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SCRAMJET ANALYSIS, TESTING

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A survey of supersonic combustion ramjet (scramjet) engine development in the United States covers development of this unique engine cycle from its inception in the early 1960's through the various programs currently being pursued and, in some instances, describing the future direction of the programs. These include developmental efforts supported by the U.S. Navy, National Aeronautics and Space Administration, and U. S. Air Force. Results of inlet, combustor, and nozzle component tests, free-jet engine tests, analytical techniques developed to analyze and predict component and engine performance, and flight-weight hardware development are presented. These results show that efficient scramjet propulsion is attainable in a variety of flight configurations with a variety of fuels. Since the scramjet is the most efficient engine cycle for hypersonic flight within the atmosphere, it should be given serious consideration in future propulsion schemes.

U. S. AIR FORCE SCRAMJET DEVELOPMENT

Air Force interest in hypersonic propulsion began in the late 1960's under exploratory development programs conducted at Marquardt. Interest in a supersonic combustion engine was intensified when a single stage earth-to-orbit vehicle (Aerospace Plane) was conceived. Two airbreathing propulsion schemes were of primary interest: namely, the air collection system requiring a subsonic ramjet to power the vehicle during the air collection and oxygen storage phase of the flight, and the supersonic combustion ramjet engine. Hydrogen fuel was selected for this application because of its intrinsic cooling capability and its high specific impulse. Both propulsion approaches were pursued by vigorous component development programs and ultimately led to the development of a subsonic combustion thrust chamber capable of hypersonic flight, and several scramjet engines. During the past decade the USAF has sponsored a number of scramjet engine programs. The following engines are representative of the different types of scramjet engines developed and ground tested in these programs:

(a) United Aircraft Research Laboratory Variable Geometry Scramjet
(b) General Electric Component Integration Model (CIM) Scramjet
(c) General Applied Science Laboratory Low Speed Fixed Geometry Scramjet
(d) Marquardt Dual Mode Scramjet

These engines were hydrogen fueled and achieved performance levels which, in general, substantiated theoretical predictions. Experience was gained regarding potential problem areas such as unfavorable combustor-inlet interactions leading to inlet unstart, and reduced combustion efficiency in divergent combustors. Although most of these engines were aerodynamically designed to operate over a wide range of hypersonic speeds and were substantiated by component tests conducted over a wide Mach number range, ground testing of the entire engine was restricted to a narrow Mach number range because of facility limitations. Hence, the full potential of these engines was never documented. A brief description of the first three engines will be given, followed by a more detailed discussion of the Marquardt Dual Mode Scramjet, which has undergone a relatively extensive testing program and is representative of an attractive concept for high speed aircraft.

UARL VARIABLE GEOMETRY SCRAMJET

A 45.72-cm-dia. water-cooled variable geometry scramjet engine was developed and tested at $M_0 = 5$ by United Aircraft Research Laboratory in the 1965-1968 time period. It was designed to operate over a wide Mach number speed range (up to Mach 12) with all supersonic combustion. The engine is axis symmetric incorporating a translating cowl which slides on three support fins. The translation of the cowl provides a variable inlet capture area and contraction ratio in order to obtain higher compression at the high Mach numbers, and more air flow at the low Mach numbers. At the same time, the cowl translation increases the combustor area ratio at the low flight Mach numbers to alleviate the problem of thermal choking, and also changes the nozzle area ratio in such a manner as to reduce the over and under expansion issues. The engine has four fuel injection stations, three on the center body and one on the cowl, and a gas generator ignition system. Over twenty free-jet tests were performed at the Ordnance Aerophysics Laboratory (OAL) in which inlet performance, pilot ignition, and engine performance under various injector configurations were investigated.

GE COMPONENT INTEGRATION MODEL SCRAMJET

Two 22.86-inch-diameter water-cooled variable geometry scramjet engines were designed and tested at $M_0 = 7$ by the General Electric Company in the 1966-1969 time period. The first engine, CIM-I, provided an evaluation of a combined set of scramjet components designed for operation up to Mach 8. CIM-I, constructed of chrome copper, had an axisymmetric mixed compression inlet with a movable centerbody, an annular combustor and a fixed annular plug nozzle. Two independent stages of normal injection were employed downstream of a small rearward-facing step to prevent propagation of combustion pressure rise from inducing separation in the inlet throat region. the combustor consisted of a constant area section followed by an 8 divergent section. Upon completion of testing in the General Electric Hypersonic Arc Tunnel, CIM-I was subsequently modified by replacing the cowl section with one having a smaller cowl lip angle to reduce external drag, and contouring some of the internal lines to increase performance. Extensive performance tests were conducted on CIM-II, to obtain the effects of varying inlet contraction ratio (13 to 25), equivalence ratio, fuel injector location, free stream Reynolds number and total enthalpy.

GASL LOW SPEED FIXED GEOMETRY SCRAMJET

A Mach 3-12 engine concept, involving a series of heat sink engine models of approximately 194 to 226 cm^2 of capture area, was developed and tested by the General Applied Science

Laboratories under the late Dr. Ferri in the 1964-1968 time period. This concept employs a fixed geometry closely integrated inlet-combustor design with low overall geometric contraction (<4), utilizing three-dimensional and combustor induced compression effects (sometimes referred to as thermal compression) to obtain an aerodynamic contraction ratio which varies with flight Mach number. At low Mach numbers, where flow disturbances propagate at large angles laterally, the swept back three-dimensional design permits large mass flow capture while preventing choking because of the large geometric flow area available. At high Mach numbers, where shock waves are highly swept, the stream tubes entering the inlet do not experience much lateral relief and thus are highly compressed in the local of large contraction. The resulting nonuniform combustor entrance flow is then diffused to relatively uniform conditions by utilizing combustion induced compression obtained from the proper placement of fuel injectors. Engine models demonstrating this concept have been tested at Mach = 2.7, 4 and 7 with inlet component tests covering Mach numbers from 2.7 to 11.3. Modifications to these designs were incorporated into a later engine model and tested at M = 7.4 in the GASL combustion heated high enthalpy blowdown tunnel under a wide variety of fuel injector patterns and fuel flow schedules.

DUAL MODE SCRAMJET

An attractive approach for the supersonic/hypersonic speed regime is the dual mode engine which combines the advantages of subsonic combustion at the lower flight speeds with supersonic combustion in the hypersonic regime. The main feature of this concept is that in principle the combustor operates in two modes: one for supersonic combustion and the other for subsonic operation. This can be accomplished by providing fuel injection at different axial locations within a common duct. the supersonic combustion section proceeds the subsonic one and acts as the subsonic diffuser of the inlet during the subsonic mode. An extensive component and engine development program was conducted by Marquardt in the 1964-1968 time period to develop this approach.

INLET DEVELOPMENT

Phase I analytical and experimental evaluations of a fixed geometry inlet which could satisfy both the low speed and high speed requirements of the Dual Mode Scramjet were conducted in mid 1965. This inlet, featuring highly swept leading edges was tested at AEDC at Mach numbers from 2 to 6. A larger scale inlet was also tested in a freejet cell at OAL at Mach 3 and 5 in combination with a combustor. Test results indicated that this type of inlet had the overall desired characteristics, but that nonuniform compression was occurring in the throat region which resulted in a low critical pressure recovery for the subsonic mode of operation.

COMBUSTOR/NOZZLE DEVELOPMENT

Phase I inlet/combustor tests conducted in the free-jet cell at OAL indicated the need for additional experimental tests to provide a reliable ignition source and possible piloting system for low Mach number operation. As a result, a series of full scale, direct-connect combustor tests was conducted at Mach 3 and 5 simulated freestream conditions at the Marquardt Research Field Laboratory. Ignitors evaluated included H_2-air, pentaborane, and fluorine.

Fluorine was shown to offer a positive and reliable ignition source under all test conditions. It was determined that piloting devices were not required in the low flight speed regime for the hydrogen fueled Dual Mode combustor. In addition to establishing ignition and piloting requirements, these tests investigated internal combustor contours and fuel injection patterns for maximum combustor performance in the subsonic and supersonic combustion modes. The ability to position the normal shock system by fuel modulation, while maintaining stable combustor performance during transition, was also demonstrated.

FREE-JET ENGINE TESTS

Based upon the results of the preceding Phase II inlet and combustor/nozzle tests, a water-cooled Dual Mode Scramjet Engine was fabricated and tested in 1967. The engine is a fixed geometry, two-dimensional configuration incorporating highly swept back features and designed to operate over a wide Mach number speed range by using subsonic and supersonic modes of combustion. Its basic nominal dimensions consist of height = 24.89 cm, width = 38.61 cm and overall length = 222.25 cm. With an inlet contraction ratio of 5.62, the capture area is 619.38 cm^2. Nozzle exit to cowl area ratio is 1.44. The fuel injection system, consisting of nine axial fuel injector locations along with two fluorine ignitors, allows for stable combustion mode transitions to be made with high overall engine efficiency. The engine model was fabricated from Inconnel 718 and Hastelloy X and structurally designed for Mach 3-8 test conditions.

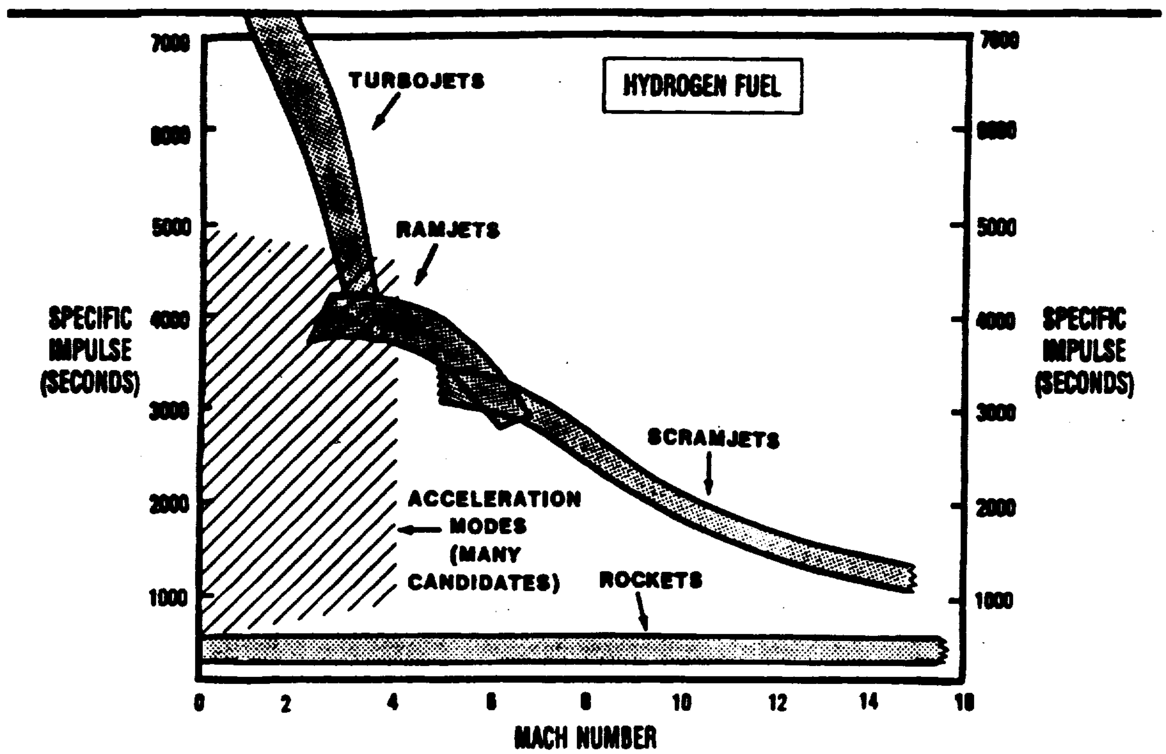
HYDROCARBON FUELED HYPERSONIC ENGINES

At the conclusion of the dual mode scramjet program and the other successful scramjet engine programs, USAF interest shifted from large scramjet vehicles to smaller missile systems leaving the hydrogen scramjet area to NASA with their HRE and other programs. As a result, attention focused on the hydrocarbons and fuels with a high density impulse. Ignition delay and reaction times for gaseous hydrocarbons are much longer than for hydrogen, hence the problem of achieving high combustion efficiencies using these fuels proved more difficult than for hydrogen. Initially, attempts were made to simply modify the existing hydrogen scramjet engines by lengthening the combustor section and using gaseous fuels such as methane and ethylene, but these met with only limited success. Extensive effort has been devoted to the development of piloting systems for use in scramjet engines employing liquid hydrocarbon fuels, and is the approach employed in the Dual Mode Hydrocarbon Scramjet. The concept of a pilot is to provide a high temperature gas source along with a large concentration of free radicals. Good supersonic combustion efficiencies have been obtained using liquid hydrocarbon fuels in tests where suitable fuel injector piloting systems have been developed.

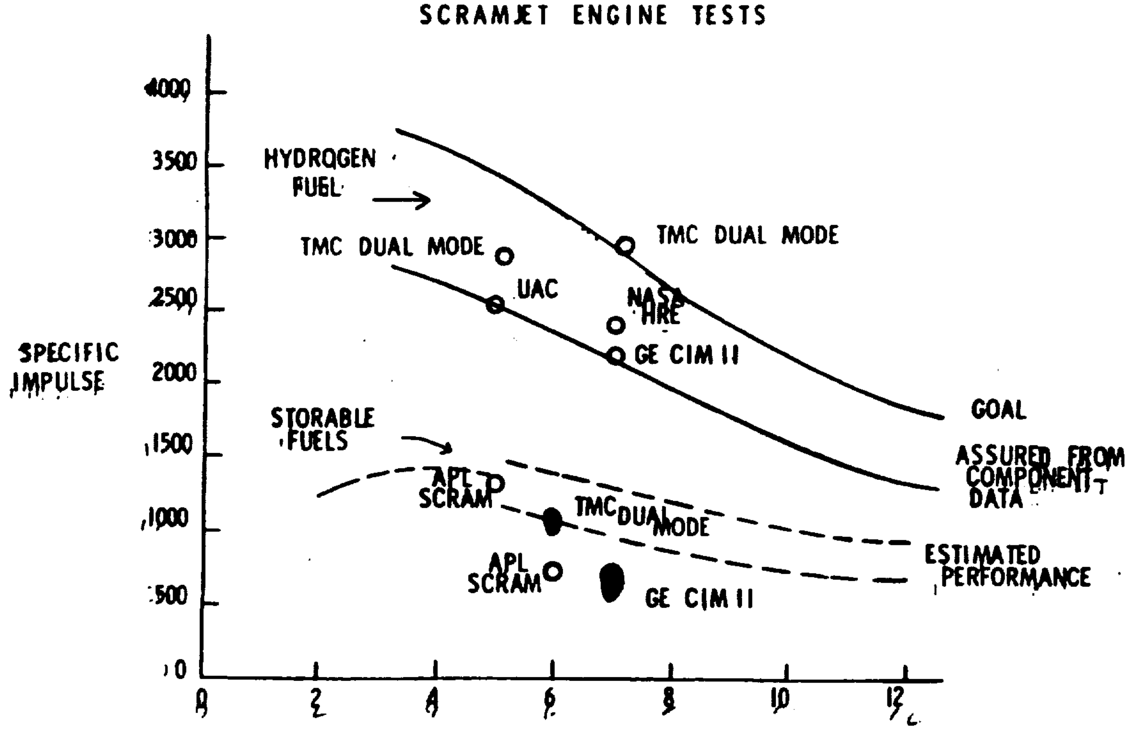
PROPOSED USAF/NASA X-24C RESEARCH VEHICLE

In light of technical interest and engineering activity relative to a variety of propulsion concepts as well as other interests existing in technical domains of structures, subsystems and miscellaneous components including avionics, efforts have been made by a joint USAF/NASA ad hoc group to describe the performance and design requirements for a low cost research vehicle. In essence, the aim of this group has been to provide a "flying wind tunnel" that would be free of some of the encumbrances encountered in ground facilities, provide a capability for demonstrating large scale propulsion and structures in the actual environment, provide data by which to correlate ground facility results, and provide an insight into synergistic effects on various systems.

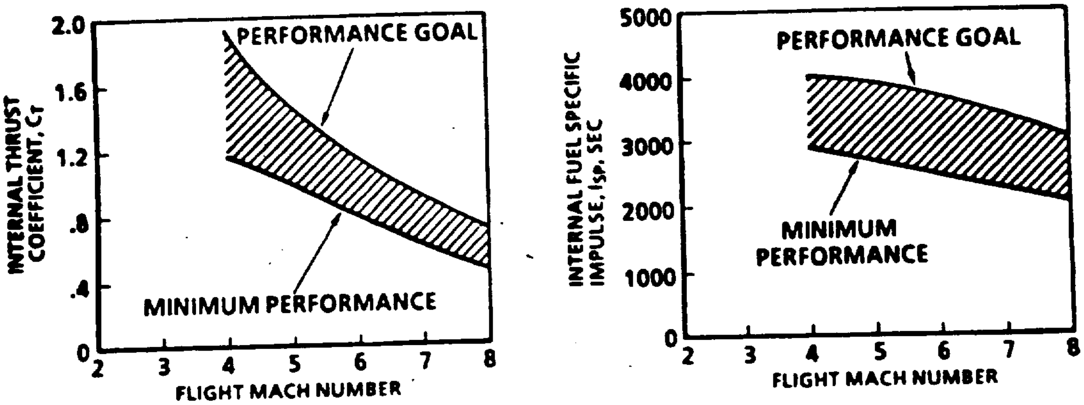
PROPULSION OPTIONS



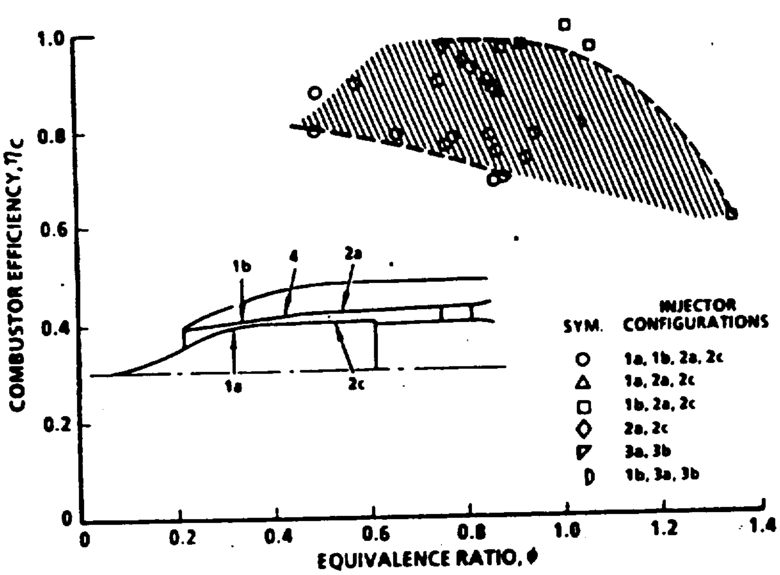
SCRAMJET ENGINE TESTS



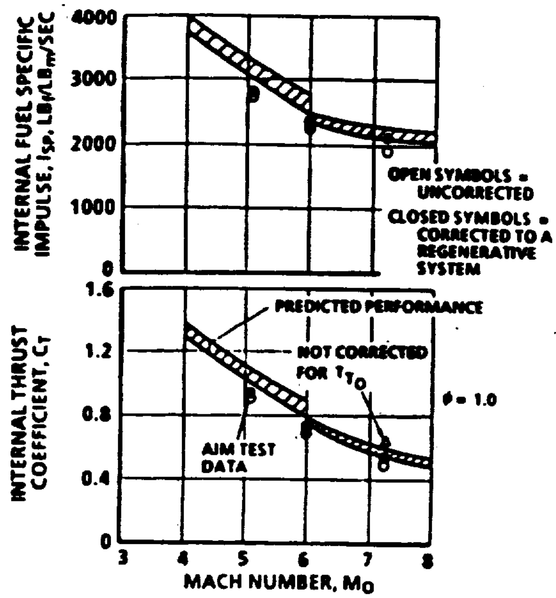
HRE PERFORMANCE GOALS



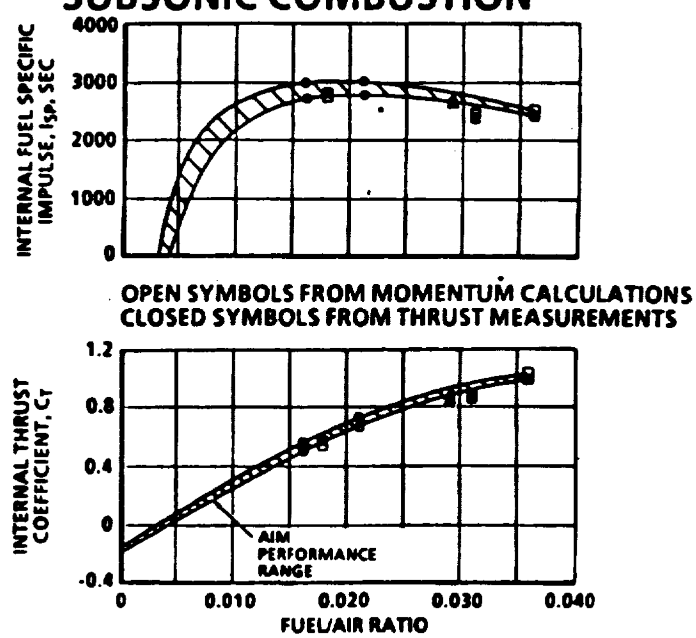
MACH 6 COMBUSTOR EFFICIENCY



AIM INTERNAL PERFORMANCE COMPARISON



MACH 5.1 INTERNAL PERFORMANCE SUBSONIC COMBUSTION



Nozzle Characteristics for RBCC Hypersonic Systems

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