Air-Breathing Launch Vehicle for Earth-Orbit Shuttle—New Technology and Development Approach

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Low-cost transportation to and from Earth orbit with systems characterized by reusability, flexibility, and "airline-type" operations is a prime goal of the space program. The air-breathing HTOL launch vehicle has inherent features which make it a candidate for such a system but, unfortunately, the lack of a developed powerplant implies a procurement cycle length on the order of a decade. The purpose of this paper is to assess the status of the air-breathing launch vehicle in the light of recent achievements in propulsion and configuration development. It is concluded that all major questions of feasibility, particularly in the area of hypersonic propulsion, have been answered favorably by the investigations of several small research engines recently completed. The remaining key problems are discussed together with some promising approaches toward their solution. Finally, important steps required to develop an operational air-breathing system by the early eighties are discussed.

Introduction

IN the past decade many studies have been made of reusable Earth-to-orbit launch systems employing air-breathing first stages. An informative review[1] of these and other hypersonic aircraft studies has been made recently by Eggers, Peterson, and Cohen, including a few excerpts from an early version of the present paper. Eggers et al, present the important features of the studies and we will not discuss them further here. An important new factor in the status of hypersonic aircraft is the NASA proposal to develop a space shuttle with a reusable, rocket-propelled first stage. In view of the fact that the air breather has been shown to have certain potential performance and operational advantages,[2] the present study was undertaken to examine in some detail the consideration that the air-breathing launch vehicle is not in a competitive position for the shuttle system. The approach used is to evaluate the present technological status of both vehicle and propulsion and to determine what is needed to complete the technology, particularly with regard to the development of an operational system.

Air-Breathing Launch Vehicle

General Concept

For the purposes of the present discussion, the ABLV is defined as an HTOL vehicle capable of relatively normal "airline-type" operations with reusability of both stages (see Fig. 1). The recently initiated NASA space shuttle studies or reusable rocket launch systems will be used as a guide for payload and other mission requirements. The second stage will be considered to be a product of the rocket shuttle program.

On the basis of recent studies, the ABLV is tentatively identified as a lifting body without wings, which represents a first-cut compromise involving considerations of aerodynamic performance, weight and volume requirements, and stage and propulsion integration characteristics. For a payload of 20,000 lb, approximate weights now under consideration in the study of Ref. 2 are total gross takeoff of a million pounds, and second-stage gross, 40,000 lb.

Presented as Paper 70-269 at the AIAA Advanced Space Transportation Meeting, Cocoa Beach, Fla., February 4–6, 1970; submitted March 10, 1970; revision received August 19, 1970.

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The effect of staging speed on weight of the two stages and the complete system is shown in Fig. 2. This analysis was based on typical second-stage results from a study of the NASA rocket space shuttle system and a NASA-Lockheed study for the first stage. The second stage becomes very large at the lower velocities, which makes it difficult to integrate with and separate from the first stage. At 10,000 fps, where the minimum gross weight occurs, the second-stage weight is roughly one-half that of the first stage, and more favorable integration can be obtained for good aerodynamic characteristics throughout the speed range. In the past, studies such as one by NASA-Lockheed have suggested that vehicles powered by subsonic-burning ramjets with a staging speed of about 7000 fps are relatively near term compared to scramjet powered vehicles with higher staging speeds. We believe, however, that scramjet development has now reached the stage where the more favorable higher staging speeds can be chosen with confidence. A principal aim of this paper is to set forth the recent scramjet developments which have generated this confidence.

With these considerations, the propulsion system selected for this discussion consists of turbine engines for acceleration to the Mach 3 to 4 range and convertible scramjets for the balance of the ascent to the staging point. The selection of the turbine engines for the lower part of the speed range is based on the advanced state of turbojet development for Mach 3 flight including the SST engine technology. Mach 3.5 and 4.0 capability with hydrogen fuel is highly desirable and, hopefully, a fairly straightforward extension of today's

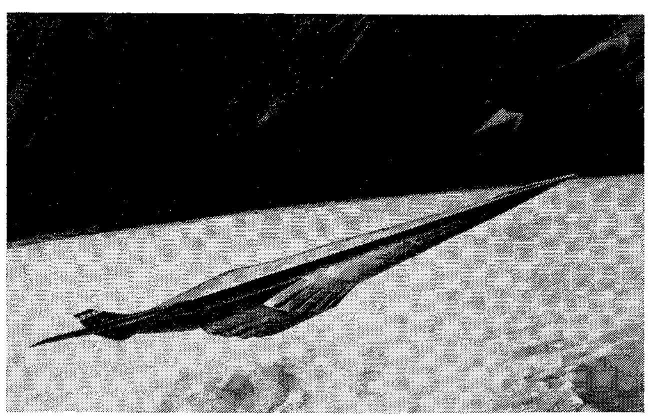

Fig. 1 Typical lifting-body concept for ABLV.

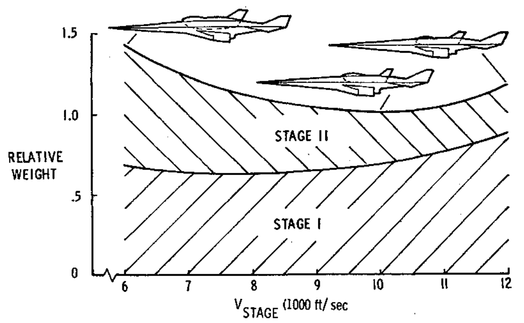

Fig. 2 Effect of staging speed on weight.

technology. The scramjet is the only air-breathing engine capable of operation from Mach 3.5 to the proposed staging flight speed. Before examining the scramjet further, a brief survey will be made of the status of several other technology areas of these vehicles.

Basic Hypersonic Technology

The basic tools for analysis and experiment in hypersonic aerodynamics, structures, and propulsion have been under development for almost 20 years. As regards theoretical frameworks, we are now in a comparable position to any other class of vehicle—there is always a desire for improvement and refinement, but the tools in hand are generally adequate for analysis and definition of new vehicle systems. Put another way, it is not a lack of these basic capabilities which is delaying or preventing the definition or achievement of new vehicle systems. The obstacles lie in other areas which we will now consider.

Structural Development

Many of the difficult structural problems of the ABLV will hopefully be solved through the greatly expanded R & D programs which are now being defined to develop the new materials and the new structural technology which are essential if a successful rocket shuttle system is to materialize. Similarities in the heating environment for the two systems are shown in Fig. 3.

The rocket shuttle trajectories were taken from a NASA-McDonnell Douglas study with first-stage re-entry a $tC_{L_{max}}$ and second-stage re-entry at L/D_{max} with bank to obtain cross range. The trajectories for both stages lie at higher altitudes and lower dynamic pressures than the ABLV. For first-stage L/D_{max} re-entry, however, altitudes and dynamic pressures would be similar to those of the ABLV. The peak temperatures for the ABLV are shown as a narrow band as they are obtained on the accelerating part of the trajectory where deviations in flight path will be small, and where the boundary layer will be nearly all turbulent. Temperatures on the first-stage rocket shuttle are, of course, dependent on the mode of re-entry, and the spread in possible temperature can be large with peak heating conditions nearly as high as for the ABLV.

The second stage will encounter temperatures well above the ABLV temperatures over most of its length. Thus, it is the second-stage requirements for reusable structural and heat protection solutions which pace the structures/materials R & D program. Presumably, these solutions can be adapted to either the rocket or ABLV first-stage vehicles. A structural problem unique to the ABLV is the fuel-cooled structure for the scramjet engine which will be discussed later.

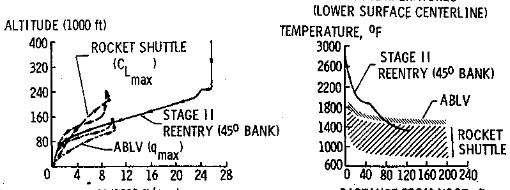

Fig. 3 Structural environment.

Configuration and Aerodynamics

While it is far too early to predict what an optimized air-breathing configuration of the 1980's will be, an attractive concept, at this point in time, is the lifting-body configuration shown in Fig. 4. Elimination of wings reduces the structural weight with only modest loss in L/D, and as can be seen by the payload sensitivities, a reduction in structural weight is some 2.5 times as important as the same percentage increase in L/D. Although tradeoff studies are sensitive to the exact configurations analyzed, lifting bodies have been shown to be at least comparable in performance to winged bodies, even when it was assumed that the same degree of integration between components was possible with both configurations. Actually, the lifting-body first stage is preferable in that it allows the second stage to be almost completely buried to minimize the loads and heating on the second stage during boost. Satisfactory engine-airframe integration can be obtained on such a configuration with the forward undersurface acting as a precompression ramp for the engine and the aft lower surface as a part of the nozzle.

The problem of engine-airframe interaction, especially the interactions between the jet exhaust and the afterbody aerodynamics with its large effect on base drag, stability, control, and trim, is a major subject for research. Recent work at Langley[3] with simplified flow models has yielded successful solutions for particular cases. Other areas of research which will require special attention are the transonic drag, which establishes the turbojet engine size, and the stage separation.

Aerodynamic Facility Requirements

For many years, the inability to achieve hypersonic tests of slender configurations with full turbulent flow has been a major concern as illustrated in the top of Fig. 5. Not only were the test Reynolds numbers low, but boundary-layer trips proved ineffective in producing turbulent boundary layers. As a result, no satisfactory method was available to bridge the gap between the low Reynolds number tunnel results, with their laminar and transitional boundary layers, and the flight conditions where turbulent boundary layers were anticipated. Furthermore, it was not known how high a Reynolds number would be required for advance development facilities. A current Langley program is now giving new guidance in these areas. For the first time, full-scale Reynolds numbers have been obtained on an aircraft type configuration at hypersonic speeds. This was done by operating the Cornell Shock Tunnel at high pressure with only enough heat to avoid liquefaction of the air. The results are shown in the lower part of Fig. 5. At the same time, the Reynolds number capability of conventional facilities has been increased. For example, Reynolds numbers based on model

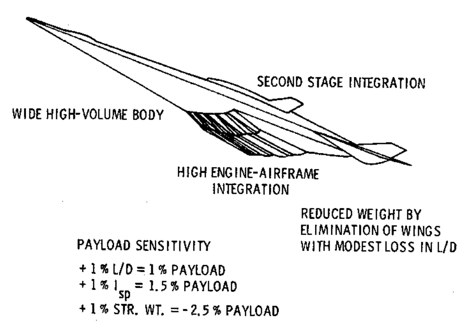

Fig. 4 Configuration.

length of 25 × 10⁶ are now available in Langley hypersonic facilities; and at these conditions largely turbulent boundary layers are found on highly swept shapes. Thus, results are now obtained which are in reasonable agreement with the expected turbulent trend through the full-scale Reynolds number data. Only a small correction of the model test data for the remaining small areas of laminar and transitional flow is needed. Our present capability of about 25 × 10⁶ appears to be adequate for the bulk of the required ABLV configuration developmental testing, using models 2 to 3 ft in length.

Under some conditions, however, greater detail or more exact simulation will be required, and at least one large national hypersonic aerodynamic facility will be needed where large models (approximately 10 ft) can be investigated in the final phase of the development process. A modification of the Langley 8-ft structures tunnel to allow aerodynamic testing has been proposed as an inexpensive way of obtaining this capability at Mach 7.6.

Status of Hypersonic Scramjet Technology

Outlook 5 Years Ago

By early 1965, scramjet research had advanced to the point where comprehensive technology evaluations could be conducted for the purpose of determining the proper direction for future programs. These evaluations concluded that the scramjet promised great potential but that the feasibility of practical operation and performance remained to be shown by complete engine experiments. As a result, an ambitious technology program was initiated with USAF, Navy, and NASA participation. This program never attained the originally hoped for magnitude because of other military involvements and funding difficulties. Nevertheless, a total of over $100 million was invested and substantial contributions were made primarily by the development and experimental evaluation of a number of small research engines. It is appropriate at this point to review, briefly, accomplishments in these engine programs.

Dual-Combustion-Mode Scramjets

Concept

In the 1965 evaluations, it was noted that there were at least two engine concepts which could be capable of efficient operation over wide ranges of flight speed, the "dual-mode" and "thermal-compression" concepts. The features of the dual-mode engine will be described using Fig. 6, which represents the Phase I version of the NASA-AiResearch Hypersonic Research Engine (HRE). The HRE is a small axisymmetric, variable-geometry, dual-mode engine designed to perform from Mach 4 to 8. The primary emphasis in the project was research on the internal aerothermodynamics to be conducted in ground facilities and in flight, using the X-15 as a test bed. The flight phase of the project has been eliminated due to termination of the X-15 program.

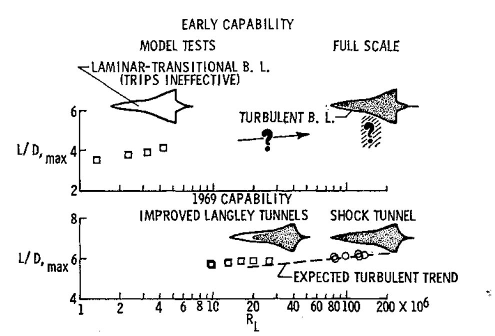

Fig. 5 Recent advances in full-scale performance prediction capability from hypersonic wind-tunnel data.

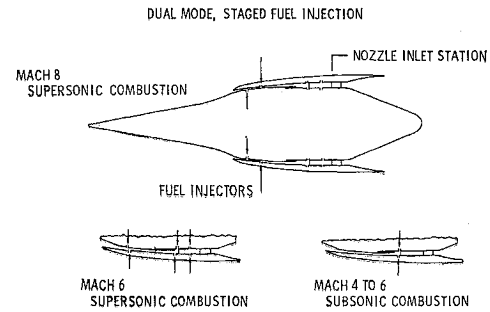

Fig. 6 NASA hypersonic research engine—Phase I.

As a result of component development during Phase II, the internal engine contours have undergone numerous changes; however, the configuration of Fig. 6 is adequate for illustrating the dual-mode principle. By examining the sketches in the order of decreasing flight Mach number, one notes that the location of the active fuel injector stages and also the combustion move downstream to larger duct areas. For the subsonic combustion case the injection is located at the step produced by the sliding joint, which serves as a flame holder and ignition source. In this case, the high-speed supersonic combustor now serves as a subsonic diffuser for the inlet. We see then that the key features of the concept are several stages of fuel injection in an expanding area combustor, which satisfy the basic aerothermodynamic geometry requirements for either sub- or supersonic combustion.

Status in 1965

In 1965, one of the main questions relating to feasibility was that stable and controllable conversion from one combustion mode to the other, which had never been attempted before in an engine, might present unexpected difficulties. Furthermore, component-interaction effects, that is, at the inlet-combustor or combustor-nozzle interfaces, were feared as possible sources of performance loss and operational difficulty. Another item of some concern was the degree to which variable geometry would be required, complicating the design of systems such as the fuel-cooled structures. The answers to these and other pertinent questions generally have been favorable, as will be noted by the following summary of status and accomplishments for the two projects on research engines of this type.

Current status of HRE project

The final design of the HRE, shown in Fig. 7, has been completed as a result of extensive component development tests on the inlet, combustor, and nozzle. The development of the fuel, control, and fuel-cooled structures systems (see a later section), which were designed for flight operation, have been completed; the fuel and control systems have been tested successfully in a "breadboard" configuration. The fabrication of a complete structural test engine has been completed, and a water-cooled aerothermodynamic test engine is nearing completion; experiments are scheduled on the structural engine in 1970 and on the aerothermodynamic

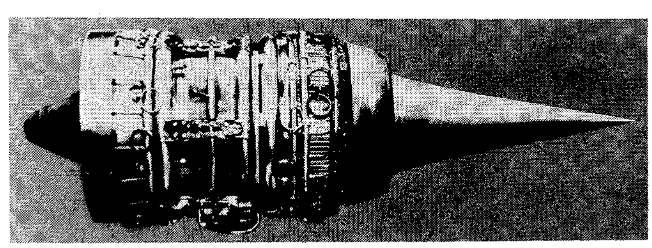

Fig. 7 NASA hypersonic research engine.

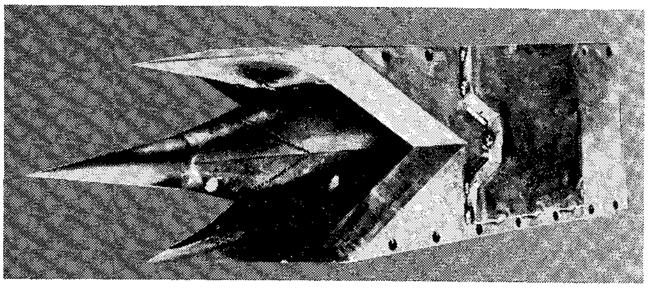

Fig. 8 GASL thermal compression engine.

engine tentatively in 1971, both in facilities with full temperature simulation.

The results obtained in the inlet development program on the inlet starting phenomena are of particular interest. The inlet design was made relatively short, primarily by using a large amount of external compression. As a result, with the spike in the starting position, the center-body boundary-layer thickness at that station was significant compared to the opening between the cowl and center body. With this flow situation, experiments conducted on early versions of the inlet design during the development program and in-house investigations[4] indicated that the starting characteristics were marginal at the low end of the speed range; these starting difficulties were caused by total pressure losses from several sources, including shock-boundary-layer interaction and nonuniform profile mixing. During these studies, effects such as wall cooling, Reynolds number, surface roughness, and leading-edge bluntness were evaluated. This problem was solved by minor recontouring of the HRE inlet, and modifying details associated with boundary-layer thickening. In the case of the ABLV, the vehicle boundary layer is expected to be thick at the inlet station; however, no starting problem is anticipated because the relatively smaller leading-edge bluntness will have a favorable effect. The over-all high performance predicted for the HRE inlet was substantiated over the entire operating range.

An interesting phenomenon also was explored in the combustor development program in connection with a downstream fuel-injector station. The fuel was injected in a region of high negative pressure gradient resulting from flow expansion, and the data indicated an inadequate heat release. The flow situation suggests that the pressure gradient suppressed the turbulence produced by the normal fuel jets, resulting in incomplete combustion. A need for parametric type experiments is evident to determine the effects of pressure gradients on mixing and combustion phenomena, and to refine our design techniques. In the case of the HRE, the problem was circumvented by moving the injector station to another location; final combustor performance will be determiend in the complete engine experiments.

The nozzle program substantiated the optimizing procedure used to design for maximum performance considering divergence, friction, and center-body-terminal-bluntness losses. The effects of entering boundary layer, wall temperature, and support struts were determined. Wall friction was found to be the predominant cause of thrust losses.

Research planned for the remainder of this program will greatly enhance the HRE contributions to scramjet technology. The aerothermodynamic engine will be tested over the speed range to establish performance maps giving the effects of basic variables such as fuel-air ratio, simulated flight altitude, inlet contraction ratio, and fuel injection schedules. From these studies, important design information will be obtained; for instance, practical chemical kinetics and component interaction effects in a complete engine configuration.

Marquardt dual-mode scramjet

The development and evaluation of this boilerplate engine has been completed successfully. In contrast to the HRE, it is a fixed-geometry engine designed for operation from supersonic to high hypersonic speeds. The performance of the inlet, which has 2-D features with highly sweptback leading edges, was substantiated over the entire range by detailed experiments. Performance experiments on the complete engine have demonstrated repeatedly stable and controllable combustion mode conversion, efficient operation, successful ignition techniques, and substantiated aerothermodynamic design procedures. This project provided favorable answers to the feasibility question in all of these areas using a geometry amenable to integration with a vehicle.

Thermal Compression Scramjets

Concept

One of the other principal scramjet-engine concepts having potentially attractive practical operating characteristics was the thermal compression concept advanced by Dr. Ferri and his coworkers in the early sixties. Thermal compression occurs in all supersonic combustors; however, in configurations proposed by Ferri, thermal compression replaced part of the inlet function, and the design involved extensive use of complex 3-D flowfields. The general over-all objective was high performance for the flight-speed range with completely fixed geometry. The early work on this concept was done at a time when analytical or experimental information on these complex principles was meager, and, as a consequence, doubts were raised as to its real feasibility. Subsequent work has substantiated the thermal compression concept, as noted in a later section; descriptions of the basic process are available in the literature.[5]

GASL scramjet flight test module

The development work on thermal compression engines has been done in the General Applied Sciences Laboratories, a subsidiary of the Marquardt Corporation. The engine test model pictured in Fig. 8 is representative of these designs. As part of the Air Force technology program, a project was initiated by Marquardt with GASL and Lockheed as sub-

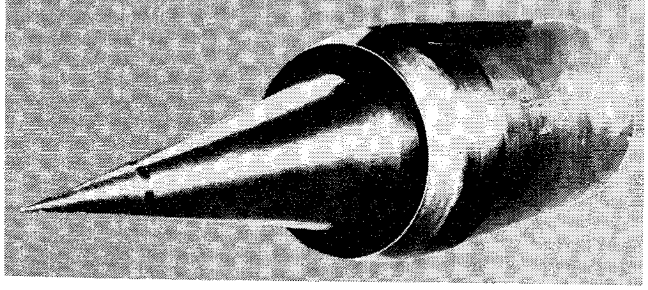

Fig. 9 General Electric CIM II engine.

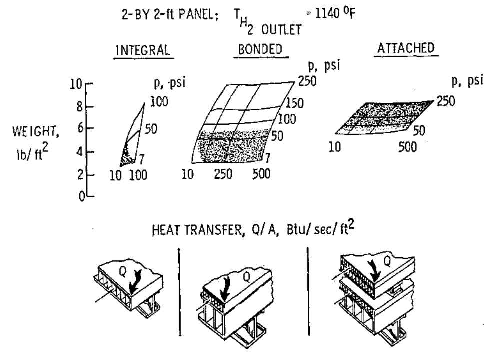

Fig. 10 Hydrogen-cooled composite structures.

contractors to conduct a rocket-boosted flight test of a scramjet powered vehicle intended to demonstrate accelerating thrust performance at hypersonic speeds. The flight aspects of this project were canceled; however, the ground investigations were completed successfully with the final engine design providing direct measurements of thrust close to the goal values. During these investigations, a successful development technique was used whereby systematic experiments were combined with analytical procedures to evolve the proper injector arrangement in a step-by-step process. This procedure was particularly helpful for the downstream injectors where the flowfield is more complex. This type of procedure, of course, has been required to some extent in the development of all types of scramjets.

GASL research scramjet

This engine was designed to perform over a speed range similar to that which would be required for the ABLV. The inlet performance was substantiated over the complete operating range, and the engine performance was determined for a hypersonic Mach number. As shown in Fig. 8, the inlet flow fields involve both planar and conical compression waves. The analytical techniques required for this type of design were developed successfully. The development approach for the combustor and injectors was the same as for the flight test module. The predicted thrust levels were realized in the final design, again by direct measurement, providing a conclusive demonstration of the thermal compression concept. This type of engine is also amenable to integration with a vehicle design.

Other Research Scramjets

UARL variable-geometry scramjet

The United Aircraft Research Laboratories have developed under Air Force funding a small variable-geometry axisymmetric scramjet for operation over a broad flight speed range with all supersonic combustion. The special features of this engine are the capability of supersonic combustion at relatively low supersonic flight Mach numbers, a unique variable-geometry design feature, and a high contraction ratio inlet. The measured engine thrust at Mach 5 was high; however, a combustor problem was encountered similar to the one for the HRE. Increased efficiency of performance appeared possible with further refinements in the combustor design.

General Electric CIM scramjet

The G. E. Component Integration Model (CIM) scramjet (see Fig. 9) is essentially a point design intended for research at Mach 7 in General Electric's arc-jet facility. NASA funded extensive performance tests on a refined model, CIM II, in which maps of the engine operating limits and performance were established in detail as functions of several variables. In addition, the data were correlated with prediction methods. The highlights of these investigations are the performance of the high-contraction ratio inlet, efficient stable combustion over wide operating ranges of fuel-air and combustor conditions, short combustion lengths, no adverse component interactions, ignition techniques, staged fuel injection, and direct thrust measurements supported by internal pressure measurements and gas samples at the nozzle exit.

Scramjet Performance

It is of interest at this point to compare the actual measured thrust performance of these small engines with the results of unpublished in-house analyses on the propulsion for the air-breathing launch vehicle. A survey of the engine data was made, and the measured specific impulse values were found to lie within a band ranging from about 80–100% of values postulated for the ABLV, depending on the particular engine and test conditions considered. Increasing the engine sizes to "full scale" would increase the performance by significant amounts, providing ample specific impulse. The data are limited to Mach 8 or less because of facility limitations; however, no adverse effects are anticipated at higher Mach numbers. The conclusion from this simple comparison and other studies made in more depth is that scramjet performance in actual test engines closely approaches values predicted on the basis of isolated high-efficiency component data.

Another pertinent factor relative to the design of the scramjet is the combustion chamber length required to obtain efficient performance and the effect of increased scale on this parameter. The small research engines just discussed all had simplified fuel injector schemes; however, the combustor lengths required for efficient operation were relatively short compared to the over-all engine dimensions. Significant reductions in combustion length relative to engine size are anticipated with increased scale because more sophisticated injector arrangements will be used and because lengths associated with chemical kinetic effects will be relatively shorter.

Fuel-Cool Structures

Hydrogen-cooled panels for application to hypersonic aircraft

The technology required to design reliable fuel-cooled structures for the hostile environment within the engine has been under development for several years. Under NASA funding, the AiResearch Company has been conducting an investigation in this area aimed at developing and substantiating methods for optimizing the designs relative to the performance of the sandwich-fin-type of heat exchanger and, also, over-all structural weights.[6] Some of this work is summarized in Fig. 10 where various types of structural concepts are associated with categories of loading in terms of heat transfer and imposed surface pressure. This technology is directly applicable to hypersonic engine structures; and for typical scramjet mission studies, the method predicts minimum structural panel weights ranging from 3 to 7 lb/ft^2. Some of these basic principles were used to design the HRE structures.

HRE fuel-cooled structures

The HRE project is the only one of the research engine projects which specified that a realistic flight-type, fuel-cooled structural system had to be designed and substantiated. The contractor has completed the design, all components have been fabricated and assembled, and tests have been conducted on some of the more critical items; a photograph of typical cooling passages and the offset fin construction is shown in Fig. 11. The heat-exchanger performance and structural characteristics will be evaluated and the design methods assessed for a fully simulated Mach 7 condition in 1970.

A number of significant advances have been made during the project relative to fabrication techniques for the engine components. Some examples are fabricating pieces to an approximate contour using an electrohydraulic forming process, step-brazing to assemble a number of pieces using as many as five braze alloys of varying temperature, and a creep-brazing technique used in conjunction with special fixtures for obtaining final shapes to specified tolerances without machining.

Other highlights of the cooled-structures effort include the successful development of relatively sharp, fuel-cooled leading edges for both the inlet cowl and the internal engine struts. These results are particularly important in a small-scale engine where the absolute value of the radius of the leading edges has to be small to avoid large performance losses.

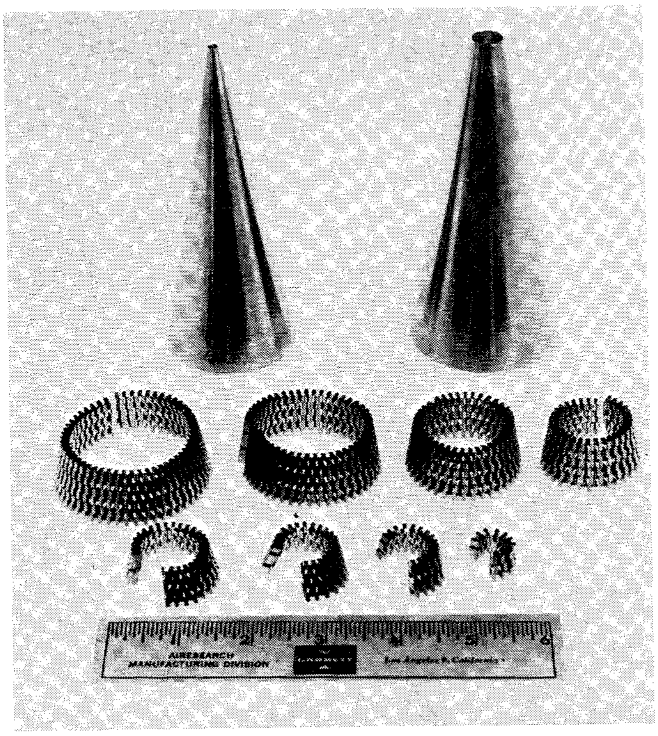

Fig. 11 Cooling fins and shells for inlet spike tip, NASA HRE.

Marquardt ramjet structures investigation

The fuel-cooled structures discussion up to this point has centered around the offset fin type of heat exchanger; however, it is also possible to apply rocket nozzle technology which consists of chamber walls made up of reinforced formed tubes. The Marquardt Corporation has conducted an extensive experimental investigation of a regeneratively cooled structure for a subsonic combustion ramjet using this type of design. The pressure and heat loading on the combustion chamber were both higher than for a scramjet; however, a high degree of design optimization was obtained resulting in a low unit weight. Generally speaking, the tube concept would be expected to be slightly heavier than the offset fin, and the heat-exchanger characteristics not quite so good.

Summary of Status

From the brief review of technology advances made in the several research scramjet programs, we conclude that the feasibility of various engine conceptual approaches has been amply demonstrated. High-performance potentials have been realized with engine configurations having practical operating characteristics and ranges; and adequate fuel-cooled structures solutions are available. Several concepts appear at this stage to be equally competitive. Naturally, there are several areas where systematic parametric-type research studies are needed, and some of these have been started. A future research task should be directed toward substantiating present analytical results which indicate that full-scale scramjets can be designed to have acceptable cooling requirements. The next logical step is to evolve specific detailed engine concepts for direct application to the ABLV; these configurations will have some notably different characteristics from the research engines, which are associated with the requirement for integration with the vehicle and with the increased scale. Which of these several conceptual approaches will prove most effective after further development for the application is not yet known. In-depth aerothermodynamic experiments on these applied concepts are now needed.

ABLV Propulsion System Development

Whether a full-fledged ABLV development program will be undertaken in the future is totally uncertain at present. The operational advantages of such a system are considerable[2] and it is not unlikely that the system would ultimately prove justifiable. In the remaining discussion we consider a hypothetical ABLV development in order to illustrate the remaining key problems and requirements in the development process. Although we will speak of an ABLV development, much of what is said would apply also to the development of any other large hypersonic vehicle system such as military or commercial cruise vehicles.

Ground Facility Requirements

The applied engine concept R & D does not require facilities which are major funding items. Aerodynamic evaluations, such as inlet studies, can be done in existing tunnels. Some additional combustion test stands are needed, and intermediate size facilities with temperature simulation are required for reduced scale, complete engine explorations. Modifications to existing facilities to permit testing structural test engines with hydrogen combustion would be relatively inexpensive; for example, appropriate modifications to the Langley 8-Foot High-Temperature Structures Tunnel would cost $3 million to $4 million.

A major facility item is required for the main engine hardware development effort to be initiated after the applied engine concept is defined and substantiated. The use of the modular engine concept illustrated in Fig. 1 reduces the test section to a practical size, as shown in Fig. 12. The general requirements are similar to the proposed true temperature tunnel for the Arnold Engineering Development Center, clean air simulation up to Mach 7+, and run times up to 5 minutes. The capability of testing one engine module at full scale requires roughly a 20-ft test section dimension and a facility investment on the order of $100 million. However, if the R & D work were done at one-half scale, as discussed in Ref. 2, a large cost reduction could be effected. A portion of the engine qualification program would be conducted in flight in any case, to extend the speed range to Mach 10.

The sketch at the bottom of the figure represents a device for reducing facility cost suggested by A. Ferri. Since a model practically can block only a fraction of the test section area, full temperature simulation for the flow near the test section walls is not needed. For purposes of discussion, the cases shown were selected, where for Case I the outer third of the duct radius contains air heated to only 1100°R, and for Case II, all the air is heated to 4000°R. Case I would require about twice the airflow but only about 70% of the energy addition. Obviously, a cost analysis study is indicated to obtain the proper tradeoff between air storage, mass flow, heater equipment, and operating cost, but substantial savings are indicated with some additional complexity.

Illustrative engine development schedule

The 10-year procurement of the ABLV engines, including the flight certification and qualification, is discussed in detail in Ref. 2. A prime feature of such a program is a block of well-defined, pacing technology items requiring an initial period on the order of 3–5 yr devoted to intensive applied concept R & D on the scramjet engine and the procurement of the ground facility.

This period would consist of several parallel investigations of various approaches to the applied engine concept, would involve significant industry participation, and would result in a detailed definition of a preferred concept on which hardware development could be based. The scramjet applied concept must not only intgrate with the vehicle configuration, but also must alleviate the transonic base drag problem, perhaps by subsonic combustion at these speeds, and must require low-coolant fuel flows over the operating range, minimal cooling during nonoperating conditions, and low-vehicle trim drag. These design restraints extend beyond the research engine studies and imply the need for relatively shorter combustors, more sophisticated fuel injector and ignition systems, and a minimum of variable geometry. Only a small start has been made on the applied concept studies, and the effort will have to be of substantial magnitude to achieve an acceptable time scale for the ABLV development.

A yearly funding of about $40 million would be required for the sum of the scramjet applied concept work and the TTT-type tunnel procurement, which is roughly an order of magnitude increase over present planning for research programs in this general area; however the total cost of this part of the program is about 2% of the total system cost. With regard to the turbine engine, additional technology is being developed in other programs, and a large engine facility to test these engines is planned at AEDC; therefore, these items are not considered a direct part of the program.

Concluding Remarks

The true status of air-breathing hypersonic technology relative to the possible development of operational hardware is believed to be as follows:

1) The past 15 to 20 years, disciplinary research and theoretical development have already provided the technical tools and an adequate technology base for defining and developing air-breathing hypersonic systems. There is no bottleneck or pacing problem to be found here. In order to approach an operational capability realistically, continuing work must feature programs focused on a practical application with further disciplinary research complementing this effort.

2) Major progress has been made in the past few years by going beyond disciplinary research and pursuing the development and investigation of the six research engines, with clear proof of feasibility in all areas. However, these programs did not deal with the complex of problems involved in developing a hypersonic propulsion system optimally integrated with the configuration and structure of a launch vehicle. We believe that the "applied concept" R & D now needed for the integrated vehicle must be accomplished early in the development program to provide reliable vehicle definition and program guidance. A period of some 4 years is likely to be required for this work.

3) The required new facilities are by no means impossible of attainment. Only one major new national facility in the

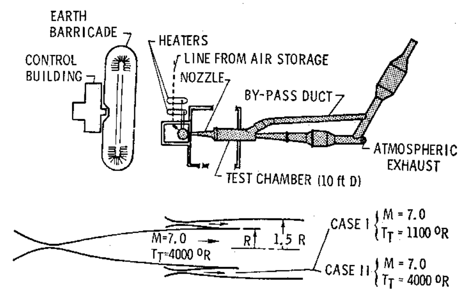

Fig. 12 Schematic of TTT facility.

$50 million to $100 million class is believed necessary. Early initiation and construction during the 4-year "applied concept" period is essential. Flight testing of the hypersonic component of the full-scale engine beyond Mach 7.5 will have to be accepted as a necessary feature of the R & D process for these vehicles.

4) Finally, we are in need of a major decision to proceed with this focused "applied concept" and facility procurement activity. These technology developments would be broadly applicable to all classes of hypersonic cruise systems, including important potential military as well as commercial transport applications.

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