THE USE OF STEADY AND PULSED DETONATIONS FOR PROPULSION SYSTEMS

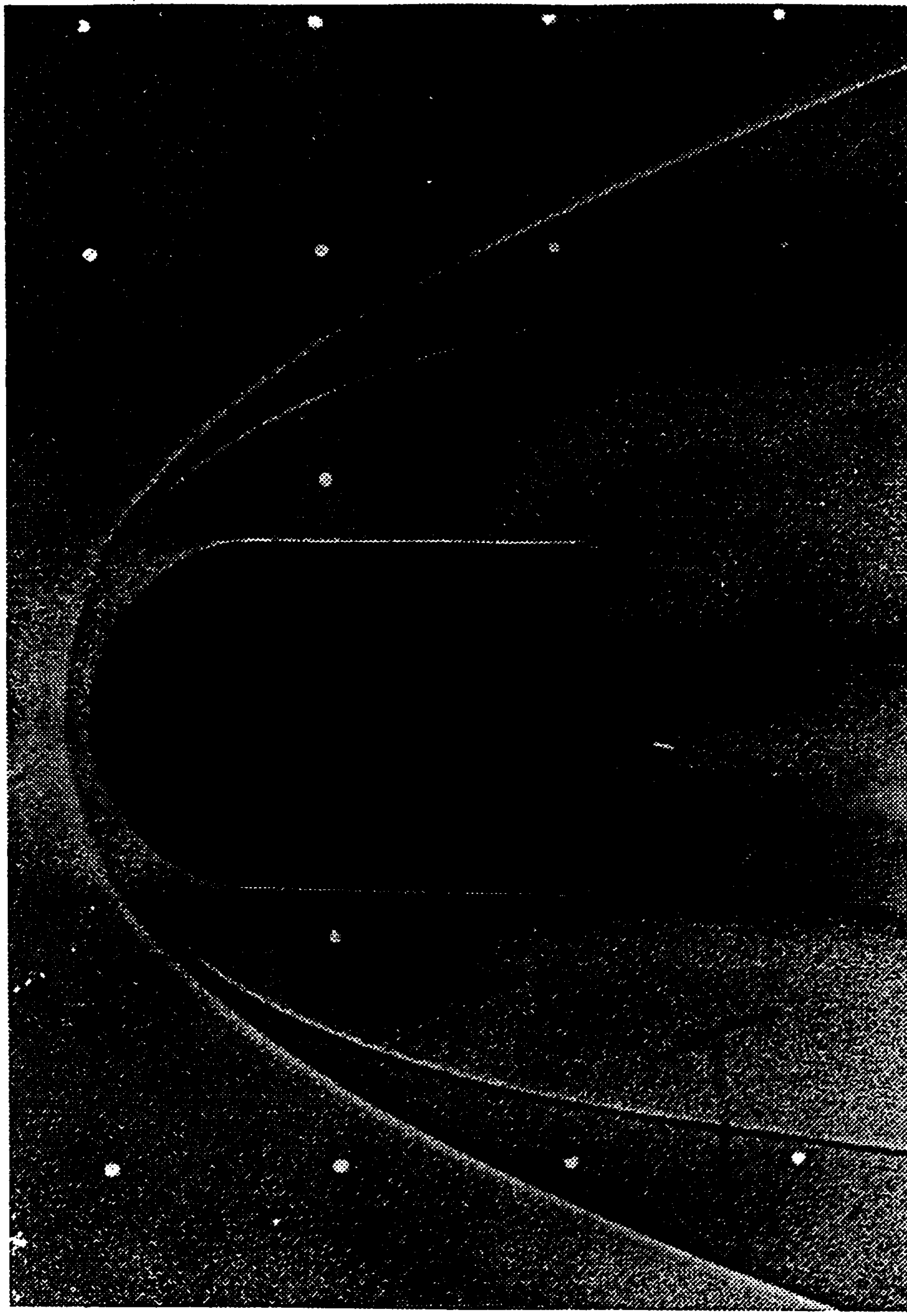
Henry G. Adelman, Gene P. Menees
Jean-Luc Cambier and Jeffrey V. Bowles

NASA-Ames Research Center

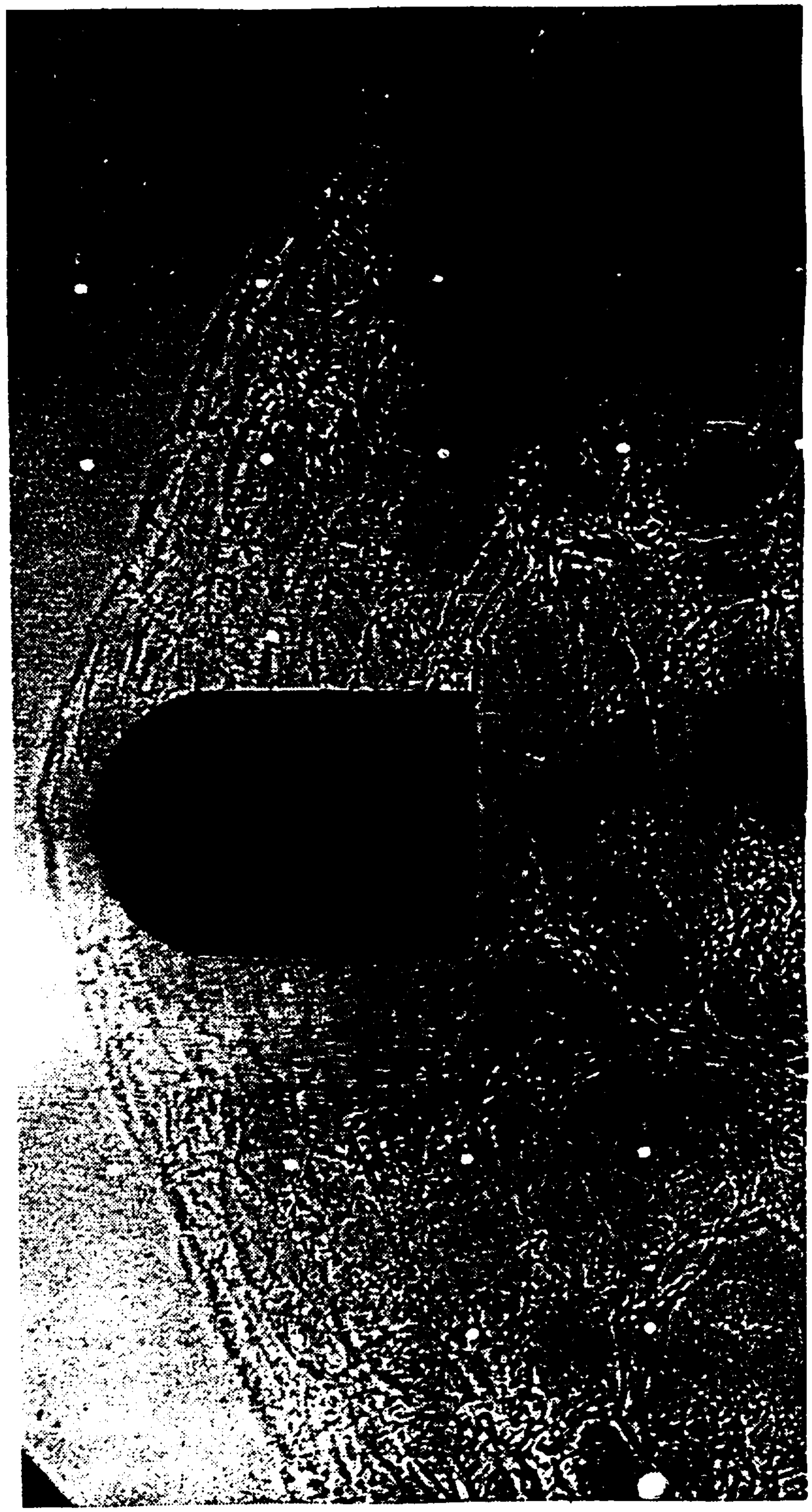
Presented to the Workshop on Advanced Transportation Systems

NASA-Langley Research Center

September 26-28, 1995



A decoupled shock and flame front created by a hypersonic body in a hydrogen-oxygen mixture. The wave combustor experiment will utilize a stationary wedge to generate the oblique waves.



A detonation wave in a hydrogen-oxygen mixture. The slightly higher projectile speed causes a coupling between the flame front and the shock which steepens into a detonation wave.

OBJECTIVES OF ODWE CONCEPT STUDIES

- DEMONSTRATE THE FEASABILITY OF THE OBLIQUE DETONATION WAVE ENGINE (ODWE) FOR HYPERSONIC PROPULSION

- DEMONSTRATE THE EXISTANCE AND STABILITY OF AN OBLIQUE DETONATION WAVE IN HYPERSONIC WIND TUNNELS

- DEVELOP ENGINEERING CODES WHICH WILL PREDICT THE PERFORMANCE CHARACTERISTICS OF THE ODWE INCLUDING SPECIFIC IMPULSE AND THRUST COEFFICIENTS FOR VARIOUS OPERATING CONDITIONS

- DEVELOP MULTI-DIMENSIONAL COMPUTER CODES WHICH CAN MODEL ALL ASPECTS OF THE ODWE INCLUDING FUEL INJECTION, MIXING, IGNITION, COMBUSTION AND EXPANSION WITH FULLY DETAILED CHEMICAL KINETICS AND TURBULENCE MODELS

- VALIDATE THE CODES WITH EXPERIMENTAL DATA AND USE THE SIMULATIONS TO PREDICT THE ODWE PERFORMANCE FOR CONDITIONS NOT EASILY OBTAINED IN WIND TUNNELS

OBJECTIVES OF TRANS-ATMOSPHERIC VEHICLE MISSION STUDIES

- COMPARE THE PERFORMANCE OF AN OBLIQUE DETONATION WAVE ENGINE (ODWE) POWERED TRANS-ATMOSPHERIC VEHICLE (TAV) TO A SCRAMJET POWERED TAV

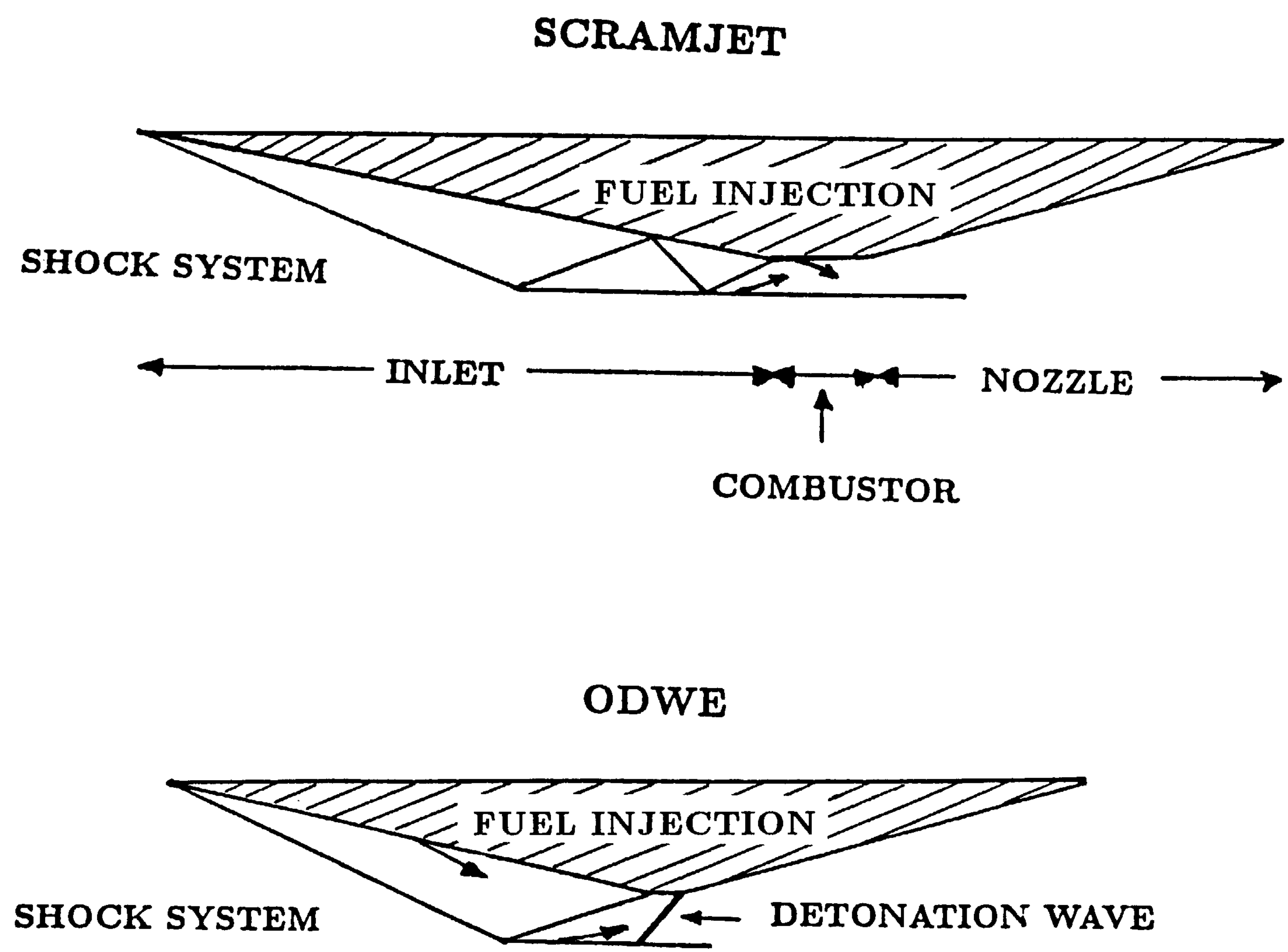
  - DEVELOP A ONE-DIMENSIONAL CODE FOR THE INLET, COMBUSTOR AND NOZZLE TO PREDICT THE PERFORMANCE OF THE ODWE AND SCRAMJET ENGINES

  - DESIGN AN OPTIMAL VEHICLE FOR BOTH AIR-BREATHING PROPULSION SYSTEMS USING A SYNTHESIS CODE FOR AERODYNAMICS, AERO-THERMAL HEATING, STRUCTURAL DESIGN, VOLUME AND WEIGHTS

  - OPTIMIZE TRAJECTORY FOR BOTH VEHICLES TO PLACE A 15,000 POUND PAYLOAD INTO A 120 NAUTICAL MILE LOW EARTH ORBIT

  - COMPARE THE PERFORMANCE OF THE ODWE AND SCRAMJET ENGINE OVER THE ENTIRE FLIGHT REGIME

  - COMPARE THE WEIGHTS AND PAYLOAD FRACTIONS FOR VEHICLES USING ODWE OR SCRAMJET PROPULSION



SCHEMATIC OF SHOCK STRUCTURE FOR SCRAMJET AND ODWE

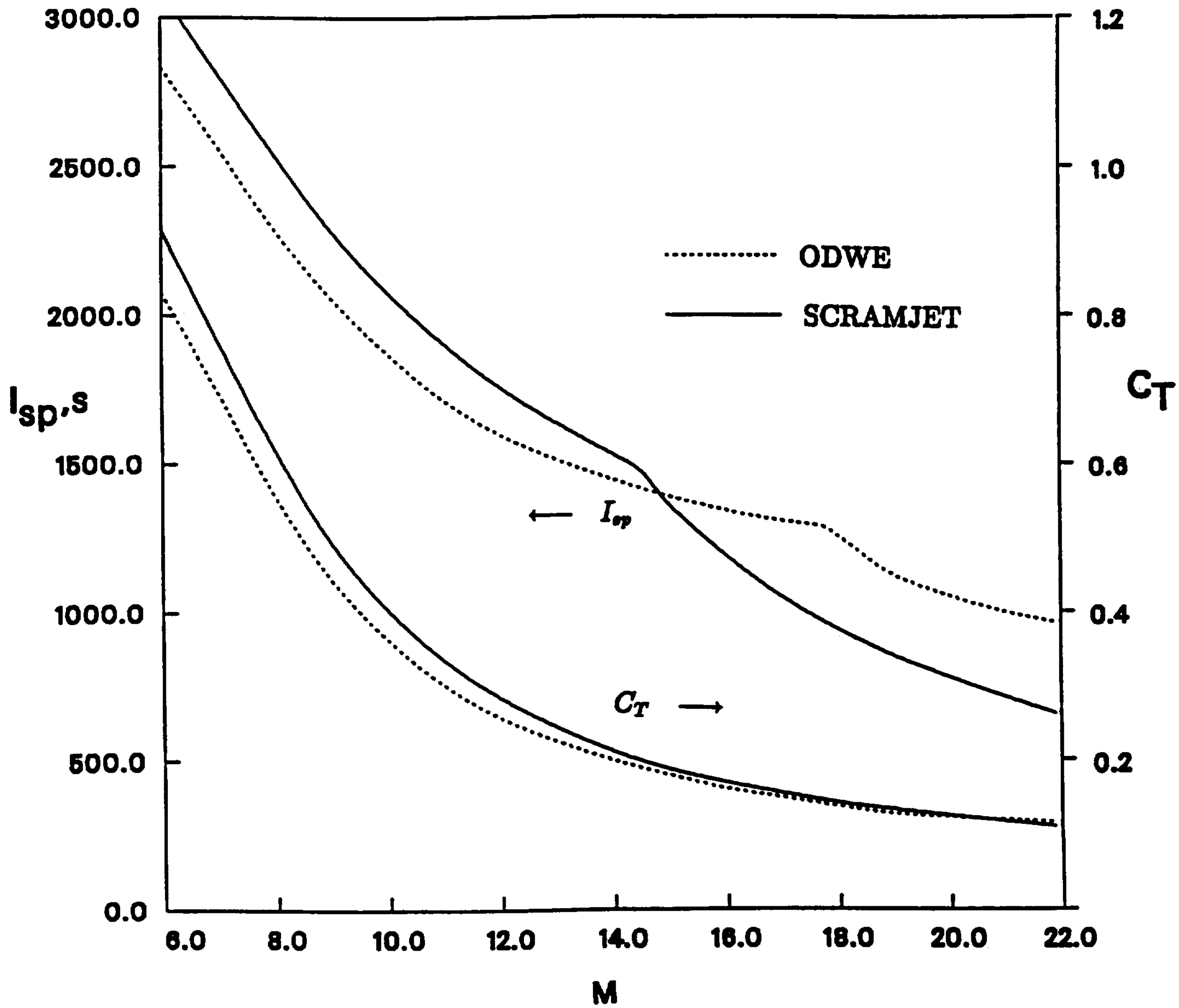


Fig. 4. Comparison of scramjet and ODWE performance characteristic: Shown are I_{sp} and C_T profiles for q=2000 psf, 90% of heat loads carried by fuel and 1100 K fuel temperature limit.

Component weight fraction	q=2000 psf	q=1000 psf
Empty Weight	28.0%	27.1%
Structure	18.4%	18.3%
Propulsion Systems	8.6%	7.8%
Fixed Equipment	1.1%	0.9%
LH_2	51.8%	50.6%
LOX	15.9%	18.8%
Payload	3.3%	2.4%

Table 1: Scramjet vehicle data for fixed payload of 15,000 lbs. Fractions are relative to total take-off weight of 460,512 (623,000) lbs for q=2000 (1000) psf.

Component weight fraction	q=2000 psf	q=1000 psf
Empty Weight	27.9%	
Structure	18.8%	
Propulsion Systems	8.0%	
Fixed Equipment	1.1%	
LH_2	54.8%	
LOX	12.5%	
Payload	3.7%	

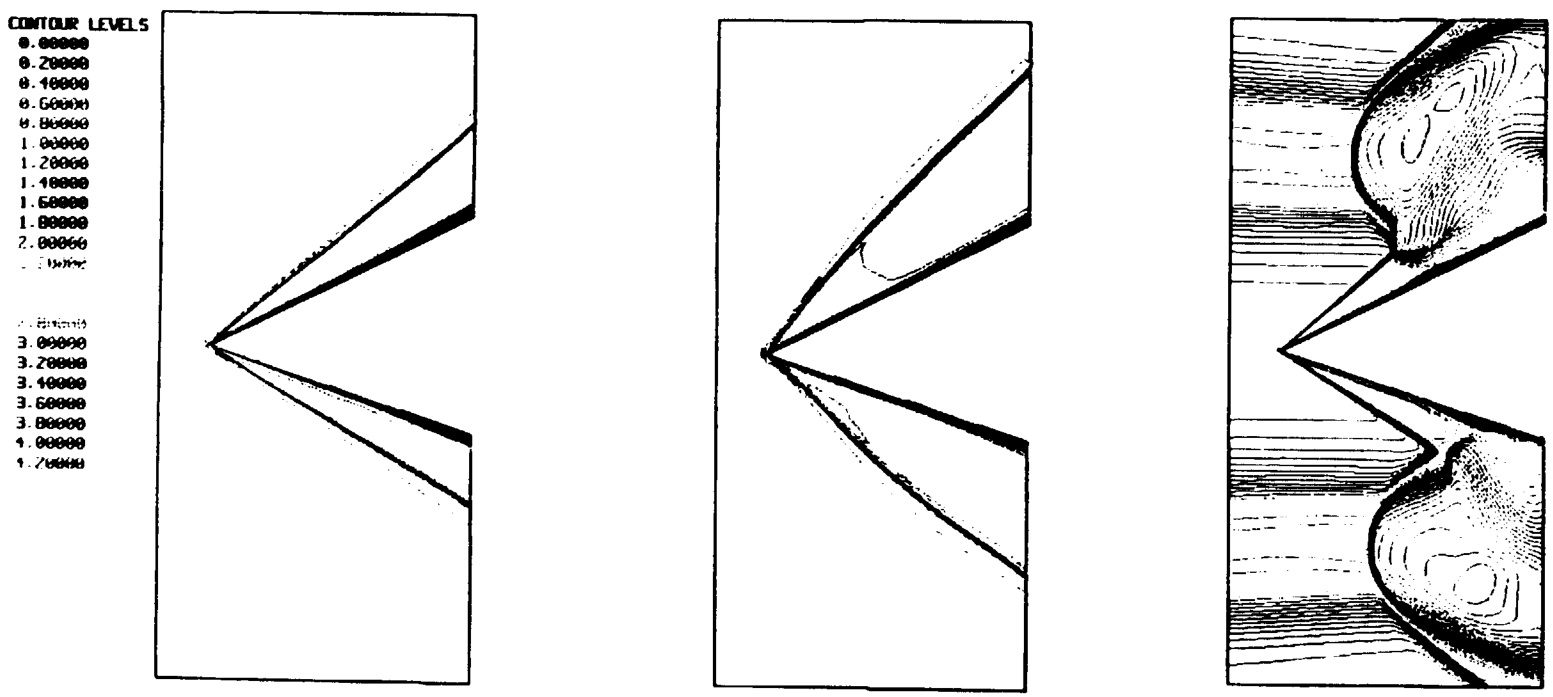
Table 2: ODWE vehicle data for fixed payload of 15,000 lbs. Fractions are relative to total take-off weight of 409,500 () lbs for q=2000 (1000) psf.

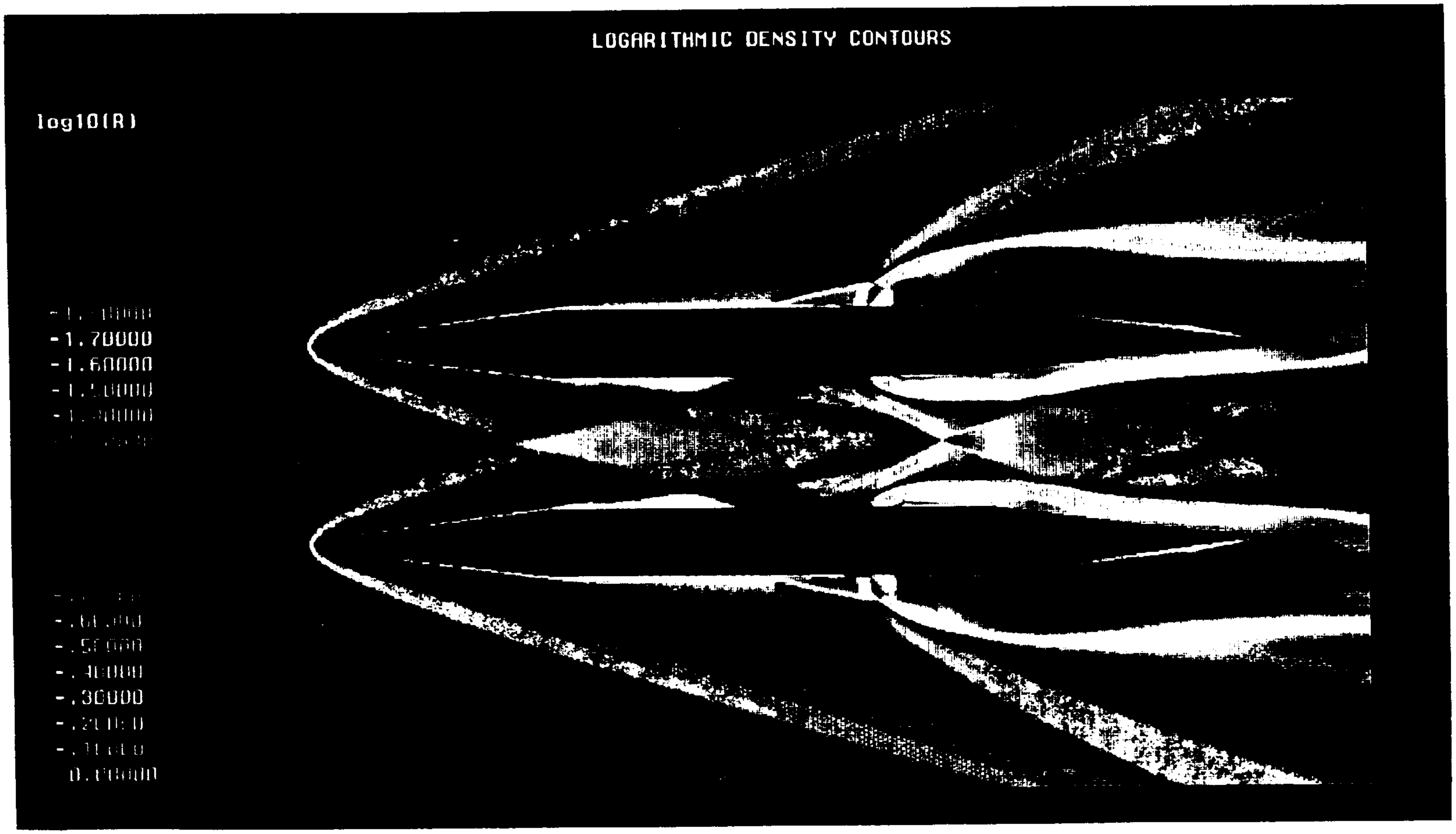
NUMERICAL MODELING OF ODWE

- MULTI-DIMENSIONAL NAVIER-STOKES COMBUSTION CODE FOR DETONATION AND FUEL INJECTION MODELING
  - 2ND ORDER TOTAL VARIATION DIMINISHING (TVD) METHOD USED TO MINIMIZE SHOCK SMEARING AND ELIMINATE OSCILLATIONS.
  - DETAILED CHEMICAL KINETICS ADDED TO MODEL DETONATIONS. OPERATOR SPLITTING COUPLES CHEMICAL REACTIONS TO FLUID MOTION. OVERALL SCHEME IS TIME-ACCURATE.

MACH CONTOURS FOR OBLIQUE DETONATION WAVES
(M_∞ = 4.2, p_∞ = 0.1 atm, T_∞ = 700 °K, H_2 Fuel)

SHOCK WAVES, PREMIXED FUEL, NO COMBUSTION	DETONATION WAVES, PREMIXED FUEL	DETONATION WAVES, STRATIFIED AIR-FUEL MIXTURE





Simulation of fuel injection from two struts in Mach 4.5 flow. The density profiles show the bow shocks and the injection shocks. The green and light blue areas indicate the fuel jets in the wake region.

EXPERIMENTAL INVESTIGATIONS OF THE ODWE CONCEPT

- DEMONSRATE THE EXISTANCE AND STABILITY OF AN OBLIQUE DETONATION WAVE IN A HYPERSONIC WIND TUNNEL

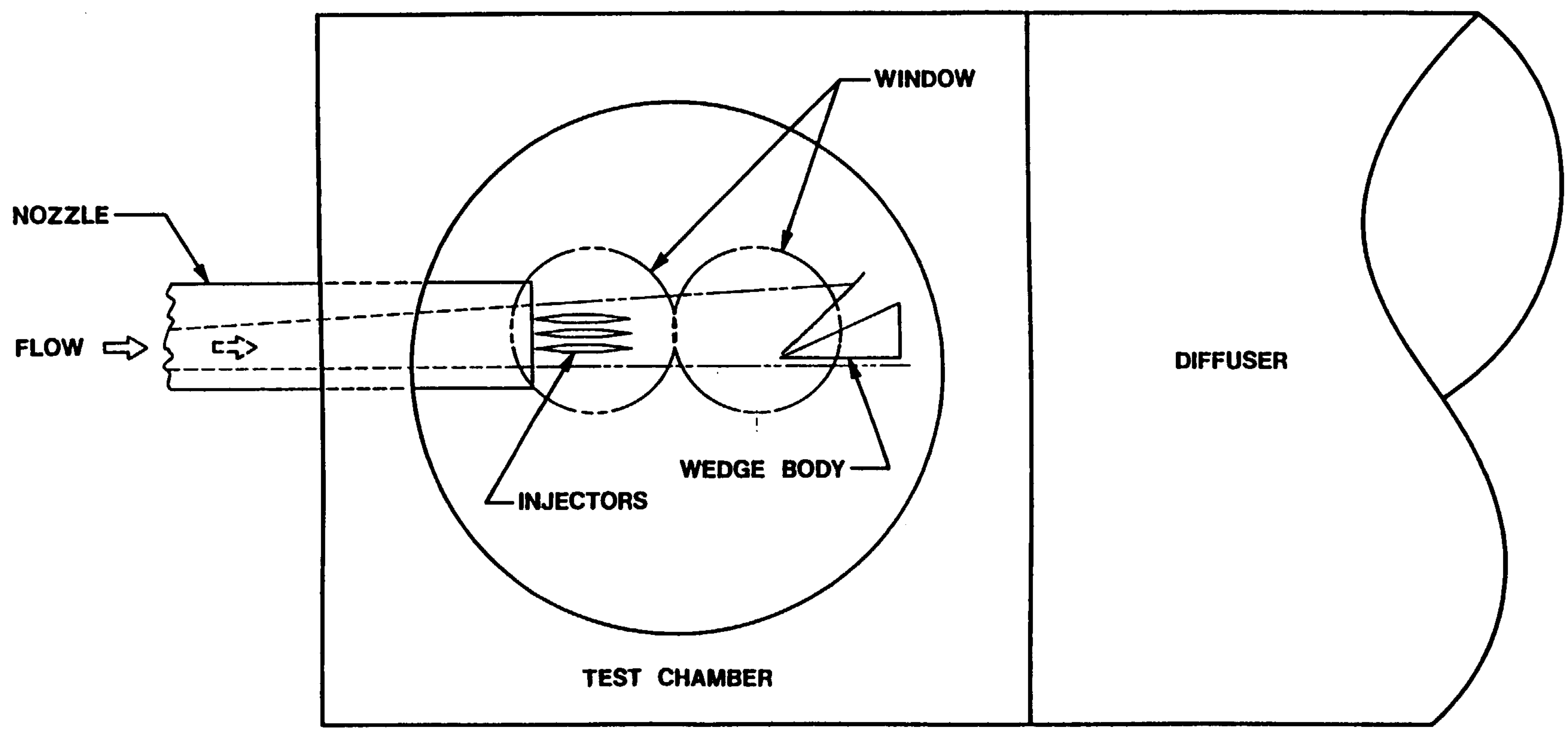
  - EXAMINE THE MIXING CHARACTERISTICS OF VARIOUS FUEL INJECTOR DESIGNS IN WIND TUNNEL WITH ON-LINE GAS SAMPLING AND MASS SPECTROMETRY

  - CREATE AN OBLIQUE DETONATION WAVE IN A 20 MW ARC HEATED WIND TUNNEL USING HYDROGEN FUEL

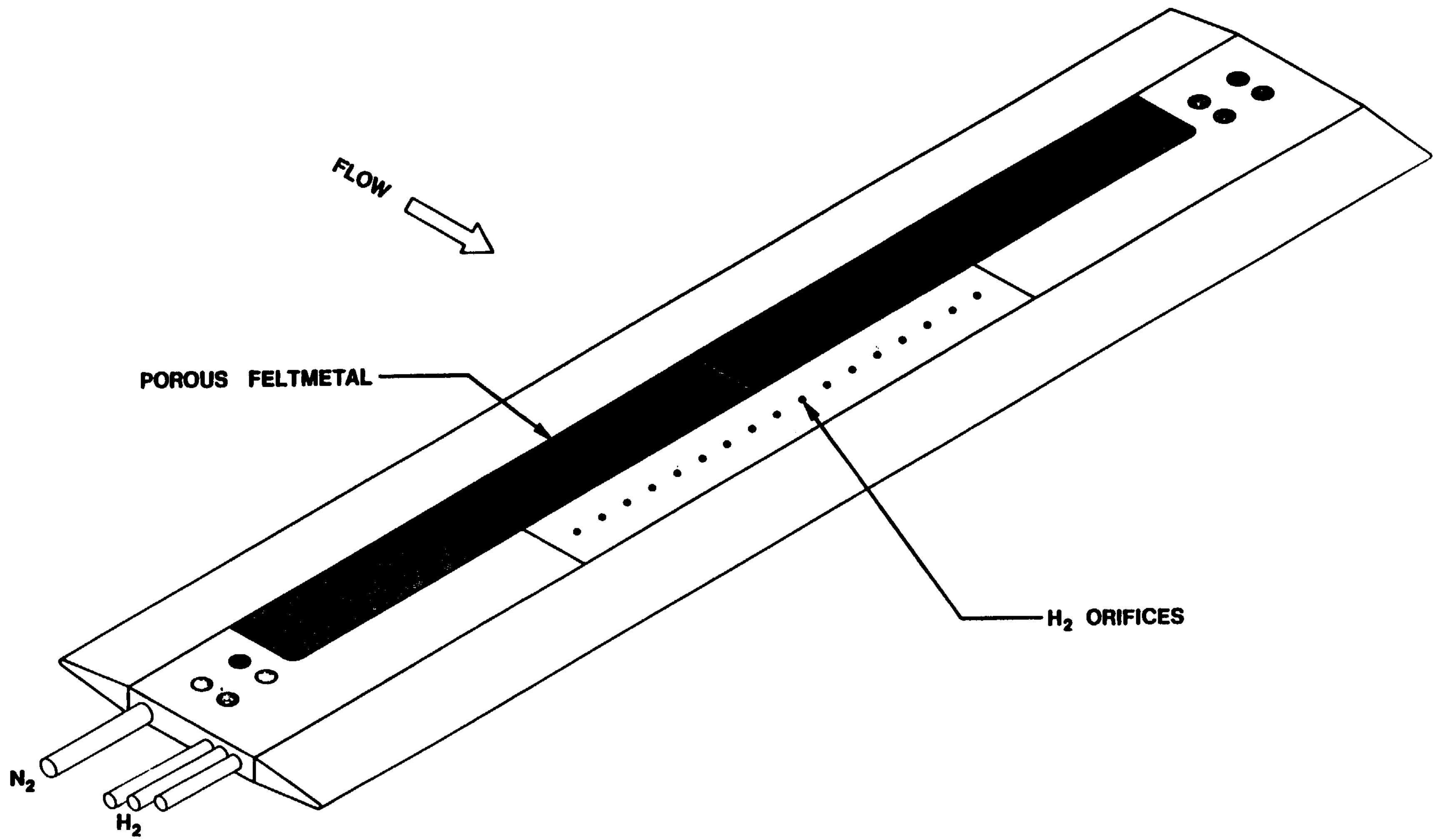
  - STUDY INFLUENCE OF TEMPERATURE AND PRESSURE ON DETONATION WAVE CHARACTERISTICS

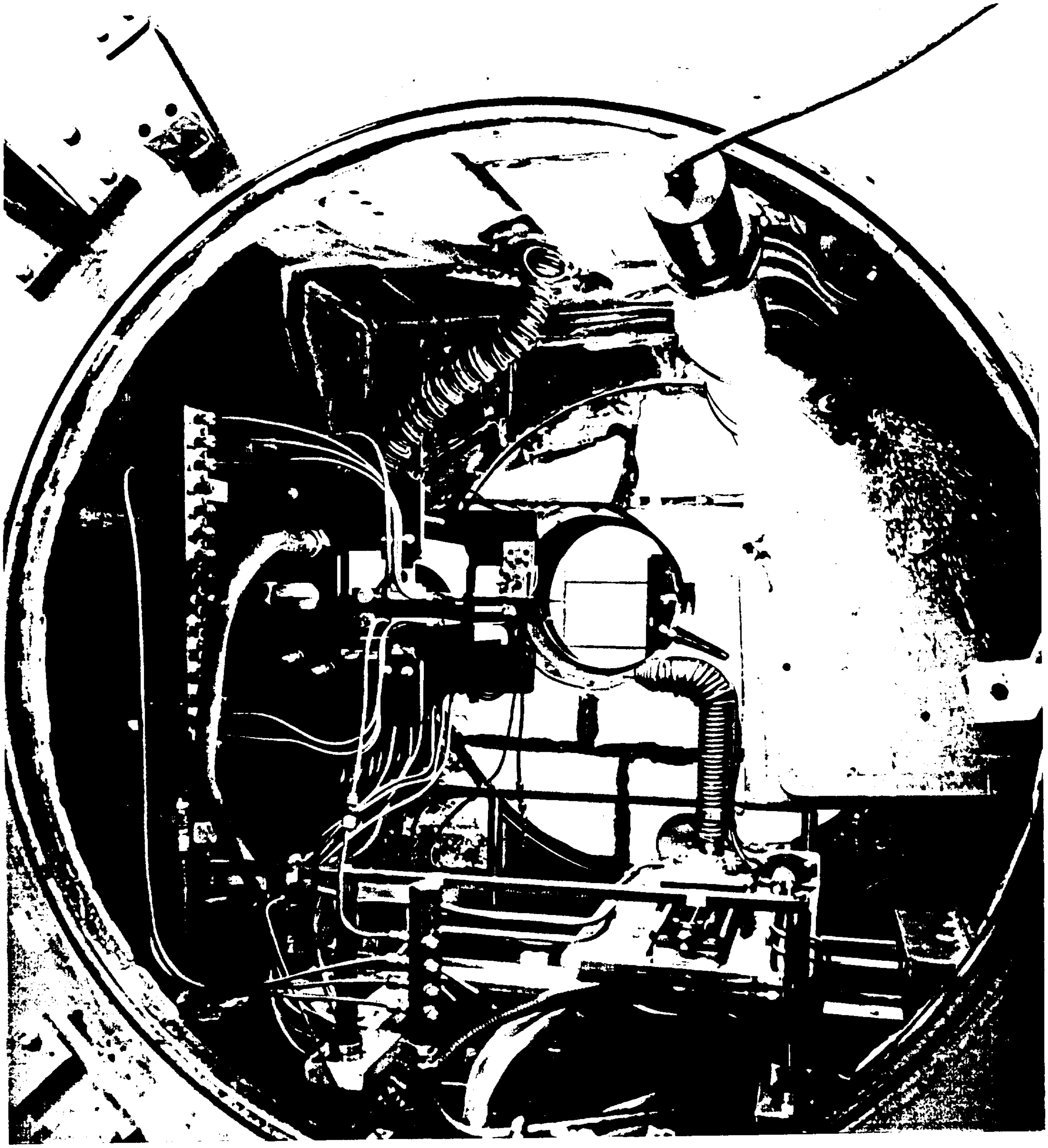
  - VALIDATE CFD CODES WITH EXPERIMENTAL INJECTION AND DETONATION WAVE DATA

SCHEMATIC OF TEST SET-UP IN 20 MW ARC HEATED WIND TUNNEL

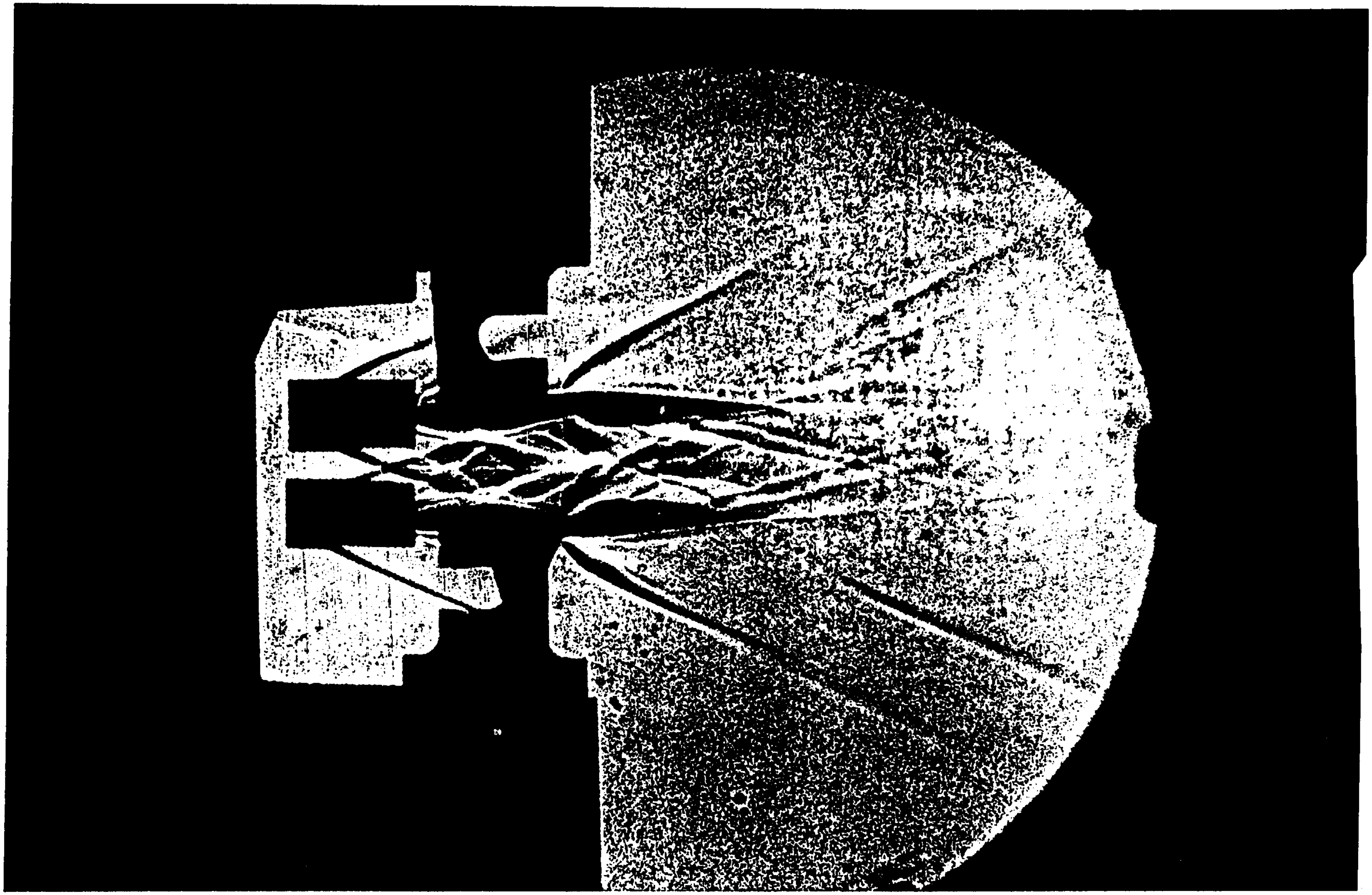


SCHEMATIC OF FUEL INJECTOR STRUT FOR ODWE TESTS





Test set-up in 20 MW Panel Test Facility (PTF) arc heated hypersonic wind tunnel. Two fuel injector struts are positioned at the exit of the semi-elliptical nozzle. The degree of air-fuel mixing is determined by a gas sampling probe on a 3-D traverse table. Mixtures are analyzed in real time by a mass spectrometer.



Shadowgraph of two fuel injection struts in Mach 4.5 flow. Fuel injection from 15 small orifices creates the second set of strong shocks. Fuel-air mixing is determined by direct gas sampling and mass spectrometer analysis.


STRUT BOW SHOCK
INJECTION SHOCK
OBLIQUE WAVE ON WEDGE BEHIND
HYDROGEN FUEL INJECTION STRUT

Schlieren photograph of an oblique wave on a wedge in Mach 4.5 flow. A single strut fuel injector is positioned slightly below the wedge. No fuel is injected in this case.

Schlieren photograph of an oblique wave on a wedge in Mach 4.5 flow with fuel injected from a single strut. Note the displacement of the oblique wave compared to the case without fuel injection.

CONCLUDING REMARKS

- A VEHICLE MISSION STUDY SHOWED THAT THE ODWE EXHIBITS BETTER OVERALL PERFORMANCE THAN A SCRAMJET ENGINE. THE ODWE POWERED VEHICLE CARRIED A 12% HIGHER PAYLOAD WEIGHT THAN THE SCRAMJET POWERED VEHICLE

- A MULTI-DIMENSIONAL MODEL OF THE ODWE SHOWED THAT A STABLE OBLIQUE DETONATION WAVE COULD BE CREATED IN THE WIND TUNNEL FOR A WELL MIXED FUEL-AIR CASE

- THE SAME COMPUTER MODEL WAS USED TO PREDICT THE DEGREE OF FUEL-AIR MIXING FOR VARIOUS INJECTOR CONFIGURATIONS

- AN EXPERIMENTAL PROGRAM WAS INITIATED FOR PROOF-OF-CONCEPT STUDIES OF OBLIQUE DETONATION WAVES IN AN ARC-HEATED HYPERSONIC WIND TUNNEL

- VARIOUS FUEL INJECTORS WERE TESTED FOR FUEL-AIR MIXING CHARACTERISTICS PRIOR TO DETONATION WAVE TESTS

- TESTS TO ESTABLISH OBLIQUE DETONATION WAVES WERE INCONCLUSIVE DUE TO LOW TEST PRESSURES AND INADEQUATE MIXING LENGTH

INVESTIGATIONS OF PULSED DETONATION ENGINES

OBJECTIVES:

- MODEL THE PDE FOR THE FIRST TIME
- PREDICT THE IDEAL PERFORMANCE: THRUST, SPECIFIC IMPULSE
- PEDICT THE MAXIMUM CYCLING RATE
- ANALYZE AIRBREATHING PERFORMANCE
- STUDY THE ROCKET MODE

APPROACH:

- DETERMINE H_2-AIR REACTION MECHANISM AND RATES
- VALIDATE REACTION MECHANISM
- UTILIZE 1-D REACTING FLUID CODE- MOZART

RESULTS:

- PREDICTED THE PERFORMANCE OF A H_2 FUELED PDE
  - CYCLING RATE DEPENDS ON LENGTH AND METHOD OF RECHARGING
  - SPECIFIC IMPULSE OF AROUND 6500 S FOR IDEAL AIRBREATHING CASE
  - ESTIMATED SPECIFIC IMPULSE OF ABOUT 700 S FOR H_2-O_2 ROCKET MODE

Study of Mixing, Combustion & Thrust Enhancement by a Pulsed Detonation Wave Augmentor

OBJECTIVES

1. Demonstrate the potential effectiveness of a Pulsed Detonation Wave Augmentor (PDWA) in enhancing the mixing and combustion in a scramjet flow at high speeds.

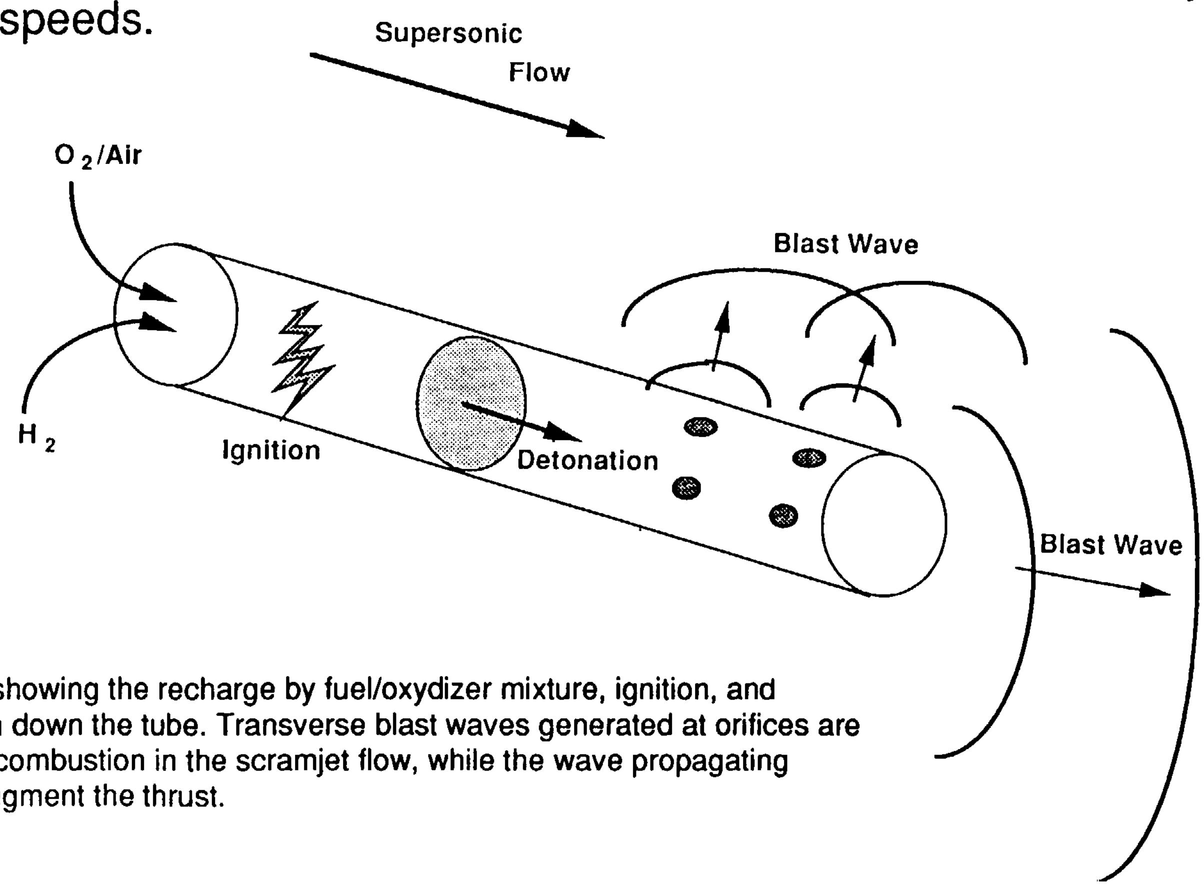
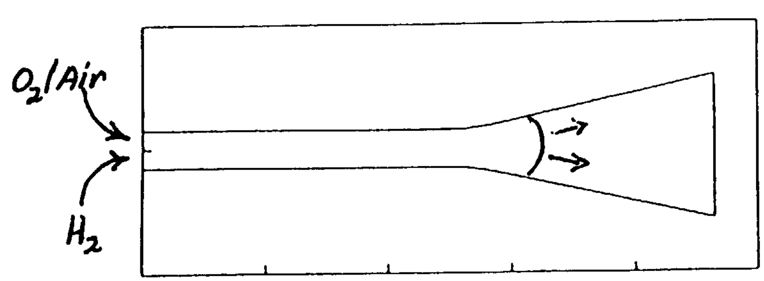


Fig.1: Schematic of PDWA, showing the recharge by fuel/oxydizer mixture, ignition, and detonation wave propagation down the tube. Transverse blast waves generated at orifices are used to enhance the mixing/combustion in the scramjet flow, while the wave propagating downward can be used to augment the thrust.

Study of Mixing, Combustion & Thrust Enhancement by a Pulsed Detonation Wave Augmentor

OBJECTIVES

2. Demonstrate effectiveness of PDWA device at generating thrust.



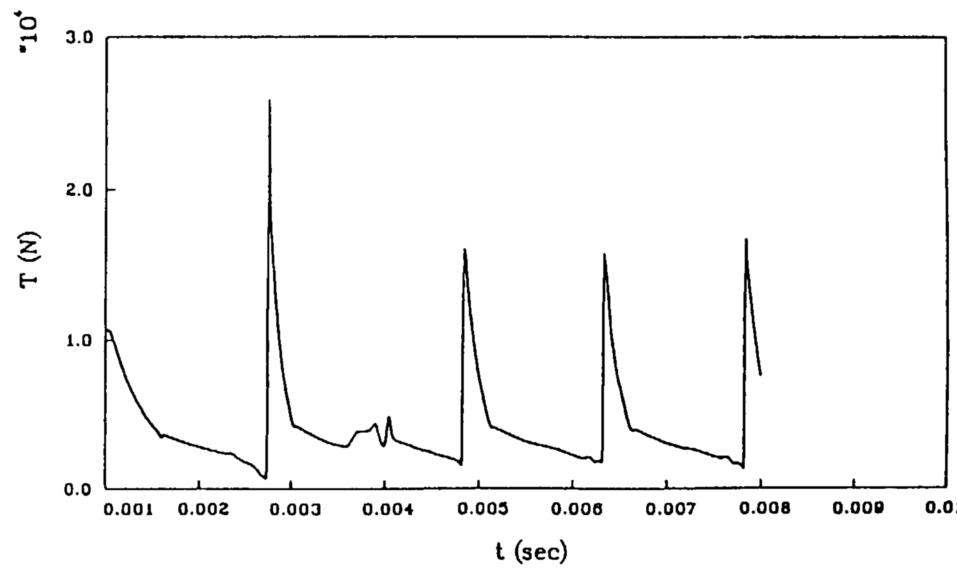


Fig.2: Results of 1D simulations showing the thrust history of a Pulsed Detonation Wave engine in a stand-alone mode. Other studies have shown that the PDW can be operated in an ejector mode with excellent efficiency.

Study of Mixing, Combustion & Thrust Enhancement by a Pulsed Detonation Wave Augmentor

OBJECTIVES

3. Study methods of integrating PDWA and scramjet engine and propose design options.

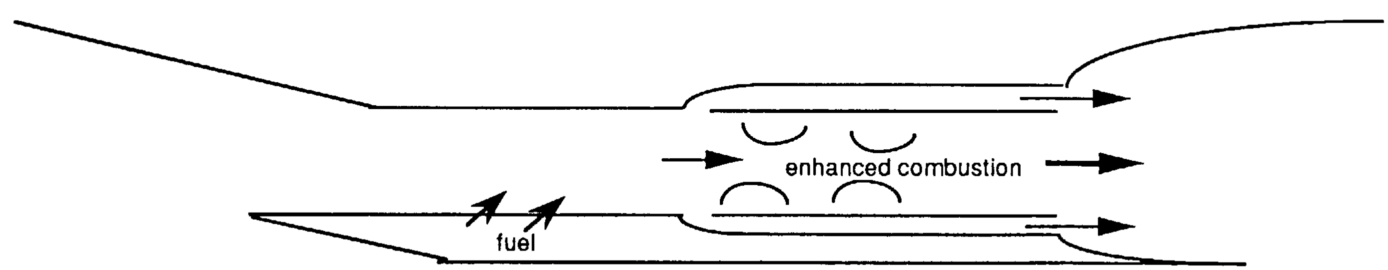


Fig.3: Schematic of scramjet engine module, attached to underside of hypersonic vehicle. PDWA devices are located near the engine walls, past the fuel injectors. Blast waves from the PDWA are used to enhance the mixing and combustion in the main supersonic stream.

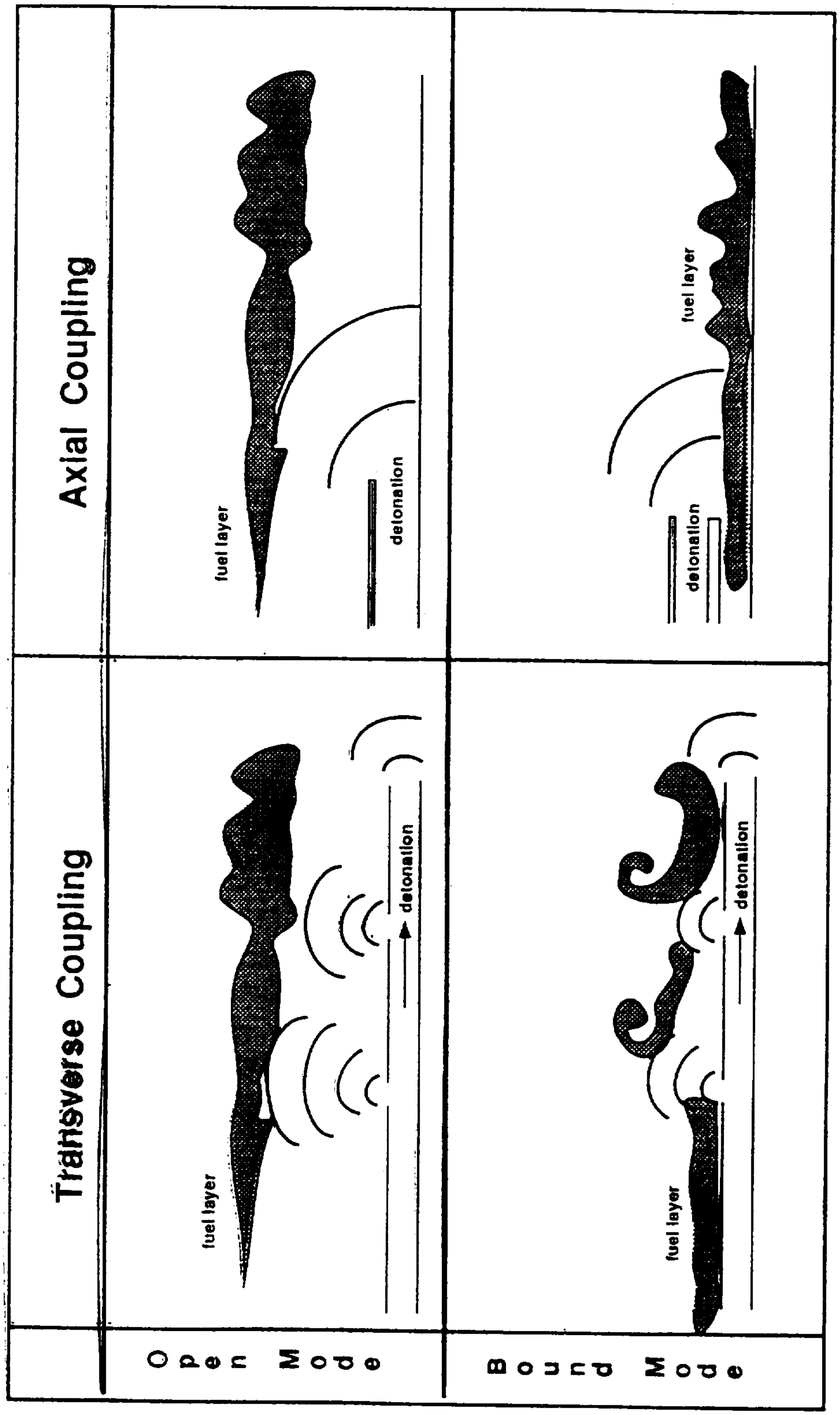


Figure 1: Schematic of PDWA concept and its four modes of operation.

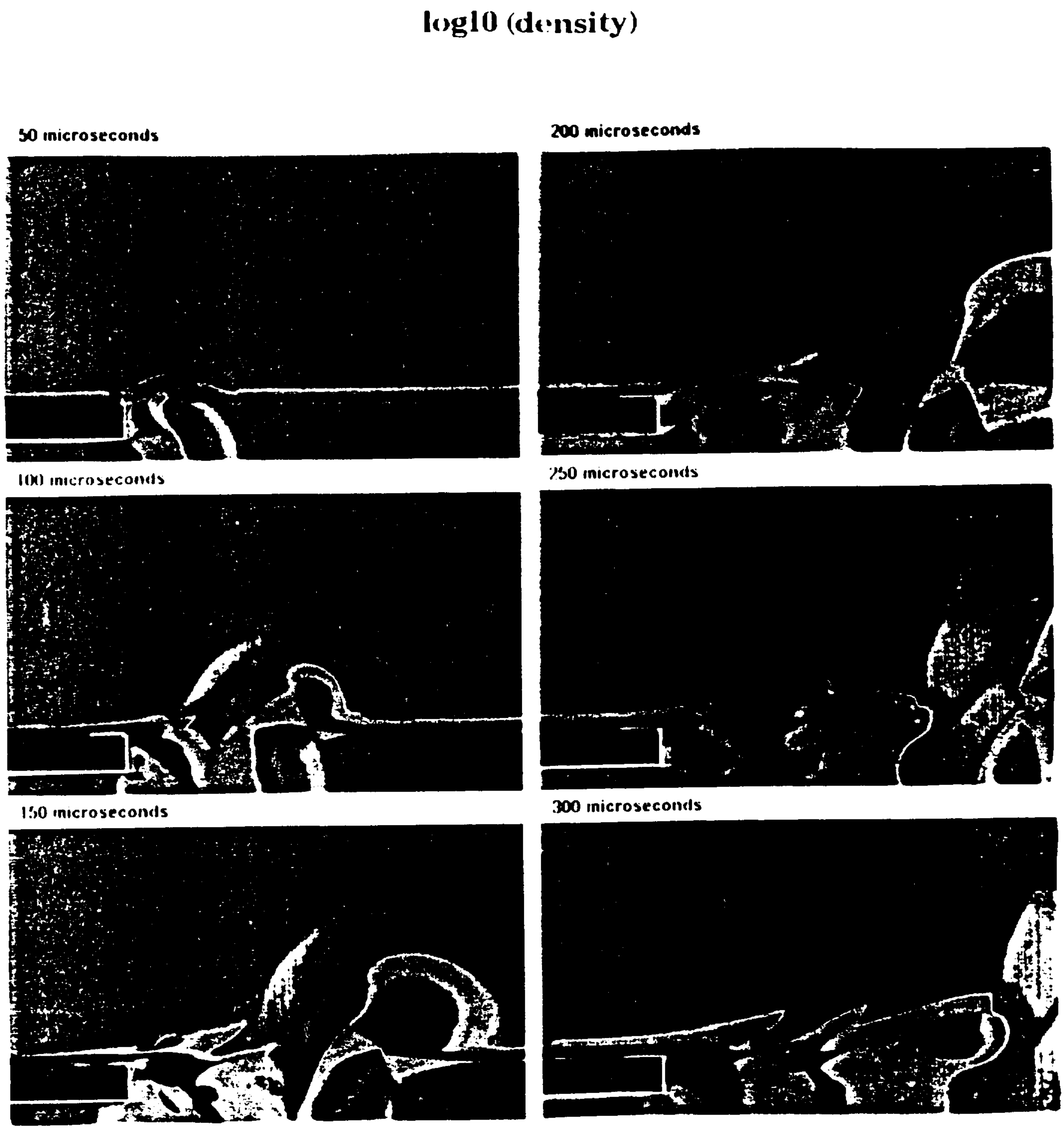


Figure 9: Time sequence of density field (log_{10} transformation) for axial coupling.

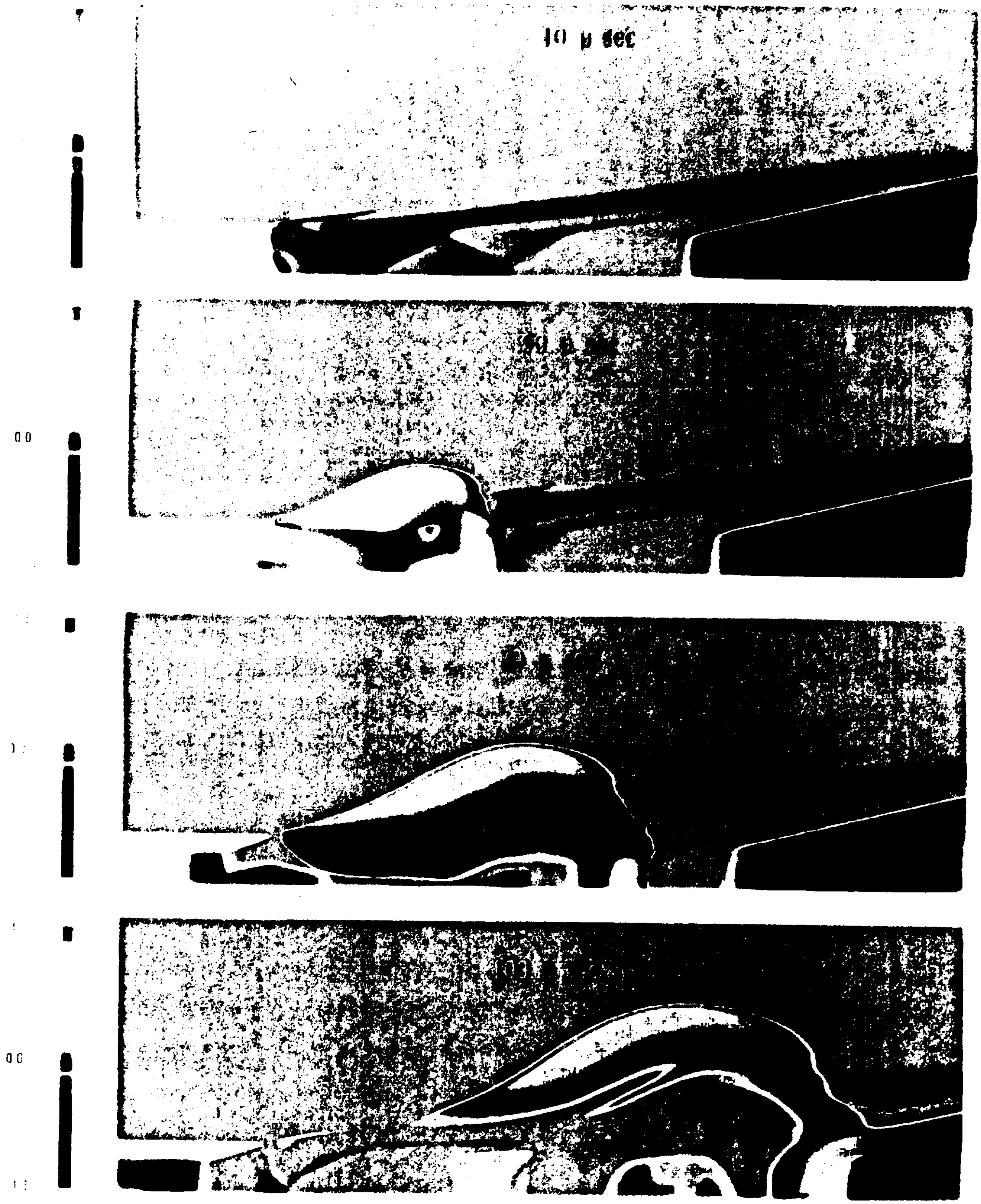


Figure 4 Pressure contours for Combined Injector/Detonation Tube sequence

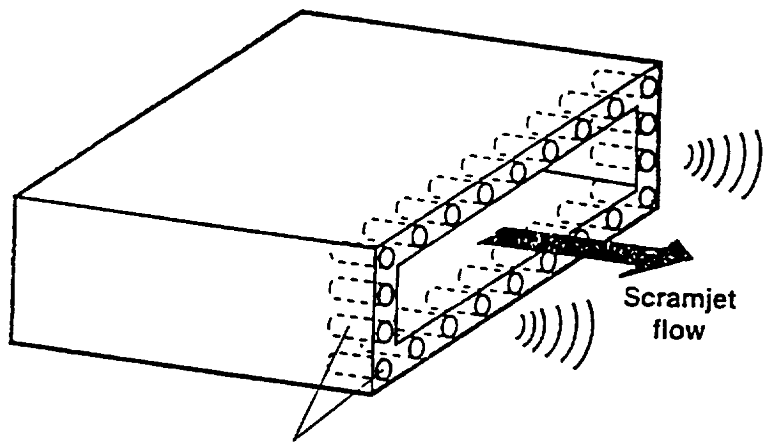


Figure 15: Preliminary design of a PDWA/scramjet engine.