Quasi-One-Dimensional Modeling of Pulse Detonation Rocket Engines

Christopher Morris

Propulsion Research Center

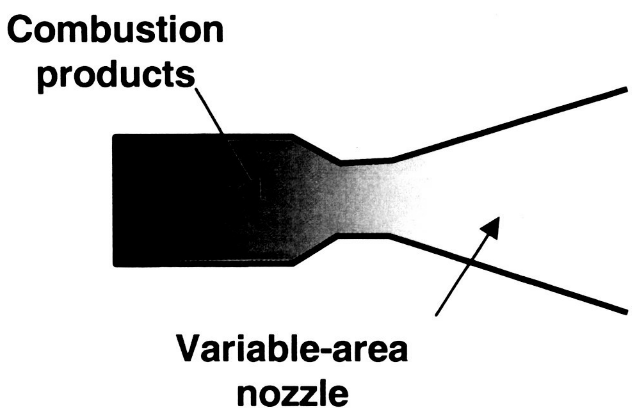
NASA- George C. Marshall Space Flight Center

Propulsion Research Center, TD 40

Marshall Space Flight Center, AL 35812

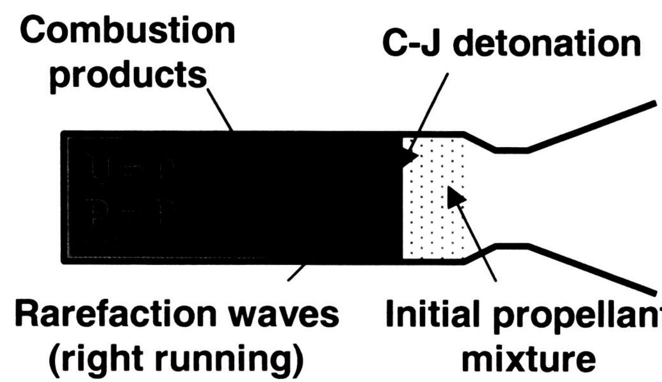
Performance Analysis of PDREs

Steady-State Rocket Engine



Steady flow

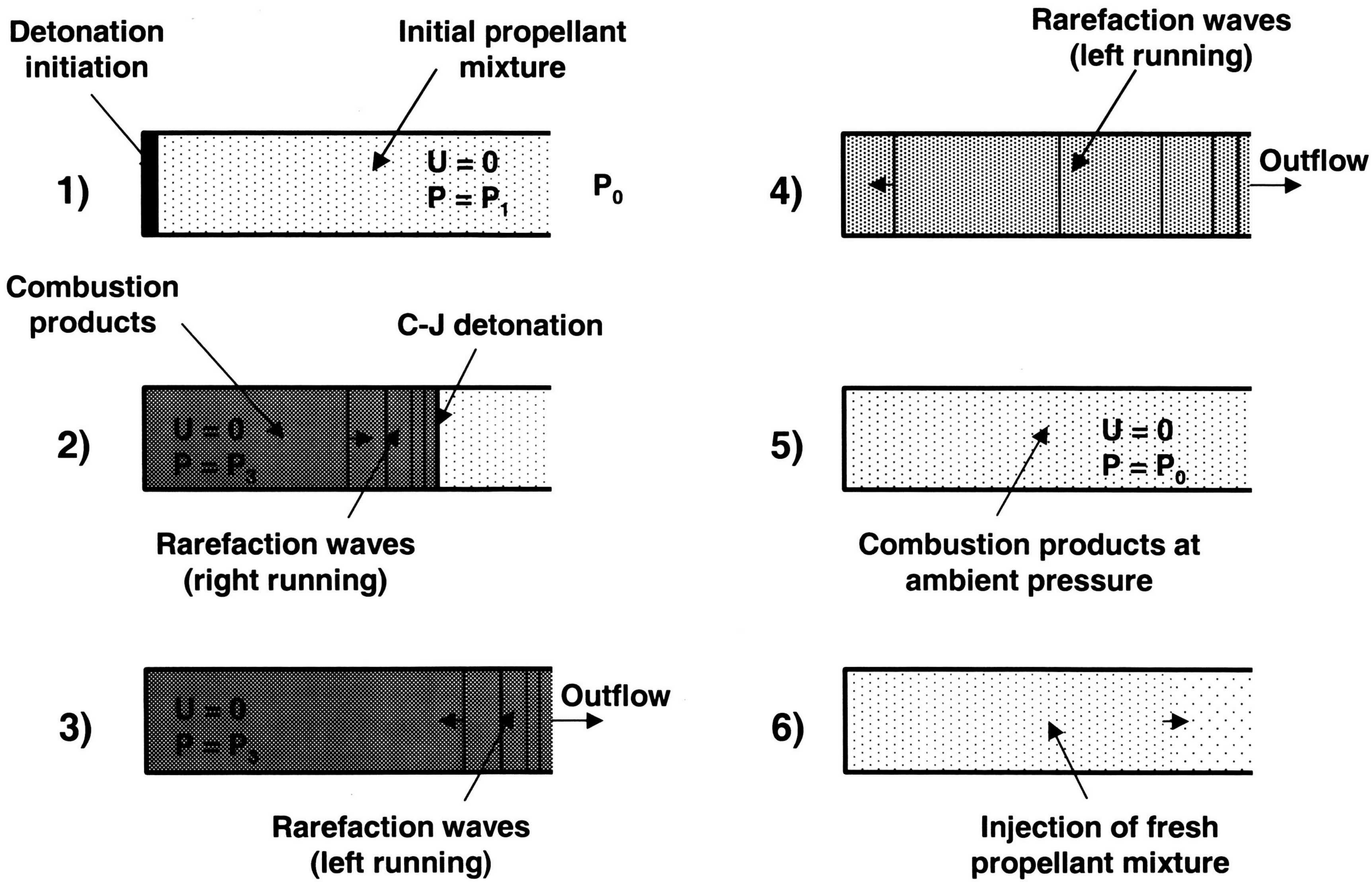
Pulsed Detonation Rocket Engine



Unsteady flow

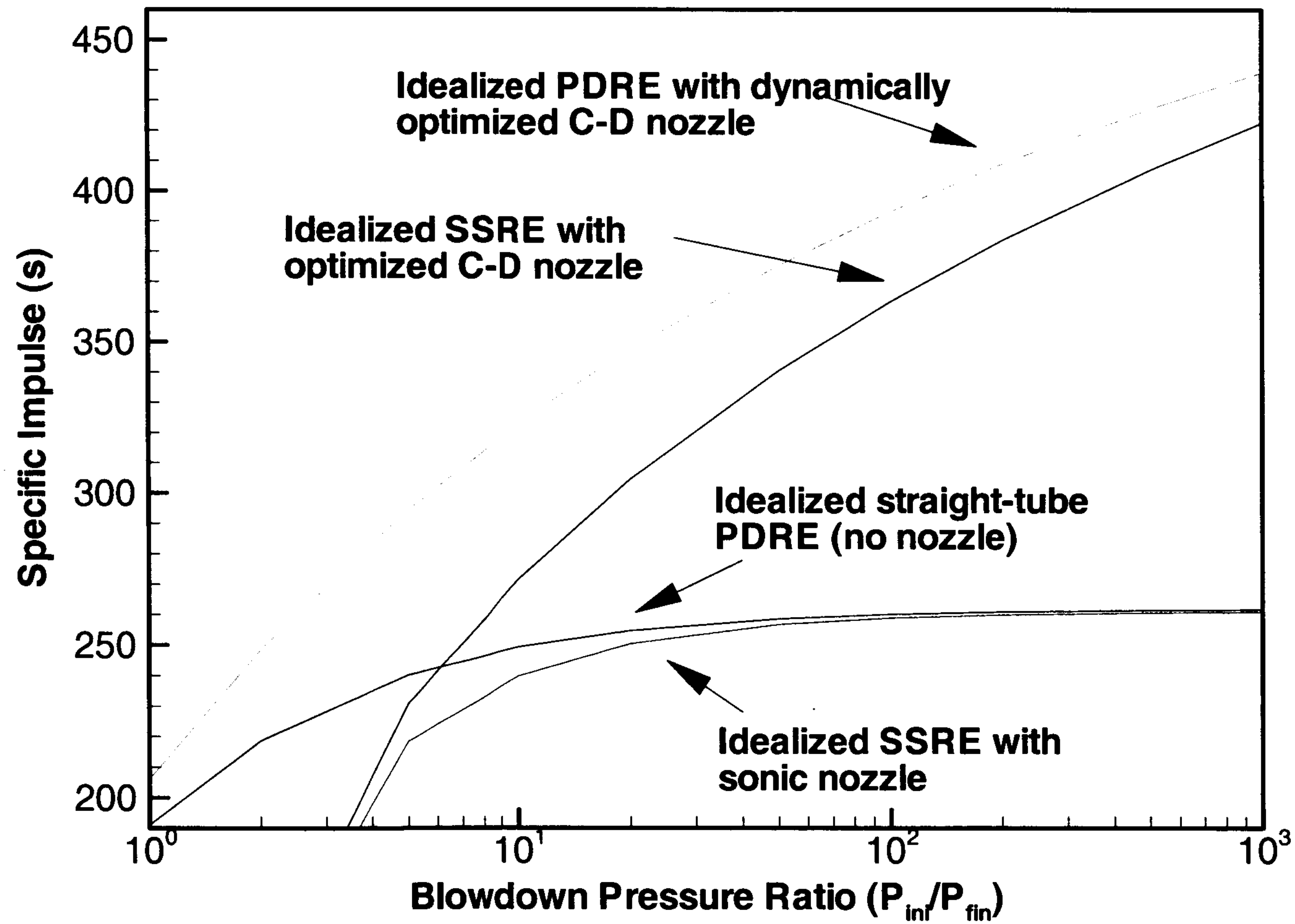
- **Pulsed Detonation Rocket Engines (PDREs) have a theoretical thermodynamic advantage over Steady-State Rocket Engines (SSREs)**
- **Unsteady blowdown process complicates effective use of this theoretical advantage in practice**
- **PRC is engaged in a fundamental study of PDRE gasdynamics to improve understanding of performance issues**

Simplified PDRE Cycle



Comparison of PDRE and SSRE Performance

H_2-O_2, $\phi = 1$, $T_{ini} = 300$ K, $P_{ini} = 1$ Atm, γ = constant



- Straight tube PDRE outperforms a SSRE with sonic nozzle at all pressure ratios
- Clear need for nozzle research to enable best possible PDRE performance

Numerical Modeling of Quasi 1-D Rocket Flows

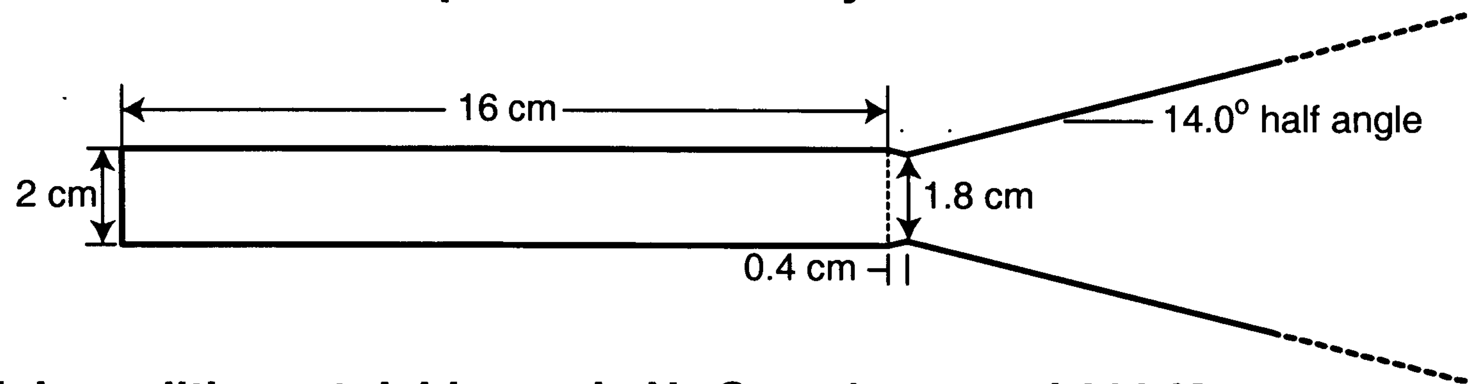
- Quasi 1-D Euler equations suitable for simplified modeling of area variation in rocket flows

- 2^{nd}-order (Strang) timestep splitting between fluid and chemistry solvers

- Fluid (Euler) convection
  - 2^{nd}-order time and space accurate symmetric-TVD algorithm (Yee, 1989)
  - Employs Roe's approximate Riemann solver for nonequilibrium ideal gases (Grossman and Cinella, 1990), and modified to ensure species positivity (Larrouturou, 1991)
- Finite-Rate Chemistry integration
  - H_2/O_2 reaction mechanism: 9 species, 18 reactions (Petersen and Hanson, 1999)
  - Stiff integration technique: Newton iteration of a linearized implicit trapezoidal method (uses Jacobian of source terms)

PDRE Performance Optimization Study

Specific Geometry Studied



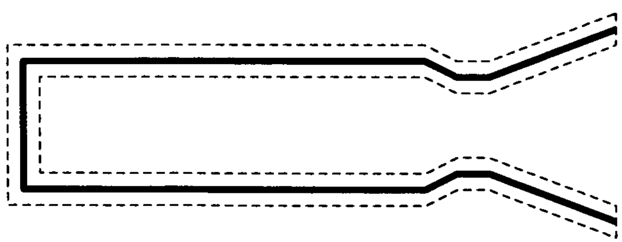
- Initial condition: stoichiometric H_2-O_2 at 1 atm and 300 K
- Closed end BC: determined by reflection
- Outflow BC: determined from ambient pressure and MOC
- Detonation initiated by a high (×10) P, T region at the closed end
- Idealized diaphragm initially isolates propellants from ambient gas
- Nozzle half angle fixed at 14.0 degrees
- Domain size scaled depending on specified throat and exit radius
- Area ratio optimized for maximum I_{sp} at each pressure ratio
- Uniform grid spacing: $\Delta x = 0.1$ mm
- Simulation run until closed-end pressure equals ambient value

Time-Accurate Thrust Calculations

Momentum Equation

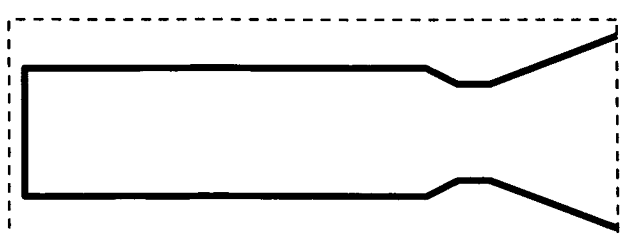
$$F_{SX} + F_{BX} = \frac{d}{dt}\int_{CV} \rho\, u\, dV + \int_{CS} \rho\, u\, \vec{V}\cdot d\vec{A}$$

Control Volume for Method 1



$$F_{SX} = \int_{CS} (P_{int} - P_{amb})\cdot d\vec{A}$$

Control Volume for Method 2

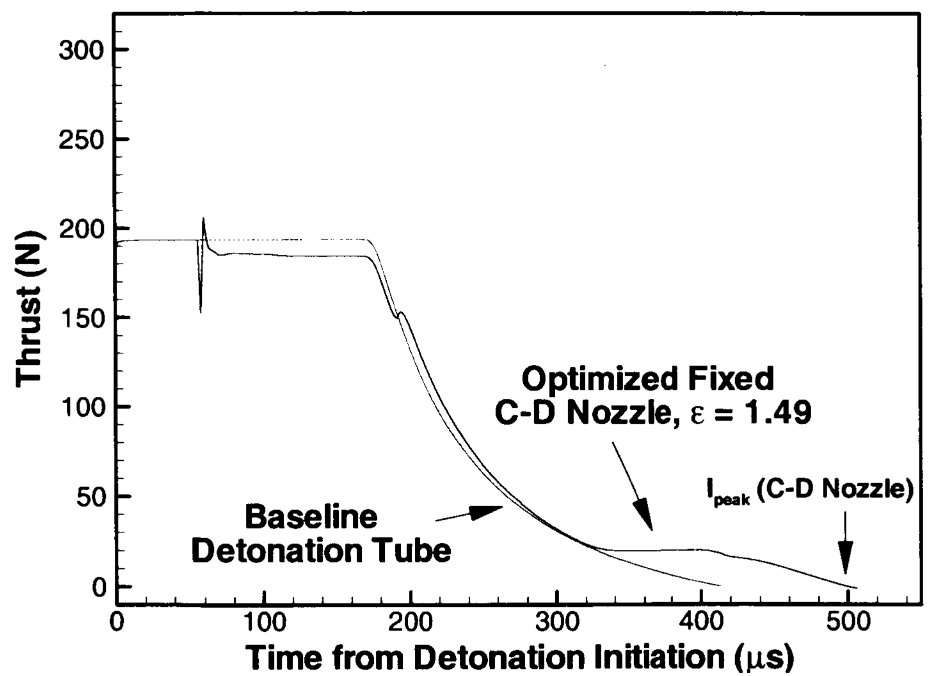


$$F_{SX} = \frac{d}{dt}\int_{0}^{L} \rho\, u\, dV + \rho\, u^2 A + A\,(P_{ex} - P_{amb})$$

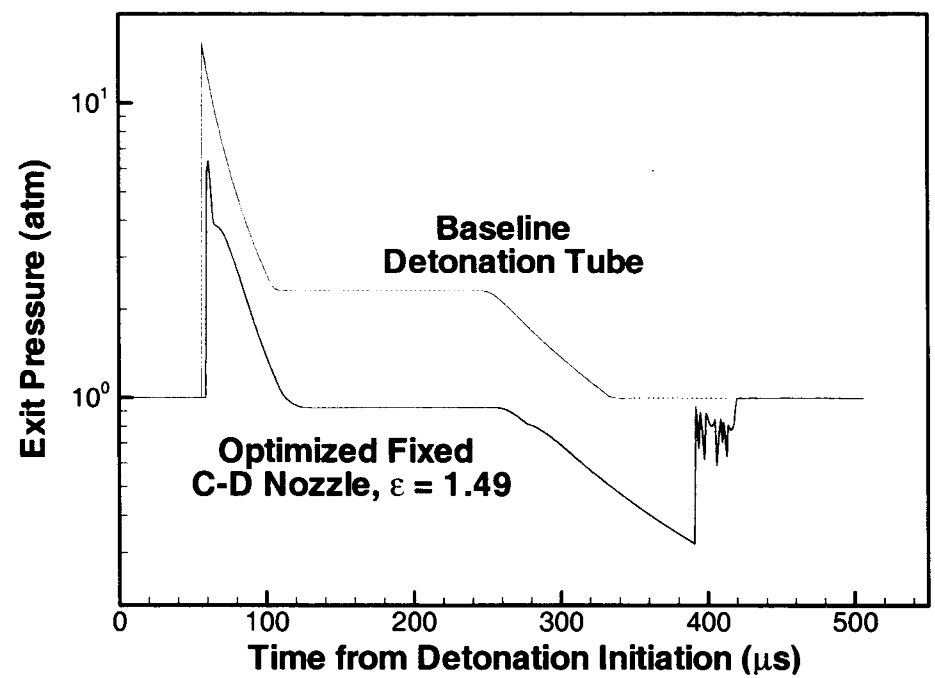
PDRE Performance at PR=1

H_2-O_2, $\phi = 1.0$, $T_{ini} = 300$ K, $P_{ini} = 1$ atm, Baseline $I_{sp} = 192.2$ s

Thrust History



Exit Pressure History

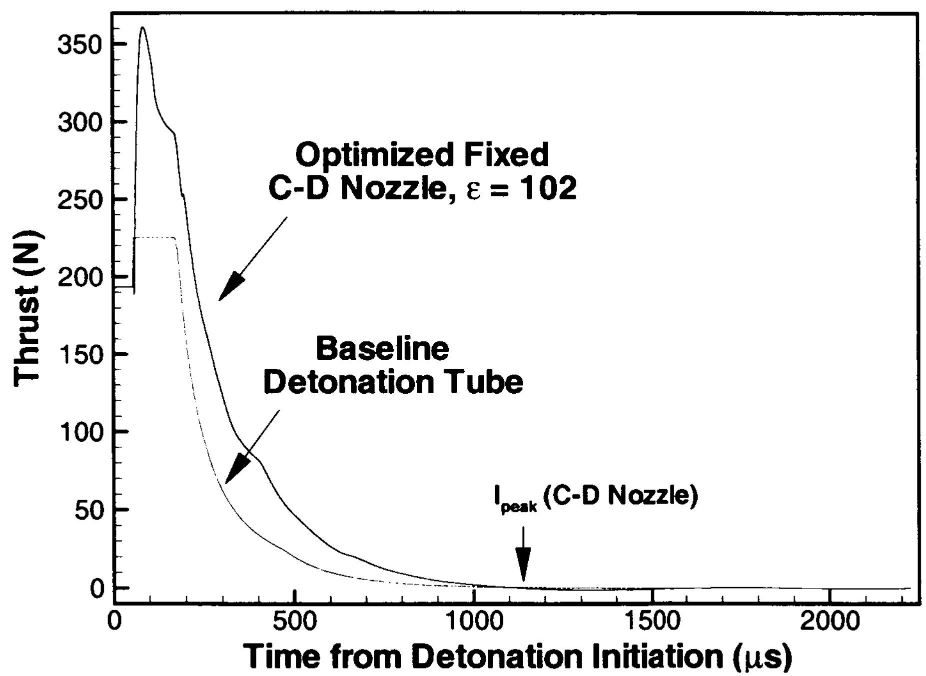


- **Optimized fixed C-D nozzle ($\varepsilon = 1.49$) can yield small improvements in specific impulse ($I_{sp} = 197.5$ s)**
- **Flow is overexpanded late in blowdown process**

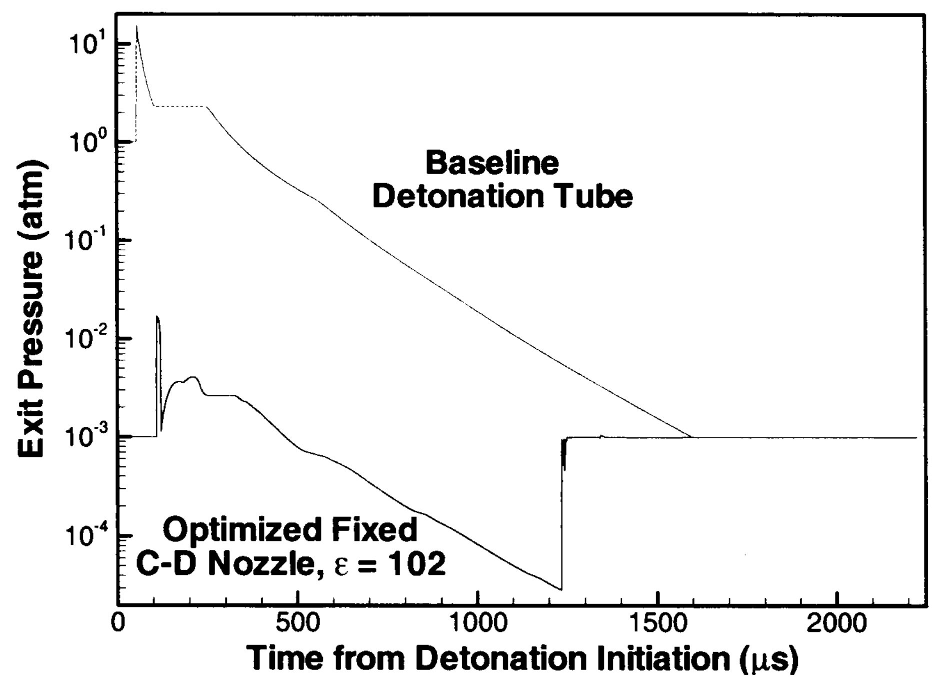
PDRE Performance at PR=1000

H_2-O_2, $\phi = 1.0$, $T_{ini} = 300$ K, $P_{ini} = 1$ atm, Baseline $I_{sp} = 262.0$ s

Thrust History



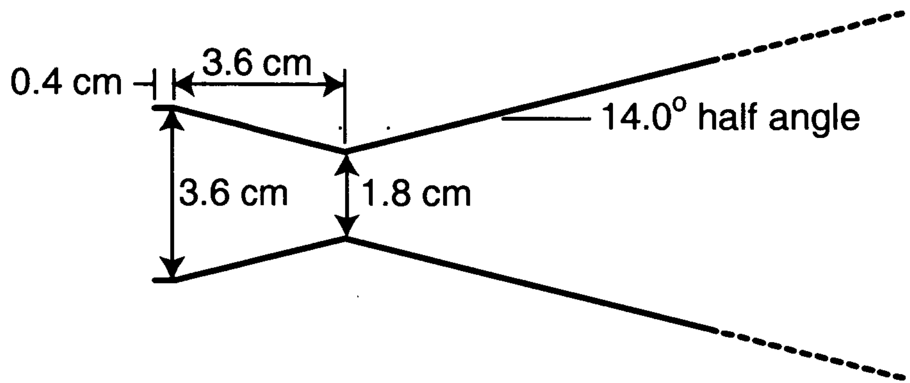
Exit Pressure History



- **Optimized fixed C-D nozzle ($\varepsilon = 102$) can yield significant improvements in specific impulse ($I_{sp} = 400.1$ s)**
- **Flow is overexpanded late in blowdown process**

Finite-Rate Chemistry Effects in SSRE Nozzles

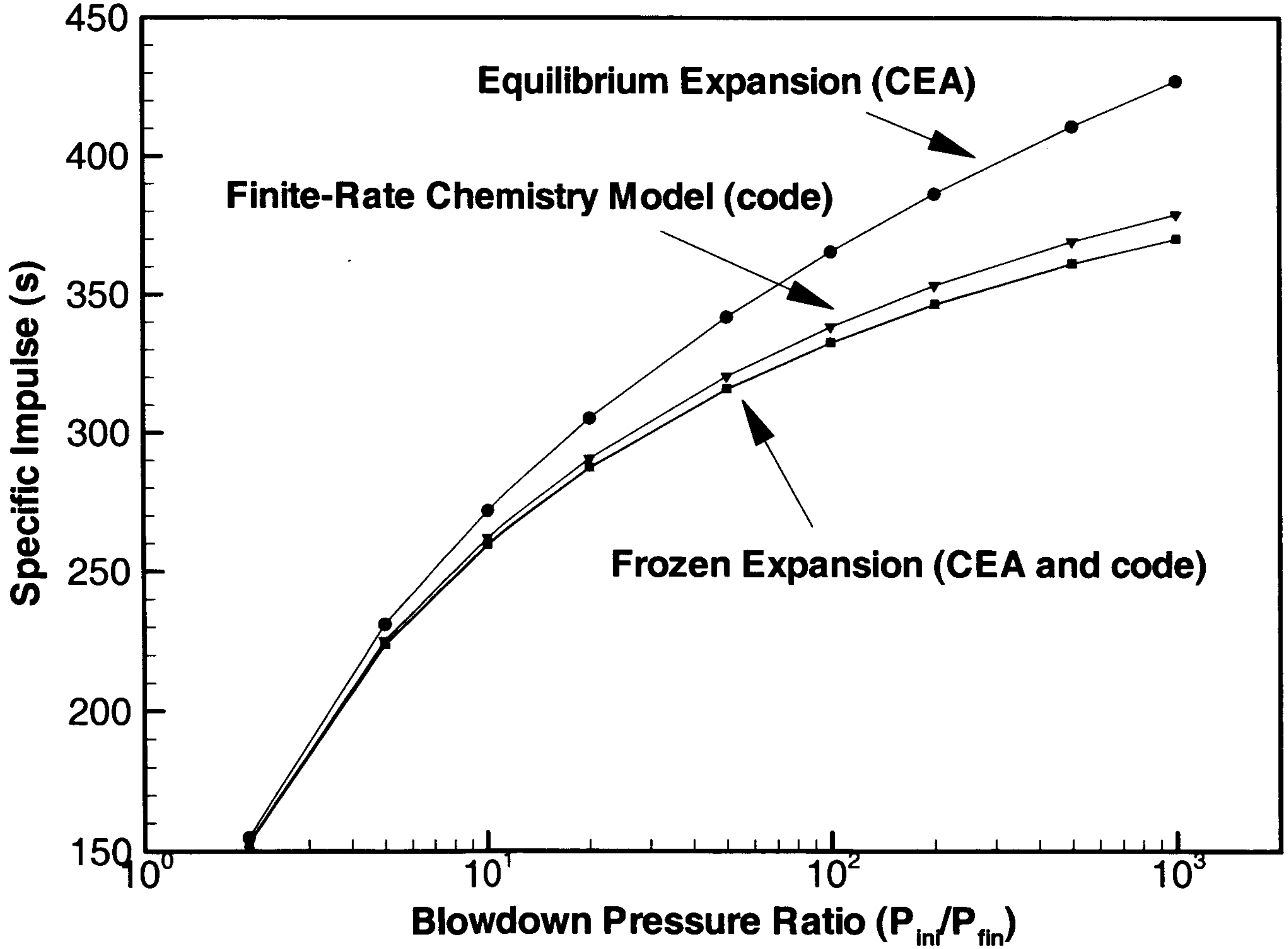
Specific Geometry Studied



- Reservoir: stoichiometric H_2-O_2 at 1 atm (equilibrium calculation by CET89)
- Inflow BC: determined from reservoir condition and MOC
- Outflow BC: determined from ambient pressure and MOC
- Nozzle half angle fixed at 14.0 degrees
- Domain size scaled depending on specified throat and exit radius
- Area ratio optimized for maximum I_{sp} at each pressure ratio
- Uniform grid spacing: $\Delta x = 0.1$ mm
- Simulation run to steady-state

Effect of F-R Chemistry on SSRE Specific Impulse

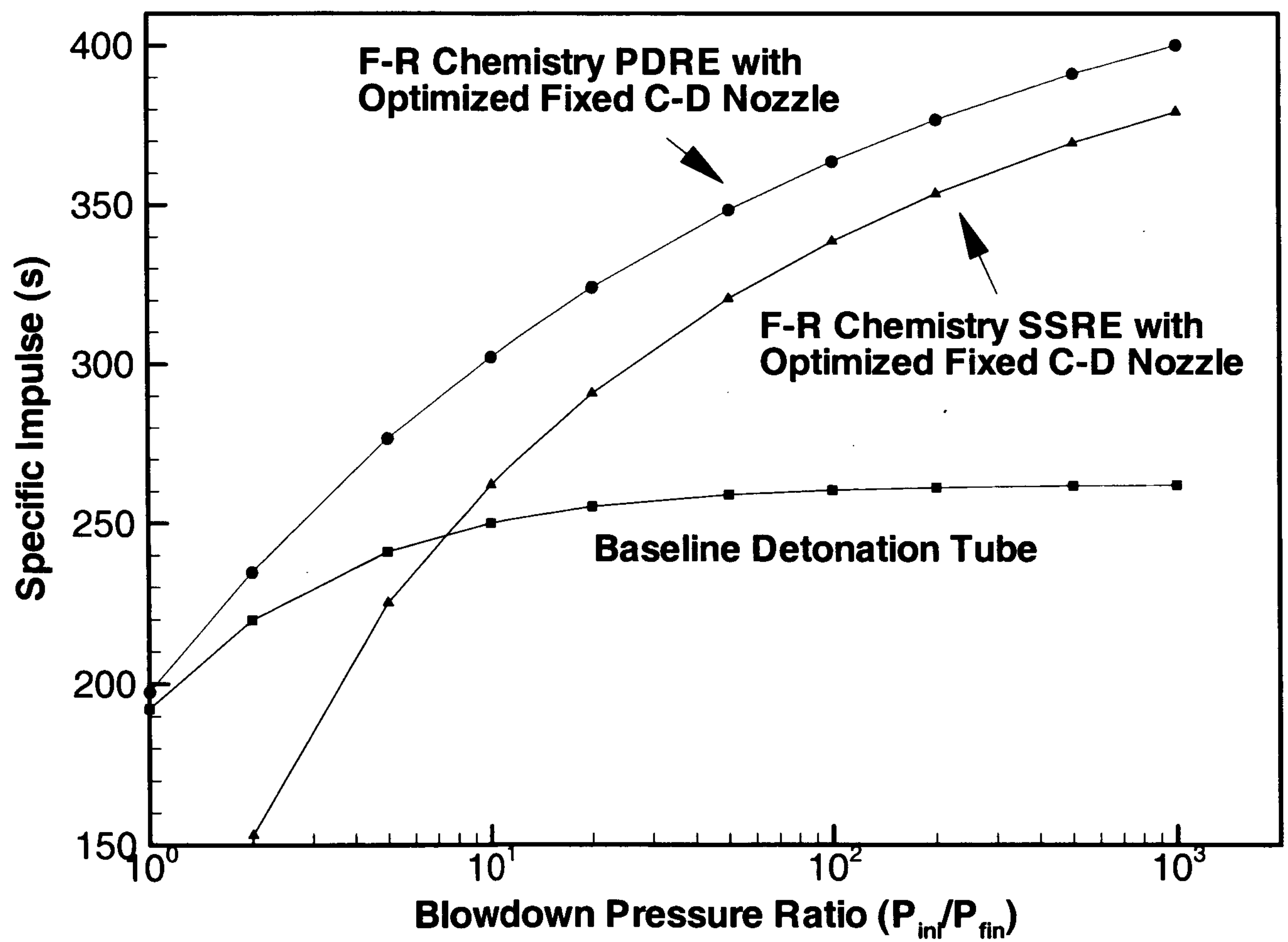
H_2-O_2, $\phi = 1.0$, $P_{reservoir} = 1$ atm



- **Finite-rate chemistry result is intermediate between the frozen and equilibrium calculations**

Rocket Specific Impulse as a Function of Pressure Ratio

H_2-O_2, $\phi = 1$, $T_{ini} = 300$ K, $P_{ini} = 1$ Atm



- **Relatively simple fixed conical C-D nozzles can enable superior PDRE performance over a wide range of pressure ratios**

PDRE Performance Study - Summary

- Nozzles are a critical performance driver in any rocket system, and the unsteady blowdown process inherent to PDREs makes nozzles a particularly important research issue.

- A quasi 1-D, finite-rate chemistry CFD code has been developed to study the effect of nozzles on the performance of PDREs.

- A converging-diverging (C-D) nozzle optimization study has been conducted for a H_2-O_2 PDRE over a pressure ratio range of 1-1000.

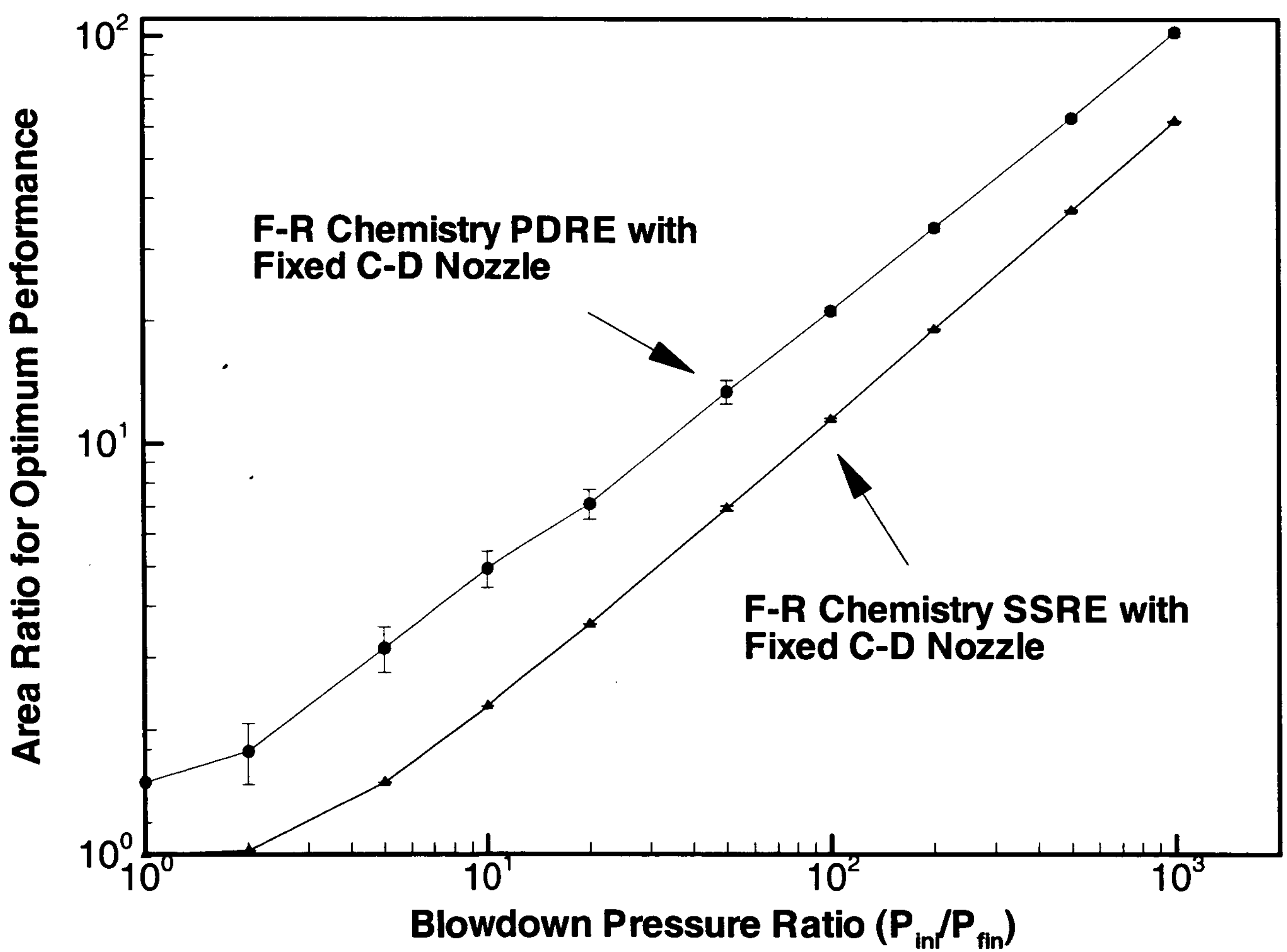
- C-D nozzles yield only marginal benefits at low pressure ratios (PR ~ 1).

- Simple conical C-D nozzles can provide significant performance improvements at higher pressure ratios.

- The results indicate that a PDRE fitted with an optimized fixed C-D nozzle can provide superior single-shot specific impulse to a comparable SSRE over a wide pressure range

Optimum Area Ratio as a Function of Pressure Ratio

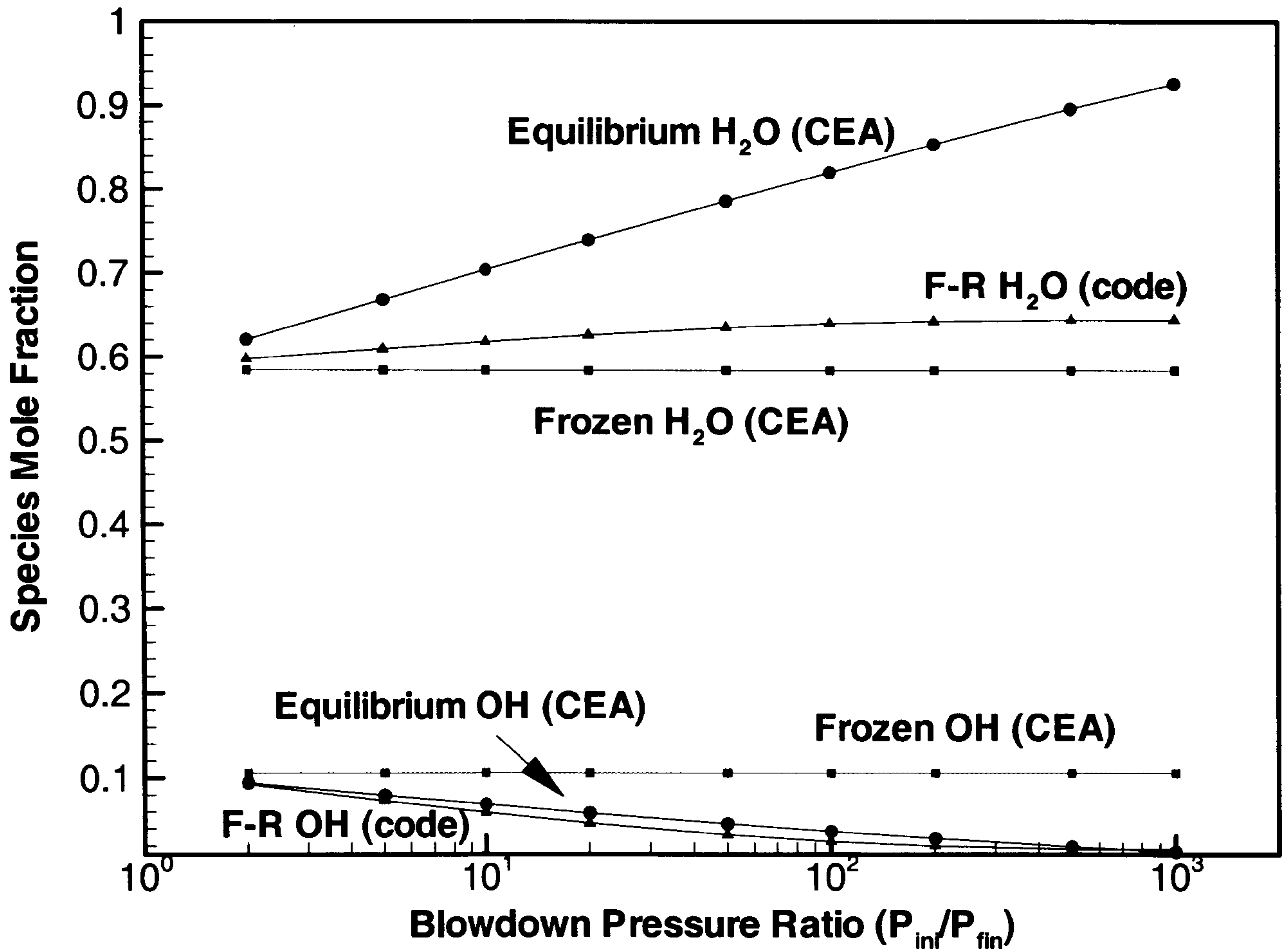
H_2-O_2, $\phi = 1$, $T_{ini} = 300$ K, $P_{ini} = 1$ Atm



- Optimum performance for a PDRE obtained at roughly 1.5× - 2.0× the area ratio of a SSRE (for the same blowdown pressure ratio)

Effect of F-R Chemistry on Exit Species Mole Fractions

H_2-O_2, $\phi = 1.0$, $P_{reservoir} = 1$ atm



- Decrease in water formation rate at lower T, P results in water concentration significantly below equilibrium values