A Pre-Mixed Shock-Induced-Combustion Approach to Inlet and Combustor Design for Hypersonic Applications

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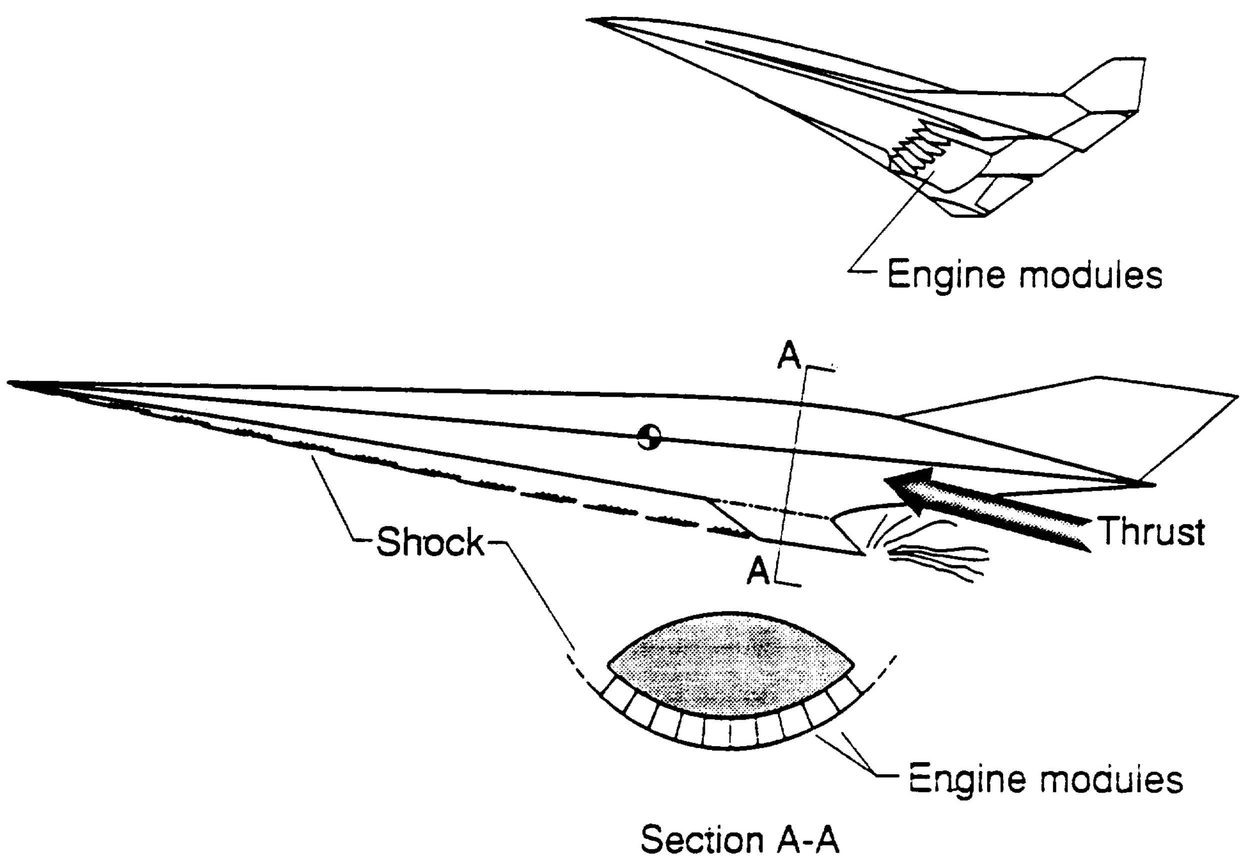
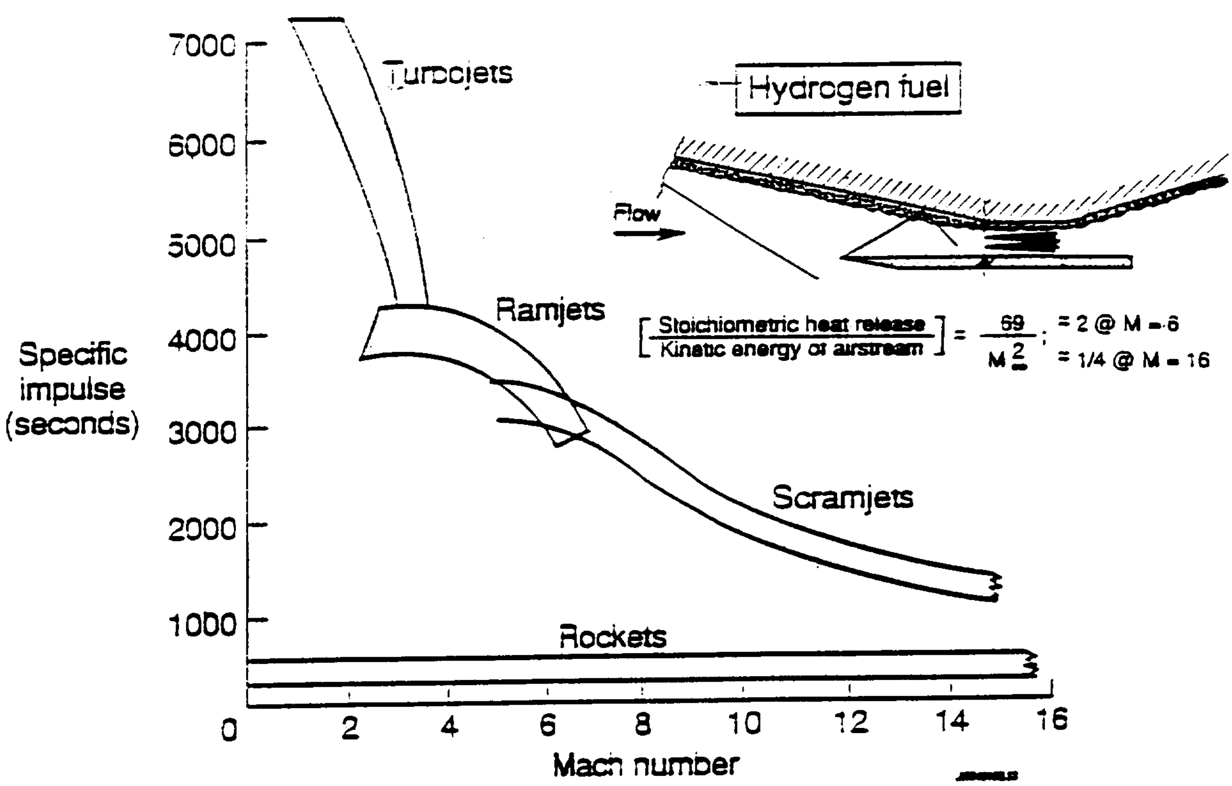
HYPERSONIC ENGINE/AIRFRAME INTEGRATION

The need for efficient access to space has created interest in airbreathing propulsion as a means of achieving that goal. The NASP program explored a single-stage-to-orbit approach which could require scramjet airbreathing propulsion out to Mach 16 to 20. Recent interest in global access could require hypersonic cruise engines operating efficiently in the Mach 10 to 12 speed range. A common requirement of both of these types of propulsion systems is that they would have to be fully integrated with the aero configuration so that the forebody becomes a part of the external compression inlet and the nozzle expansion is completed on the vehicle aftbody.



PROPULSIVE PERFORMANCE vs MACH NUMBER

Propulsive performance for the scramjet is reduced at higher Mach numbers, with the degree of reduced performance a strong function of flowpath efficiency. The ratio of the energy added to the flowpath through combustion of the fuel relative to the kinetic energy of the airstream becomes much smaller at higher Mach numbers so that losses in the flowpath results in a much larger loss in propulsive performance as Mach number is increased



Major Thrust Loss Mechanisms

Hypervelocity Scramjet Propulsion Flow Path

Major loss mechanisms are outlined in this figure, and loss mitigation/thrust enhancement approaches are suggested. A variation of the oblique detonation wave engine (ODWE), which has the potential for reducing combustor size, is the subject that I will discuss in this paper.

Forebody

- Wave drag
- Friction drag
- Heat transfer

Inlet

- Wave drag
- Friction drag
- Heat transfer (bleed drag not a problem, air too-hot to take aboard/bleed)

Combustor

- Heat addition
- Mixing incl. losses due to mixing ennancement techniques
- Wave drag/shocks
- Skin friction
- Heat transfer
- Incomplete combustion
- Fuel inj. angularity

Nozzle/afterbody

- Divergence
- Disassociation
- Thrust vectoring for lift/trim
- Skin friction
- Heat transfer, incl. catalysity
- Wave drag/shocks

Major Loss Mitigation/Thrust Enhancement Approaches

Forebody

- Transition delay
- *Thin leading edge

Inlet

- Separation control
- Favorable wave interference
- *Transition delay
- *Multiple (weak) shocks

Combustor

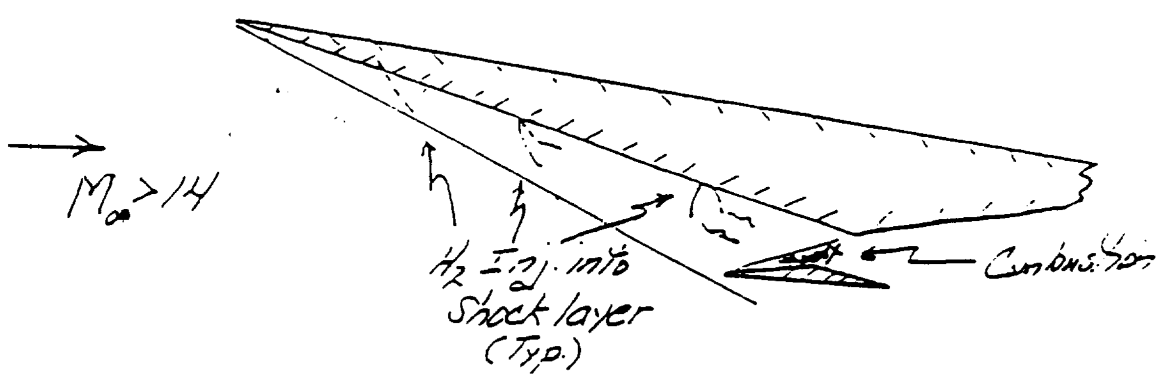
- *ODWE (red. combustor size)
- *Cavities with mass addition
- *Low loss mixing enhancement, e.g. turb. "destab."
- *Fuel heating/nearly parallel inj.

Nozzle/afterbody

- mixing with coolant inj./red T
- *Metal oxide catalysts
- *Relaminarization
- *Optimized for non-uniform inflow, trim

"DETONATION WAVE"/Shock-Enhanced Combustion

The ODW engine mode of operation is to inject fuel from the forebody, mix with air within the shock layer, and detonate when crossing a strong shock wave formed by the engine cowl. The benefits derived from this concept would be a reduced combustor size reducing weight, friction, and heat load. Three fundamental problems are noted. The strong shock wave associated with the detonation wave will cause reduced inlet performance and increased combustor dissociation. Fueling will be very difficult from only one surface, having to cross the shock layer without mixing across the shock and thus causing fuel to pass outside of the engine. The third problem involves developing a geometry that would operate over a wide speed range.

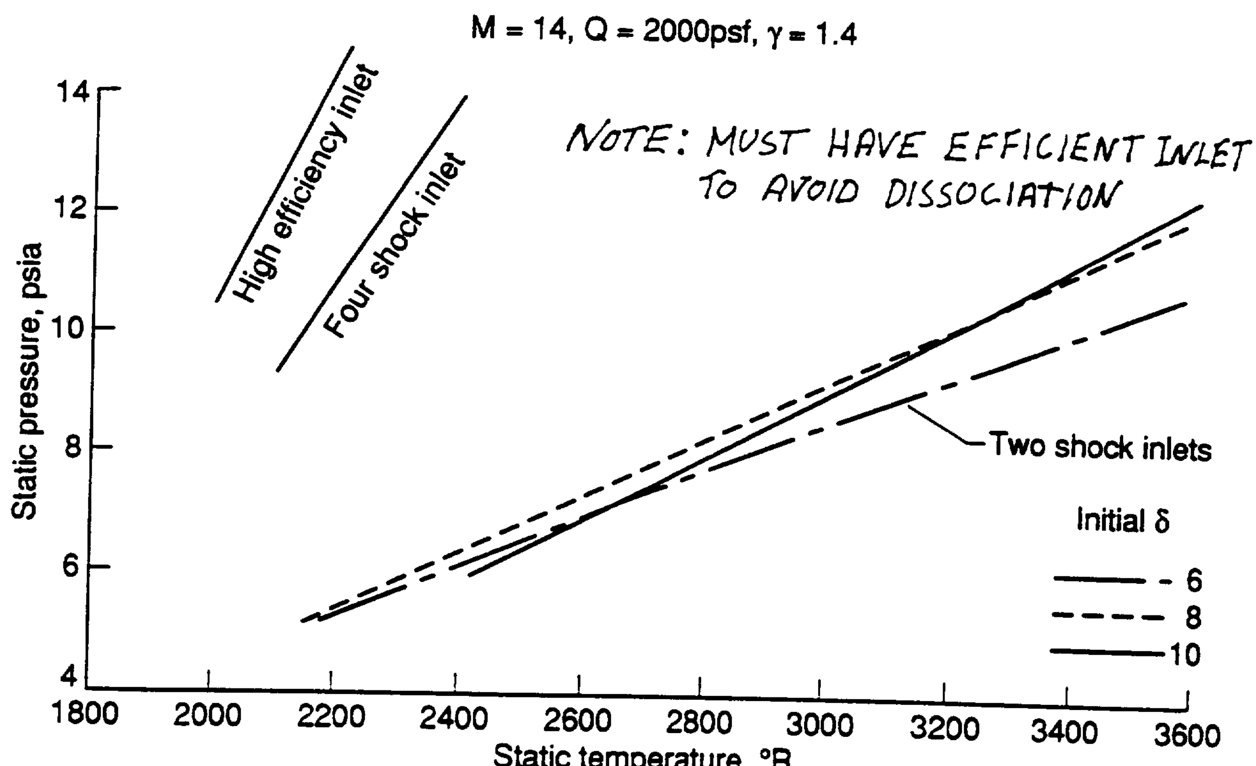


PROBLEMS:

- Strong shock waves; low inlet efficiency and high combustor dissociation
- Abstract fueling concept requiring advanced approaches
- High Mach engine, requires two-stage-to-orbit vehicle

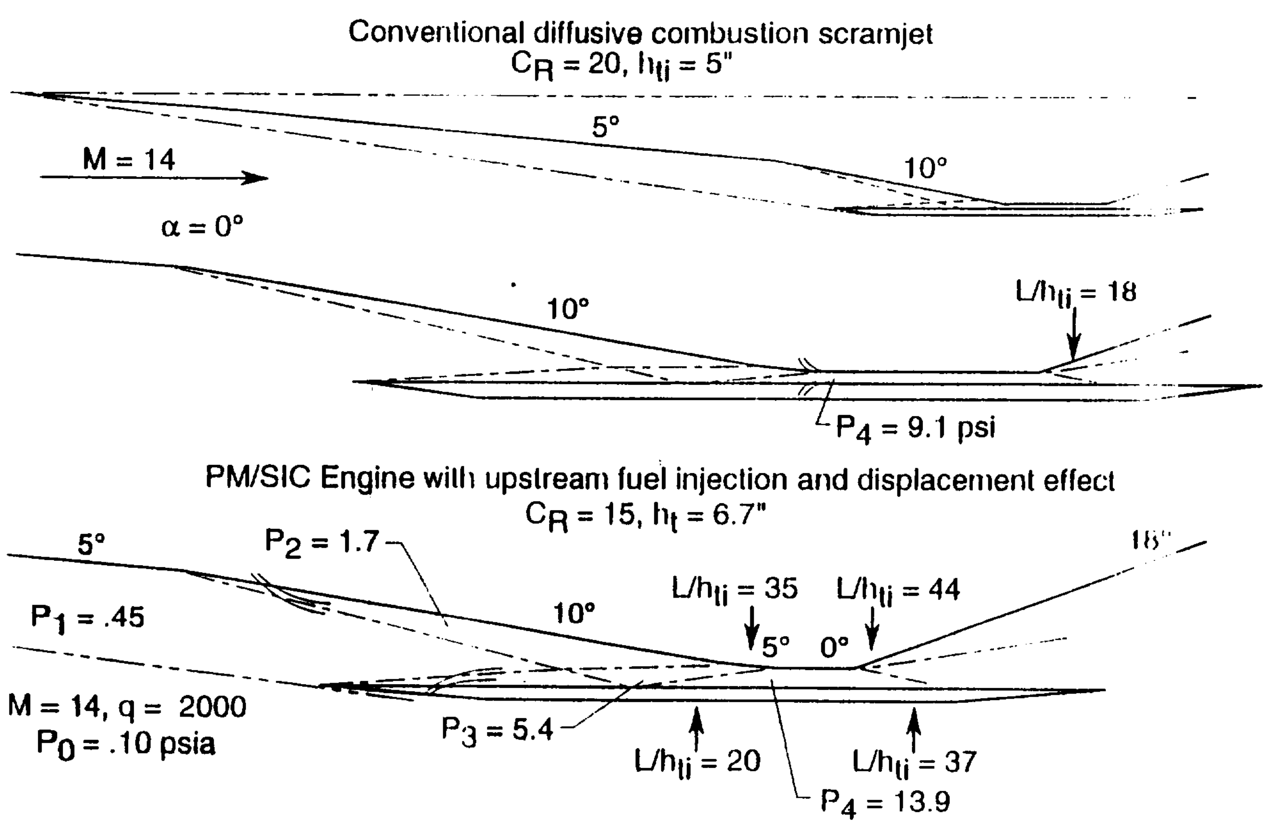
STATIC CONDITIONS AT INLET THROAT

This figure illustrates the difference between accomplishing the inlet compression process with weak shock waves as opposed to strong shock waves. By compressing the inlet flow to a given static pressure level with weak shock waves the total pressure recovery would be higher and, perhaps even more important, static temperature would be significantly lower. Dissociation of the combustion products is a strong function of static temperature and, since the nozzle expansion process is basically frozen, represents a loss in the scramjet cycle performance.



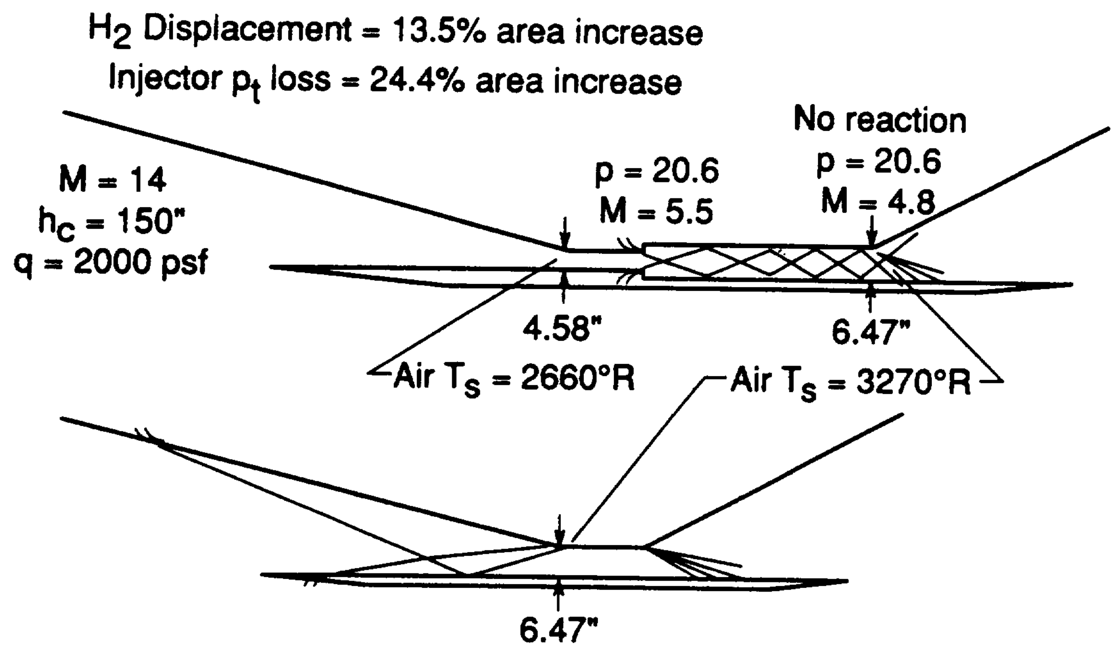
BASIS FOR PRE-MIXED SHOCK-INDUCED COMBUSTION ENGINE DESIGN

The basis for the proposed engine cycle is thus a conventional external/internal inlet compression process made up of weak shock waves. Fuel injectors that would normally be located aft of the inlet throat are moved forward just downstream of the origin of the shock waves entering the inlet. Static pressure and temperature is relatively low at this point, and combustion occurs as the fuel/air mixture passes through the weak oblique shock waves that raise static pressure and temperature to a level that will allow ignition and reaction. The combustor is not entirely eliminated, and must be long enough for ignition and reaction to be completed.



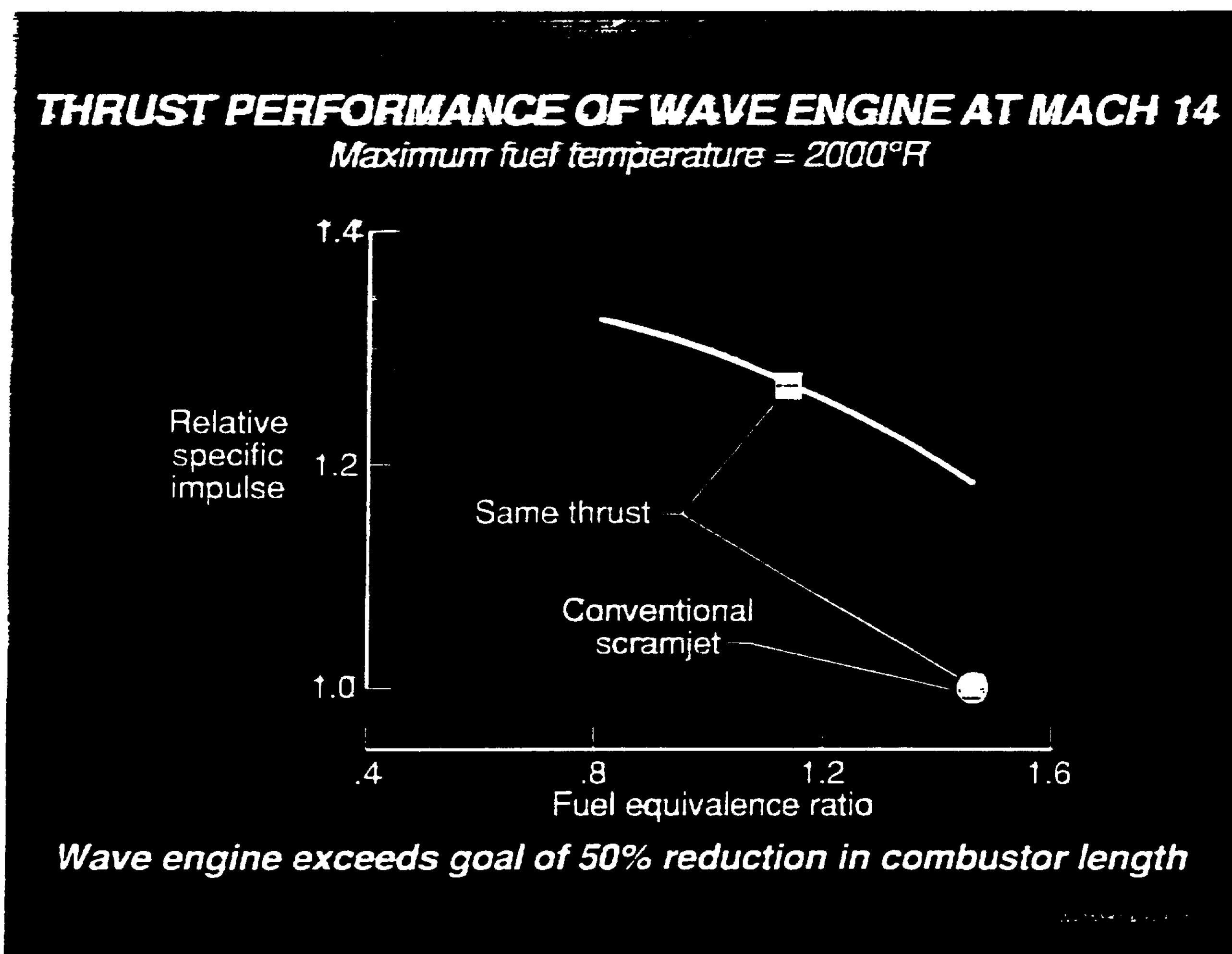
IMPACT OF FUEL INJECTION ON DC & PM/SIC ENGINES

An additional benefit of upstream fuel injection is illustrated in this figure. In a conventional diffusive combustion engine air is compressed by the inlet to a given static pressure and then the fuel is added. To avoid a large pressure rise at the fuel injectors, which would result from the volumetric displacement of the fuel and the resulting shock waves, the combustor area is typically increased. For this example, to maintain the same static pressure before reaction takes place, the combustor area would need to be increased by about 40%. With upstream fuel injection fuel displacement and shock waves resulting from the injection of fuel add to the compression process that occurs within the inlet so that the inlet throat is larger and the physical inlet contraction ratio is reduced. If shock wave losses are the same in both cases the inlet throat for the upstream fuel injection case would be the same size as the increased combustor area of the first case.



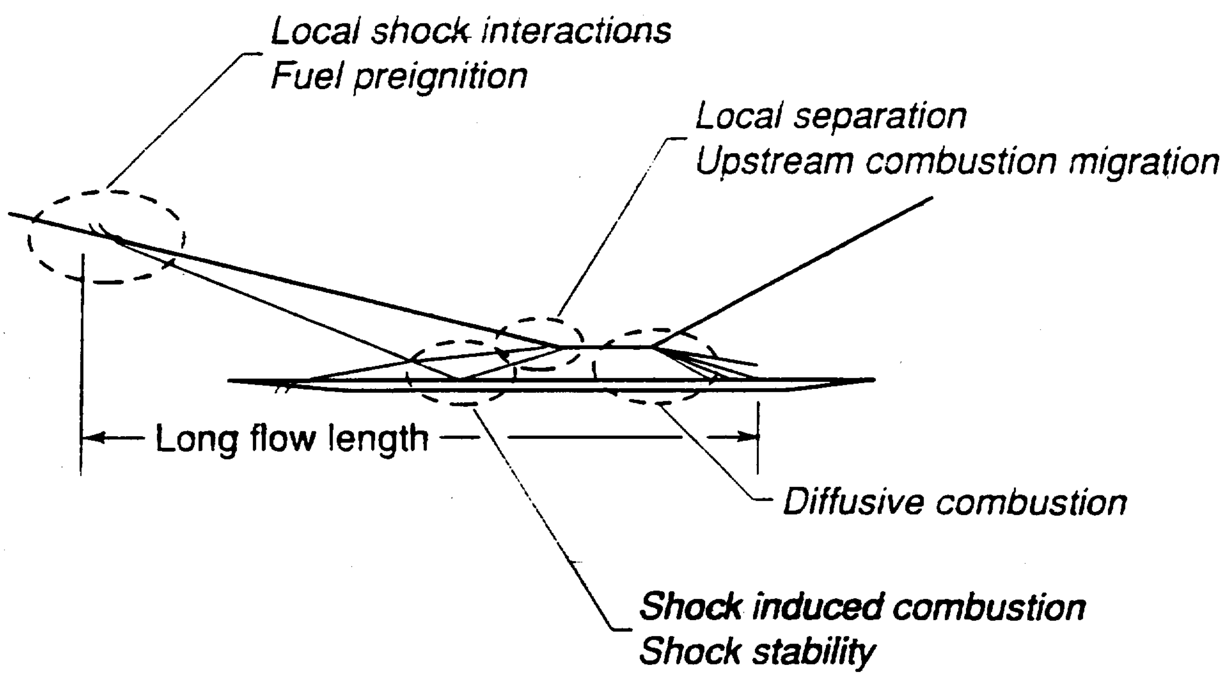
PERFORMANCE AT MACH 14

The schematic from the previous figure was used as the basis for a comparison of the cycle performance of these two engine concepts at Mach 14. The conventional scramjet operates at a fuel equivalence ratio of 1.5 to achieve a heat balance with a fuel temperature of 2000R. Because of the reduced combustor length the "wave engine" that utilizes upstream fuel injection achieves a heat balance with a 2000R fuel temperature at a fuel equivalence ratio of .8 and, because of reduced wall friction, a considerable increase in specific impulse. At the same thrust level a 25% increase in specific impulse is realized. This performance is better than earlier estimates for the ODWE which would have a shorter combustor but would have a strong shock wave in the form of a detonation wave and resulting high dissociation losses.



FLOW PHYSICS OF PM/SIC ENGINE

The promise of higher performance illustrated in the previous figures can only be realized by solving problems associated with unique flow physics of this engine concept. Static pressure and temperature is low at the point of fuel injection, but the fuel must pass through a very hot boundary layer. Analysis has shown this to be a problem so that the challenge is to devise a fuel injector design that will avoid preignition while providing good mixing between the air and fuel. Stability of the weak combustion inducing shock wave is also a concern. and a strong shock wave must be avoided to reduce dissociation during the combustion process. In addition, flow separations due to the pressure rise on the inlet shoulder where a thick boundary layer exists must be avoided. Note that their is room for continued diffusive combustion in the lower region of the combustor.



Basic Flow Physics Research Program

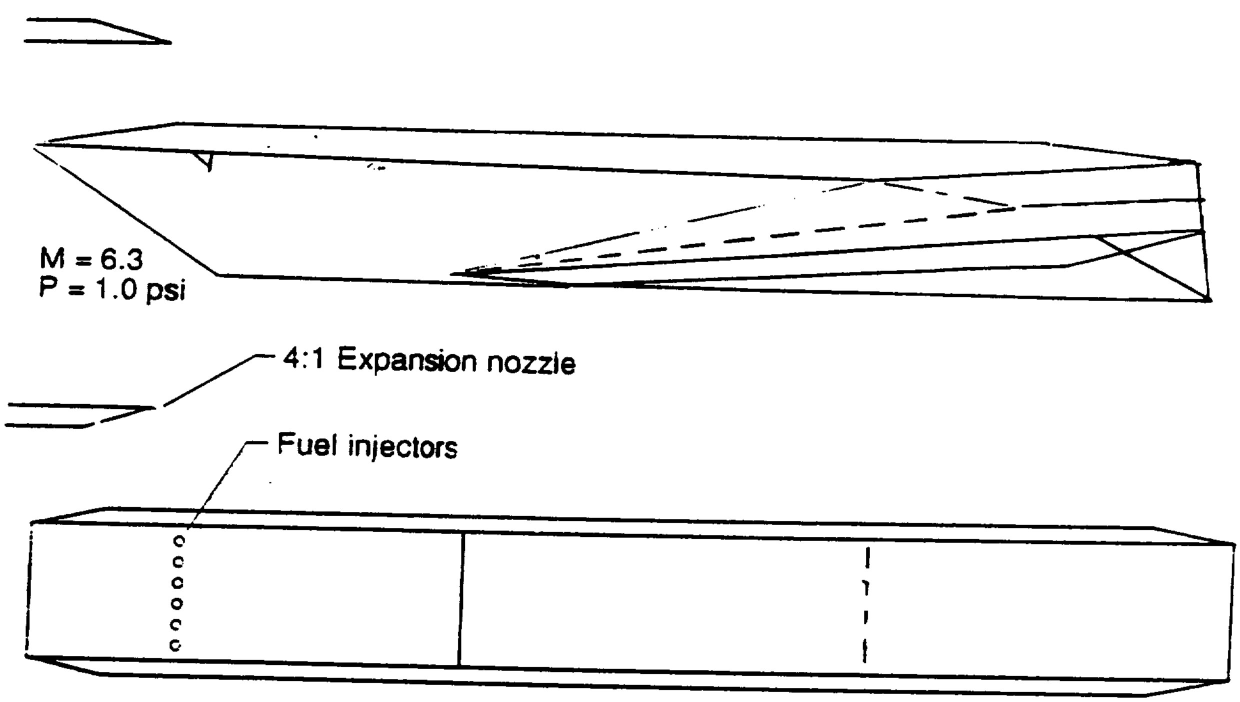
A research program is currently underway to address the basic flow physics associated with upstream fuel injection. A computational effort will be followed by an experimental effort. The experimental effort will be guided by the computations and will also be used to verify the computational results

- Computational
  - Preignition
  - Fuel/air mixing
  - Combustion shock stability
- Experimental
  - HYPULSE @ M = 14
  - AHSTF @ M = 8 using NASP Model

PM/SIC MODEL FOR HYPULSE

The planned experimental program includes a relatively simple model for the HYPULSE expansion tunnel consisting of a flat plate and a shock generator held together by flat sidewalls. A 4:1 area ratio nozzle attached to the HYPULSE tunnel expands the flow to the conditions that would be present at the upstream fuel injector location.

A near term test is also being planned for the Arc Heated Scramjet Test Facility using an available engine model which has been tested extensively in recent years. Adding upstream fuel injection to this model will allow direct comparison with a conventional scramjet operation at Mach 7 and 8.



SUMMARY

A higher level of inlet/combustor integration through injecting the fuel in the inlet, upstream of the combustor, has the potential for increasing flowpath efficiency at hypersonic speeds through:

- o reducing combustor length; reduced friction and heat load
- o reducing inlet contraction ratio; reduced drag and variable geometry

CHALLENGE

- o Develop fuel injectors that will:
  - o avoid preignition that would lead to increased inlet drag
  - o result in efficient mixing to minimize combustor length
- o Understand interactions between the weak shock wave, combustion, and the thick forebody boundary layer

PLANS

- o Continue CFD analysis of upstream fuel injection and shock induced combustion in the presence of a thick boundary layer
- o Conduct experiments to verify computational analysis and to assess overall effect of PM/SIC on engine performance at Mach 7 +