N92-21535

NASA's HYPERSONIC PROPULSION PROGRAM: HISTORY AND DIRECTION

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Research into hypersonic propulsion; i.e., supersonic combustion, was seriously initiated the Langley Research Center in the 1960's with the Hypersonic Research Engine (HRE) project. This project was designed to demonstrate supersonic combustion within the context of an engine module consisting of an inlet, combustor, and nozzle. In addition, the HRE utilized both subsonic and supersonic combustion (dual-mode) to demonstrate smooth operation over a Mach 4 to 7 speed range. The most impressive technological advances were made in the structures area, where a flight weight, actively cooled structure for the complete engine was built and tested up to Mach 7 enthalpies in the 8 foot High Temperature Structures Tunnel (currently referred to as the High Temperature Tunnel). In addition, separate aerodynamic tests were conducted in the Lewis Plumbrook facility. Flight tests were to be carried out on the X-15, but did not occur due to delays in the construction of the HRE and early cancellation of the X-15 program. While the HRE was fully successful in meeting it's two primary objectives; 1) development of flight weight actively cooled structures and 2) demonstration of internal thrust from a dual-mode scramjet, no attempt was made to address integration to a vehicle or to achieve useful installed thrust. As a practical propulsion system the HRE had three major drawbacks: 1) the axisymmetric centerbody design resulted in large surface areas to be cooled, limiting maximum practical Mach number; 2) the "drooped" inlet cowl, required to make the inlet operate properly, resulted in high installed cowl drag; and 3) the resulting external engine shape let to a fundamental integration problem with the airframe.

Consequently, the program turned it's attention toward defining an engine design that would have higher installed performance potential; i.e., reduced internal surface area, low external wave drag, and good vehicle integration characteristics. The objective was to develop and demonstrate the technology for such an integrated engine having a high Mach number capability by virtue of it's low internal surface area. In addition, it was felt that the high temperatures and resulting extreme structural design conditions associated with hypersonic flight would dictate fixed geometry or only modest variable geometry designs. Thus, the hypersonic aspects of the engine were emphasized and multi-cycle features deferred until mission requirements and low-speed operational characteristics were defined. After pursuing a number of approaches, these considerations resulted in three dimensional inlet/engine designs utilizing inlet/sidewall compression surfaces and a vertical throat. At about the same time (late 1960's), cruise and airbreathing launch vehicle studies were being completed by industry that featured two-dimensional inlets and turboramjet/scramjet engines. This led the Ames and Lewis Research Centers to focus inlet research on two-dimensional inlet designs involving large moving panels. However, because of the variable geometry requirements and presence of strong shock waves inherent to that design approach, these designs were considered impractical for high hypersonic Mach numbers.

Responding to the cancellation of the X-15 program and the HRE flight tests, Langley Research Center initiated studies in the early 1970's to focus technology on both hypersonic structures and propulsion systems. At about this time, propulsion ground facilities were also becoming available for direct connect and free jet tests over the Mach 4 to 8 speed range. Thus, a program was put in place that focused propulsion development on a Hypersonic Research Airplane (HRA). The HRA would be rocket boosted to hypersonic speeds and would cruise on dual-mode scramjet propulsion to demonstrate efficient installed performance. However, with the demise of hypersonic research in the mid to late 70's the HRA and most other hypersonic related activities were canceled, with only a small program being maintained in hypersonic propulsion. The propulsion program thus concentrated on fundamental supersonic combustion studies and free jet propulsion tests for the three dimensional fixed geometry engine design to demonstrate inlet and combustor integration and installed performance potential.

Starting in the early 1980's, studies were initiated with Lockheed, Pratt & Whitney, and the Lewis Research Center, to define a fully integrated vehicle and propulsion system that would lead to the design of an inlet for tests by NASA. That project was completed and produced the Mach 5 inlet that is currently being tested in the Lewis Research Center 10x10 tunnel. Several variations of the turboramjet engine were studied, all incorporating a two-dimensional, variable-geometry inlet system which was considered acceptable over the Mach 2.5 to 5 speed range. The turboramjet engine variations included an in-line turbojet and ramjet, a wraparound turboramjet, and an over/under turboramjet. The in-line engine was similar to the current Sanger engine, but was deemed unacceptable because only one engine could be operated at a time and because of concerns about the aerodynamic transition from turbojet to ramjet. The wraparound turboramjet was the industry standard for the 60's and 70's, but tended to have a large surface area that resulted in cooling problems at Mach 5. In addition, the central location of the turbojet put it in a "pressure cooker" during hypersonic flight. Results of the studies identified the over/under engine with a split inlet feature as the most desirable. The inlet external compression ramp doubles as a flow splitter when the turbojet is operating, forming separate inlets for the turbojet and ramjet. The result is a relatively compact engine with a minimum surface area in the ramjet flowpath, reducing it's weight and cooling requirements at Mach 5. Separate turbojet and ramjet nozzles are contained in both the wraparound and over/under turboramjet engine and allow both engines to operate simultaneously so that sufficient thrust and a smooth transition can occur between the two cycles.

NASA's contintuing efforts in hypersonic propulsion research through the 1970's enabled the development of supersonic combustion technology and helped to make possible the initiation of the NASP program. Interest in hypersonic research was revived with NASP in the mid-80's and required a dramatic expansion of these research activities. This has been particularly true iwith respect to the engine free-jet test facilities at the Langley Research Center where the contractor subscale engines have been extensively tested. NASP also helped bring about the reactivation of other test facilities such as the Ames 16 inch Shock Tunnel, the Langley Mach 18 Helium Tunnel, and the HYPULSE expansion tunnel at CALSPAN. Between the two NASP engine contractors, both classes of inlets and engines studied in the 60's and 70's have been addressed including two-dimensional and three-dimensional sidewall compression inlets. However, the NASP requirement for airbreathing propulsion from takeoff to near orbit forced an important extension of the earlier hypersonic propulsion work; multicycle operation over a wide speed range. Thus, the complexities of variable geometry requirements were coupled to the most severe mission environment possible where extreme heating conditions and a high mission sensitivity to propulsion efficiency and weight exists. Work performed by the NASP contractors has resulted in ingenuous and, perhaps, breakthrough designs for implementing variable geometry within these engine shapes that had not been considered in the past. In addition, the importance and complexity of nozzle designs to recover hard earned thrust at hypervelocity speeds, where net thrust is only a small fraction of the gross thrust (i.e., high loss sensitivity) has been emphasized and appreciated. While the contributions from the NASP program have been impressive, efficient airbreathing Single Stage to Orbit (SSTO) vehicles are an extremely challenging problem requiring much additional research. However, NASP will be required to take an engineering approach to develop the X-30 within the near-term without the luxury of fully optimizing component design and performance, or the propulsion flowpath. Thus, the continuing need for a generic program to investigate and optimize alternative propulsion flowpath technologies, engine cycles, and fuel types.

Generic Hypersonic Propulsion Program

Two recent developments that most influence the application of airbreathing propulsion to hypersonic vehicles are 1) the NASP program which emphasizes airbreathing propulsion to orbit, and 2) research into endothermic hydrocarbon fuels which will provide cooling capacity up to flight speeds of Mach 7 or 8 with storable hydrocarbon fuels. Thus, interesting hypersonic propulsion initiatives exist for both hydrogen and hydrocarbon fueled applications The Air Force Wright Laboratories (AFWL) also conducts research programs into hypersonic airbreathing applications and recently briefed the Scientific Advisory Board (SAB) Hypersonic Panel on their Hypersonic Technology Initiative plans. AFWL sees as their research priorities hydrocarbon fueled first stage launch vehicles and hydrocarbon cruise missiles both of which require a strong ongoing program into endothermic hydrocarbon fuels research.

Consequently, the NASA Generic Hypersonic Propulsion (GHP) program is designed to complement the NASP and AFWL programs through a balanced research program with focused augmentations in both hypervelocity research and lower speed (Mach 4 to 8) hydrocarbon fueled vehicle applications. However, within the current limited funding the GHP program will concentrate principally on basic tool building activities, with focused research into more efficient SSTO propulsion systems to complement the NASP program. These activities will continue to be the principle focus for the program in FY 1992/3. In addition, research up to Mach 8 will continue at a modest level utilizing existing propulsion facilities to explore more efficient approaches SSTO and Two Stage to Orbit (TSTO) airbreathing launch systems. The long-term program emphasis is described in the following sections.

Augmentation in the hypervelocity arena (Mach>14) recognizes the importance of efficient airbreathing propulsion to space launch vehicle performance at high hypersonic speeds. At these speeds, the energy contained within the propulsion airstream becomes very large such that the energy added by the combustion of fuel represents only a small percentage of the energy contained within the flowpath. Net thrust then becomes the difference between two very large quantities, the stream thrust approaching the inlet cowl and the gross thrust from the nozzle exhaust. Therefore, losses within the propulsion flowpath will have a dramatic effect on net thrust and thus, overall vehicle performance is much more sensitive to propulsive performance in this speed regime. In addition, little research has been conducted at these speeds so that our understanding of the propulsion flowpath and supersonic mixing and combustion process is not nearly as mature as at the lower speeds (Mach 4 to 8). The hypervelocity program will strive to understand the propulsion flowpath chemistry and physics and devise means of minimizing component losses much like propulsion research conducted over the past two decades at lower speeds. Initially, research would be focused on the high speed end setting aside the constraining requirements of low-speed propulsion system performance. Once the flowpath and loss mitigation processes are better understood, that technology may be applied to further optimize the high Mach end of the SSTO propulsion system and may also be applied to propulsion system designs for the second stage of a TSTO launch vehicle or a cruise missile. Vehicles that only operate at the hypervelocity speeds (Mach 10 to 20) will have propulsion systems that could be fixed geometry and are not constrained by lower speed propulsion requirements. One focus of the program will be to explore innovative approaches for this class of vehicle, such as a detonation wave scramjet, to find ways to make substantial improvements in the performance potential of airbreathing launch vehicles. One centerpiece of such a hypervelocity program must be the development of advanced facilities to allow propulsion tests at the high energy levels associated with hypervelocity speeds. A near-term opportunity exists to achieve a significant increase in propulsion test capability by adding a "free piston driver" to the existing HYPULSE expansion tunnel. Other appropriate ground test capability also exists at the Ames Research Center in the 16 inch Shock Tunnel and the Direct Connect Arcjet Facility (DCAF). In addition, flight test augmentation will be required to provide critical data to provide ground based experimental test correlations and to validate analytical tools and Computational Fluid Dynamics (CFD) codes.

The planned hydrocarbon fuel augmentation will impact a number of hypersonic vehicle classes which have the potential to effectively utilize the heat capacity contained within endothermic fuels. With storable hydrocarbon fuels, vehicles can become much smaller and flight operations much easier. Again, this involves two classes of vehicles having propulsion systems of varying complexity; 1) multicycle engines incorporating a turbojet and ramjet or scramjet operating from takeoff to cruise or staging speeds, and 2) cruise missiles operating over a narrow Mach number range. Multicycle engines may be derived from the turboramjet cruise vehicle studies of the 1980's and will benefit directly from the Mach 5 inlet research currently being conducted at the Lewis Research Center. The over/under turboramjet engine is adaptable to replacing the ramjet flowpath with a dual-mode scramjet, significantly increasing the Mach potential of that engine to Mach 7 or 8. This potential results from the reduced pressure and heat load of the scramjet flowpath allowing a wider flight corridor and reduced cooling requirements. Missile applications may not be constrained by lower speed requirements and may therefore be readily adaptable to three dimensional fixed geometry inlets and other innovative concepts. The enabling technology for these classes of vehicles is an efficient dual-mode scramjet which burns endothermic hydrocarbon fuel. Inlet, combustor, and nozzle components all have unique operating requirements imposed by hydrocarbon fuels. Some feature, such as a pilot, is required to allow the fuel to react and burn at supersonic speeds. The program will be fully coordinated with the AFWL to prevent duplication of effort particularly in the areas of mission analysis and fuels research.

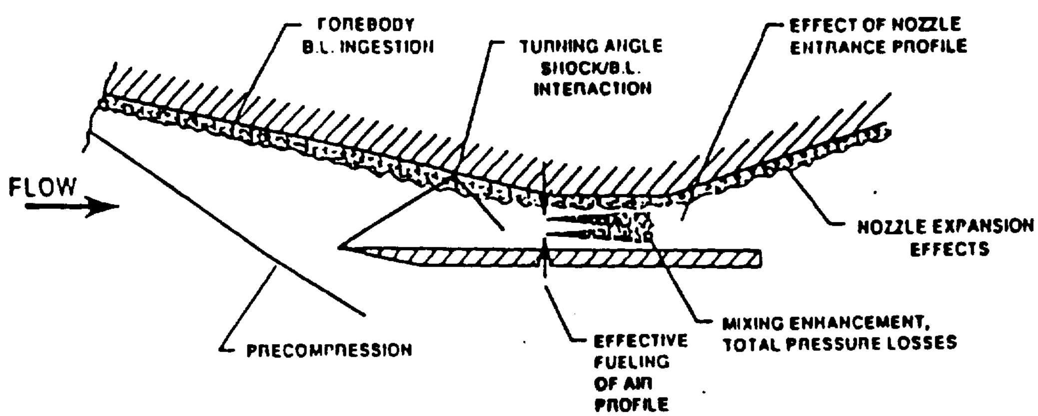
HYPERSONIC PROPULSION: HISTORY

- Early work focused on fundamental studies of supersonic mixing and combustion, and the demonstration of that technology for an airframe integrated fixed geometry scramjet module from Mach 4 to 8.

- NASP built on and this work to develop multi-cycle engines that could operate from Mach 0 to 20, introducing extensions to supersonic combustion technology as well as variable geometry in a high heating environment.

- Recent AFWL studies into endothermic fuels opened possibilities of hypersonic applications for hydrocarbon fuels utilizing ramjet and dual mode scramjet propulsion cycles.

HYPERSONIC PROPULSION SYSTEM



FUSELAGE FOREBODY
- SHOCK LOCATION
- DYNAMIC PRESSURE INCREASE
- LOCAL MACH NO. DECREASE
- BOUNDARY LAYER THICKNESS
- LONGITUDINAL & LATERAL STREAMLINES DEVIATION

COMBUSTOR
- EFFICIENCIES
- INJECTORS
- MIXING LENGTHS
- COOLING REQ'S

INLET
- EFFICIENCIES
- STARTING CHARACTERISTICS
- VARIABLE GEOM
- INLETS INTERACTION
- BOUNDARY LAYER INGESTION

EXHAUST NOZZLE
- EFFICIENCIES
- MODULE INTERACTION
- FLOW STATES

OVERALL PROGRAM GOALS AND OBJECTIVES

- DEVELOP TOOLS TO ENABLE RESEARCH, DESIGN AND ANALYSIS OF ADVANCED HYPERSONIC PROPULSION SYSTEMS
- CONDUCT BASIC GROUND EXPERIMENTS AND SUPPORT FLIGHT RESEARCH PROGRAMS TO ESTABLISH FUNDAMENTAL UNDERSTANDING AND PERFORMANCE ENHANCEMENTS FOR HYPERSONIC PROPULSION SYSTEMS
- CONTRIBUTE TO AND INTERACT WITH MISSION ANALYSIS AND VEHICLE SYSTEM STUDIES TO DEFINE ENABLING PROPULSION TECHNOLOGIES FOR HYPERSONIC VEHICLES

PROGRAM ELEMENTS

- PROPULSION SYSTEM STUDIES
- INLET FLOW PHYSICS AND DESIGN
- COMBUSTOR FLOW PHYSICS AND DESIGN
- NOZZLE FLOW PHYSICS AND DESIGN
- PROPULSION FLOWPATH TECHNOLOGY
- EXPERIMENTAL AND COMPUTATIONAL CAPABILITIES

PROPULSION SYSTEM STUDIES

GOALS AND APPROACH

DEVELOP CRITERIA FOR HYPERSONIC PROPULSION SYSTEM DESIGN AND PERFORMANCE

- MISSION/SYSTEMS STUDIES
- NASP PROGRAM INTERFACE
- NASA AND DOD PROGRAM INTERFACE
- DETAILED DESIGN STUDIES

INLET FLOW PHYSICS AND DESIGN

GOALS AND APPROACH

DEVELOP ENABLING TECHNOLOGY FOR HIGH PERFORMANCE HYPERSONIC INLETS

- FUNDAMENTAL FLOW PHYSICS RESEARCH
- SUB-SCALE MODEL TESTS
- JOINT DESIGN EFFORTS
- INLET PERFORMANCE ENHANCEMENT
- FLIGHT RESEARCH PROGRAMS
- HYDROCARBON FUELS STUDIES

COMBUSTOR FLOW PHYSICS AND DESIGN

GOALS AND APPROACH

DEVELOP ENABLING TECHNOLOGY FOR HIGH PERFORMANCE COMBUSTORS

- HIGH SPEED MIXING AND COMBUSTION
- FUEL INJECTION CONCEPTS
- HYDROCARBON FUEL CONCEPTS
- COMBUSTOR EFFICIENCY IMPROVEMENTS
- CFD CODE CALIBRATION
- FLIGHT RESEARCH SUPPORT

NOZZLE FLOW PHYSICS AND DESIGN

GOALS AND APPROACH

DEVELOP ENABLING TECHNOLOGY FOR HIGH PERFORMANCE NOZZLES

- NOZZLE LOSS MINIMIZATION
- SCRAMJET NOZZLE TESTS
- COMBUSTOR- NOZZLE INTEGRATION
- FLIGHT RESEARCH SUPPORT

PROPULSION FLOWPATH TECHNOLOGY

GOALS AND APPROACH

DEVELOP AN UNDERSTANDING OF AIRFRAME/ENGINE FLOW PATH AND ENGINE-COMPONENT INTERACTIONS, AND INVESTIGATE ALTERNATIVE ENGINE CONCEPTS

- COMPONENT INTERACTION EVALUATIONS
- SUB-SCALE ENGINE CONCEPTS
- NOZZLE-AFTERBODY INTERACTIONS
- LARGE-SCALE BOILER-PLATE ENGINE TESTS
- ALTERNATIVE HIGH MACH ENGINE CONCEPTS
- FLIGHT RESEARCH SUPPORT

EXPERIMENTAL AND COMPUTATIONAL CAPABILITIES

GOALS AND APPROACH

PROVIDE EXPANDED EXPERIMENTAL TEST CAPABILITIES INCLUDING ADVANCED DIAGNOSTIC INSTRUMENTATION; AND DEVELOP ADVANCED COMPUTATIONAL METHODS ADDRESSING PROPULSION COMPONENT DESIGN AND ANALYSIS

EXPERIMENTAL

- ADVANCED INSTRUMENTATION CONCEPTS
- FLIGHT TEST CAPABILITY ENHANCEMENTS
- FACILITY UPGRADES
- ADVANCED FACILITY CONCEPT STUDIES

COMPUTATIONAL

- CFD CODE CAPABILITY ENHANCEMENT
- INTERACTIVE ENGINEERING METHODS
- NOSE-TO-TAIL ANALYSIS METHODOLOGIES

PROGRAM FOCUS

- **PURSUE ENABLING TECHNOLOGY BASE FOR SCRAMJETS**
- **EXPLORE INNOVATIVE HYPERVELOCITY ($M > 14$) PROPULSION CONCEPTS**
- **DEVELOP MACH 4-8 HYDROCARBON FUELED ENGINES**

PAYOFFS

SCRAMJETS

- PROVIDE CONTINUING RESEARCH DATA BASE, EXPERTISE AND FACILITIES FOR SUPPORT OF NASP

HYPERVELOCITY

- ACHIEVE INHERENTLY HIGHER ISP FOR AIRBREATHING PROPULSION SYSTEMS VS. ROCKET PROPULSION
- EXTEND HIGH PERFORMANCE RANGE OF SSTO
- OPTIMIZE INNOVATIVE CONCEPTS FOR 2ND STAGE AIRBREATHERS

HYDROCARBON FUELS ☞ (HIGH DENSITY, STORABLE FUELS)

- INCREASE OPERATIONAL FLEXIBILITY
- REDUCE VEHICLE SIZE, WEIGHT AND COMPLEXITY

CRITICAL RESEARCH ISSUES

HYPERVELOCITY ☞ HIGH SENSITIVITY TO LOSSES, I.E. NET THRUST << GROSS THRUST

- INCREASED FUEL THRUST
- REDUCED INLET WAVE DRAG
- IMPROVED MIXING
- REDUCED MIXING, FRICTION AND HEAT LOSSES
- EVALUATION OF DETONATION WAVE ENGINES
- ALTERNATIVE FUELS
- REDUCED DISSOCIATION LOSSES IN NOZZLE AND COMBUSTOR
- MISSION STUDIES
- GROUND TESTING FACILITIES, INCLUDING INSTRUMENTATION
- CFD/TRANSITION/TURBULENCE ETC. TOOLS FOR M >> 1

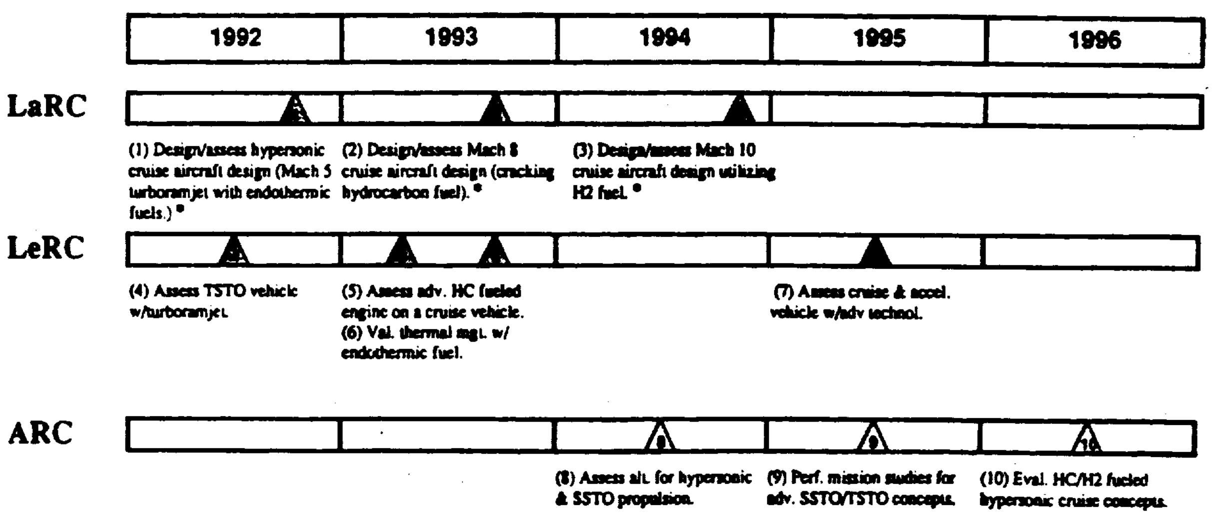
CRITICAL RESEARCH ISSUES

HYDROCARBON FUELS (ENDOTHERMIC)

- IGNITION/PILOTING
- FUELS/CATALYSTS/HEAT EXCHANGERS (INTEGRAL)
- MODE CHANGE (TURBO TO RAMJET TO SCRAMJET)
- INLETS WITH SUBSONIC PILOTING
- EMISSIONS/POLLUTION
- DUAL PHASE FUEL OPERATION
- HIGH TEMPERATURE TURBOMACHINERY
- COMPONENT/VEHICLE INTEGRATION

RESEARCH MILESTONES

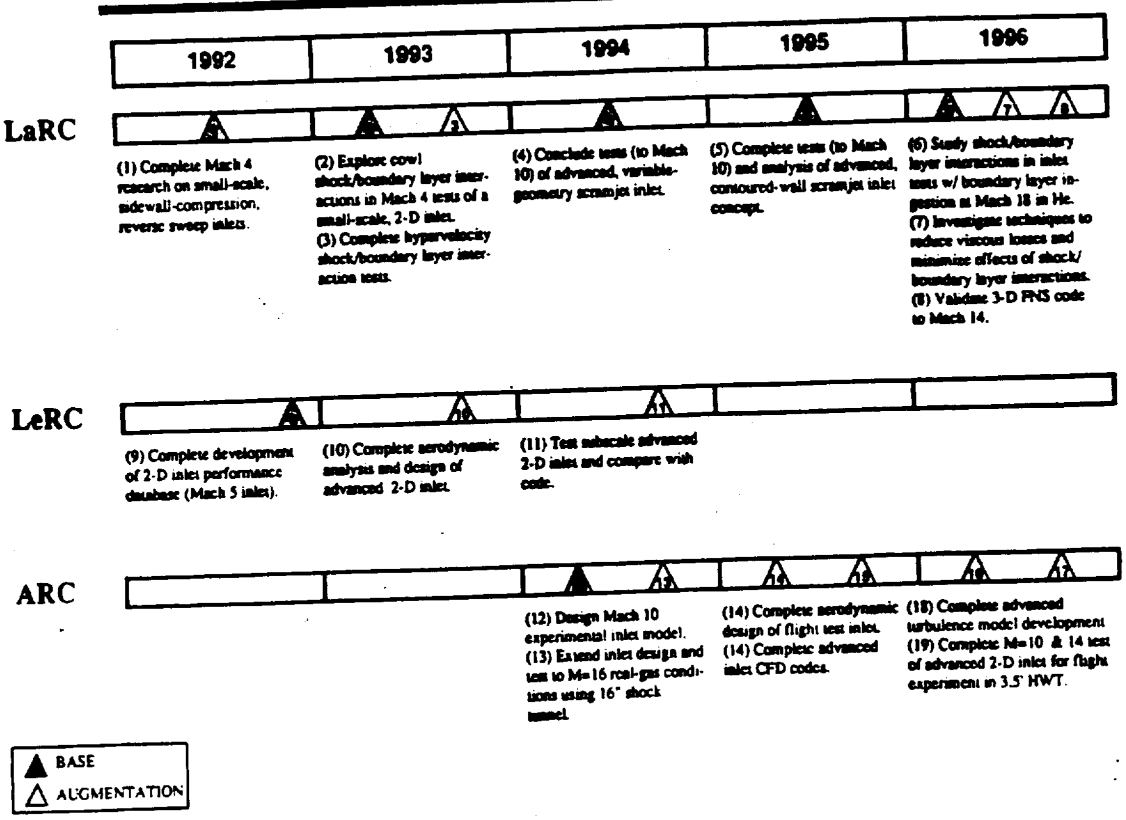
PROPULSION SYSTEMS STUDIES



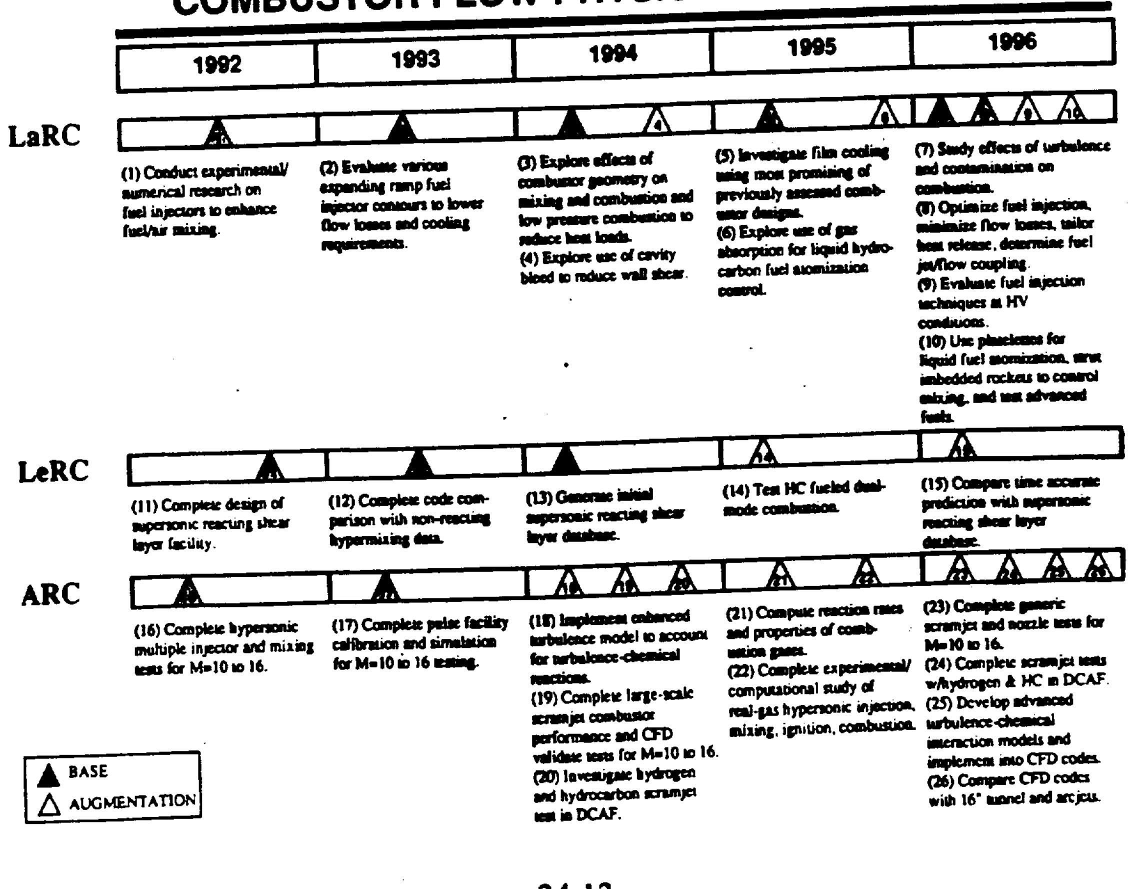
▲ BASE
△ AUGMENTATION

* RN money through RJ (Larry Hunt's work)

INLET FLOW PHYSICS AND DESIGN



COMBUSTOR FLOW PHYSICS AND DESIGN



NOZZLE FLOW PHYSICS AND DESIGN

	1992	1993	1994	1995	1996
LaRC	(1) Evaluate entrance profile effects on nozzle performance in direct-connect (M=7) & subscale engine tests (M=6).	(2) Numerically assess flight M=8 nozzle performance with and without film cooling. (3) Optimize nozzle for M=17 HYPULSE combustor & numerically test time-equivalent M=10-20 nozzles.	(4) Assess entrance profile effects on nozzle performance in subscale parametric engine tests (M=4.7-8). (5) Complete numerical nozzle optimization studies to minimize divergence losses.	(6) Complete generic nozzle design optimization over complete parameter space.	(7) Explore coupling between mixing & combustion & resultant inflow effects on nozzle performance. Study nozzle kinetics. (8) Measure thrust in M=13, 17, 20 combustor-nozzle test.
LeRC	(9) Develop Mach 4-7+ nozzle database.	(10) Develop CFD codes with improved physics and chemistry.	(11) Test SERN nozzle/afterbody for Mach 4-7+ vehicles.		
ARC	(12) Complete powered slot-nozzle 3.5' HWT tests for CFD validation to M=10. (13) Complete nozzle kinetics studies at M=10-16 for CFD validation.		(14) Complete shock tube/flow expansion measurements of H2-O2 rates.		

▲ BASE
△ AUGMENTATION

PROPULSION FLOWPATH TECHNOLOGY

	1992	1993	1994	1995	1996
LaRC	(1) Resolve primary scramjet operability/ performance problems (M=3.5-6) during tests of H2, subscale, parametric scramjet.	(2) Initial H2-fuel, subscale engine tests of parametric scramjet (M=4.7-8) & an advanced subscale scramjet (M=3.5-6).	(3) Complete H2-fuel, subscale engine tests of the parametric scramjet (M=4.7-8) & the advanced, subscale scramjet (M=3.5-6).	(4) Complete M=4.7-8 tests of the advanced subscale scramjet. (5) Investigate operation of detonation scramjet at HV speeds in HYPULSE. (6) Assess performance of subscale, HC scramjet (M=3.5-6) in CHSTF.	(7) Test 2nd generation subscale, advanced scramjet (M=3.5-8). (8) Investigate diffusive burning scramjet in HYPULSE. (9) Test large scale, advanced scramjet in 8' HTT. (10) Test large scale HC scramjet in 8' HTT.
LeRC	(11) Demonstrate closed-loop control on GBE.	(12) Demonstrate ramjet-to-scramjet transition control on GBE. (13) Define critical component technologies and demonstrate thermal management for HC fueled engines.		(14) Demonstrate noise-to-tail optimized components.	(15) Direct connect test of HC engine in PSL-4.
ARC			(16) Complete shock impingement heating and film cooling large-scale combustor studies for M=10-16. (17) Investigate shock impingement heating and film cooling in arcjet facility. (18) Develop and validate coupled inlet-combustor-nozzle code.	(19) Computationally demonstrate inlet unstart with boundary layer bleed control. (20) Assess concept of flowpath flight experiment. (21) Test wave enhanced combustion concept (arcjet).	(22) Complete study of two-phase shock impingement/ cooling phenomena.

▲ BASE
△ AUGMENTATION

EXPERIMENTAL/COMPUTATIONAL CAPABILITY

	1992	1993	1994	1995	1996
LaRC	(1) Initiate technical evaluation of a large-scale Free-Piston Driven Expansion Tunnel (FPDET). (2) Demonstrate PLIF in HYPULSE, activate 30Hz CARS, develop MIE scattering technique for reacted silane. (3) Complete development of basic nozzle CFD analysis code & nozzle chemistry package.	(4) Obtain HYPULSE calibration data at flight unit Reynolds No. using free-piston driver. Complete technical eval. of FPDET concept. (5) Demonstrate PLIF temp. mapping in HYPULSE & demo. the relief technique in DCSCTF. (6) Enhance inlet/nozzle analysis codes with improved algorithms, turbulence models and dynamic grid generation.	(7) Dedvelop pre-PER and cost estimate for FPDET. Prepare CoF process documentation/PER for FPDET. (8) Install HC fuel system in DCSCTF. (9) Obtain planar temperature PLIF using OH in DCSCTF & direct model force measurement in HYPULSE. (10) Develop 3-D CFD inlet/nozzle design optimization procedure.	(11) Begin final design of FPDET. (12) Complete GPV studies using silane. (13) Complete development of large eddy simulation code for modeling high-speed reacting flows. (14) Complete validation of CFD predicted inlet performance, thrust & shear forces in nozzles simulating flight M=13-20.	(15) Begin construction of FPDET. (16) Evaluate diode lasers for measurement of density and velocity. (17) Continue development of diagnostics for pulse facility. (18) Develop turbulence combustion models for Reynolds averaged Navier Stokes combustion code. (19) Validate inlet/nozzle codes for inlet unstart, module-module interactions and with flight data.
LeRC	(20) Validate RPLUS with hyper-mixing nonreacting data. (21) Compare enhanced RPLUS code with GBE.	(22) Design non-interference air mass flow measurements. (23) Incorporate PDF turbulence model in CFD code.	(24) HTF reactivation.	(25) PDF modeling validated in CFD code.	(26) Demonstrate prototype air mass flow measurement.
ARC		(27) Develop/install optical diagnostics in pulse and arcjet facilities. (28) Develop/validate efficient inlet code for flight test development.	(29) Develop/implement strategies for code efficiency, accuracy, robustness. (30) Develop CFD codes for arcjet flow modeling.	(31) Experimentally quantify flowfield from arcjet facility. (32) Install laser diagnostics in arcjet facility for combustion measurements. (33) Validate CFD code for arcjet modeling.	

▲ BASE
△ AUGMENTATION

HYPERSONIC PROPULSION DIRECTION

The base program will concentrate on tool building, and basic research in the following areas :

<u>Flight Research -</u> Provide appropriate ground tests and analysis to support experiment design and calibration efforts.

<u>Hypervelocity Research -</u> Conduct basic research studies for optimizing high-end performance, and explore specific high payoff approaches for application to advanced SSTO vehicles and the second stage of TSTO vehicles.

<u>Hydrocarbon Research</u> - Address basic research into supersonic combustion and piloting techniques unique to hydrocarbon fuels, and support integrated low-speed/high-speed propulsion system studies.