Pyrotechnics and Propellants

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Outline

- **Pyrotechnics**
- Propellants (Low Explosives)

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DETS

Pyrotechnics

Pyrotechnics

- **Pyrotechnic** is a material containing a fuel and oxidizer that when ignited produce heat, flames, sound, colored light, smoke, and some gas.

Pyrotechnics

- **Pyrotechnic** characteristics
  - Usually the fuel is metal and the oxidizer is salts or metal oxides
  - Chemically metastable
  - Very low reaction rates
  - Produces a large amount of energy

Fuels	Oxidizers	Reactants
Aluminum	Ammonium Nitrate	Aluminum Oxide
Boron	Ammonium Perchlorate	Barium Oxide
Iron	Barium Chlorate	Boron Oxide
Magnesium	Barium Nitrate	Carbon Dioxide
Phosphorus	Barium Peroxide	Carbon Monoxide
Silicon	Iron Oxide	Chromium Oxide
Titanium	Lead Chromate	Lead Oxide
Lactose	Lead Oxide	Magnesium Oxide
Shellac	Lead Peroxide	Nitrogen
Hexachloroethane	Potassium Chlorate	Potassium Carbonate
Starch	Potassium Nitrate	Potassium Chloride
Anthracene	Potassium Perchlorate	Potassium Sulfide
PVC	Sodium Nitrate	Silicon Dioxide
	Strontium Nitrate	Sodium Chloride
		Strontium Oxide
		Titanium Dioxide
		Water
		Zinc chloride

Pyrotechnics

- **Types**
  - Heat
  - Light
  - Sound
  - Smoke
  - Delay

Pyrotechnics

- **Heat**
  - Usually metal-salt or metal-metal oxide mixture with no binders
  - Uses
    - Ignition mixtures
    - Thermites
    - Incendiaries
    - Heat pellets for thermals batteries
  - Metal-salt mixture
    - Sensitive to impact, flame, and sparks
    - Used mainly in ignition mixtures
  - Metal-metal oxide
    - Not sensitive to impact, flame, and spark
    - Used mainly as thermite material and heating devices

Thermite

- With Termite the more reactive metal (Aluminum) reduces the metal Oxide (Iron Oxide Fe_2O_3), Oxidizing itself and releasing a substantial amount of energy during the reaction.
- The two most common types of Thermite are made using either Iron(III) Oxide, Fe_2O_3 (also known as Hematite), or using Iron(II, III) Oxide, Fe_2O_4 (also known as Magnetite).
  - The Iron Oxide is mixed with finely powdered Aluminum metal.
- When the Thermite reacts, liquid Iron metal and Aluminum Oxide, Al_2O_3, is produced as a result.
  - Al melting point is ~1,221˚F
  - Alumina melting point ~3,763˚F
  - Fe melting point is less than 3,000˚F
  - Ignition temperature is above 2,200˚F
  - Reaction temperature is between ~3,632˚F to 5,000˚F**
  - This temperature of the sun is ~10,000˚F

$$2Al + Fe_2O_3 \xrightarrow{heat} Al_2O_3 + 2Fe$$

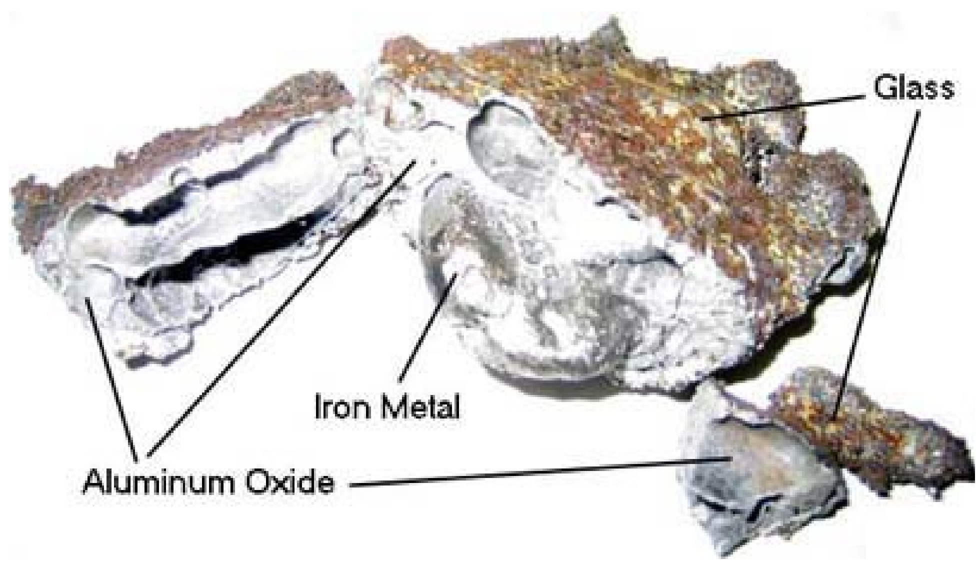
**Chemistry of Pyrotechnics, Conkling, 2nd Edition

Pyrotechnics

- **2000 grams** of Fe_2O_3 thermite, filling a large coffee can, reacts on top of a ¼” thick, steel, I-Beam. The resulting reaction is so intensely hot that it melts its container and the steel beam, spilling vast amounts of molten Iron and Al_2O_3 everywhere.

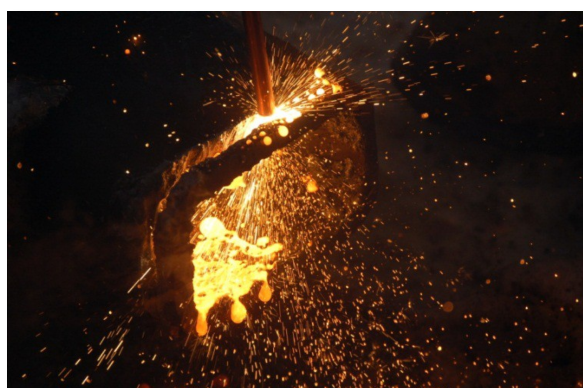
Thermite

- Al/Fe_2O_3 is the most common Thermite used today for welding
- The products from this reaction are
  - Molten Iron
  - Alumina
- The molten Iron is the heat transfer medium to perform the specific work
  - Welding of railroad tracks together



Exothermic Torch

- An exothermic cutting torch is a copper pipe packed with metal wires.
- Pure oxygen gas is passed through the pipe from an oxygen cylinder and regulator.
- The end of the pipe is lit with a high temperature source.
- The copper sleeve burns and is used as a pre-heating source for the metal inside the sleeve.
- The iron in the steel burns in the oxygen coming down the pipe to produce enormous heat and a liquid slag of iron oxides and other materials, which dribbles and splashes out.
- The temperature reached in the center of the combustion zone is ~10,000˚F or greater. This is significantly higher than the melting point of any substance on earth.
    - Concrete melts at ~3500˚F
    - Steel at less than 3000 ˚F
- The flow and pressure of the oxygen also helps to blow the slag out of the cut zone.

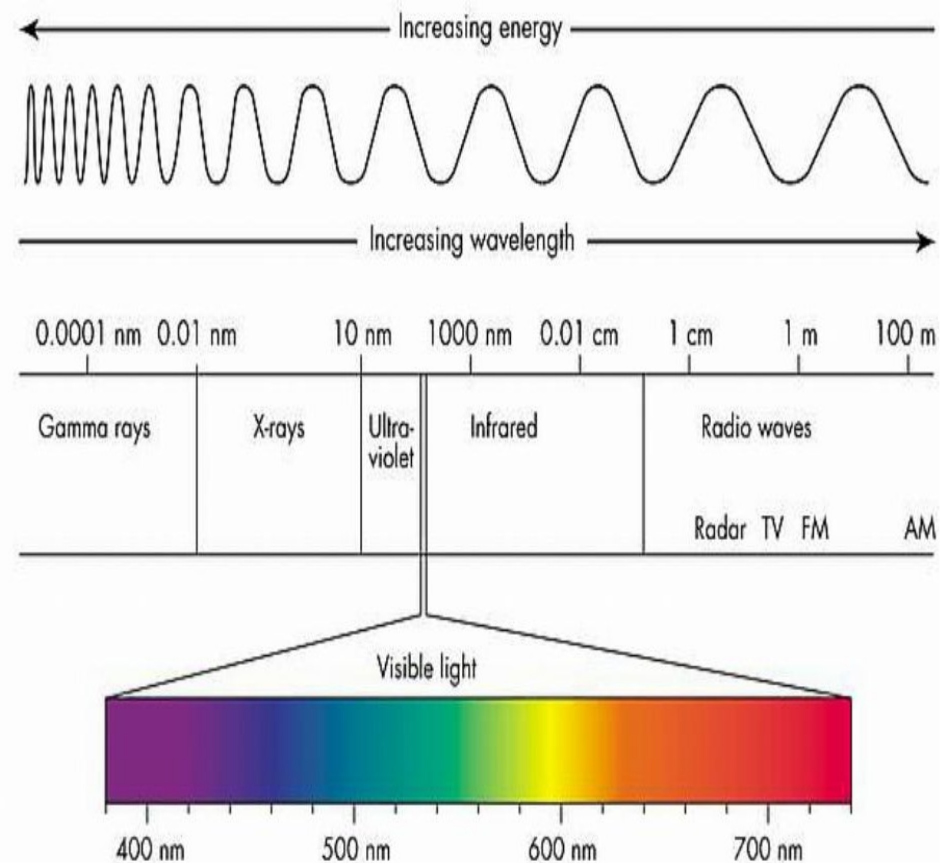


Pyrotechnics (Energetic Materials)

- **Light**
  - Two Categories
    - Flash Powder
    - Flares
  - Flash Powders
    - Metal-salt mixtures
    - Burn very rapidly where some almost produce detonation velocities
      - Reaction rates as high as 1 km/s
    - Usually packed loose or pressed lightly
    - Used to produce delays, stun individuals, or simulate detonations
  - Flare
    - Metal-salt and binder mixture
    - Burns slowly
    - Used to produce a sustained light

Pyrotechnics (Energetic Materials)

- **Light** (cont'd)
  - Physics
    - Material's electrons are in a lowest energy state
    - Electrons are excited to a higher energy state
      - Electrons in higher energy state are unstable and want to return back to their ground state
  - Upon return to ground state energy is released as
    - Heat
    - Phonon (Light)
      - Electromagnetic radiation which gives it a wave speed and length (Frequency)



Pyrotechnics (Energetic Materials)

- **Sound**
  - Two Types
    - Loud, sharp, short duration sound
    - Whistle sound for long durations
  - Loud, sharp, short duration sound
    - Black powder or photoflash mixtures used in light cardboard tubing
  - Whistle sound for long durations
    - Mixture compressed and burned in an open-ended container which produces the whistling sound

Pyrotechnics (Energetic Materials)

- **Smoke**
  - Reaction produces a large amount of gases which, disperse the smoke into the environment
  - Reaction burns at low temperatures
  - Organic dyes used produce different colors
    - Dye sublimes and condenses into the air to form small solid particles
    - These dyes are strong absorbers of light
    - In essence, the small particles act like filters by absorbing a certain spectrum of wavelength and reflecting the rest
    - The reflected light is what is seen

Pyrotechnics (Energetic Materials)

- **Delay**
  - Use controlled burn rates
  - Metal-metal oxide and metal-salt mixtures used
  - Used in safety fuse
  - Some mixtures produce gas

Propellants

Definition

- Presence of a fuel and oxidizer
  - Many propellants consist of explosive materials
- Chemically metastable
- Minimal porosity
  - Great efforts are taken during propellant production to reduce the level of porosity
- Thermally initiated
- **Propellants** undergo a rapid auto combustion that proceeds at subsonic rates
  - **Combustion** not **detonation**
- The reaction produces thermal energy, gases and hot particles

Definition

- Burn rate controlled by design pressure of the rocket or gun chamber
- Confinement enhance reaction
- **Power**
    - Thrust
- Propellants are also known as low explosives
- The rate of reaction is usually between a few cm/s up to approximately 1000 m/s

Propellants

- **Types**
  - Gun Propellants
    - Single-base
    - Double-base
    - Triple-base
    - Composite
    - High energy
    - Liquid
  - Rocket
    - Double-base
    - Composite
    - Liquid

Propellants

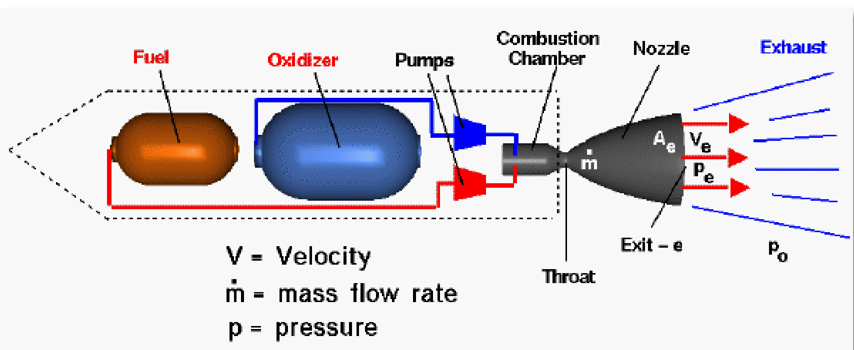
- **Single-base**
  - Composed of one energetic material (nitrocellulose) and a binder material
  - Guns
    - Used in pistols to artillery weapons
- **Double-base**
  - Composed of two energetic materials (nitrocellulose - nitroglycerine) and a binder material
  - Guns
    - Used in pistols and mortars
    - Disadvantage is the excessive erosion of the gun barrel due to high flame temperatures and muzzle flash
  - Rockets
    - Small grains used in small rocket motors
    - Cast large grain used in large rocket motors

Propellants

- **Triple-base**
  - Composed of three energetic materials (nitrocellulose – nitroglycerine - nitroguanidine) and a binder material
  - Guns
    - Used in tanks and large caliber guns
  - Nitroguanidine helps to reduce flame temperature and muzzle flash
- **Composite**
  - Composed of a fuel and oxidizer that chemically solidify when mixed together with a polymer binder
  - Guns
    - Used in pistols and mortars
    - Disadvantage is the excessive erosion due to high flame temperatures and the presence of muzzle flash
  - Solid rocket propellant mixture examples
    - Ammonium perchlorate (oxidizer), Carboxy or Hydroxy-terminated polybutadiene (fuel), Aluminum and other additives

Propellants

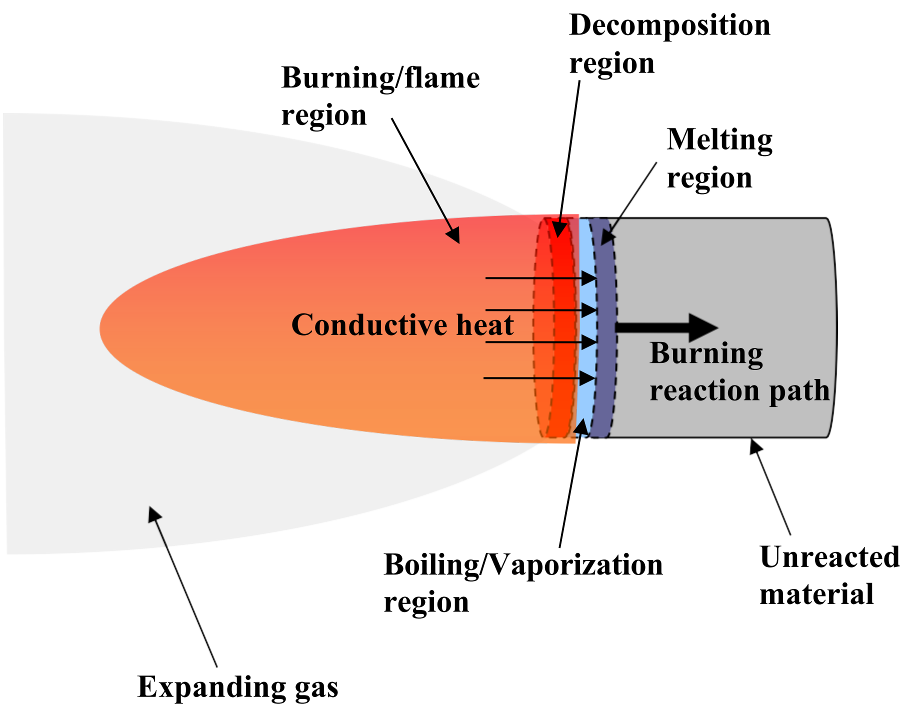
- **High Energy**
  - Nitroguanidine replaced by RDX to increase the power
  - Used in tank guns
  - Disadvantage of extensive gun barrel erosion from very high temperatures and the possibility of a detonation



- **Liquid**
  - Two types
    - Monopropellant
      - Single material
      - Hydrazine, Hydrogen peroxide, etc.
    - Bipropellant
      - Two separate materials mixed together in the combustion chamber
      - Unsymmetrical Dimethylhydrazine (UDMH) and Inhibited Red Fuming Nitric Acid (IRFNA); etc.
  - High energy output per unit volume
  - Cheap and lightweight
  - Less vulnerable to accidental initiation
  - High storage capacity
  - Drawbacks
    - Toxic

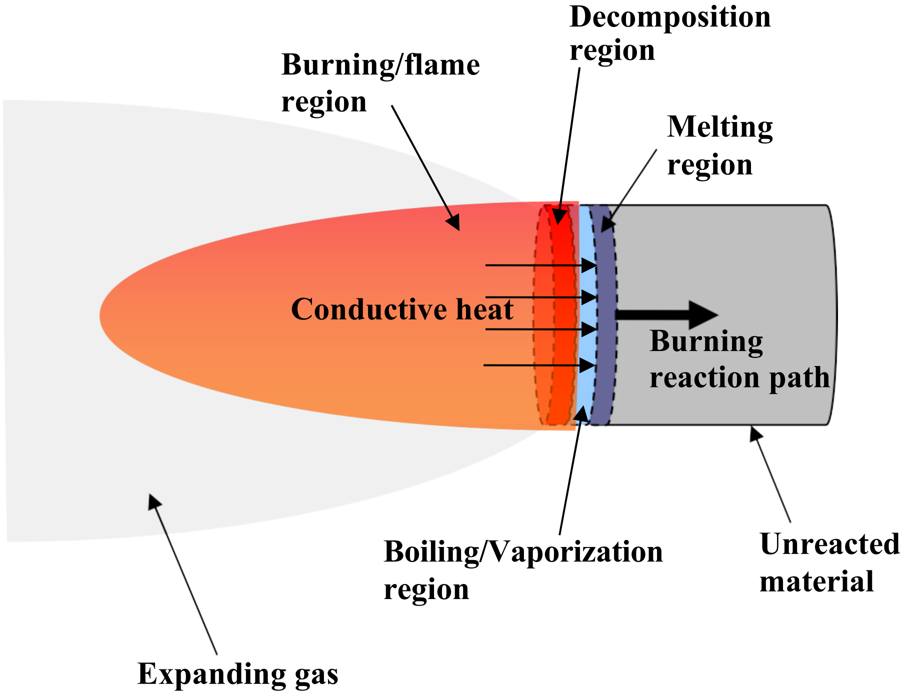
Initiation

- Propellants are usually thermally ignited
- Thermal ignition causes surface to melt
- As the temperature at the melted surfaces continues to increase boiling and vaporization occurs



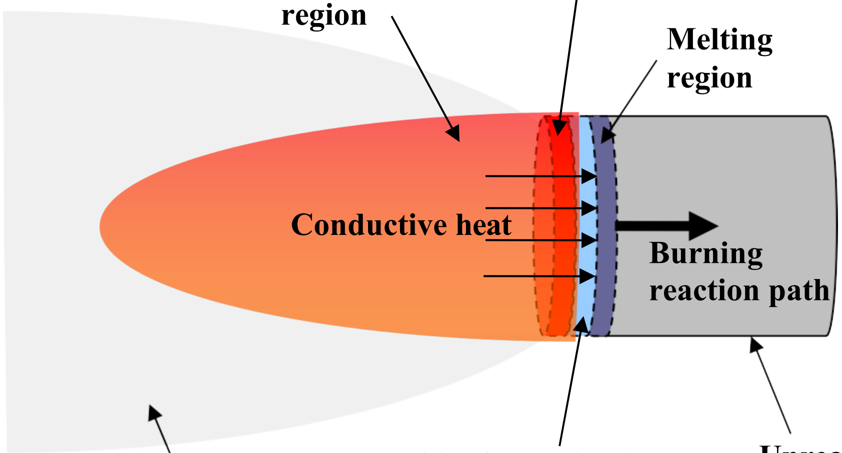
Propellants

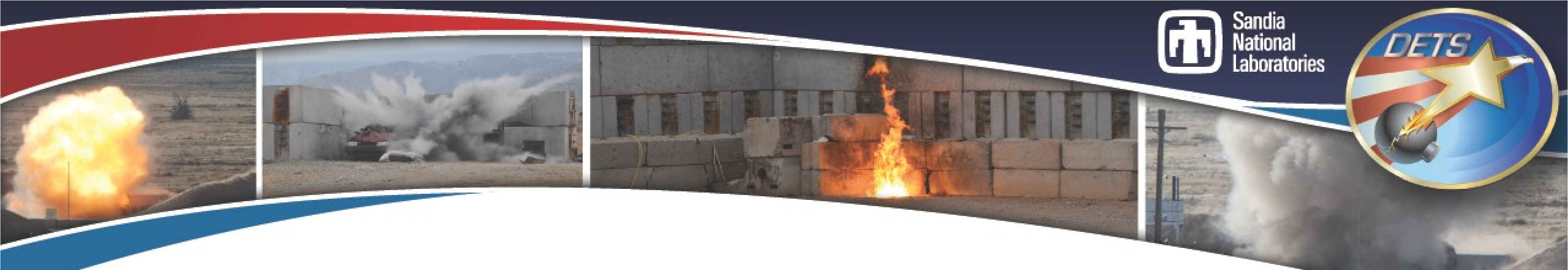
- Thermal energy (usually in the form of a flame), gases and hot particles
- Heat from this process is transferred back into the next surface layer producing a self-sustaining subsonic deflagration
    - Conduction
    - Convection
    - Radiation



Initiation

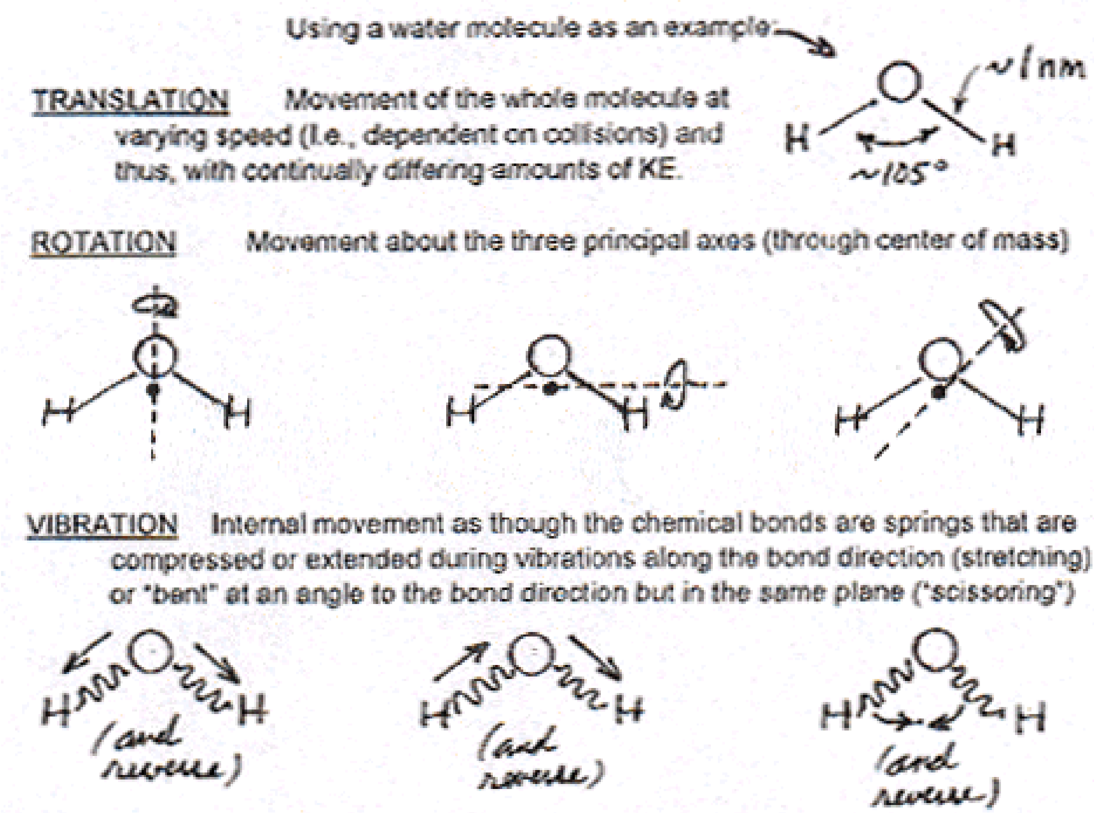
- **Conduction**
  - Thermal energy (molecular vibration) is conducted along solids from hotter to cooler
  - Factors maximizing conductive feedback
    - Compacted composition
    - Metal fuels
    - Metal casing and core wire





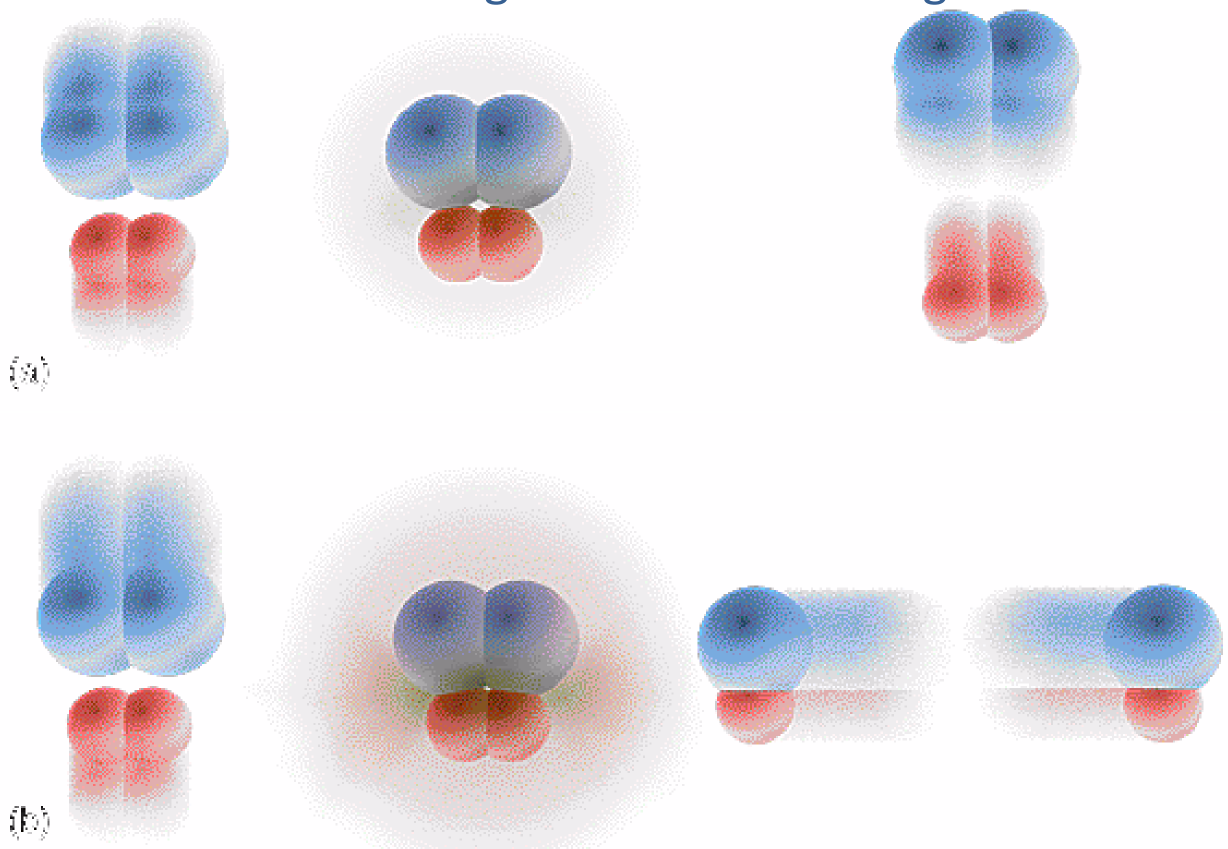
Propellants

- Decomposition occurs in the boiling and vapor region
    - The energy in that area is enough to break the bonds of molecules
    - The bonds break because of motion or kinetic energy of the atoms within the molecules



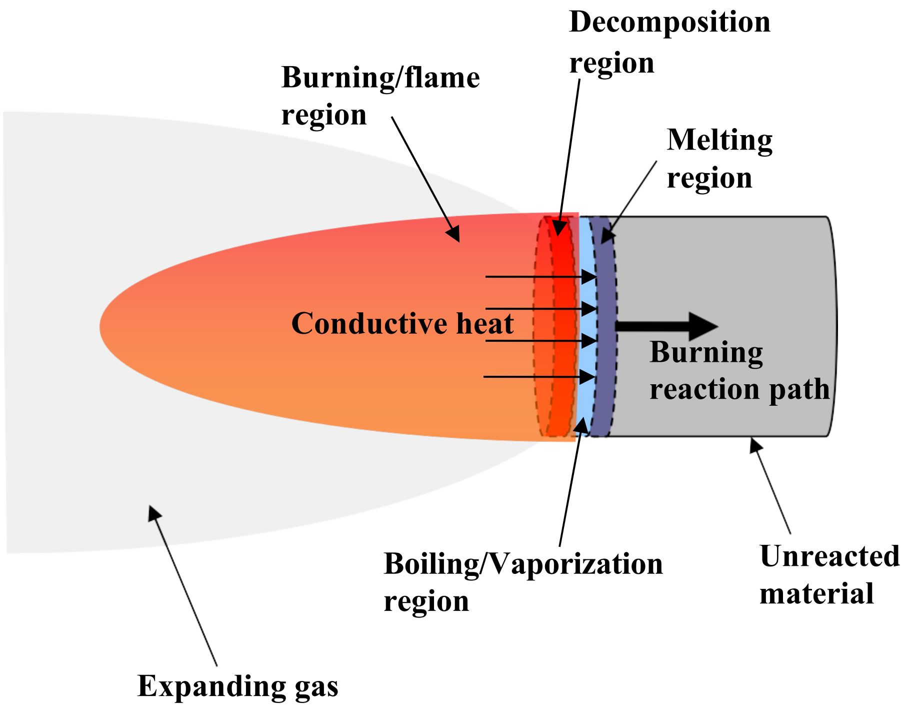
Chemical Kinetics

- Example of bonds not breaking and bonds breaking



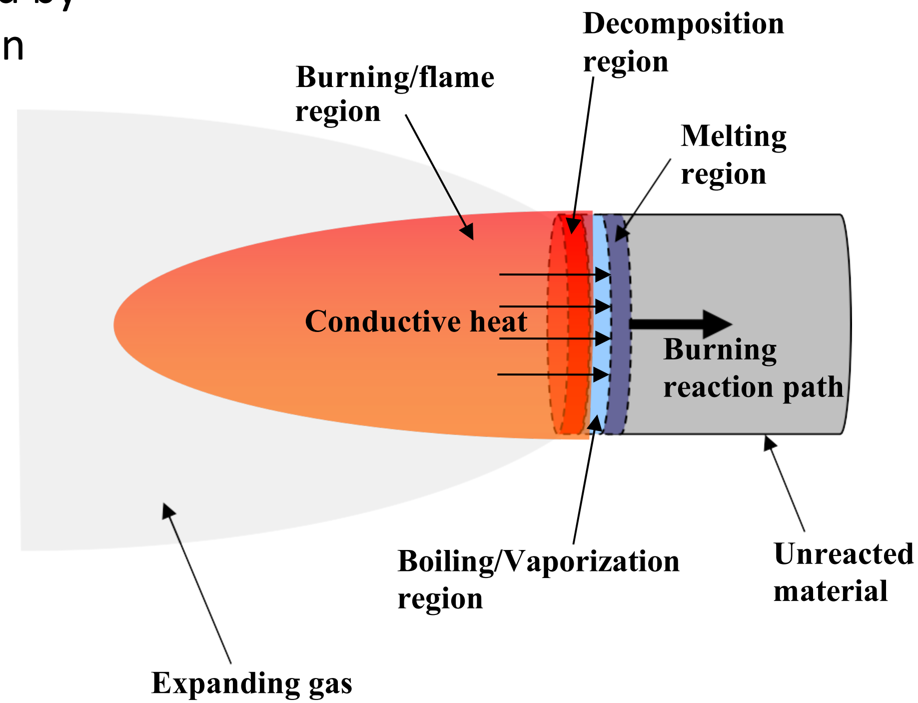
Initiation

- **Convection**
  - Hot gases penetrate the solid composition along spaces between grains (fire path)
  - Factors maximizing convective feedback
    - Uncompact composition
    - Granulated composition
    - Cracks in composition
    - Damaged composition



Initiation

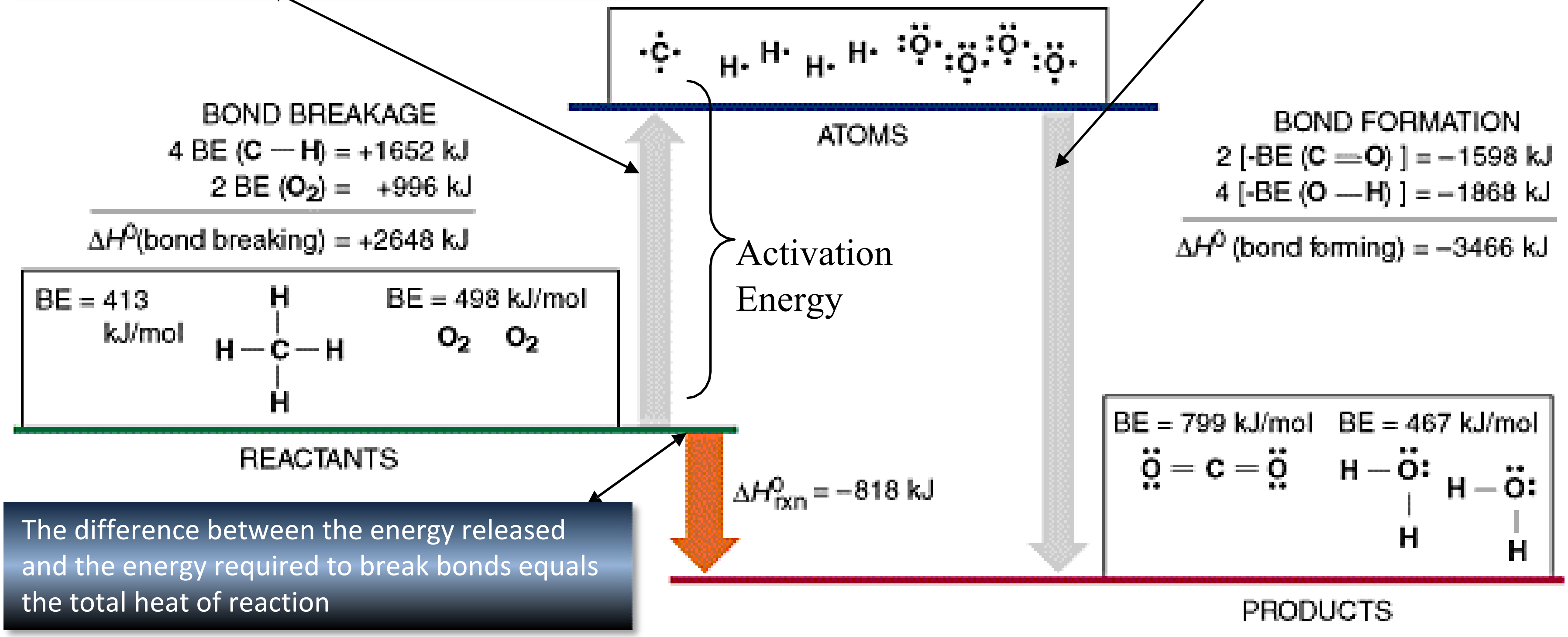
- **Radiation**
  - Thermal (infrared) radiation, emitted from flame and glowing particles, is absorbed by incompletely reacted composition
  - Factors favoring radiative feedback
    - Solid or liquid particles in flame
    - Dark or black composition



Chemical Reaction

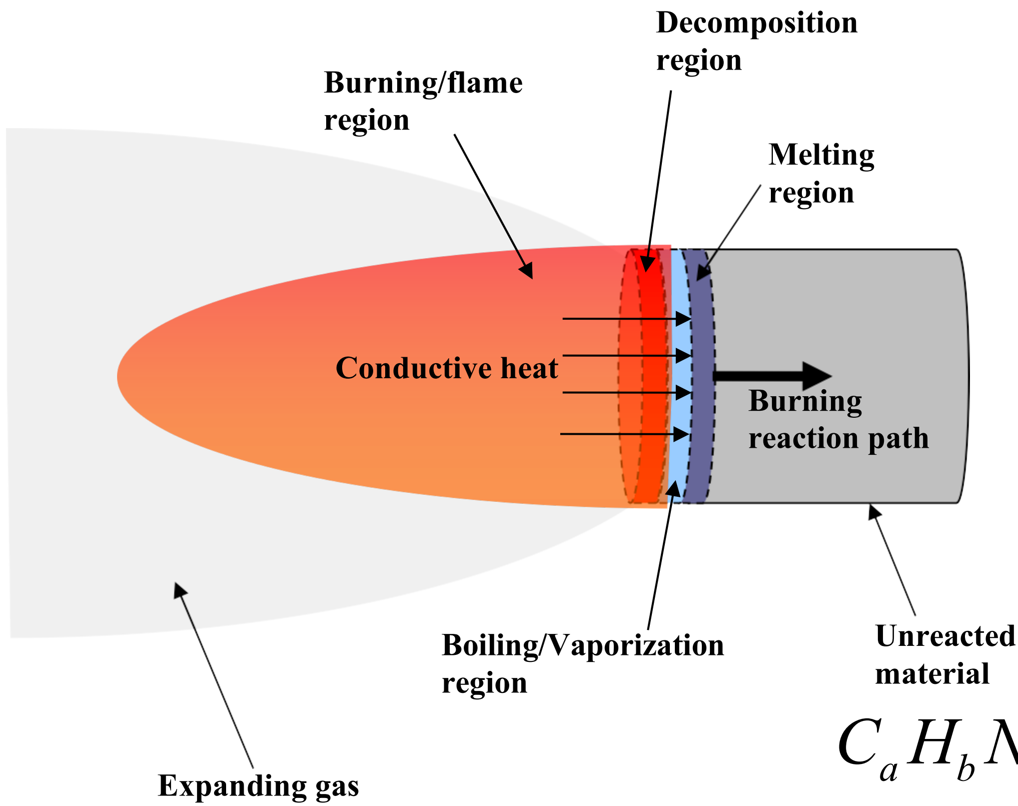
- Energy imparted into the material
- Each material will have a characteristic energy required to break bonds

Energy released when new bonds are formed to produce more stable molecules



The difference between the energy released and the energy required to break bonds equals the total heat of reaction

Propellants

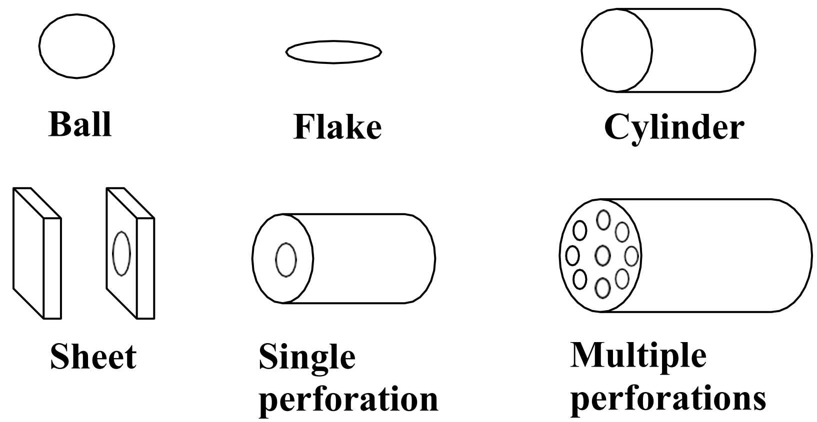


$$C_a H_b N_c O_d$$

$$n_1 CO_2 + n_2 H_2 O + n_3 N_2 + n_4 CO + n_5 H_2$$

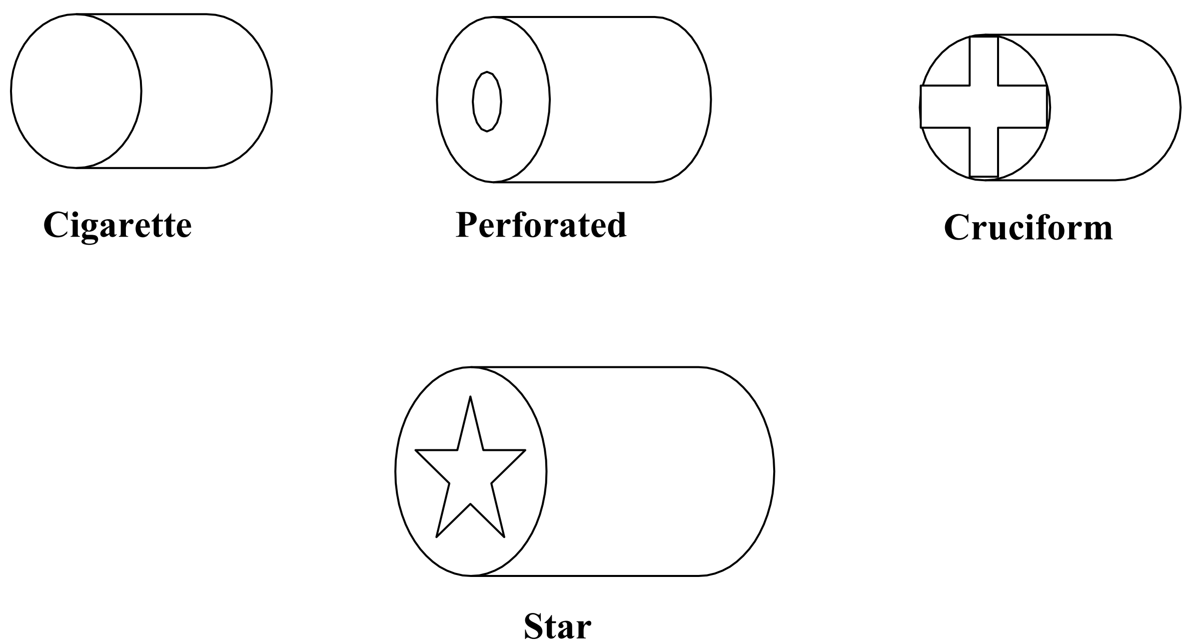
Propellants

- The profile of the burn is very dependent upon the geometry of the grain
- Some common types of grain for guns
  - Ball
  - Flake
  - Cylinder
  - Single perforation
  - Multiple perforation
  - Sheet



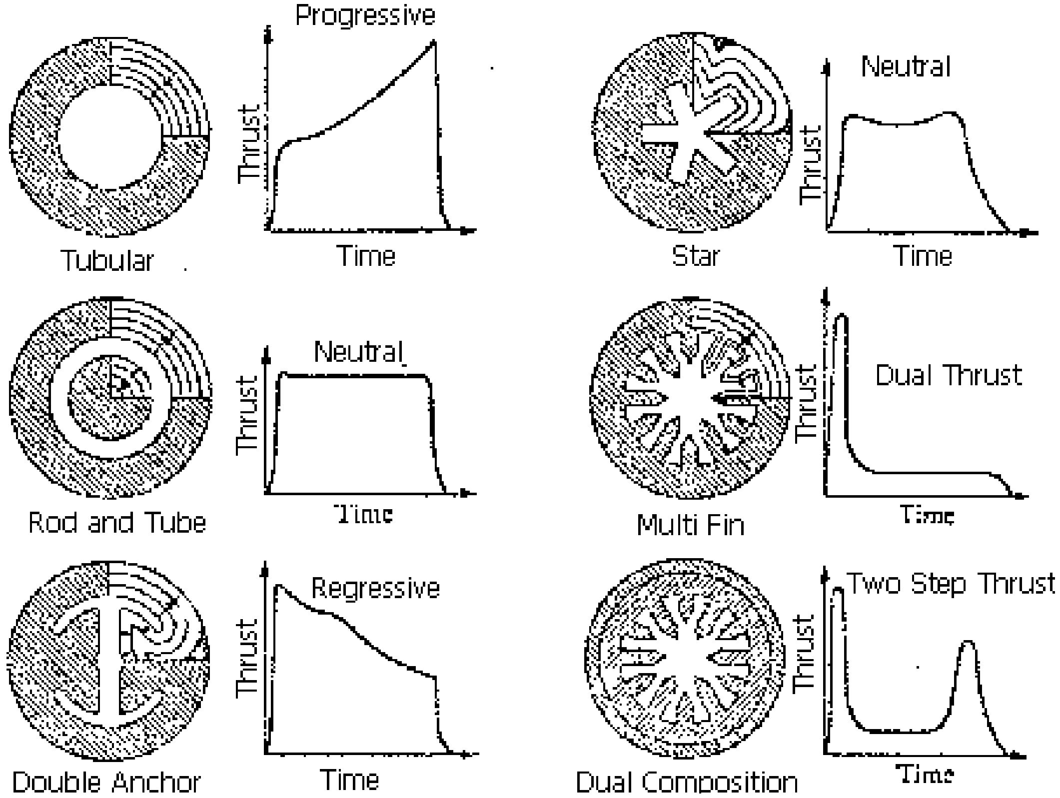
Propellants (Energetic Materials)

- Some common types of grains for rockets
  - Cigarette
  - Perforated
  - Cruciform
  - Star



Propellants (Energetic Materials)

- Typical thrust profiles

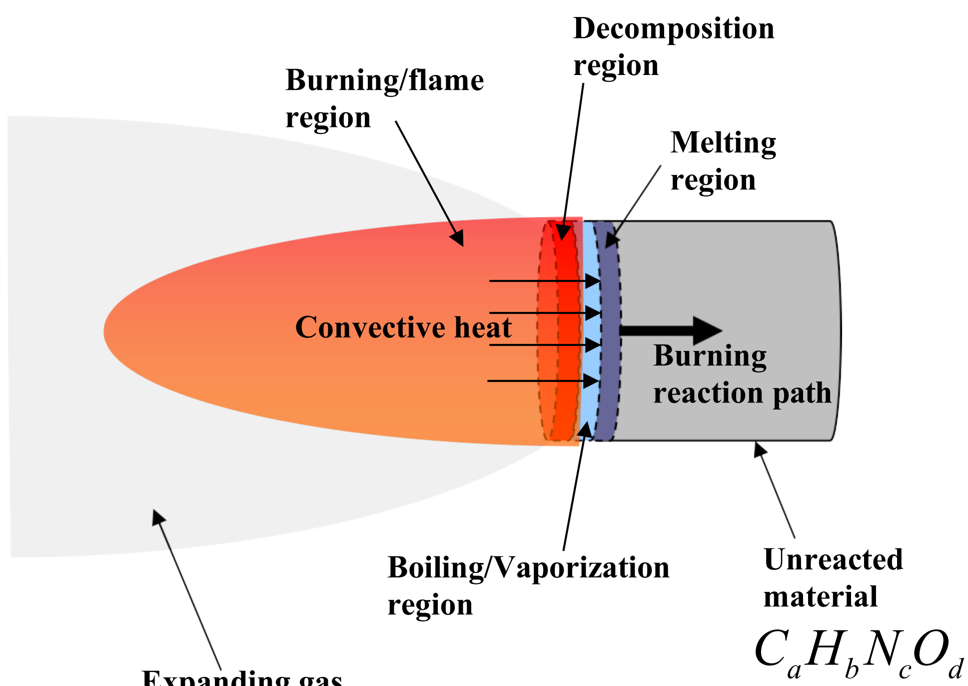


Gun Propellants Grain Performance

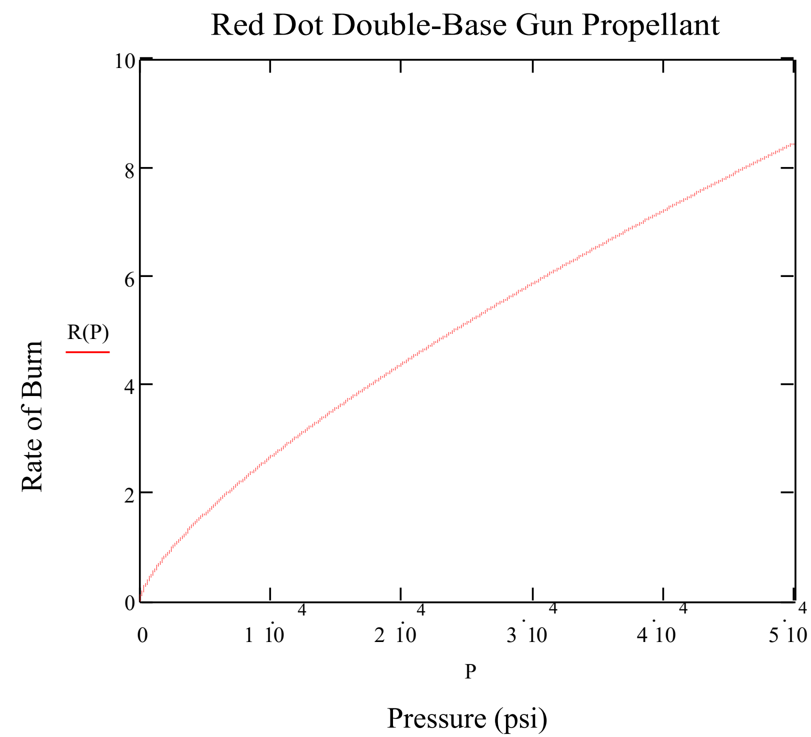
- The burn rate of propellants follows the pressure exponent law
  - $r = aP^n$
    - r is the burn rate in in/s or mm/s
    - P is the pressure in psi or Mpa
    - n is a constant dependent upon the chemical composition of the propellant (it is dimensionless)
    - a is a constant dependent upon the initial chemical composition and the temperature of the propellant [(in/s)/(psi) or (mm/s)/(MPa)]
  - In Paul Cooper and Stanley Kurowski's book, Introduction to the Technology of Explosives, on page 43, table 2.1, shows a list of some common gun propellants along with the above constants "a" and "n"
    - Based on these values, one may adjust the pressure to see how the burn rate increases

Gun Propellants Grain Performance

- From Cooper's book, Red Dot propellant constants are
  - a= 0.00350 and n = 0.720

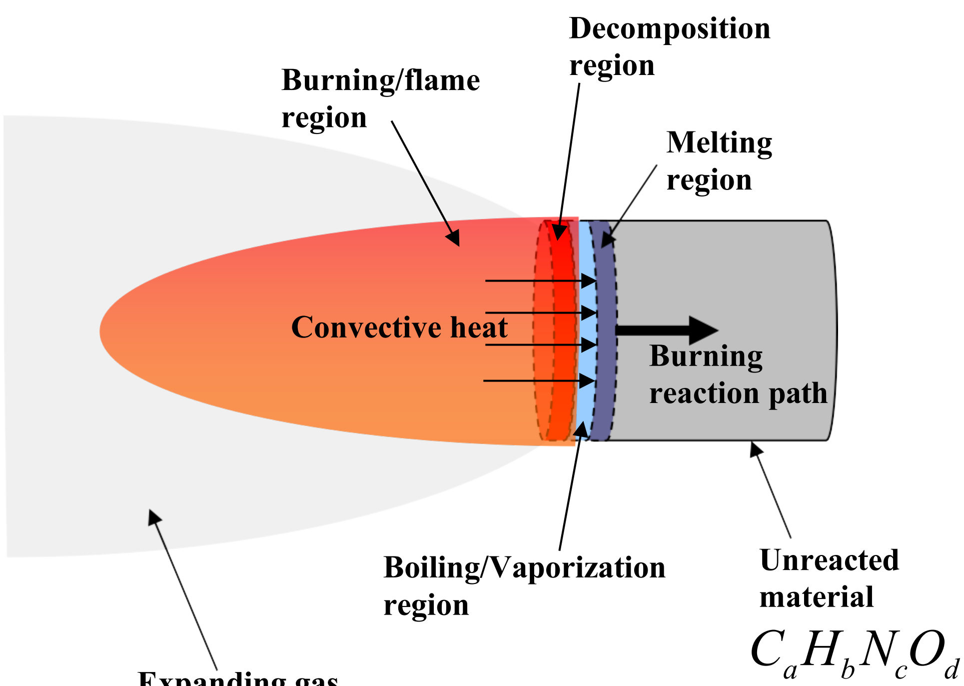


$$n_1 CO_2 + n_2 H_2O + n_3 N_2 + n_4 CO + n_5 H_2$$

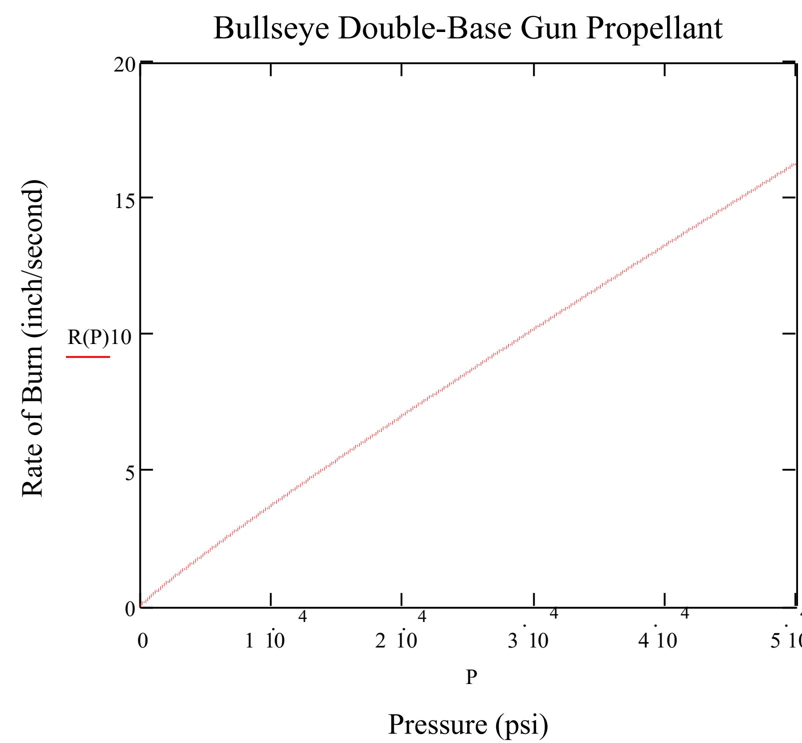


Gun Propellants Grain Performance

- From Cooper's book, Bullseye propellant constants are
  - a= 0.000775 and n = 0.920



$$n_1CO_2 + n_2H_2O + n_3N_2 + n_4CO + n_5H_2$$



Interior Ballistics

- By knowing the reaction temperature, one may the use equation below to find the specific energy or force constant of the propellant (used in ballistics)
  - The maximum amount of work done by the unit mass of propellant
  - The force exerted on the projectile

$$f = PV = nRT_a$$

- f = specific energy (Joule/gram)
- P = pressure
- V = volume of system
- n = mols/gram
- R = universal gas content (3.314 Joule/mol – Kelvin)
- T_a = adiabatic flame temperature (Kelvin)

Interior Ballistics

- By dividing the force constant equation by the total volume ($V = A_i \cdot l_b$) that the gaseous products will occupy then multiply by the total weight of the propellant charge, one may find the average pressure

$$P_{avg} = \frac{nRT_a}{V} M_p$$

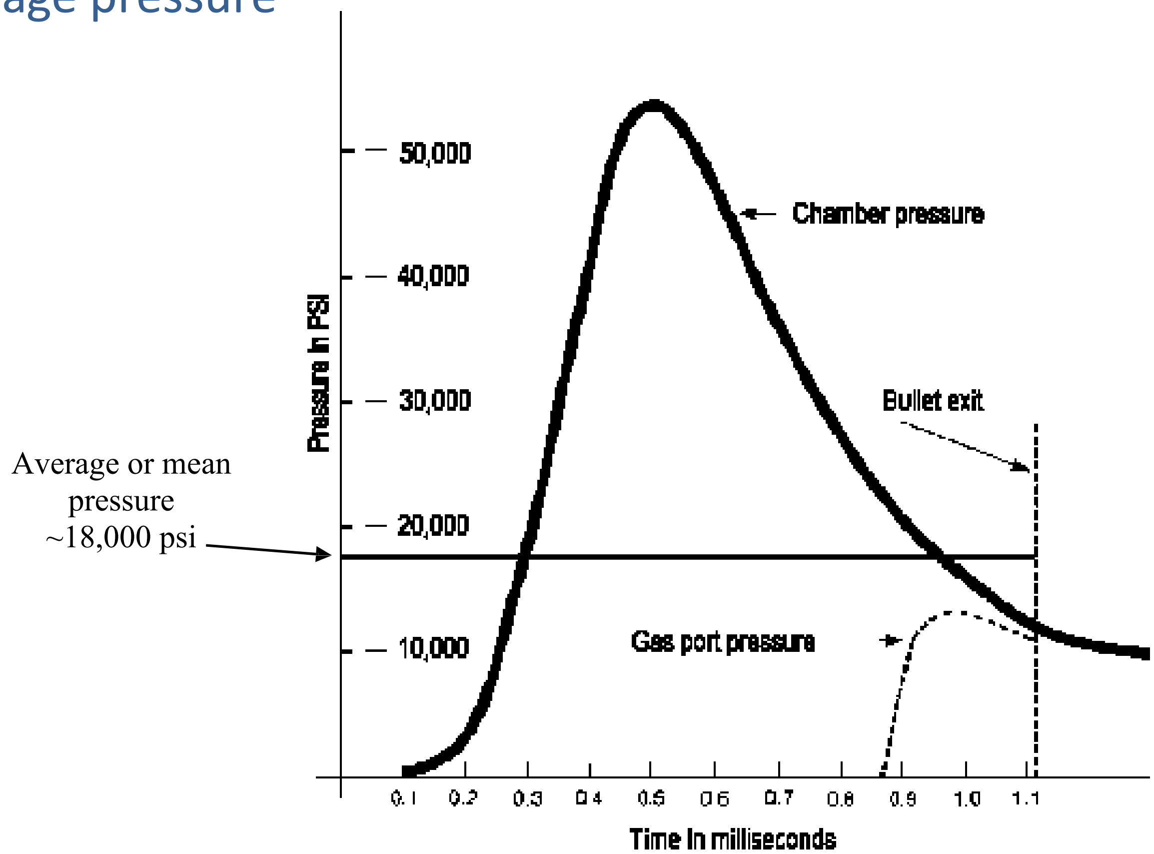
- Based on the average pressure the approximate velocity of the bullet or projectile exiting the end of the barrel is

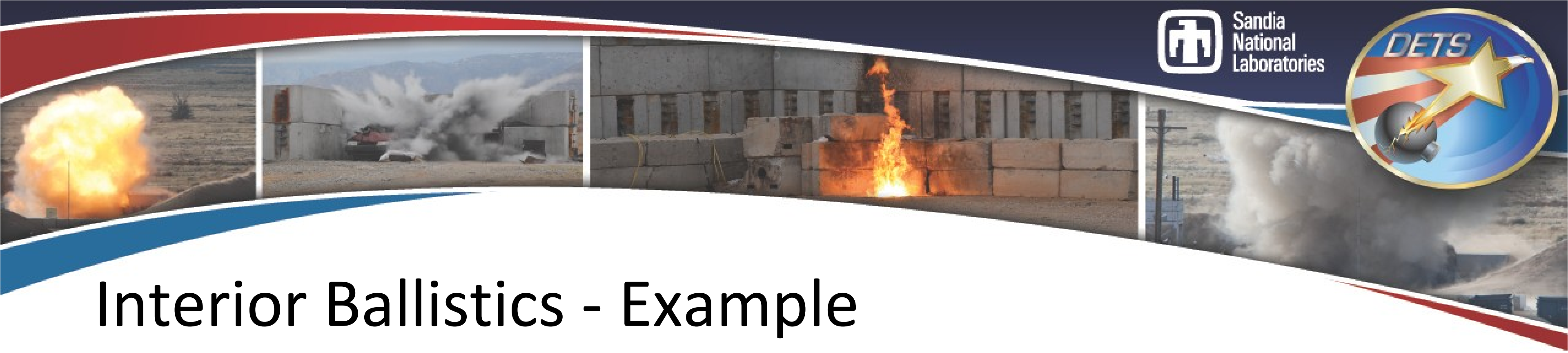
$$V_{be} = \sqrt{\frac{2 \times \left(P_{avg}\right) L_b A_{bi}}{M_p}}$$

  - V_{be} = velocity of the bullet at the end of the barrel
  - P_{avg} = the average pressure
  - L_b = length of the barrel
  - A_{bi} = the cross-sectional area of the inside the barrel
  - M_p = the mass of the projectile

Interior Ballistics

- The average pressure





Interior Ballistics - Example

- Using red-dot propellant, where n = 0.037 mol/gram and T_a = 3200 Kelvin (from Cooper's book, mentioned earlier, page 54)

$$P_{avg} = \frac{nRT_a}{V} = \frac{(0.037\, mol/gm)(8.314\, J/mol \times K)(3200K)}{(0.192\, in^2)\,(30\, in)} \times 105\, grain = 10{,}366\, psi$$

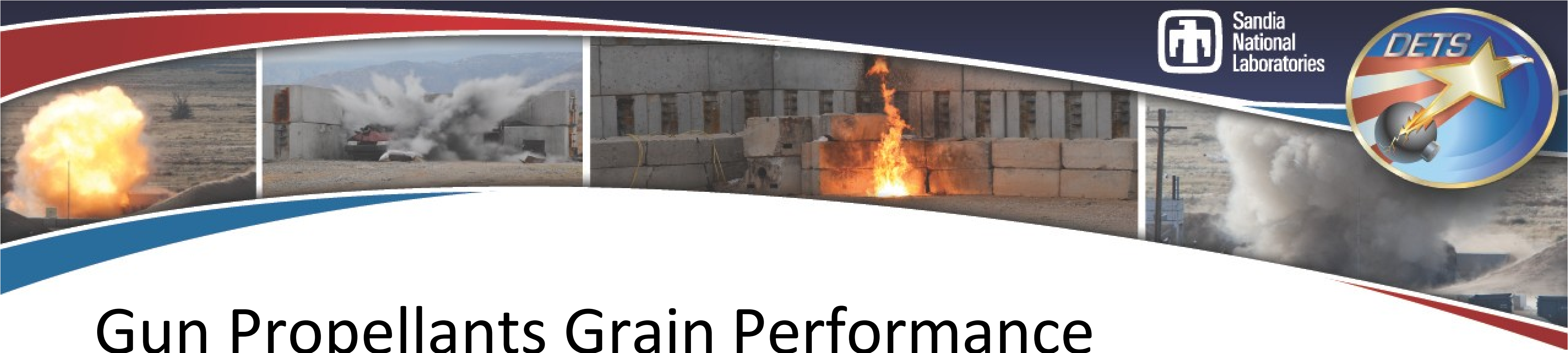
- Using a 12 gauge shotgun shooting a slug, where
    - Diameter = 0.5 in
    - Length of the barrel is 30 in
    - Cross-sectional area is $\pi r^2 = 0.192\ in^2$
    - Mass of slug is 437.5 grain

$$V_{be} = \sqrt{\frac{2 \times (P_{avg}) L_b A_{bi}}{M_p}} = \sqrt{\frac{2 \times (10{,}366\, psi)(30\, in)(0.192\, in^2)}{437.5\ grain}} = 1616\, \frac{ft}{s}$$

- It takes 105 grains of red-dot propellant to produce a velocity of ~1600 ft/s

Gun Propellants Grain Performance

- $r = aP^n$
  - r is the burn rate in in/s or mm/s
  - P is the pressure in psi or MPa
  - n is a constant dependent upon the chemical composition of the propellant (it is dimensionless)
    - It describes the pressure dependency
      - n < 1 energetic material deflagrates
        - » 0.7 – 0.9 or greater for gun propellants
        - » 0.2 0.5 for DB rocket propellant
        - » 0.1 – 0.4 for AP based composite rocket propellant
      - n > 1 energetic material detonates
  - a is a constant dependent upon the initial chemical composition and the **temperature** of the propellant [(in/s)/(psi) or (mm/s)/(MPa)]

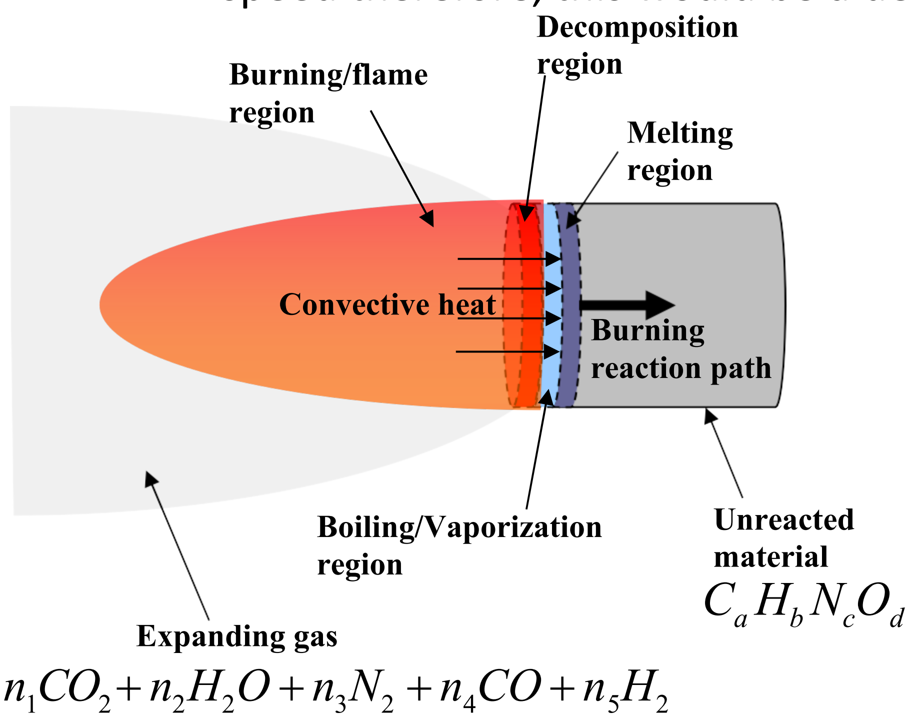


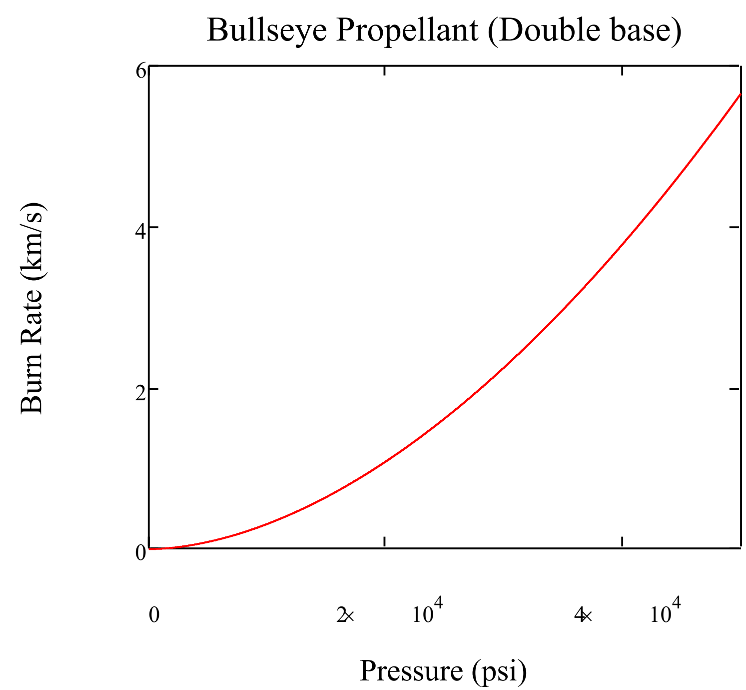
Gun Propellants Grain Performance

- The thermal energy generated by propellant combustion is distributed to various non-effective energies
- The energy losses of a caliber gun are approximately
  - Sensible heat of combustion gas - 42%
  - Kinetic energy of combustion gas - 3%
  - Heat loss to gun barrel and projectile - 20%
  - Mechanical losses - 3%
- The remaining part of the energy, 32 %, is used to accelerate the projectile.
- It is obvious that the major energy loss is the heat exhausted from the gun barrel.
- This is an unavoidable heat loss based on the thermodynamic law
  - the pressure in the gun barrel cannot decrease until the combustion gas is at the atmospheric temperature

Gun Propellants Grain Performance

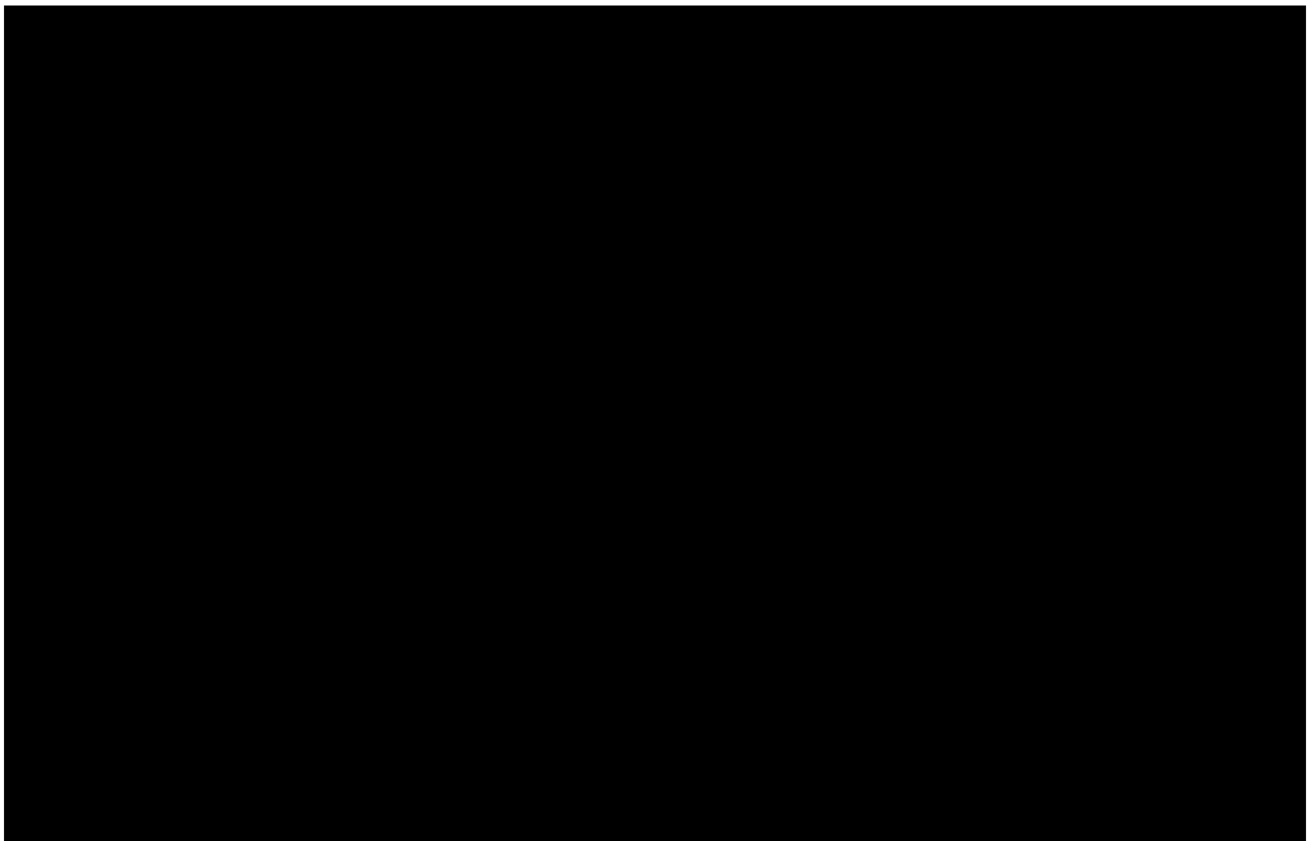
- From Cooper's book, Bullseye propellant constants are
  - a= 0.000775 and n = 1.8
  - $2 \cdot 10^5$ in/s = 16,670 ft/s (5080 m/s) which is well above this materials sound speed therefore, this would be a detonation





Propellants

- Can Propellant detonate?



Propellants

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Propellants

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