

GENERAL DYNAMICS

Ordnance and Tactical Systems–Canada Valleyfield

Effect of the flame structure on nitrocellulose-based materials deflagration properties

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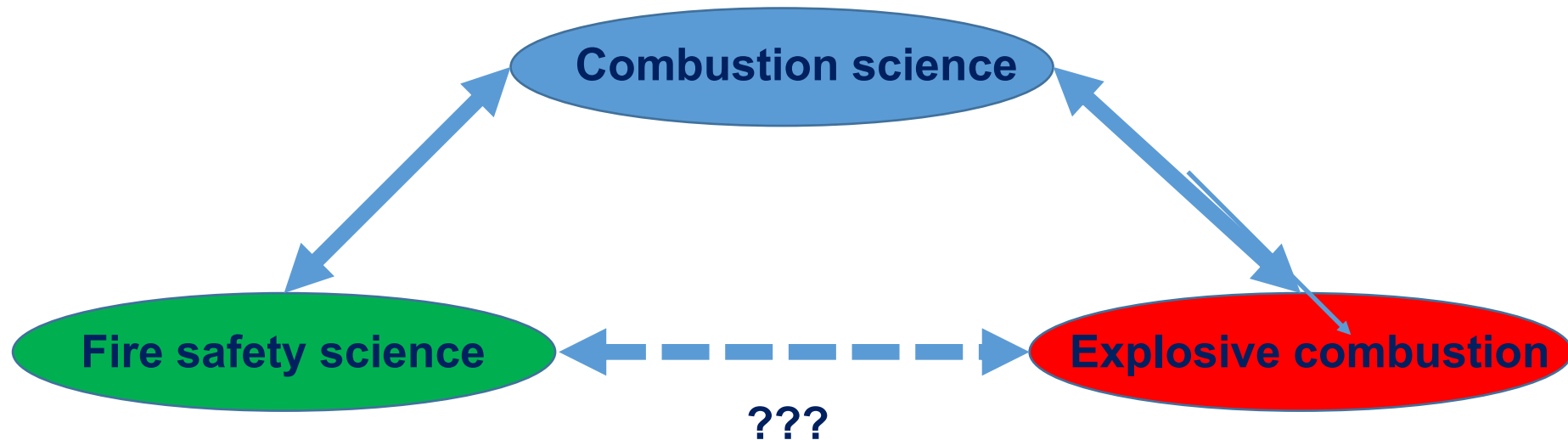
VALLEYFIELD

* Organization: Frederick Paquet Scientific Consulting

Prologue

Shall they be a family in name only; or shall they in all their actions be true to the name?

- Plato (The Republic, bk 5)



Summary

Combustion generalities

NC combustion

Combustion science

Explosive combustion

NC fire safety science



VALLEYFIELD
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GENERAL DYNAMICS

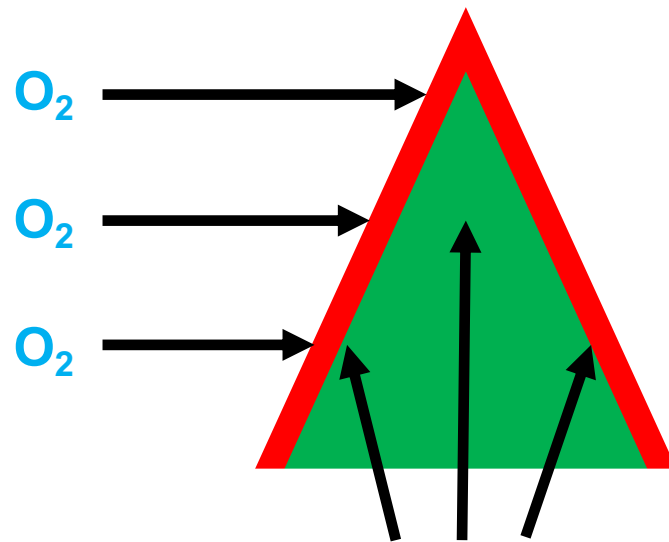
Ordnance and Tactical Systems—Canada Valleyfield

Flame structures – a duel of time scales

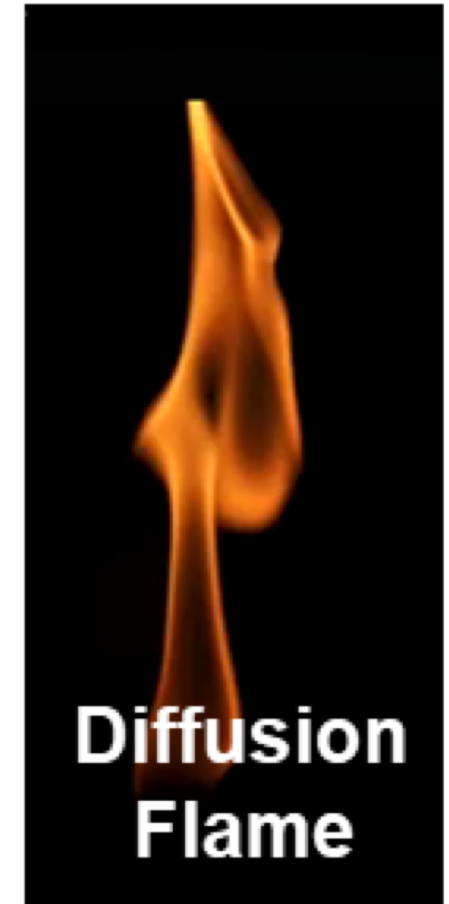
Fuel and oxidizer are separated

Reactants diffusion and convection into a flame sheet

→ Limiting convective mixing timescale



Gaseous fuel in center zone
Gaseous O_2 surrounding
Thin flame zone → flame sheet



Flame structures – a duel of time scales

Fuel and oxidizer mixed at/near molecular level

Cold reactants propagate in hot combustion products

Propagation rate depends on flame structure

Thermal diffusion timescale → heating the reactants

Burning timescale → reactions kinetics

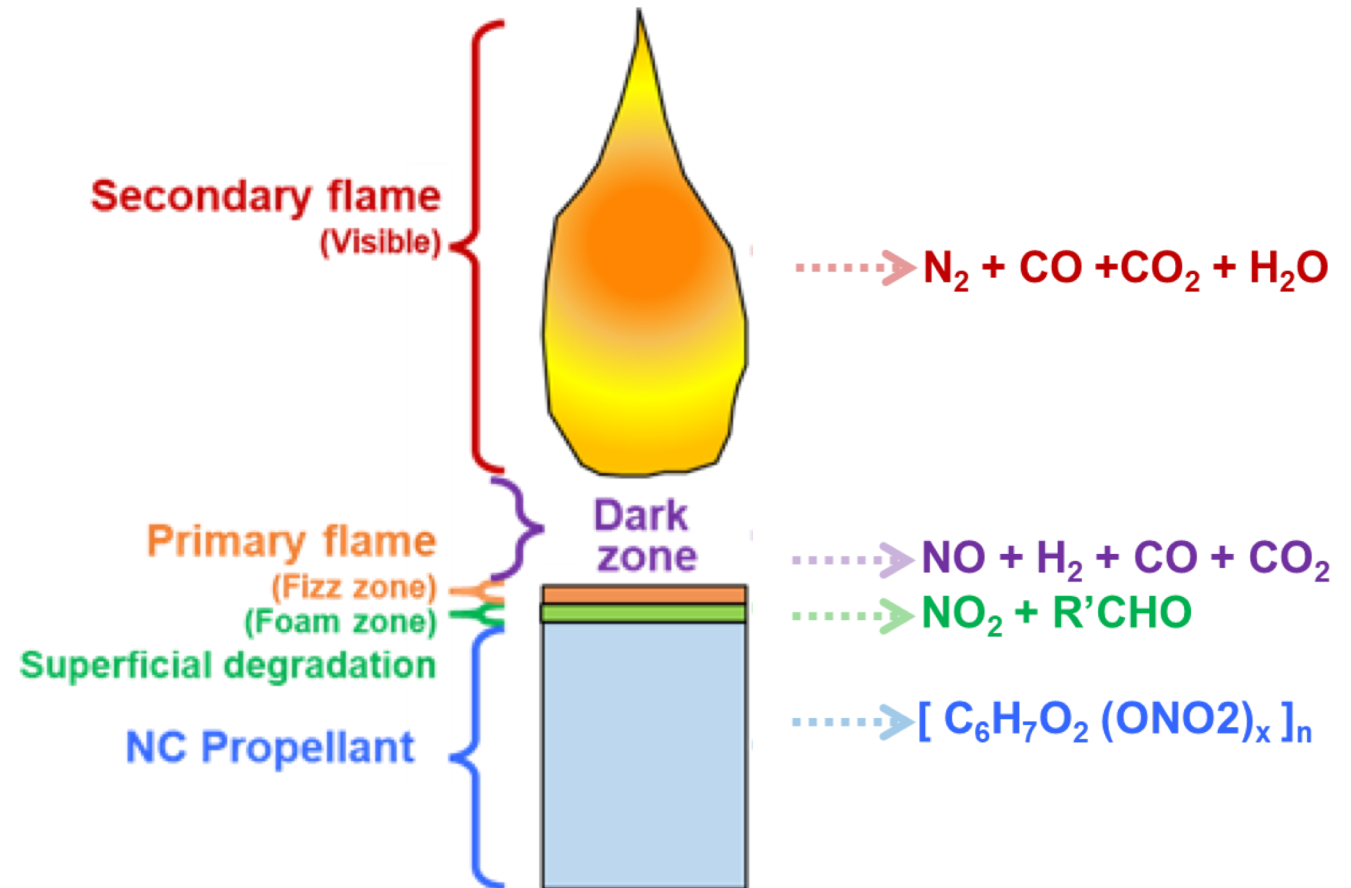
**Premixed
Flame**



Nitrocellulose flame structure



Heterogeneous premixed flame



Nitrocellulose flame structure

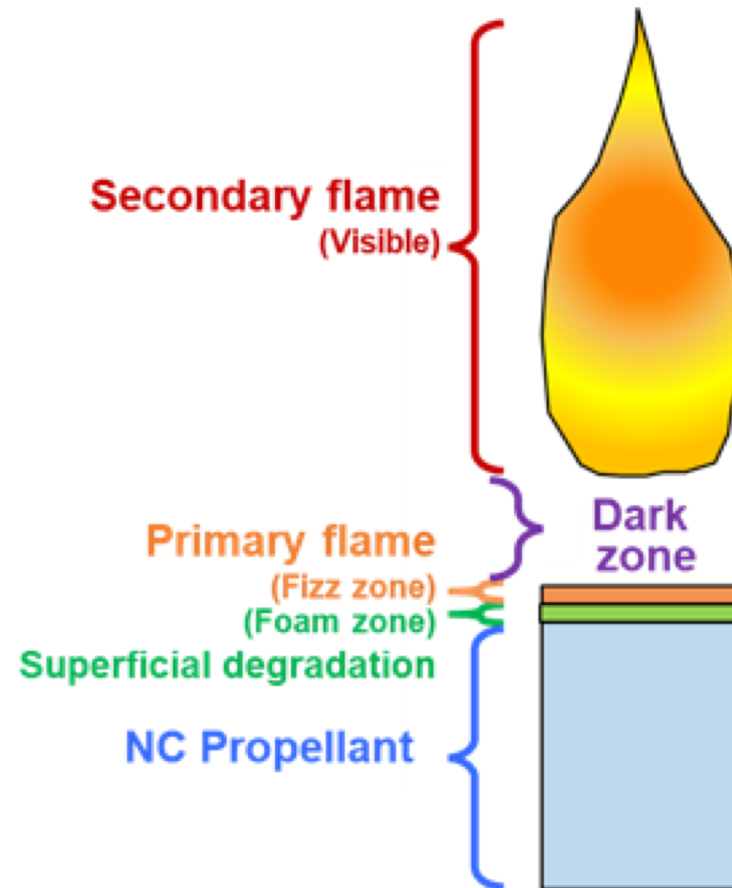


Diffusion
Flame



Premixed
Flame

Heterogeneous
premixed flame



Luminous flame

→ Higher temperature

No luminous flame

→ Lower temperature

Heating zone (feedback)

Nitrocellulose burning rate



LBR

(Linear Burning Rate)

Flame front velocity
at the surface of the
burning propellant

Linear burning rate

- Perpendicular
- Average



Flame propagation rate (surface, vertical, horizontal)

Flame front velocity (gases, dusts)

Mass burning rate

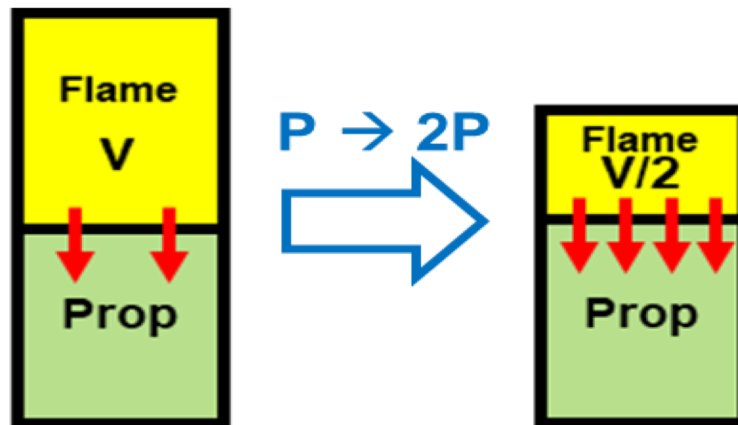
Detonation velocity ...

Nitrocellulose burning rate

Pressure dependant flame structure
flame structure goes through transitions
linear burning rate (LBR) goes also through transitions.

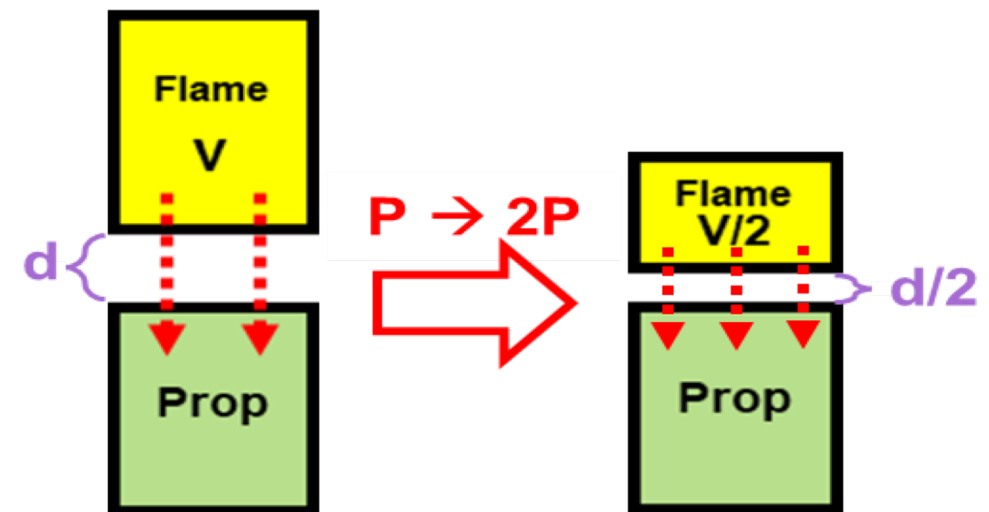


Flame in contact with
surface of propellant



LBR proportional to ΔP

Flame separated from
surface of propellant



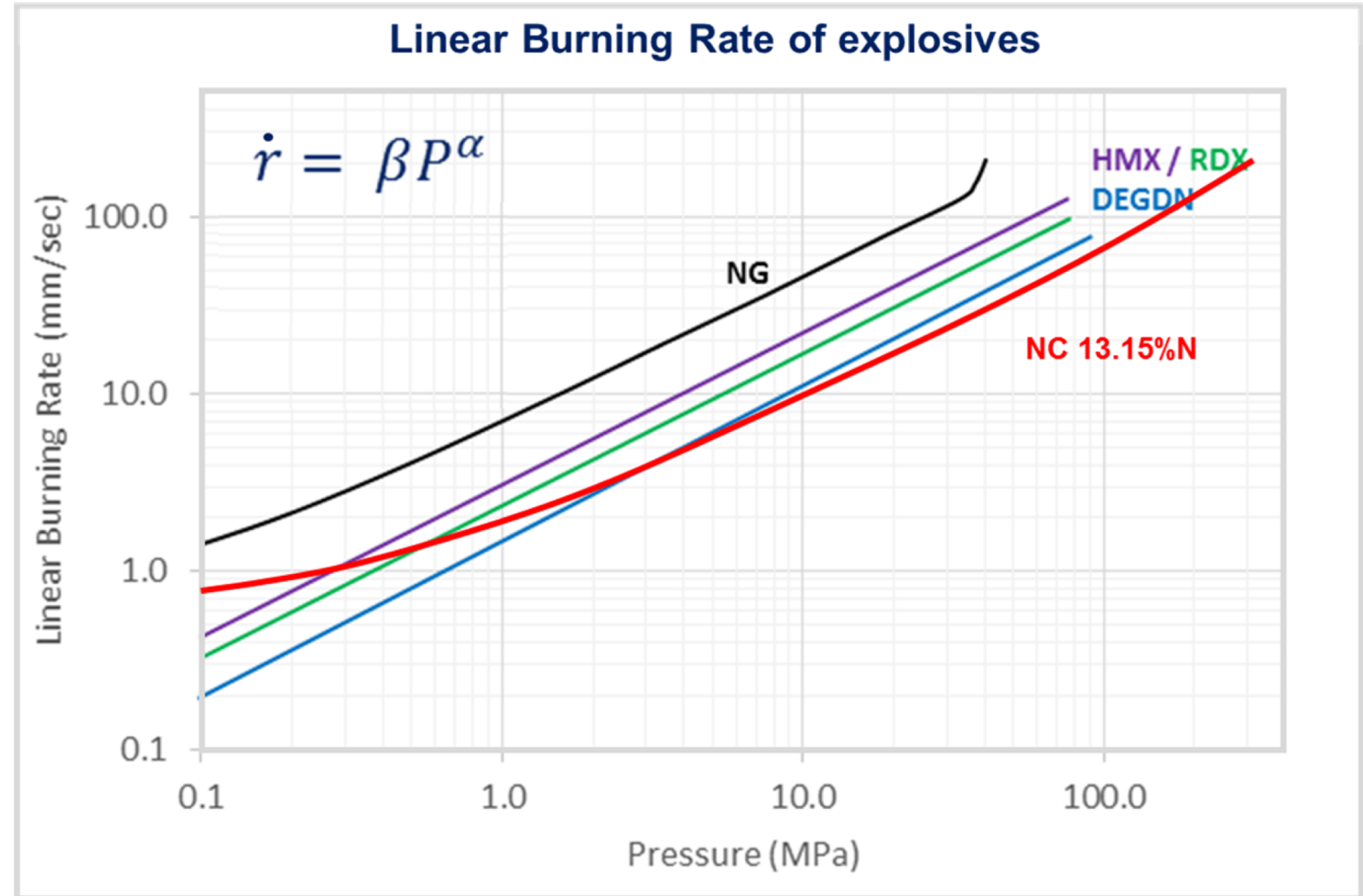
LBR not proportional ΔP

Nitrocellulose burning rate

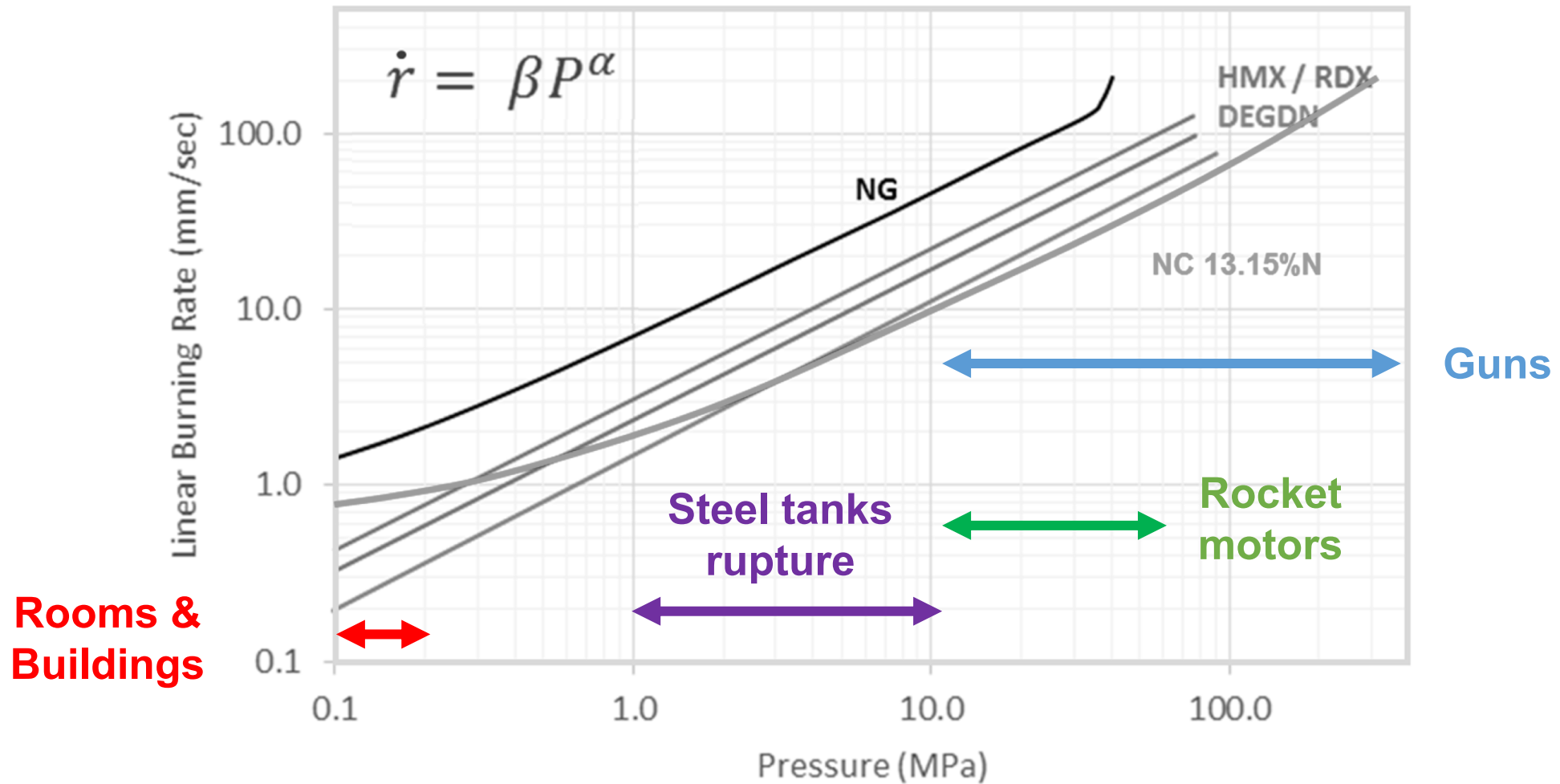


LBR

(Linear Burning Rate)
Flame front velocity
at the surface of the
burning propellant

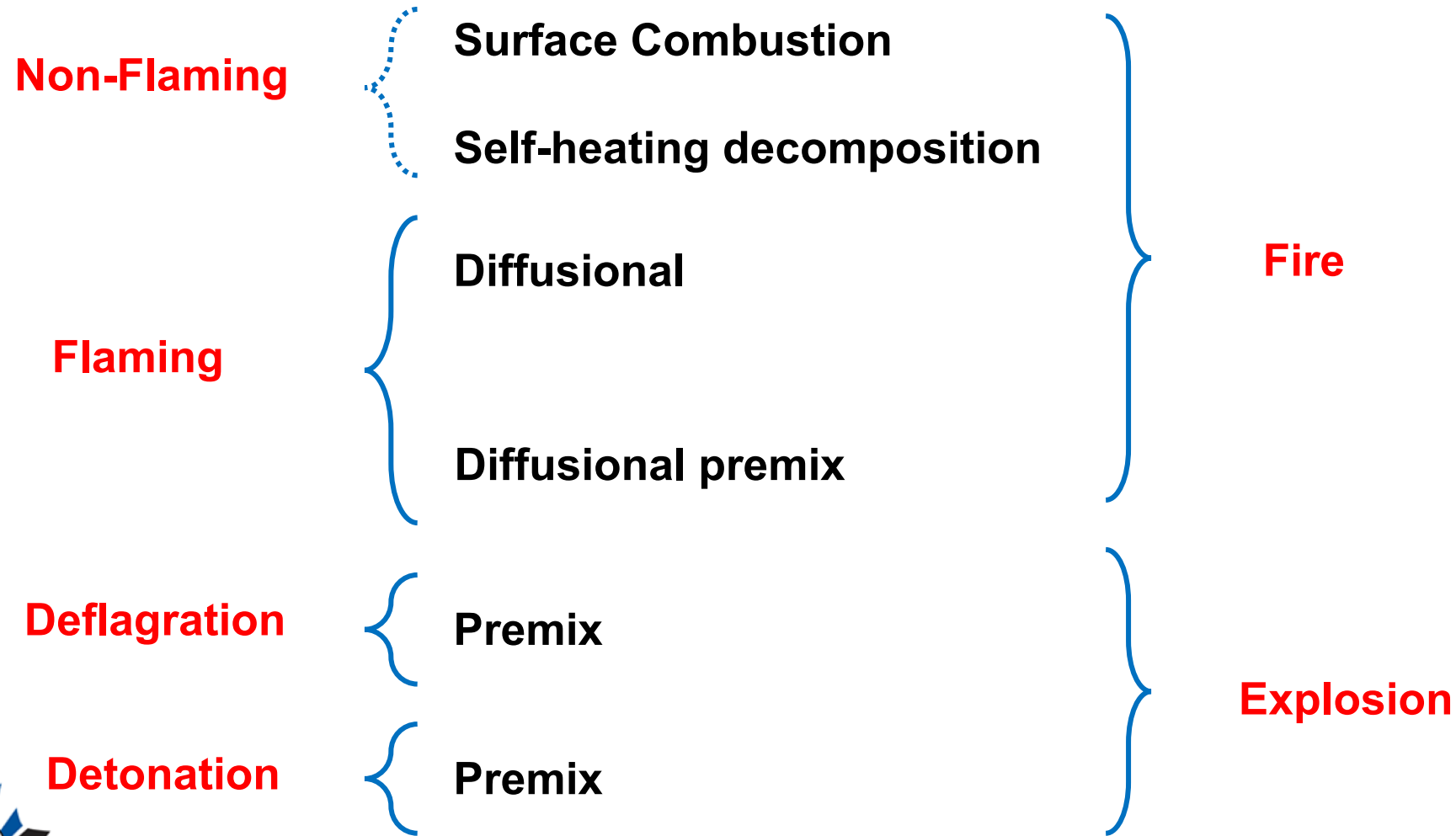


Nitrocellulose burning rate – contextualized



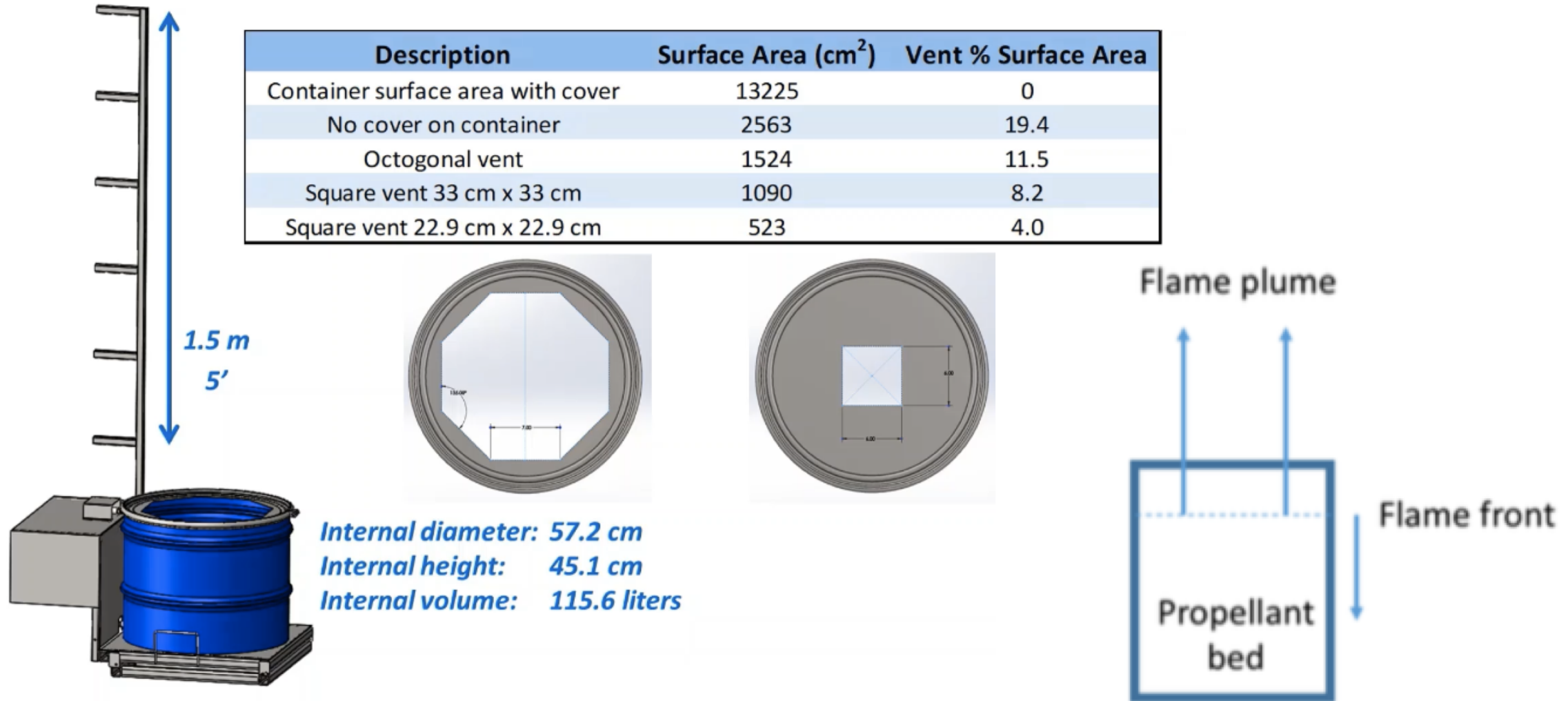
Combustion, fire and explosion

Main modes of combustion for fuels in air or mixtures of fuel/ox



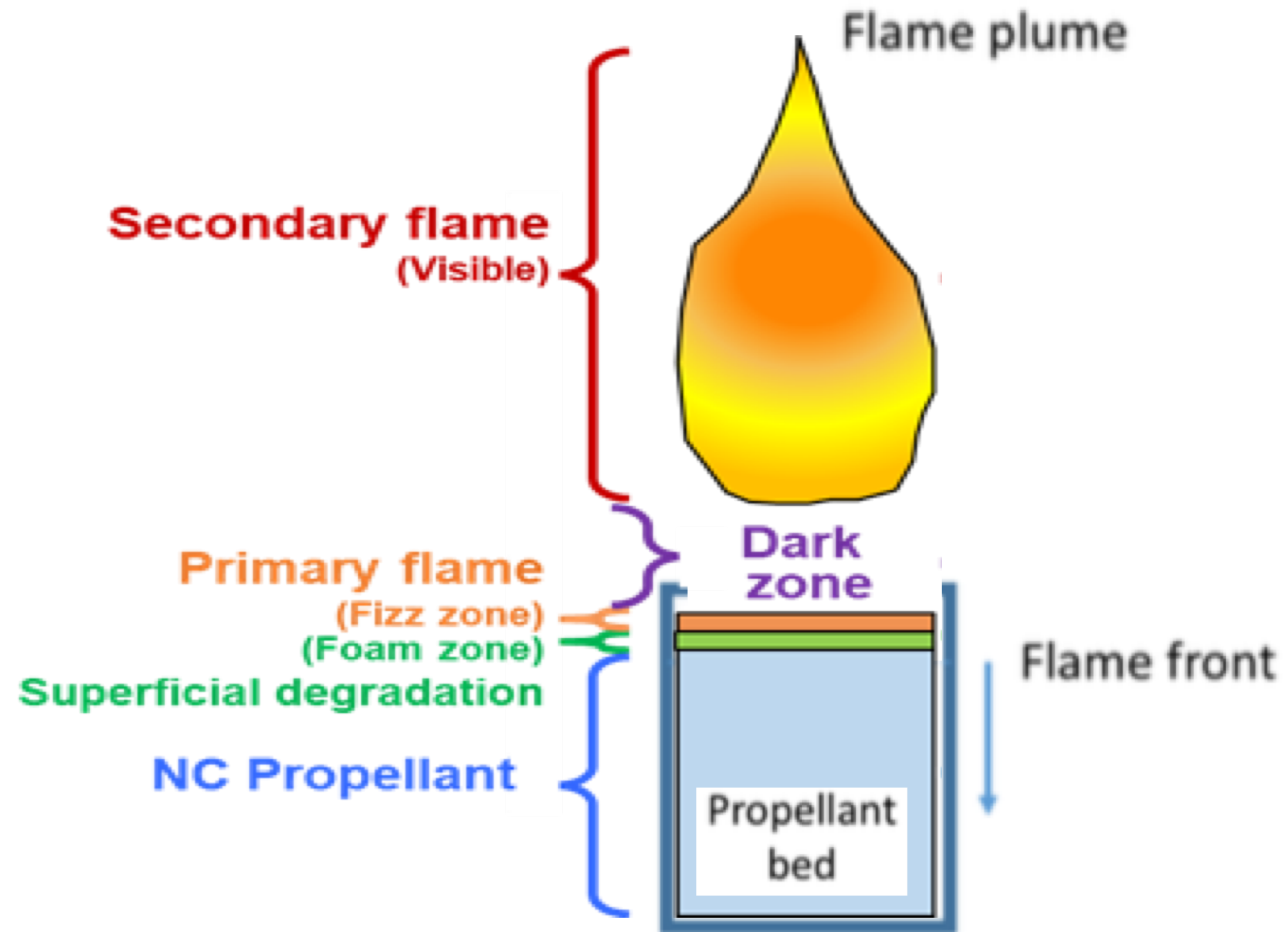
NC-based products fire safety

What, where, when, how ?



NC-based products fire safety

What, where, when, how ?



- Natural convection
- Pressure driven flow
- Air entrainment
- Equation of state

Additives (Large web triple base propellant, 8 kg, 4.0% venting area) Flame structure modification

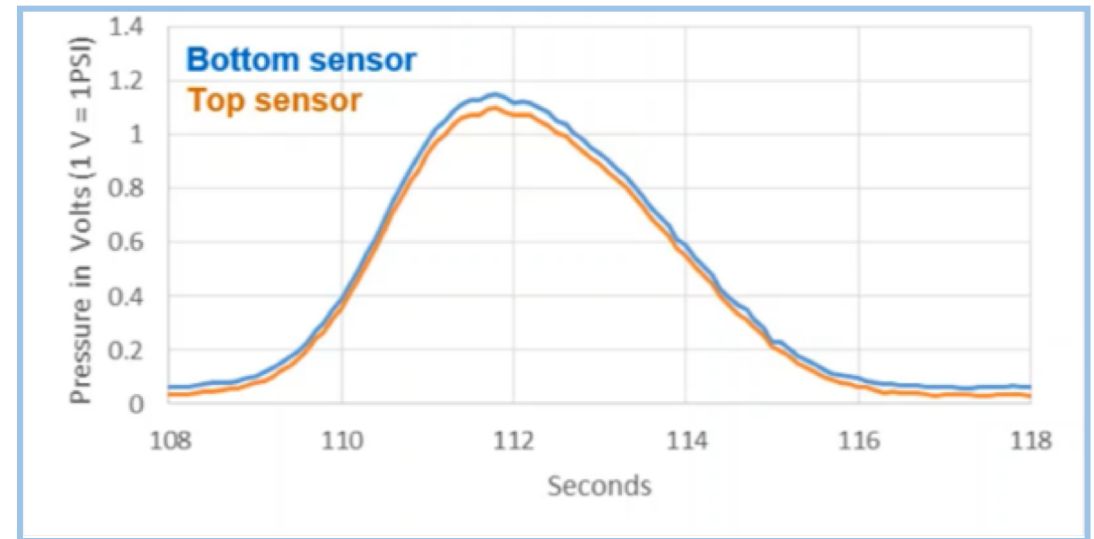


Slower burning propellant

Very little or no dark zone

Secondary flame in enclosure

→ larger pressures



Additives (Large web triple base propellant, 8 kg, 4.0% venting area)

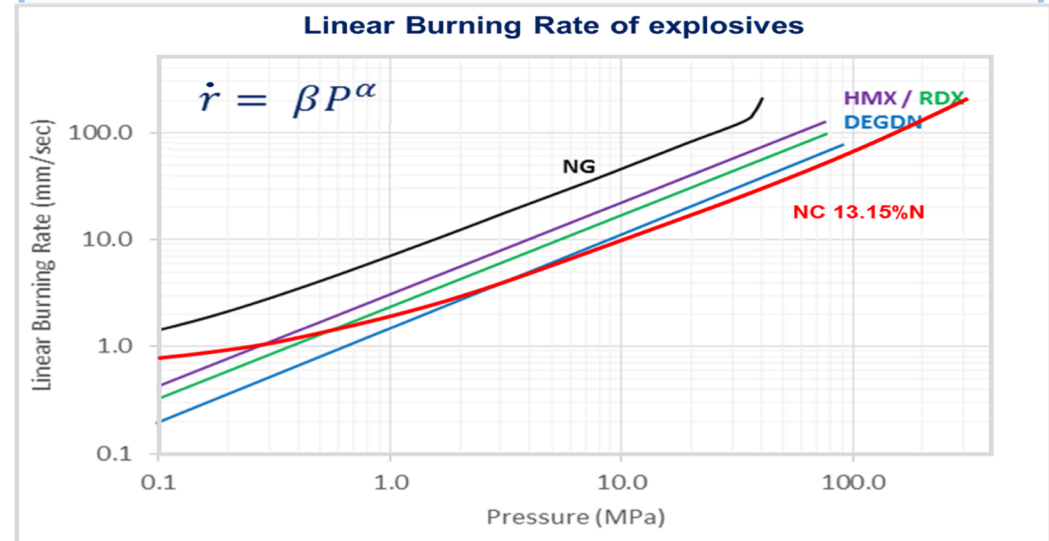
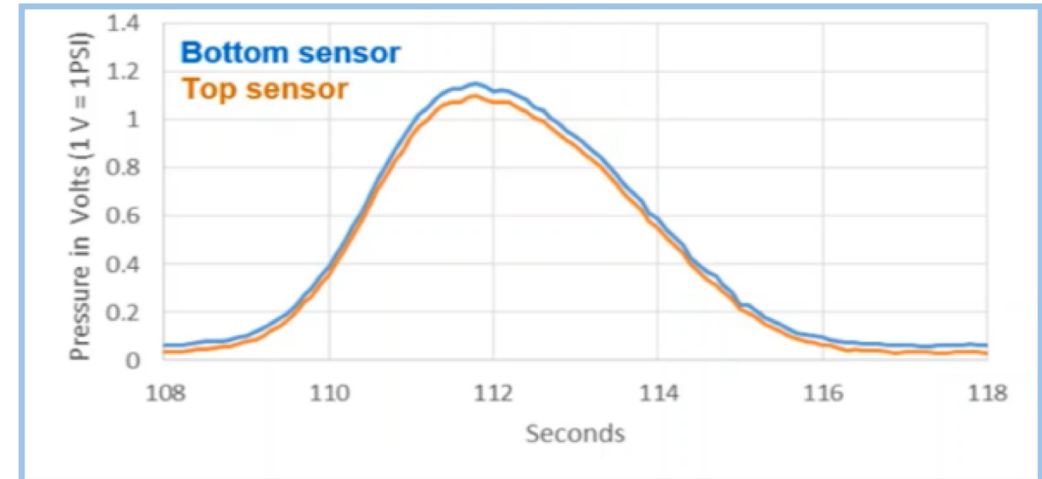
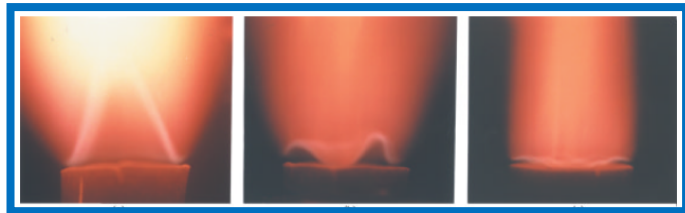
Flame structure modification



For most explosives, including
nitroguanidine (NQ):

At all pressures, the luminous flame stand
near the surface of the material and the
pressure exponent is near unity

Typical HMX flames at 3 pressures



Additives (Celluloid material, 8 kg, 4.0% venting area) Flame structure modification



Slow burning formulation with high surface area

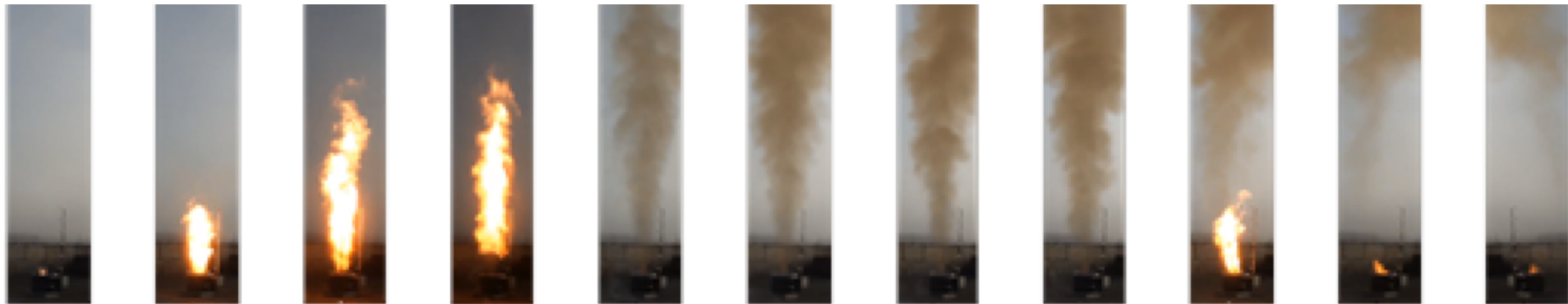
Generation of a toxic and explosive gaseous mixture

Subsequent ignition of the gaseous mixture

- Easy to mitigate initial reaction
- Gas explosion risk (equipment, rooms, ducts)
- Intoxication risk

Configuration (IMR riffle propellant, 8 kg, 4.0% venting)
flow field – flame structure interaction : flame detachment

During this test, the main flame goes through transitions:



ignition

increasing burning rate

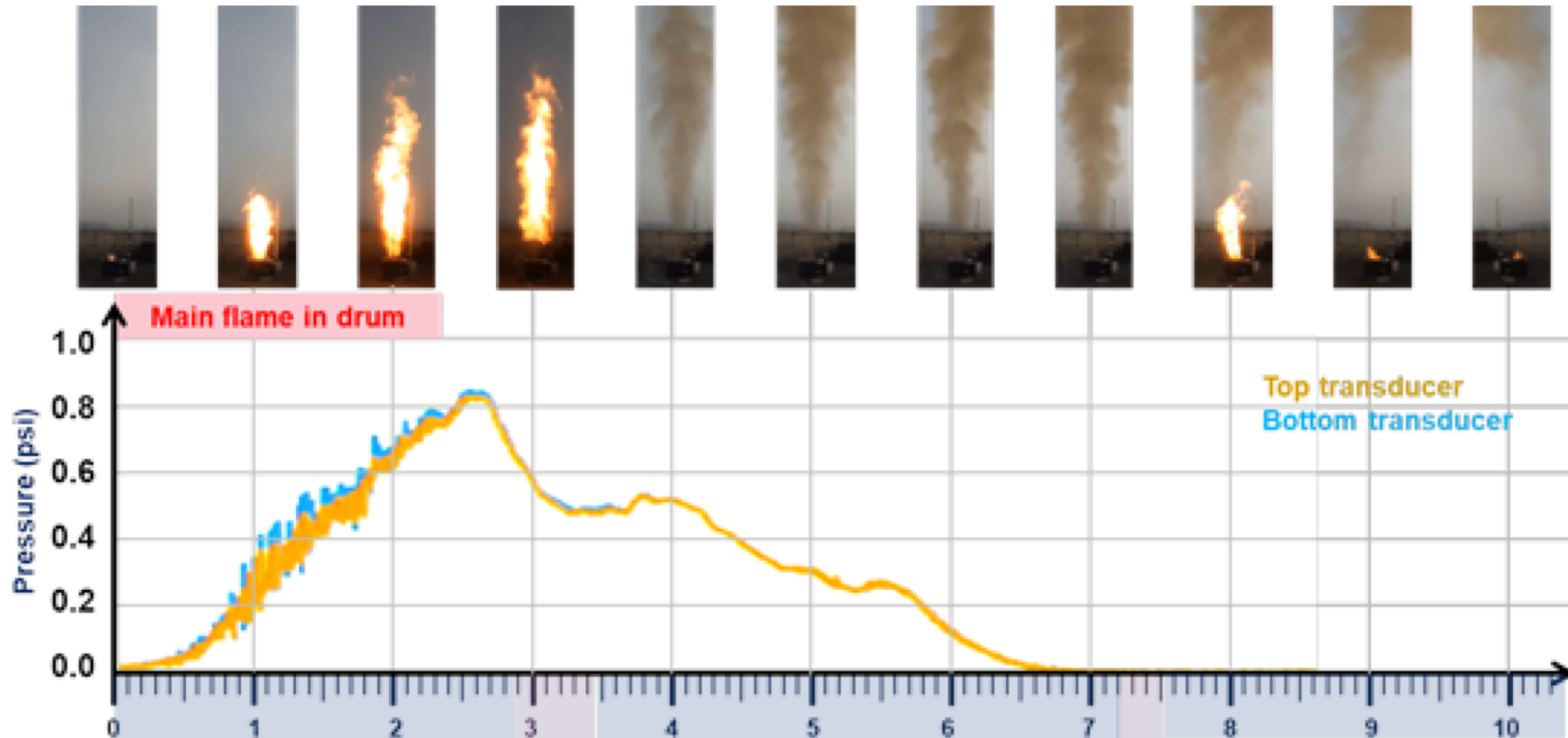
flame detachment

sudden extinction at high venting rate

flameless venting of decomposition gases,
re-ignition

final extinction.

Configuration (IMR riffle propellant, 8 kg, 4.0% venting)
flow field – flame structure interaction : flame detachment



Configuration (IMR rifle propellant, 8 kg, 4.0% venting)
flow field – flame structure interaction : flame detachment

During this test, the main flame goes through transitions:

ignition – flame detachment – flame leaving enclosure – secondary flame extinction

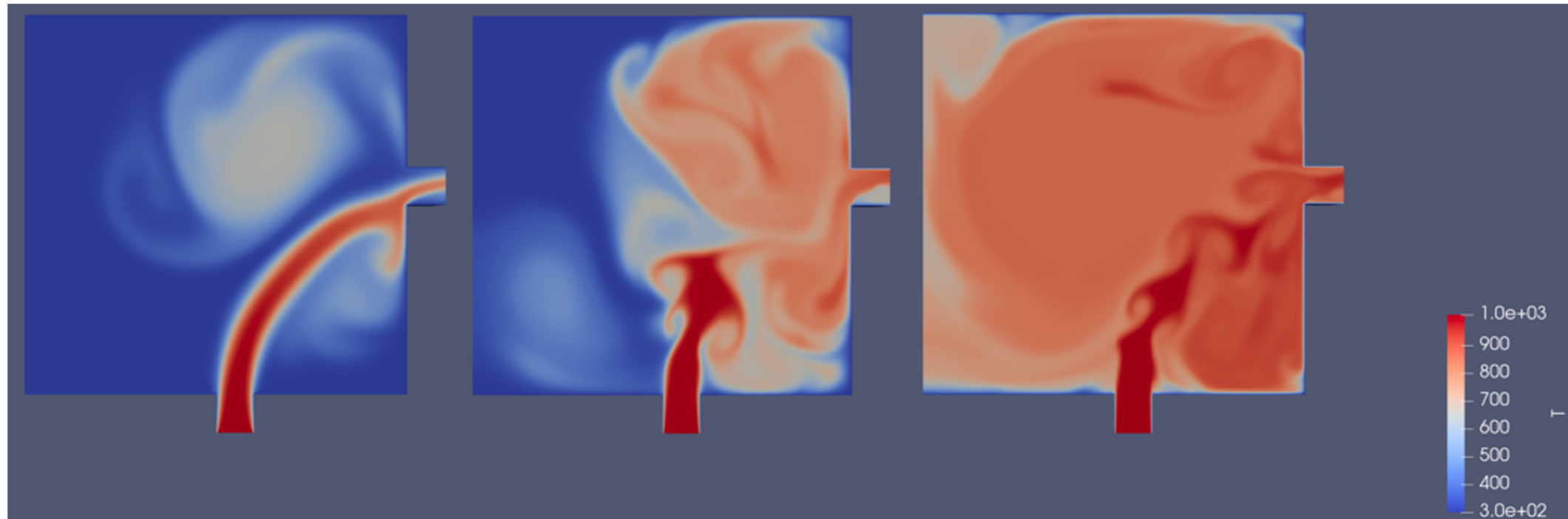
Flame detachment → Enclosure pressure drop

Flame leaving enclosure: highly dependent on flow conditions (laminar turbulent)

Combustion: kinetics vs thermodynamics vs flow conditions

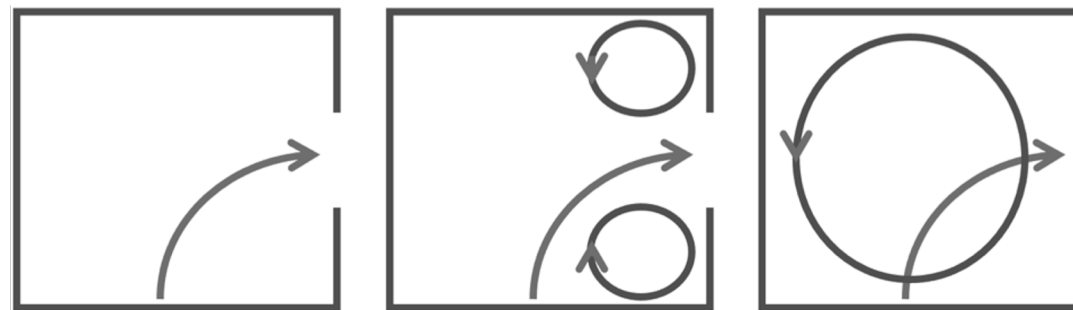
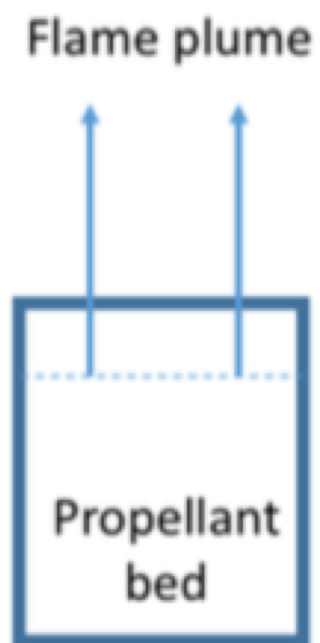
flow field – flame structure interaction : flame detachment & turbulent mixing

Flame leaving enclosure: highly dependent on flow conditions (laminar turbulent)

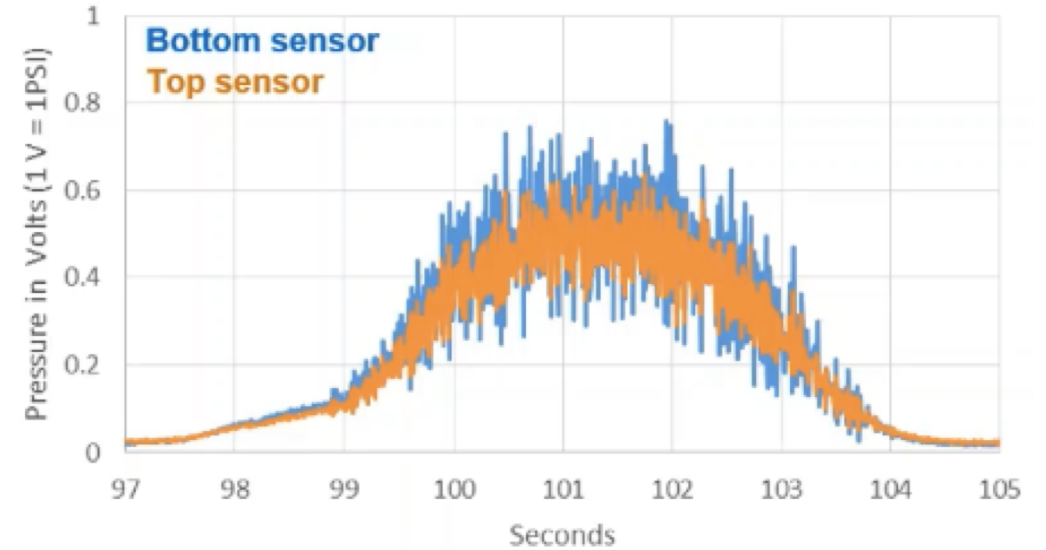


→ 2D simplified (unreactive) CFD combustion flow temperature model

flow field – flame structure interaction : turbulent mixing



Configuration (IMR rifle propellant, 16 kg, 8.0% venting) flow field – flame structure interaction : flow instabilities



Possibilities:

- Turbulent flame
- Intrinsic hydrodynamic instability (Darrieus-Landau type)
- Coupling with enclosure (cavity)

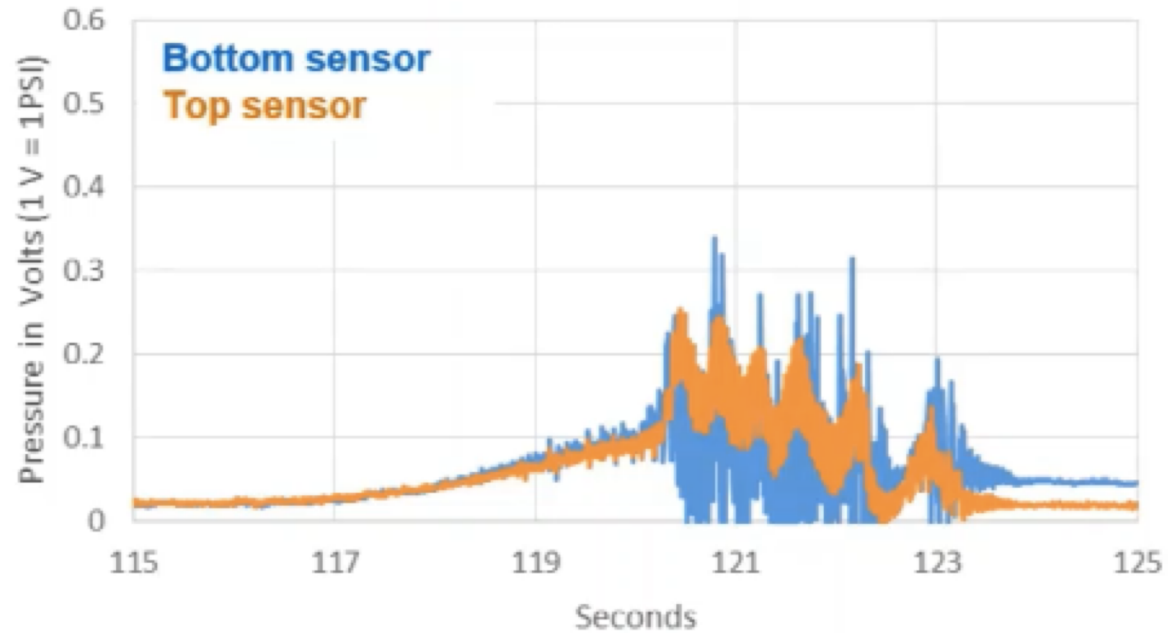
Configuration (Large web single base propellant, 8 kg, 8.0% venting)
flow field – flame structure interaction : flow instabilities



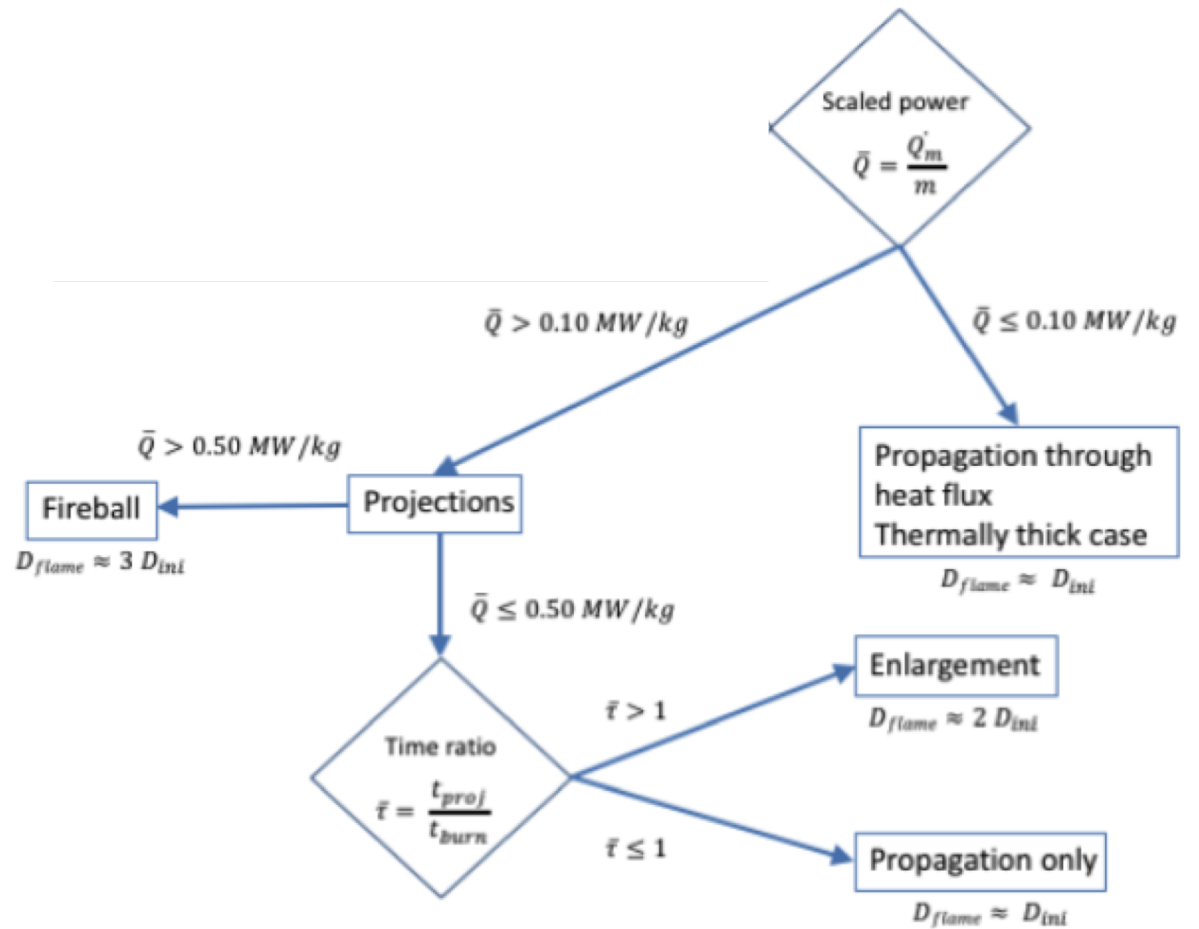
Smooth induction with flame liftoff

Sudden onset of thermoacoustic resonance (1st - 2nd harmonics)

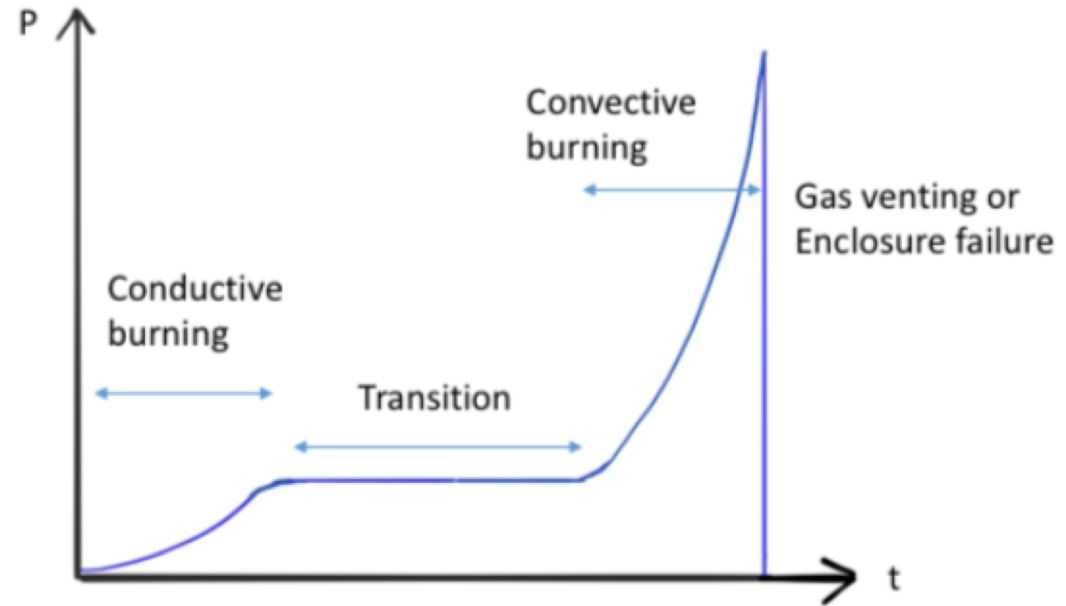
→ Risk of dangerous oscillations



Configuration (M30 rifle propellant, 12 kg, 8.2% venting) flow field – flame structure interaction : entrainment and projections



Configuration (IMR rifle propellant, 8 kg, 4.0% venting) Effect of confinement



pressure driven forced convection
VS
buoyant plume natural convection flow

Nitrocellulose detonation Characteristics

NC can easily be detonated with a performance similar to that of TNT

Detonation impossible when the solvent content is larger than 15-20%



Product	VOD (m/s)	Bulk density (g/cc)
NC	7,200	1.20
Single base	5,600	0.98
Double base	3,100	0.89
Double base	3,400	0.59

(%)	(%)	(cal/g)	(cal/g)	(cal/g)	(GPa)	(cc/g)	(m/s)	(g/cc)	(%)	(dimensionless)
NC 13%	H2O	HOE	E0	E-CJ	P-CJ	V-CJ	VOD	TMD	%TMD	HOE NC / delta E
100	0	1033	-586	431	2.25265	0.444	7241	1.66	1	1.02
95	5	941	-746	407	2.06261	0.46	7051	1.61	1	0.90
90	10	850	-907	375	1.87492	0.477	6993	1.56	1	0.81
85	15	744	-1068	342	1.69452	0.496	6722	1.51	1	0.73
80	20	667	-1228	309	1.52358	0.515	6556	1.47	1	0.67
75	25	575	-1388	278	1.36863	0.534	6378	1.43	1	0.62

* Steel or PVC tubes with HE boosters

* Comparison of Cheetah calculated available energy and CJ states

Nitrocellulose detonation Initiation

Two main modes:

Shock to detonation (SDT)

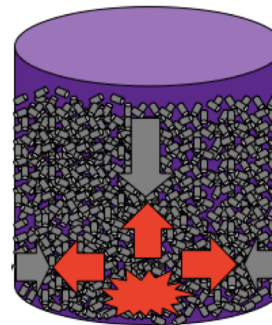
- Nearby detonation
- Mechanical explosion



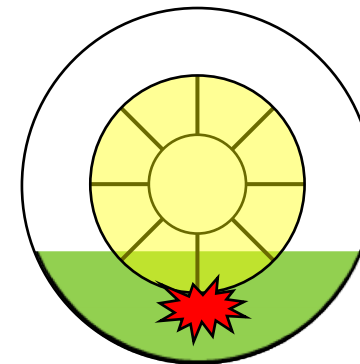
Deflagration to detonation (DDT)

- Thermal ignition
- Confinement

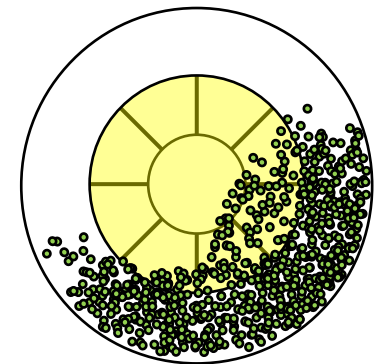
Critical height



Static



Rotation



Epilogue – Safety, necessity and uncertainty (ontological, epistemic and aleatory)

Single 1D setup → 14-15 burning behaviours

- Composition
- Configuration
- State variables

Modelling tools:

- Pressure evolution
- Venting
- Heat fluxes
- Flame propagation
- Sensitivity (impact, friction, ESD, heat, etc.)
- Mitigation (sprinklers, disposition, structures, uniforms, egress, etc.),
- Explosive safety decision process

Epilogue – Safety, necessity and uncertainty (ontological, epistemic and aleatory)

“One good test is worth a thousand expert opinions”

- Wernher Von Braun

NITROCELLULOSE

“While those whom devotion to abstract discussions has rendered unobservant of the facts are too ready to dogmatize on the basis of a few observations”

- Aristotle (On generation and corruption, bk 2)