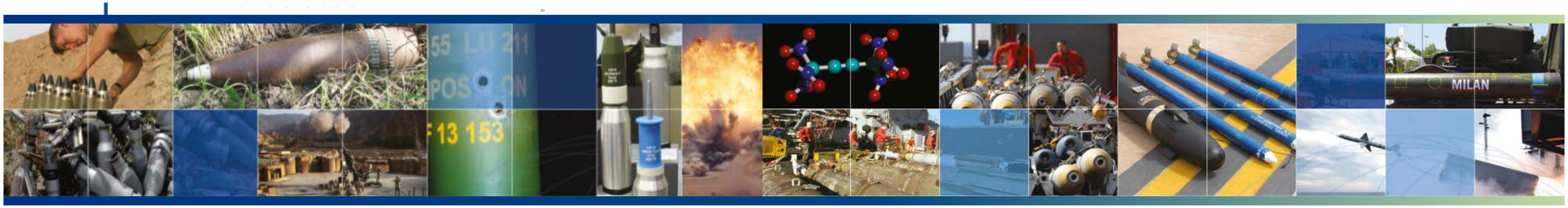

REACTION MECHANISMS FOR ROCKET MOTORS

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OVERVIEW

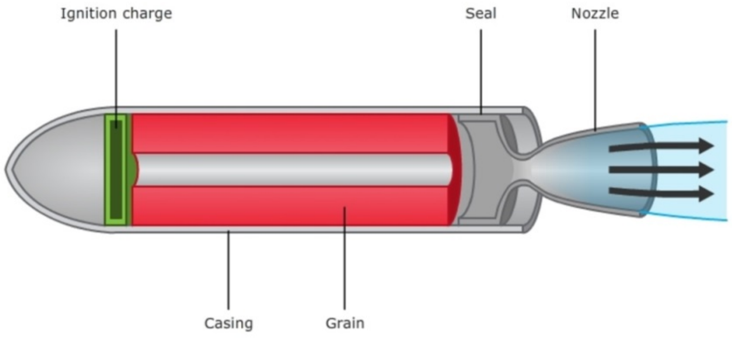
Introduction

1. Mechanical stimuli considered in this study
2. Decomposition Regimes
3. Transition pathways
4. Ways to improve SRMs' IM Signature of SRM

Conclusions

CONTEXT OF THIS STUDY

A Solid Rocket Motor configuration is simple… **But only at first sight!**



Elements	Functions
Propellant grain	Burns and generates hot gases (typically 3,000 – 3,500 K) Controls rate and profile of hot gas generation Common propellant families used for SRM: mostly double base (CDB, EDB, CMDB) and composite propellants (with active or inert polymer matrix)
Motor case	Withstands high pressure (up to 5 MPa), hot gases Solid propellants storage container
Nozzle	Accelerates hot gases to supersonic velocity Controls direction of hot gases
Igniter	Ignites propellant grain on command
Insulation	Prevents hot gases from burning through case
Skirts	Attach points to payload

Now what happens in case of accidental scenarios during the SRM's lifecycle?

INTRODUCTION

- General SRMs' IM Signatures agreed by experts during the MSIAC workshop on IM Technology Gaps[1] :

Rocket Motor Type		**IM Signature**					
		FCO	**SCO**	**BI**	**FI**	**SR**	**SCJ**
Reduced Smoke		IV	IV	IV	IV	Pass	IV
Composite		III	I	III	III	Pass	III
Min Smoke Rocket Motor	**XLDB**	IV	I	I	I	I	I
	CDB	IV	III	IV	I	I	I
	EDB	IV	III	IV	I	I	I

→ This study aims to better understand the reaction mechanisms occurring under **mechanical threats** applied on Solid Rocket Motors

[1] Sharp, M.W., MSIAC IM Technology Gaps Workshop – Output from the Rocket Motor Technology Discussion Group, MSIAC Report L-183, January 2014

1. MECHANICAL STIMULI

Only mechanical threats are considered in this study:

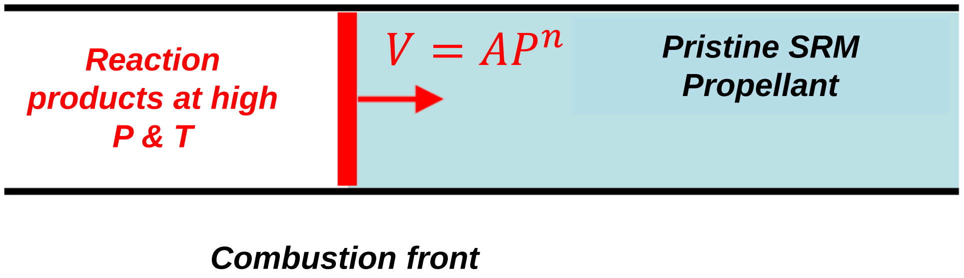
Threat	Bullet	Fragment	SCJ	EFP
Corresponding STANAG	4241	4496	4526	No existing STANAG
Projectile mass	42 g (12.7 mm M2 AP bullet)	18.6 g	Not relevant, continuous jet	A few hundreds of g
Material	Steel	Steel	Copper	Copper, Steel, Al
Diameter to impact	Not relevant. Perforating cone shaped	14.3 mm (conical shape)	1 to 5 mm	10 to 100 mm
Typical velocity at impact or velocity recommended by STANAG (when existing)	850 m/s	1830 and 2530 m/s	6000 to 8000 m/s for the jet tip	100 to 2000 m/s
Energy	20 kJ	30 and 60 kJ	V^2d between 100 and 300 $m^3.s^{-2}$	Between 100 and 200 kJ as an estimation for the average

Was considered as a credible mechanical threat for SRMs but not standardized

2. DECOMPOSITION REGIMES

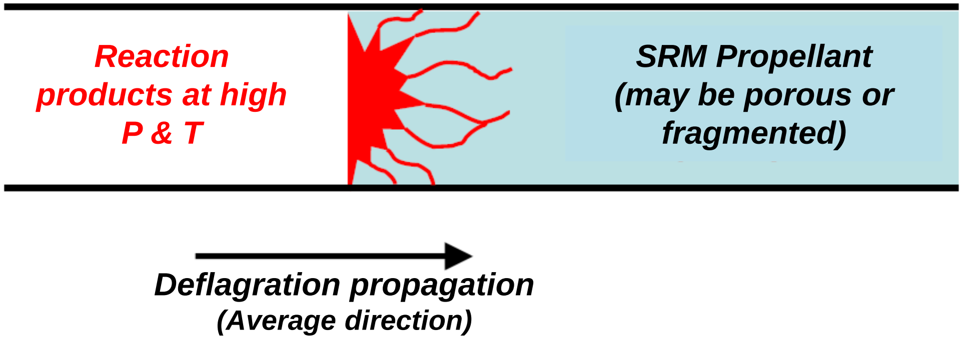
Design mode for a SRM:

Combustion

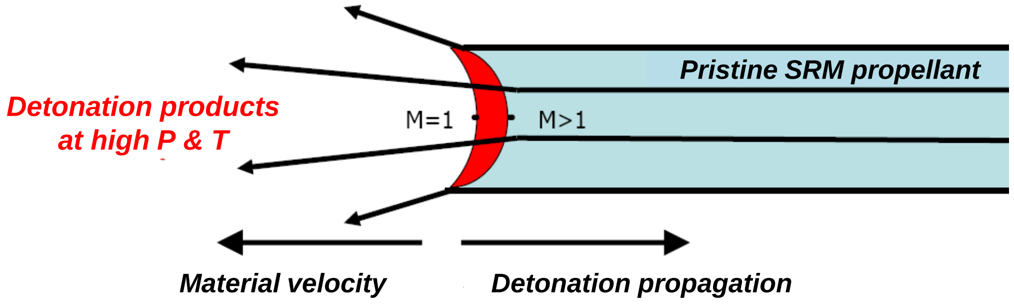


Abnormal regimes:

Deflagration



Detonation

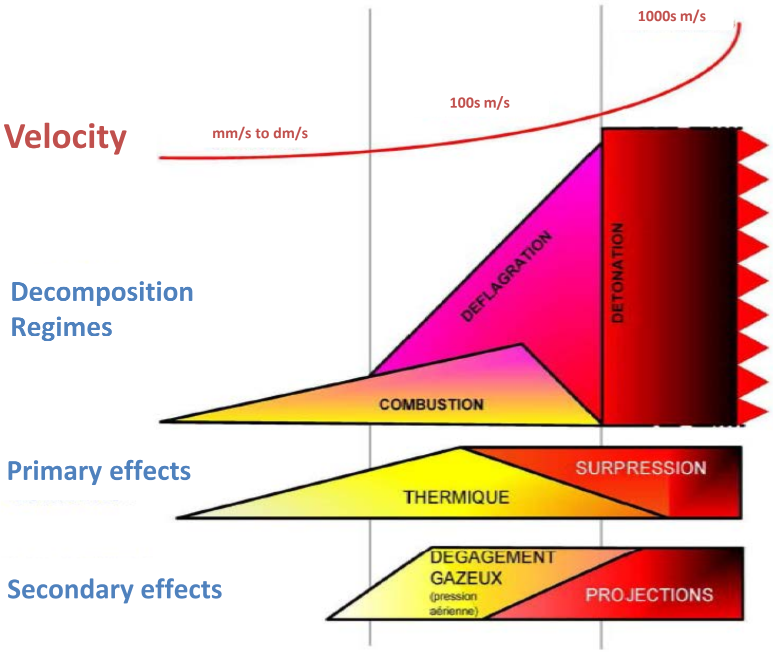


2. DECOMPOSITION REGIMES

- Characteristics of the different decomposition regimes

Decomposition Regime	Combustion	Deflagration	Detonation
Order of magnitude of propagation velocity within the material	10^{-3} - 10^{0} m/s	10^{2} m/s*	10^{3} m/s
Primary effects	Thermal	Blast	Blast / fragments or debris (if light casing or no casing)
Secondary effects	Toxic	Thermal Possible fragments	Fragments / blast (if casing)

* contrary to combustion and detonation, the deflagration velocity is not an intrinsic parameter for the propellant

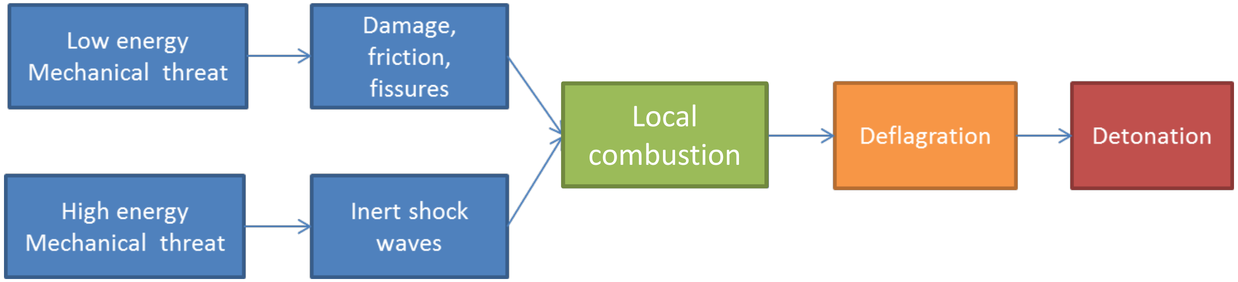


Guide de bonnes pratiques en pyrotechnie, Guide SFEPA n°9, 2009

3. TRANSITIONS - DDT

In an SRM impacted by a mechanical stimulus, the Deflagration to Detonation Transition scenario is the following one:

1. The mechanical stimulus induces either damages, friction, fissures, or non reactive shock waves in the solid propellant
2. Depending on its ability to be ignited, the propellant locally burns in a **combustion** process but the combustion gases will infiltrate the damaged propellant, more gases are produced → the pressure increases → the burning rate increases → … it becomes a **deflagration**
3. If nothing prevents the deflagration velocity to continuously increase inside the grain (self stabilization, increased damage or case break-up), then it will necessarily reach the sound velocity of the unreacted propellant → it becomes a **detonation**



3. TRANSITIONS - DDT

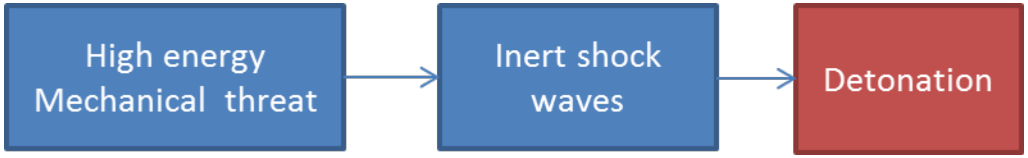
Some key factors influencing the ability of a propellant to undergo DDT:

- A **too high value for coefficient *n*** (in Vieille’s law) that prevents the combustion from stabilizing itself
- **Poor mechanical properties** for the propellant, that lead to fracture and therefore to an increased burning surface
- A **strong casing**, or no venting device that would allow the gas pressure to be released
- A value higher than **18 MPa/ms** for the maximum change in pressure as a function of time, obtained from friability tests
- A **small critical diameter in detonation**. Note that this concept is not trivial for SRMs → the hydraulic diameter is to be used to account for the bore effect

3. TRANSITIONS – SDT & BSDT

The scenario for Shock to Detonation Transition in an SRM impacted by a mechanical stimulus is the following one:

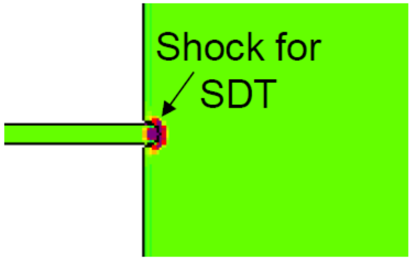
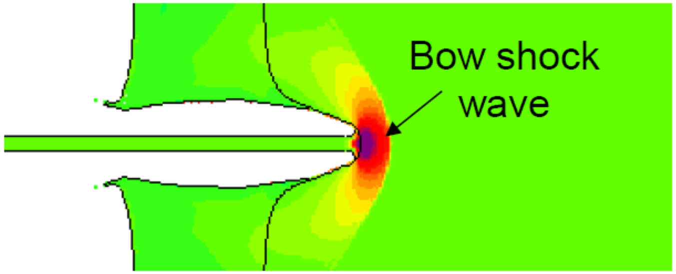
1. The high velocity impact induces a shock wave in the propellant
2. The propellant will detonate if and only if the 2 following conditions are met:
   - the **energy flux is greater than the energy threshold for ignition**. That is to say, the pressure level has to be higher than the initiation pressure and it must be applied over a sufficient duration
   - the above condition must be **applied on a surface greater than the propellant’s critical diameter in detonation**


High energy Mechanical threat → Inert shock waves → Detonation

3. TRANSITIONS – SDT & BSDT

In the case of extremely high energy impacts such as EFP or shaped charge jet attacks, and depending on the critical diameter of the impacted energetic material, the detonation process may be either:

- **directly initiated** when the jet hits the energetic material → prompt SDT
- or, for larger critical diameters, **initiated at some distance from the first impact**, that is to say in the depth of the energetic material that was impacted → Bow Shock to Detonation Transition or BSDT

	
SDT at first impact when the SCJ hits the energetic material: it only occurs if the critical diameter is small enough	**BSDT** in depth of the energetic material: the energy is lower than the one at first impact but the surface on which it is applied is larger

Péron, P-F., Shaped Charge Jet Review - Recommendations for the Review of STANAG 4526 Edition 2, MSIAC Report O-151, February 2013

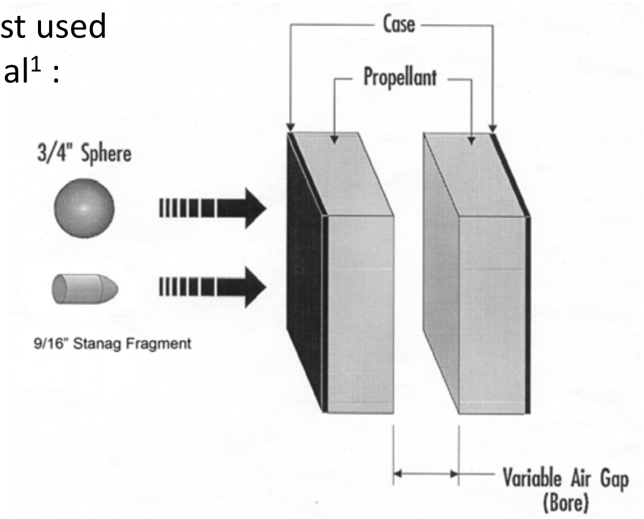
3. TRANSITIONS – BVR & XDT

Although extensively studied, these processes remain misunderstood

In the case of SRMs, the Burn to Violent Reaction process may represent the first step of an Unknown (X) to Detonation Transition

Some relevant test set-ups were used in the US and in the UK to study the parameters related to BVR and XDT process:

Open configuration in the BVR test first used by Finnegan et al[1] :



Confined configuration used by Haskins & Cook[2] :

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[1] Finnegan, S., The bore effect and XDT, Joint NIMIC/TTCP KTA 4-20 Workshop on Cookoff and XDT Mechanisms, March 1996

[2] Cook, M.D., Haskins, P.J., Fragment Impact of Energetic Materials – A Review of Experimental Studies and an Analysis of Reaction Mechanisms, 14th International Symposium on Detonation, 2010

3. TRANSITIONS – BVR & XDT

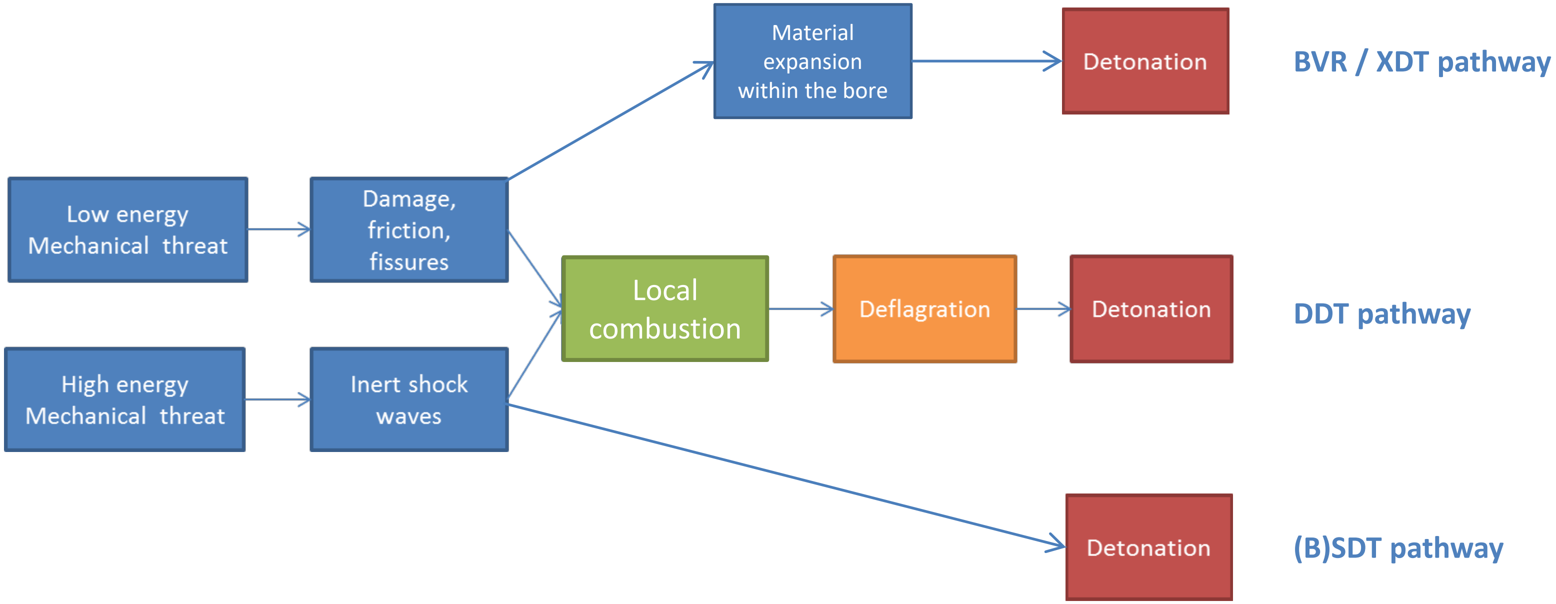
After several years of studies on this subject, and many relevant experiments Haskins & Cook were able to propose the key steps for BVR/XDT mechanisms:

1. A sufficiently fast impact (but below the SDT threshold) to generate rapidly moving damaged energetic material
2. A space into which the material can expand (e.g. the bore of a rocket motor)
3. A secondary surface for the damaged material to impact.
4. SDT of the damaged material following impact. Clearly, this will be dependent on the density and nature of the energetic material and the shock pressure generated on impact
5. Shock initiation (back detonation or "retonation") of the main charge resulting from the detonation of the damaged material

Cook, M.D., Haskins, P.J., Briggs, R.I., Flower, H., Ottley, Ph., Wood, A.D., Cheese, Ph.J., An investigation into the mechanisms responsible for delayed detonations in projectile impact experiments, International Detonation Symposium on Detonation, 2006

The BVR process would stop somewhere during step 4 of the above mechanism. If the conditions are met to initiate a detonation, then BVR is not appropriate anymore, it would then be called an XDT

3. TRANSITIONS – GLOBAL PATHWAY CHART



WAYS TO IMPROVE SRMS' IM SIGNATURE

The IM community has been working on different and promising ways to decrease the response level of Solid Rocket Motors (SRMs) under mechanical solicitation

Some relevant examples have been found in the open literature on this subject:

	Examples	Complexity level	Advantages
Change the propellant	Use of low sensitivity composite propellant instead of Double Based propellant	Very high level of complexity, may need to re-qualify the whole system	The most efficient solution to decrease the reaction type under all IM threats
Change the munition design	Use composite or hybrid casings instead of metallic ones	High level of complexity	Very efficient to mitigate mechanical impacts, but also Fast Cookoff
Change the way to store the munitions	Use a bore mitigant, add barriers or deflectors between munitions, head-to-tail arrangements	Low level of complexity	Can be easily adapted to existing storage configurations

CONCLUSIONS

- Mechanical stimuli remain a major issue for solid rocket motors to be fully compliant with IM requirements, especially for Double Base propellants

- To improve the IM signature of SRMs, we need to better understand their reaction mechanism. Hopefully this study is of interest in this perspective

- Some promising ways were found to improve the IM signature for SRMs under mechanical impacts, either at the early stages of a future SRM's development, or for already in-service systems

- More details will be found in the upcoming MSIAC limited report on this topic. Coming soon…

Questions?