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EMERGING HYPERSONIC PROPULSION TECHNOLOGY

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Abstract

Currently there is a renewal of interest in the utilization of air breathing engines for hypersonic flight. The use of such engines in accelerative missions is discussed, and the nature of the trade-off between engine thrust-to-weight ratio and specific impulse is highlighted. It is also pointed out that the use of a cryogenic fuel such as liquid hydrogen offers the opportunity to develop both precooled derivatives of turboaccelerator engines and new cryogenic engine cycles, where the heat exchange process plays a significant role in the engine concept. The continuing challenges of developing high speed supersonic combustion ramjet engines are discussed. The paper concludes with a brief review of the difficult discipline of vehicle integration, and the challenges of both ground and flight testing.

Introduction

The early decades of aviation were characterized by the pursuit of speed, of range, and of extended range at high flight speeds. The push for higher speed was characterized in the 1950's and 1960's by the X-series of aircraft which pushed into the supersonic regime with Mach 2 (X-1) and Mach 3 (X-2) vehicles. It culminated in the X-15 research aircraft, which flew almost 200 flights and pushed man to his highest-yet speed in an airplane -- Mach 6.7. The energy built up by these endeavors was re-directed in the 1960's into the space program and into practical systems for both military and civil application. It is significant that in the last decade the maximum speed of the commercial airliner (Concorde) has remained in the Mach 2 region, and for high speed military aircraft (SR-71), in the Mach 3 region.

This plateau in the pursuit of traditional aviation goals has been recognized in the USA by the Office of Science and Technology Policy (OSTP) which has responded with a firm statement of National Aeronautical R&D goals[1]. Three national goals have been enumerated: a Subsonics goal to renew the technology for a fuel-efficient, modern national airspace system; a Supersonics goal to attain long distance, fast, efficient transportation with particular emphasis on the Pacific Rim; and a Transatmospheric goal to pursue research to achieve routine operations both in and out of the atmosphere, with conventional runway operation. The last two goals encompass high speed flight from supersonic to orbital speeds.

The potential of high speed commercial flight is currently being evaluated in the USA under NASA's High Speed Civil Transport (HSCT) program. No final recommendations have yet evolved from this program, but it may be anticipated that a second generation SST and/or Hypersonic Transport (HST) will receive endorsement. It should also be noted that both France and the USSR have recently shown interest in high speed commercial airliners. In addition to such long range cruise aircraft, there has been a proliferation of studies of aircraft-like vehicles as first stage launch vehicles or indeed as single stage-to-orbit (SSTO) vehicles. Such studies, at various levels of investment, include efforts by the USA[2], the United Kingdom[3], Germany[4, 5], France[6, 7], Japan[8], and the USSR[9]. Although these ongoing studies can arbitrarily be divided into cruising vehicles and accelerator vehicles this is not a hard and fast distinction. Thus the acceleration phase of a predominately cruising hypersonic vehicle is a significant phase of the total flight, and similarly a dedicated accelerator vehicle may require substantial cruise capability to obtain access to desired orbit planes.

A general discussion of the probable evolution of high speed commercial transports is difficult to structure because the foundational technologies change markedly with increasing flight speed. Kuchemann[10] has classified the aerodynamic progression of cruising aircraft in order of ascending Mach No as: classical straight wing aircraft, swept wings and waverider aircraft - as shown in Figure 1. Also shown in the figure is the associated variation in conventional engine cycle; also both fuel type and structural concept vary with Mach number. It is apparent that a Mach 4 aircraft will be quite different from, say, a Mach 6 aircraft. It is also apparent that such high speed vehicles will have to perform effectively at subsonic speeds. In the last major U.S. effort to build an SST the need to accommodate both low speed and high speed flight requirements led to the evolution of a significantly new engine technology, namely that of variable cycle engines. With even higher maximum flight speeds it is to be expected that advanced variable-cycle engines[11] and new engine cycles[12] will emerge to bridge the wide speed range.

The choice of the next high speed civil aircraft will of course be dominated by commercial, operational, and environmental considerations. The speed/range choice(s) to satisfy passenger demand in the next century typically encompasses maximum speeds from Mach 3 to Mach 6, and cruise ranges from 6500 to 9000 nm. Compatibility with existing airport and ATC infrastructure is desired, and cost comparability with current large subsonic jets is sought. And,

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of course, the conventional environmental requirements concerning noise, shock overpressures, emissions, and atmospheric hazards (ozone, radiation) must be observed. A stimulating discussion of the challenges of introducing a next-generation High Speed Transport is available in Reference 13.

The ultimate aeronautical challenge however is the achievement of orbital conditions with a single-stage vehicle using primarily airbreathing propulsion. This elegant but elusive approach to space transportation is a classical aeronautical concept. For this vehicle the flight spectrum from horizontal take-off to orbital speed is encompassed and the propulsion system(s) is required to operate efficiently over this wide speed range. The aerodynamic configuration will presumably not incorporate variable geometry in the interest of light weight, and it should be possible to restrict operation to a single fuel, namely hydrogen, unless significant advantages accrue from the use of additional propellants.

As previously discussed in earlier papers[14, 15], liquid hydrogen offers the opportunity to synthesize new aero propulsion systems because of its high cooling capacity and also because of the high specific work potential of hot hydrogen. Thus liquid hydrogen may be used to precool, or even liquify the engine airflow. Also when used to cool internal or external flow surfaces the resulting hot hydrogen may be used to generate significant mechanical work or thrust. It is also apparent that by cooling the external surface it is possible to change vehicle drag and significantly affect the vehicle aerodynamic characteristics. Thus the introduction of liquid hydrogen can affect the vehicle aerodynamics, the propulsion cycle, and the structural design. The creation of such totally integrated systems is a major challenge to the parent technical organizations which are, conventionally, separated into airframe and engine teams. Also the conventional accounting for thrust and drag forces, and energy balances, must be carefully handled to avoid confusion in such totally integrated vehicle systems. Furthermore the overall energy utilization of the vehicle can only be rationally handled by an Exergy based approach[16, 17].

From this point the discussion will primarily apply to the accelerator class of vehicle. There is of course much which is also applicable to hypersonic cruising vehicles.

Overall Propulsion Considerations

The potential performance of conventional engine cycles, using hydrogen fuel, is approximately shown in Figure 2. It is apparent that as flight speed increases the turboaccelerator class of engine is supplanted first by the subsonic combustion ramjet and second by the supersonic combustion ramjet. Consequently, for a hypersonic flight vehicle operating at a maximum speed above Mach 7.0 a multi-mode propulsion system will be required. Bearing in mind the limitations of materials, such an engine system might operate as a turboaccelerator to speeds of the order of Mach 4.0, then transition to subsonic ramjet operation to say Mach 6.0, and then be operating totally as a supersonic combustion engine for speeds above about Mach 7.0. Now Figure 2 affords a simple comparison of various engine cycles based on fuel specific impulse (Isp) and therefore appropriate to cruise flight performance where the Breguet equation is used to compare ranges. However for acceleration missions the performance of an engine must be compared on the basis of both its specific impulse and its corresponding thrust-to-weight ratio.

Low Speed Propulsion Trade-Offs

For maximum payload capability it is desirable for a candidate engine to possess high specific impulse, a high installed thrust-to-weight ratio and the capability to function over a broad Mach number range. For an acceleration mission the typical trade-off between specific impulse and thrust-to-weight ratio is, as previously noted[14], of the form shown in Figure 3.

For each class of engine the thrust loading of the vehicle must be chosen to optimize the appropriate payload fraction. Different aircraft thrust loadings are required for each engine class and consequently the corresponding initial vehicle accelerations are different. Thus the rocket class of engine requires a higher initial acceleration for optimum payload fraction than the turboaccelerator class. It is unfortunately true, however, that for propulsion systems there is no class of engine which simultaneously possesses high specific impulse and high installed thrust-to-weight ratio. Typically, high specific impulse engines such as turbojets are mechanically complex, and therefore heavy, whereas lightweight engines such as rockets generate relatively low specific impulses. Barrere[18] has recently drawn attention to the relationship between engine thrust-to-weight ratio and basic specific impulse: a similar functional relationship was also noted by Builder and Cuadra[19] in evaluating candidate transonic acceleration engines.

In order to improve the acceleration capability of engines three basic approaches can be outlined.

a. For the turboaccelerator class of engine the appropriate approach is to increase the engine thrust-to-weight ratio

b. For the rocket class of engine attention should be focused on improving the specific impulse.

c. It would be expected that an engine type intermediate between the turboaccelerator and the rocket engine, for example the air turborocket, may offer a performance superior to its progenitors.

Candidate Low Speed Engines

The speed capability of the basic turbojet engine has evolved steadily from the basic afterburning engine to current turboramjet designs. These latter engines have typically been configured in tandem, wrap-around, and over-under geometries: more recently the variable cycle turbofan ramjet and the turbine bypass engine[11] have been of interest. However, with conventional technology these engines are relatively heavy as candidate accelerators.

In regard to improving the thrust-to-weight ratio of turboaccelerator engines a major initiative is underway in the U.S.A. to double the thrust-to-weight ratio of advanced turbine engines by the year 2000. This initiative is known by the acronym IHPTET - Integrated High Performance Turbine Engine Technology.

The basic engine performance can be improved by increasing turbine inlet temperature and by improved internal aerodynamic efficiencies. There are however even more significant gains available by reducing engine weight by the use of new or improved materials, utilized in simpler, innovative engine structures. An example of a typical weight saving in a rotating assembly is shown in Figure 4.

Although dramatic improvements in core engine thrust-to-weight ratio can be confidently anticipated there remains the question of reducing the installed weight of the engine. Typically, for a pod-mounted installation, the core engine weight is only a fraction of the total pod weight. With increasing flight Mach numbers the length of the inlet supersonic and subsonic diffuser ducts increase and the pressure and thermal loads become very high. Thus high Mach number inlets, and for that matter, exhaust nozzles, are heavy components of the propulsion system, and there is a major need to devise compact lightweight inlets and nozzles with minimal variable geometry. In this regard there is currently a resurgence[20] of interest in supersonic throughflow engines which may pay useful dividends.

In regard to the rocket class of engine there has been a continuing drive to improve specific impulse as discussed in Reference 14. One approach has been to improve the propulsive efficiency of the rocket by extracting work from the thrust chamber to drive a propeller or fan: This approach has led to the concept of the air turborocket engine: new versions of this concept have been devised[15]. Another approach is to replace, either completely or partially, the conventional liquid oxidizer by atmospheric air. The problem here is to pump the captured airflow from the intake pressure to combustion chamber pressure levels without incurring the penalty of heavy and complex turbomachinery systems - see the schematic arrangement in Figure 5. The compression penalty may be reduced by substantially cooling the intake flow prior to the compressor entry. In the extreme case the intake air can be condensed and subsequently pumped compactly and efficiently in the liquid phase. This approach has led to the concept of the simple liquid air cycle engine[21]. The cooling process is carried out using either cryogenic fuel or cryogenic propellants[22] as illustrated in Figure 6. In the case of liquid hydrogen fuel the cooling capability is sufficient to directly condense air, but the corresponding equivalence ratios vary from about 6 to 10. Thus compared to a rocket engine the simplest liquid air cycle engine yields an improvement in specific impulse (Isp ~ 1000) with some increase in weight due to the heat exchanger and the air handling systems. The operating equivalence ratio of the basic liquid air cycle engine can be considerably reduced by adding additional compression and cooling stages. Such variations of the basic cycle leads to a family of engines usually referred to as "cryojets"[14]. Once again specific impulse can be considerably improved but only at the cost of decreased thrust-to-weight ratio.

Precooling has also received attention in regard to conventional turboaccelerator designs, initially from the point of view of extending the flight Mach number capability of such engines. In cases where the maximum Mach number of the engine is limited by the compressor exit temperature then precooling of the air can permit significant increases in flight speed. However, it was soon realized that additional potential performance advantages exist and that the precooled turboaccelerator can be a significant contender for high speed flight. Kunkler[4, 23] and Hewitt[24] have extended the precooling concept to include both air-hydrogen and air-air heat exchangers in the air cooling system - see Figure 7. Hewitt[24] has also pointed out that modulation of the degree of precooling with flight Mach number can result in constant compressor inlet temperature operation, and possibly constant inlet pressure, resulting in running the compressor with a simplified flow function. Thus in an overall sense the introduction of precooling can potentially improve engine thrust performance, and reduce engine size: nevertheless, flow matching with minimal variable geometry is a challenge. Also, because of the increased flight Mach number capability it may be possible to defer transition to other engine modes to much higher speeds. Furthermore the ground test problem is simplified in that the core engine, which experiences temperatures less severe than those corresponding to the flight Mach number, can be developed in available test facilities. The outstanding potential performance advantages are however tempered by the practical difficulties of fabricating lightweight, reliable heat exchangers and avoiding the fouling problems of flight operations.

The thermodynamic spectrum of candidate precooled engines is illustrated in Figure 8 and the trade-off between engine performance parameters is broadly indicated in Figure 9. The potential performance advantages of air precooling have led to a re-emphasis on the role of heat exchanger processes and components in jet engine technology. Of course, heat exchangers have been previously considered[25] for conventionally fueled engines but are now receiving renewed emphasis with cryogenically fueled sytems.

The above discussion does not exhaust the innovative uses of cryogenic fuels. In regard to internal engine flows the potential to radically improve hot-section cooling may permit significant increases in maximum combustion temperature. Similarly the use of hydrogen as an engine/airframe coolant produces a source of hot hydrogen which can be used to do work in the overall propulsion system. Although it is not always possible to separate rigorously the airflow associated with a hypersonic vehicle into external and internal airflows, it is still conventional to treat such flows as separate aerothermodynamic systems. Such an approach cannot continue since the efficient production of the overall aero-propulsion forces on an actively cooled vehicle is inextricably linked through the cryogenic fuel circuits and many other coupling mechanisms. The overall energy bookkeeping of the total aerothermodynamic system which constitutes the vehicle can be rationally addressed by the explicit use of Exergy methods which have been successfully applied to many complex thermodynamic systems in recent years[17].

High Speed Propulsion

For speeds in excess of Mach 4 it is generally necessary to transition from the turboaccelerator to the conventional ramjet mode. However, as outlined in the previous section, it may be possible in the future to extend the capability of the turboaccelerator class to speeds in excess of Mach 4.0. In this case direct transition to a scramjet mode may become possible. The characteristics of the conventional subsonic combustion hydrogen burning ramjet are well understood and have been verified in ground tests to speeds in excess of Mach 6. As is well known the performance of the subsonic-combustion ramjet deteriorates at hypersonic speeds due to real gas effects and internal losses; and the structural design of the engine becomes very difficult due to the high internal temperatures and pressures.

Thus for really high speeds it is necessary to utilize the supersonic combustion engine (scramjet). The scramjet engine potentially offers outstanding specific impulse performance to high hypersonic Mach numbers as pointed out by several authors[26, 27]. Such performance estimates are, of course, theoretical and the upper practical speed limits of such engines have not been established on an engineering basis.

The speed range between the conventional ramjet and the scramjet can be bridged by the dual mode engine - see Figure 10. The dual mode engine is one in which, initially, subsonic combustion is employed at lower speeds (typically Mach 3-6) with transition to the supersonic combustion mode at speeds in excess of about Mach 6[28]. This class of engine has undergone extensive analysis and ground test in the U.S.A.[29, 30], in France[31], and the USSR[32]. The demonstration of dual mode operation by Harper[33] in the U.K. is also of interest. It is probable that this class of engine will be the next workhorse engine for future hypersonic vehicles.

As shown in Figure 10 the supersonic combustion ramjet engine offers progressively higher performance than the conventional engine at speeds in excess of about Mach 6. It is difficult to be precise about the point of transition to supersonic combustion because mixed flow conditions can exist in the combustor until substantially higher Mach numbers are attained, and in any event one-dimensional flow concepts and criteria are difficult to apply. The phenomenon of supersonic flow through the engine introduces totally new technology challenges compared to the conventional ramjet. These challenges are principally associated with the wave interaction phenomena generated by the basic engine processes of diffusion, fuel injection, mixing, combustion, and expansion[34].

Regarding diffusion, at a given flight Mach number the amount of diffusion, in terms of velocity ratio ($^{V}2/_{V_o}$) or enthalpy ratio ($^{h}2/_{h_o}$), is a significant determinant of engine performance as illustrated in Figure 11.

In one-dimensional analysis an optimum amount of diffusion is required to maximize engine performance. Simplistically, this optimum may be said to determine the engine capture area ratio and associated compression ratio, and it of course determines the level of temperature and pressure at entry to the combustor. However this is not the end of compression effects in the engine because, for a given combustor configuration, the processes of fuel injection, mixing and heat release, will all exert an influence on the overall evolution of the flow. Thus the presence of fuel injector struts or other protrusions into the combustor will generate shock/expansion fields. In general, complex wave patterns will be transmitted through multiple interactions downstream through the engine from their point of origin. The art of scramjet design thus lies in the effective utilization of these wave processes, to enhance combustion and thrust generation, while avoiding critical phenomena such as major flow separations, excessive thermal loading, and unstart of the combustor or inlet.

The degree of diffusion also falls between certain bounds[26] as illustrated in Figure 12. A minimum diffusion is required primarily to ensure appropriate pressure and temperature levels for efficient combustion. However, too much diffusion results in excessive thermal and mechanical loads, and can produce dissociation and non-equilibrium effects in the combustor, leading to severe thrust losses in the nozzle. It is also appropriate to note that because of the accumulation of losses associated with shock wave propagation, skin friction, and heat transfer that engine length is always at a premium. Opposing this requirement is the need for adequate length for the processes of fuel injection, mixing and combustion. Also opposing this requirement is the possibility, dependent on inlet and combustor design details, that a significant isolator length may be necessary between the inlet and combustor to avoid unfavorable interactions[35].

As noted earlier the degree of diffusion is a significant performance parameter. The overall diffusion process is carried out partially by the aircraft forebody (precompression), or in some installations by a wing surface[36], and partially by the engine module intake.

These precompression and post-compression processes may be non-adiabatic and possess large wall boundary layers. Therefore the usual one-dimensional parameters for assessing intake losses and starting criteria are not rigorously applicable at the higher speeds, and new performance parameters have to be derived to embrace this situation - see, for example, the definition of "compression efficiency" introduced by Billig and Van Wie[37]. Once again the engine compression process and the vehicle aerodynamics are inextricably coupled, not only through the flow turning processes[38, 39] but also through the forebody flow field, potentially involving shock/boundary layer interactions with laminar, transitional or turbulent boundary layer flows. In the case of an actively cooled forebody there is a further coupling through the aerothermodynamics of the cooling process. Once again the challenge is to use all such flow couplings to overall vehicle advantage.

The supersonic combustor represents a major technological challenge in engine development. Once again the existence of supersonic throughflow presents the problem of adding energy, usually in a fixed geometry configuration, while avoiding the pitfalls of undesired thermal choking at lowspeeds and excessive loss mechanisms, or thermal loadings, at any speed. Early efforts at demonstrating supersonic combustion have addressed geometries such as; the constant area cylinder, the cylinder-cone and step-cylinder configurations, and have also included many two-dimensional geometries. Injection techniques have included both wall and strut elements with injection at normal, tangential, and angled directions to the airflow. In addition to the problem of adequate fuel penetration to give the required transverse fuel distribution, the fuel injection must of course be tailored to give appropriate longitudinal coverage. Following ignition and stabilization, spatial control of the heat release, as a function of flight speed, has to be maintained by means of the fuel injection system and its control mechanism. A considerable data base on the mixing and heat release characteristic of various injector arrangements has been developed at NASA Langley[40] and the modeling strategy for such complex flows has been well documented in the pioneering efforts of Anderson[41], and Billig[42] and his associates at Johns Hopkins University. As a result of such efforts, together with many international contributions such as those of Baev[43] and Swithenbank[44], a good understanding of the generic behavior of supersonic combustion systems exists, at least to Mach 7-8 flight conditions. However the establishment of a mature technology base is dependent on the detailed understanding and enhancement, (e.g., Marble[45], Dimotakis[46]) of the component processes of fuel injection, flow interaction, mixing, heat release and final production of translational gas energy. Fortunately, the emergence of powerful CFD techniques[47] has permitted a more structured approach to modeling the elemental combustor processes: the CFD approach, combined with complementary experiments, should permit relatively confident synthesis of candidate combustor designs.

The exhaust nozzle is a critical component of the engine in that the final stream thrust increment is generated by the nozzle flow, and the net thrust of the engine is very sensitive to the level of nozzle performance. This performance is closely coupled to conditions at the combustor exit flow surface (not usually planar in the one-dimensional sense) and the initial expansion segment of the nozzle may be developed as part of the combustor-nozzle combination. The development problem of the nozzle is well understood from an internal flow viewpoint; the effects of entry flow nonuniformity, chemical nonequilibrium, wall friction and heat losses, and nonaxial exit flow vectors must be addressed. However, the overall aerodynamic effects of two-dimensional asymmetric nozzle flow on force generation and moments, and the effects of mismatched expansion and external-internal flow interactions[48] have unprecedented importance and are largely unknown. The pioneering effort of Lewis, et al[49] is of interest.

The scramjet engine is currently the most promising engine for hypersonic flight. However, the application of both steady and nonsteady detonation waves to high speed propulsion schemes has had a long history and recently there has been a renewal of interest in the Oblique Detonation Wave Engine[50, 51]. The problems traditionally associated with this engine include: the uniqueness and stability of such detonation waves; the mechanism of premixing the fuel with the inlet airstream; and the prevention of "flashback" through the mixing zone. It is hoped that the application of numerical simulation[52] and modeling will resolve some of these issues. Up to this point, heat addition to the internal flow has been considered. Heat addition to the external flow is of considerable relevance primarily to relieve base drag in the transonic speed range. It is also possible to modify the basic lifting and propulsive forces associated with a high speed vehicle by selective external heat addition. Thus the approach used in internal flows, namely to synthesize a multi-dimensional flow where the basic wave structures constructively interact with regions of heat addition may also be applied to external flow fields. See for example the works of Broadbent[53]. This arena of diabatic flow aerodynamics was discussed in a prior paper[14] and the reader is referred to this paper and its References.

Integration

For optimum flight performance the aerodynamic, structural, and propulsion elements of the vehicle have to be integrated into a cohesive whole taking every opportunity to synergistically enhance performance. For a cruising vehicle such integration can be simplistically discussed using the Breguet Range equation as shown in Figure 13. The constraints of the Breguet equation can of course be avoided by staging or refueling. The comparable equation for an accelerating vehicle is also shown. For a single stage vehicle some similar relief could be obtained by refueling or air collection[54]. In the acceleration case it should be noted that the overall propulsive parameter is the "effective" specific impulse, which couples the basic impulse of the flight engine to the overall vehicle thrust/drag characteristics. For an airbreathing engine such characteristics are of course dependent of the flight trajectory. There are conflicting flight path requirements: to maintain high engine thrust, a high dynamic pressure trajectory is desirable, however, the converse is true in regard to heating and pressure loads. Thus, trajectory optimization is also an integration issue. In regimes of minimum thrust margin a sharp loss in effective impulse can occur. This can be relieved by thrust augmentation typically by simple mass addition. Thus the use of water injection to augment turbojet and ramjet thrust is well documented. Similarly, augmentation by simple fuel and/or oxidant injection can be an effective way to provide excess thrust and enhance overall performance. The overall spectrum of such air breathing elements utilizing thrust augmentation or rocket-assist is well covered covered in an early foundational paper by Lindley[55]. Such techniques may be an attractive alternative to over-sizing an acceleration engine simply to overcome regimes of minimum thrust margin.

As flight speed increases the engine size also grows and soon dominates the vehicle configuration. The only efficient way to accommodate this reality is by total integration of the vehicle and propulsion systems. Essentially, the entire undersurfaces of the forebody and aftbody provide propulsion functions, and their contributions to the thrust, drag, and control of the vehicle are of paramount importance. Considerable ingenuity is required to tailor the vehicle configuration and its associated flow fields, to the engine installation and its mass flow characteristics. Typically, matching of the engine pumping characteristics and the available airflow over a wide speed range requires variable geometry. Such complexities may be alleviated by the judicious use of precooling in cryogenic engine systems.

In addition to the basic engine installation, the thermodynamics of both the overall active cooling circuits and the engine fuel utilization system must be such as to avoid unnecessary losses of available energy. The energy of the basic hydrogen-air system is marginal for the single stage to orbit mission. Thus energy must be conserved, and utilized in the most effective manner. Once again, an exergy based approach can be used to address total vehicle thermodynamics.

Regarding minimization of the structural weight fraction the design problems are severe. The vehicle will be subject externally to both high dynamic pressures and high temperature levels during ascent, while internally, low temperature cryogenic storage must be maintained. The engine structure is also subject to even higher internal pressures and temperatures, possibly in box-like actively cooled structures. Integration of the basic engine and airframe structures is essential to avoid duplicative weight elements. Fortunately new high-temperature materials are emerging to alleviate the design problem; nevertheless the achievement of a reusable high temperature structure of minimum structural fraction is a major challenge. As in the case of the engine, ground test validation of candidate structural approaches and assemblies is a demanding requirement.

A similar challenge is the development of a comprehensive vehicle control system. This is a significant architectural and engineering problem.

Finally, it is apparent that the eventual success of such a closely integrated vehicle demands a technological organization which possesses a broad yet unified view of the parent technologies and which approaches its task with a very high degree of teamwork. An enormous number of variables enter the evolutionary process of arriving at a near optimum configuration, and efficient management of such a process will require powerful management tools. Of course the process of vehicle development is not ended when fabrication and early flight demonstration is attained. The demonstration of full flight capability will, as noted earlier, only be completed by incremental flight development over an extended period.

Test Facilities

In previous years the testing of high speed flight engines has evolved to a disciplined sequential ground test process leading to flight qualification and flight demonstration. Full simulation of supersonic flight conditions has involved large scale plant, handling substantial mass flows at high enthalpy and high pressure conditions. The process of producing a large supersonic stream tube at the correct simulated flight Mach number is not trivial. Correctly designed axisymmetric nozzles can be used for discrete Mach number simulation. Such conventional facilities can currently simulate conditions which approximately correspond to typical Mach 7/8 flight speeds. Traditional criteria for both tunnel starting, with various blockages, and the avoidance of excessive transient loads can be applied. One new requirement for multi-mode engines will be the convincing demonstration of stable mode transitions. Such transitions will generally occur at Mach numbers below about 8 and thus such tests can be undertaken in suitably modified conventional facilities.

For significantly higher speeds, ultra-high enthalpies (and of course correspondingly high pressures) are required, and although many schemes have been postulated to achieve such enthalpies, the currently available test facilities are limited to relatively short duration systems.

The use of short-duration facilities to test scramjet engine components has been well established over the last twenty five years in the U.S.A.[56], the USSR[43] and other locations.

Such facilities, supported by increasingly sophisticated instrumentation and diagnostics have been invaluable in estimating the potential aerothermodynamic performance of inlets, combustors, and nozzles through tests lasting only a few milliseconds. The application of the supercomputer to the analysis of both aerothermodynamic flows[57] and structural design, can make maximum use of such short-duration test data. However the process of validating the performance and durability of a full scale flight engine is somewhat removed from the elemental tests performed in short-duration facilities, although these latter tests are essential. Currently an incremental flight test procedure appears to be the only logical course to proceed safely with engine certification.

In the future, extended duration ground tests at high speeds will require new facilities. Such facilities must avoid generating the simulated stagnation (or reservoir) conditions in the facility both because of engineering limitations and because the test gas may often be in a dissociated state. Consequently one must look to generating the required test enthalpy by progressive acceleration of the test gas by MHD or other energy transfer processes.

In any event a fundamental need exists for the incremental flight testing of hypersonic engine systems.

Conclusions

The current renewal of interest in hypersonic flight, and in low-cost access to space has emphasized the accelerative aspects of aircraft performance, in contrast to the previous emphasis on cruising flight. The necessity to use cryogenic fuels at the higher speeds has also introduced many avenues of opportunity in creating new engine designs and vehicle concepts. From a propulsion viewpoint it has been shown that multi-cycle propulsion is essential for high speed flight. For propulsion at lower speeds it should be noted that the trade-off between specific impulse and engine thrust-to-weight ratio generates interest in a wide variety of existing and "new" engine cycles. Evaluating the overall merits of such cycles requires comprehensive analysis; many of these "new" cycles require heat exchange elements; and finally the integration of these engine concepts into a cohesive vehicle design is of key importance.

At the higher speeds we conclude that the hydrogen burning supersonic combustion engine offers outstanding potential for hypersonic missions. However, the technologies for realizing such potential will require extensive computer analysis, and experimental test, to yield comprehensive engine design data. It is also noted that external heat-addition around lifting-propulsive bodies[59, 60] may play a significant role in emerging designs.

The challenge of test validation of high speed engines is real, requiring the evolution of a comprehensive ground test and incremental flight test strategy.

Currently we stand at a crucial point in aeronautical history. Aeronautics has steadily advanced along the traditional flight corridor to achieve relatively conventional flight to speeds approaching Mach 4.0. Such cruising flight may be regarded as an established stable boundary condition at the lower speed end of the flight corridor. At higher speeds another established steady condition exists namely orbital "flight." Between these established stable states a whole range of transatmospheric flight regimes exist. Currently, passage through the transatmospheric region is of a transient nature involving insertion to, and re-entry from, orbital conditions, or transient "zoom" operations. However, in the longer term, ability to operate in the transatmospheric region may be of considerable interest as the fields of aeronautics and space continue to merge.

It is clear that entry into the hypersonic flight regime means that long term commitments must be made to embark on new areas of technology in engines, fuels, aerothermodynamics, materials and structures. Similarly the whole infrastructure supporting operation of hypersonic cryogenically-fuelled vehicles must be addressed. Such changes will tend to be more revolutionary than evolutionary and should be recognized as a major shift in traditional aeronautical development. As previously noted[14] we stand at an exciting point in aeronautical, or rather aerospace, history: new vehicle configurations and engine concepts are emerging, and these opportunities need to be addressed in a cohesive, imaginative fashion. Fortunately, the supercomputer is now available to address both engineering and management problems[61]. However, the overall strategy for evolving such efficient high-speed vehicles is a complex and major challenge[10] - a point first stressed by Kuchemann[10] and recently reemphasized by Dorrington[62]. Although such major changes in aeronautical development have been latent for some decades, the current emphasis in hypersonics now requires dedicated attention so that the required engineering disciplines and methodologies can be brought together in appropriate management structures.

In the United States, the National Aero-Space Plane (NASP) program is providing the avenue for this dedicated attention. NASP is a technology program with the goal to develop and demonstrate the advanced technologies; the demonstration is to be in an experimental flight vehicle designated the X-30. Unlike the X-15, the X-30 will take off under its own power. The concept centers on a manned, hydrogen-powered, single-stage-to-orbit vehicle capable of horizontal takeoff and landing, reaching orbital speeds, and cruising for sustained periods at hypersonic speeds[2]. Obviously, this program is a tremendous challenge; however, with appropriate attention, dedication, and support, the way can be paved for a new generation of aerospace vehicles for the twenty-first century.

REFERENCES

1. National Aeronautical R&D Goals. Executive Office of Science and Technology Policy, Washington DC, USA, 1987.

2. Piland, W.M., "Technology Challenges for the National Aero-Space Plane," Paper No. IAF-87-205, Presented at the 38th Congress of the International Astronautical Federation, Brighton, UK, Oct 1987.

3. Wilson, G.P., HOTOL "Aerospaceplane for Europe," Paper No. IAF-87-208, Presented at the 38th Congress of the International Astronautical Federation, Brighton, UK, Oct 1987.

4. Kunkler, H., and Kuczera, H., "Turbo-ramjet Propulsion Systems Concepts for Future European Space Transport (Sanger)," Paper No. IAF 87-265, Presented at the 38th Congress of the International Astronautical Federation, Brighton, UK, Oct 1987.

5. Kramer, P.A., and Buhler, R.D., "Hybrid Rocket/Airbreathing Propulsion for Ballistic Space Transportation," J. Spacecraft and Rockets, Vol 17, No 4, Jul-Aug 1980.

6. Bouillot, J.C., Fazi, C., and Roubertie, J.M., "French Approach in Future Launch Systems," Paper No. IAF-87-209, Presented at the 38th Congress of the International Astronautical Federation, Brighton, UK, Oct 1987.

7. Doublier, M. and Pouliquen, M., "Progress in Airbreathing Combined Engines for Space Transportation Systems," Paper No. IAF-87-262, Presented at the 38th Congress of the International Astronautical Federation, Brighton, UK, Oct 1987.

8. Tanatsugu, N., et al, "Analytical Study of Space Plane Powered by Air-Turbo Ramjet with Intake Air Cooler," Paper No. IAF-87-264, Presented at the 38th Congress of the International Astronautical Federation, Brighton, UK, Oct 1987.

9. Bazhanov, V.I., and Stepchkov, A.A., "An Analysis of the Parameters that Determine Ramjet Maximum Thrust," Izvestiya VUZ. Aviatsionnaya Tekhnika, (Soviet Aeronautics), Vol 26, No. 1, 1983, pp 12-16.

10. Kuchemann, D., The Aerodynamic Design of Aircraft, Pergamon Press, 1978.

11. Blevins, G., Hartsel, J., and Powell, T., "Variable Cycle Concepts for High Mach Applications," AIAA-87-2103, AIAA/SAE/ASME/ASEE 23rd Joint Propulsion Conference, San Diego CA, 29 Jun-2 Jul 1987.

12. Swan, W.C., and Schott, G.J., "New Engine Cycles -- Opportunity for Creativity," Astronautics & Aeronautics, Jan 1975.

13. Loomis, J.P., High Speed Commercial Flight -- The Coming Era, (ISBN 0-935470-37-9), Battelle Press, Columbus OH, 1987.

14. Curran, E.T., Leingang, J.L., and Donaldson, W.A., "A Review of High Speed Airbreathing Propulsion Systems," Presented at the Eighth International Symposium on Air Breathing Engines, Cincinnati OH, 15-19 Jun 1987.

15. Glickstein, M.R., and Powell, T.H., "Advancements in Hydrogen Expander Airbreathing Engines," AIAA-87-2003, AIAA/SAE/ASME/ASEE 23rd Joint Propulsion Conference, San Diego CA, 29 Jun-2 Jul 1987.

16. Malinovskii, K.A., "Exergy Analysis of Turbojet Engine Cycle," Izvestiya VUZ, Aviatsionnaya Tekhnika, (Soviet Aeronautics), Vol 27, No. 1, 1984, pp 32-37.

17. Bejan, A., "Second Law Aspects of Thermal Design," HTD-Vol 33, Presented at the 22nd National Heat Transfer Conference and Exhibition, Niagara Falls NY, 5-8 Aug 1984.

18. Barrere, M., "Quelques Remarques Sur Les Systems De Propulsion Multifonctions Ou 'Combines'," Acta Astronautica, Vol 15, No. 11, 1987, pp 931-935.

19. Builder, C.H., and Caudra, E., "An Elemental Approach to Propulsion Selection for the Supersonic Transport," IAS Paper No. 62-72, Presented at the IAS 30th Annual Meeting, New York NY, 22-24 Jan 1962.

20. Franciscus, L.C., "The Supersonic Fan Engine --An Advanced Concept in Supersonic Cruise Propulsion," NASA Technical Memorandum 82657, Prepared for the 17th Joint Propulsion Conference, Colorado Springs, CO, 27-29 Jul 1981.

21. Jeffs, R.A., and Beeton, ABP, "Liquid Air Cycle Engines for High Speed Aircraft," Journal of the British Interplanetary Society, Vol 19, 1963-64, pp 484-490.

22. Kajita, et al, "Air Condensation Type Airbreathing Propulsion System," Paper No. IAF-86-180, Presented at the 37 Congress of the International Astronautical Federation, Innsbruck, Austria, Oct 1986.

23. Kunkler, H., "The Influence of Air Precooling Before Compression in Air Breathing Engines of a Space Launcher," Proceedings of the Second International Symposium on Air Breathing Engines, Royal Aeronautical Society, 1974.

24. Hewitt, F.A., "Air Breathing Propulsion for Advanced Orbital Launch Vehicles," Paper No. IAF-87-266, Presented at the 38th Congress of the International Astronautical Federation, Brighton, UK, Oct 1987.

25. Young, P.H., "The Heat-Exchanger Cycle. Has Its Time Come?," AIAA-75-961, 14th Anglo-American Aeronautical Conference, Los Angeles CA, 4-7 Aug 1975.

26. Curran, E.T., and Stull, F.D., "The Potential Performance of the Supersonic Combustion Ramjet Engine," ASD-TR-63-336, Aeronautical Systems division, Wright-Patterson AFB, Ohio, May 1963.

27. Merkulov, I.A., "Problems of Space Air-Breathing Jet Engines," Akademiya nauk SSSR. Izvestiya. Energetika i transport, no. 5, 1965, 159-172.

28. Curran, E.T., and Stull, F.D., "The Utilization of Supersonic Combustion Ramjet Systems at Low Speeds," USAF Report RTD-TDR-63-4097, January 1964.

29. Waltrup, P.J., Anderson, G.Y., and Stull, F.D., "Supersonic Combustion Ramjet (Scramjet) Engine Development in the United States," Proceedings of the 3rd International Symposium on Air Breathing Engines, DGLR, 1976.

30. Stull, D.F., Jones, R.A., and Zima, W.P., "Propulsion Concepts for High Speed Aircraft," SAE Paper 751092 Presented at the National Aerospace Engineering and Manufacturing Meeting, Culver City, Los Angeles CA, 17-20 Nov 1975.

31. Marguet, R., and Huet, C., "Research of an Optimum Solution for a Fixed Geometry Ramjet in the Mach 3 - Mach 7 Range with Successively Subsonic and Supersonic Combustion," ONERA TP No. 656E (1968).

32. Baev, V.K., Golovichev, V.I., and Tretyakov, P.K., "Combustion in Supersonic Flow," The Physics of Combustion and Explosion, Vol 23, No. 5, Sep-Oct 1987, pp 5-15.

33. Harper, L., "Comments on Supersonic Combustion," Twelfth Symposium (International) on Combustion, Poitiers, France, 1968, pp 1138-1139.

34. Stalker, R.J., Morgan, R.G., and Netterfield, M.P., "Wave Processes in Scramjet Thrust Generation," Combustion and Flame 71, 63-77, 1988.

35. Waltrup, P.J., "Liquid Fueled Supersonic Combustion Ramjets: A Research Perspective of the Past, Present and Future," AIAA-86-0158, Aerospace Sciences Meeting, 1986.

36. Huet, C., "Bilan Propulsif, Jusqu'a Mach 7, D'un Statoreacteur Monte Sous Une Aile," La Recherche Aerospatiale, No. 133, Nov-Dec, 1969, pp 3-14, NASA TT F-12,951.

37. Billig, F.S., and Van Wie, D.M., "Efficiency Parameters for Inlets Operating at Hypersonic Speeds," Symposium Papers, AIAA Eighth International Symposium on Air Breathing Engines, Cincinnati OH, 1987.

38. Bazhanov, V.I., and Stepchkov, A.A., "On the Limiting Values of the Specific Parameters of Ramjet Engines," Izvestiya VUZ. Aviatsionnaya Tekhnika, (Soviet Aeronautics), Vol 28, No. 4, 1985, pp 77-78.

39. Bazhanov, V.I., and Stepchkov, A.A., "Selection of Parameters of Air Intake Without Transition Through the Speed of Sound," Izvestiya VUZ. Aviatsionnaya Tekhnika, (Soviet Aeronautics), Vol 27, No. 1, 1984, pp 69-71.

40. Northam, G.B, and Anderson, G.Y., "Survey of Supersonic Combustion Research at Langley," AIAA Paper 86-0159, 1986.

41. Anderson, G.Y., "An Examination of Injector/Combustor Design Effects on Scramjet Performance," Presented at the 2nd International Symposium on Air Breathing Engines, Sheffield U.K., March 1974.

42. Billig, F.S., "Combustion Processes in Supersonic Flow," Symposium Papers, Seventh International Symposium on Air Breathing Engines, AIAA 1985.

43. Baev, V.K., Shumskiy, V.V., and Yaroslavtsev, M.I., "Some Methodical Aspects of Studying Gasdynamic Models with Heat and Mass Supply in Pulsed Wind Tunnels," The Physics of Combustion and Explosion, Vol 23, No. 5, Sep-Oct 1987.

44. Swithenbank, J., and Chigier, N.A., "Vortex Mixing for Supersonic Combustion," Twelfth Symposium (International) on Combustion, Poitiers, France, 1968.

45. Marble, F.E., Hendricks, G.J., and Zukosbi, E.E., "Progress toward Shock Enhancement of Supersonic Combustion Processes," AIAA Preprint AIAA-87-1880, Joint Propulsion Conference, 1987.

46. Dimotakis, P.E., and Hall, J.L., "A Simple Mode for Finite Chemical Kinetics Analysis of Supersonic Turbulent Shear Layer Combustion," AIAA Prepring AIAA-87-1879, Joint Propulsion Conference, 1987.

47. Dash, S.M., et al, "Computational Models for the Analysis/Design of Hypersonic Scramjet Components - Part I: Combustor and Nozzle Models," AIAA-86-1595, Presented at the AIAA/ASME/SAE/ASEE 22nd Joint Propulsion Conference, Huntsville AL, 16-18 Jun 1986.

48. Novak, C.J., and Cornelius, K.C., "Investigations of Low Speed Nozzle/Afterbody Performance for a Generic Hypersonic Configuration," AIAA Preprint 88-0196, Presented at the AIAA 26th Aerospace Sciences Meeting, Reno NV, 11-14 Jan 1988.

49. Lewis, W.G.E., Herd, R.J., and Herbert, M.V., "Lift Characteristics of Asymmetric Exhaust Nozzles at High Flight Speeds," Journal of the Royal Aeronautical Society, Nov 1966.

50. Townend, L.H., "Detonation Ramjets for Hypersonic Aircarft," Royal Aircraft Establishment Technical Report, TR 70218, 1970.

51. Sheng, Y., and Sislian, J.P., "A Model of a Hypersonic Two-Dimensional Oblique Detonation Wave Ramjet," UTIAS Technical Note No. 257, July 1985.

52. Cambier, J.L., Adelman, H., and Menees, G., "Numerical Simulations of Oblique Detonations in Supersonic Combustion Chambers," 8th International Symposium on Air Breathing Engines, Cincinnati OH, 1987.

53. Broadbent, "Flows with Heat Addition," Progress in the Aerospace Sciences, Vol 17, No. 2, 1976 pp 93-108.

54. Nau, R.A., "A Comparison of Fixed Wing Reusable Booster Concepts," SAE Publication P-16, SAE Space Technology Conference, Palo Alto CA, 9-12 May 1967.

55. Lindley, C.A., "Performance of Air-Breathing and Rocket Engines for Hypervelocity Aircraft," ICAS Paper 64-557, Presented at the ICAS Fourth Congress, Paris, 1964.

56. Anderson, Griffin Y., "An Outlook on Hypersonic Flight," Paper No. AIAA-87-2074, Presented at the AIAA/SAE/ASME/ASEE 23rd Joint Propulsion Conference, San Diego CA, 29 Jun-2 Jul 1987.

57. Barber, T.J., and Cox, G.B., Jr., "Hypersonic Vehicle Propulsion: A CFD Application Case Study," Paper No. AIAA-88-0475, Presented at the AIAA 26th Aerospace Sciences Meeting, Reno NV, 11-14 Jan 1988.

58. Fishbach, L.H., et al, "NASA Research in Supersonic Propulsion - A Decade of Progress," AIAA-82-1048, AIAA/SAE/ASME 18th Joint Propulsion Conference, Cleveland OH, 21-23 Jun 1982.

59. Townend, L.H., and Edwards, J.A., "Base Pressure Control for Aerospace Vehicles," Proceedings of Symposium: Fluid Dynamics and Space, VKI, Rhode-Saint-Genese, 25 and 26 June 1986 (ESA SP-265, August 1986).

60. Edwards, J.., and Stollery, J.L., "Some Effects of Shock/Wake and Shock/Flame Interaction," Presented at the 14th International Symposium on Shock Tubes and Waves, Sydney, Australia, 1983.

61. Petrov, B.N., et al, "Methods of Computer Search of Variants for the Problems of Vehicles Systems Composition Synthesis," IAF Paper IAF-80-A-38. Thirty First IAF Congress, Tokyo, Japan, 1980.

62. Dorrington, G.E., "Optimum Directions for Air-Breathing Launch Vehicle Design," AIAA Preprint AIAA-87-1818, Presented at AIAA/SAE/ASME/ASEE 23rd Joint Propulsion Conference, San Diego CA, 1987.

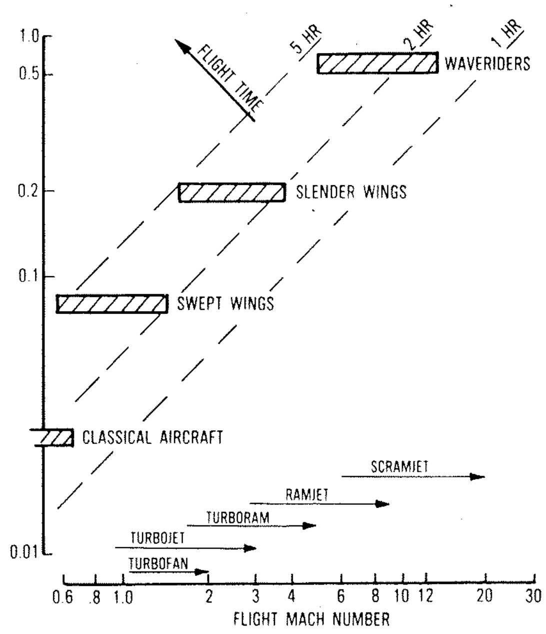

Figure 1 Classification of Aircraft Shapes and Engine Cycles

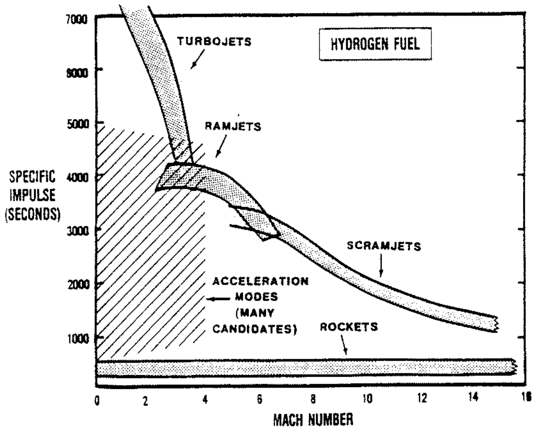

Figure 2 Approximate Performance of Hydrogen Fueled Engines

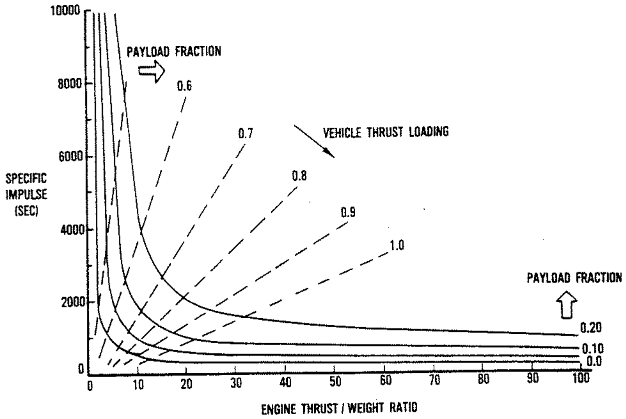

Figure 3 Typical Trade-Off: Specific Impulse and Engine Thrust-to-Weight Ratio

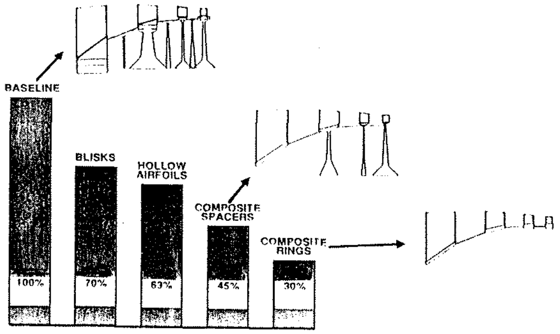

Figure 4 Potential Weight Reduction of Turbo-Engine Compressor

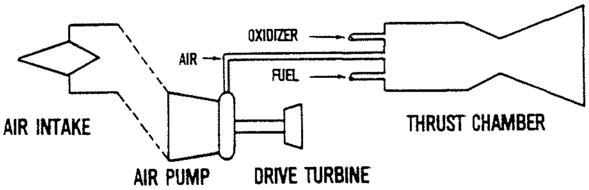

Figure 5 Challenge of Pumping to High Pressure with Minimum Weight

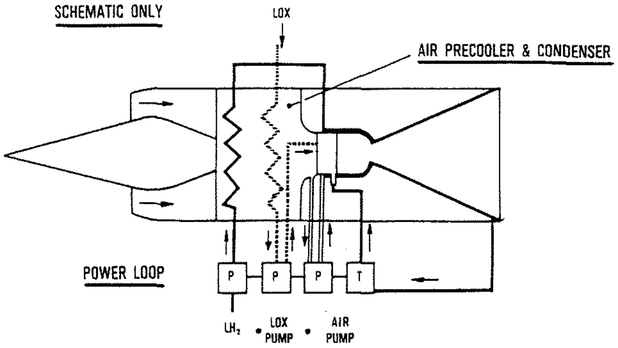

Figure 6 Cryogenic Engine Using Propellants

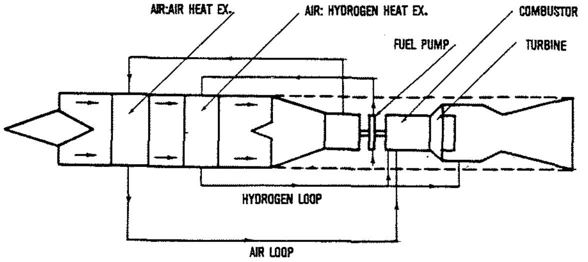

Figure 7 Staged Precooling of Turbo-Engine

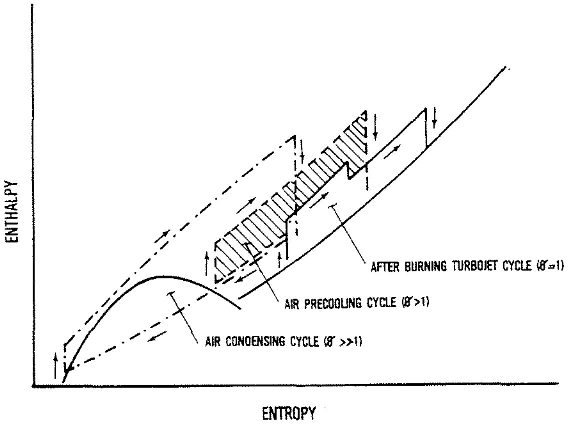

Figure 8 Thermodynamic Cycle Spectrum

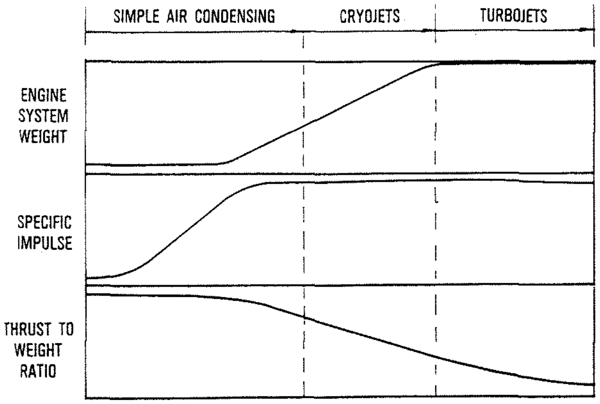

Figure 9 Classification of Accelerative Engines

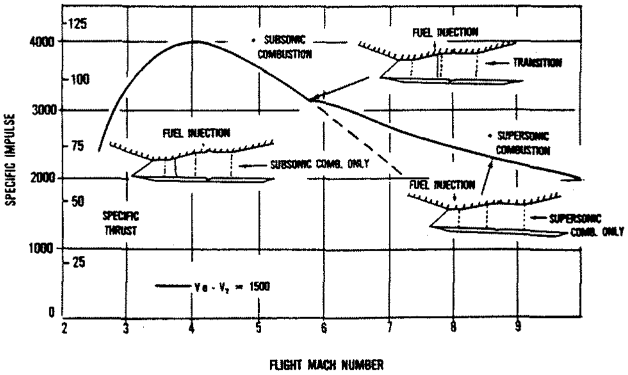

Figure 10 Dual Mode Ramjet Performance

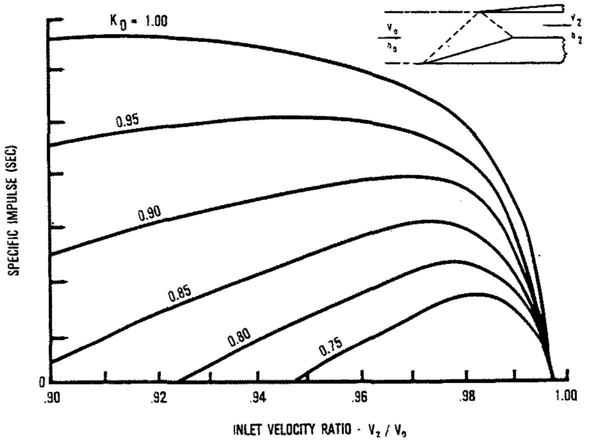

Figure 11 Effect of Diffusion on Scramjet Performance

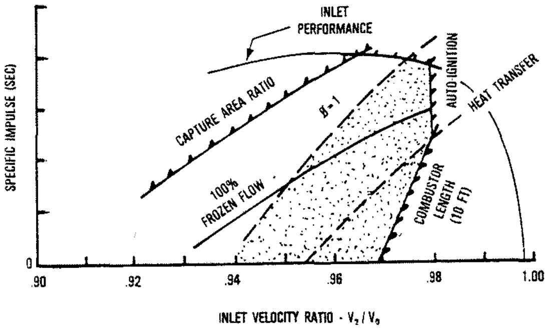

Figure 12 Constraints on Scramjet Design

- **RANGE**

$$R = \left(V \frac{L}{D}\right) I_{sp} \ln \frac{W}{W - W_F}$$

- **ACCELERATION**

$$\Delta V = \left(\frac{T-D}{T}\right) I_{sp} \ln \frac{W}{W - W_F}$$

Figure 13 Basic Vehicle Performance Expressions