Ablation Modeling of a Solid Rocket Nozzle

Mark E. Ewing, Galen H. Richards, Micheal P. Iverson, and Daron A. Isaac
ATK Aerospace Systems, Promontory, Utah

5th Ablation Workshop
February 28 – March 1, 2012, Lexington, Kentucky

Overview

Castor 30® motor description

Ablation model

CFD (Fluent ®) modeling for boundary conditions

Hero ablation modeling

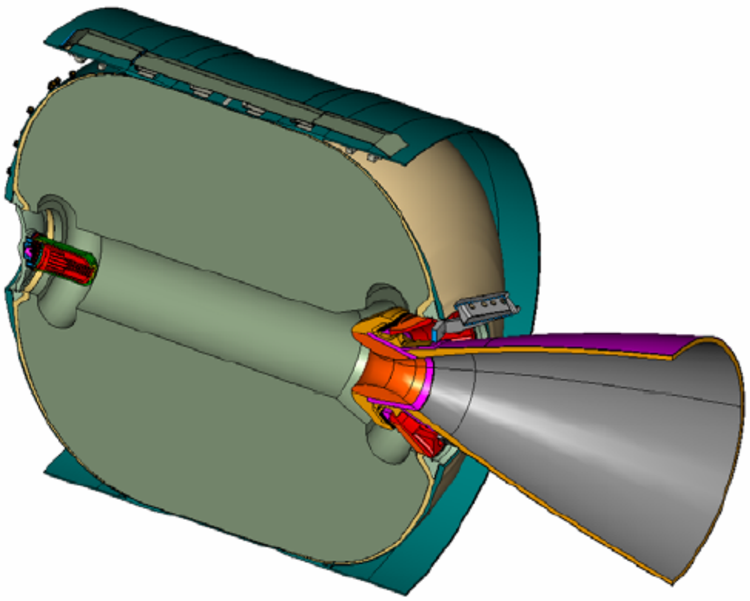
FEM Builder model coupling

Modeling results

FEM Builder coupling capabilities

On-going work

CASTOR 30



VECTORABLE NOZZLE IN-LINE UPPER STAGE BOOSTER

The CASTOR 30 is a low cost, robust, state-of-the-art upper stage motor. This development motor is 138 in. long and nominally designed as an upper stage that can function as a second or third stage depending on the vehicle configuration. The design of the CASTOR 30 uses all flight proven technology and materials.

MOTOR DIMENSIONS

Motor diameter, in.	92
Motor length, in.	138

MOTOR PERFORMANCE (73°F VACUUM)

Burn time, sec	143
Average chamber pressure, psia	762
Total impulse, lbf-sec	8.34M
Web time average thrust, lbf	58,200

NOZZLE

Housing material	Aluminum
Exit diameter, in.	47.5
Expansion ratio, average	50

WEIGHTS, LBM

Total loaded	30,998
Propellant	28,300
Case	899
Nozzle/Igniter/TVA	748
Other	1,051

TEMPERATURE LIMITS

Operation	+30°-100°F

PROPELLANT DESIGNATION

Modified TP-H8299, HTPB polymer, 20% aluminum

PRODUCTION STATUS .... In-design

Ablation Model (In-Depth)

- **Pyrolysis**

$$\frac{\partial \rho_s}{\partial t} = -(\rho_v - \rho_c)\frac{\partial \alpha}{\partial t}$$

rate of solid density change

$$\alpha = \frac{\sum_i x_i \alpha_i}{\sum_i x_i}$$

overall versus component extent-of-reaction

$$\frac{\partial \alpha}{\partial t} = \frac{\sum_i \frac{\partial \alpha_i}{\partial t}}{\sum_i x_i}$$

overall pyrolysis rate

$$\frac{d\alpha_i}{dt} = A_i e^{\left(-\frac{E_{a,i}}{RT}\right)}(1-\alpha_i)^{m_i}$$

Arrhenius model for component extent-of-reaction

- **Mass/Momentum Equation**

$$(\rho_v - \rho_c)\frac{\partial \alpha}{\partial t} + \nabla\cdot\left(\frac{\hat{\rho}_g}{\mu_g}\mathbf{\Gamma}\nabla P\right) - \hat{\rho}_g(\phi_c - \phi_v)\frac{\partial \alpha}{\partial t} - \frac{\phi\hat{\rho}_g}{k_g}\frac{\partial P}{\partial t} + \phi\beta_g\hat{\rho}_g\frac{\partial T}{\partial t} = 0$$

generation — advection (permeation) — storage

  - Neglected storage (quasi-steady)

$$(\rho_v - \rho_c)\frac{\partial \alpha}{\partial t} + \nabla\cdot\left(\frac{\hat{\rho}_g}{\mu_g}\mathbf{\Gamma}\nabla P\right) = 0$$

generation — advection (permeation)

  - 1-D simplification (with neglected storage)

$$\dot{m}_g''(x_p) = -\frac{1}{A}\int_{x_p}^{x_b} A\frac{\partial \rho_s}{\partial t}dx$$

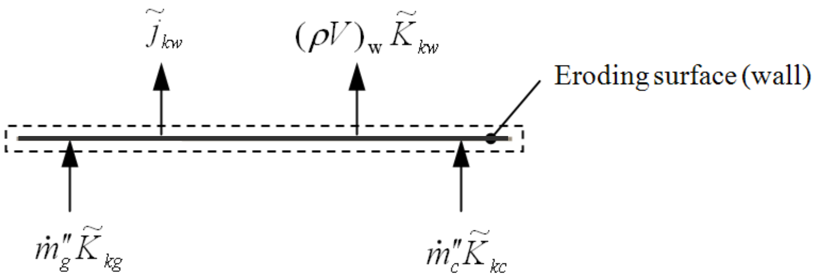
- **Energy Equation**

$$(Q_s - h_s + h_g)(\rho_v - \rho_c)\frac{\partial \alpha}{\partial t} + \hat{\rho}_g\phi\frac{\partial h_g}{\partial t} + \rho_s\frac{\partial h_s}{\partial t} + \hat{\rho}_g\mathbf{v}_D\cdot\nabla h_g - \nabla\cdot\mathbf{K}\nabla T = 0$$

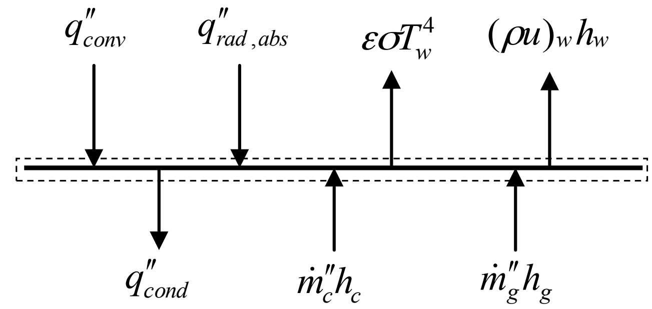
pyrolysis energy — storage — advection — conduction

Hero
(Heat Transfer and Erosion Analysis Program)

Ablation Model (Surface Model)



Control-surface for elemental balance



Control-surface for energy balance

- **Unity Lewis number**

$$q''_{cond} = \rho_e u_e C_H [H_r - (1+B')h_w + B'_c h_c + B'_g h_g] + \alpha_w q''_{rad,inc} - \varepsilon\sigma T_w^4$$

- **Equal diffusion coefficients**

$$q''_{cond} = \rho_e u_e C_H (H_r - h_w)_{f.e.g} + \rho_e u_e C_M \left[\left(\sum_i K_{ie} - \sum_i K_{iw}\right) h_i^{T_w} + B'_c h_c + B'_g h_g - B' h_w\right] + \alpha_w q''_{rad,inc} - \varepsilon\sigma T_w^4$$

- **Unequal diffusion coefficients**

$$q''_{cond} = \rho_e u_e C_H (H_r - h_w)_{f.e.g} + \rho_e u_e C_M \left[\left(\sum_i Z^*_{ie} - \sum_i Z^*_{iw}\right) h_i^{T_w} + B'_c h_c + B'_g h_g - B' h_w\right] + \alpha_w q''_{rad,inc} - \varepsilon\sigma T_w^4$$

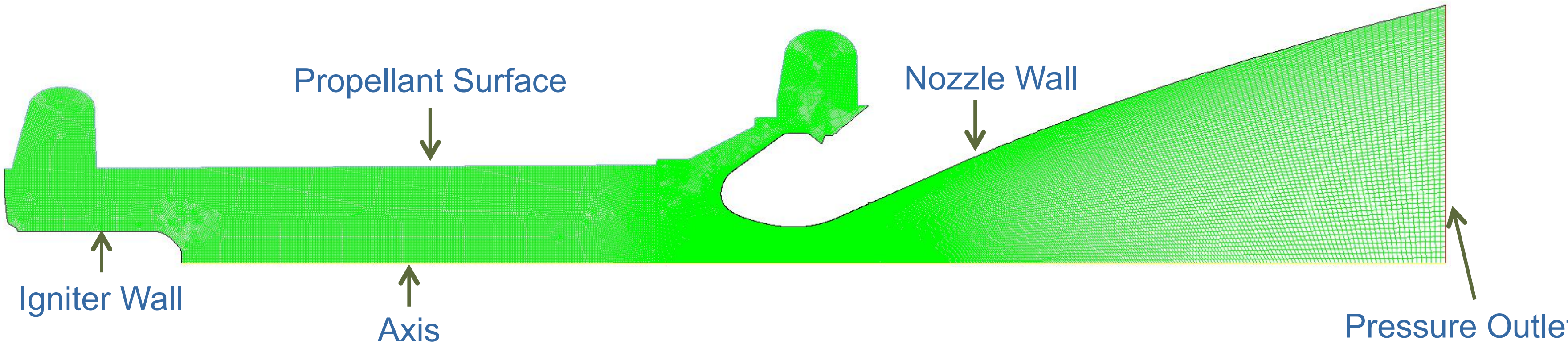
- **Surface ablation rate**

$$\dot{s}_{chem} = \frac{\dot{m}''_c}{\rho_c} = \frac{B'_c \rho_e u_e C_M}{\rho_c}$$

Thermochemistry "B-prime" tables from ACE code

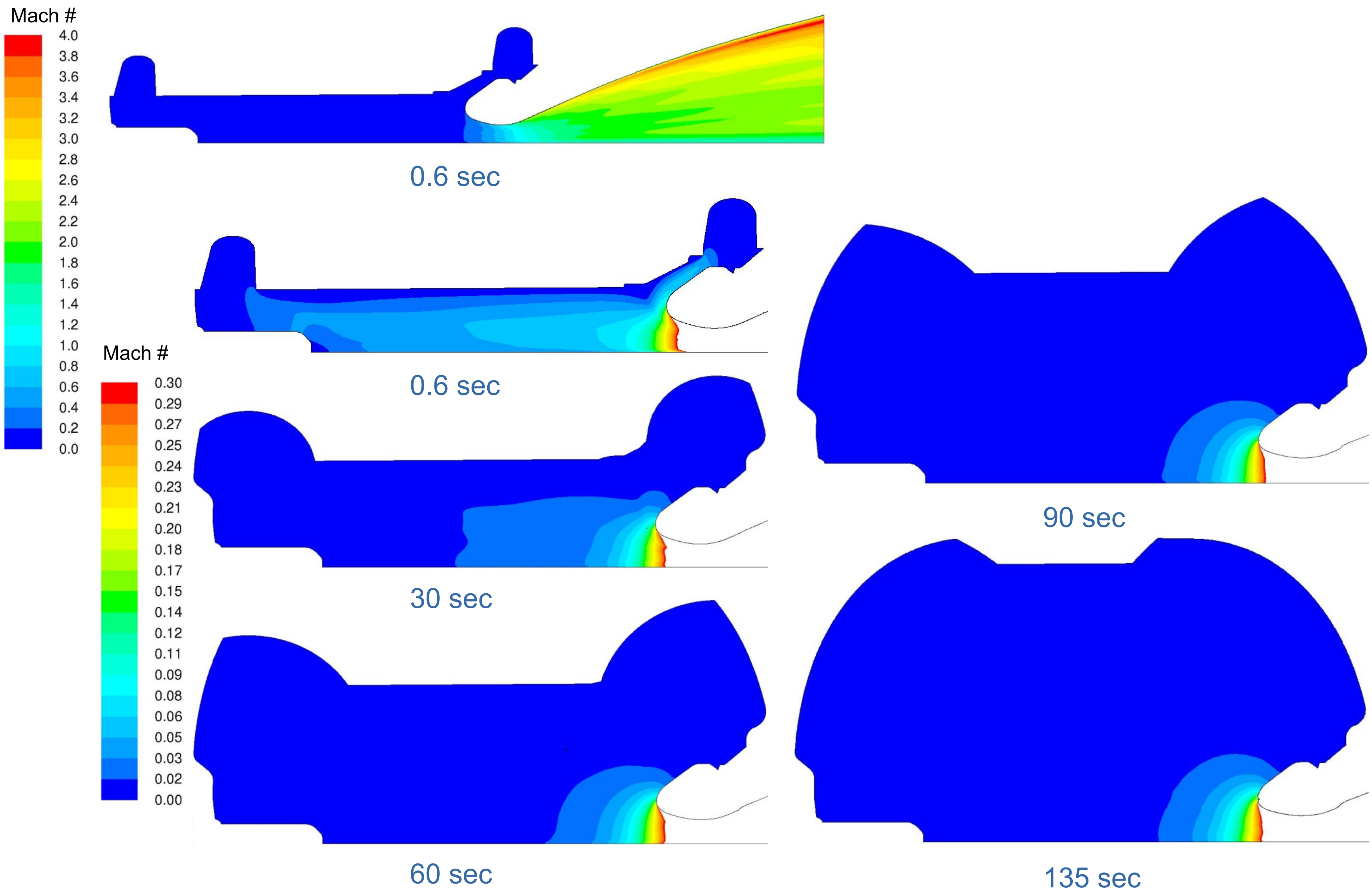
Heat transfer coefficients from CFD modeling

CFD Modeling (Approach)



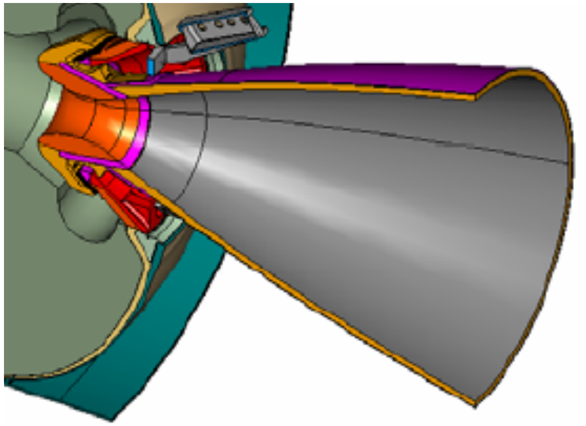
- 2D axi-symmetric, steady state, 2-phase, non-reacting CFD model
- Simulated 0.6, 15, 30, 45, 60, 75, 90, 105, 120, 135 sec burn times
- Propellant mass flow rate adjusted to match measured chamber pressure
- Gas properties from NASA Lewis chamber properties at appropriate pressures, frozen chamber C_p and molecular weight, temperature dependent thermal conductivity and viscosity
- K-Omega, SST turbulence model, y^+ values 30-100
- 34.6 wt% Al_2O_3 liquid at equilibrium
  - 24% large agglomerates, sizes from quench bomb data (40-300 microns)
  - 76% fines
- ATK droplet breakup model with size dependent critical Weber number

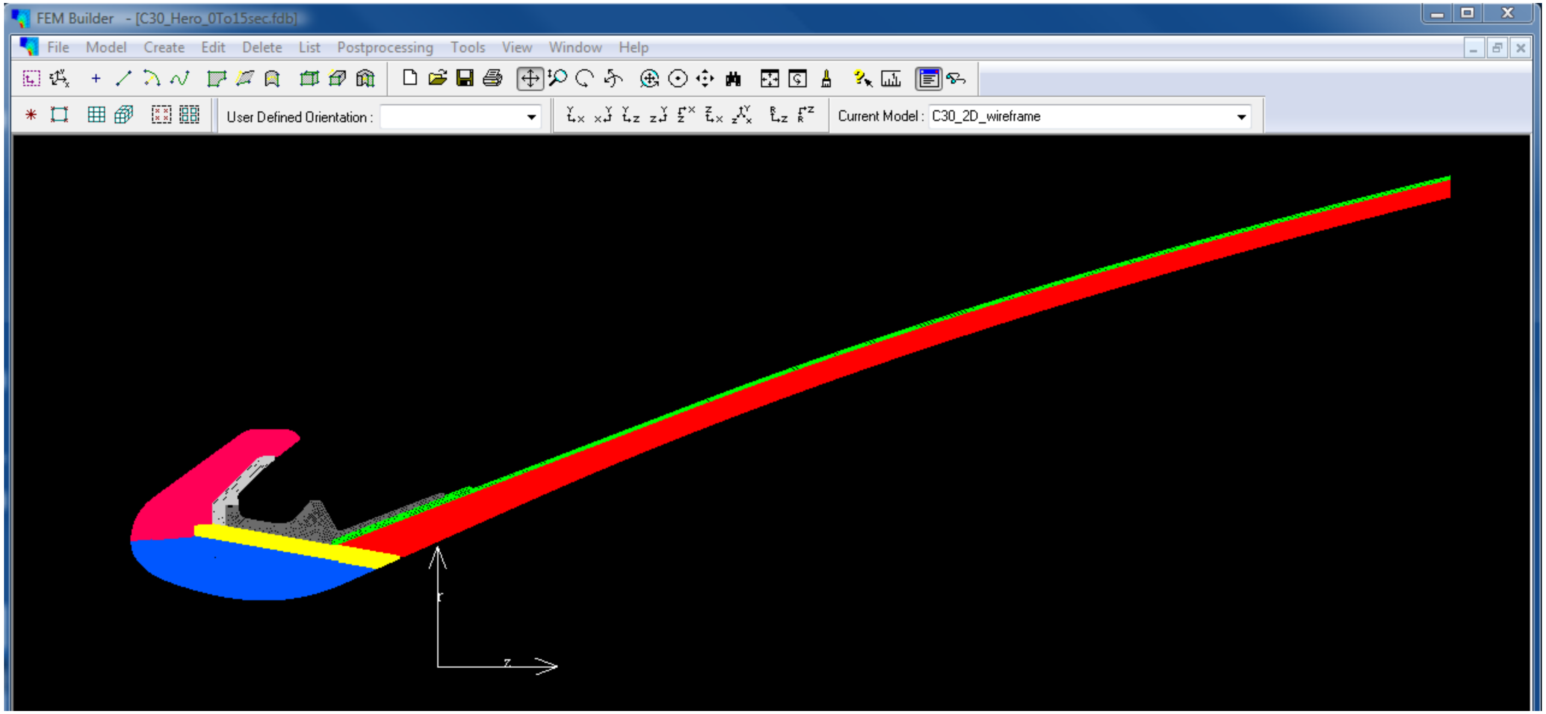
CFD Modeling (Mach #)



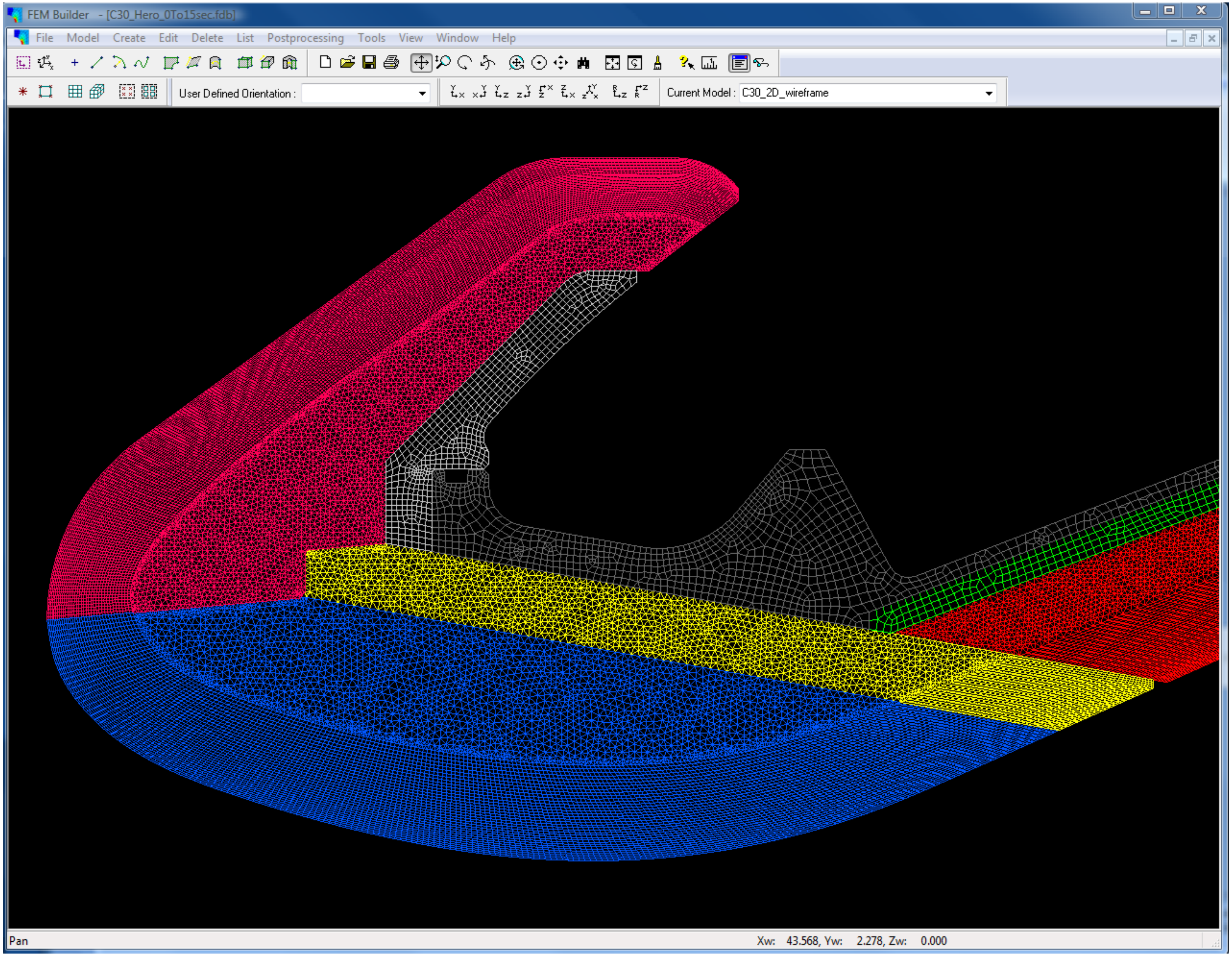
Hero Ablation Modeling (Overview)

- 81,092 elements (1st order)
- Heat transfer, pyrolysis, pore pressure, thermochemical surface ablation
- 0 – 155 sec
  - Δt = 0.01 through 1.5 sec
  - Δt = 0.05 through 155 sec





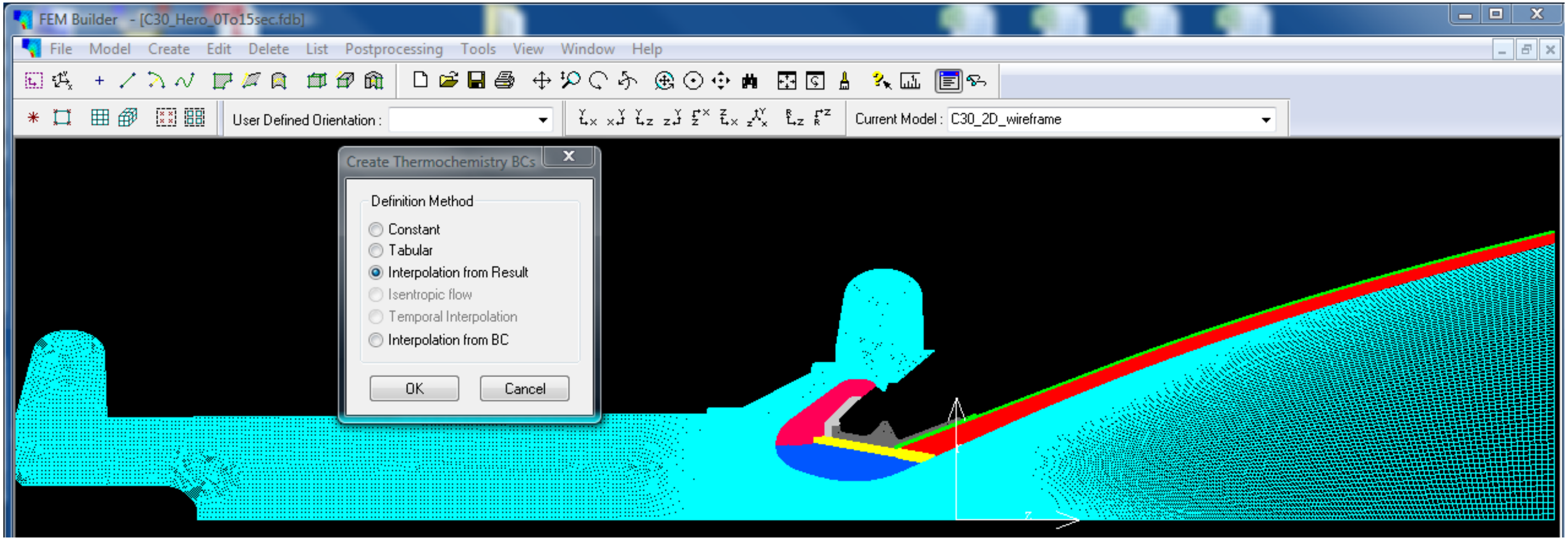
Hero Ablation Modeling (Grid Details)



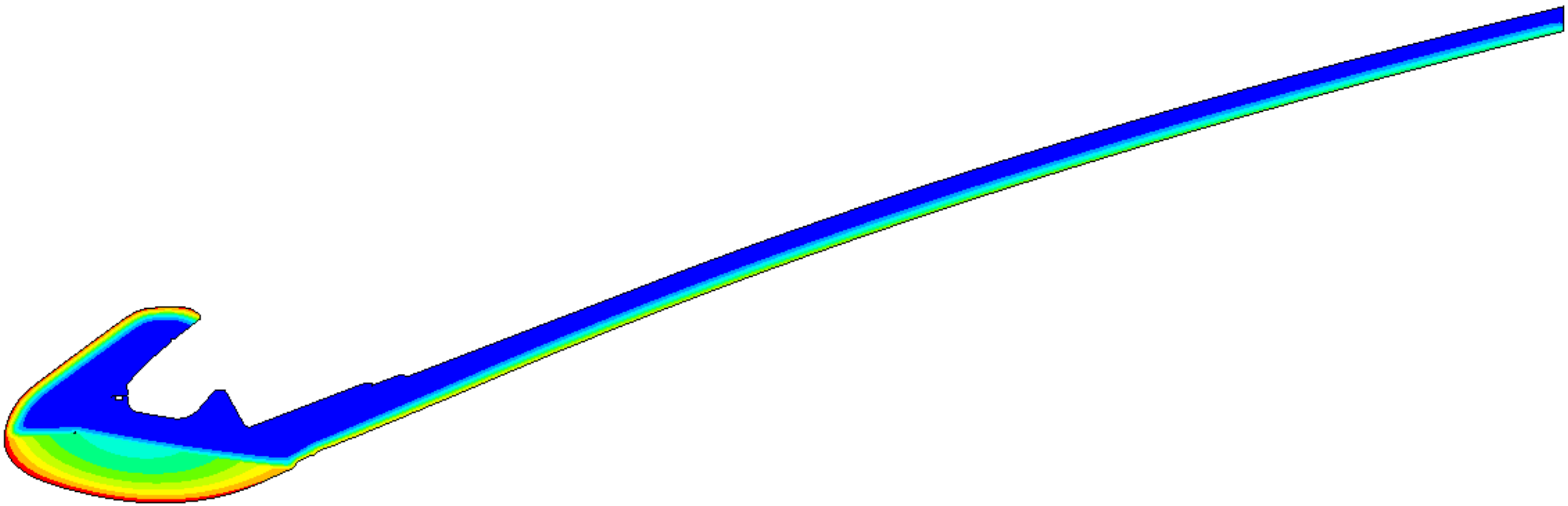
DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

FEM Builder Model Coupling

- Initial boundary conditions calculated in Fluent and imported into Hero using FEM Builder (~ 0 sec)
- Hero run for 15 sec (boundary conditions modified within Hero based on transient pressure)
- Eroded surface (at 15 sec) imported into Fluent
- Boundary conditions recalculated
  - Eroded surface
  - Propellant burn-back
  - Imported into Hero
- Process repeated in 15 sec interaction intervals through 155 sec

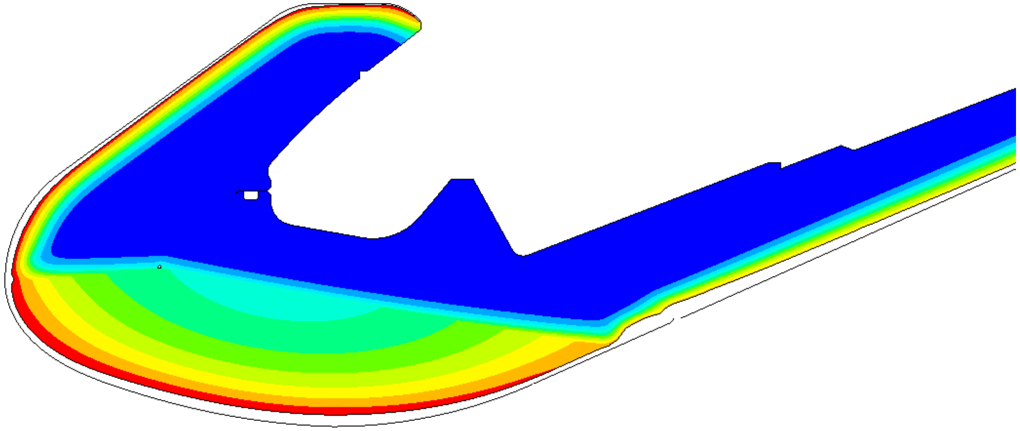


Modeling Results (Temperature Contours at Intermediate Time)

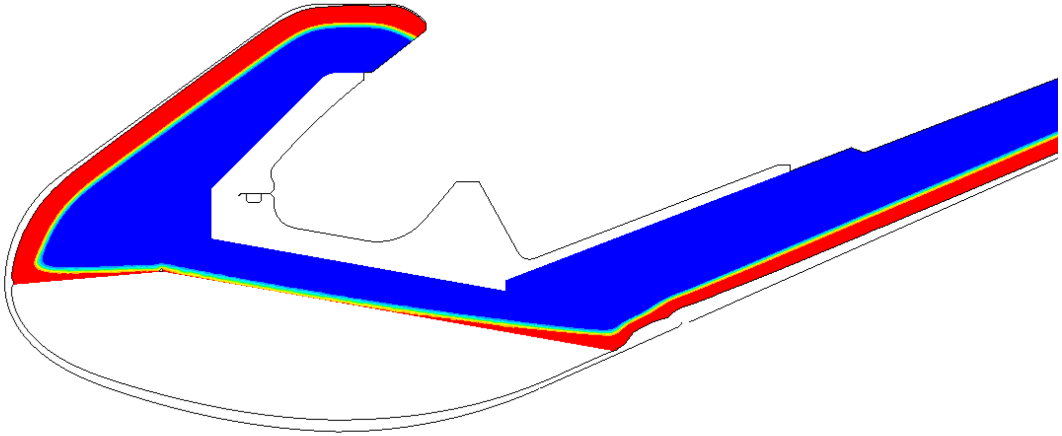


Temperature Contours of Full Nozzle

Modeling Results (Contours of Temperature and Char)

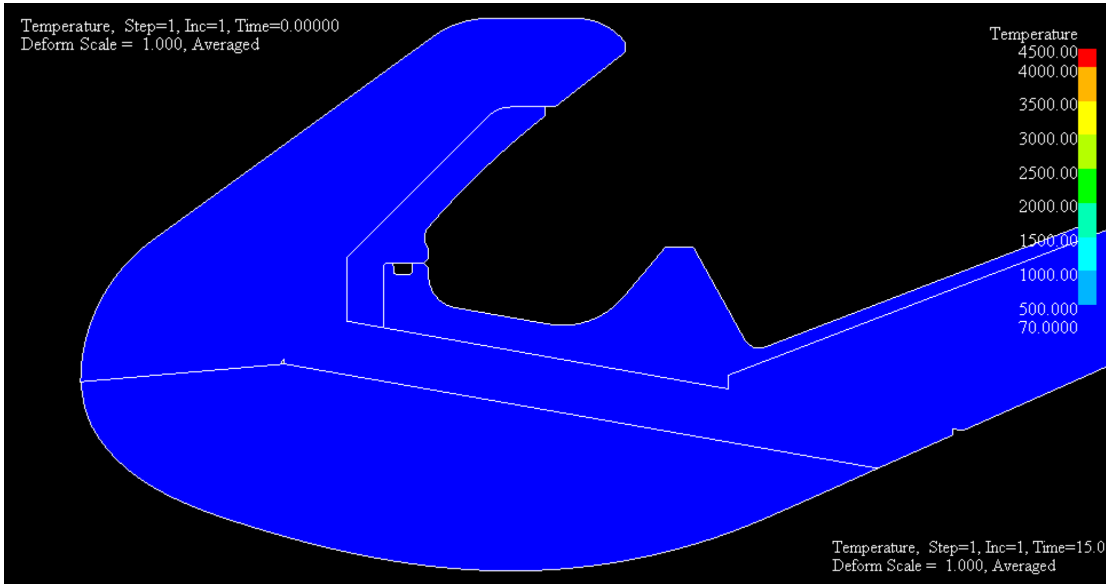


Temperature Contours in Throat Region

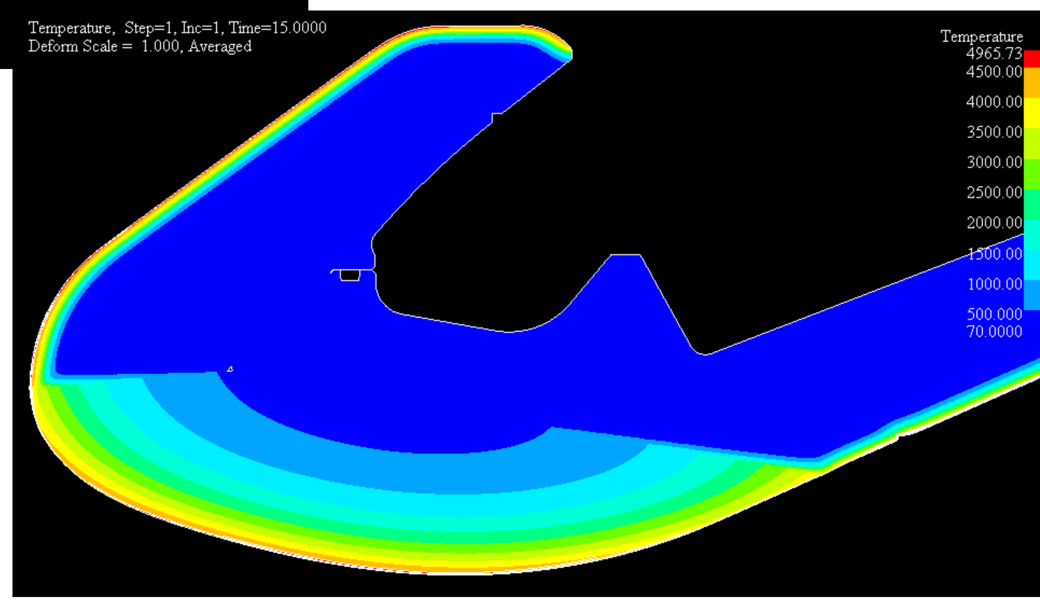


Extent-of-Reaction (Char) Contours in Throat Region

Modeling Results (Animated)



0 – 155 sec



15 – 30 sec

FEM Builder Coupled Fluid-Thermal-Structural Interaction Analysis

Solutions type/Time domain

- CFD – Quasi steady
- Heat transfer – Transient
- Structural – Quasi steady

CFD – Structural Interactions

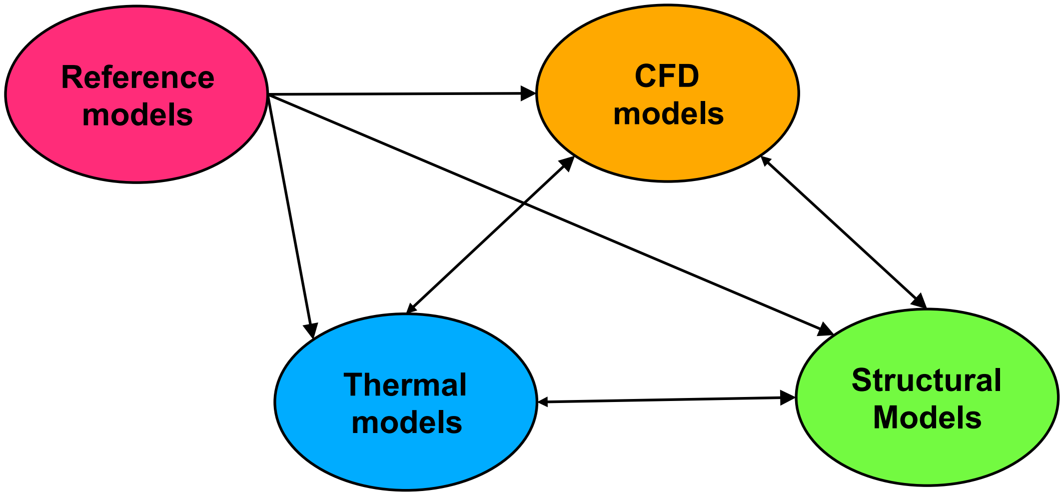
- Pressure on structure
- Displacement of CFD boundary

CFD – Thermal Interactions

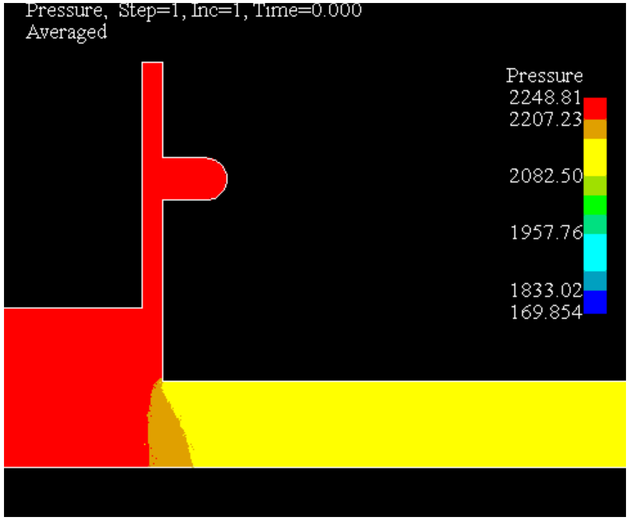
- Surface temperature for CFD model
- Heat flux from CFD model
- Ablation from thermal model (modifies CFD boundary)
- Particle impingement (Slag)

Thermal – Structural interactions

- Temperature is applied to the structural model
- Pore pressure (causes stress & permeability is strain dependent)
- Deformation of thermal model



Model Coupling Capabilities



Flow/Structural Coupling Example

On-going Work

- CFD 2-phase reacting flow
- Conjugate CFD/ablation modeling
- Grain burn-back modeling
- Additional GUI (FEM Builder) support for generation of coupling scripts
- Surface thermochemistry code development
- Slag impingement heating and erosion modeling
- Comprehensive validation against historical data
- Improved material property characterization methods

Acknowledgements and Model Availability

Acknowledgements

- This work was funded by the Air Force Research Laboratory, Solid Rocket Motor Branch at Edwards Air Force Base, under program direction of Lester Knox

Program availability

- For questions about availability contact:

Thomas Richardson, Program Manager

Thomas.Richardson@atk.com

(435) 863-3410

Charley Bown, Marketing

Charley.Bown@atk.com

(435)863-5274