A NUMERICAL TOOL FOR VALIDATING SOLID PROPELLANTS IGNITION MODELS

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Summary

- Introduction
- General presentation of the CFD tool
- Ignition models
  - Temperature threshold ignition criterion
  - Kinetic threshold ignition criterion
  - Low pressure combustion model
- Results
- Conclusion and further work

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Introduction

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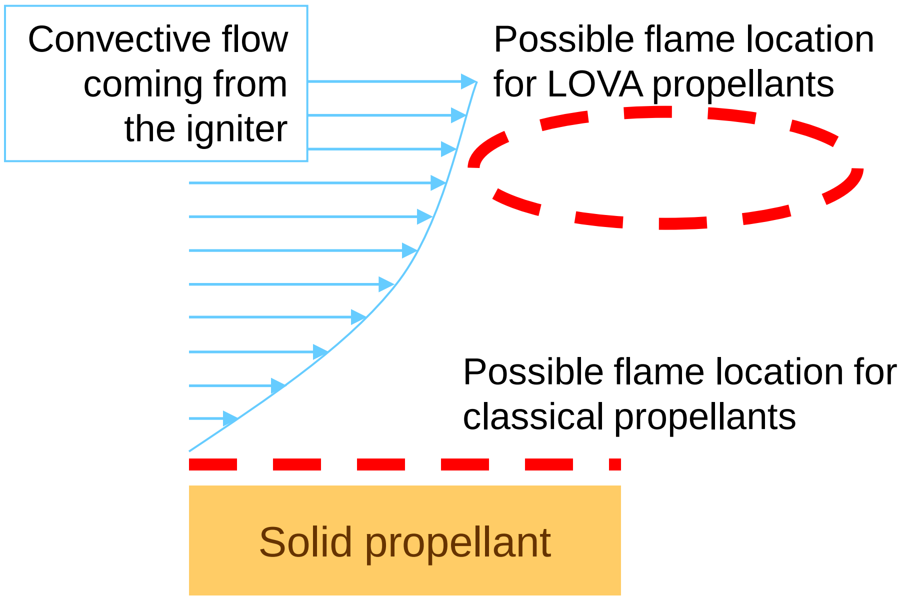
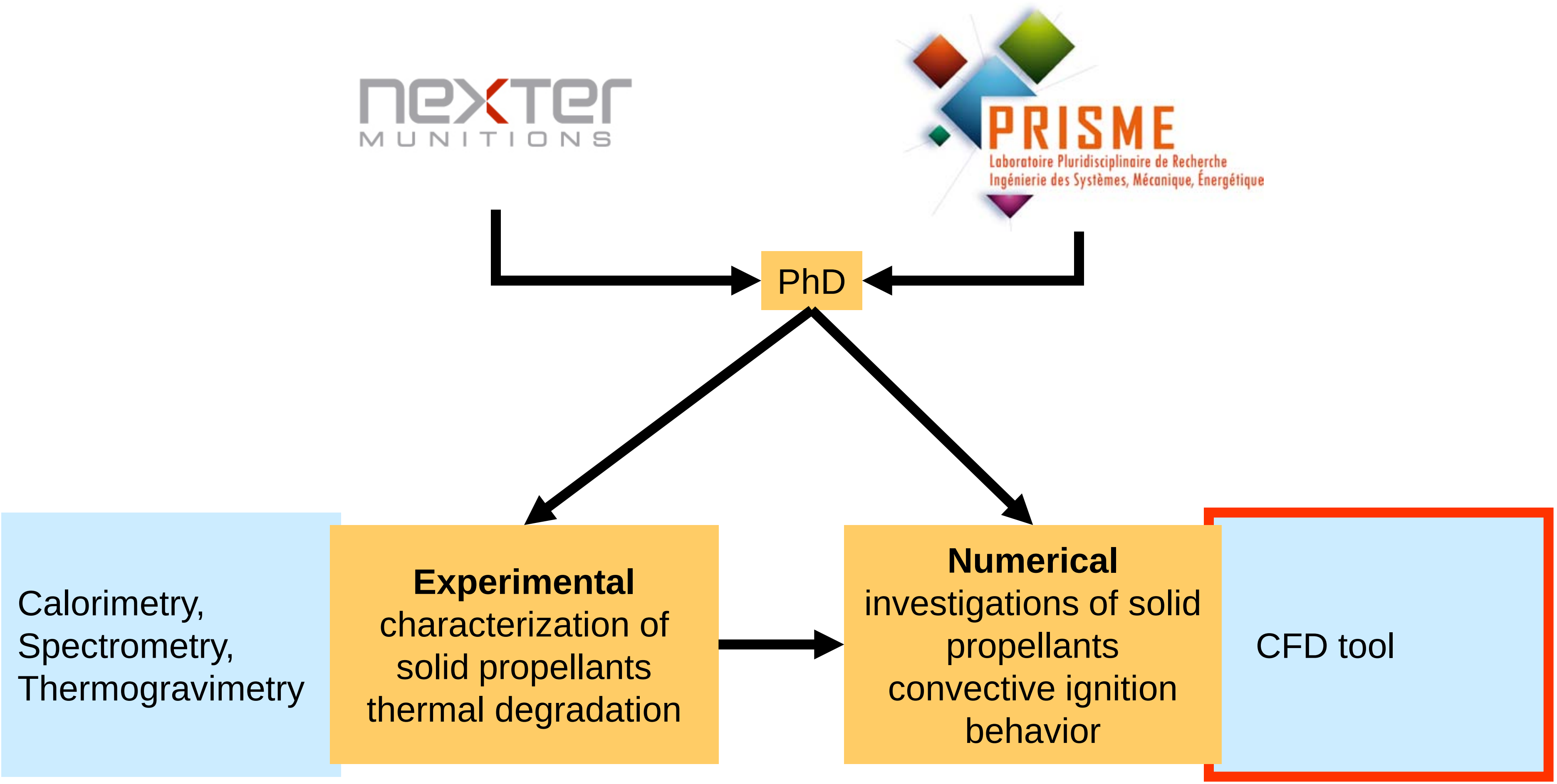
- Nitrocellulose-based solid propellants
  - Rapid activation of the thermal degradation
  - Homogeneous material, leading to premixed flames
  - Small gap between the solid and the flame zone



- LOVA solid propellants
  - *Strongly influenced by the chemical composition and pressure of the surrounding gas phase*
  - *Thermal degradation occurs at higher temperatures*
  - *The solid propellant can be heterogeneous, leading to diffusion flames*
  - *The gap between the solid and the flame can be greater*
  - *the reactive species emitted from the propellant can be advected away and react in cooler parts of the chamber*
  - *At high pressures, the reactive system behave like the Vieille's law.*


PRISME
Laboratoire Pluridisciplinaire de Recherche
Ingénierie des Systèmes, Mécanique, Énergétique
PhD
Calorimetry,
Spectrometry,
Thermogravimetry
Experimental
characterization of
solid propellants
thermal degradation
Numerical
investigations of solid
propellants
convective ignition
behavior
CFD tool

Summary

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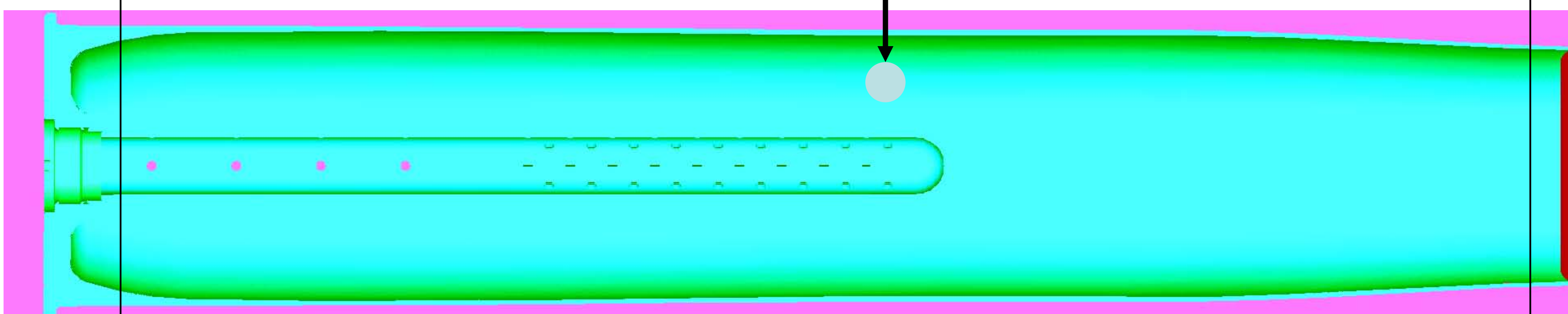
General presentation of the CFD tool:

Local submodels at the grain scale

- Pre-heating of the energetic material
- Decomposition kinetics
- Boundary layer effects
- …



Propellant bed scale

Gaseous mass and heat transport at high velocity.
Mass, heat and momentum transfers with the porous media

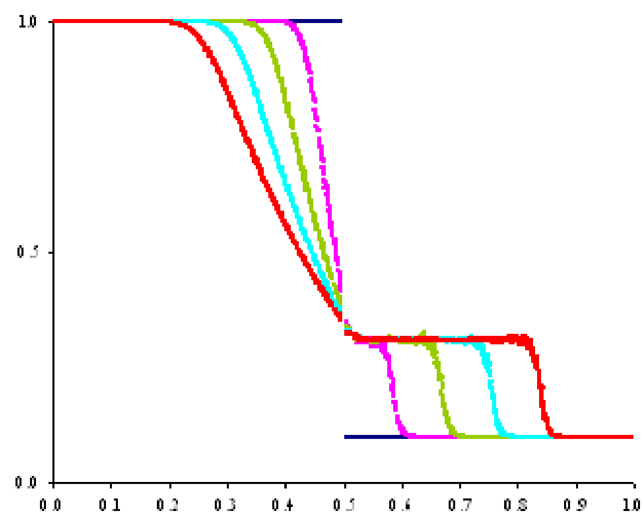
General presentation of the CFD tool: the gas phase

- Hypotheses for the fluid flow
  - Eulerian description
  - Chemical equilibrium
  - Constant properties (air)
  - Ideal gas hypothesis

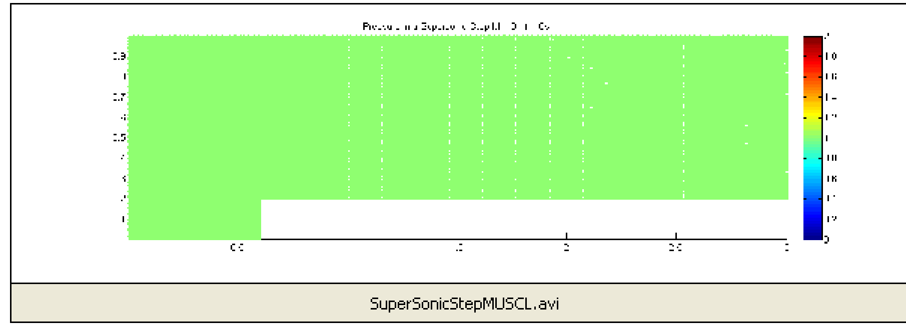
$$\partial_t \vec{\Phi} + \vec{V} \cdot div\left(\vec{\Phi}\right) = \vec{F} \qquad \vec{\Phi} = \left(\rho, \rho\vec{V}, \rho E\right)^T$$

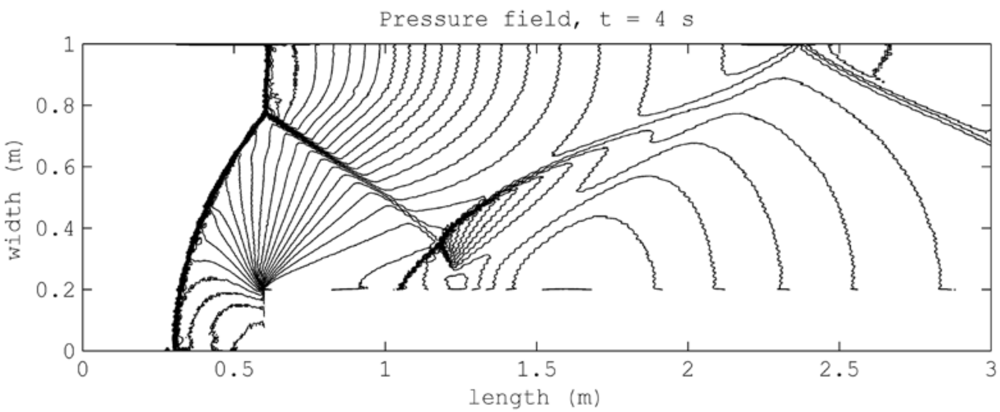
$$\vec{F} = \begin{pmatrix} \dot{\rho} \\ -\overline{grad}\left(P\right) - \vec{d} \\ -\vec{V} \cdot \left[\overline{grad}\left(P\right) + \vec{d}\right] + \dot{Q} \end{pmatrix}$$

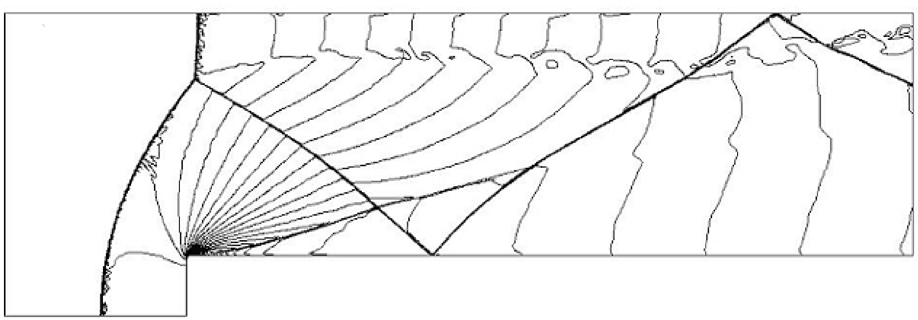
- Validation of the gas phase behavior: SOD shock tube
  - The propagation of the shock and rarefaction waves agrees with the analytical solution.



- Validation of the gas phase behavior :
  - Mach 3 wind tunnel with a step : comparison of the pressure fields with a numerical solution at t = 4s



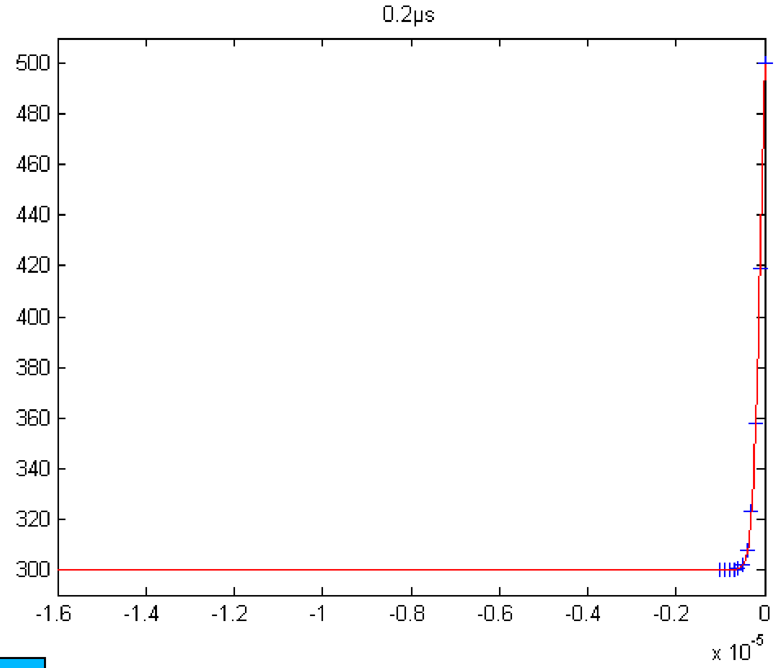




The numerical scheme (AUSM+) based on finite volume method provides relevant results, with moderate numerical diffusion effects.
It is appropriate for describing the flow in the porous medium.

P. Woodward, P. Colella. “The numerical simulation of two-dimensional fluid flow with strong shocks,” in *Journal of Computational Physics*, vol. 54 pp: 115-173, 1984.

$$\rho_s C_s \cdot \left(\partial_t T + r \cdot \partial_x T\right) = \lambda \cdot \partial_x^2 T + Q_s \cdot \Omega_s$$



$$\dot{Q} = h \cdot \left(T_{s,x=0} - T_g\right)$$

$$h = \frac{\lambda_g}{D_s}\left(2 + 1.8 \cdot \mathrm{Re}^{1/2} \cdot \mathrm{Pr}^{1/3}\right)$$

- Hypotheses on the solid phase
  - Static
  - Composed of one single chemical specie
  - Thermally conductive
- Description
  - Finite difference method (exponential scheme) on de-refined mesh.
- Validation
  - Kelvin problem (figure)

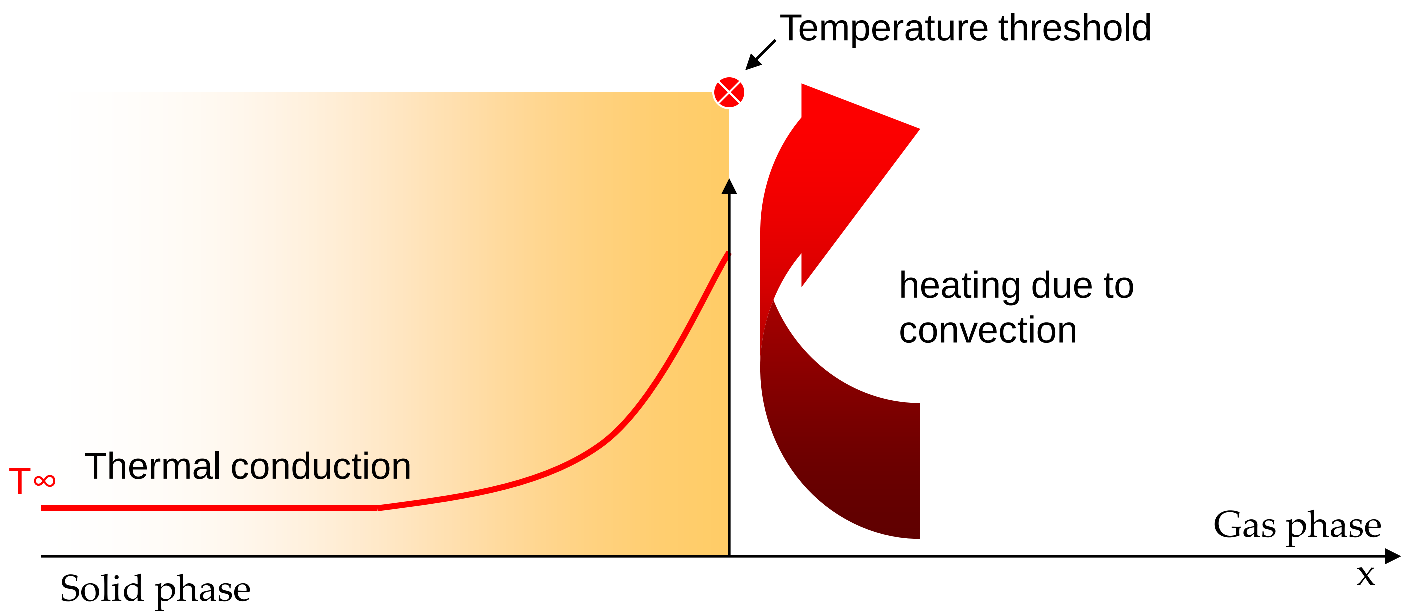
Summary

Temperature Ignition Criterion

1. Convective heating of the solid phase
2. At T>400K, the propellant ignites:

   The solid phase is not further described, and the global combustion behavior follows Vieille's law

Typical Internal ballistics ignition criterion

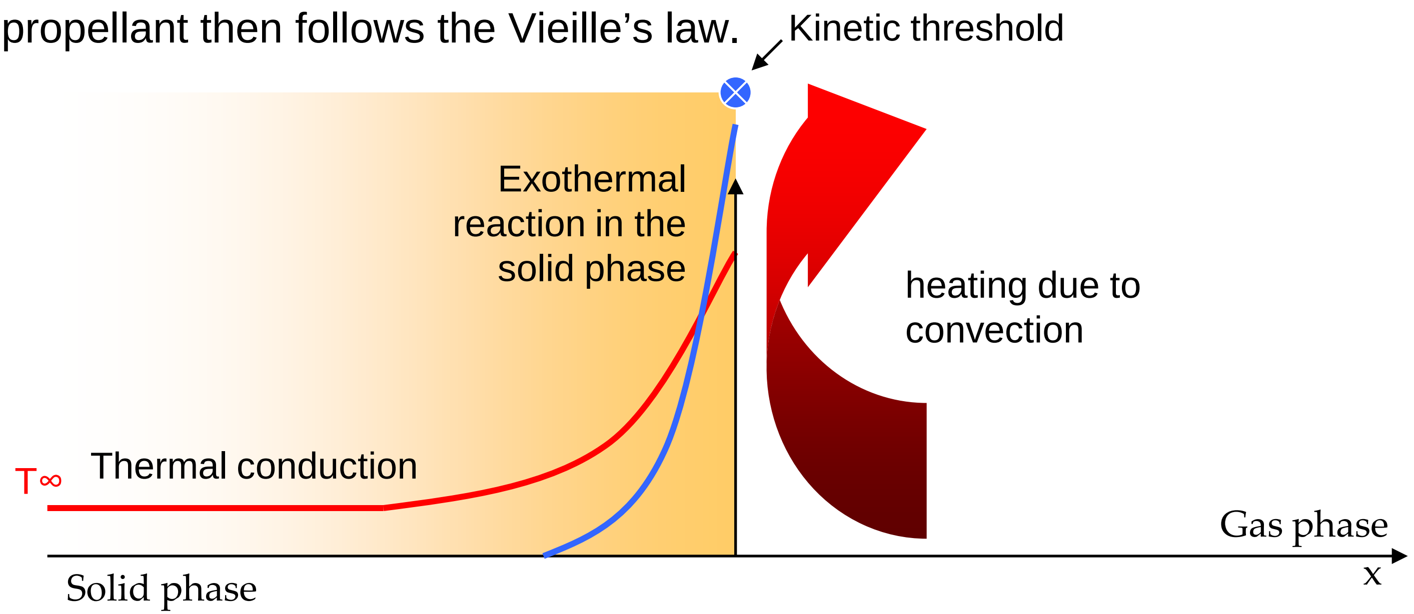


Kinetic ignition criterion G.Lengellé and coll., 1991

1. Convective heating of the solid phase
2. An exothermal reaction is activated in the solid phase (zero order)
3. Ignition occurs once the heat release participates over 15% to the temperature rise:

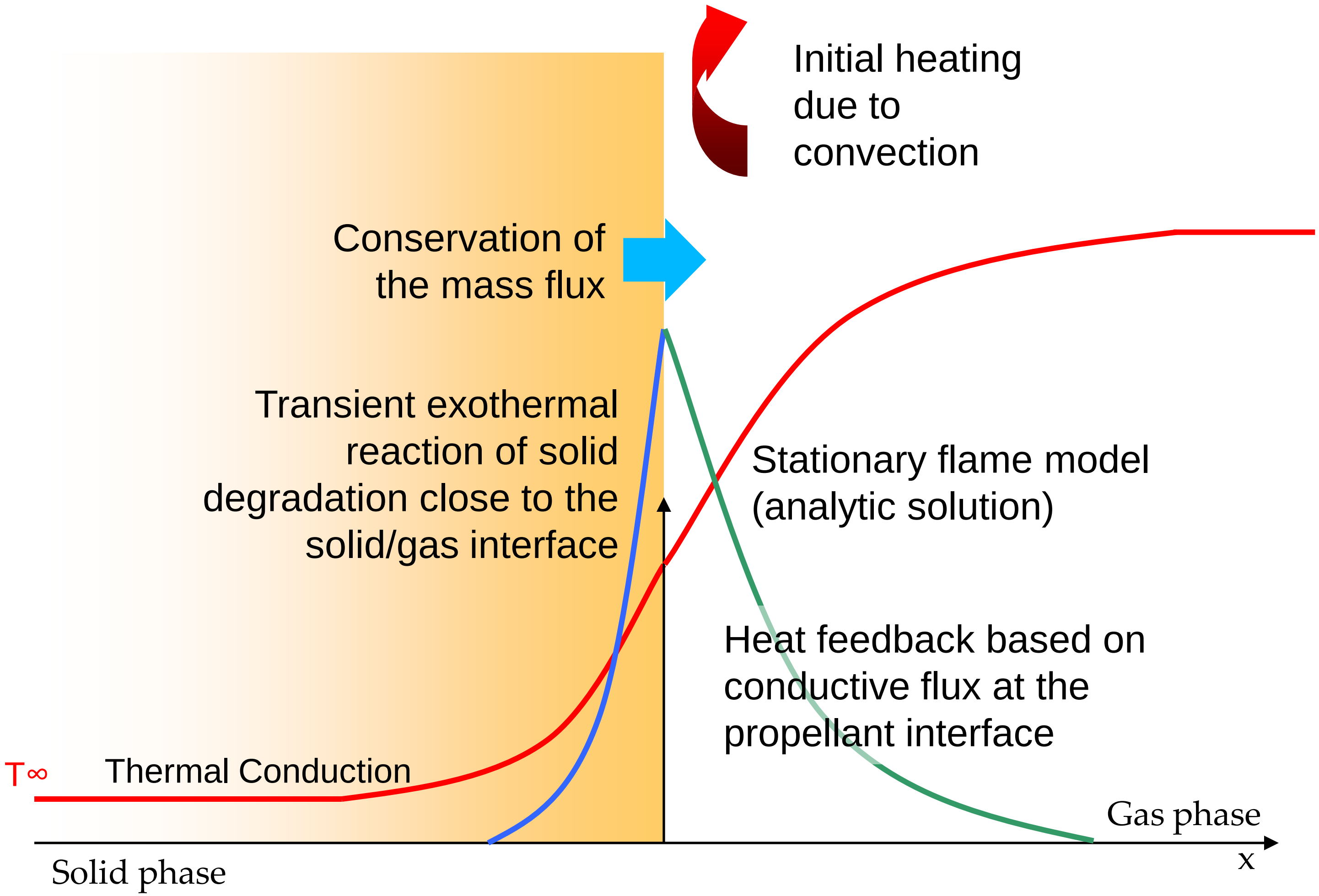
   The combustion behavior of the solid propellant then follows the Vieille's law.

Evolution of the ignition delay as a function of the incoming heat flux



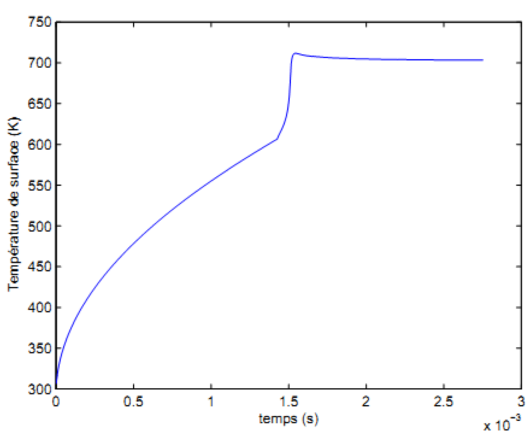
Low pressure combustion model

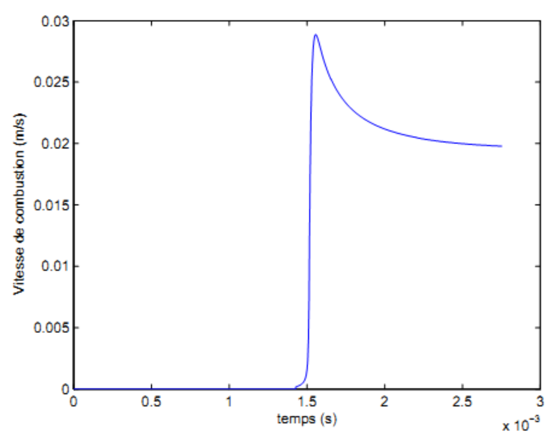
J. Nussbaum, 2007.

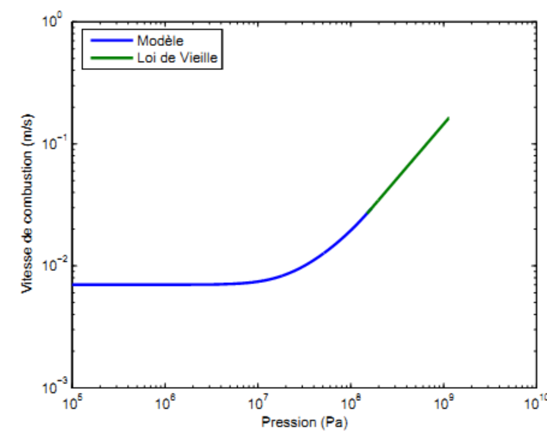


Low pressure combustion model

1. Constant interaction between solid and gas phase
2. The solid is thermally conductive
3. An exothermal degradation reaction takes place in the solid, while a stationary flame stabilizes in the gas phase.
4. The heat released in the gas phase is transferred to the solid phase by convection. It sustains the thermal degradation.
5. With the increase of temperature, the model converges continuously to Vieille's Law without resorting to an ignition criterion.







NUSSBAUM, phD thesis, 2007

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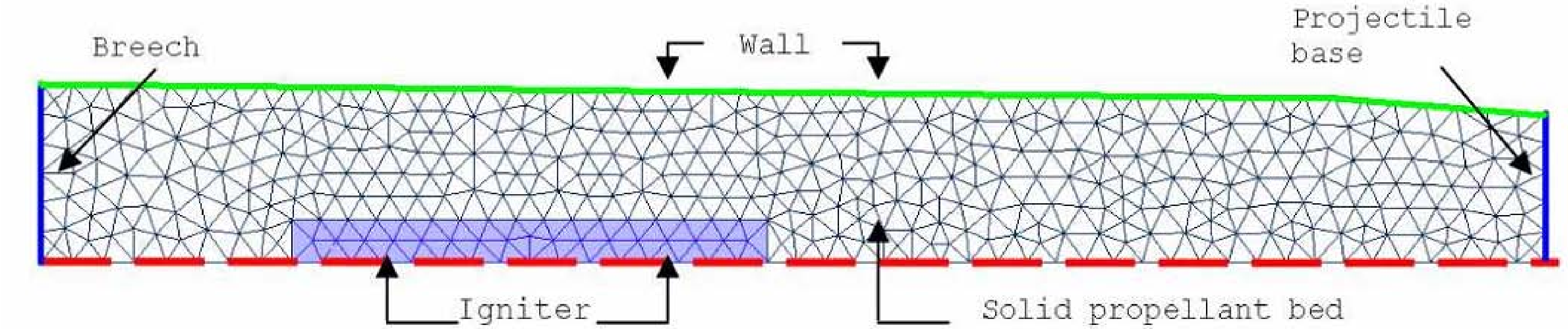
Geometry representative of a 105 mm gun chamber.
Axial symmetry.

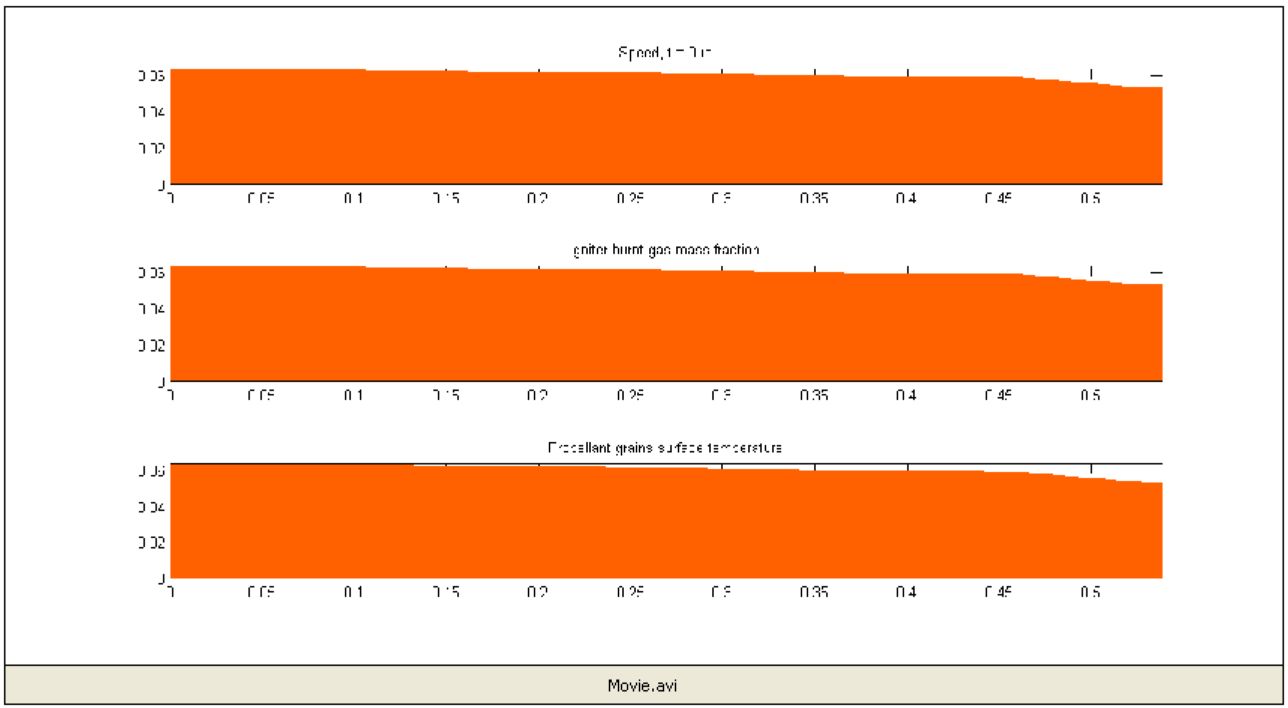
The calculation is considered complete when the pressure at the projectile tail reaches 40MPa.



The igniter is modeled as a mass and heat flux released in this part of the computational domain

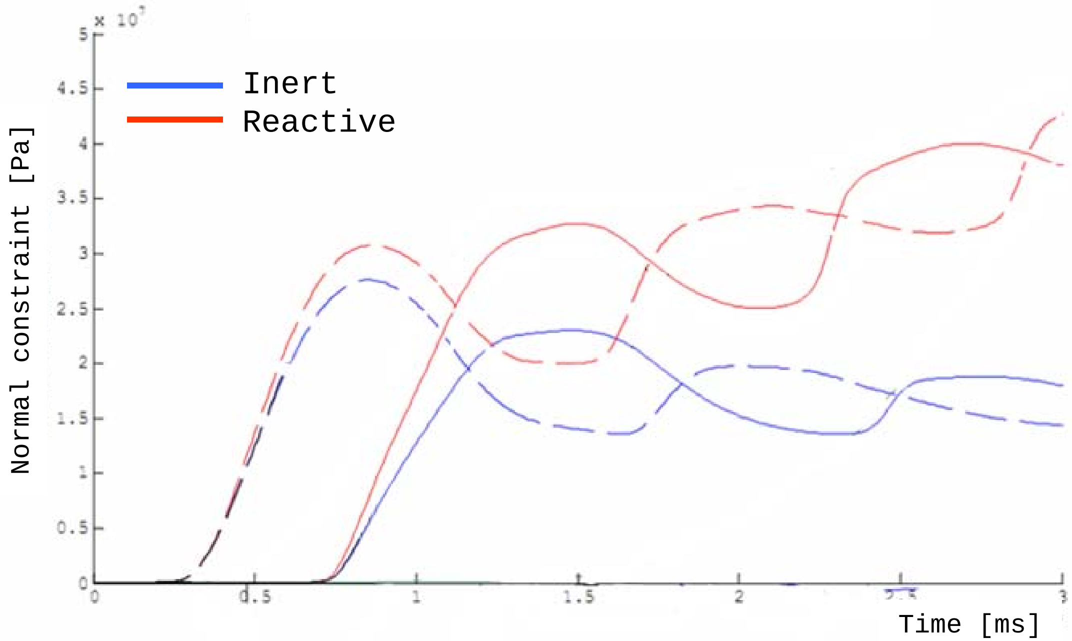
Results

- Ignition models are compared with an inert shot (non-reacting propellant bed).
- Special care is taken to ensure the energetic consistency between the models.
- Ignition models are compared through the breech and projectile tail pressure evolution.



Results

- **Temperature threshold ignition criterion**
  - Temperature threshold set to 400 K
  - The first cell ignites at *t*=150 µs.
  - Ignition starts close to the igniter.
  - The grains ignite ~8 cm after the hot gases wave front.

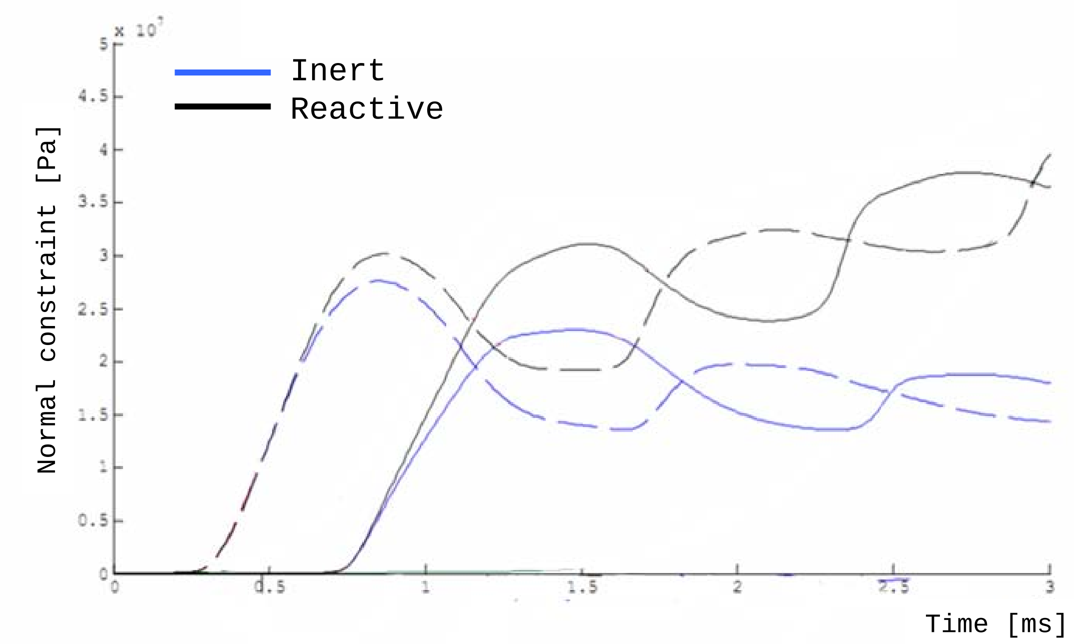


- The ignition wave reaches the projectile base at *t*=680 µs.
- At his instant, the pressure magnitude at the breech is 40 % higher than in the inert case.
- The pressure homogenises in the gun chamber with oscillations as in the inert case.
- The value of 40 MPa at the breech is reached at *t*=2,9 ms.

Solid kinetics ignition criterion

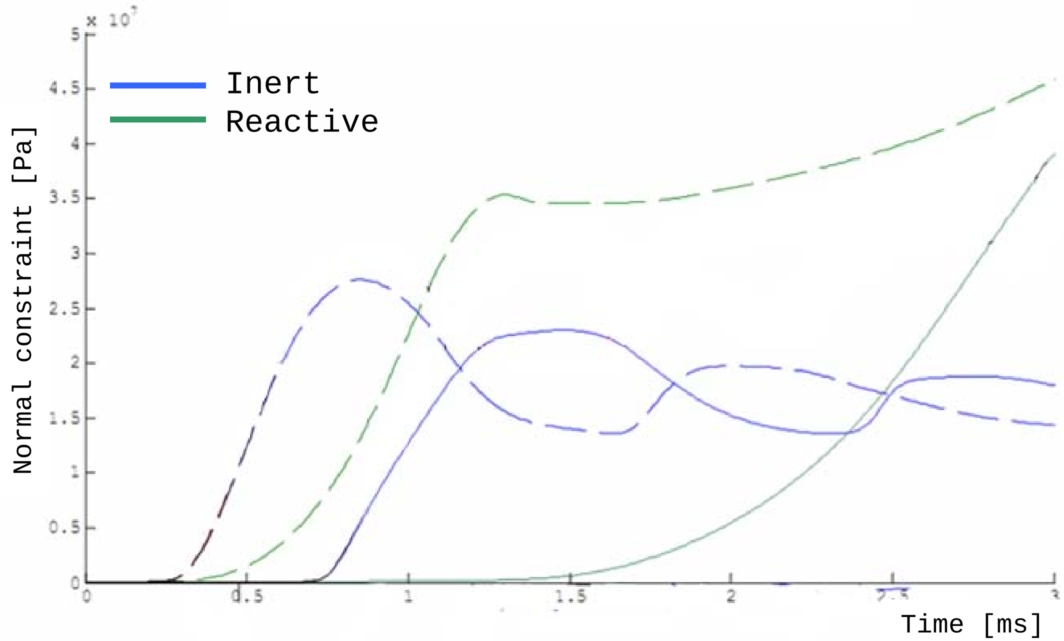
- Able to predict the ignition delay dependence to the incident heat flux
- The pressure evolutions at the breech and projectile are similar to the previous ignition criterion (they resort to the same Vieille's Law)

- The flow structure is not much influenced by the ignition criterion.
- The intensity of pressure waves is practically the same
- (It is slightly lower as the ignition delay is increased, resulting in a slower rise of the ignited fraction of propellant).



Results

- **Low pressure ignition model**
  - delayed pressure rise
  - smoother pressure evolution than with the other models



- The burned gases are emitted by the solid propellant at a relatively low velocity
  - This has an effect comparable to a increased drag on the high velocity main flow
  - The pressure evolution at the projectile base is then smoothened by these effect.

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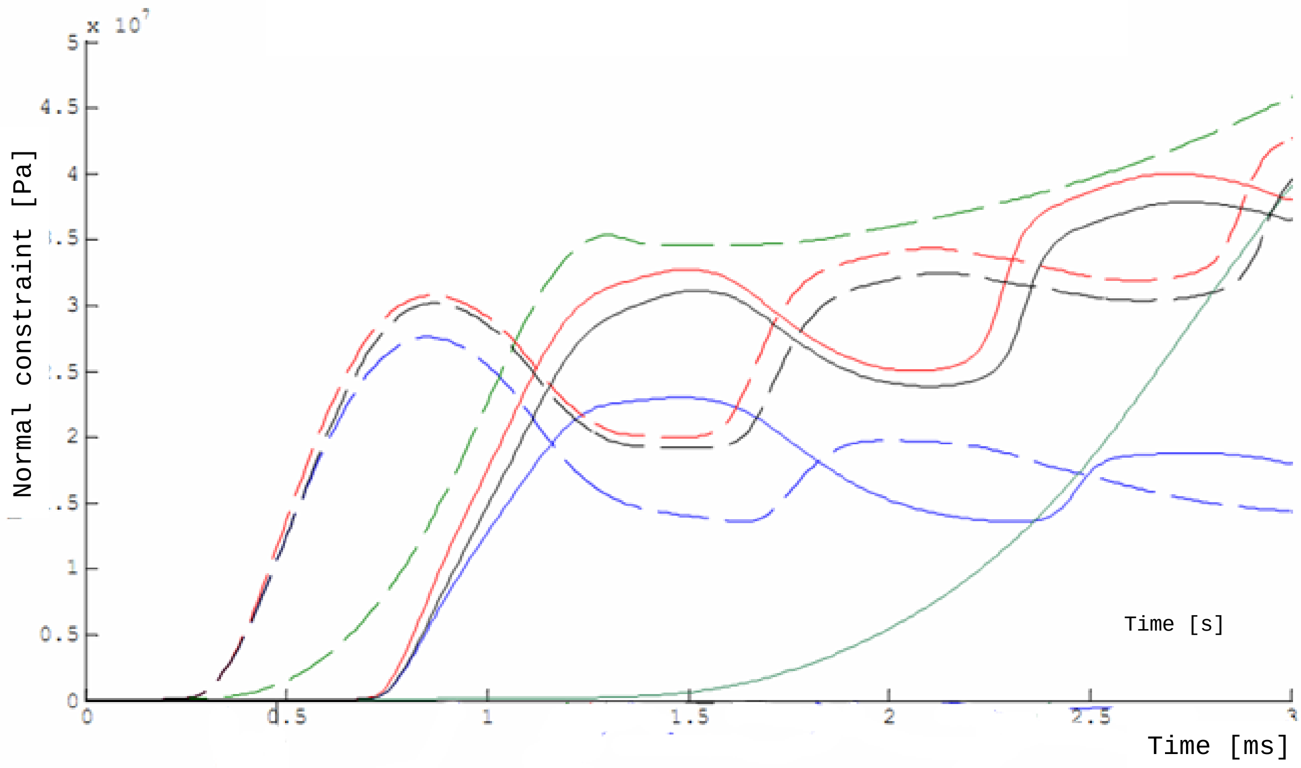
Conclusion

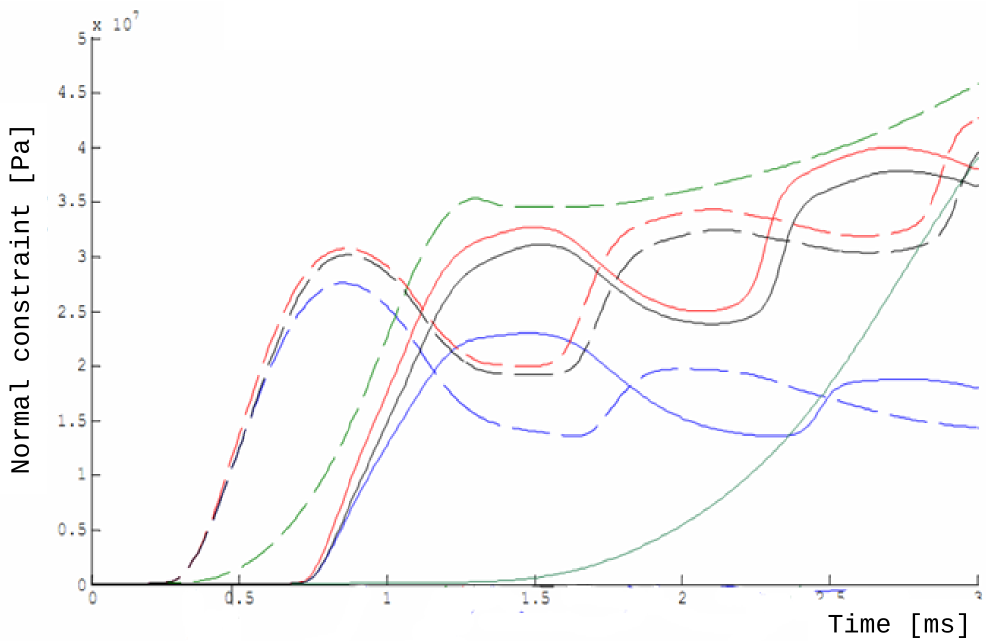
- A CFD code is developped within the framework of a collaboration between NEXTER Munitions and the PRISME Laboratory.
  - It allows to compare and validate ignition models for LOVA propellants.
    - Three ignition models were tested and compared.



Conclusion

- Similar pressure evolutions obtained for :
  - the temperature ignition criterion
  - the solid kinetics ignition criterion

  Due to :
  - similar ignition temperatures
  - the same Vielle's Law



- The third ignition model presents a very different behavior
  - the pressure rise is delayed
  - higher pressures are reached later
  - with a smoother evolution.

  Due to :
  - complex heat and mass transfer interactions between the solid and the gaseous phase.
  - a different description of low pressure combustion of solid propellant
  - This model is therefore better suited to the pressure dependant behavior of LOVA propellants.

Further works

- Further works
  - For the gas phase : future use of CHEMKIN routines for calculating chemical kinetics and equilibriums
  - For the solid phase : Description of a multi-component energetic material and prediction of the emission sequence of the reactive gases.