Naval Surface Warfare Center Dahlgren Division

Barrel Heating and Cook Off in Powder Guns

Presented by

Jon Yagla, PhD

Senior Member, International Ballistics Society

Integrated Engagement Systems (E) Department

WELCOME

Insensitive Munitions and Energetic Materials Technology Symposium

Indianapolis, Indiana

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The Leader in Warfare Systems Development and Integration

Barrel Heating in Hot Guns

- Hot guns can be very dangerous.
- If a cartridge is allowed to remain in a hot gun, it may explode.

I will discuss:

- Barrel heating during action time
- Barrel heating during blowdown

- Concurrent barrel cooling

- Heat transfer to a cartridge loaded into a hot gun
- Time until cook off

Important Lessons Learned IM Test Development

Liquid Fuel Fire Computer Simulation

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Fast-Cook-Off Test :

Liquid Propane Gas vs Kerosene Pool Fire

Fabien Chassagne (DGA/DT/CAEPE)

DGA

DÉLÉGATION GÉNÉRALE POUR L'ARMEMENT

Fire dynamics simulation

- Numerical code : FDS (Fire Dynamics Simulator) developed by the NIST (USA)
- Well-adapted to simulate hydrocarbon fire (Low Mach number flow)
- 3D, multi-species, Large Eddy Simulation (LES), Radiative heat transfer modeling by Finite volume method

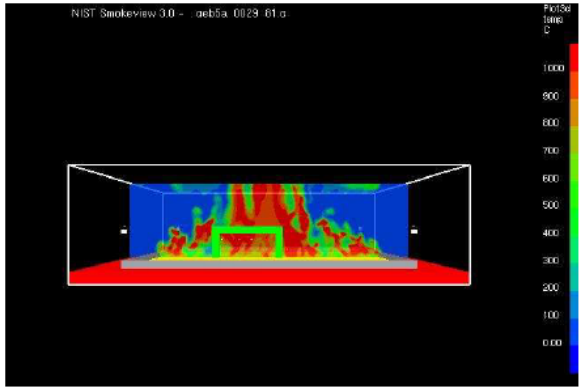
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad \text{(mass)}$$

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho Y_i \mathbf{u}) = \nabla \cdot (\rho D_i \nabla Y_i) + \dot{m}_i''' \quad \text{(species)}$$

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u}\right) + \nabla p = \rho \mathbf{g} - \nabla \cdot \overline{\overline{\tau}} \quad \text{(momentum)}$$

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot \rho h \mathbf{u} = \frac{Dp}{Dt} - \nabla \cdot \mathbf{q}_r + \nabla \cdot k \nabla T + \sum_i \nabla \cdot h_i \rho D_i \nabla Y_i \quad \text{(energy)}$$

Conservation equations



Example of Kerosene Fire

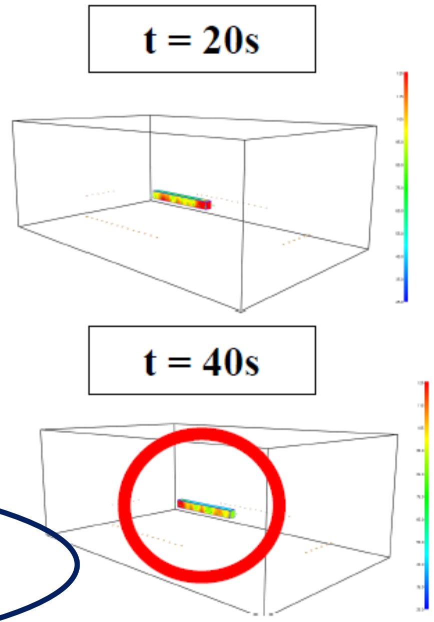
"Multi-species" includes solid phase carbon particles (JJY)

We Found that 90% of the Heating is Radiation from Carbon Particles

- Calculated **heat exchanges** between the munitions and the flames

Time-Averaged Heat Flux (kW/m²)	LPG Fire	
Incident Heat Flux Φinc	104,1	
Radiative Heat Flux Φrad	84,2	89,7%
Convective Heat Flux Φconv	9,6	10,2%
Net Heat Flux Φnet	93,9	

Heat flux is mainly due to radiation ($\varepsilon_{munitions}$ = 0.9) but is not uniformly applied to the munitions



Radiation heat flux is 90%

Convection heat flux is 10%

We Learned that the Fraction of Carbon Particles is *Very Small*

We Learned The Mass Fraction Of Carbon Particles Is ***Very Small***

Heat Flux Measurement In Fires

STANAG 4240 Fuel Fire Experts Meeting

Meppen, Germany Feb. 2-4, 2010

Dr. Sheldon Tieszen[1]
Manager, Fire & Aerosol Sciences
Sandia National Laboratories

1. Dr. Sheldon Tieszen, PhD; Manager, Fire and Aerosol Sciences. *Heat Flux Measurement in Fires*; STANAG 4240 Fuel Fire Experts Meeting; Meppen, Germany, 2–4 February 2010

Soot Production Laminar Flames

Table 1. Peak Soot Concentrations in Laminar, Low-Strain Steady Diffusion Flames

fuel	flame	peak fv reported	Reference	Method	assumption	current best estimate of fv
methane	79 mm high coannular	3×10^{-7}	[64]	HeNe extinction	K_e = 4.9 (D&S)	1.7×10^{-7} (K_e = 8.5)
propane	85 mm high coannular	6×10^{-6}	[64]	HeNe extinction	K_e = 4.9 (D&S)	3.5×10^{-6} (K_e = 8.5)
ethylene	91 mm high coannular	13×10^{-6}	[64]	HeNe extinction	K_e = 4.9 (D&S)	7.5×10^{-6} (K_e = 8.5)
ethylene	88 mm high coannular	10×10^{-6}	[65]	Ar-ion extinction (514 nm)	K_e = 4.9 (D&S)	5.8×10^{-6} (K_e = 8.5)
ethane	88 mm high coannular	3×10^{-6}	[65]	Ar-ion extinction (514 nm)	K_e = 4.9 (D&S)	1.7×10^{-6} (K_e = 8.5)
acetylene	6 mm high coannular (smoke pt)	15×10^{-6}	[66]	path-ave HeNe extinction	K_e = 3.5 (L&T)	6.2×10^{-6} (K_e = 8.5)
ethylene	75 mm high coannular (smoke pt)	6×10^{-6}	[66]	path-ave HeNe extinction	K_e = 3.5 (L&T)	2.5×10^{-6} (K_e = 8.5)
propane	150 mm high coannular (smoke pt)	4×10^{-6}	[66]	path-ave HeNe extinction	K_e = 3.5 (L&T)	1.6×10^{-6} (K_e = 8.5)

- **Jet Fuel ~ 6 ppm Propane ~ 1.6-3.5 ppm**
- **Peak Soot Concentration of Jet Fuel ~ 3 x Propane (all else equal).**

Sandia National Laboratories

Fast Cook Off Lesson on Radiation

Two Burners Worked – Radiation from carbon particles met the requirement. Stoichiometric fires w/o Carbon did not.

Liquid Injection

Meppen, Germany

China Lake, USA

Pre-Mixed Injection

't Harde, Netherlands

Bofors, Sweden

Gaseous Injection

Dahlgren, USA

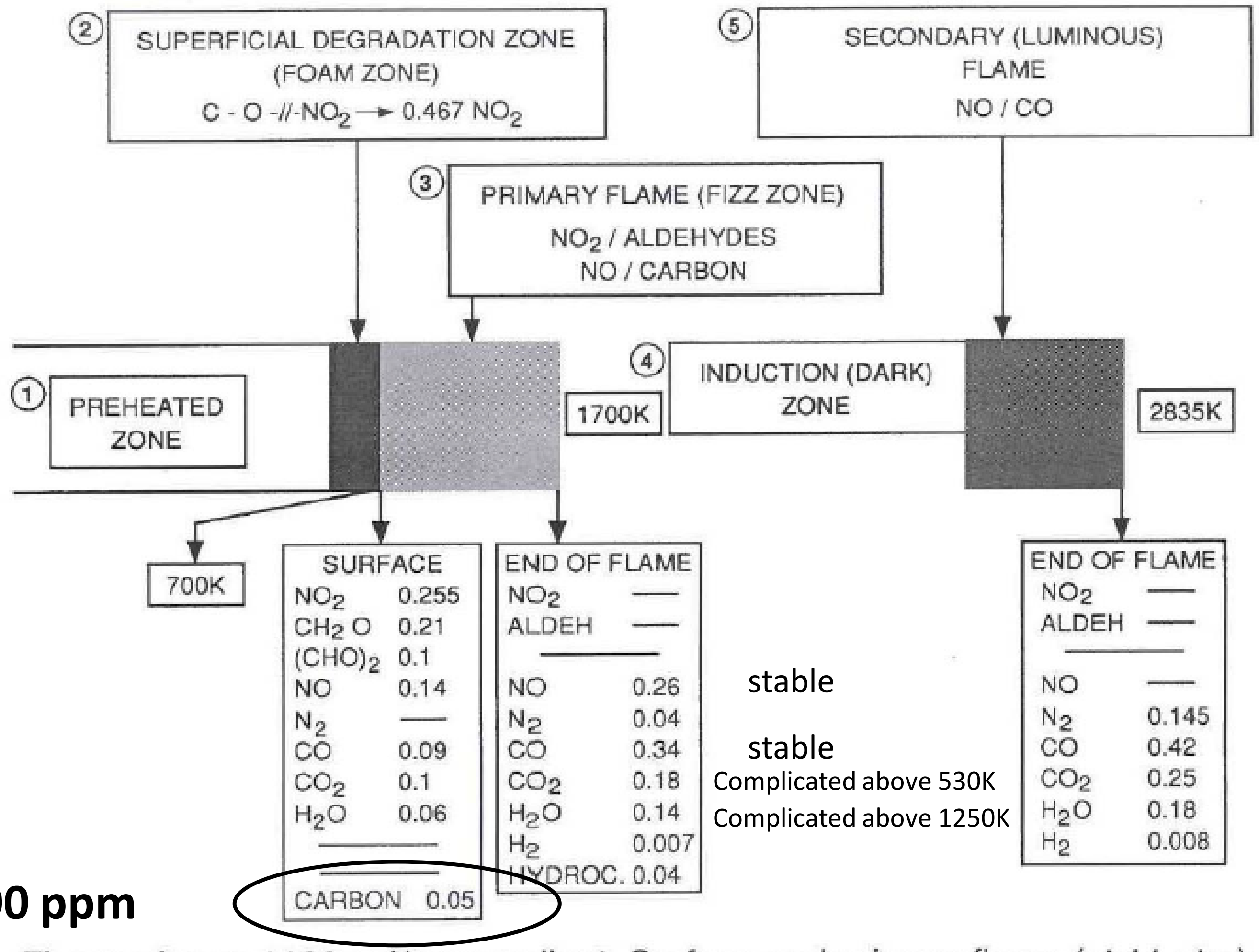
In the NATO "Science of Cook Off Workshop"

Combustion of Solid Propellants

G. Lengellé, J. Duterque, J.F. Trubert
Research Scientists, Energetics Department
Office national d'études et de recherches aérospatiales (ONERA)

This paper showed there was free carbon in low concentrations in propellant combustion.

Carbon: 0.05, 5%, or 50,000 ppm



Figures for an 1100 cal/g propellant. Surface and primary flame (at 11 atm) mass fractions from gas analysis

Figure 5: Various Zones of the Combustion of a Double Base Propellant.

Conclusions for Gun Barrel Heating

- There are ample carbon particles entrained at T_{gas} for gas radiation emissivity = 1.0.

- The powder flame temperature, T_{flame}, will add additional radiation at the flame temperature.

- The flame temperature, T_{flame}, may heat the carbon particles and add additional radiation at the flame temperature.

- **Action time** Temperature will be flame radiation plus gas radiation

- **Blowdown** Gas radiation plus convection

Propellant Heating from a Single Shot in a 30mm Machine Gun

Total Heating = Action time (while projectile is in the gun) + Blowdown time

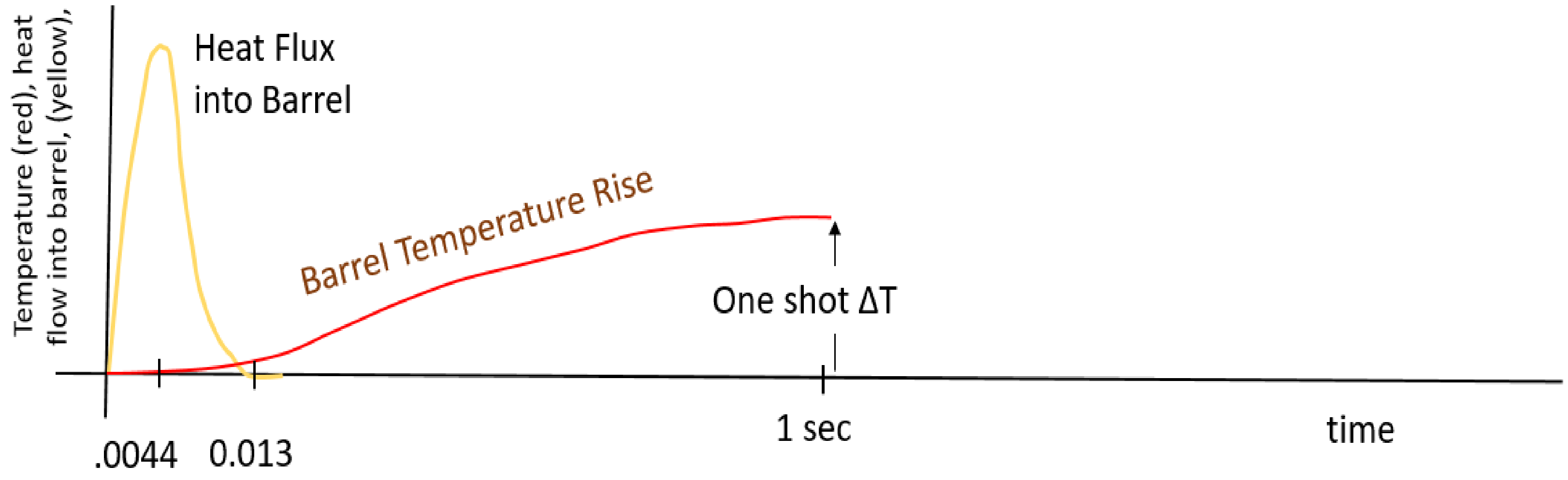
This is data for 30mm

t_A = .0044 seconds, Intense barrel heating due mainly to radiation during action time

t_B = .013 Barrel heating during blowdown due to radiation and convection

$t_A + t_B$ = 0.017 Total barrel heating time

t_{RoF} = Rate of fire, 1 second between shots for 30mm



Mechanical Heating

Engraving

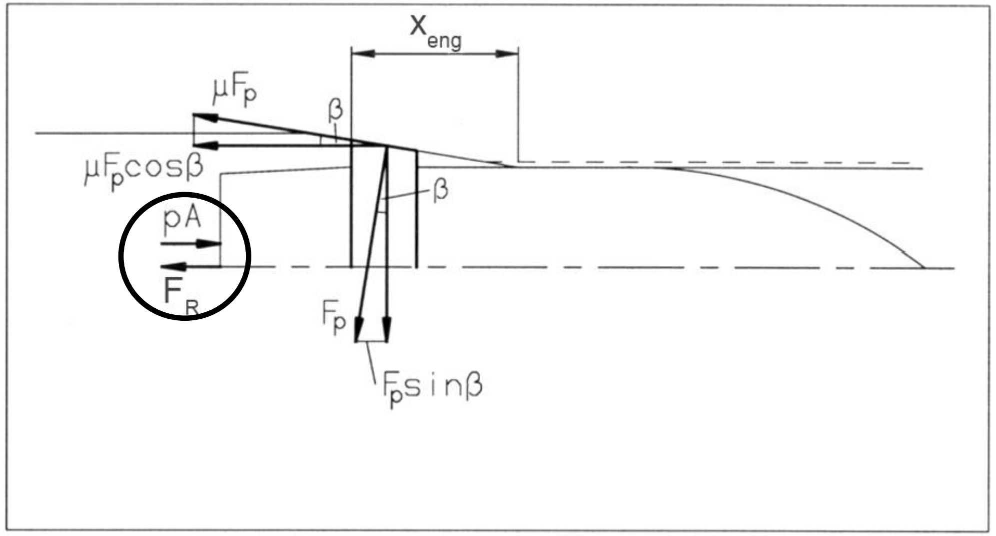


Fig. B. 3. Initial Engraving Geometry (β = half angle of the forcing cone, x_{eng} = engraving length).

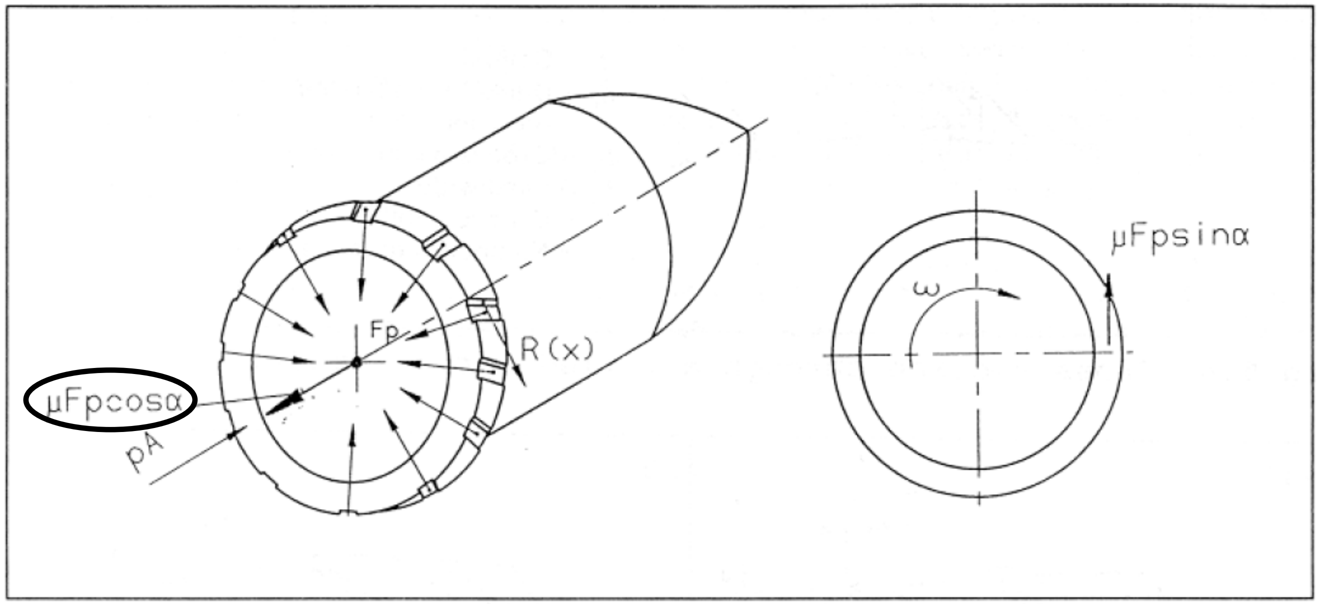


Fig. B. 5. Definition of the pressing force $F_P(x)$ and its components [2].

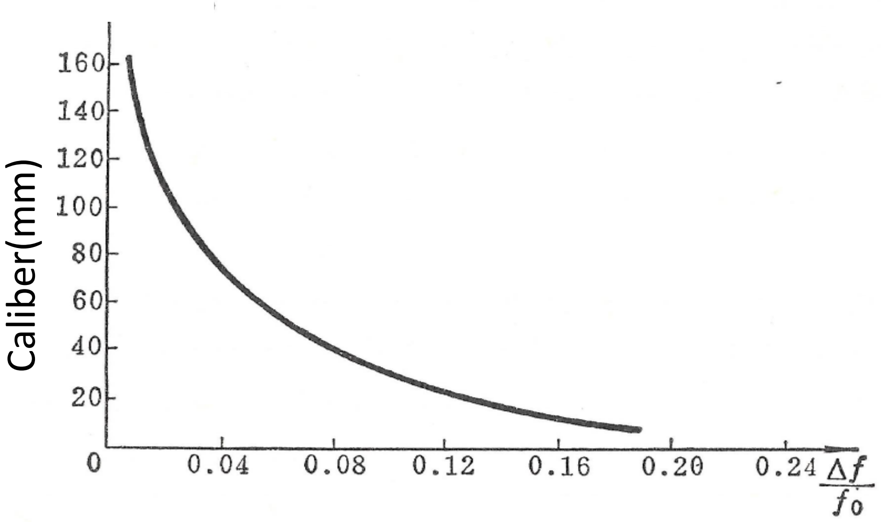
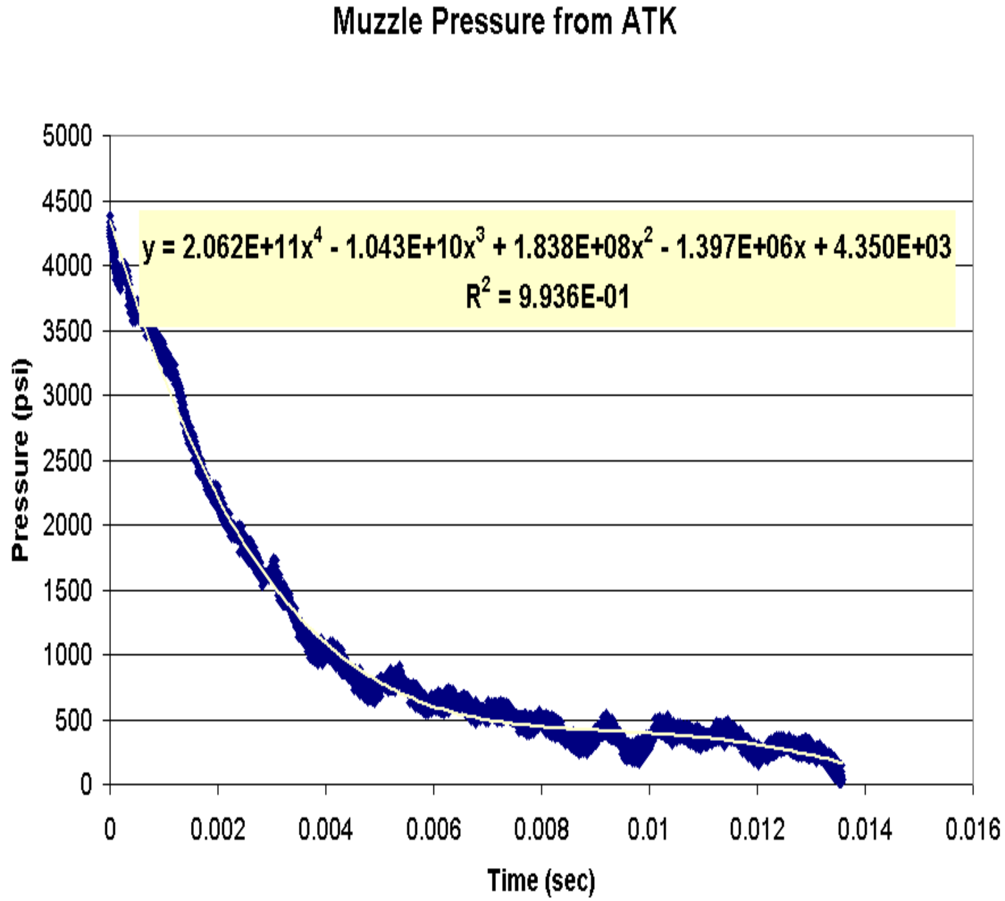


Fig 2.5 The heat loss $\frac{\Delta f}{f_0}$ vs the caliber

Blowdown

Blowdown in Various Stages



$p_f / p_i = [1 + t/\tau]^{2\gamma/(1-\gamma)}$

Barrel and gas characteristic time $\tau =$

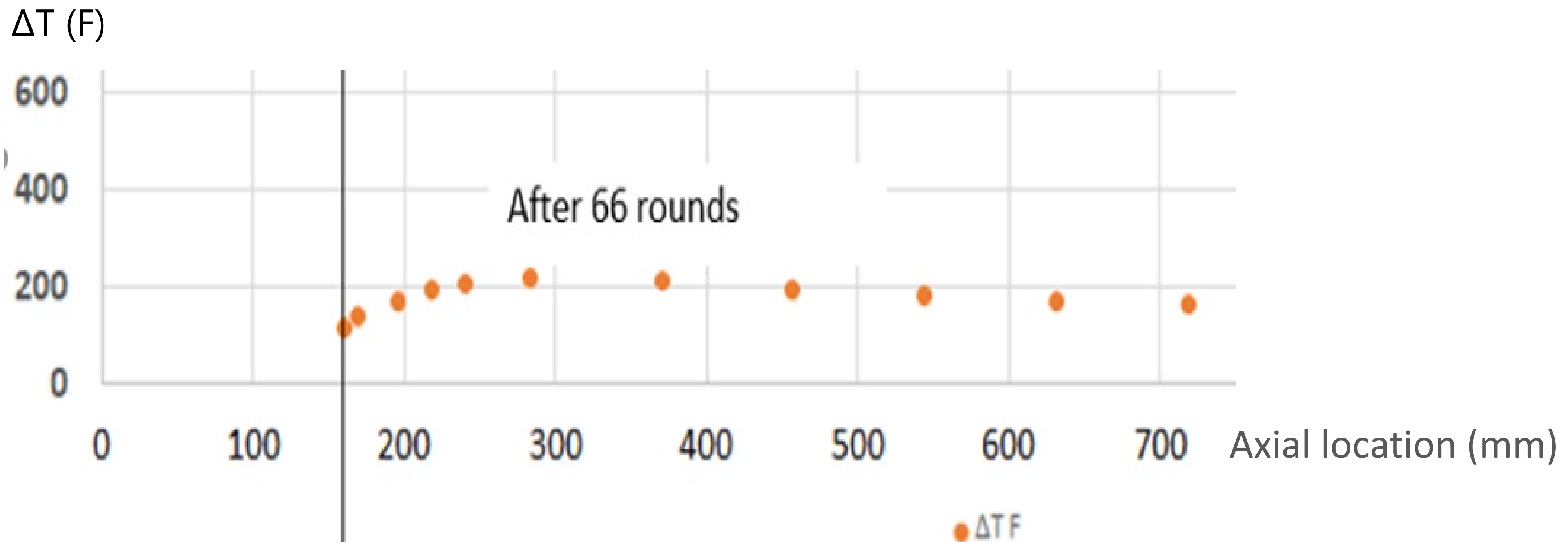
$2(V/AC_i)\{[(2/(\gamma+1)^{(\gamma+1)/(\gamma-1)}]^{½}\}/(\gamma-1)$

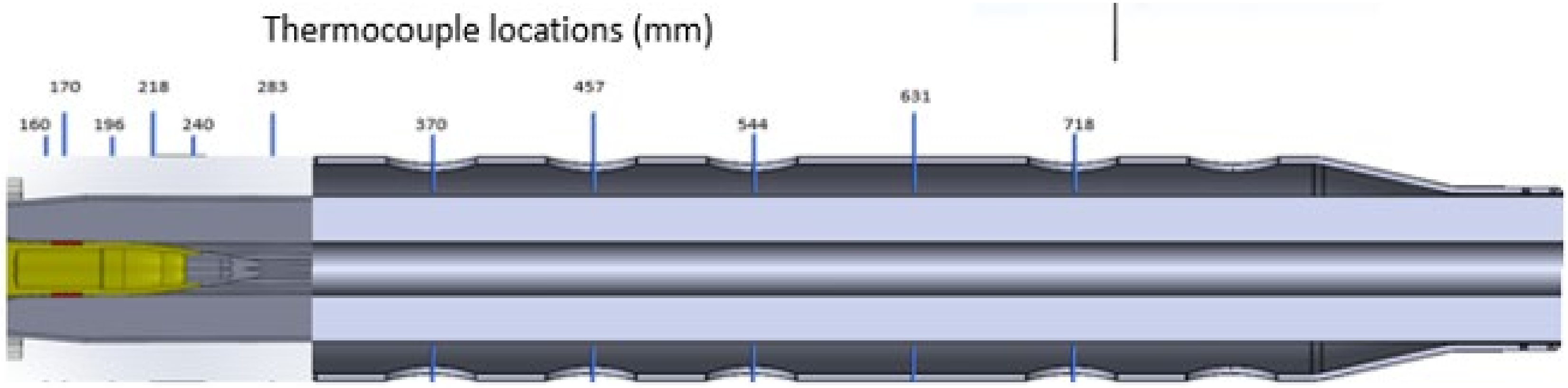
Polytropic flow equations to get ρ, T, speed of sound

Compressible flow equations for convection and radiation

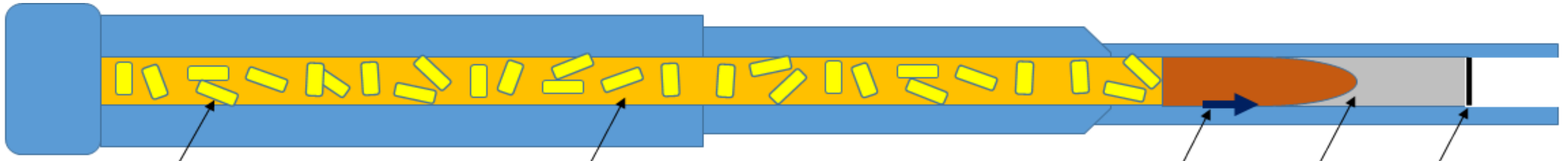
1. Yagla, Jon J. *Pressure Vessel Discharge Non-dimensional Equations*, Paper No. 190335551; 28th International Symposium on Ballistics; Atlanta, Georgia, 22–26 September 2014. DTIC AD 1154106

Barrel Temperatures after Many Rounds Fired



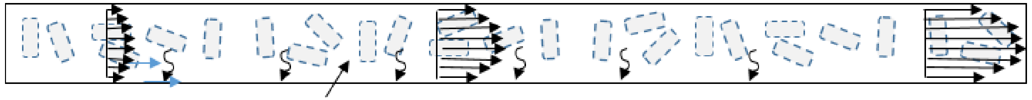


Let's Do the Math: Conventional Gun (Action Time)



Convection

T_{bulk} = 2835 K



Velocity ~ 0, no convection

T_{bulk}

Gas temperature

$q'' = h_c (T_{bulk} - T_{gun})$

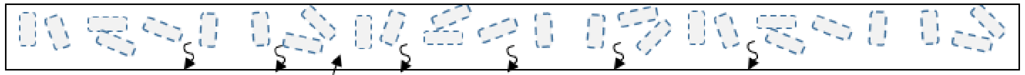
h_c = convection coefficient

Velocity = Vp, maximum convection

Small, < 5% of total heating

Radiation from gas at T_{bulk}

T_{bulk} = 2835 K



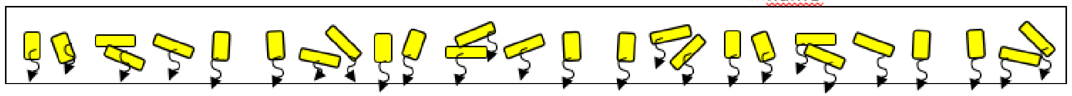
T_{bulk}

$\varepsilon\sigma T^4_{bulk}$ $T^4 \sim 2835^4$

About 30% of the radiation heating

Radiation from propellant grains at T_{flame}

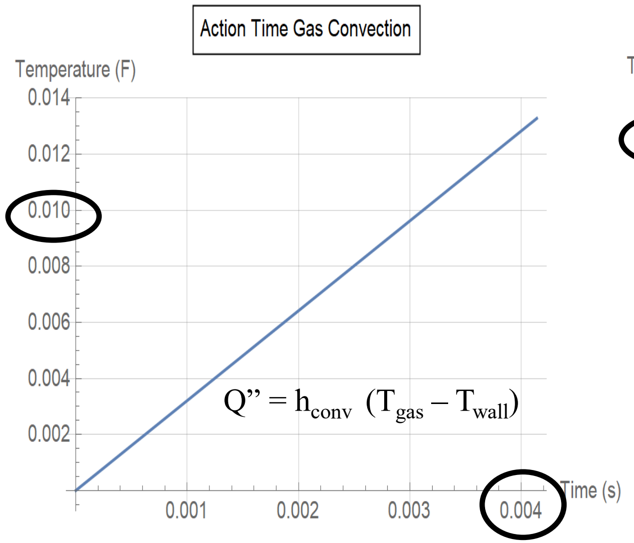
T_{Flame}= 3800 K

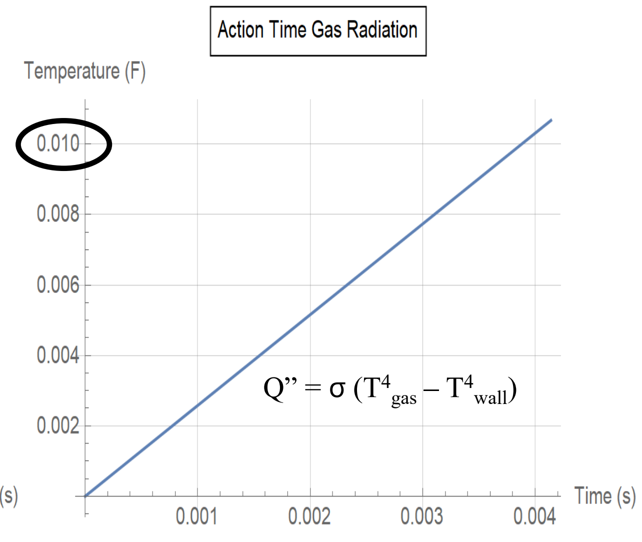


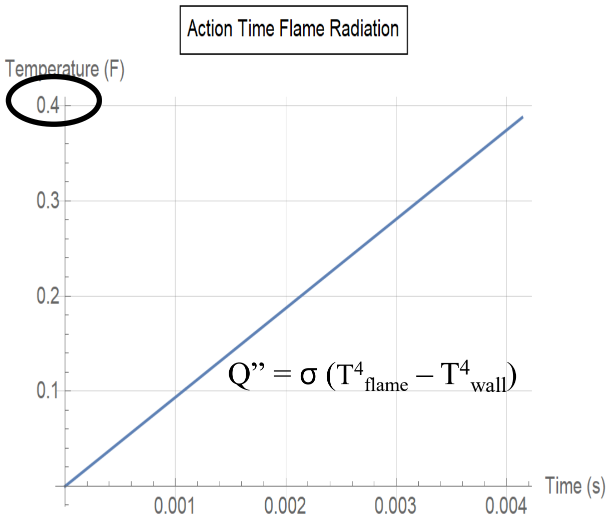
$\varepsilon\sigma T^4_{flame}$ $T^4 \sim 3800^4$

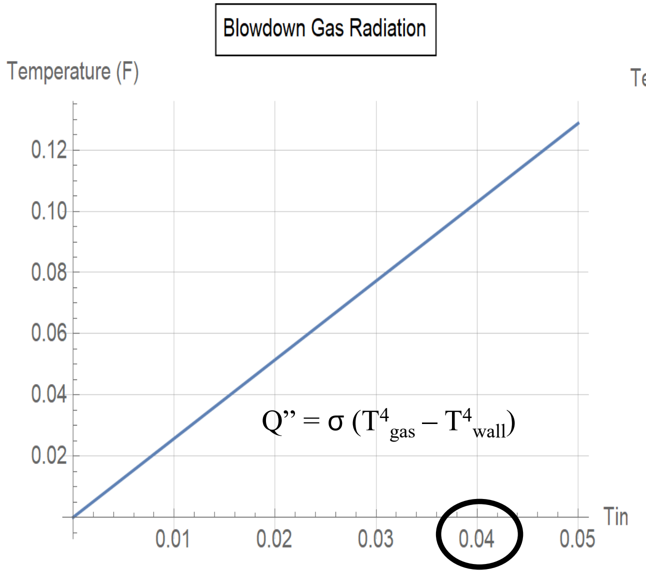
About 70% of the radiation heating

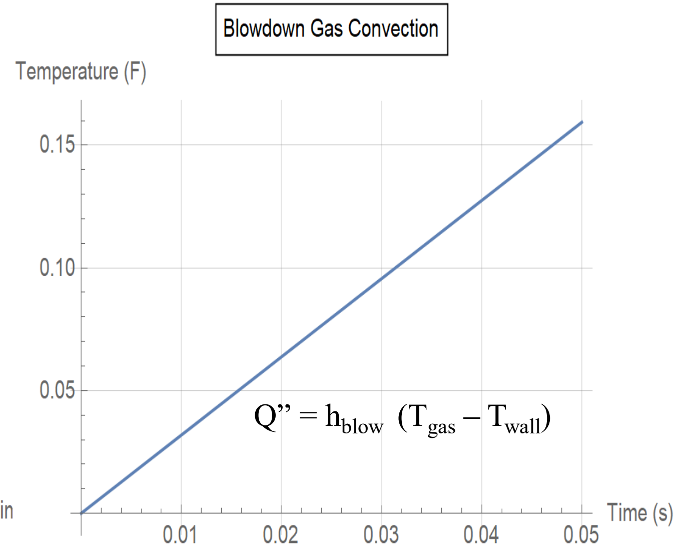
Action Time and Blowdown Gas Dynamic Heating

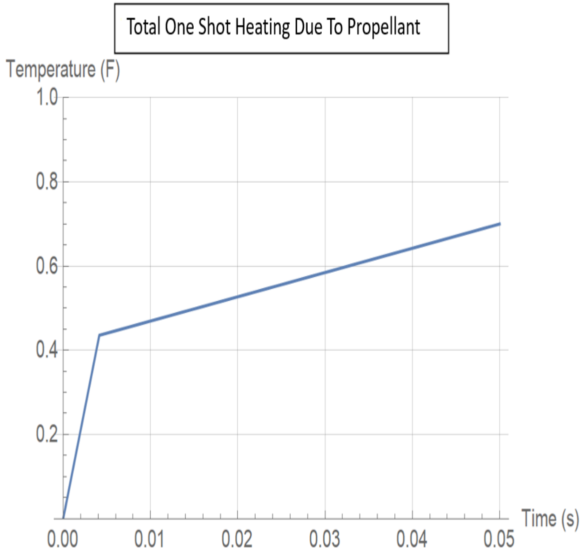




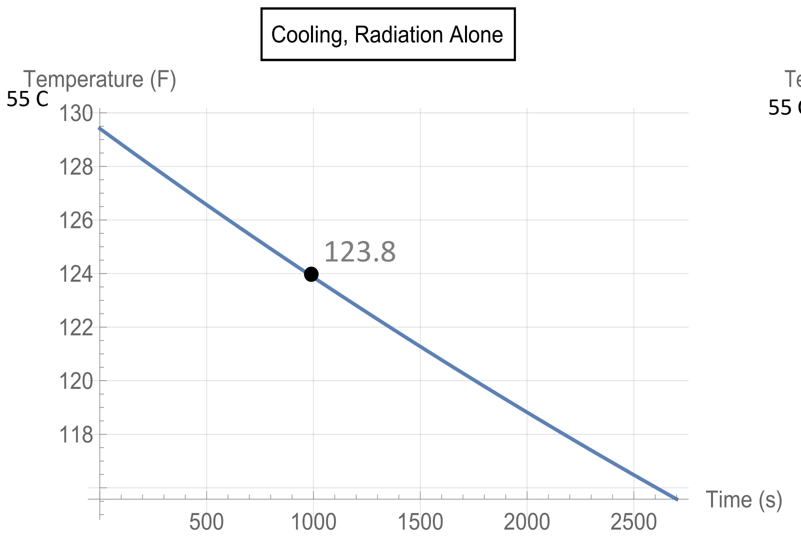


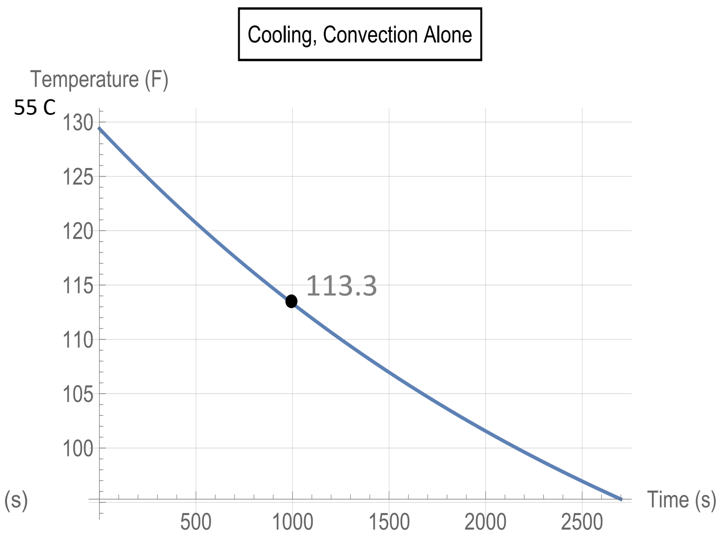


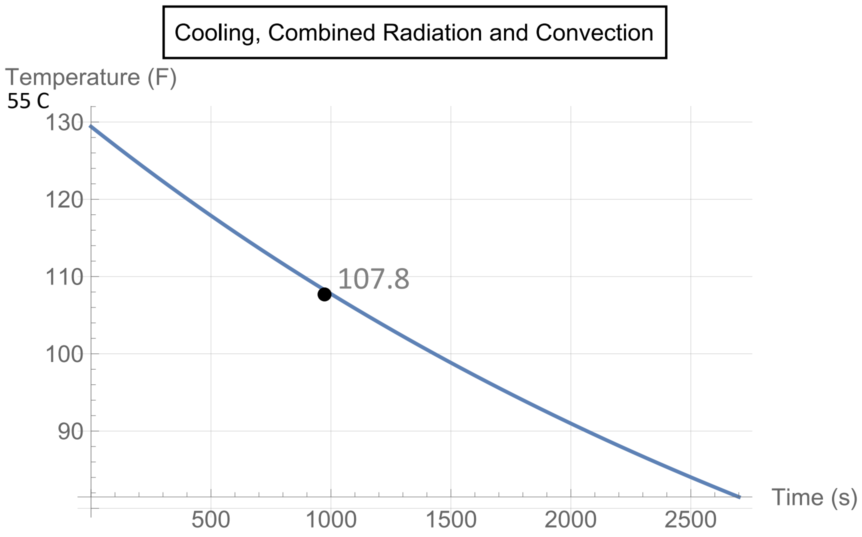




Radiation and Convection Cooling

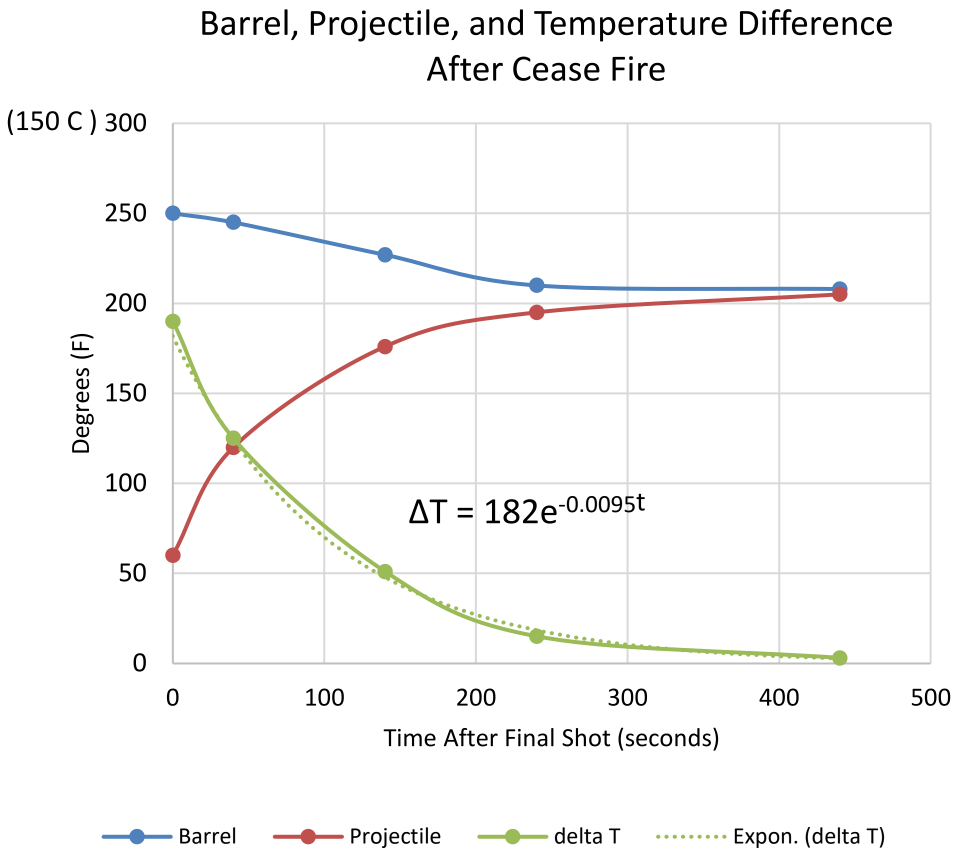






Barrel Heating a Projectile – *See the Poster for Details*

Laboratory apparatus to measure the heat transfer function of the barrel-to-projectile system with a segment of a barrel and instrumented cartridge. The difference between barrel temperature and the projectile temperature allows direct calculation of the heat transfer coefficient as shown on the left.

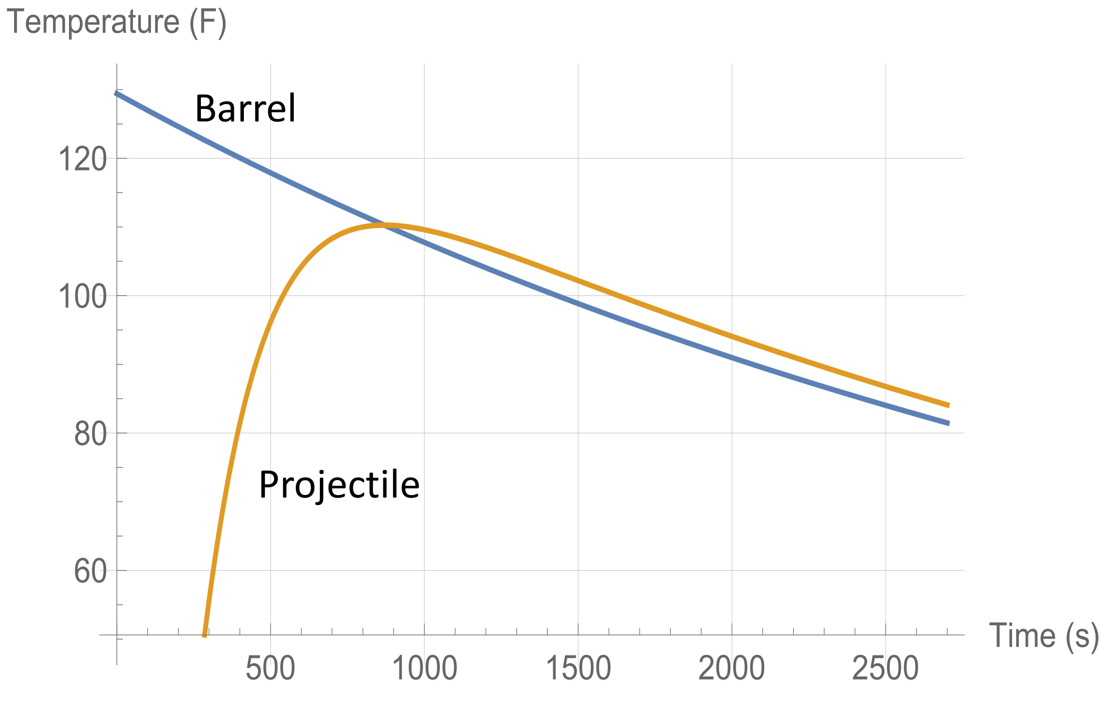


Experimental data shows the difference between the barrel and projectile in gun firing and cooling follows a curve similar to Newton's Law, an exponential function

Calculation of Projectile Temperature and Experimental Data

Theory

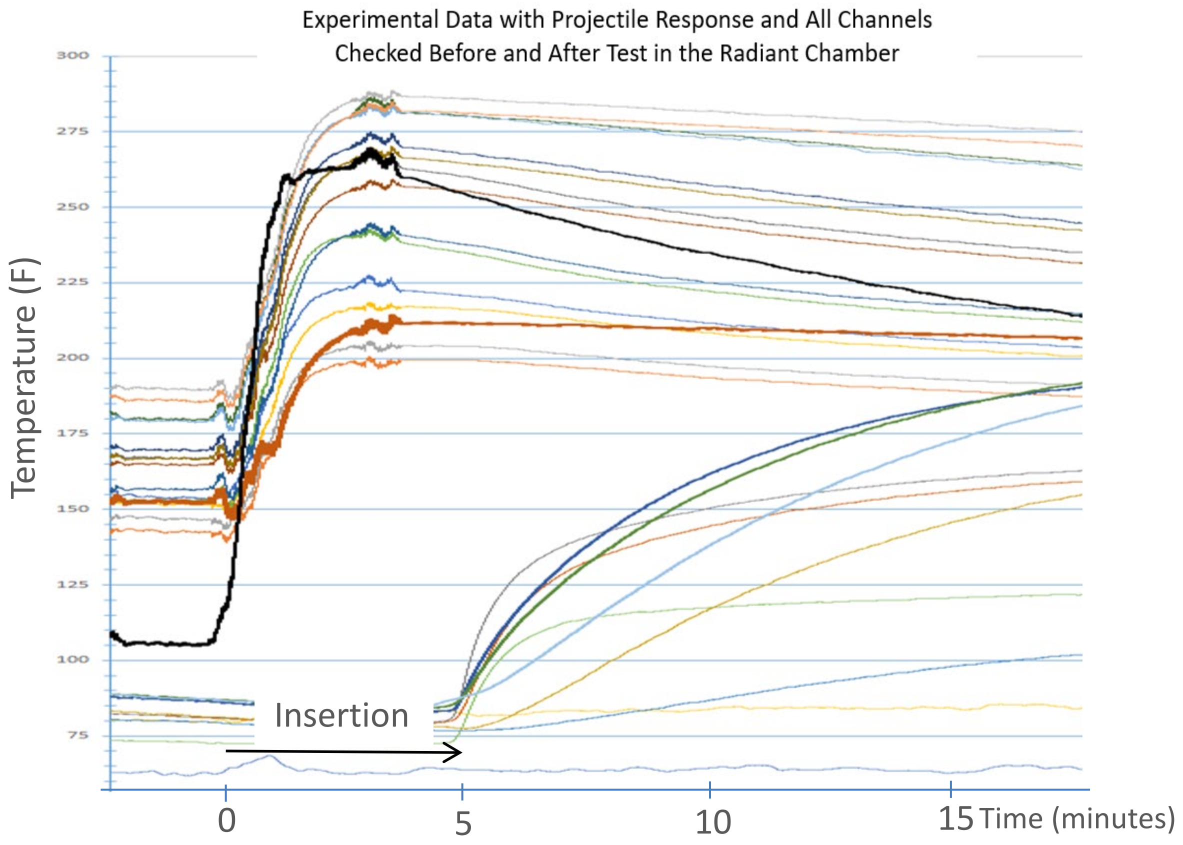
Barrel Cooling and Projectile Heating With Delayed Insertion



It took about 5 minutes to open the breech, insert the projectile and begin recording data

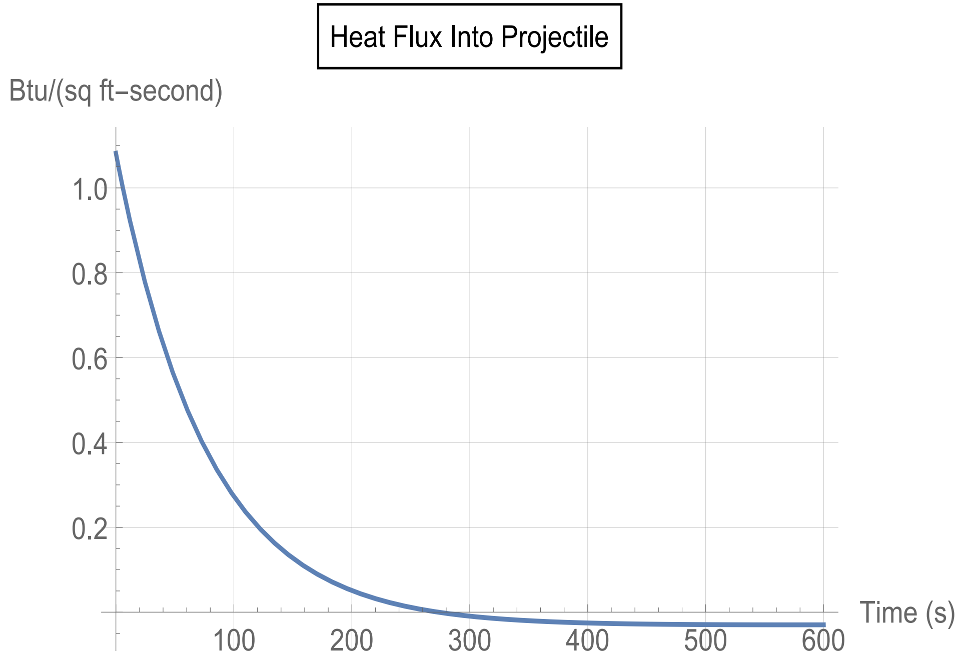
Experiment

Experimental Data, Barrel Above, Cartridge Below

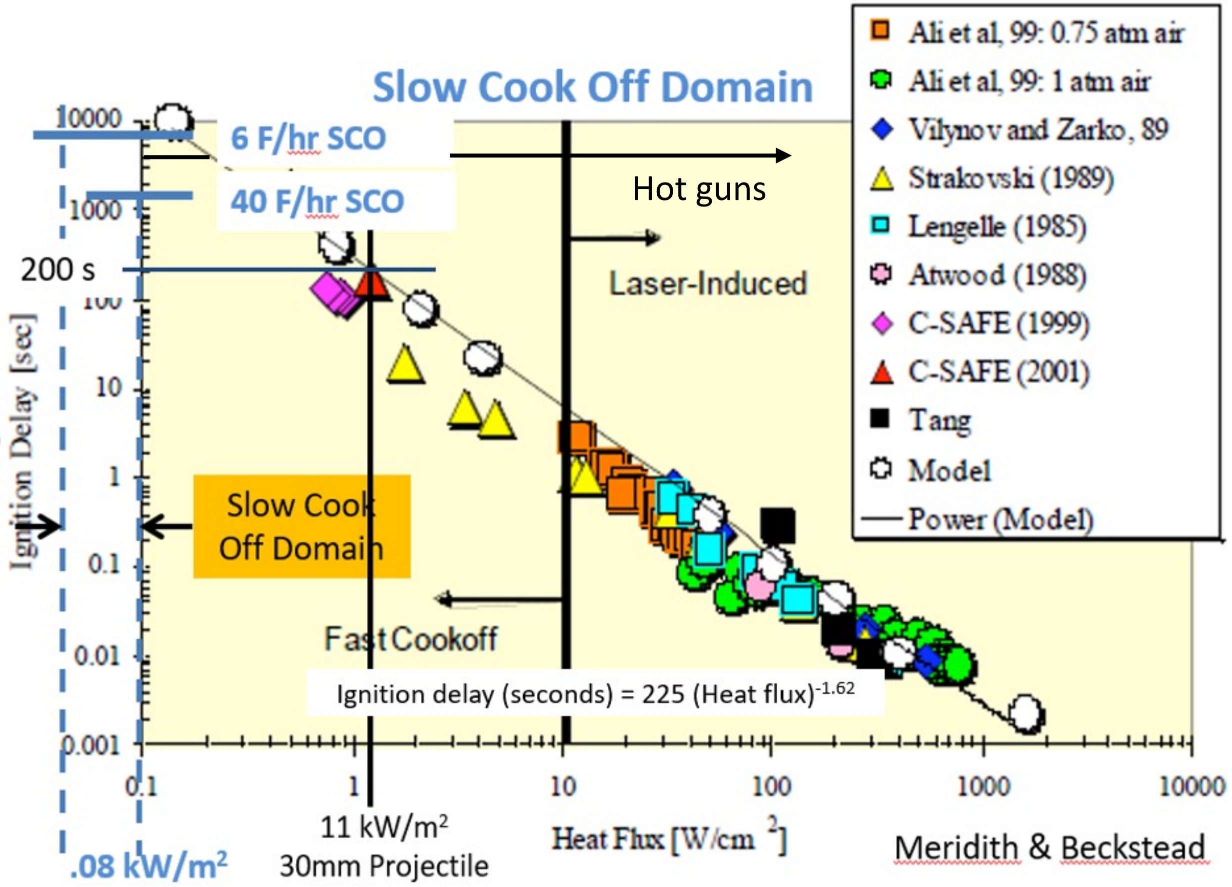


The starting temperatures are staggered because the gun was cooling from previous firings

Estimating the Time to Cook Off



The heat flux can be calculated from the derivative (dT/dt) of the projectile temperature curve



Cook-Off

Summary

- Knowledge from IM test development led to understanding of gun and projectile heating
- Barrel heating is caused by friction, convection, and radiation
- Convection is initially small and increases from 0 to its maximum value at the muzzle
- Radiation is from incandescent flames and entrained carbon
- Radiation can be the dominant heating mechanism in hypervelocity guns
- Barrel heating can be calculated
- Projectile heating and cook off can be predicted

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Thank You

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