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Update on gas flow and heat transfer modeling in small arms systems

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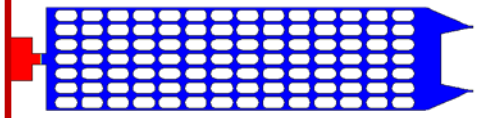
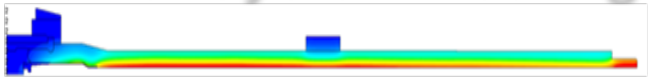
May 25, 2011

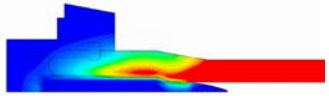
Computational Fluid Dynamics Modeling in Small Arms

Propellant combustion and motion

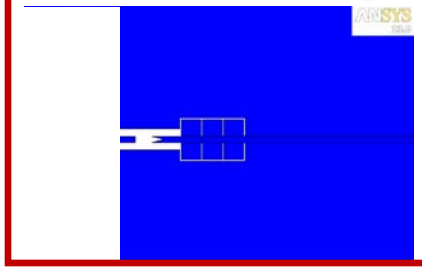


Barrel/System heating

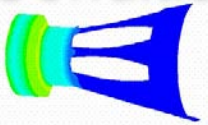




Muzzle flow with chemistry

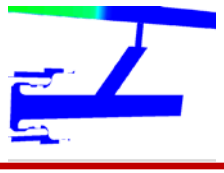


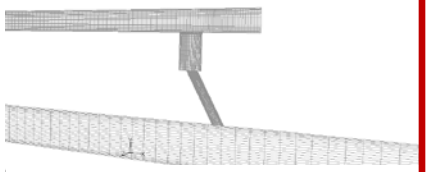
Recoil Conditions



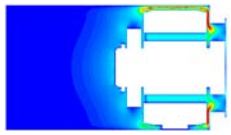
Internal gas flow

- Mechanism actuation
- Particle flow/erosion

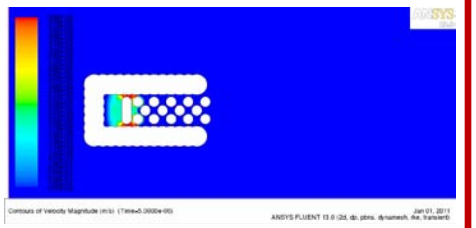




Auxiliary Devices



Multiple projectile motion



Malcolm Baldrige National Quality Award 2004 Award Recipient

CFD Modeling in Small Arms

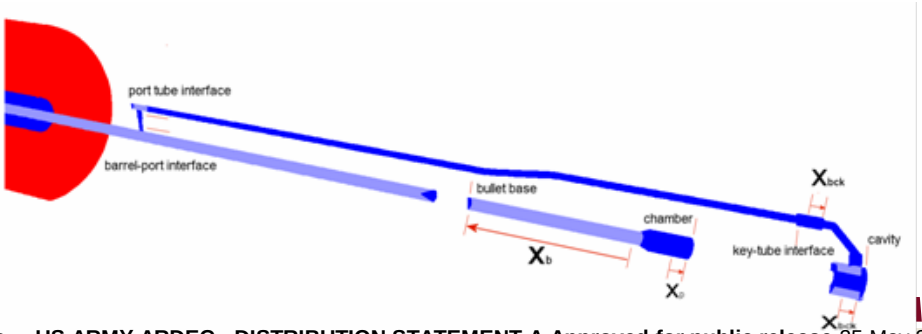
- Internal weapon gas and particle flow
- Heat transfer
- Muzzle flow including reacting flow
- Multiple projectile/particle motion, interaction and applications
- Improved propellant burn models
- Future Plans

CFD Modeling in Small Arms

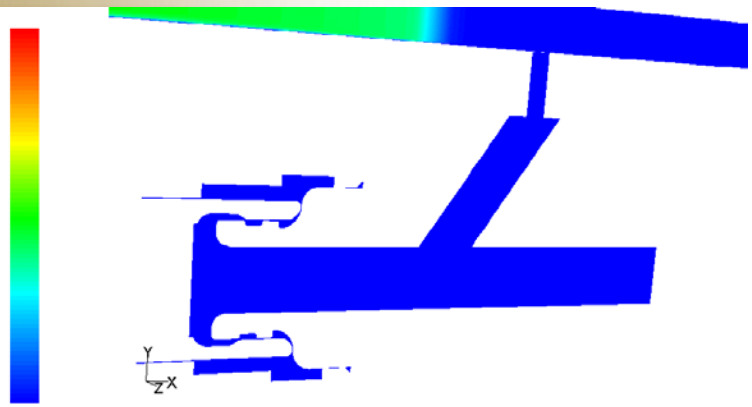
Internal gas flow
- Mechanism actuation
- Particle flow/erosion

Internal gas flow modeling

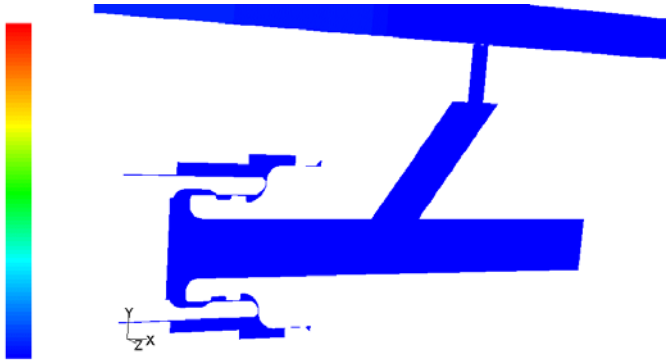
- Simulate internal gas flow that drives operation of weapon system
  - Simulate actuation of weapon mechanisms and estimate unlocking velocities
  - Virtually measure the pressures, temperatures and flow rates throughout the system
  - Estimate relative timing of events during system operation
  - Investigate transport of particulate matter with flow and related particle impact based erosion



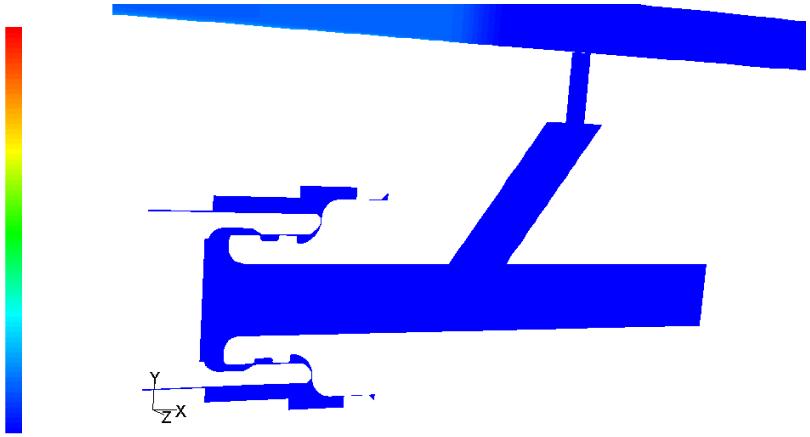
Animations of flow conditions near gas block in M249



Velocity

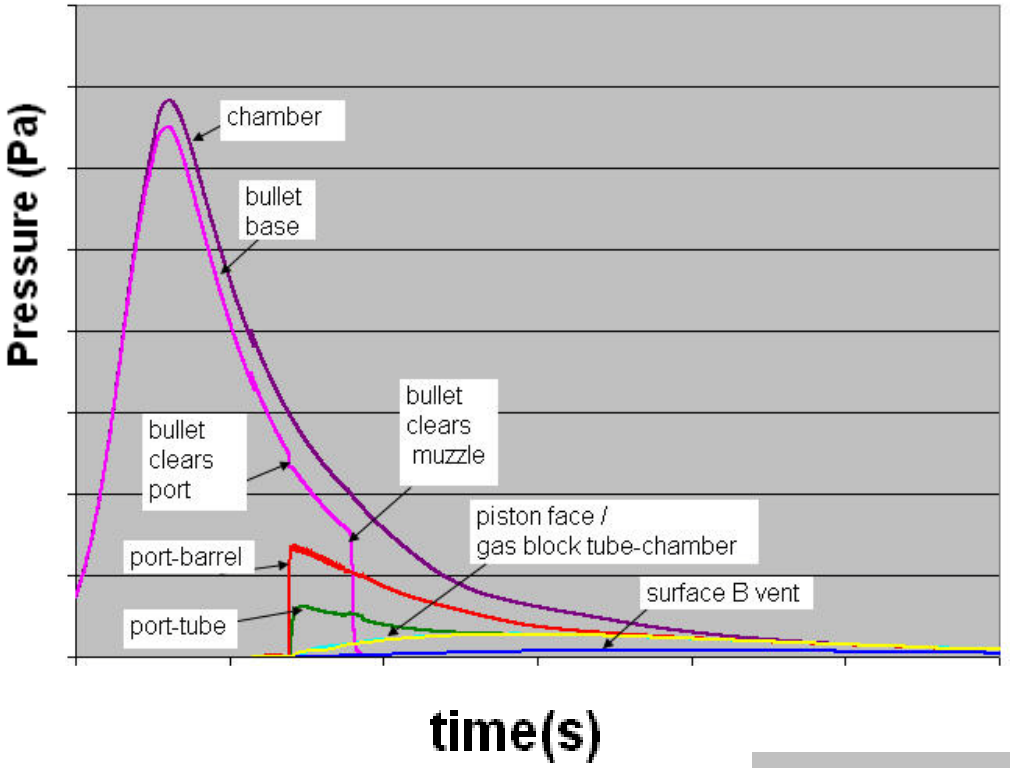


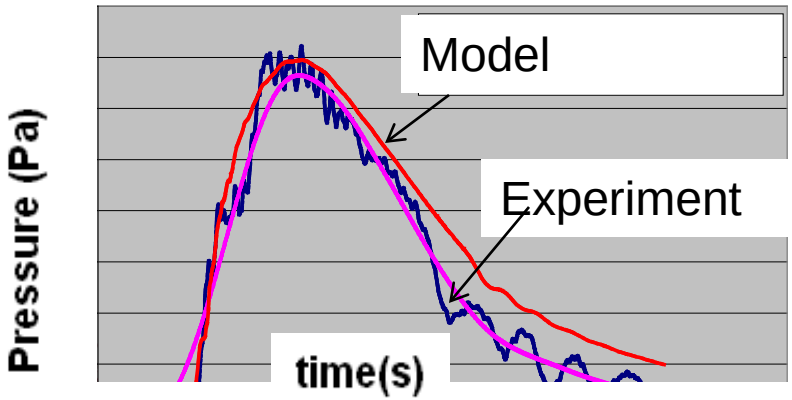
Pressure



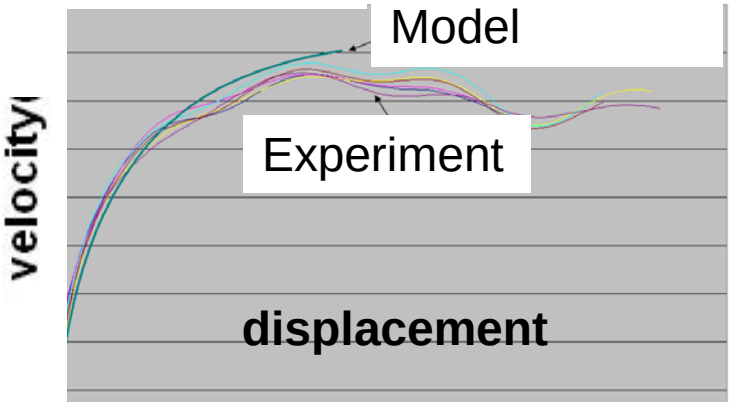
Temperature

Representative data from M249 model



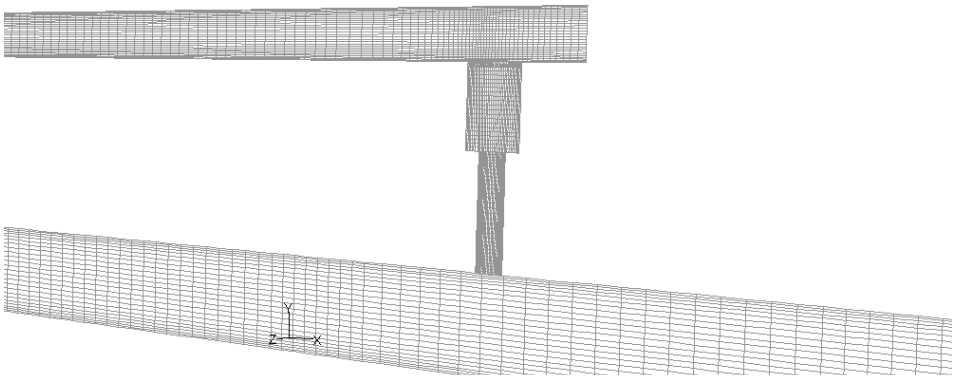


Pressure results



Bolt motion

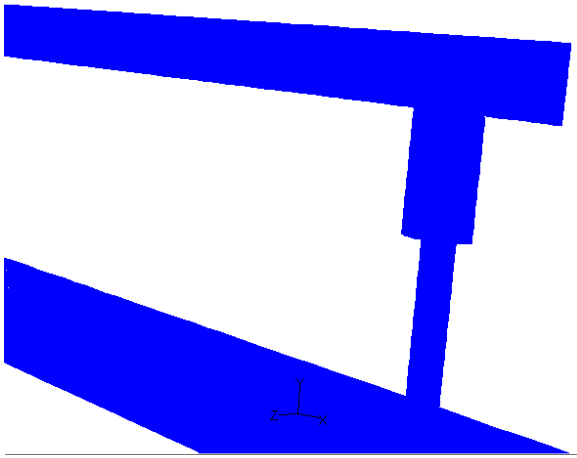
Particle flow in port area



- Establish trends in particle flow patterns
- Investigate methods to control particle motion

Particle matter carried with gas flow

- Investigate erosion effects due to particle impact



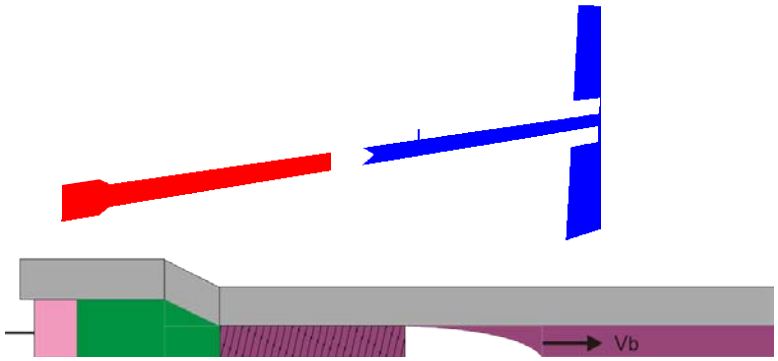
Particle impact based erosion

CFD Modeling in Small Arms

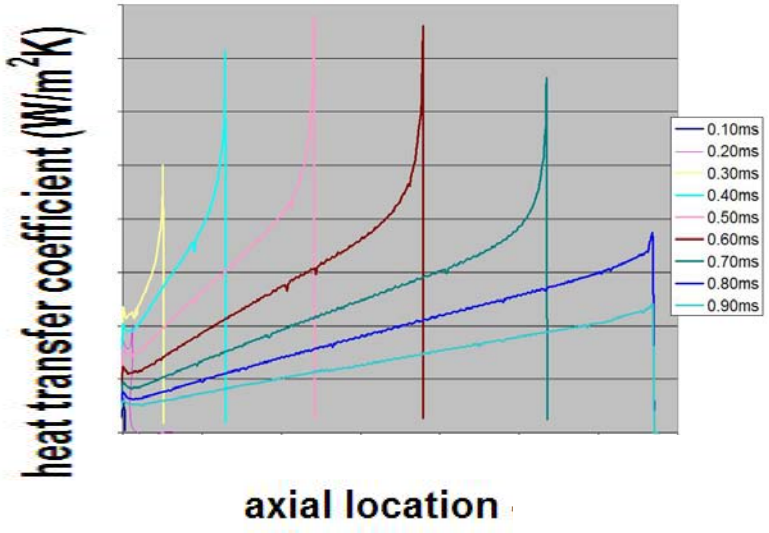
Barrel/System heating

Heat transfer for multiple rounds fired

- Investigate heat flow patterns and temperature field as multiple rounds are fired at various firing rates
  - Investigate effects of geometry changes
  - Investigate effect of various materials
- Two steps
  - Fluid flow and heat conduction for single shot



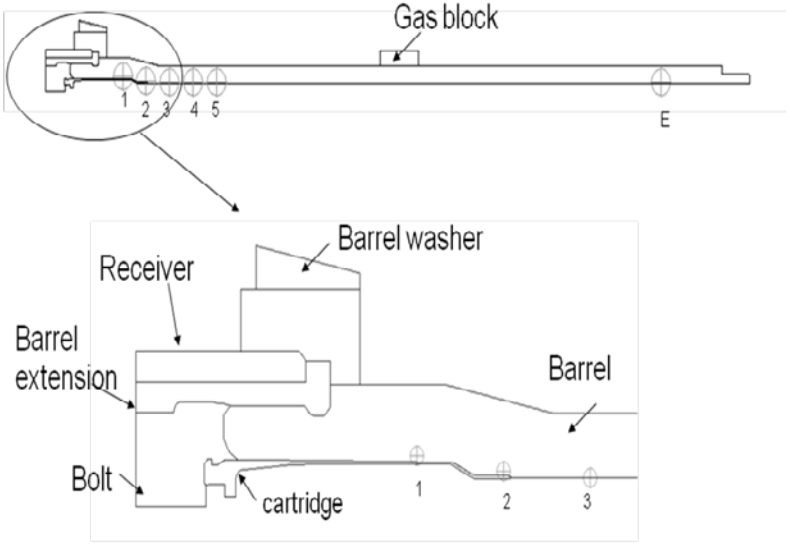
Single shot
gas flow and heat
conduction



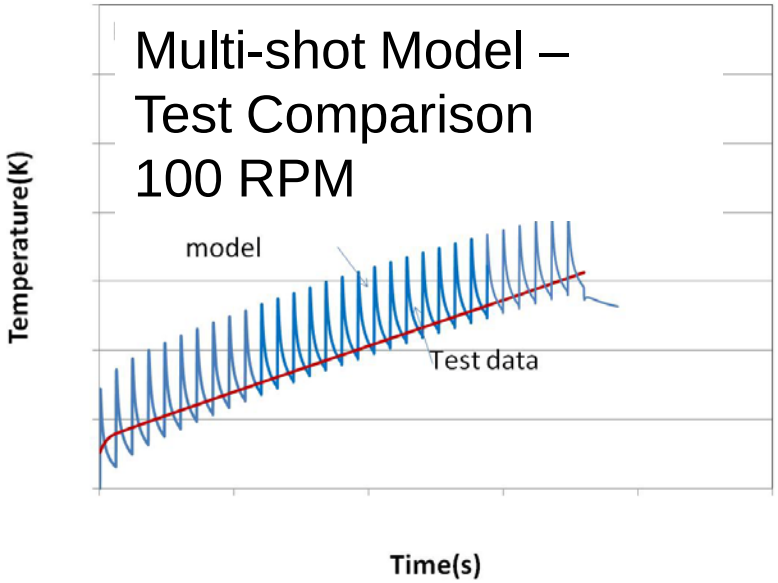
Heat transfer coefficient data

Heat transfer for multiple rounds fired

- Multi-shot heat conduction
  - Includes cartridge insertion/extraction
  - Includes magazine change

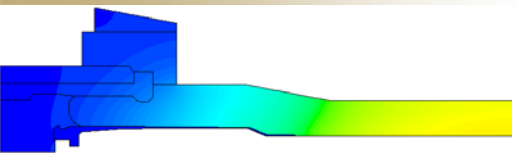
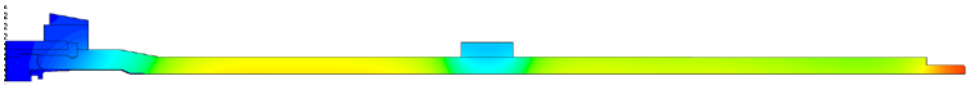


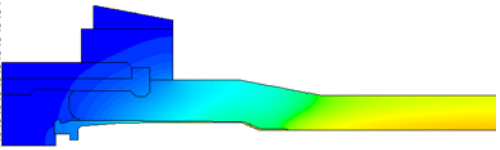
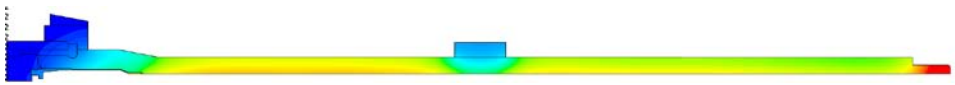
System

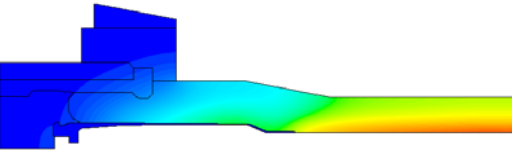
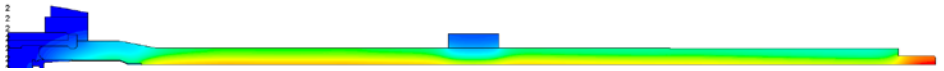


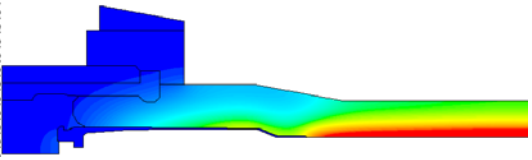
Temperature at a point

M4 – Temperature Contours – 30 Rounds


100 RPM



200 RPM



400 RPM
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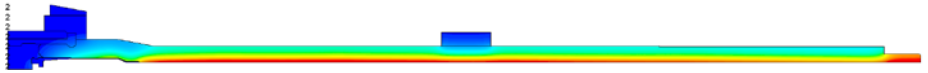
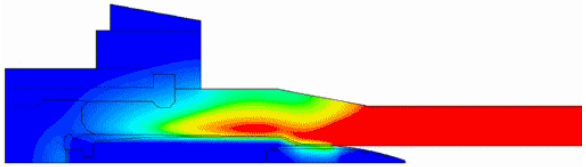
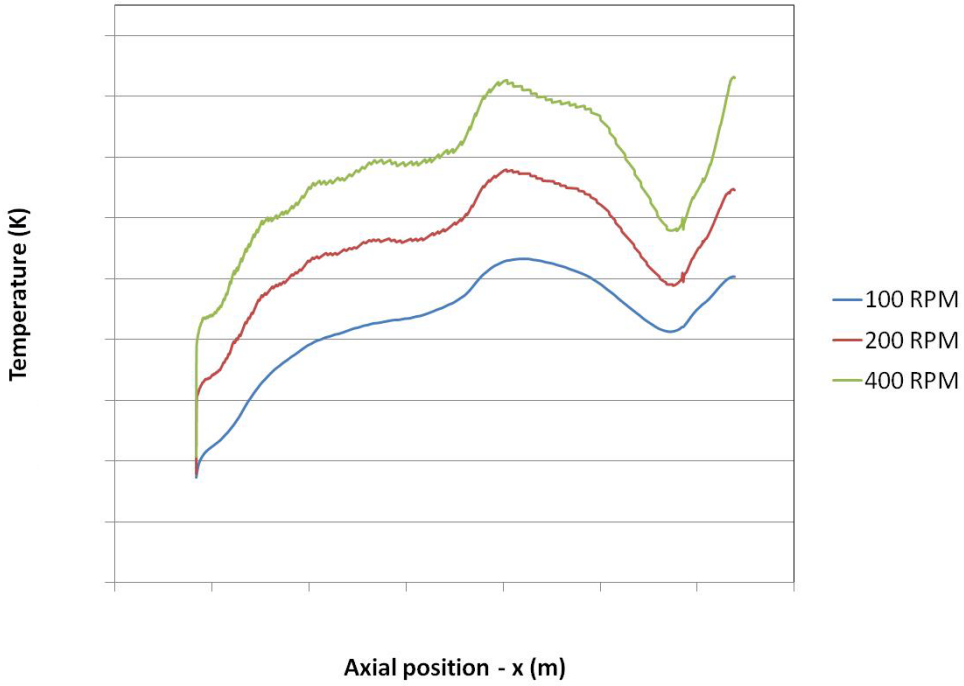


- Temperature contours after 30 rounds are fired

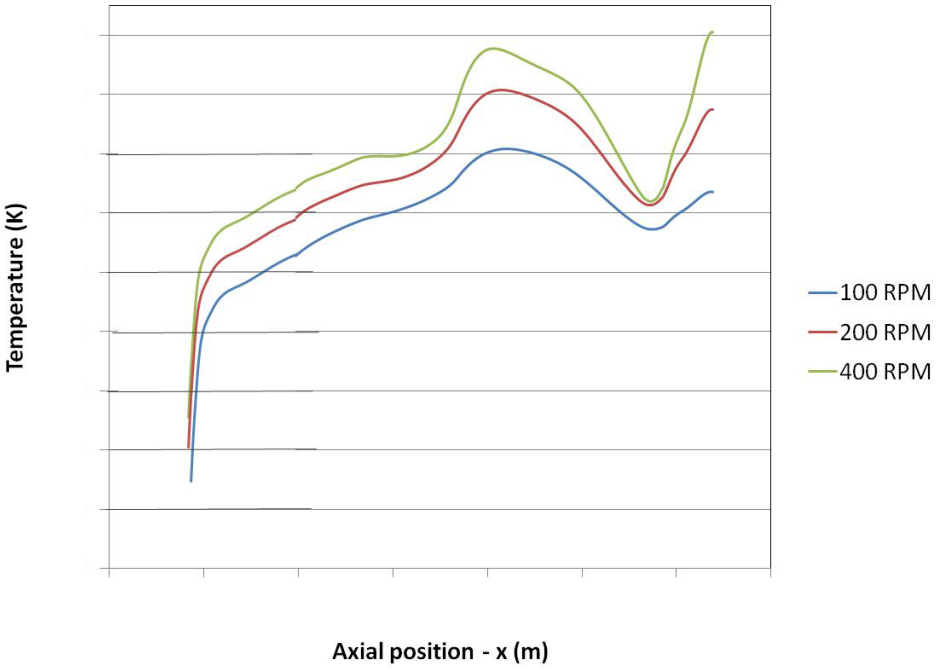


- Cartridge insertion into heated barrel

Bore axial temperature distributions



250 rounds



400 rounds

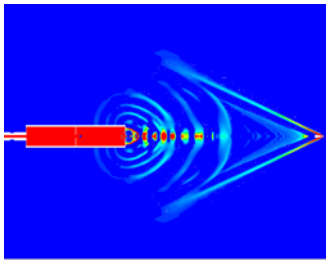
- Axial temperature variation – differences with firing rate decrease as more rounds fired

CFD Modeling in Small Arms

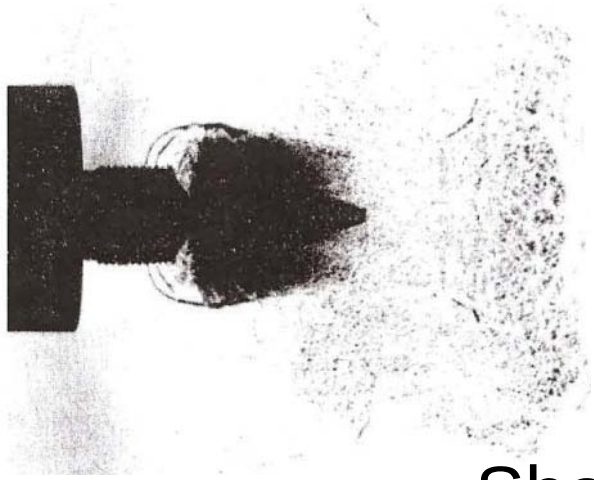
Muzzle flow with chemistry

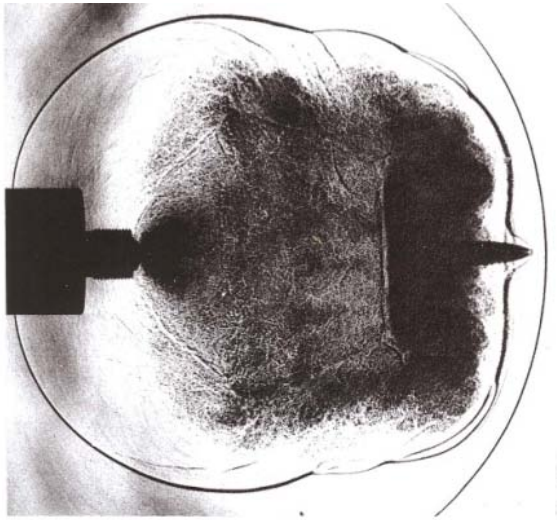
Muzzle flow

- Understand and assess muzzle device performance (sound and flash)
- Estimate temperatures, pressures, flow field, chemical composition
- CFD Model improvements
  - Refinement of numerical methods :
    - Turbulence, material properties
    - Solution methods / parameters, mesh type, size, refinement
  - Incorporation of chemical reactions :
    - Custom multispecies real gas model and material properties
    - Arrhenius based chemical kinetic model/reaction rates
    - Various chemistry related solution methods and parameters

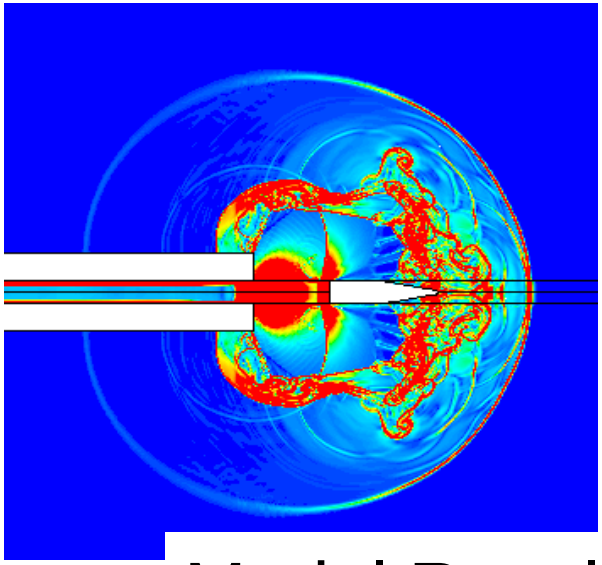


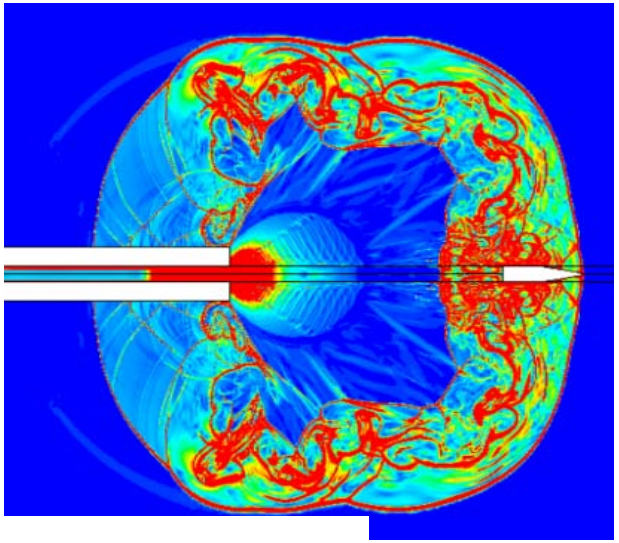
Non-reacting muzzle flow model





Shadowgraphs

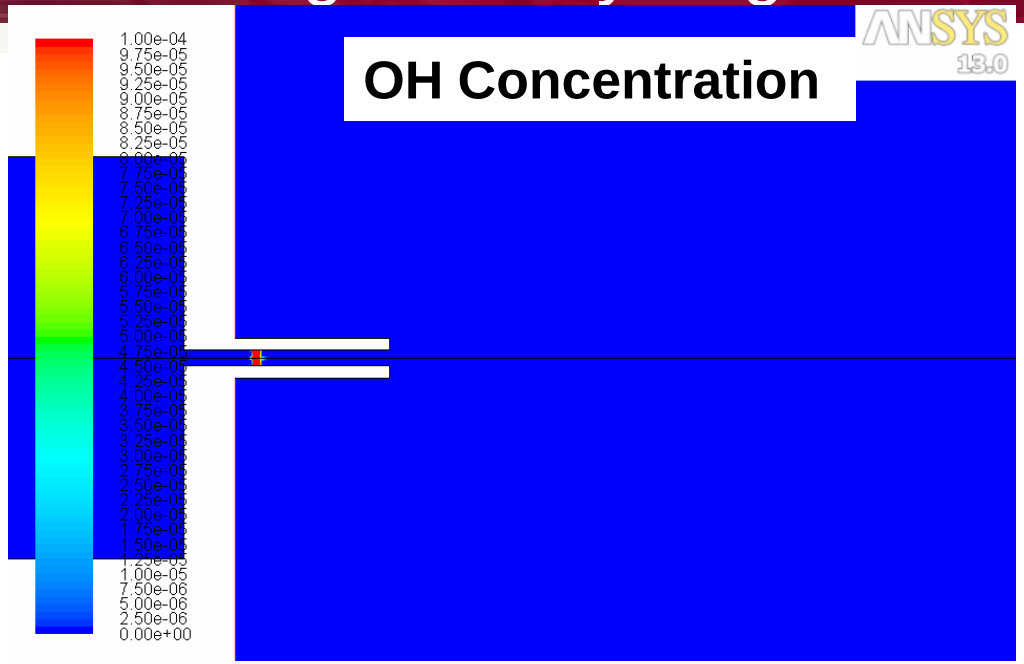


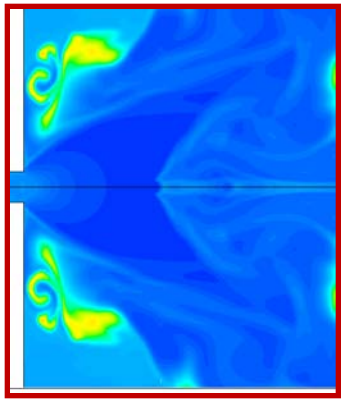


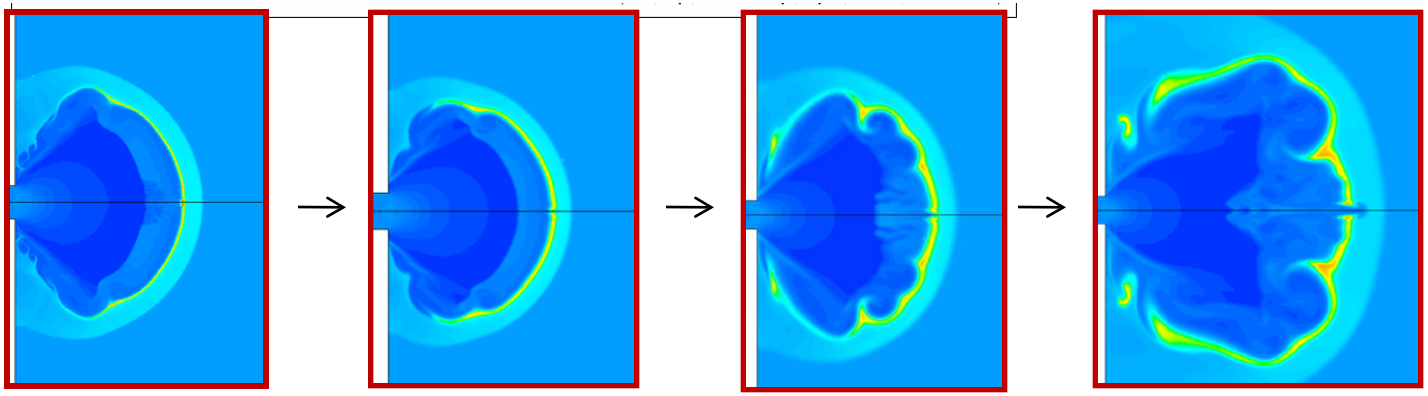
Model Results – Density Gradient

Reacting Flow Hydrogen Model

- Simplified H_2 and air system to develop modeling method
- Radical concentrations/ temperature correlate with reaction
- Flame development and separation
- Consistent with published results

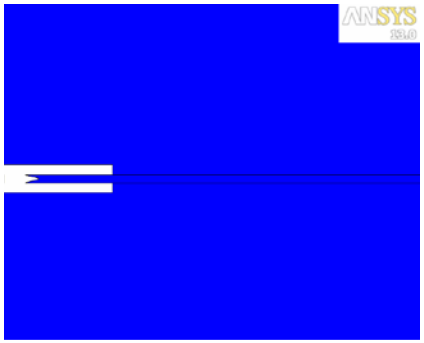
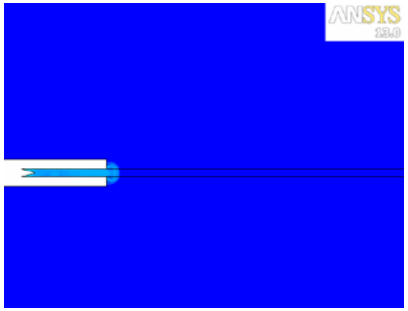
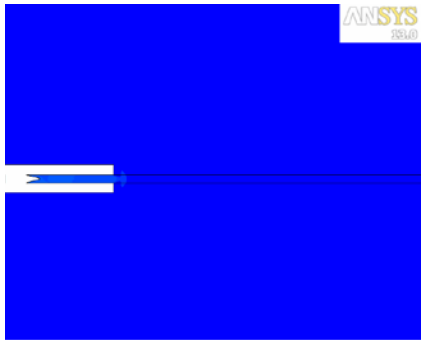






Good Comparison to results in : Numerical study of spontaneous ignition of pressurized hydrogen release into air *Int. J. Hydrogen Energy*. Xu et.al.(2010)

Gun system with reacting flow – muzzle geometries

OH Mass Fraction	Temperature	Pressure
		
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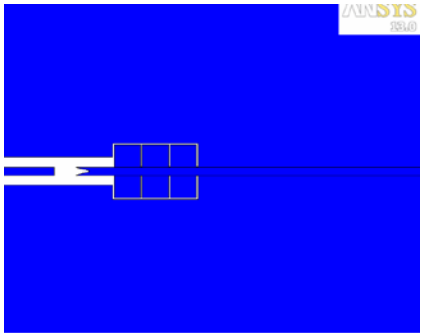	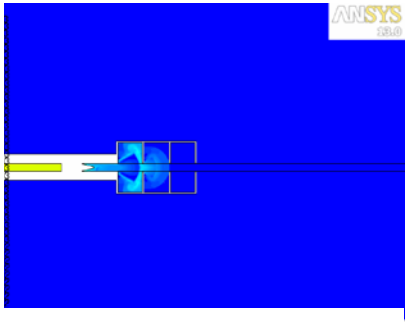	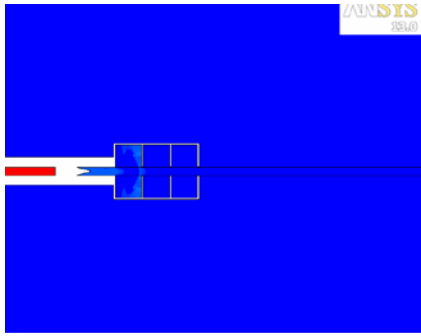
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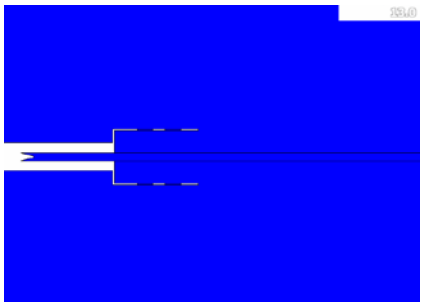
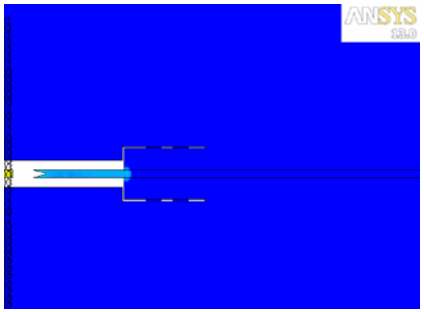
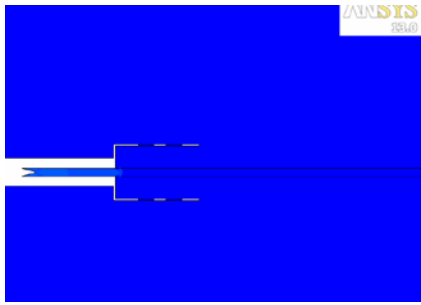
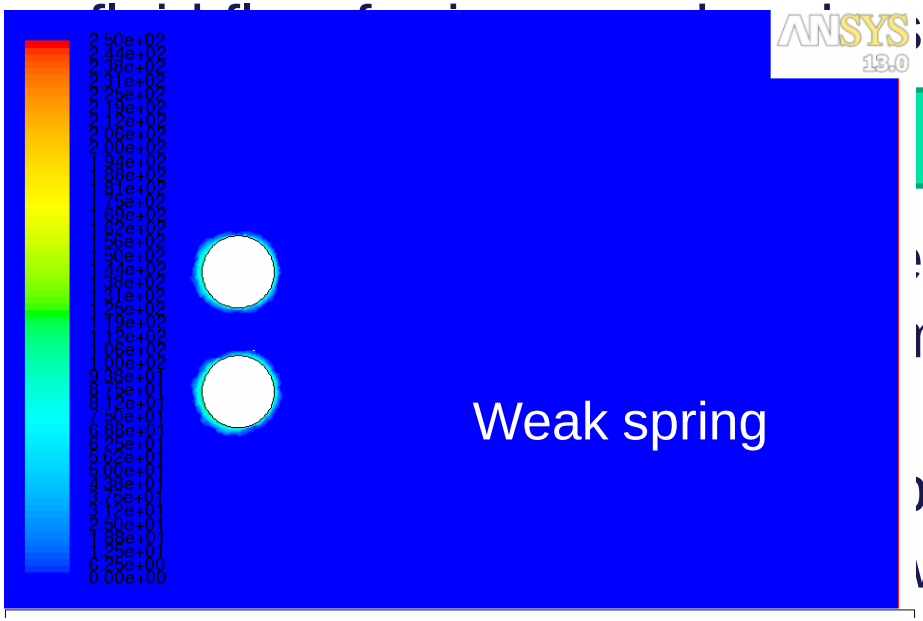
		
SLOT	SLOT	SLOT

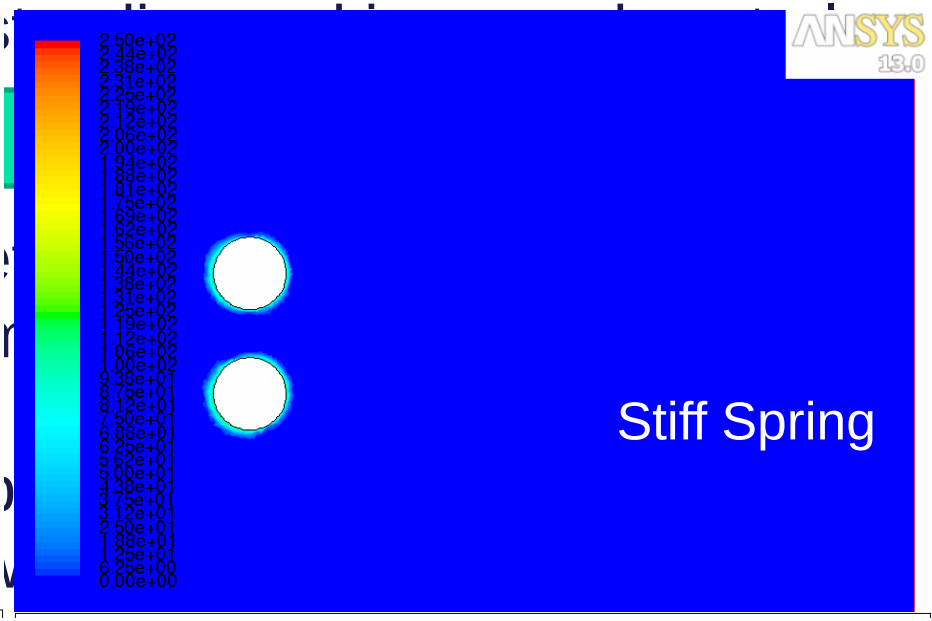
CFD Modeling in Small Arms

Multiple projectile motion

Multiple Projectile/ Large Particle Simulations

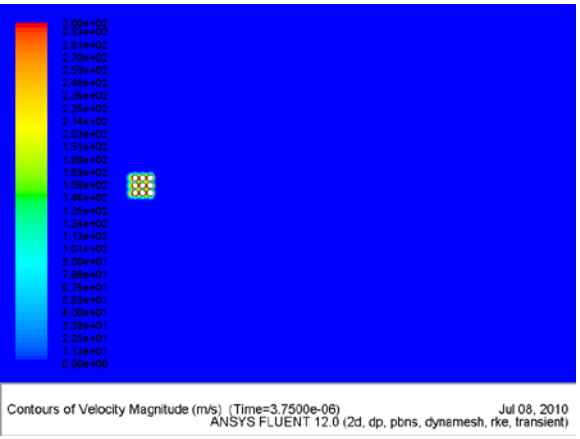
- Develop capability to simulate the motion of multiple interacting projectiles – shot gun pellet spread
  - Direct simulation of coupled particle flow and high speed

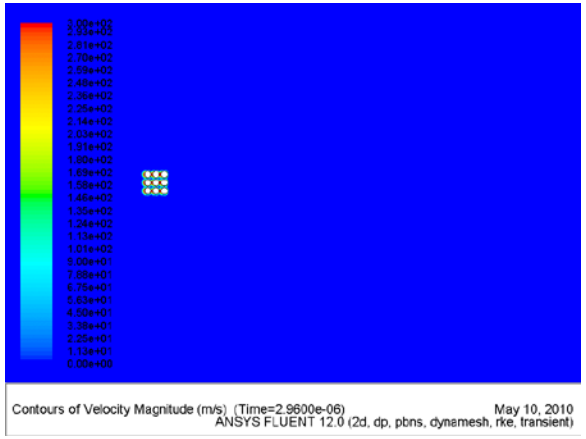


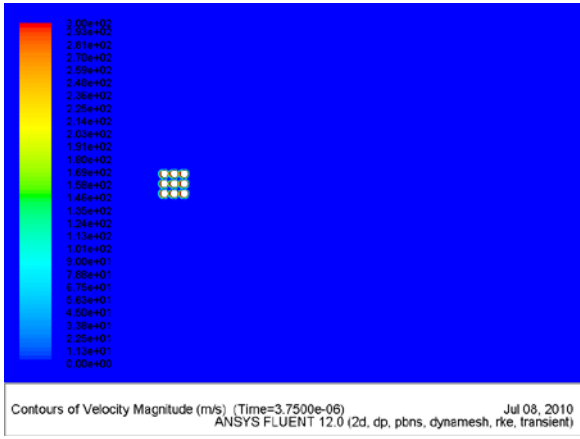


particle deformation with impact
  - Application to general particle phenomenon(propellant)

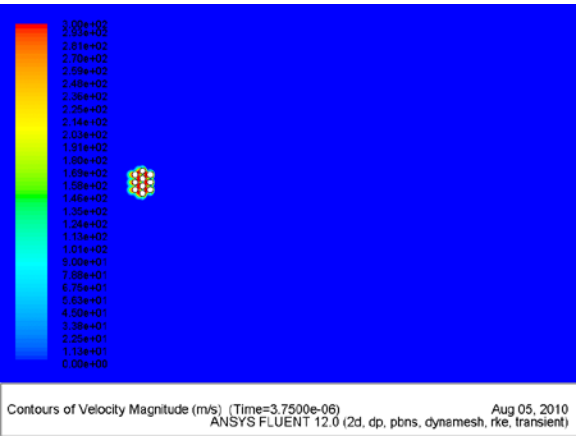
Free Particle Motion Results – Velocity Contours

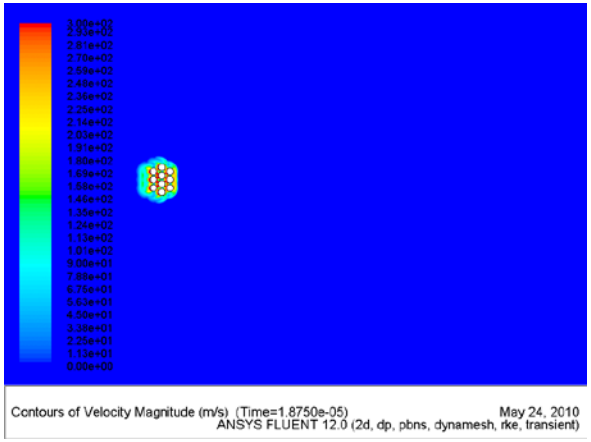


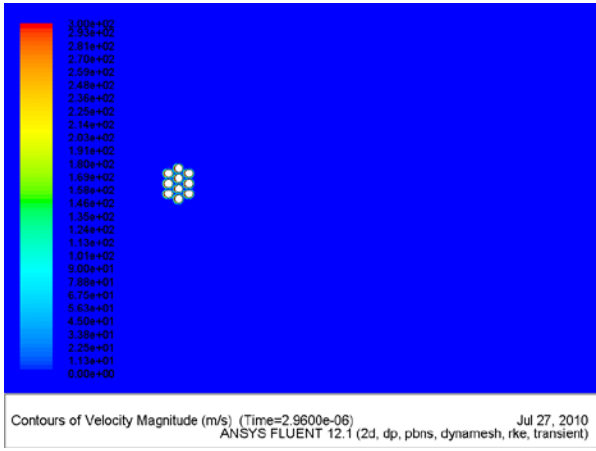




Inline Array







Offset Array

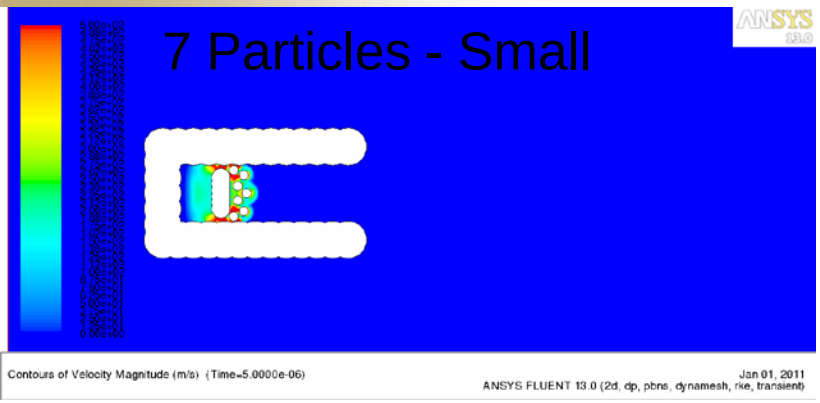
R/R_{nom}=0.5

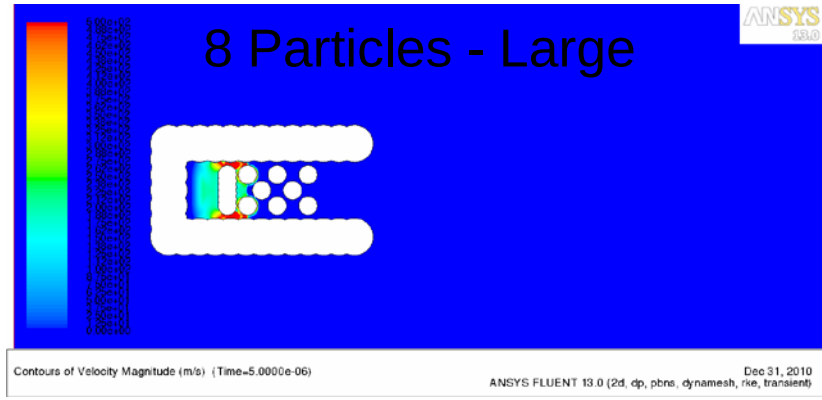
R/R_{nom}=1.0

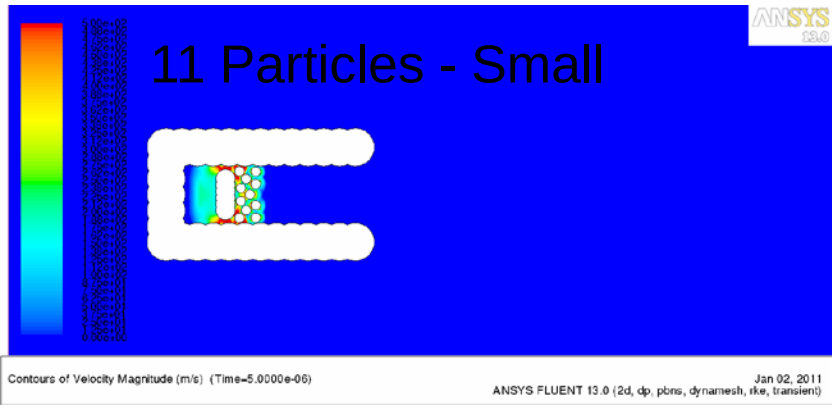
R/R_{nom}=2.0

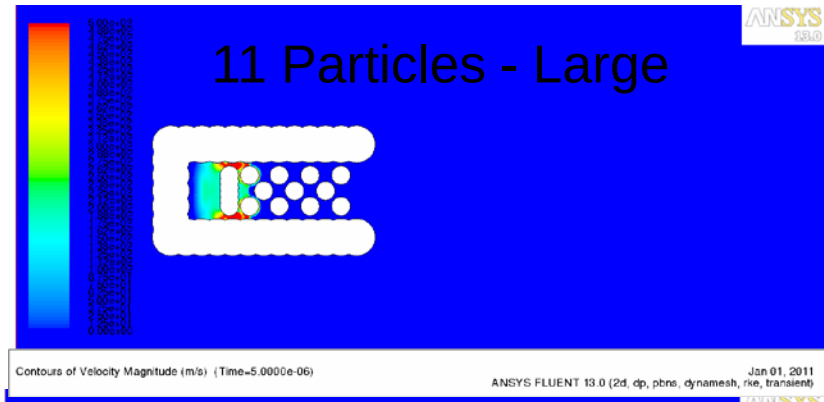
All for $\rho/\rho nom$ = 1 b/D = 1.25 Instantaneous plots at 1 ms

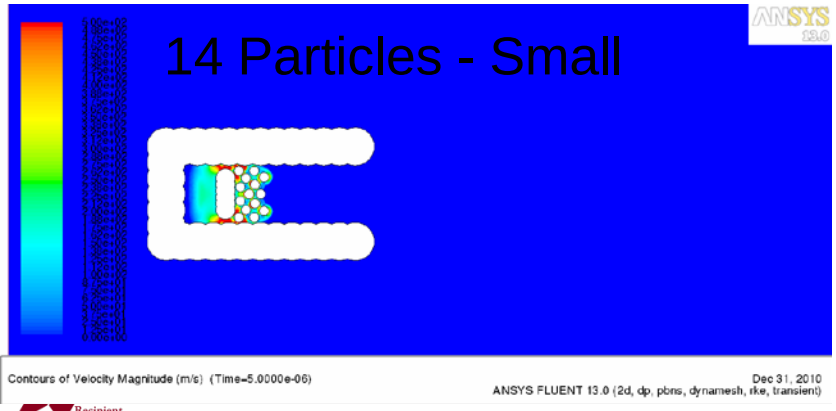
Particle Expulsion – Particle Count and Size Velocity Contours

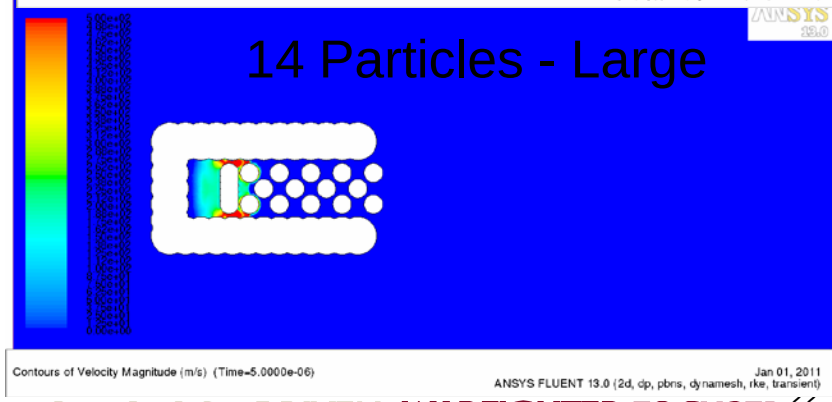










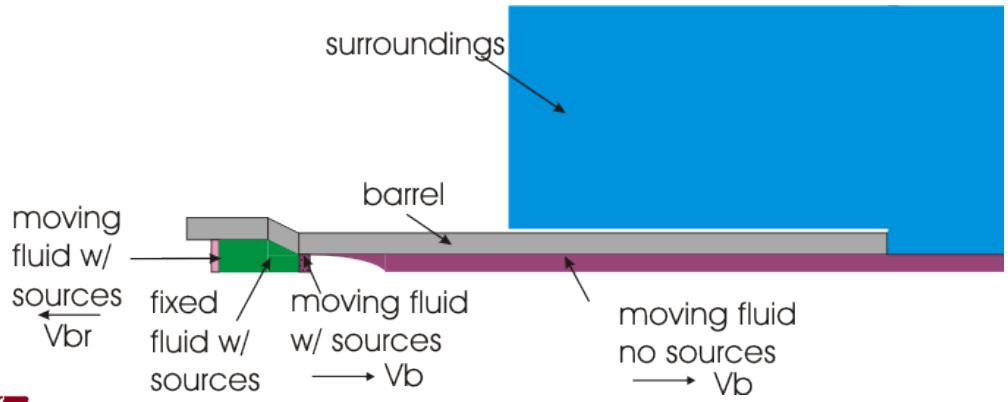


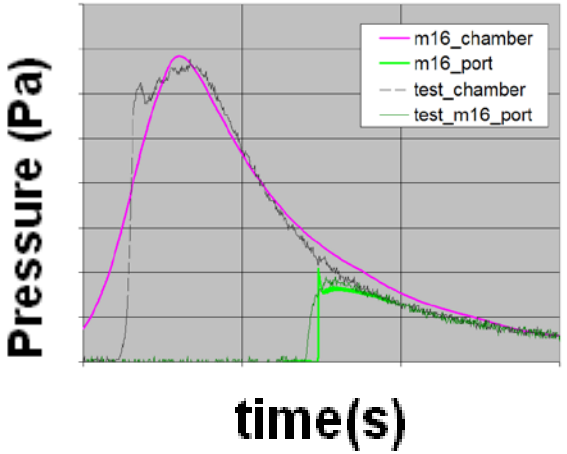
CFD Modeling in Small Arms

Propellant combustion and motion

Propellant Combustion

- Current method = “Bulk effect” of combustion model
  - Estimate propellant burn rate from average gas pressure and remaining propellant surface area
  - Apply consistent uniform energy, mass, momentum sources to entire volume of gas behind the bullet.
  - Sufficient for many analyses
  - Can not capture local pressure effects and motion of propellant grains particularly in the chamber.





System

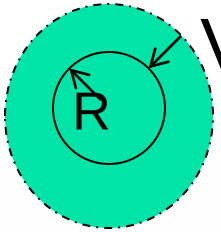
Comparison of results

Propellant Combustion

- Investigate two phase simulation (solid and gas) to model propellant combustion
  - Standard two phase methods available in commercial software not conducive to propellant burn conditions
    - Requires low particle packing density
    - Does not track particle motion/changing particle size
    - Applicable to limited solver and material properties
  - Develop alternative method using direct particle modeling method described earlier with changing particle size and consistent mass, momentum, energy sources

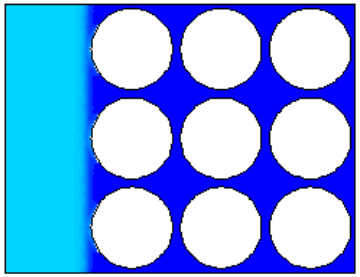
Propellant Combustion

- Propellant burn simulation with moving particles
  - Interaction between particles and particles and walls
  - Changing size of particles to account for propellant burned – based on local pressure



$V=\beta P^{\alpha}$

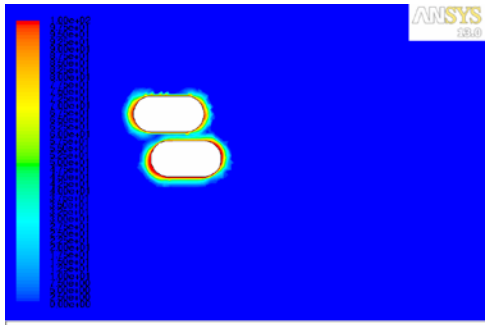
  - Local mass, momentum, energy sources around each particle - based on burn rate and surface area of particle
  - Moving wall

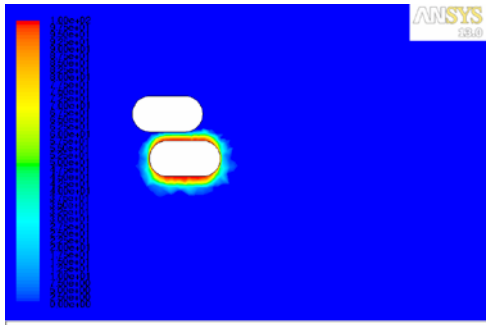


Pressure field contours

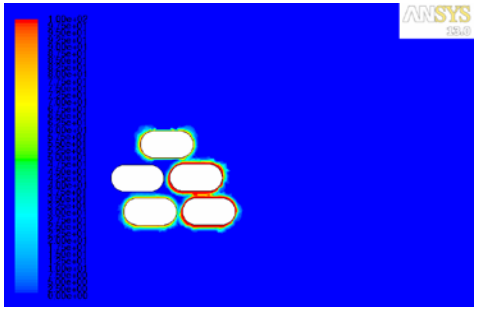
More realistic propellant grain shape

- Modification of collision detection and collision model



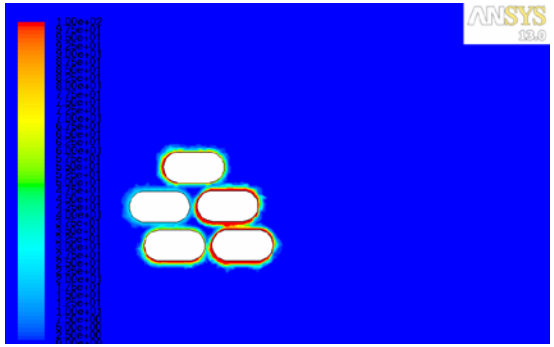


2 – particle collisions



5 – particle collisions

- Modification of method to simulate change in particle size and in method to assign the mass, momentum, and energy sources



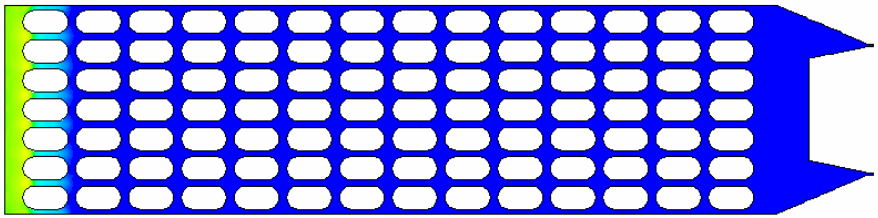
5 – particle collision with burn model

Refined Propellant Combustion Model Development

More realistic propellant grain shape in more realistic system

- Includes “primer,” moving bullet base, cartridge with propellant grains

ANSYS 13.0



Further work

- Inclusion of chemistry in propellant burn
- Inclusion of particles/particle burn in muzzle flow
- Simulation of deforming or shape changing particles
- Inclusion of contact between general system components during weapon operation
- Coupling of fluid and stress analysis

Conclusions

- CFD is a tool to gain further insight into the phenomenon related to the operation of weapon systems
  - Greater model complexity, better results, greater computational expense
  - High speed compressible turbulent gas flow conditions highly dependent on material property and turbulence models
  - Increased round count, lower temperature gradients, reduced differences in temperature field distributions with firing rate
  - High temperatures as fluid comes to rest on solid surfaces increases likelihood of chemical reactions nearby
  - Particle motion and fluid flow are highly coupled
  - For metal particles, particle deformations upon high speed collisions need to be modeled
  - Changing size and shape of particles influences particle motion and the flow