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ABSTRACT:

CFD Flowfield Simulation of Delta Launch Vehicles in a Power-on Configuration

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This paper summarizes recent work at McDonnell Douglas Aerospace (MDA) to develop and validate computational fluid dynamic (CFD) simulations of under expanded rocket plume external flowfields for multibody expendable launch vehicles (ELVs). Multi-engine reacting gas flowfield predictions of ELV base pressures are needed to define vehicle base drag and base heating rates for sizing external nozzle and base region insulation thicknesses. Previous ELV design programs used expensive multibody power-on wind tunnel tests that employed chamber/nozzle injected high pressure cold or hot-air. Base heating and pressure measurements were belatedly made during the first flights of past ELVs to correct estimates from semi-empirical engineering models or scale model tests.

Presently, CFD methods for use in ELV design are being jointly developed at the Space Transportation Division (MDA-STD) and New Aircraft Missiles Divison (MDA-NAMD). An explicit three dimensional, zonal, finite-volume, full Navier-Stokes (FNS) solver with finite rate hydrocarbon/air and aluminum combustion kinetics was developed to accurately compute ELV power-on flowfields. Mississippi State University's GENIE++ general purpose interactive grid generation code was chosen to create zonal, finite volume viscous grids. Axisymmetric, time dependent, turbulent CFD simulations of a Delta DSV-2A vehicle with a MB-3 liquid main engine burning RJ-1/LOX were first completed. Hydrocabon chemical kinetics and a k-ε turbulence model were employed and predictions were validated with flight measurements of base pressure and temperature. Zonal internal/external grids were created for a Delta DSV-2C vehicle with a MB-3 and three Castor-I solid motors burning and a Delta-II with an RS-27 main engine (LOX/RP-1) and 9 GEMs attached/6 burning. Cold air, time dependent FNS calculations were performed for DSV-2C during 1992. Single phase simulations that employ finite rate hyrocarbon and aluminum (solid fuel) combustion chemistry are currently in progress. Reliable and efficient Eulerian algorithms are needed to model two phase (solid-gas) momentum and energy transfer mechanisms for solid motor fuel combustion products.

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CFD FLOWFIELD SIMULATION OF DELTA LAUNCH VEHICLES IN A POWER-ON CONFIGURATION

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11th Workshop for Computational Fluid Dynamic (CFD) Applications in Rocket Propulsion

PROBLEM

- CFD internal/external reacting gas (power-on) flowfield predictions are needed for engineering design of expendable launch vehicles (ELVs)

  [1] base pressure (base drag) [2] base heating rate (insulation)

- ELV cold/hot air or reacting gas wind tunnel tests require long lead times and are very expensive
- ELV base region environments often determined during initial flights

OBJECTIVE

- Utilize state of the art CFD methods to predict power-on multibody ELV flowfields
- Reduce or minimize wind tunnel testing and flight measurements of base region pressures and heating
- Reduce ELV design cycle costs and aerodynamic uncertainties

APPROACH

- Apply, modify, improve existing and developing CFD techniques to predict power-on flowfields for multibody and multi-engine Delta ELVs

- Cooperative, multi-year research effort by MDA-STD, MDA-NAMPD, and Miss. State NSF/ERC

- Grid Generation

  Employ advanced GENIE^{++}, zonal, structured, grid generation code

- Navier-Stokes Flow Solver

  Time dependent, Reynolds averaged, 3D Navier-Stokes code

  Explicit Runge-Kutta integration procedure

  K-epsilon turbulence model (Jones & Launder, high Re. no. form)

  TVD dissipation scheme (Yoon and Kwak)

  Zonal, contiguous grid capability

  Finite rate combustion chemistry routines (explicit) hydrocarbon (RJ-1 or RP-1) and aluminum based solid motor fuel

  Robust, well validated CFD code for ELV power-off flowfields (see AIAA-91-1727 and AIAA-92-2681)

APPROACH (Continued)

VALIDATION

Perform a series of increasingly complex power-on simulations

(1) Single body Delta DSV-2A with MB-3 main engine burning (LOX/RJ-1) with finite rate chemistry (0° and 3° angle of attack)

(2) Delta DSV-2C with MB-3 main engine plus 3 Castor-I solids burning Hot air, single phase, finite rate reacting gas (0° angle of attack)

(3) Delta-II with RS-27 LOX/RP-1 main engine plus 9 GEMs (or Castor-IVAs) attached/6 burning

0° angle of attack to minimize grid size and computer time

Perform cold air (constant gamma) solutions before reacting gas simulations to remove grid errors

Assume single phase gas reactions w/o surface combustion

Utilize Delta launch vehicle flight measurements of base surface pressures, temperatures, heating rates

PROGRESS & RESULTS

(1) AXISYMMETRIC DELTA DSV-2A POWER-ON SIMULATION (AIAA-91-3338)

Two zone overlapping viscous grid (internal and external)

Thin-layer Navier Stokes flowfield simulations

MB-3 main engine (LOX/RJ-1) with finite rate hydrocarbon combustion chemistry

Chamber temperature, pressure, mass ratios are known

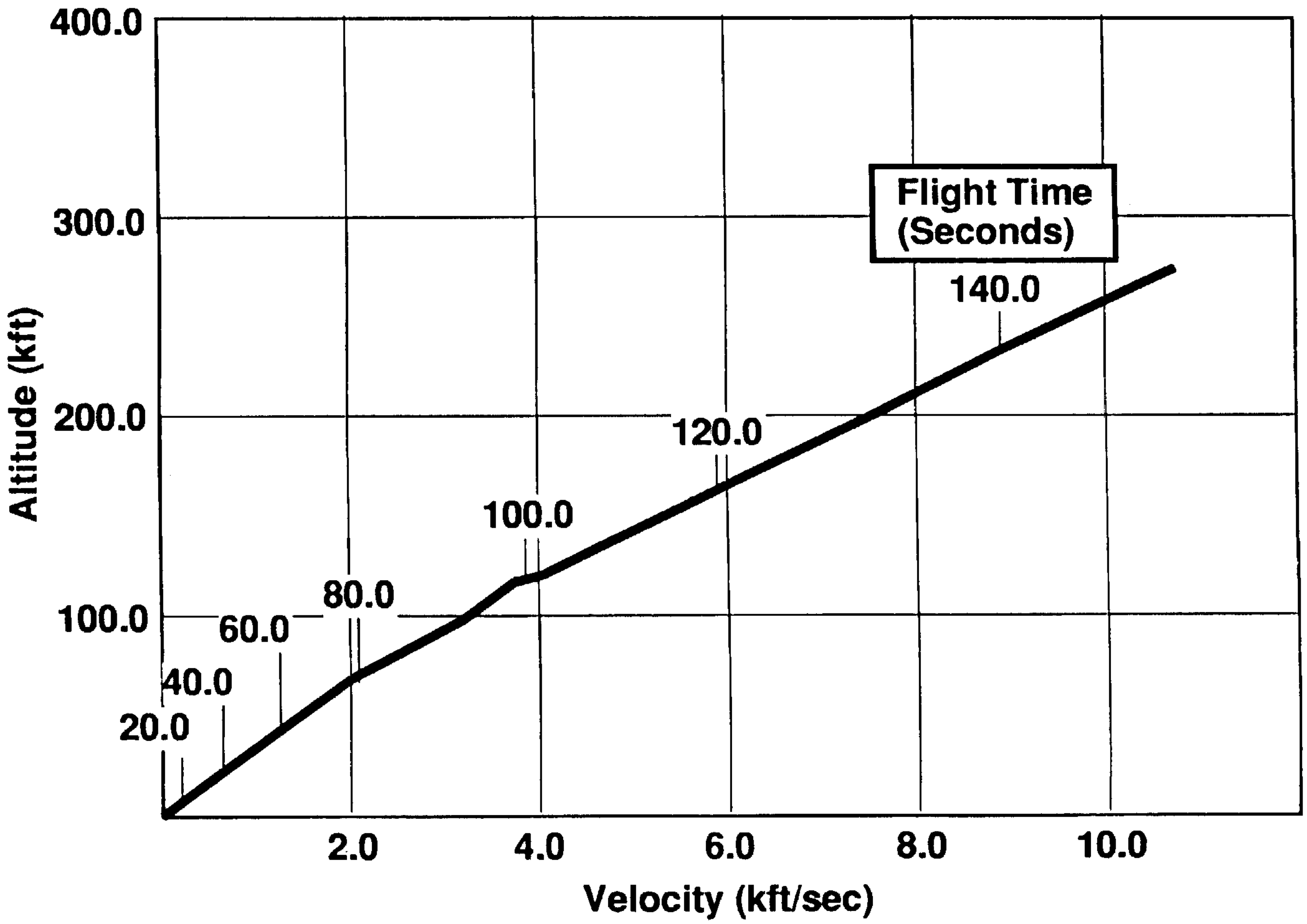
Nozzle exit momentum and mass flow matched at nozzle exit

Four Mach number-trajectory points simulated (axisymmetric, 0° angle of attack)

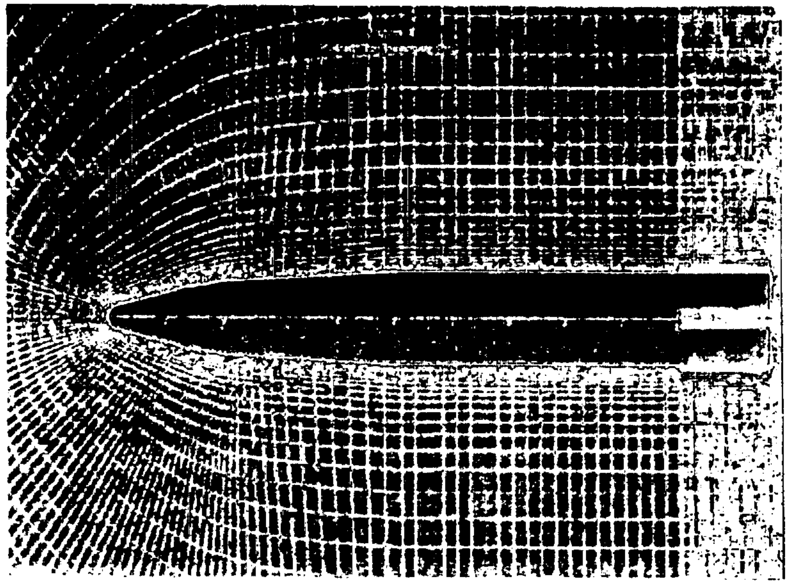
Predicted base pressures and temperatures well validated

Demonstrated angle of attack effects on nozzle and base surface pressures

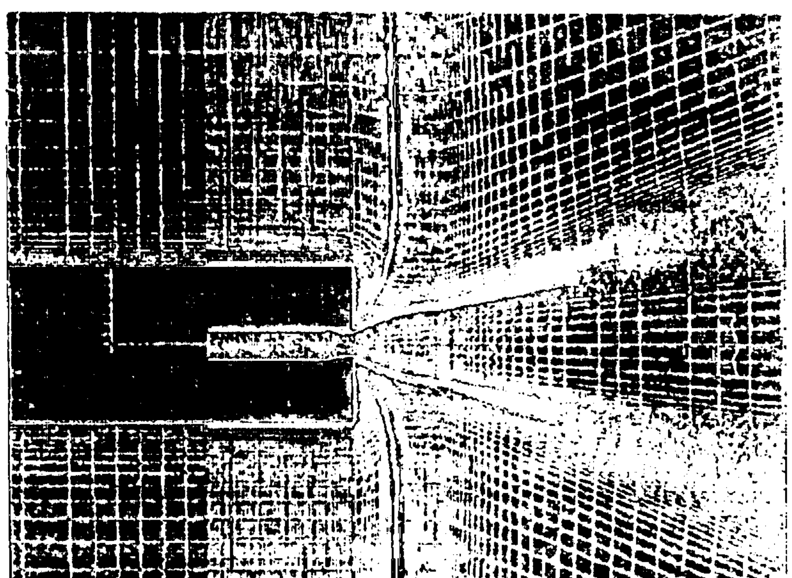
DELTA DSV FLIGHT 419 RECONSTRUCTED TRAJECTORY



DELTA DSV-2A TWO-ZONE OVERLAPPING AXISYMMETRIC GRID



Forebody Grid



Downstream and Base Region Grid

DSV FLOWFIELD MACH NUMBER CONTOURS

VED2951 M20DE

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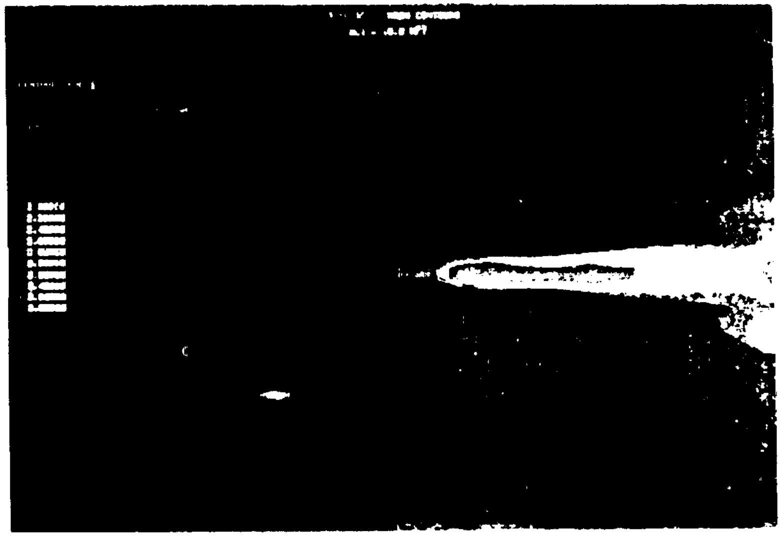
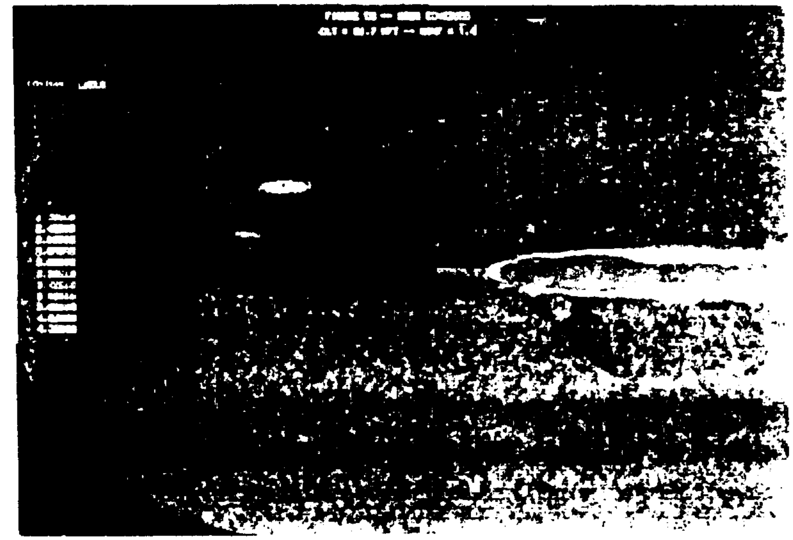


Altitude = 18 kft,
Mach Number = 1.01



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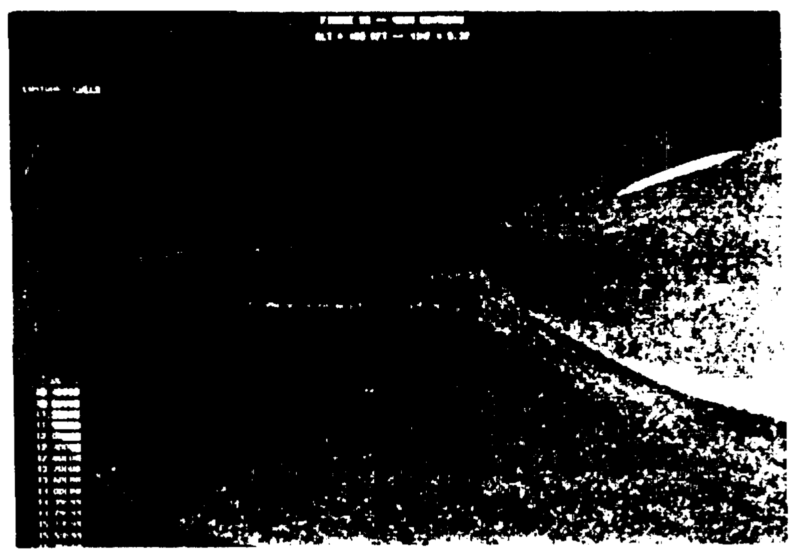
Mach Number = 1.4



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Mach Number = 5.37

DSV EXPANDED FLOWFIELD MACH NUMBER CONTOURS

VED2952 M20DE

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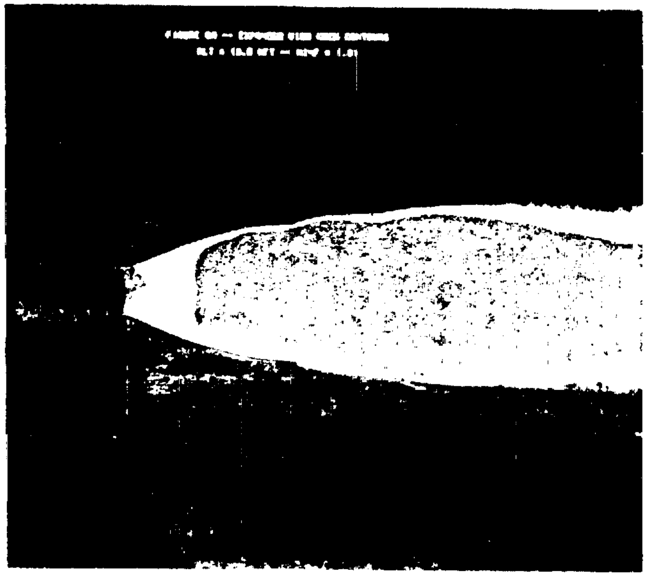
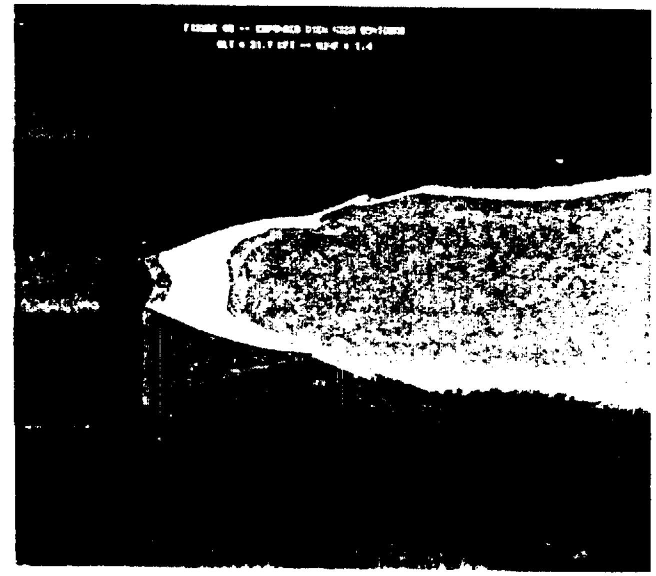


Altitude 18 kft,
Mach Number = 1.01



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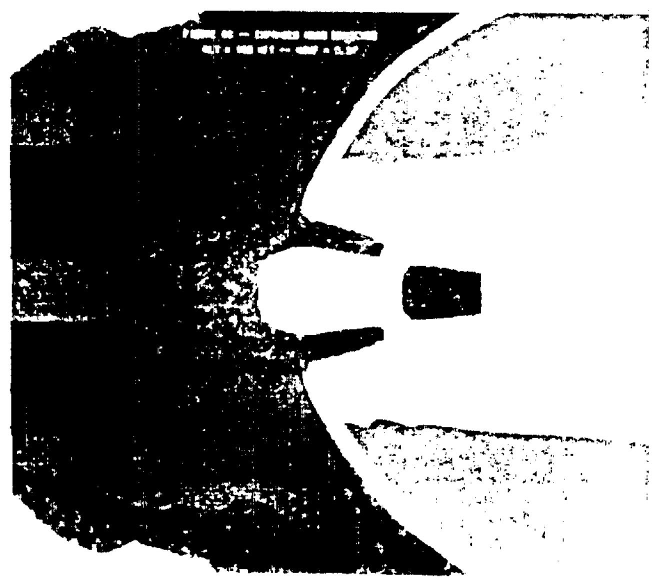
Mach Number = 1.4



Altitude = 160 kft,
Mach Number = 5.37

DSV FLOWFIELD CO_2 MASS FRACTIONS

VED2953 M20DE

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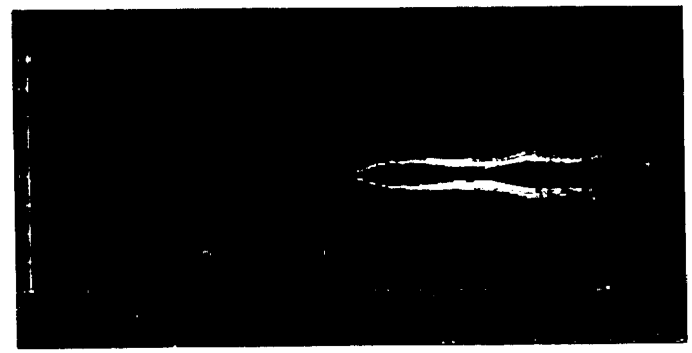
Altitude = 18 kft,
Mach Number = 1.01



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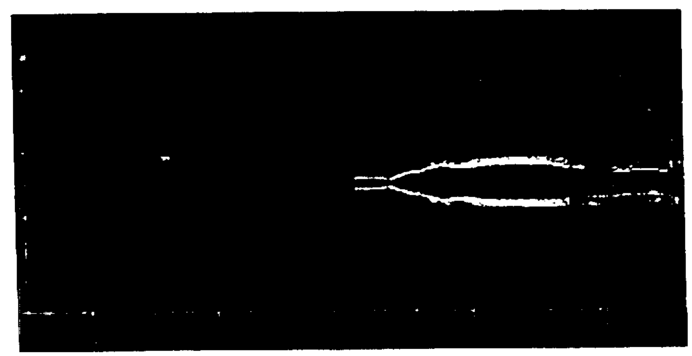
Mach Number = 1.4



Altitude = 160 kft,
Mach Number = 5.37

DELTA DSV BASE SURFACE TEMPERATURE
COMPARISON OF CFD PREDICTION VS FLIGHT MEASUREMENTS

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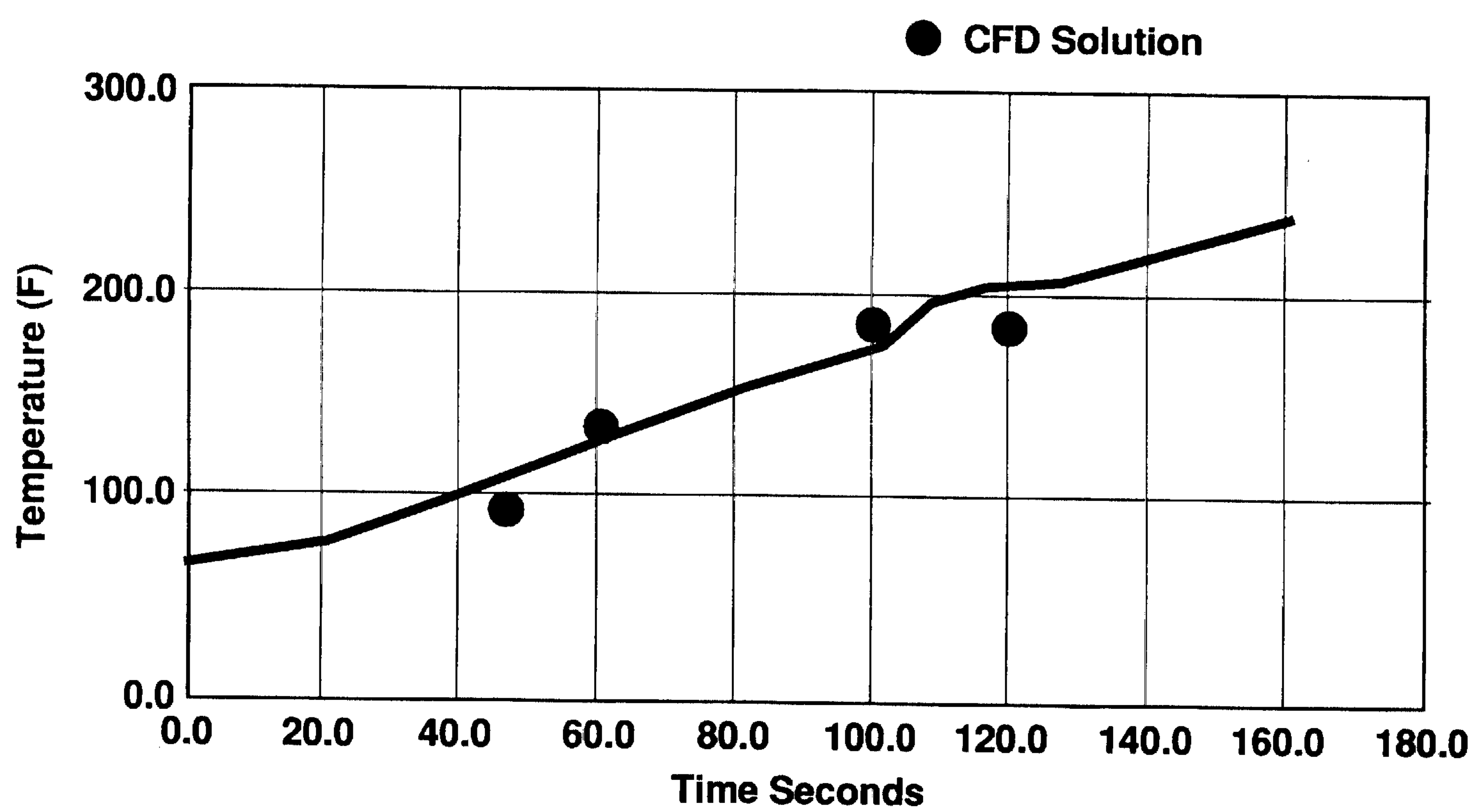
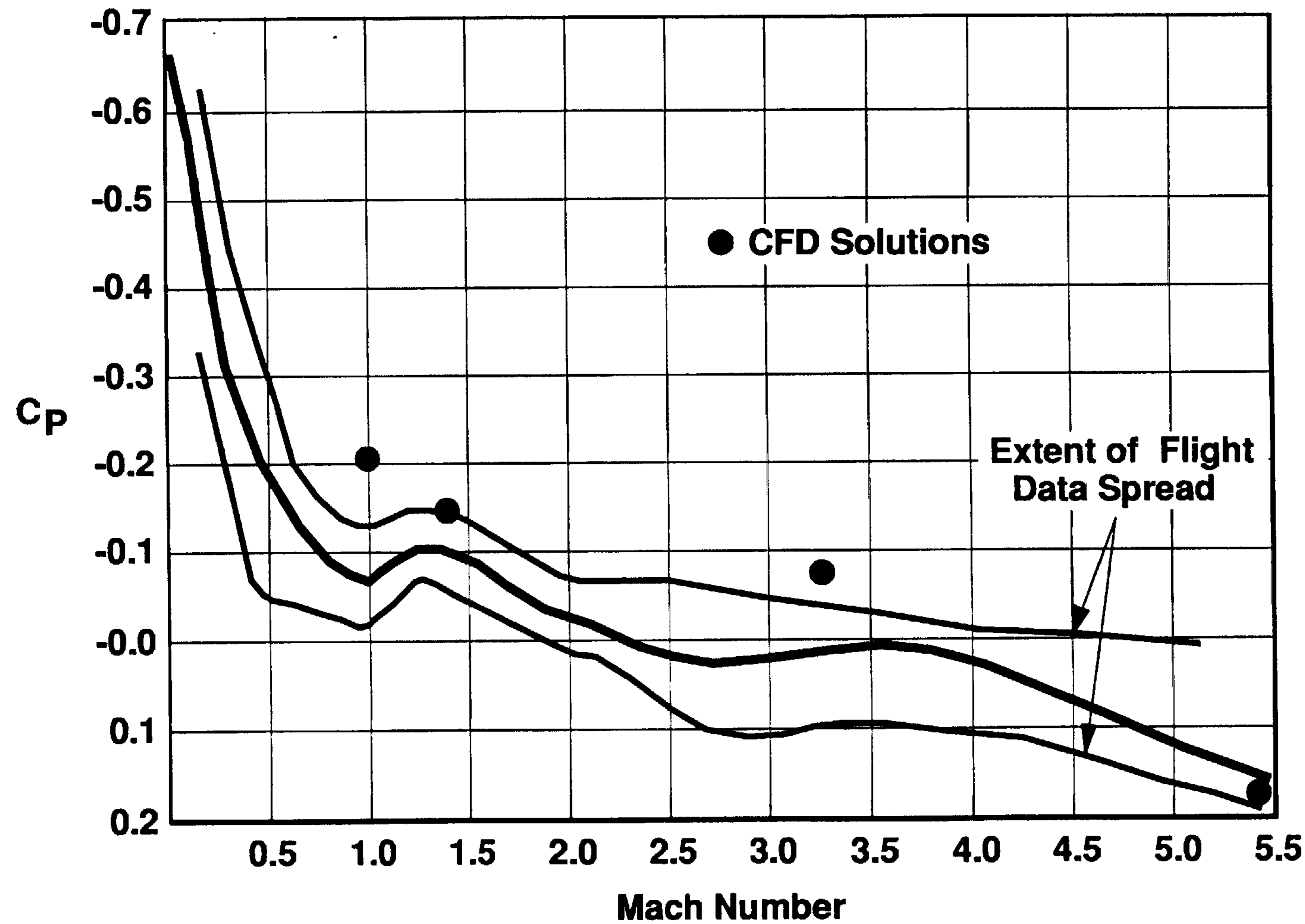
VED2958 M20DE



DELTA DSV BASE PRESSURE COEFFICIENTS COMPARISON OF CFD AND FLIGHT MEASUREMENTS

VED2954 M20DE

MDA–Space Transportation Division



PREDICTED DELTA DSV BASE REGION SURFACE PRESSURE COEFFICIENTS

VED2956 M20DE

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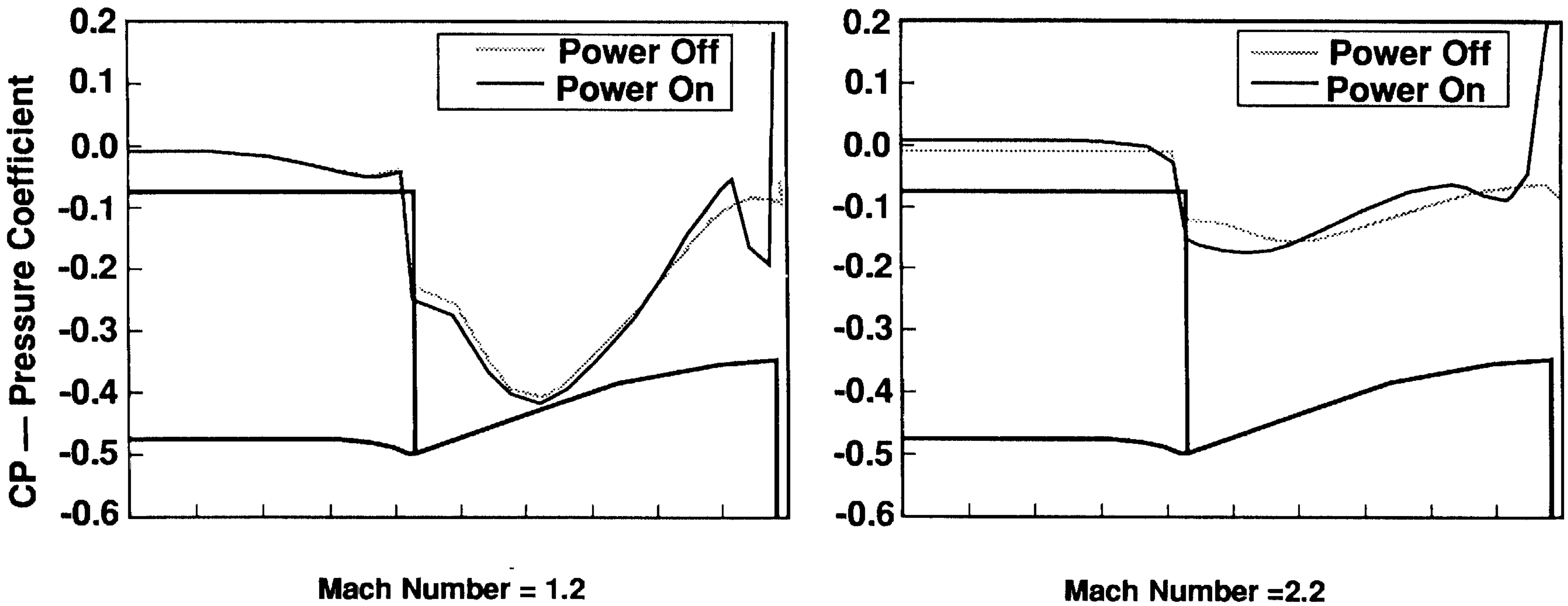

PREDICTIONS OF DELTA DSV AFT VEHICLE CIRCUMFERENTIAL SURFACE PRESSURE
MACH NUMBER = 1.01, ANGLE OF ATTACK = 3.0 DEGREES

VED2957 M20DE

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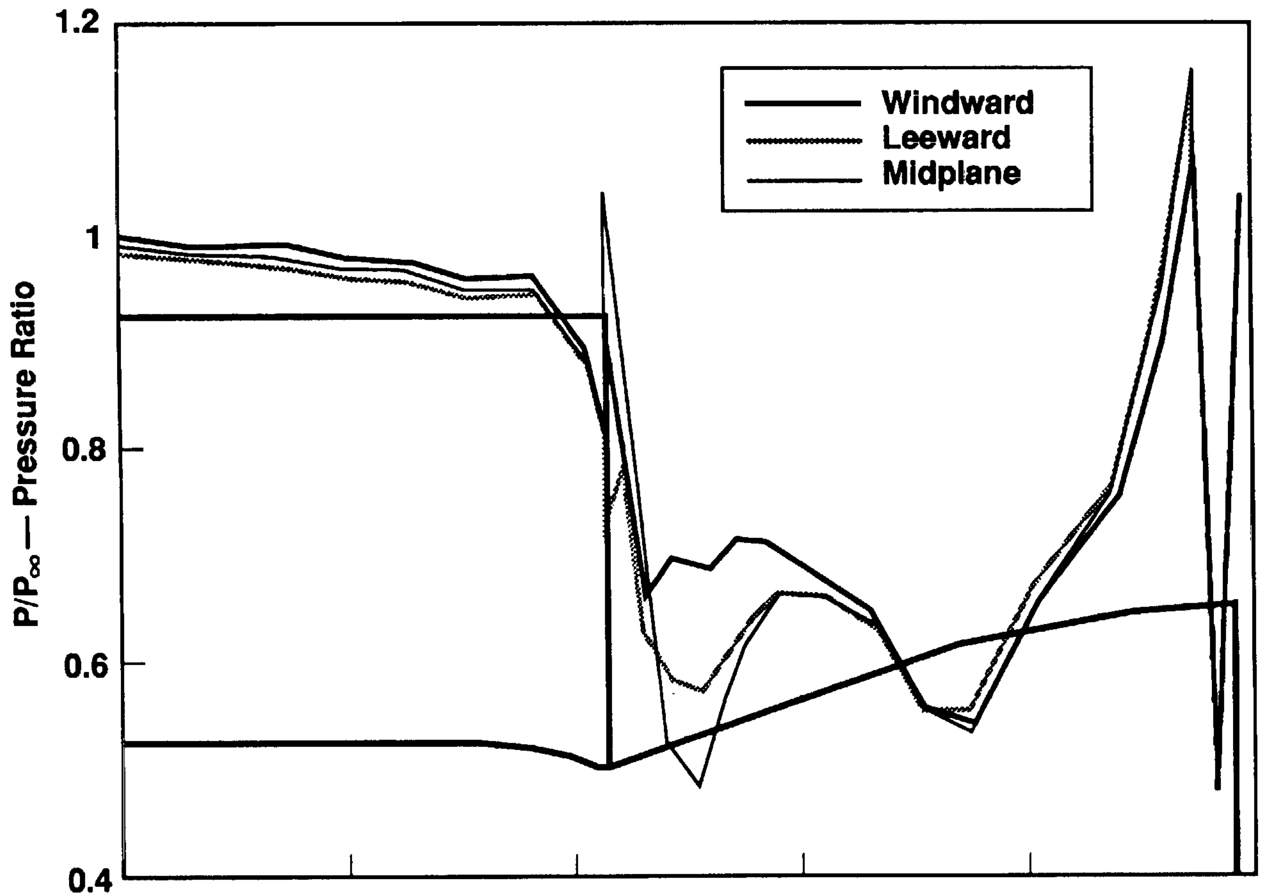


PROGRESS & RESULTS
(Continued)

(2) <u>THREE DIMENSIONAL DSV-2C POWER-ON SIMULATIONS</u> (in progress)

160-105-40 I-J-K global grid, 8 zones (60° circumferential arc region)

Full Navier Stokes flow code simulations

Three Castor-1 solids (TP-H8038 fuel) plus MB-3 liquid main (LOX/RJ-1)

Hot gas, 0° angle of attack at Mach No. = 1.4 (completed)

Perform single phase, reacting gas simulations at 0° angle of attack (in progress)

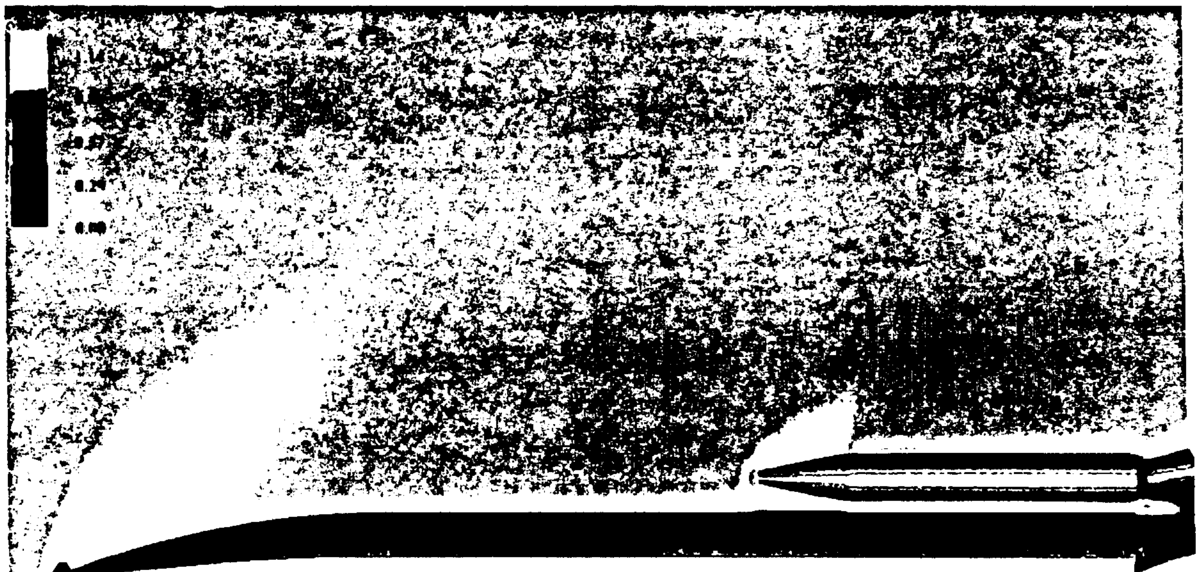
Employ aluminum solid fuel finite rate combustion chemistry

THREE-DIMENSIONAL DELTA DSV-2C POWER-ON MULTIBODY, FLOWFIELD SIMULATION

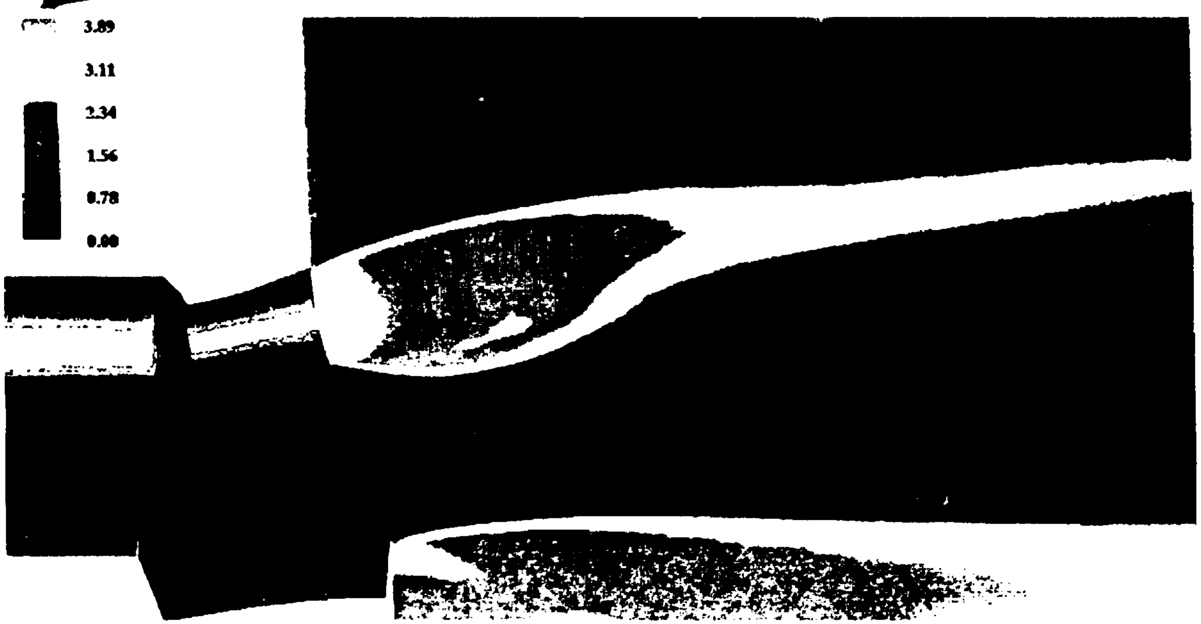
MACH NO. = 1.4, K-E TURBULENCE MODEL, ANGLE OF ATTACK = 0 DEG

VED2950 M20DE

MDA–Space Transportation Division



Mach Number Contours
Upstream Flowfield
Symmetry Plane



Mach Number Contours
Base Region and
Plume Flowfield

SUMMARY AND CONCLUSIONS

- Results from DSV-2A (single engine) reacting gas simulations are encouraging
- Single phase, reacting gas CFD simulations for multibody, DSV-2C and Delta-II vehicles are in progress
- Work needed to develop/modify efficient, accurate Eulerian algorithms to empirically model interaction of entrained aluminum oxide particulates

  Quantification of solid particulate and reacting gas exchange of:

Mass	(sublimation or vaporization)
Momentum	(particle drag)
Energy	(radiation, convection)