HRA inboard profile; design features: B-52 compatible wing span, height, and vert tail "notch;" conventional LDG DR; field break; removable tanks; and instrumentation bay.

from the airbreathing propulsion system under test may be variable or, on some flights, nonexistent when flight dynamics, structures, heat transfer, etc. are test objectives. If a multi-rocket engine installation is used, all but one engine can be shut down and the remaining one modulated as required. The use of a variable drag device (speed brake) may also be utilized.

Cost for development of throttling and qualification (man rating) of an engine is estimated at 15-25 million dollars. The YLR-99, which was used in the X-15, can be throttled and is man rated. Also, several engines and spare parts are available from the X-15 program. However, the capability to produce this engine no longer exists, and the cost of new tooling and fixtures to produce and test the YLR-99 would probably ex-

Table 1 Propulsion—rocket engines [13,a]

	Storable LR-81 Agena (Bell)	Cryogenic RL-10A-3-3 Centaur (P&WA)	Cryogenic YLR-99 X-15 (Thiokol)	Storable LR-91 Titan II (Aerojet)
Thrust vacuum, lb	17,600	15,000	58,000-19,000	100,000
Maximum thrust at 35,000 ft (std nozzle)	16,500	11,000	56,000	88,000
Number of engines required	3	3	1	1
Fuel	UDMH	LH_2	NH_3	UDMH-N_2H4
Oxidizer	IRFNA	LO_2	LO_2	N_2O_4
I_{sp} (sec) (std nozzle) vacuum	293	444	271	315
I_{sp} 35,000 ft (std nozzle)	260	350	260	285
Weight per a/c	942#	906#	1025#	1280#
Reusability	60 min-o/h Throttle capability to 33%	120 min-o/h Throttle capability to 33%	30 min-o/h Presently throttlable to 40%	47 min-o/h Throttle capability to 15%

[a]Assumptions: $W_{\text{launch}} = 56{,}000$ lb, horizontal launch at 45,000 ft, M = 0.80.

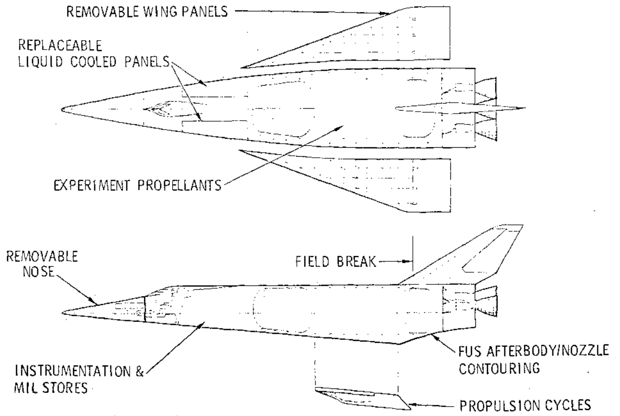

Fig. 3 General research accommodations.

ceed the throttling development and qualification testing of another "in-production" engine.

The LR-91 Titan II engine has much higher thrust than required but would provide growth capability and faster acceleration to test conditions. Also, the simplicity of a single engine installation is advantageous. Development of throttling capability down to 15% (the expected HRA steady-stage drag) would be expensive and difficult. Recent information from Aerojet states that the throttling to below 50% would not be economically feasible. The use of small sustainer engines for maintaining flight conditions is being considered.

The LR-81 engine has an excellent record in space usage as the Agena engine, and has several advantages for the HRA. The manufacturer, Bell Aerospace, has conducted studies of adapting the LR-81 to the HRA requirements. [12] The engine is man-rated (Gemini target vehicle), in production, reusable with a minimum of one hour between overhauls, reliable, and easily maintained. Modification to allow throttling appears to consist of changing the gas generator fixed venturi to a variable type. Tests have shown thrust chamber capability to operate at the throttled (200 psia) 6000 lb thrust level with no appreciable decrease in I_{sp}(267 from 268). Re-qualification testing would still be required.

The RL-10 engine is a current production engine used in the Centaur upper stage. Although test engines have demonstrated idle and throttled operation capability, a throttlable engine has not been qualified. The LH_2-LO_2 propellants offer the advantage of simplified tankage since LH_2 will certainly be required for the scramjet test engines and for structural cooling test panels. Cryogenic propellants also have their disadvantages in insulation requirements, loading, and hold time limitations, venting, and boiloff loss during B52 flight to drop point requiring B52 topoff capability. Also, the low density of LH_2 requires considerably larger tankage than the "storable" propellants increasing HRA length by 110 in.

Although considerably more tradeoff studies need to be done in order to select the optimum (performance and cost) engine, the LR-81 Agena engine has been used as the basepoint in the Rockwell preliminary design studies. Analysis shows a lower vehicle empty weight of the LR-81 engine configuration due primarily to the shorter fuselage length. It is obvious that boost engine selection has considerable influence on vehicle configuration and overall performance. Further detailed analysis is required.

Two other major factors which must be considered in the selection of the boost engines are the thrust levels of the various engines, and the number of engines required and their propellant consumption. Since many HRA test flights will be conducted using rocket propulsion only, sufficient propellant must remain on-board at the end of the climb phase to provide sustaining thrust while these tests are being conducted. Obviously, for a low cost program, the minimum number of engines required for boost which will maximize the test time available at start of cruise for the least gross weight vehicle is the most desirable. To accomplish an analysis of this optimization, RI employs a simple computer program which inputs the vehicle weight and aerodynamic characteristics together with selected engine parameters along a climb trajectory. Variations in thrust-to-weight ratios, I_{sp}, climb path, etc., can then be made and the resulting fuel remaining at the end of the climb phase determined.

The requirement for maintaining constant Mach number cruise conditions can be accomplished by 1) shutting down all of the boost engines but one, and 2) throttling the remaining engine until its thrust equals the vehicle's drag. If the selected boost engine's thrust level is high and only partial throttling can be permitted, it is possible that too much thrust exists for cruise and additional means must be used to obtain a thrust-equal-drag condition. Figure 4 illustrates a situation in which the throttled rocket engine thrust is greater than the vehicle's drag and additional drag devices must be employed. There are limits, however, for using drag devices to offset the high thrust so that this condition must be borne in mind in the selection of an engine.

Need for Flight Test of Airbreathing Propulsion Systems

Development of dependable aircraft propulsion systems depends on accurate simulation of flight and operational conditions. In the past, this has been fairly easy to accurately simulate in altitude wind tunnels of ground test facilities. As operation Mach numbers and altitudes increased, this became

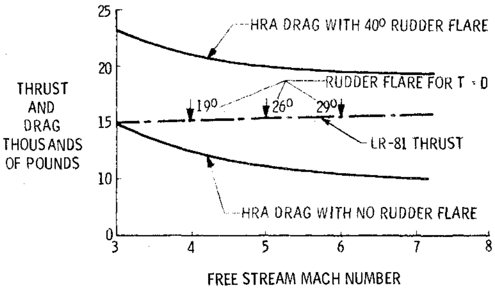

Fig. 4 Thrust-drag balancing with rudder flare.

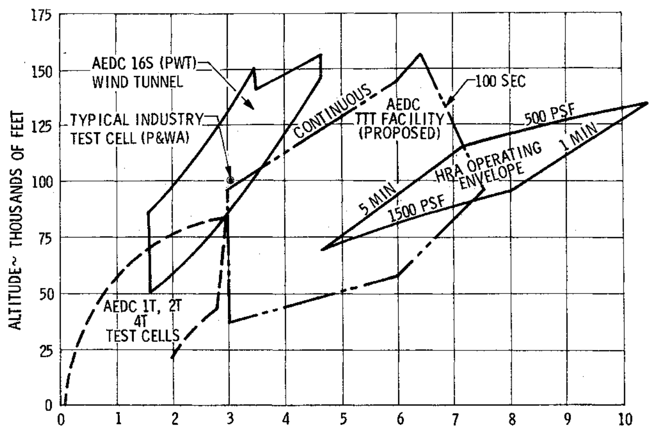

Fig. 5 Full scale engine test facility capability.

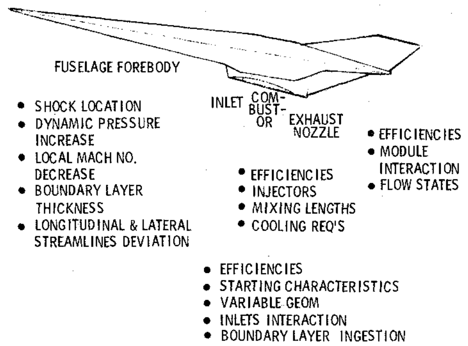

Fig. 6 Hypersonic propulsion system.

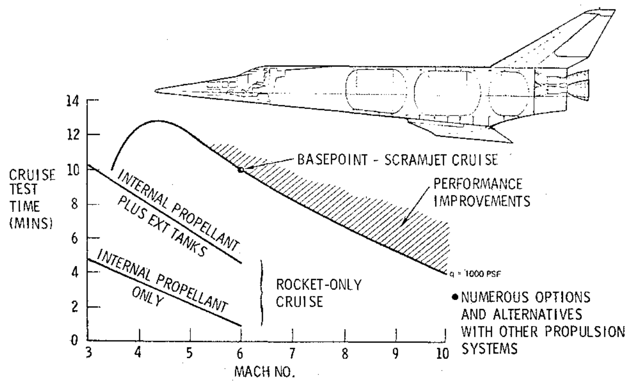

Fig. 7 Cruise time vs Mach number.

more and more difficult, particularly with the need to test variable position inlets as an integral part of the propulsion system. As Mach number increases, the aircraft itself becomes more a part of the propulsion system where the forebody is the inlet ramp and the aft fuselage is the nozzle. Therefore, ground simulation becomes exceedingly difficult and costly. Two basic modes of ground testing are the direct connect and the freejet methods. Direct connect is the least complex and utilizes all of the available air flow which has been preconditioned to simulate conditions at the engine inlet station. Such testing is adequate for some of the engine development, but the interaction of airplane shock patterns, inlet-engine interactions, boundary-layer variations, fluctuating, and uneven engine face flow profiles due to aircraft attitude variations are not simulated.

Freejet testing simulates more closely the flight conditions by including the inlet and aircraft forebody parts and by passing over half of the air around the outside of inlet/engine. However, freejet testing has deficiencies such as lack of aircraft shock pattern simulation, Reynolds number difference from free flight, direct fired heating (in some facilities) of air to reach high ram temperatures, limitations in angle of attack, and yaw angle variations due to test section diameter. In addition, the dynamic and vibration conditions of actual flight cannot be duplicated. In many cases, the rate of change in angle of attack or inlet temperature and flow conditions have caused compressor stall or inlet unstarting from fuel control response to inlet variations. These dynamic conditions cannot be realistically simulated in the freejet tunnel test.

In the past, flying test beds have been tried with subsonic and supersonic (unmanned) propulsion systems. It was generally concluded that ground facility testing was much more productive and less costly. This may still be true, but the ground facilities required to even partially simulate the propulsion system flight environment and dynamic conditions for high supersonic and hypersonic aircraft do not exist, and will cost over 250 million dollars to construct.[11] Figure 5 shows approximate present full-scale engine development test capability and HRA test envelope. Adequate propulsion test facilities exist for aircraft with maximum speeds up to Mach = 3.0 such as the B-1, F-14, F-15, etc., while only a small number of facilities exist for propulsion testing above Mach 3.0. Such facilities have not been identified for military requirements since the projected needs for Mach 3 + aircraft have been limited and in any case are identified for the 1990-2000 time period. It is therefore concluded that early attainment of advanced propulsion technology may be obtained in a cost effective manner by a multi-use flight research vehicle. A very close look must now be taken at the economics of a hypersonic test vehicle or propulsion system flying test bed in the light of today's needs and present technology to obtain hypersonic test conditions in flight.

The determination of overall propulsion system performance, on a hypersonic vehicle using a scramjet, depends on simulation or duplication of forebody/inlet and afterbody/nozzle shapes and the conditions they produce over a wide range of flight conditions. Present and planned ground facilities are limited in their capability to produce the freejet conditions required for realistic flight simulation.[15]

The two ground test facilities with hypersonic propulsion system testing capability are the NASA Lewis Plum Brook Facility and the USAF-AEDC Aero and Propulsion Unit. Testing of the AiResearch Hypersonic Research engine has recently been completed at the NASA Lewis Plum Brook Facility. Freejet tests of this 18-in. capture diam engine at Mach 7 were at facility maximum conditions and considerable difficulty was experienced in obtaining/maintaining test conditions. Angle of attack variations during this testing were limited to $\pm 3°$.

The AEDC Aero and Propulsion Facility[14] has a higher airflow and Mach number capability and a 16 ft diam test section compared with the NASA Plum Brook 8 ft test section. Mach numbers up to 5.6 with 3500° R clean air and Mach 8.0 (6000°R) with vitiated air direct fired heaters are possible at AEDC with blowdown airflows approaching 1000#/sec. At the present time, the capability to simulate exhaust altitude pressures does not exist. Funding has been requested for tying in existing exhauster facilities which will provide a 2-3 psia exhaust pressure at the low airflows (100-200#/sec) of the modular scramjet. With utilization of the proposed ASTF exhausters 1 psia or less may be possible.

These two test facilities utilize fixed geometry (fixed Mach number) nozzles which prohibit flight profile simulation or any dynamic variation of angle of attack, yaw, etc. The fabrication of variable Mach number nozzles to operate at the high temperatures involved would be technically difficult and very expensive. The development of a hypersonic research and test vehicle (HRA) which can provide a flying test bed for advanced propulsion systems is within today's technical capability. The HRA could be operational in the early 1980 time period at a lower cost than that of expanded capability ground test facilities. The HRA will provide complete flight dynamics and attitude variables which cannot be achieved in any other way.

Advanced Propulsion Testing

The basic elements of a hypersonic airbreathing propulsion system are illustrated by Fig. 6 emphasizing the fact that the propulsion system is an integral part of the vehicle and not just an add-on package. The advantage is using the airbreathing propulsion even on flights primarily for other test purposes is shown by Fig. 7. The available steady-state test time is greatly extended by the use of the ramjet/scramjet airbreathing propulsion (test) system to provide sustaining thrust instead of the rocket engine. Thus, on flights where the primary test objective is obtaining heat transfer and active coolant panel data, the installation and use of a scramjet propulsion system may be advantageous to extend test time. For early flights at minimum cost, this could be a simple ramjet of existing technology. Indications are that test time requirements for cooling panels and obtaining heat transfer data are higher than engine data requirements. Ground test data on the NASA AiResearch Hypersonic Research Engine[16] (HRE) shows that a hydrogen cooled lightweight engine reaches stabilized conditions very quickly (20-30 sec) and steady-state requirements may depend more on data recording equipment than on engine temperature/stabilization During ground tests, 1-2 min is adequate.. Thus, it will be possible to obtain data at several steady-state or many transient conditions during one test flight.

Testing of higher mass rotating component engines such as turboramjet (at lower Mach number) will require more time to reach stable conditions. Information from both General Electric and Pratt and Whitney indicates that 5 min of test time should be adequate. The capability to test large turbine engines such as turboramjets is limited on the HRA as configured for B52 launch. The largest full-scale engine of this type that could be simply attached to the bottom of the fuselage as shown by Fig. 8 is about 40 in. due to ground clearance. For larger engines, major aft body modifications would be required as shown by Fig. 9. Since the operating regime of large turboramjet engines is in the Mach 2-4.5 region, it may be more logical to utilize ground facilities or aircraft such as the YF12 which in the future may be capable of flight in excess of Mach 3.

An operational hypersonic vehicle would use rocket or turbocycle engine for takeoff and acceleration up to about Mach 3. Above Mach 3, the rotating part of the engine would be bypassed with subsonic combustion ramjet operation up to Mach 5 where it becomes more efficient to allow supersonic flow through the engine and burn the fuel in a supersonic flow field. Figure 10 shows the possible increase in inlet pressure recovery ($PT_2/PT_\circ$) by not decelerating the flow to subsonic conditions. At least a 100% improvement can be realized above the Mach 6 flight condition. If the combustion efficiency can be maintained and the exhaust expanded sufficiently, a significant overall propulsion system performance improvement results.

With the HRA, a significant increase in test time can be achieved by early ignition of the ramjet/scramjet test engine to supplement or replace part of the rocket engine thrust during the boost phase. Figure 11 shows the thrust available from the test engine shown in the configuration drawings which was a dual-mode ramjet-scramjet concept. Specific fuel consumption of the scramjet is in the area of 2500-3500 compared with 440 for the best rocket engine. If rocket propulsion can be replaced by scramjet, a proportionate amount of propellant weight will be saved.

Test Time Required in Range Capability

As previously noted, the time-to-test required for various propulsion systems and elements ranges from 2-5 min. Other areas to be researched by the HRA may go more than 5 min. When these flight times are coupled with flight speeds up to Mach 10, considerable distances can be transversed. Our aim is a low-cost program to utilize existing test range facilities, thus research test requirements must be kept in line with the test range capability. The considerations which are involved in determining the test range's capability are emergency landing sites for the test vehicle, radar tracking along the flight path

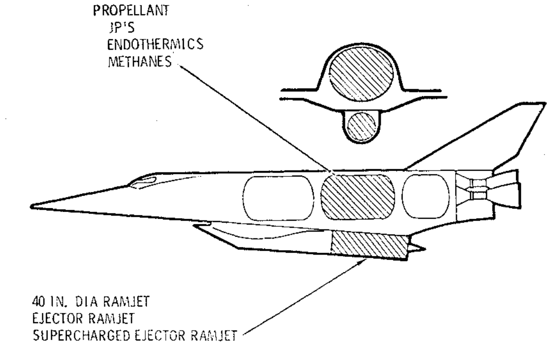

Fig. 8 External ramjet installations.

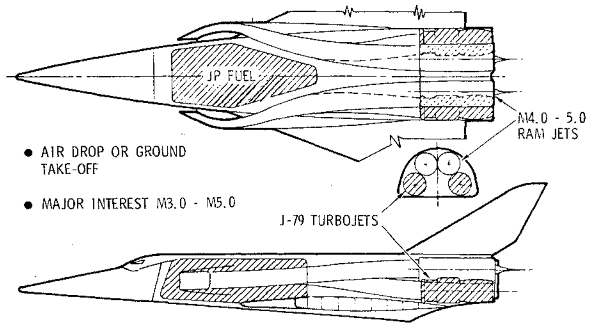

Fig. 9 Alternate system testing.

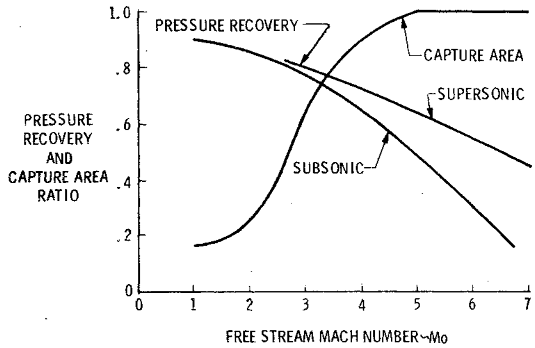

Fig. 10 Air induction system characteristics.

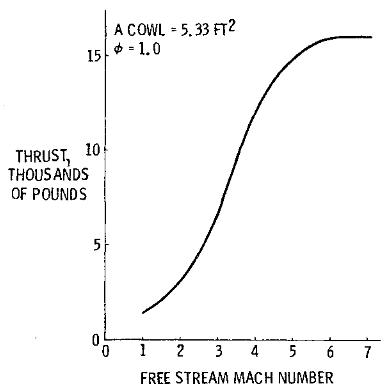

Fig. 11 Scramjet thrust along ascent flight path.

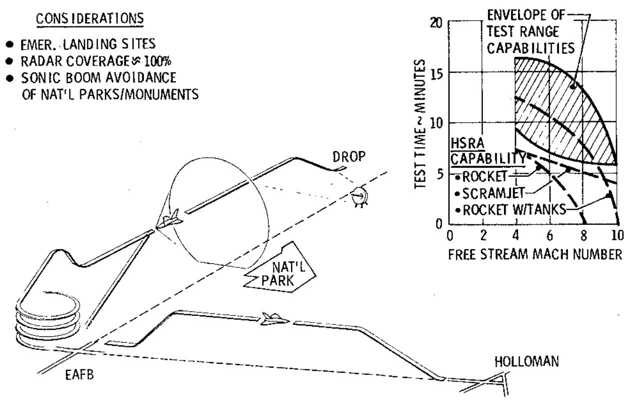

Fig. 12 Flight test range capability.

from drop to recovery and avoidance of national parks and monuments if the vehicle creates a sonic boom. Figure 12 illustrates these conditions and the test time available at the existing test range at Edwards AFB.

Conclusions

The HRA concept is a viable research airplane project for the future. In accepting reasonably sized research packages, it can perform flight evaluations in the true environment. As Hugh Dryden so succinctly stated for the X-15, the purpose of the HRA will be "...to separate the real from the imagined problems and to make known the unappreciated problems." It will do this by focusing and stimulating technology development toward possible/probable systems of the future. It will also validate and/or demonstrate significantly critical technologies.

The experiences gained in the X-15 Research Airplane program, combined with a low cost approach to the HRA system and the need to rebuild the supersonic-hypersonic technology base provides for an excellent point of departure to bring the HRA program into being in the not-too-distant future. While the paper has concentrated on the propulsion aspects, similar benefits would be realized in Aerodynamics, Thermodynamics, Materials, Structures, Guidance and Control, Stability and Control, Missile Launchings, etc.

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