# Turbulent Reacting Flow Modeling of Solid Propellant Rocket Motors

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An advanced space and weapon systems company

# Actively Involved in Improved Environment Modeling Approaches for Solid Propellant Rocket Motors

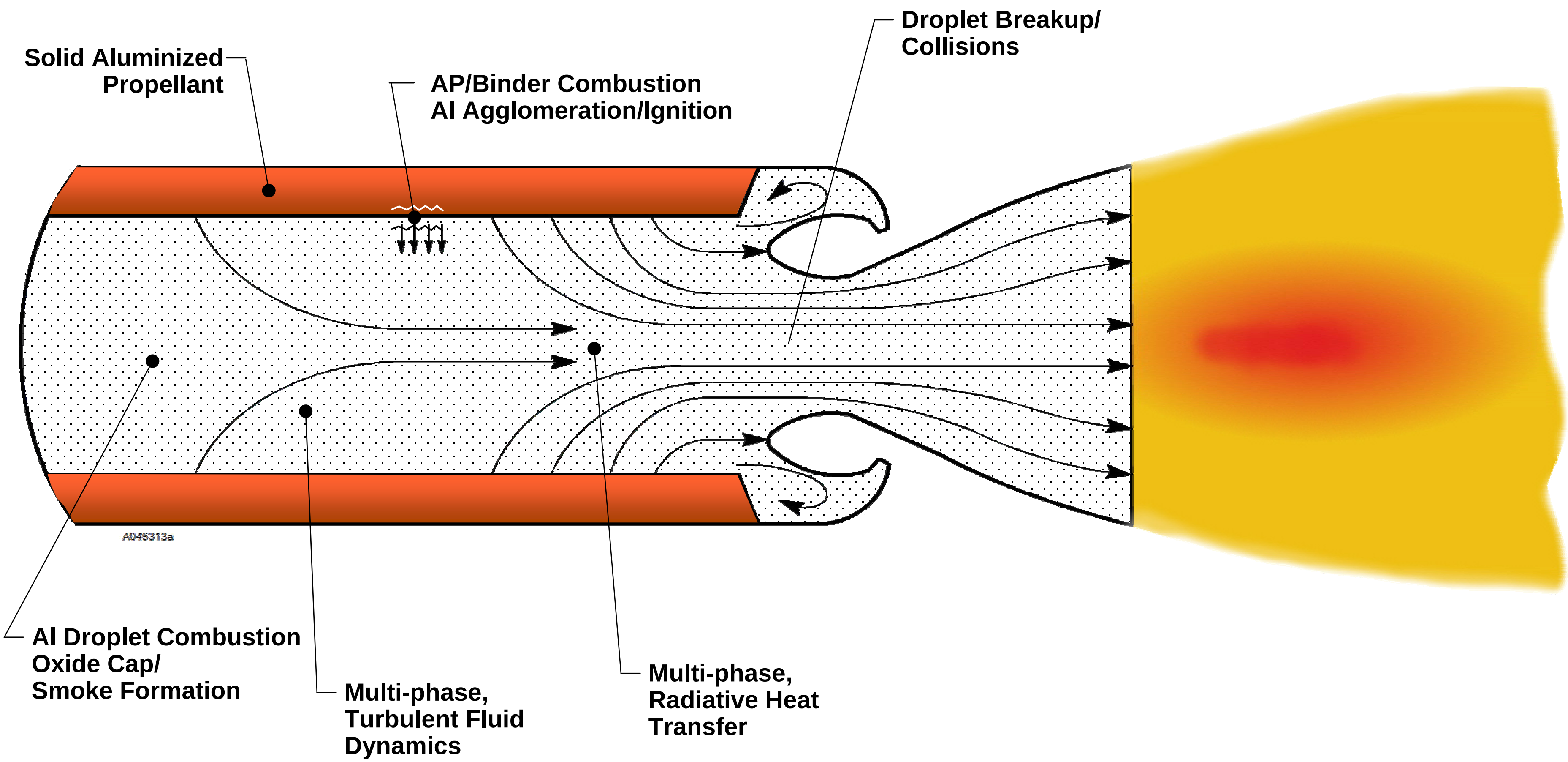
- Review published approach, based on comprehensive CFD modeling. (Sabnis, J.S., “Numerical Simulation of Distributed Combustion in Solid Rocket Motors with Metalized Propellant,” Journal of Propulsion & Power, Vol. 19, No. 1, 2003)

- Details of current areas of development cannot be shared because of ITAR restrictions

# OUTLINE

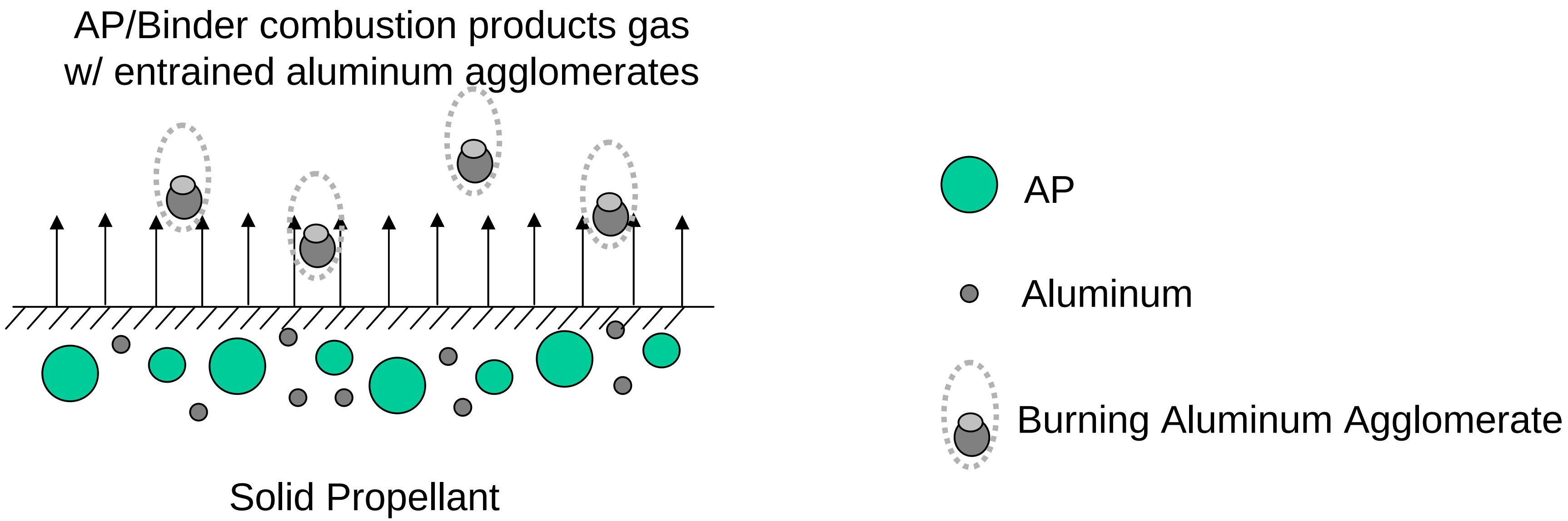
- Overview of rocket motor flowfield
- Propellant Surface Combustion
- Multi-phase, turbulent fluid dynamics
- Aluminum droplet combustion
- Droplet breakup and collisions
- Conclusions

# Major Physical and Chemical Mechanisms

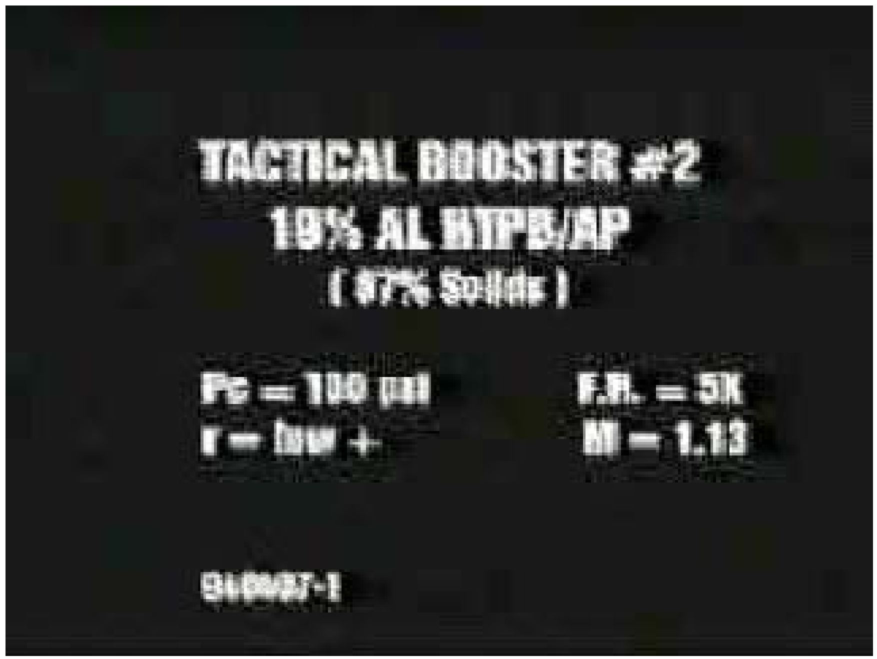


# Aluminized Propellants have both Gaseous and Condensed Phase Combustion Products

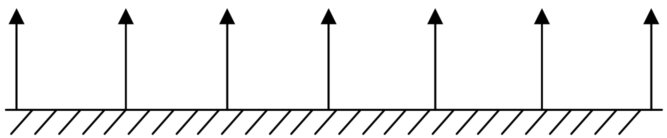
AP/binder flame is thin at propellant surface, while aluminum agglomerates are entrained into combustion gas and burn relatively slow



# Propellant Combustion Movie

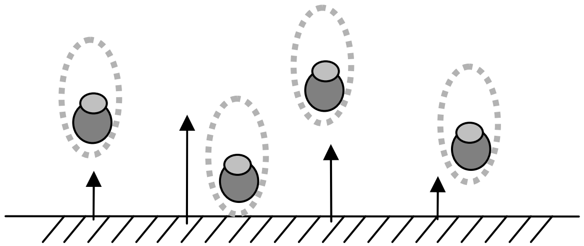


# Surface Combustion Modeling Assumptions



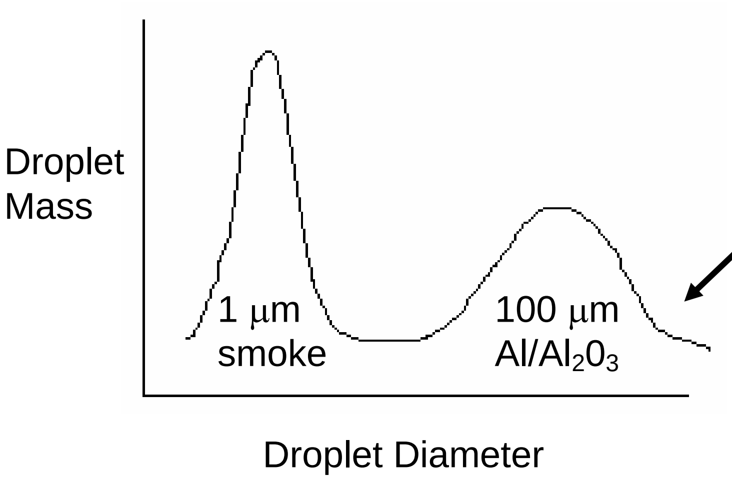
## Gas Propellant Boundary

- Gas evolution rate - $Ap^n$
- AP/Binder flame temperature ~75% of final 'mixed out' temperature
- Equilibrium gas AP/binder/$Al_2O_3$ smoke composition



## Droplet Propellant Boundary

- Aluminum ignites ~2300 K
- Aluminum agglomerates at propellant surface
  - Pocket model
  - Measured size distribution



# Turbulent Fluid Dynamics

Low-Re two equation (k-ε) model

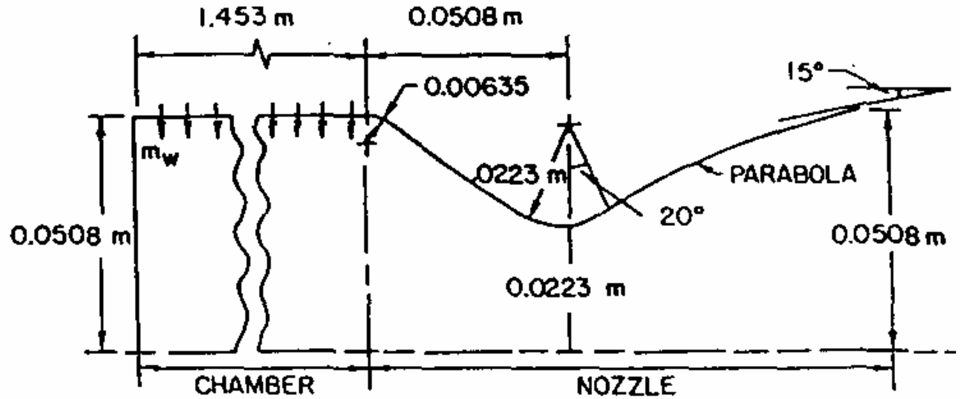
## Model Highlights

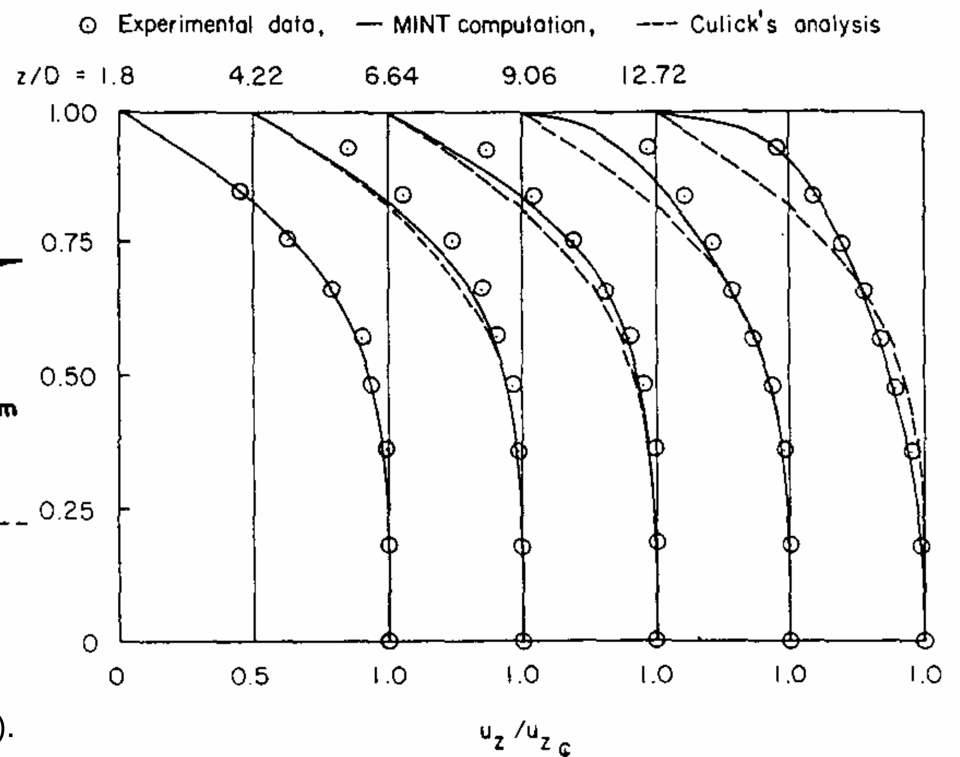
Captures transition from laminar to turbulent flow

Captures transition from 'inlet' to 'blowing wall'

Eddy Viscosity Relationship

$$\mu_\varepsilon = \frac{\rho C_\mu k^2}{\varepsilon}$$

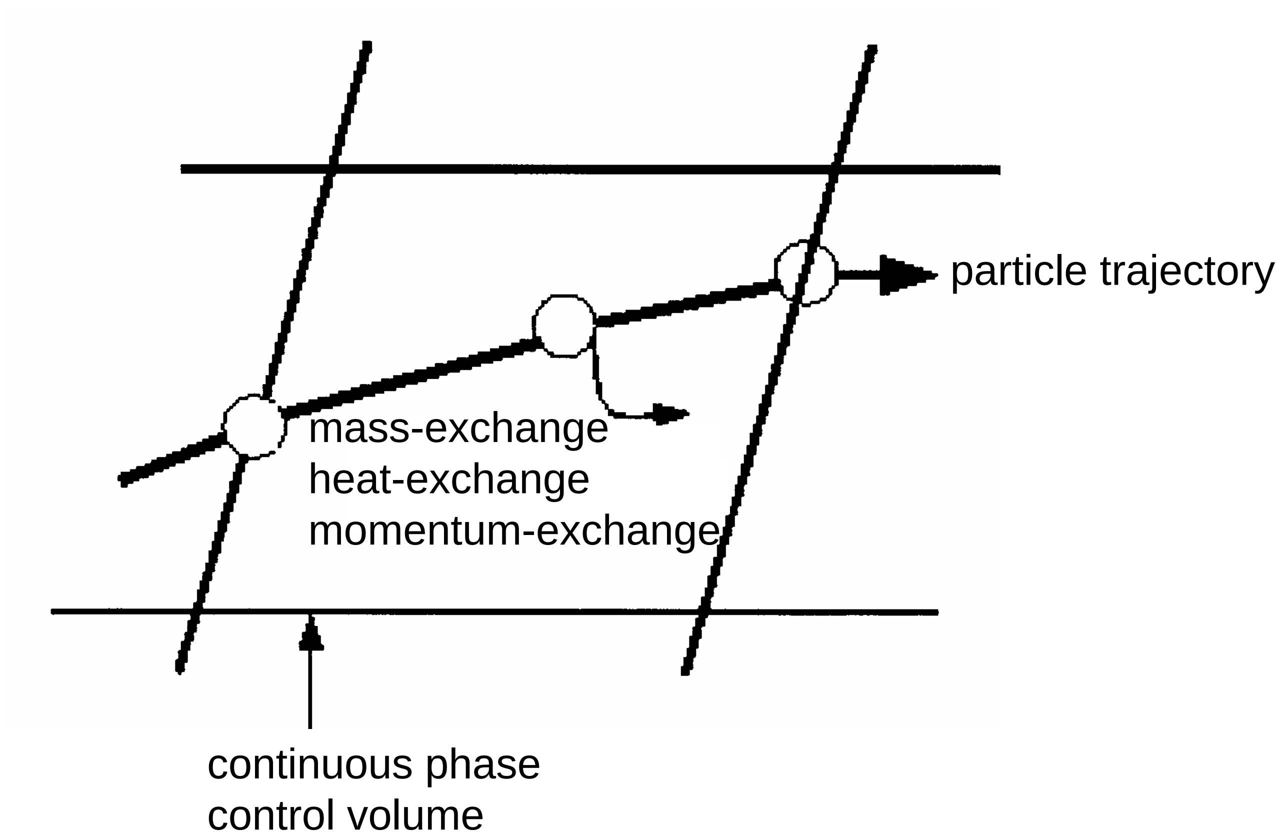



Sabnis et al. "Navier-Stokes Analysis of Solid Propellant Rocket Motor Internal Flows", J. Propulsion, Vol. 5, No. 6, (1989).

# Discrete Droplet Tracking

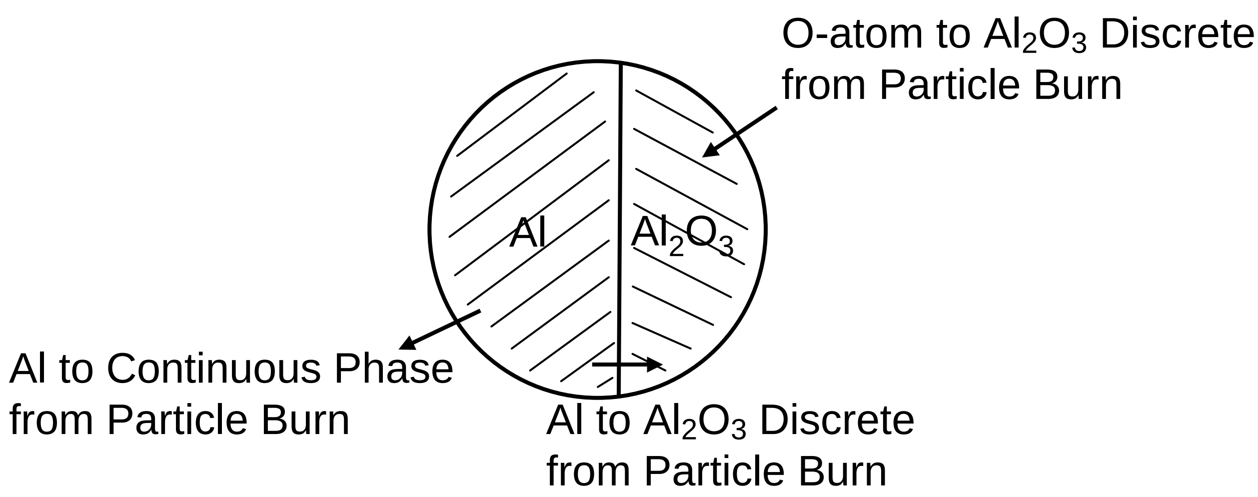
Lagrangian models assume dilute particle loading



# Aluminum Droplet Combustion

Droplet rapidly approaches boiling pt of Al during burn

1-step Al burn rate (Hermsen, 1981)
(Widener & Beckstead, 1998)



# Aluminum Particle Burn Rate

1-step models account for oxide cap effects

Modified Hermsen

$$\frac{D}{D_0} = \left[1 - \frac{kt}{D_0^{1.8}}\right]^{\frac{1}{1.8}}$$

$$k = f\left(Y_{products}, P, Sh\right)$$

Tuned to lab experiments and adjusted for solid rocket motor data

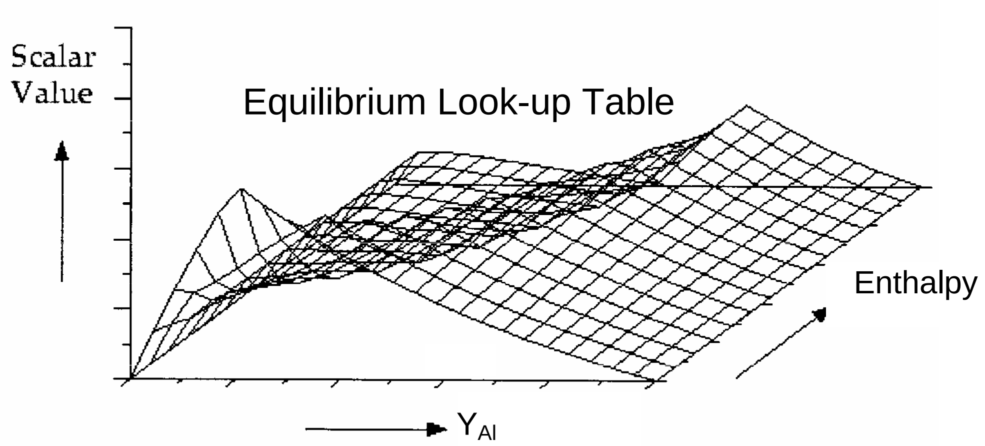
# Gas-Phase Combustion Modeling

As aluminum droplet burns, equilibrium with remaining gas is assumed

Elemental aluminum mass fraction transport equation

$$\frac{\partial(\rho Y_k)}{\partial t} + \nabla \cdot \left(\rho \vec{U} Y_k\right) = \nabla \cdot \left(\rho D \nabla Y_k\right) + \sum_i \alpha_{ki} m_{vi}$$

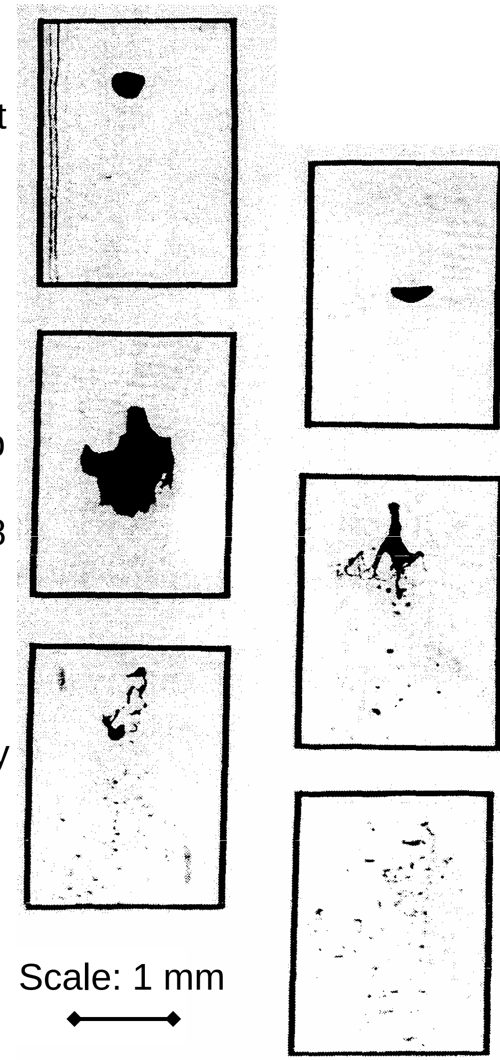
Tabular data for gas-phase composition vs Al mass fraction and enthalpy



# Droplet Breakup Results from High Speed Shear as Droplets Enter Nozzle

Breakup is controlled by the critical droplet Weber number

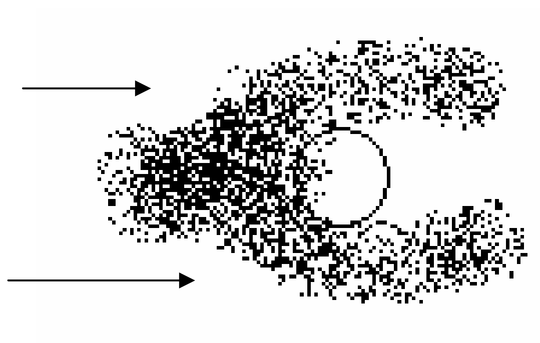
$$We_c = \frac{\rho |U_R|^2 D_P}{\sigma_P}$$




*Craig, J.E., “Conventional and Liquid Metal Droplet Breakup in Aerodynamic Nozzle Contractions,” AIAA 84-0201.

# Droplet Collisions

- Neglect large particle collisions
- Agglomeration due to collision of smoke particles
- “sweeping” model with collection efficiency



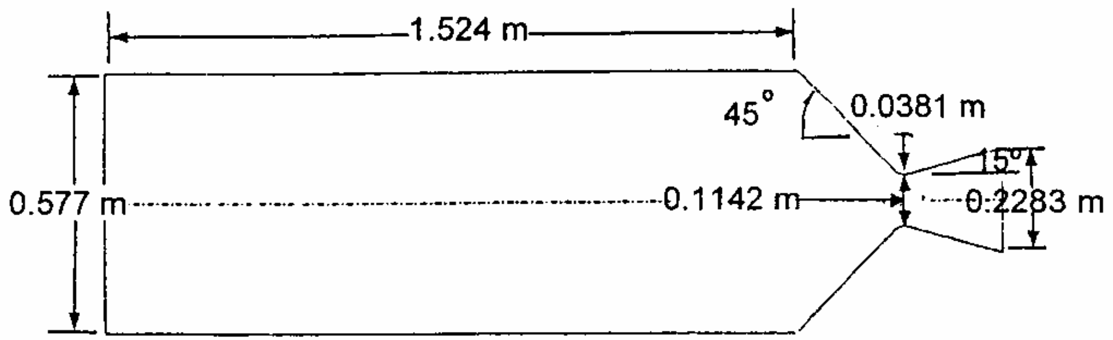
$$\frac{d\left(m_{Al_2O_3}\right)_{col}}{dt} = \pi R_p^2 \rho \left|U_R\right| Y^s_{Al_2O_3} \eta_c$$

# CFD Code Application

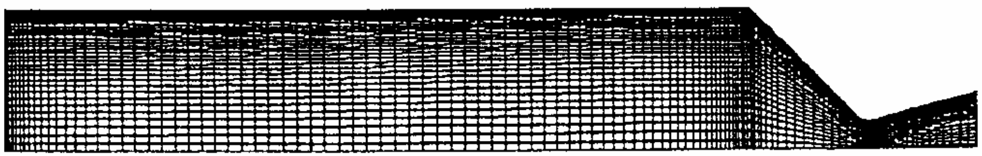
Super BATES test motor with 15% aluminum in solid propellant

**Table 1 Propellant data**

| Property | Value |
|---|---|
| Composition | |
| AP | 71.00% |
| Binder (HTPB) | 14.00% |
| AL | 15.00% |
| Density | 1794.6 $kg/m^3$ |
| Burn rate | $9.0678 \times 10^{-3}$ m/s |




Motor Geometry



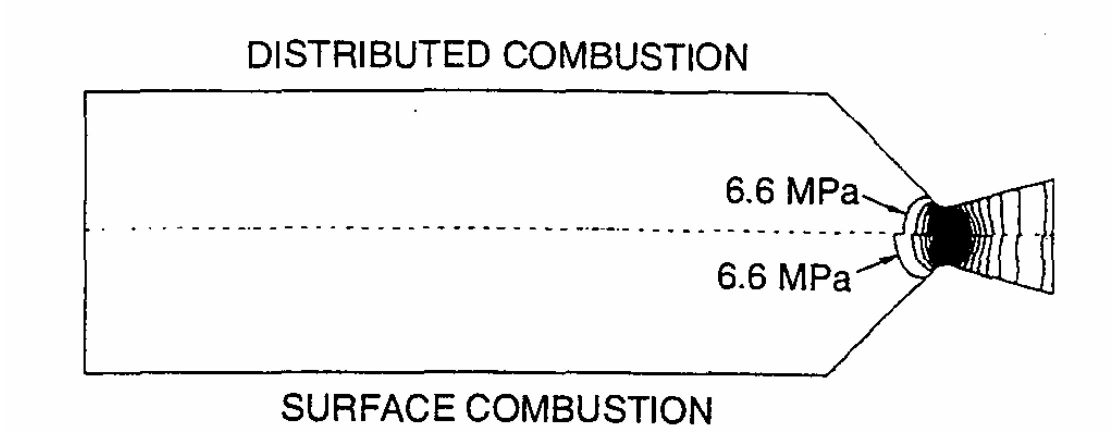
Computational Domain & Grid

*Sabnis, J.S.., "Numerical Simulation of Distributed Combustion in Solid Rocket Motors with Metalized Propellant, J. of Prop. & Power, 19(1), 2003."

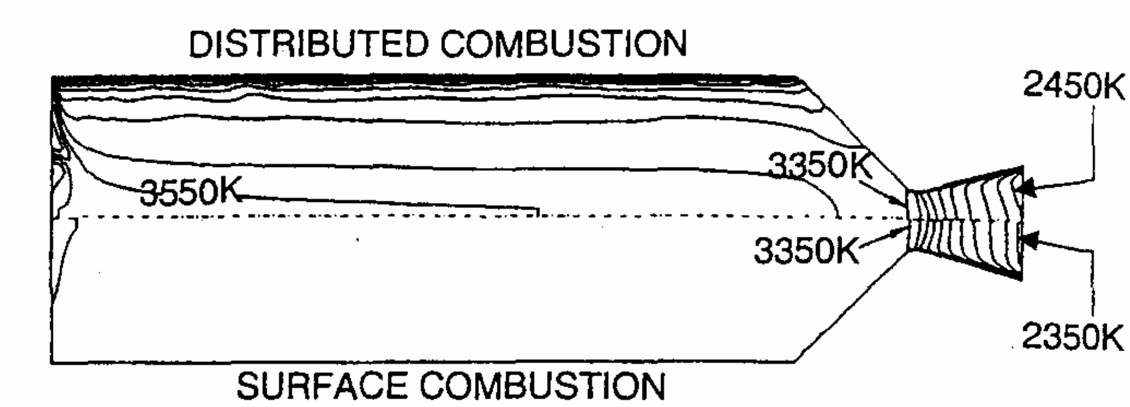
# Predicted Motor Pressure and Temperature

Distributed combustion (finite Al burn rate) shows temperature to be nonuniform

Pressure (MPa)



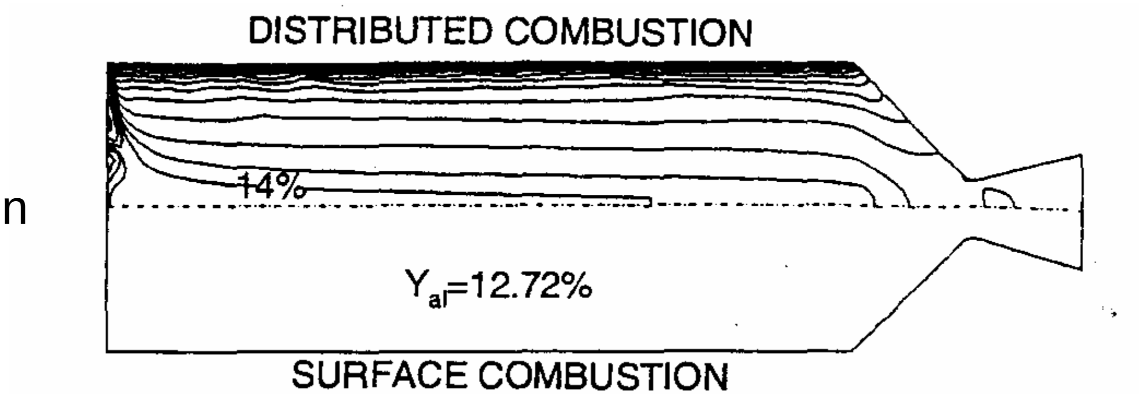

Temperature (K)



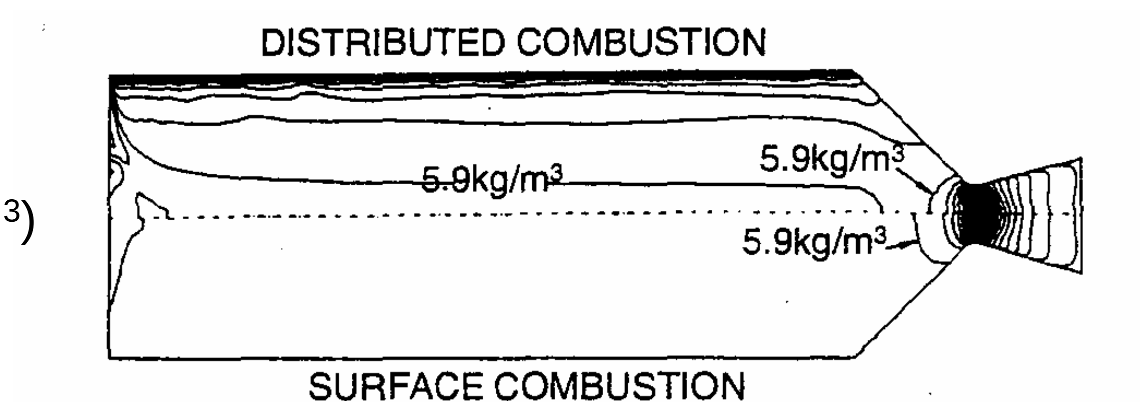
# Aluminum Mass Fraction and Density

94.3% of aluminum burns out before exiting nozzle

Aluminum Mass Fraction




Density (kg/m³)



# Conclusions

- Two-phase, distributed combustion model for metallized propellants was developed and applied
- Results of model show ability to simulate distributed combustion of aluminum in solid rocket motors
- CFD model provides a more sophisticated tool for solid rocket internal flow predictions
- CFD model still requires information regarding particle size distributions at propellant surface and fraction of metal that burns at propellant surface
- Application of the CFD model has been demonstrated, but validation of the model against carefully controlled experimental data would be nice
    - Will probably never happen
    - Must rely on post-test analyses of material response