Barrel Heating for Hot Gun Cook-Off Thermal Analysis

Paper Number 23501

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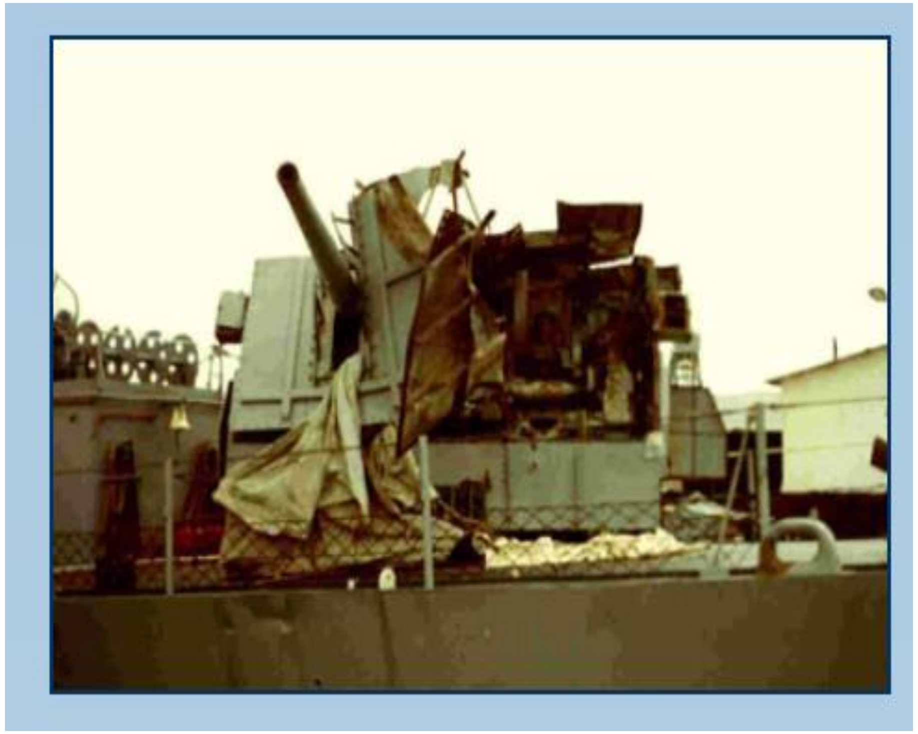
Gun and Electric Weapon Systems (E)

Hot Gun Safety

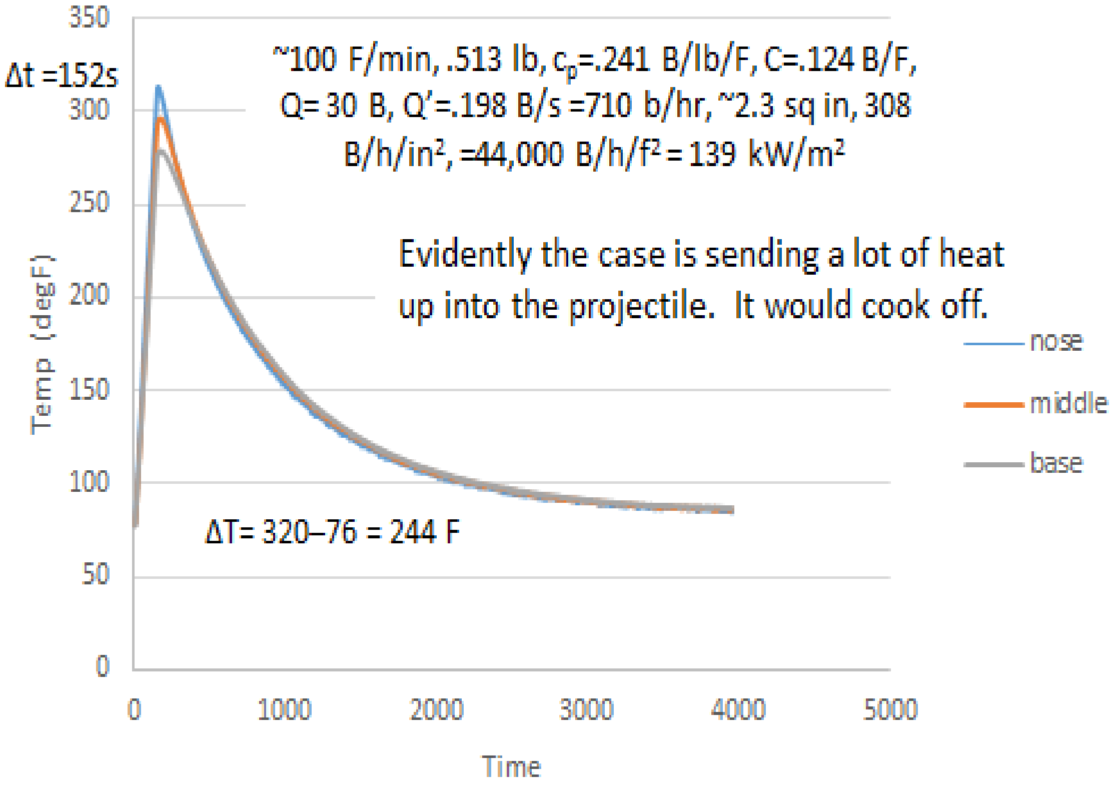
A fire mission may call for hundreds of rounds of ammunition to be expended in a short period of time. The "hot gun" safety concern is for a round to be loaded into the gun, and fail to fire for some reason. If the round cannot be ejected it may cook off in the chamber. The picture on the left shows an explosion in a 16-inch gun turret. The left gun of the 5"/38 cal. mount (right) was thrown 900 ft. into the sea when a projectile detonated in bore. Guns are also installed in aircraft and fighting vehicles, where the there is no place to escape or hide.



Laboratory Experiment With a Cartridge in a Radiant Chamber

Cartridge With Thermocouples in Radiant Chamber

Sample calculation of the heat flux into a round in the radiant chamber from measured temperature



The heat flux of 139 kW/m^2 is what we see in fast cook-off testing

Stages of Heating and Modeling

- Action time – projectile starts from rest and travels down to the muzzle exit plane
- Blowdown – hot propellant gas vents out of the barrel causing additional heating
- Heat Soaking – barrel accumulates heat which decays only slightly between rounds

Heating starts when the projectile first begins to move. Pressure forces the projectile into the bore. For small arms the bullet jacket is “engraved” at this time. For larger calibers, driving bands of metal or plastic are used. The engraving process happens quickly, and there is plastic deformation of the band that causes heat. Since the band is in contact with the barrel, heat flows into the barrel at this time. It also flows into the projectile body. Pressure on the base of the projectile and hydrostatic pressure caused by acceleration cause the projectile to swell and push the barrel radially outward, creating frictional heating of the barrel and the projectile. The torque applied to the barrel causes frictional heating as the band slides along the shoulders of the rifling lands. It takes great force to push a fired projectile back through the barrel, indicating large friction is present.

Internal ballistics models are used to move the projectile down the barrel during the action time. The velocity, viscosity, flame temperature, bulk temperature, and pressure are computed as functions time and distance. From the Reynolds numbers and Nusselt numbers, convection to the barrel can be calculated. Radiation is calculated from the Stephan-Boltzman equation.

Blowdown starts when the projectile band crosses the muzzle exit plane. The velocity, temperature, and pressure in the barrel can be calculated using formulas developed for designing muzzle brakes. The barrel vents over a time period much longer than the action time. Even though the heat fluxes are smaller, they act over a longer period of time and provide a comparable amount of heat.

Outline

Action time – In bore period. Projectile starts from rest and travels down to the muzzle exit plane

5 slides

Blowdown – Hot propellant gas vents out of the barrel Convection and Radiation

3 slides

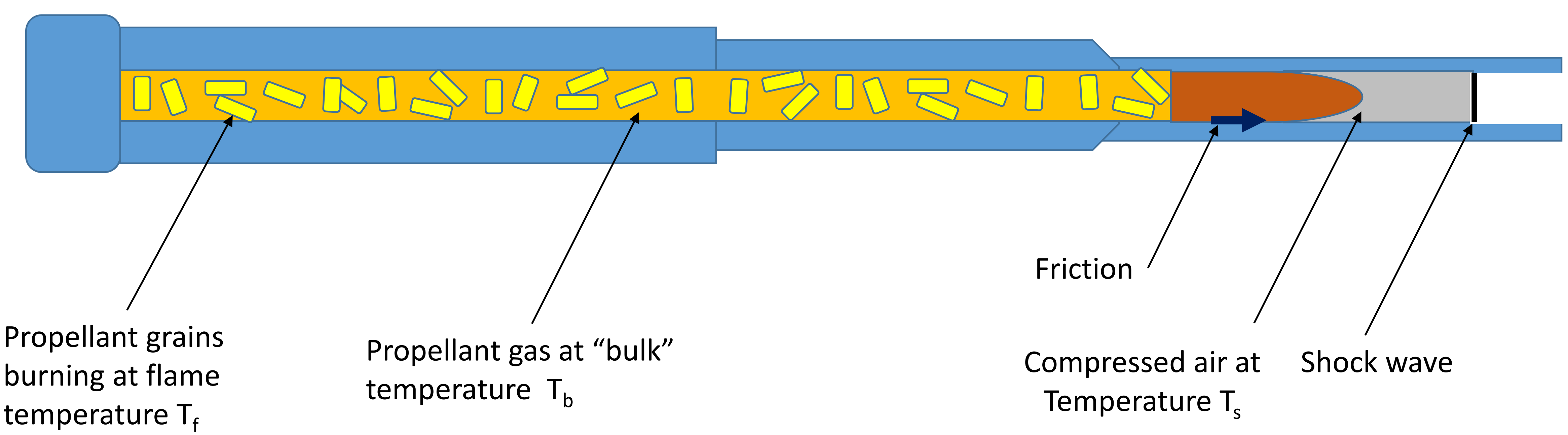
Lumped Parameter Models – complete math model of a barrel with a projectile

3 slides

Current Experiments – Instrumented 105mm barrel and projectile

2 slides

Sources of Heat in Barrel



Luminous Particles and Chemistry

Combustion of Solid Propellants

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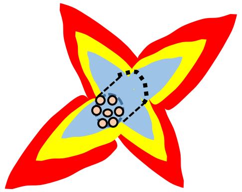
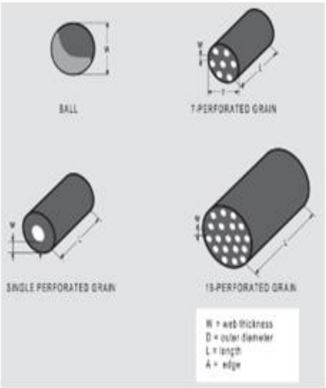
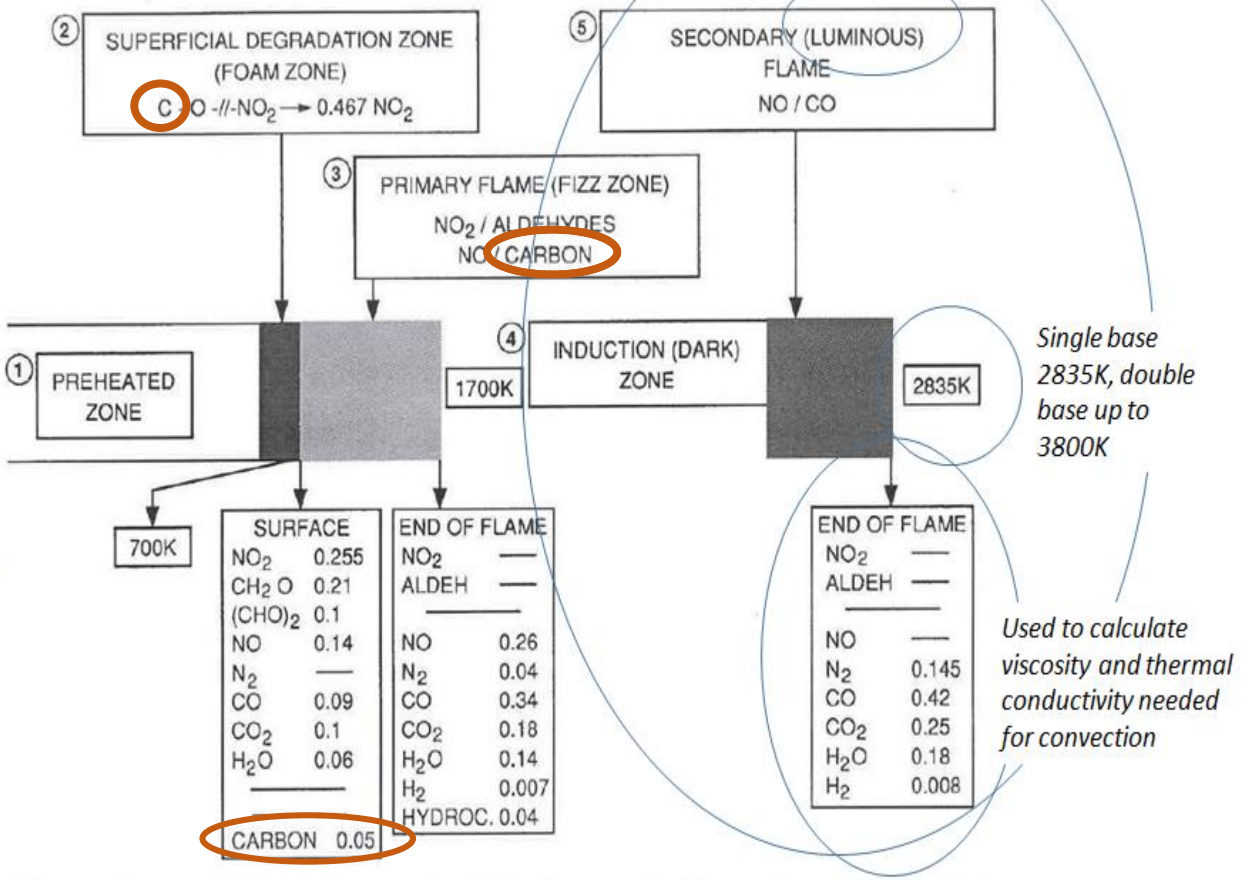




Propellants are designed to burn at a nearly constant rate. As the outer surface area diminishes, the inner area increases. The radiation output should be nearly constant. (jjy)

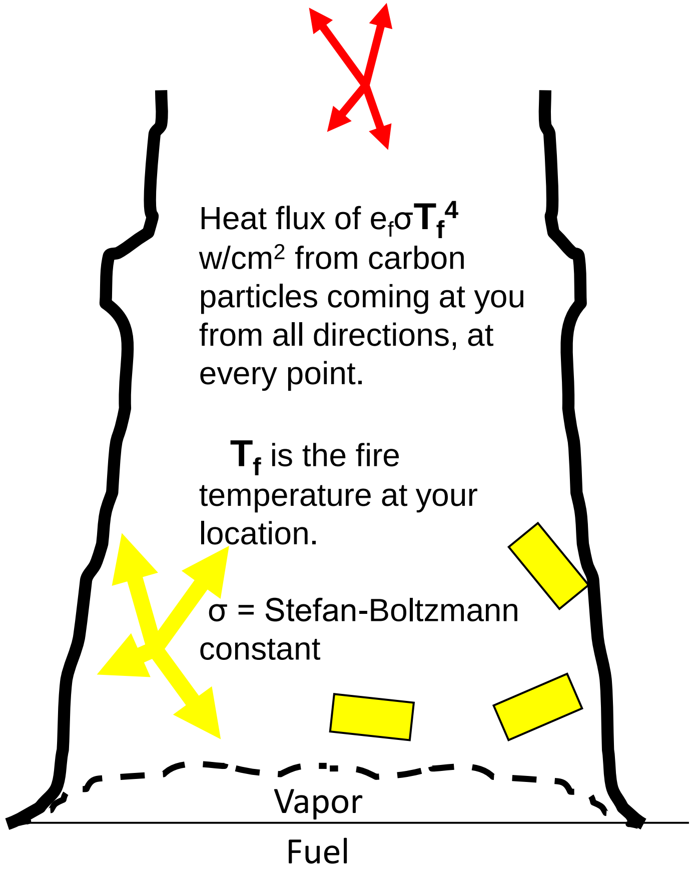
https://www.vihtavuori.com/tech-blog-powder-grain-shapes/



Single base 2835K, double base up to 3800K

Used to calculate viscosity and thermal conductivity needed for convection

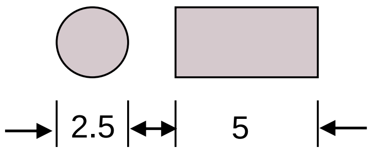
Fast Cook-Off : *90% of the heat is radiation,*
10% is convection



The same formulas are used for gun barrel heating

Worked Example – Heat absorbed by a cylinder in a 1750 deg F Sooty Fire

$e_f \sigma T_f^4$ B/hr/ft² emitted from fire in all directions

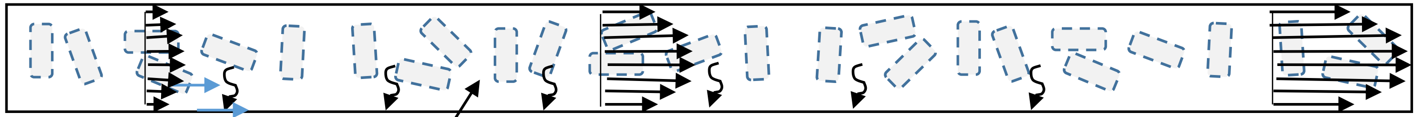


e_b= 0.9

Stefan-Boltzman Constant	σ	1.7140E-09	B/hr/ft^2/deg R^4
Emissivity of fire	e_f	1.00	
Temperature of fire	T_f	1750 +460 =2210 R	
Emitted radiation	**q"**	1.1144E+04	B/hr/ft^2
Surface area of Cyl.	**A**	.273 ft^2	
Total incident radiation on cylinder	**q'**	11,100 B /hr	
Absorbed for e_b=0.9		**10,000 B/hr**	

Gas Dynamics Mechanisms for Heat Transfer to Barrel During Action Time

Convection



Velocity ~ 0, no convection

T_{bulk}

Gas temperature

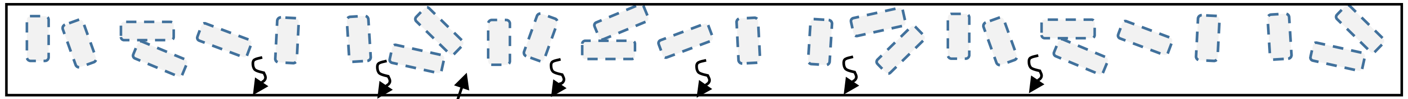
$q'' = h_c\,(T_{bulk} - T_{gun})$

h_c = convection coefficient

Velocity = Vp, maximum convection

Small, < 5% of total heating

Radiation from gas at T_{bulk}

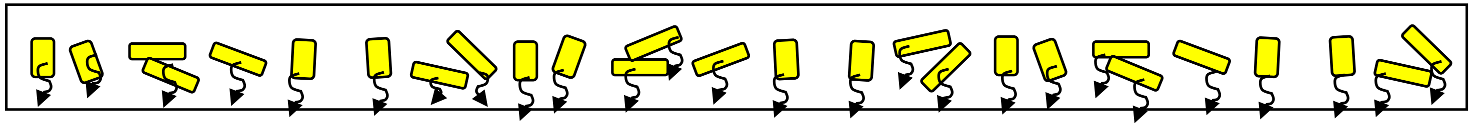


T_{bulk}

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

About 30% of radiation heating

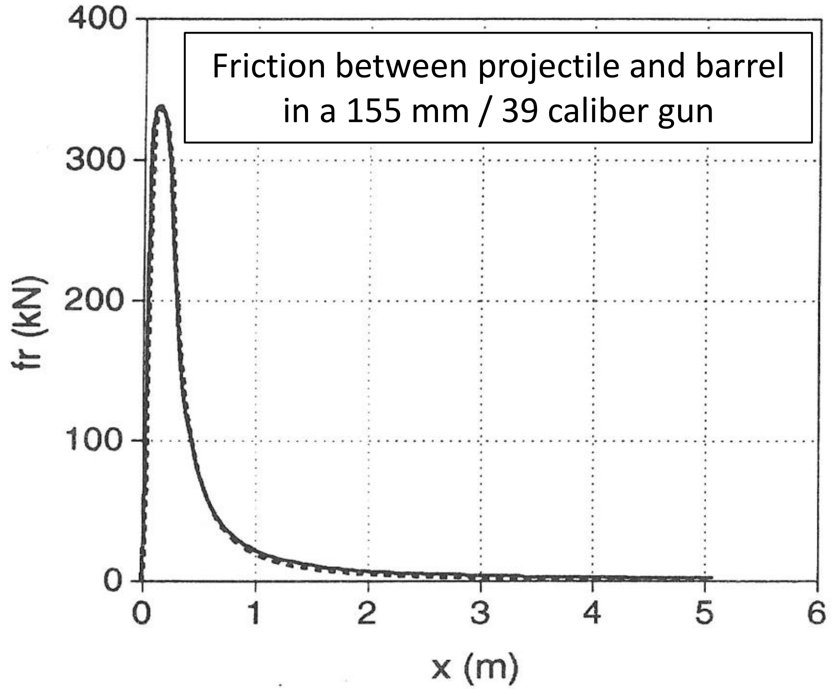
Radiation from propellant grains at T_{flame}



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

About 70% of radiation heating

Friction Between Projectile and Bore for 155mm Howitzer



A. Tuomainen "The Thermodynamical Model of Interior Ballistics," Acta Polytechnica Scandinavica, Applied Physics Series 205, Helsinki

This curve was integrated to estimate the energy using $q = \int F_f \, dx$. The result was115 kNm (85000 ft lb or 109 BTU) per shot. This 0.43% of the total energy in the propellant.

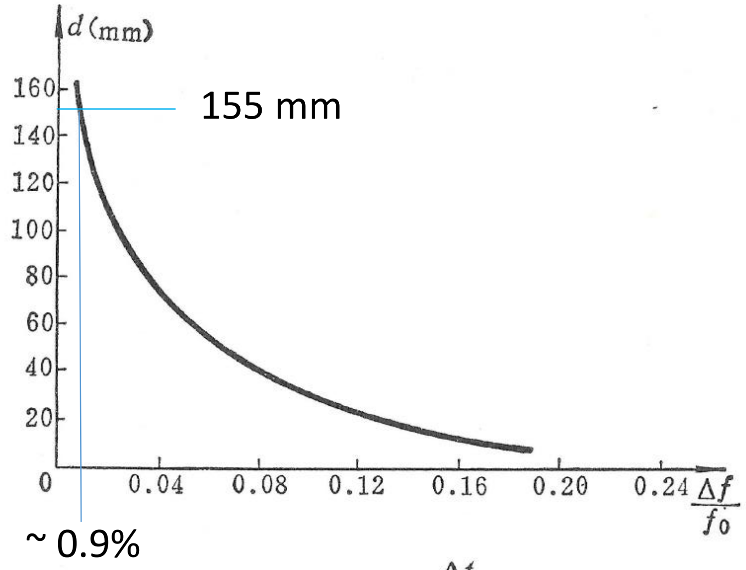


Fig 2.5 The heat loss $\frac{\Delta f}{f_0}$ vs the caliber of conventional guns

Bao Ting-Yu "The Theory of Potential Equilibrium for Ballistics and its Application," Defense Publishing House. Beijing, P.R. China, 1988.

The ratio of $E_{Friction}$ (Δf) to the total energy in the propellant, f_o, for guns of caliber 10 mm to 160 mm was calculated by Bao. The result of 0.4% is the same order of magnitude as in Tuomaninen.

Although the frictional energy is a small percentage of the total chemical energy available, it is a significant player in barrel heating

Barrel Heating During In-bore Period Summary

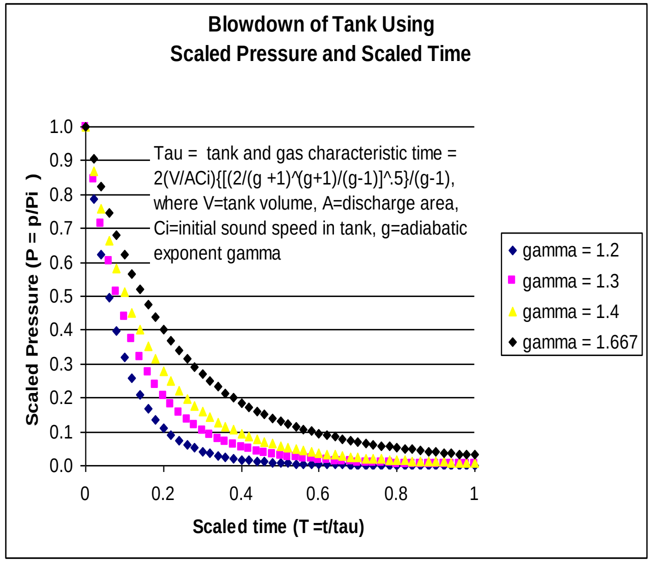
- Heating starts when the projectile first begins to move.

- The barrel heating is mainly radiation:
  Part of the radiation is from the propellant gas at the bulk temperature T_{bulk}
  Part of the radiation is from the flame temperature of the propellant T_{flame}

- The barrel heating by convection is small, and highest at the muzzle:
  Zero at the breech
  5% of the total heating at the muzzle

- The friction heating is hard to calculate and a small portion of the total energy, but a significant contributor to barrel heating.

Gas Dynamics Mechanism for Heat Transfer to Barrel During the Blow Down Time Period

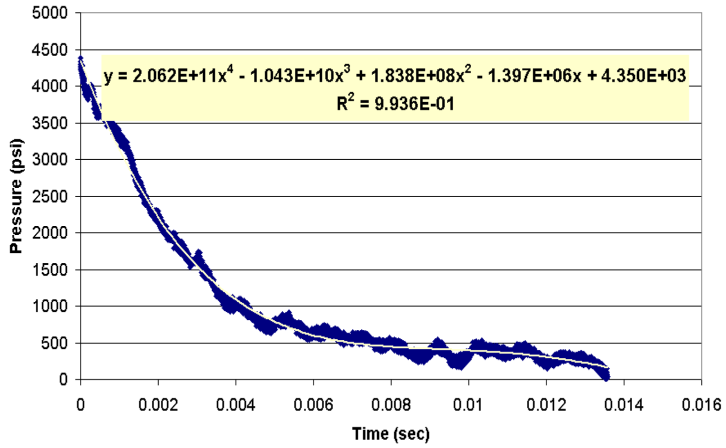


$$\left(\frac{p_f}{p_i}\right) = \left[1 + \frac{t}{\tau}\right]^{2\gamma/(1-\gamma)}$$

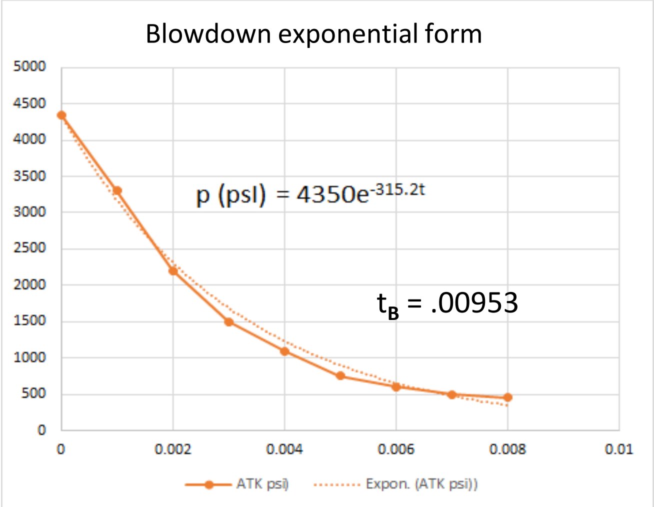
A =bore area
C = sound speed
p_i = initial pressure
p_f = pressure at time t/τ
τ = time constant
γ = adiabatic exponent

The velocity can be calculated from gas dynamics, then the Reynolds number, then the Nusselt number, and then the convection coefficient, h_c, and finally the heat flux q"

Jon J. Yagla "Pressure Vessel Discharge Non-dimensional Equations"
Paper No. 19033551 28th International Ballistics Symposium, Atlanta



A pressure vs. time record from the muzzle in test. A curve was fit to the data.



Heat transfer shorthand:

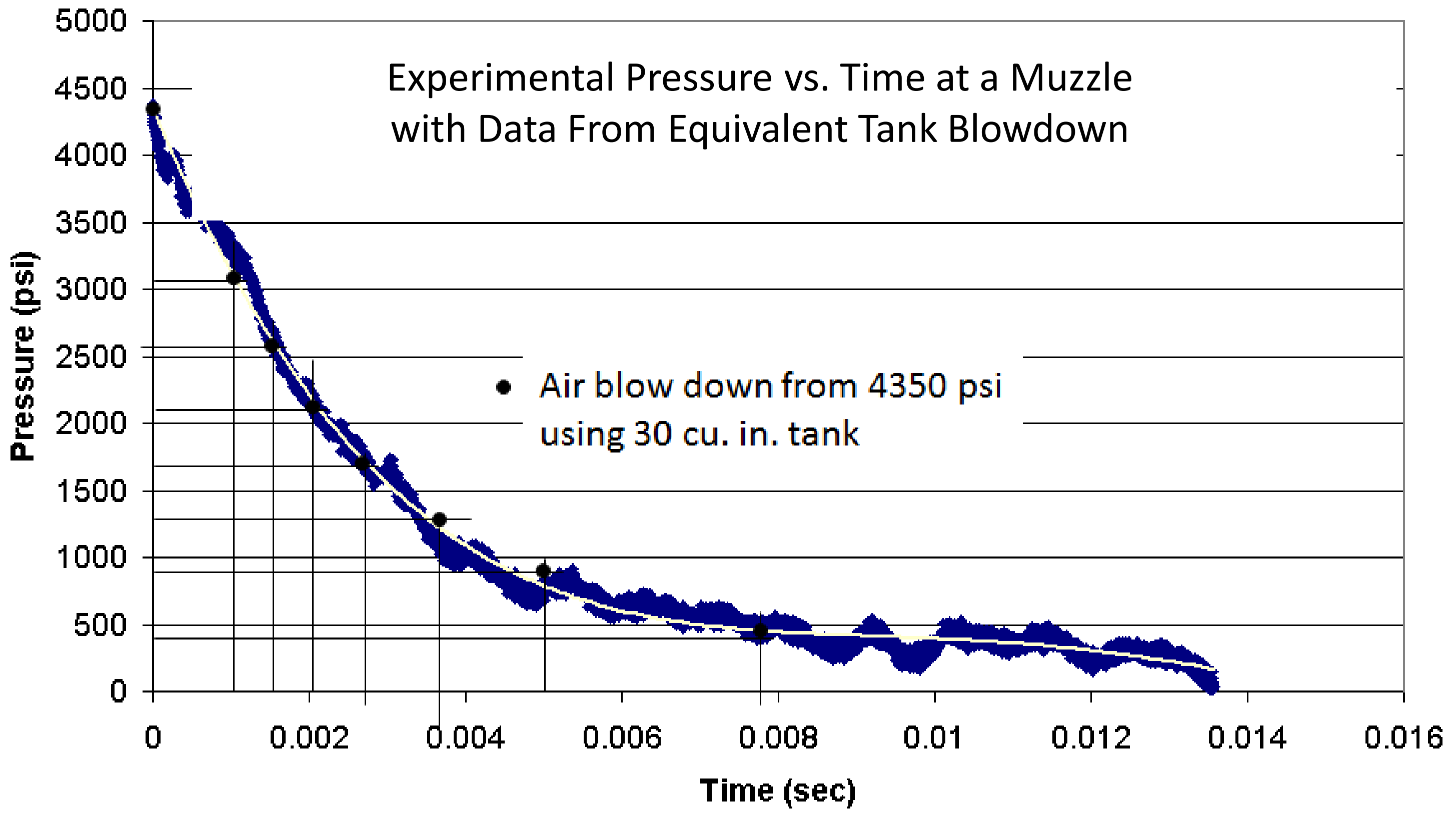
q = quantity of heat energy

Q = larger quantity, ∑ q's

q' = flow of heat per unit area, or per unit of time

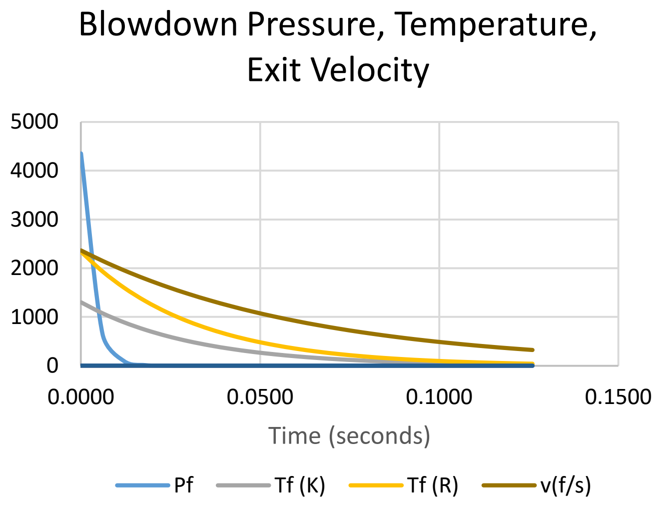
q" = flow of heat per unit time per unit of area, the "heat flux"

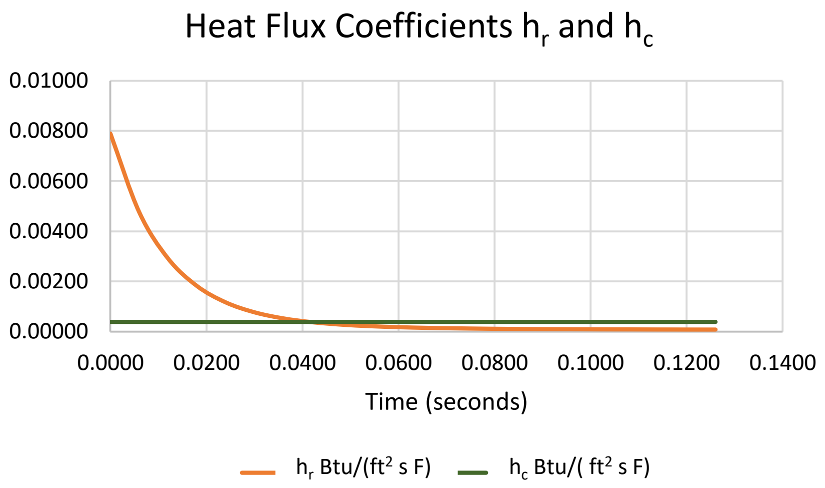
Matching Compressed Air to a Gun Barrel Blow Down

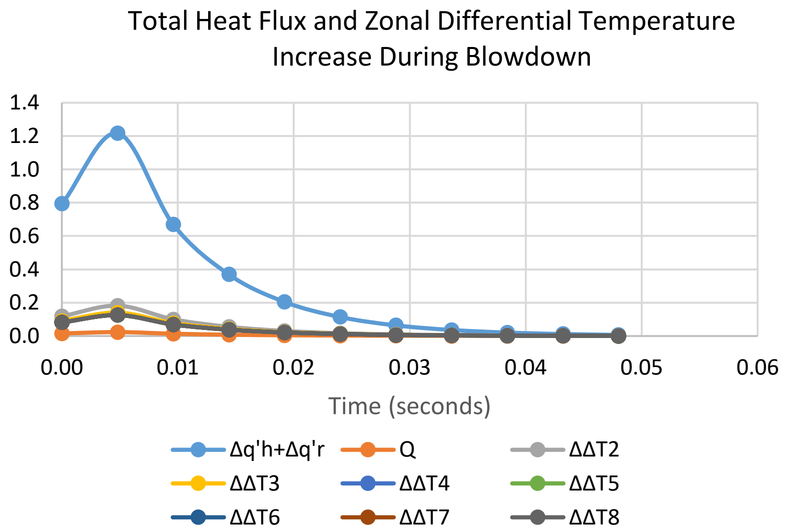


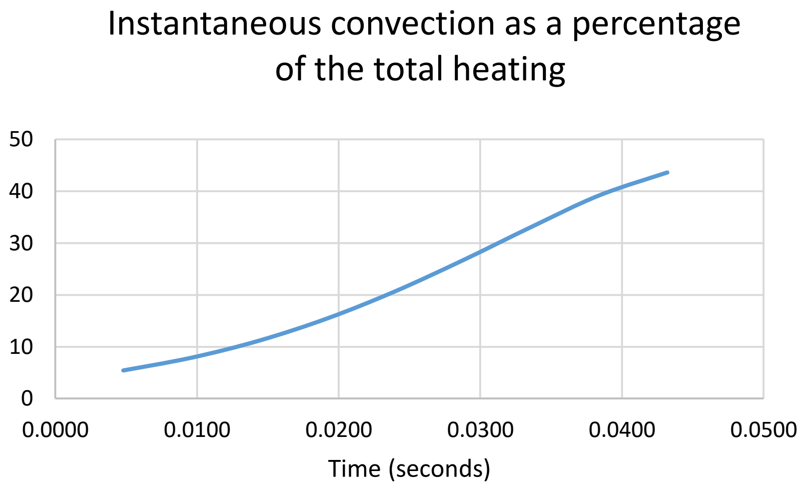
The compressed air blow down data are shown on the gun barrel blow down plot by the circular plotting symbols. They lie nicely on the gun barrel blow down curve. This shows a gun barrel obeys the dimensionless formulas. It also shows a cold gas discharge from a tank of compressed air can provide a precise simulation of the gun pressure. The formula is used to compute the temperature and velocity in the barrel, then Reynolds number, Nusselt number and heating from radiation and convection.

Example of Results for a 30mm Gun (work in progress)



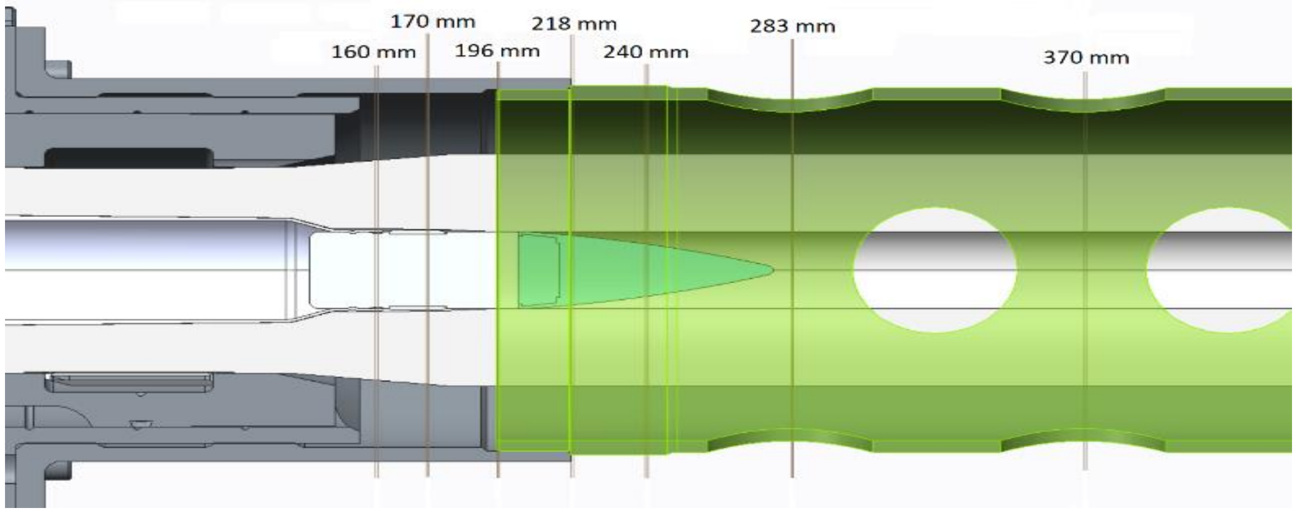


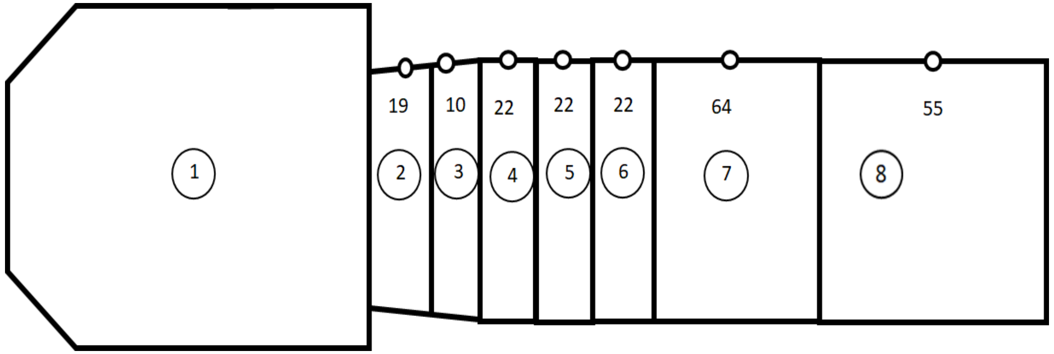




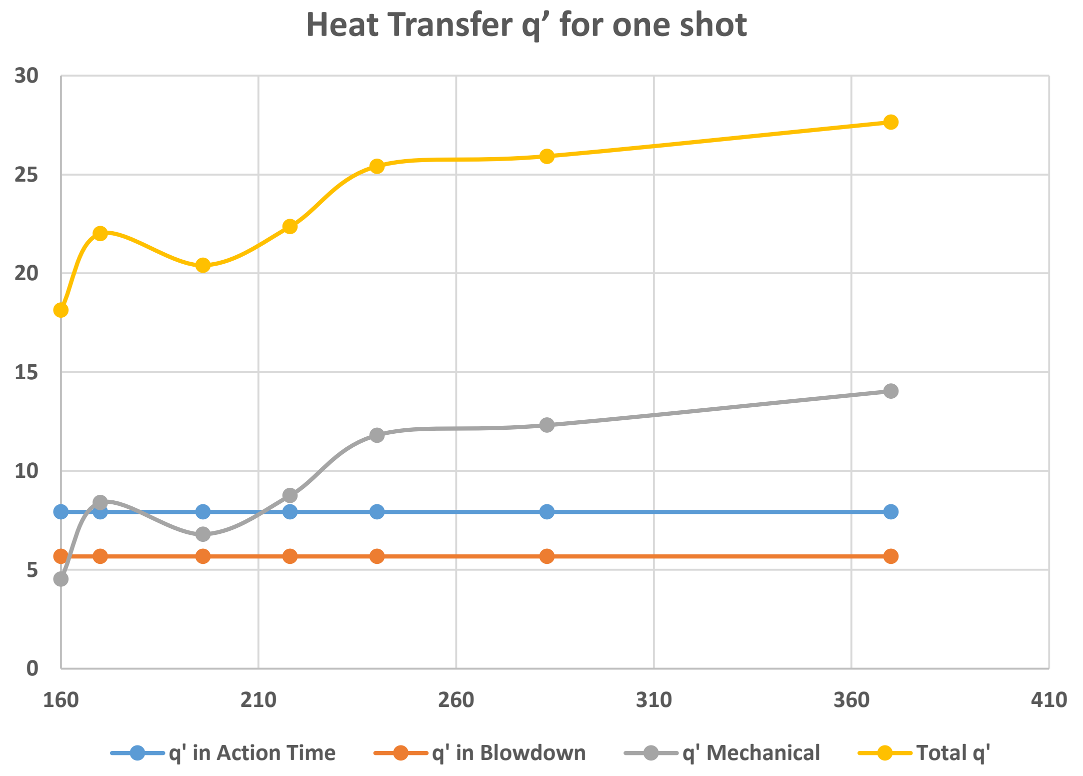
Lumped Parameter Model for Barrel Heating In Cartridge Region

The chamber region was divided into heating zones centered on thermocouple locations.
The volume, mass, surface area, and heat capacity was calculated tor each zone.
The measured temperature data were processed for each zone to determine q (per shot) and Q for a mission of 66 rounds.
Heating from radiation and convection was calculated for each zone.
The difference between the calculated heating and measured heating was calculated and attributed to mechanical losses of deformation and friction.





Semi-empirical Model Results for Chamber and Shot Start Region

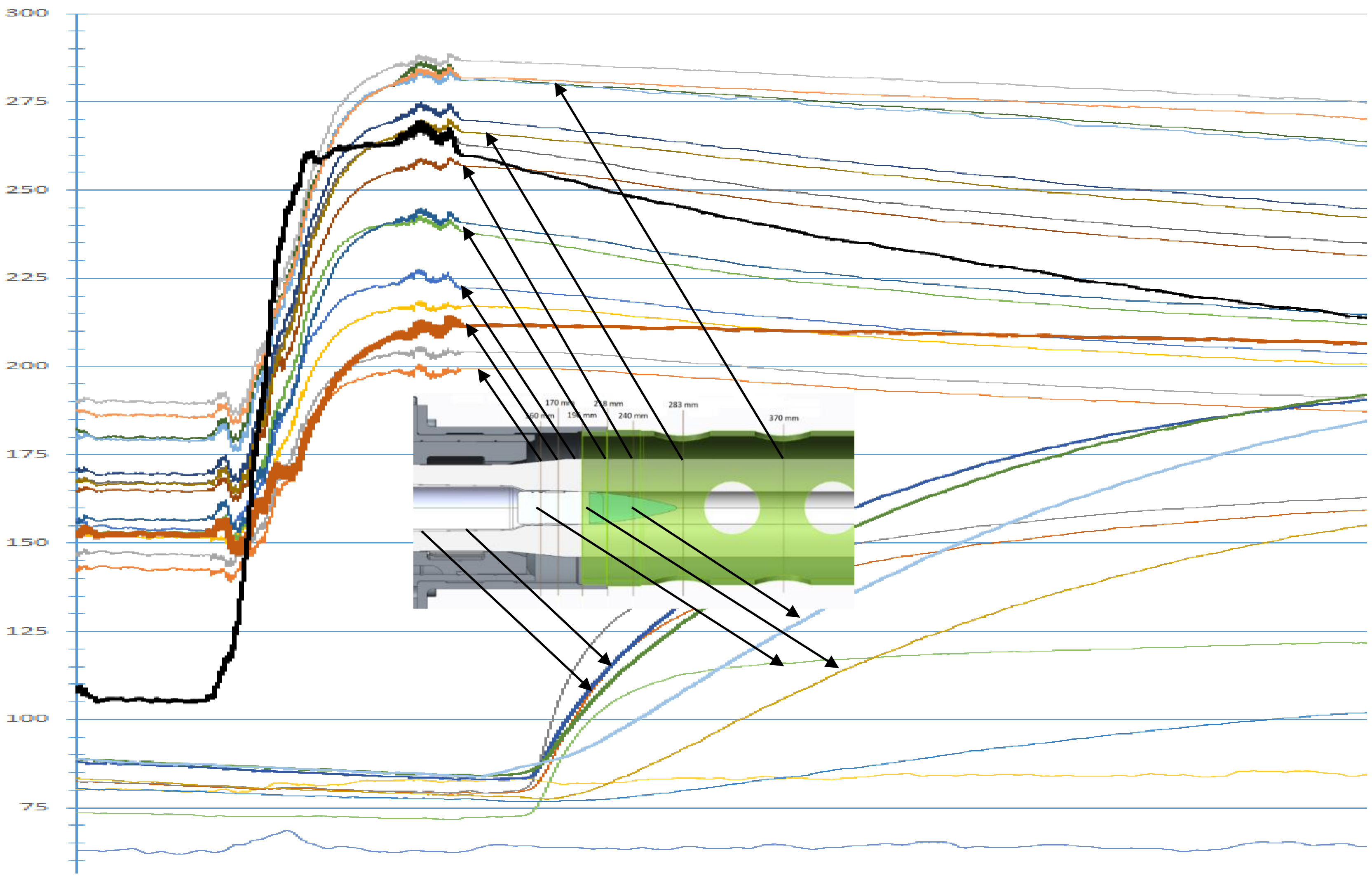


Using the yellow curve to left:

zone	x-station	q' in Action Time	q' in Blowdown	q' Mechanical	Total q'
2	160	7.93	5.68	4.53	18.14
3	170	7.93	5.68	8.40	22.01
4	196	7.93	5.68	6.80	20.41
5	218	7.93	5.68	8.75	22.36
6	240	7.93	5.68	11.81	25.42
7	283	7.93	5.68	12.32	25.93
8	370	7.93	5.68	14.03	27.64

- q’ = total heat flowing into zone / inner (I.D.) surface area of zone (Btu/ft^2)
- ΔT= q’ A / C , where A = inner surface area and C heat capacity of the zone
- Heat consists of conduction, convection, and radiation. The mechanical portion is attributed to friction and other heating mechanisms

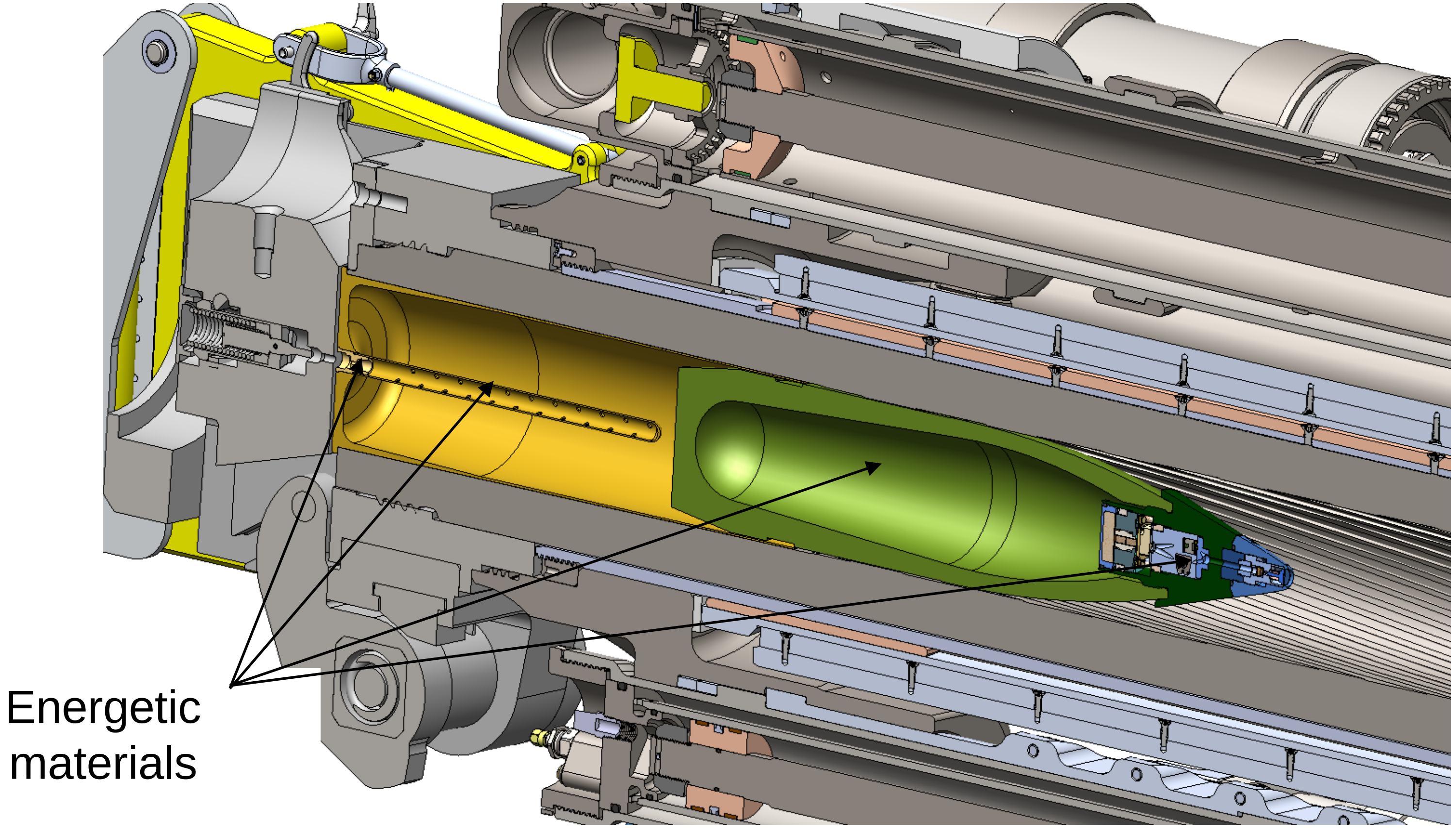
Example Cartridge Temperatures, 30 Rounds



Experimental Heating Data From 30 Rounds

x (thermocouple)	Tmax	ΔT
mm	F	F
160	202	142
170	214	154
196	227	167
218	243	183
240	268	208
283	272	212
370	286	226

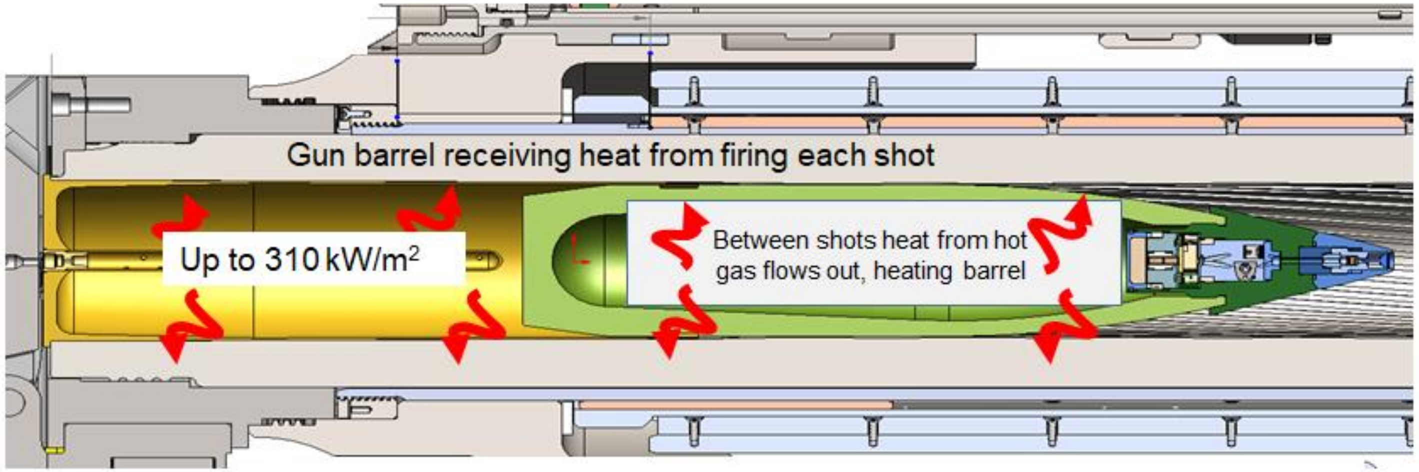
105 mm Hot Gun Cook-Off Experiment



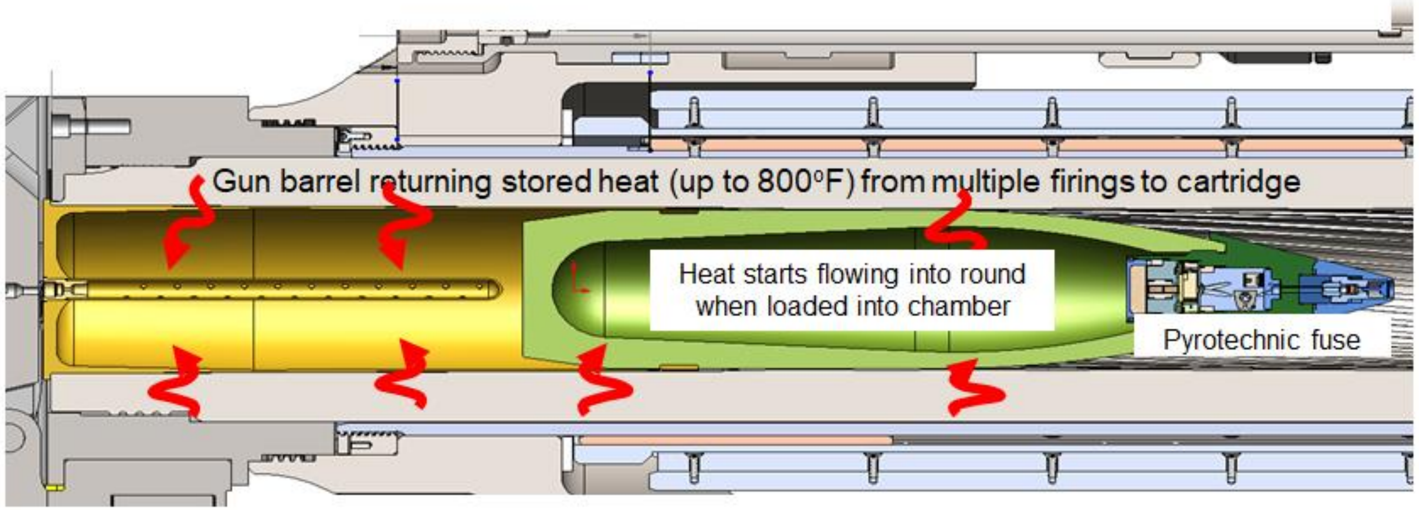
Repeated firing gets the gun barrel very hot. Should a round that has been loaded into the gun not fire, a potentially hazardous condition exists. ***If it not promptly removed it may cook-off.***

Heat Flows During Rapid Continuous Firing

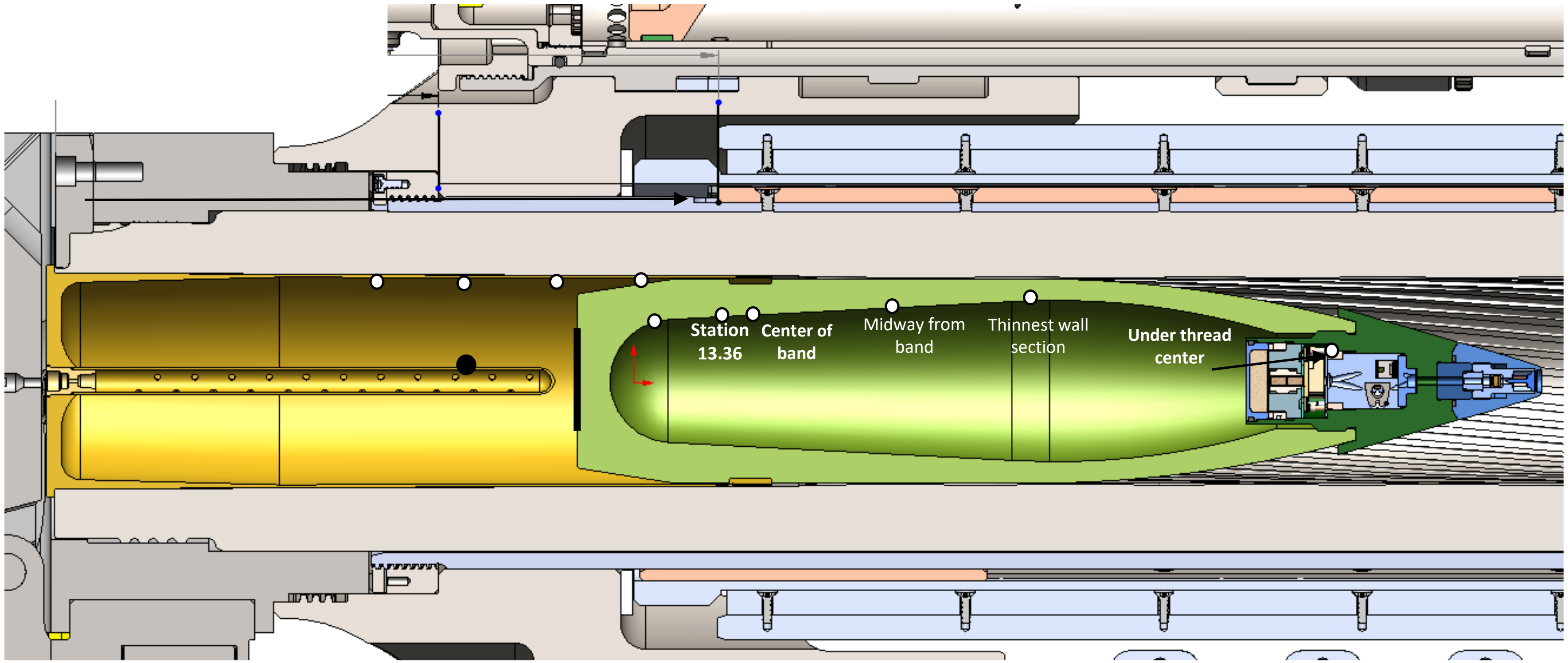
Heat flowing from chamber into barrel in $t_A + t_B$ (~ .020 sec)



Heat flowing from barrel into cartridge (~ 1 sec)



Opportunity to Leverage Data From Forthcoming Test with Instrumentation



105mm Hot Gun Test 2021. The projectile has been filled with material to simulate Composition B and the thermocouples have been tested.

Summary

Hot guns can be very dangerous

Barrel heating is in two stages: Action Time and Blow Down

Radiation, convection, and friction are the main heat transfer mechanisms

Radiation is caused by hot propellant gas and radiating propellant grains

Convection is relatively small, then increases during blowdown

Temperature measurements in the barrel and cartridge provide experimental confirmation and provide data to converge models