Roxel IM technology, analysis of trial results, future IM programmes in France and UK

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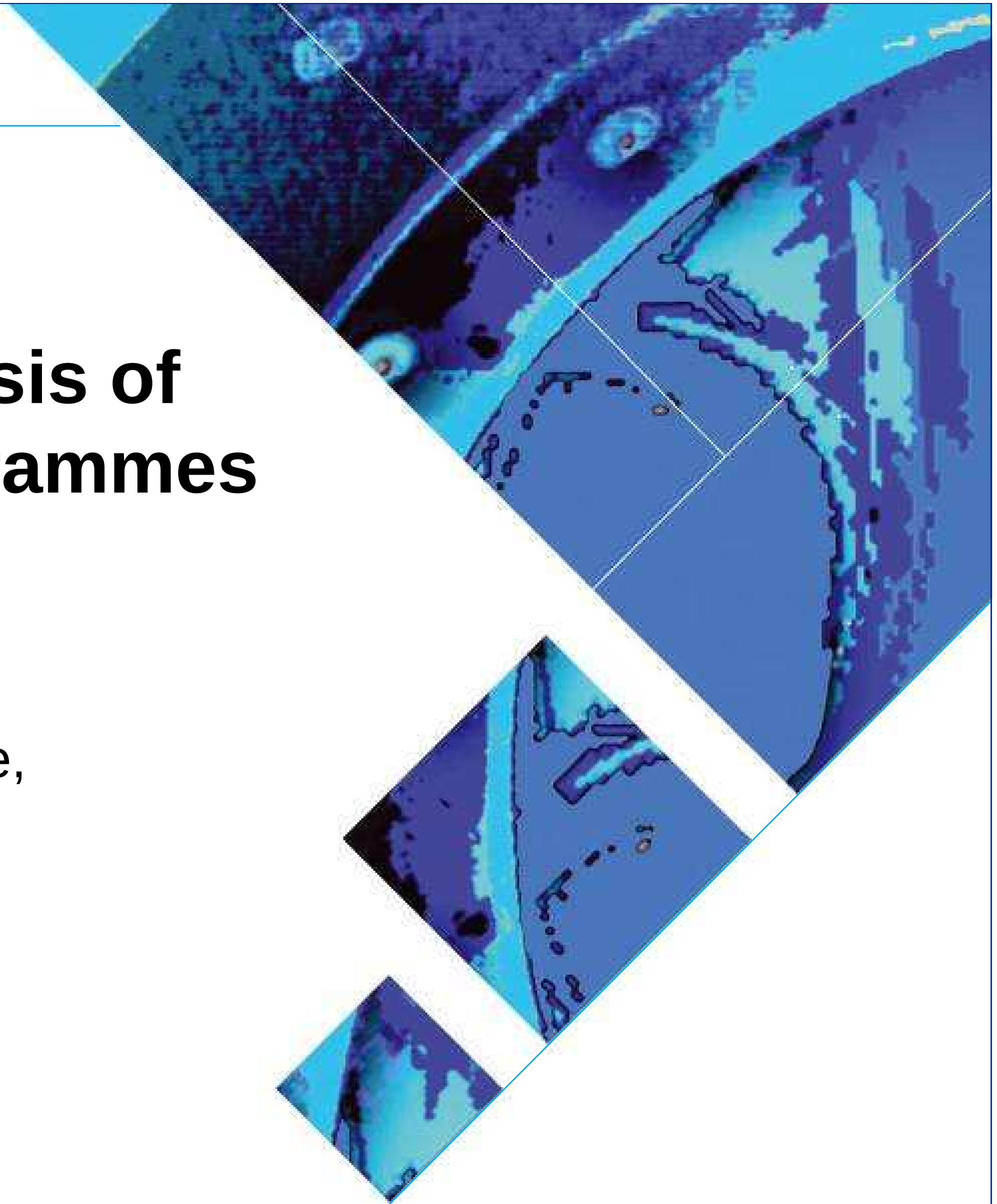
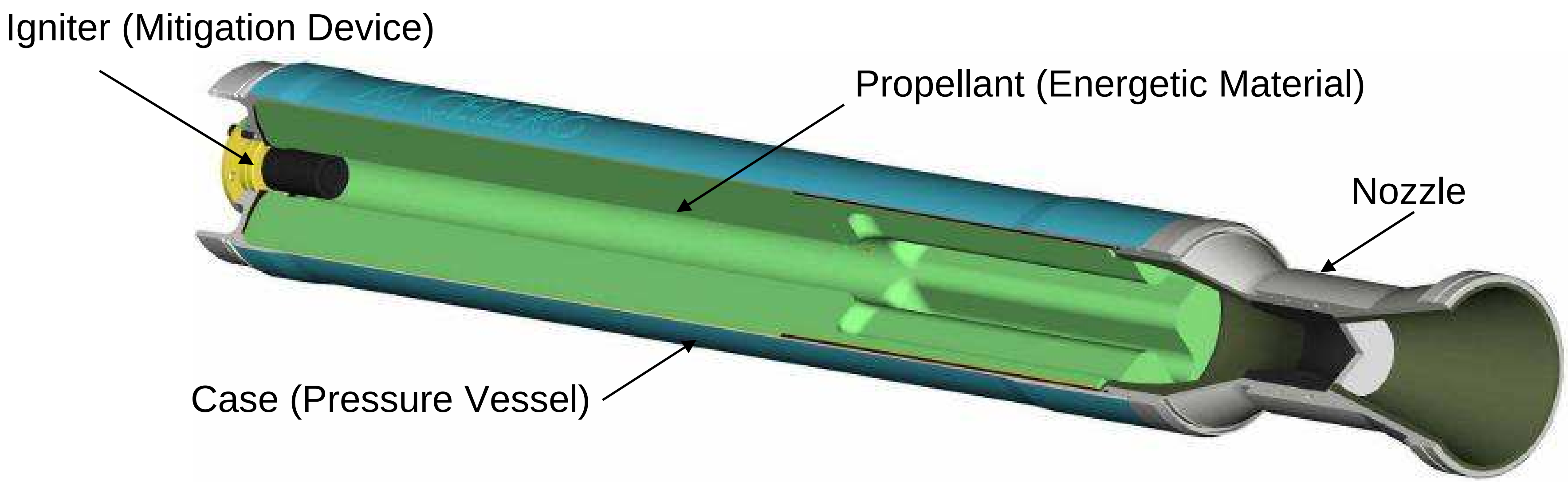
Roxel
Propulsion systems



Summary

1. Introduction
2. Roxel's main IM trial results
3. Analysis of test results and key technology
   - Propellants, Cases, Mitigation devices and Modelling
4. Challenges with RM IM response assessment
   - Influence of test conditions
   - Interpretation of test results
5. IM technology gap and new research areas
   - French MOD ARP APTE programme
   - UK programmes
6. IM low cost design methodology
7. Conclusion

Introduction: Rocket Motor Overview



A Rocket Motor (RM) must deliver thrust, by expansion of hot gas generated by an Energetic Material (propellant) burning under pressure in a case (pressure vessel), through a nozzle, at any moment of its life time.

Insensitive Munition (IM) RM must minimise the probability of inadvertent initiation and the severity of subsequent collateral damage to weapon platform logistic systems and personnel when subject to an unplanned stimuli.

This requires designers to meet this complex challenge to achieve a fully IM compliant RM able to deliver the maximum desired energy.

Introduction: Roxel IM Approach

- IM response of a Rocket Motor (RM) is a critical requirement
- For over 15 yrs Roxel has developed an IM technology design approach based on:
  - Understanding of the behaviour of energetic materials and RM reactions under stimuli
  - Modelling and calculations
  - Participation of Roxel experts in international IM groups
  - **Database setup of more than 200 IM trials on demonstrators and RM's**

Slow Heating

Fast Heating

Shape Charge Jet

Bullet Impact

Fragment Impact

Sympathetic Reaction

Acronyms

- List of key acronyms within presentation

ALU	Aluminium
AP	Ammonium Perchlorate
APTE	Amelioration Propulsion Tactique
ARP	Advanced Research Programme
BI	Bullet Impact
CDB	Cast Double Base
CF	Carbon Fibre
CFRP	Carbon Fibre Reinforced Plastic
EDB	Extruded Double Base
EM	Energetic Material
EMCDB	Elastomeric CDB
FH	Fast Heating
FI	Fragment Impact
GAP	Glycidil Polyazoture
HBR	High Burning Rate
HFI	Heavy Fragment Impact
HTPB	Hydroxy Terminated Polybutadiene
HTPE	Hydroxy Terminated Polyether
HVM	Hyper Velocity Missile
HVSG	High Velocity Shot Gun
IM	Insensitive Munition
KOA	Kevlar Overwrap Aluminium
LMA	Low temperature Melting Alloy
LTI	Low Temperature Igniter
MD	Mitigation Device
NG	Nitro Glycerine
PID	Pre Ignition Device
PV	Pressure Vessel
REF	Reference
RM	Rocket Motor
RRPR	Reduced Range Practice Rocket
SCJ	Shaped Charge Jet
SDT	Shock to Detonation Transition
SH	Slow Heating
SMA	Shape Memory Alloy
SR	Sympathetic Reaction
SSL	Steel Strip Laminate
XDT	Delayed Detonation Transition
XLDB	Cross Linked Double Base

- References used in the subsequent table are used throughout the presentation to refer to corresponding trial results : [27] refers to trial result “Ref 27” in table Page 6

Selection of Roxel IM Test Results

Ref.	Specimen Status	Technology Description			IM Characteristic of rocket motor (tested)						
		Propellant	Case	Mitigation Technology	FH	SH	BI	FI	HFI	SR	SCJ
	NATO STANAG 4439				V	V	V	V		III	III
	FRANCE INSTRUCTION DGA 260 IPE MURAT ***				V	V	V	V	IV	IV	III
2	RM In Service	EDB	Alu.	-	V	V	N/R			I	
3	RM. Demonstrator	EDB	Alu.	-	V	V	V	N/R		<III	
5	RM. Demonstrator	EDB	SSL	PID (Pre Ignition Device)	V	V	V				
9	RM. Demonstrator	EDB S1	Alu.	-	V	IV	V			I	
10	RM. Demonstrator	EDB S2	Alu.	-	V	IV	v			<III	
11	RM In Service	CDB	KOA	-	IV	III	IV			III	I
12	RM In Service	EDB	KOA	-	IV	IV	IV			V	IV
13	RM In Service	EMCDB	SSL	-	V		V				
14	RM In Service	Composite	Alu.	-	V		V				
15	RM In Service	CDB	KOA	-	V		V				
16	RM. Demonstrator	EDB	KOA	-	V		N/R				
17	RM. Demonstrator	XLDB 2	CRFP	-	V		N/R				
18	RM under Qualification	CDB	KOA	-	V		V				
19	RM under Qualification	CMDB	KOA	-	V		V				
20	Tech. Demonstrator	Composite	KOA	LTI (Low Temperature Igniter)	V	IV					
21	RM In Service	EDB	Steel	-	IV	IV	V	I		II	I
22	RM. Demonstrator	GAP Comp.	KOA	-	V		N/R				
23	RM In Service	Composite	SSL	LTI	V	IV	V				
24	RM In Service	Composite	Steel	Intumescent paint	V						
25	RM. Demonstrator	Composite	Steel	Membrane	V						
26	Tech. Demonstrator	Composite HTPE	SSL	-	V	III	III				
27	RM. Demonstrator	Composite HTPE	SSL	LTI	IV	II	IV		III		IV
28	RM In Service	Composite 1	Steel	-	III		V				
29	RM. Demonstrator	Composite 1	Steel	Membrane	V						
30	Tech. Demonstrator	Composite 1	Steel	-	IV	III	IV		III		
31	Tech. Demonstrator	Composite 1	Steel	Weakened case	IV	III	IV		III		
34	Tech. Demonstrator	Composite 1	Steel	Steel case + CF patches	IV	III					
37	RM. Demonstrator	Composite 2	Steel	-	III						
38	Tech. Demonstrator	Composite 2	Steel	Foam A		II	V				
39	Tech. Demonstrator	Composite 2	Steel + CF	-	IV	II	IV		III		
40	Tech. Demonstrator	Composite 2	Steel + CF	Membrane, LTI	V	III			III		
42	Tech. Demonstrator	Composite 2	Steel	Foam A		II	V				
45	Tech. Demonstrator	XLDB 3	Steel + CF	-	V	IV	IV		I		
46	Tech. Demonstrator	XLDB 1	Steel	-	V		I				
47	RM. Demonstrator	CDB	CFRP	-	V		V	V		V	
48	RM. Demonstrator	EMCDB	SSL	PID, shear closure	V	V	V	V		V	
49	RM In Service	Composite	Steel	-	III	I					
50	RM. Demonstrator	Composite	Steel 1	Weakened case, LTI	III	III					
51	RM. Demonstrator	Composite	Steel 2	Weakened case, LTI	V	III	IV	IV			
52	RM In Service	Composite	Alu.	-	V		IV				
53	RM In Service	Composite	Alu.	-	V		IV		III		
54	RM In Service	CDB	SSL	-	V		V	V			
55	RM In Service	composite	Steel	-		II	III				

Roxel

Test results & key technology: Propellants

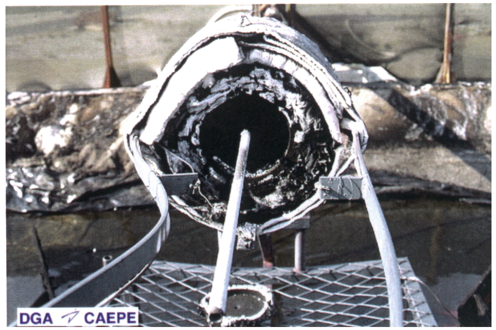
EDB, CDB, CMDB, and new XLDB & GAP propellants give:

- Type V or IV response for FH and SH
- Type V or IV response **with** adequate barrier or storage configuration for BI, FI and SR *[12, 47, 48]* but if **without** this configuration then Type I, II or III for FI, SR & SCJ *[2, 9, 21]* since they are more sensitive to intense shocks due to NG, explosive fillers and combustion instability suppressant content
  - *1% of refractories in some EDB & CDB propellants increase the FI SDT sensitivity by 500 m/s [9,10]*
- NG replaced by less sensitive Nitrate Ester leads to type V or No Reaction for BI *[17, 22,]*

[54] Type V FH, BI & FI (2530m/s): CDB with refractories

[21] Type IV BI : EDB

[21] Type I SCJ, SR: EDB

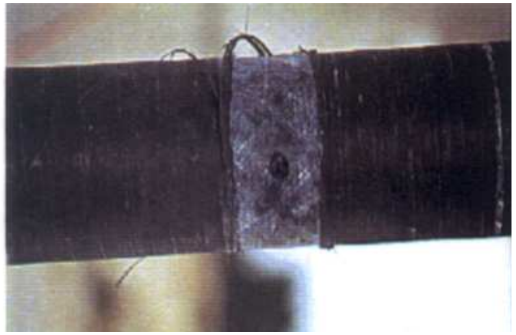


[17] Type V, NR: XLDB2

[47] Type V FH, BI, SR & FI (2530m/s): CDB no refractories

[21] Type IV SH : EDB

[22] NR GAP RDX KOA



[17] Type NR: XLDB2

Test results & key technology: Propellants

Composite HTPB propellants give:

- Type V & IV reaction for FH, BI and FI aggressions. Large motors, High Burning Rate propellant or a very strong case can lead to Type III reactions *[28,37,49,50,55]*
- Type I or II very violent reaction to SH aggression (without any Mitigation Devices) due to AP damage & bulk propellant exothermic reaction. Promising additives (at propellant level for SH) have not been effective in RM's *[38, 39, 42, 49, 55]*

Composite HTPE propellant give:

- Type V response in SH lab tests has not been successful when tested in RM *[26, 27]*

[14] Type V FH : COMP HTPB

[14] Type V BI : COMP HTPB

[51] Type IV FI 1754 m/s : COMP HTPB

[49] Type I SH : COMP HTPB

[27] Type III & NR HFI :COMP HTPE

[27] Type II SH : COMP HTPE

Test results & key technology: Cases

RM Case main function is to withstand internal pressure during RM operation.

- Case properties have a strong influence on the level of confinement and reaction violence for FH, BI, FI aggressions when EM is ignited, and a moderate influence on RM responses for SH, SR, SCJ aggressions *[28, 37, 49, 50]*
- Al, SSL, KOA, CFRP cases lose mechanical properties very quickly under FH & BI aggressions and commonly lead to venting upon ignition of propellant, which is able to burn benignly at atmospheric pressure giving Type V reactions or type IV in case of propulsion, ejections or overpressure for large motor *[3, 5,11,13, 23, 52, 53, 54, …]* .
- Weakened steel cases with an appropriate manufacturing process and grain design, lead to case rupture prior to ignition of propellant for FH *[51]*

[28] Type III FH : Steel

[23] Type V FH, BI : SSL

[51] Type V FH : Weakened Steel

[52] Type V FH : ALU

[19] Type V FH, BI : KOA

Test results & key technology: Mitigation devices

Several types of mitigation devices have been developed and tested

- Thermal barriers (Internal and/or external & membrane) delay the reaction and potentially control the case failure mode and decrease the response to a Type V for FH aggression. *[24, 25, 29]*
- PID and LTI initiate EM at a temperature lower than the threshold of thermal reaction for SH aggression and can improve the RM reaction from a Type I or II to a Type III or IV *[5, 20, 23, 27, 48, 50, 51].*
- Foam in the inner bore of the charge to avoid SDT or XDT for BI & FI *[38, 42].*
- LMA, SMA, and active venting systems have been tested at laboratory scale

2.75" SSL with PID:
SH Type V (BWB / WDT91 trial photo)

[24] Type V FH

Intumescent Paint expansion

Type of foam

[38, 42] Type V BI : Steel + Foam

[38, 42] Type V BI foam in bore

[5, ,20, 23, 27, 48, 50, 51] PID, LTI

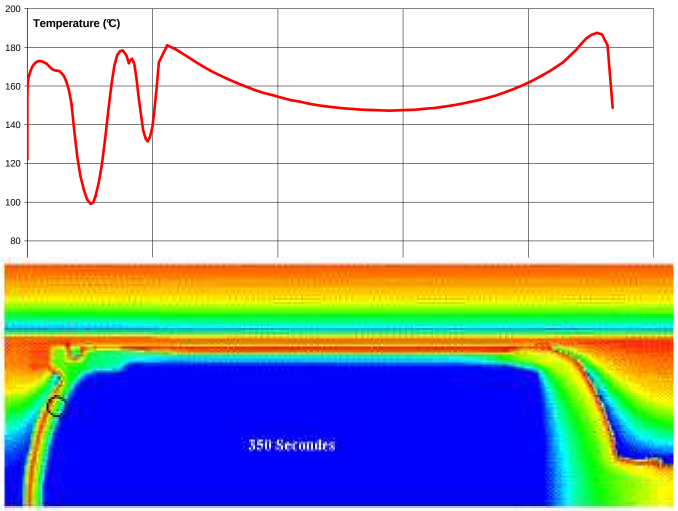
Test results & key technology: Modelling

Modelling of the IM phenomena is conducted for thermal aggressions, but still in preliminary studies for mechanical aggressions

- Will highlight problematic design features and further the design of IM mitigation technology *[19, 53]*
- Assist in IM trial instrumentation and results analysis (reaction time, temperature state of specimen)
- Requires reliable input data, sometimes difficult to obtain in order to conduct accurate state modelling of the stimuli:
    - Wind, fire, positioning within trial, clamps and fixings, mechanical characteristics, etc…

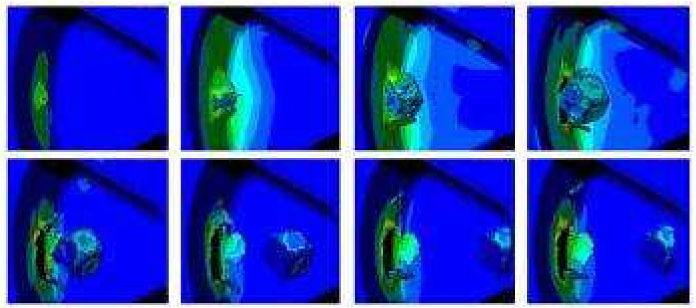
Challenging to predict the subsequent reaction effects

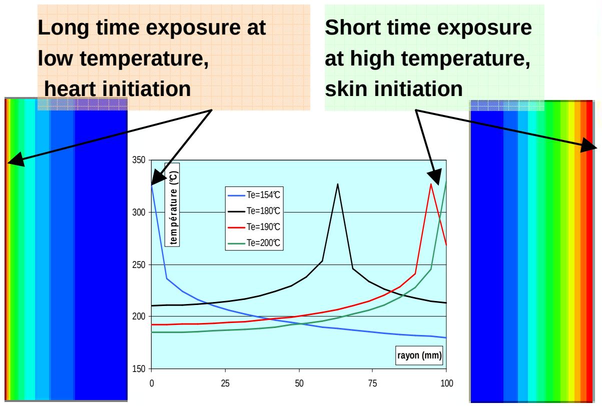
- EM state under aggression and initiation process, distance of inert and EM projections, overpressure levels, number of fragments, etc…



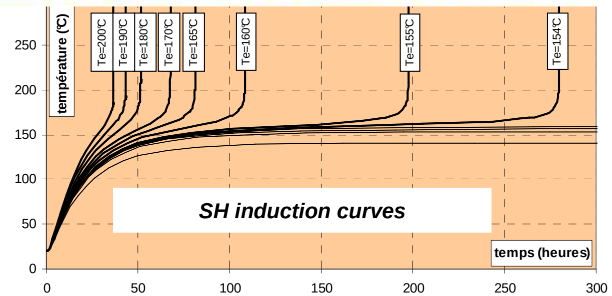
[19] ***Thermal insulation design to validate ignition point***

FI on a metallic case calculation





SH temperature calculation



Synthesis of key Roxel IM technology

- **Thermal threat: Fast Heat (FH) & Slow Heat (SH)**
  - Case technologies & venting devices to decrease and control burst effects (FH & SH)
  - Thermal barriers to delay reaction and possibly give orientation to a case failure (FH)
  - Pre-ignition of propellants at a temperature lower than the threshold of EM thermal reaction (SH)
  - PID or LTI combined to case venting technology could achieve the best IM response
  - Modelling and simulation of thermal state in RM (FH & SH)

- **Mechanical threats: Bullet Impact (BI) & Fragment Impact (FI) Sympathetic Reaction (SR) & Shape Charge Jet (SCJ)**
  - Less shock sensitive propellants: low Card Gap Test and High Velocity Shotgun result (> 600m.s^{-1}) and modified propellants (SH)
  - Appropriate storage barriers, case technologies to absorb impact energy & increase venting at EM reaction or disrupt effectively upon impact
  - Internal barrier, foam in the inner bore of the charge
  - Modelling and simulation of mechanical EM state in RM (BI & FI)

Challenges with RM IM response assessment

- During last 20 years IM tests have been conducted in various test centres (SNPE, DGA / CAEPE, UK MoD, and others) and are very often subject to discussions on tests conditions and results interpretation.

- IM trials are not perfect tests, they are very costly with low repeatability

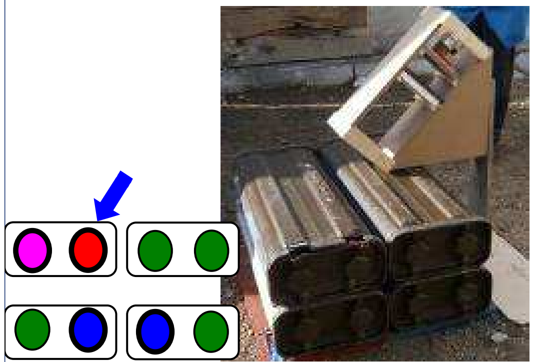
- Even if they are in accordance with STANAG and AOP, test's centre experience, safety requirements, measurements, and of course weather conditions can induce test variabilities.

- The analysis of test results and their interpretation can be subject to discussions giving opportunity to doubt about IM reaction type assessment

Influence of test conditions

Specimen positions: Distance above fire, Horizontal/Vertical, distance of donor acceptor, SR SCJ configurations

Fuel distance (cm)	30	40	50	60	70
T° (°C)	812	901	935	983	986





Attachments and fixings: Rigidity, dimensions of support, thrust safety devices

[51] Type V FH
CASE DEFORMATION IN SUPPORTS



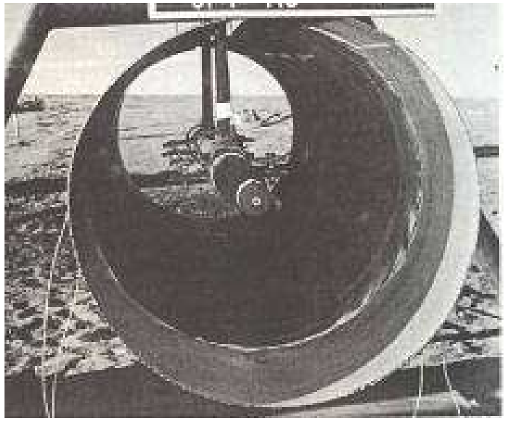
[52] Type V? FH
SUPPORT BROKEN and PROPELLANT EJECTION AT 15.2 M


Influence of test conditions

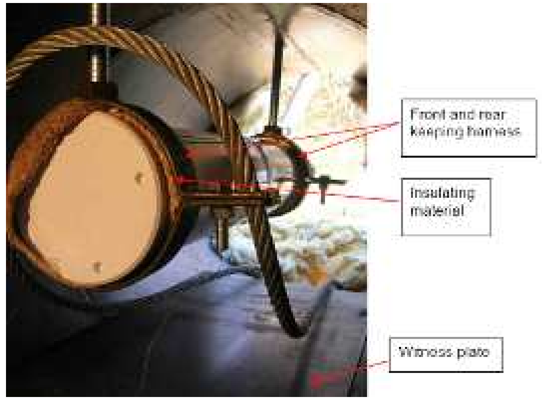
Cell characteristics: Confinement of specimen, protection against ejection & blast pressure

[49, 50, 51] SH HEAVY CELL

[20] SH LIGHT CELL



SH PROTECTION CELL



[21] SH PROTECTION CELL

[27] SH PROTECTION CELL

Weather conditions: Wind, temperature, rain

[14] WIND EFFECT

Influence of test conditions

Characteristics of aggression

- FH: Type & temperature of fuel (fuel, wood, gas)
- HFI: Fragment material, mass & shape (spherical or parallelipedic)
- BI, FI, HFI: Velocities difficult to reach accurately
- BI, FI, HFI: Choice of impact position not discussed
- SH: Heat rate, initial temperature (possibility of 100°C?)
- SCJ: Shape charge type specified in Stanag is not available

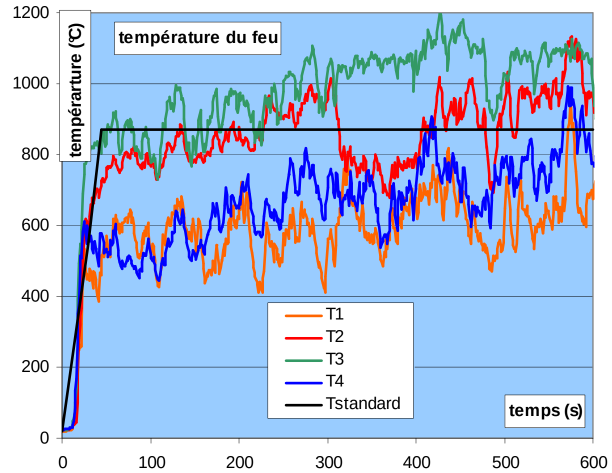
FH FUEL AND GAS AGGRESSION

Validity of a test non compliant with Stanag: No test?

- Temperature and delays, velocity, impact point, heat rate, measurements insufficient or not available
- A clear IM response (I to V) is not really possible for SR : the expected result is *"Transmission or No Transmission of Detonation"*. For example it does not seem possible to justify a Type V or IV reaction

IMPACT NOT COMPLIANT

ALTERNATIVE BLAST PRESSURE MEASUREMENT METHOD "CHALARD BOX"



TEMPERATURES NOT COMPLIANT

Measurement difficulties (blast pressure and video) for SH

Interpretation of test results

STANAG 4439 edition 2 and AOP-39 edition 2 give definitions, threats, IM requirements, test procedures and guidance for interpretation of responses

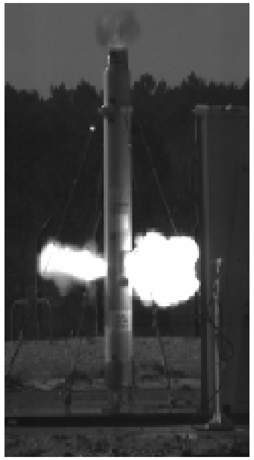
RESPONSE TYPE	MUNITION BEHAVIOUR		EFFECTS			
	ENERGETIC MATERIAL	CASE	BLAST	PROJECTION OF ENERGETIC MATERIALS	PROJECTION OF FRAGMENTS	OTHER
I	-Detonation -Supersonic decomposition reaction	-Very fast plastic deformation -Total fragmentation	-Intense shock wave -Damage to neighbouring structures	-All the materials react	-Perforation, plastic deformation or fragmentation of adjacent metal plates.	-Large craters in the ground.
II	-Partial detonation	-Partial fragmentation + large fragments	-Ditto	-Ditto	-Ditto	-Ditto -Proportional to % of detonating material
III	-Fast combustion of confined material (Explosion) -Local pressure build up	-Violent breaking into large fragments	-Blast effect < detonation -Damage to neighbouring structures -ΔP > 50 mbar at 15 m	-Scattering of burning materials -Risk of fire	-Long range projection -Damage to metal plates (breaks, rips, cuts)	-Small craters in the ground
IV	-Combustion/Deflagration -Non-violent pressure release	-Breaks but does not fragment into more than 3 parts -Expulsion of end caps -Gases release through opening	-Blast effect limited to ΔP < 50 mbar at 15 m	-Scattering of materials -Risk of fire	-Expulsion of end caps and large structural parts -No significant damage	-Damage caused by heat and smoke -Propulsion of unattached sample
V	-Combustion	-Split in a non-violent way -Smooth release of gases -Separation of ends	-Blast effect limited to ΔP < 50 mbar at 5 m	-Energetic materials remain nearby (< 15 m)	-Debris remains in place, except covers -No fragment of more than 79J or more than 150g beyond 15m	-Heat flow < 4 KW/m^2 at 15 m

Red = The key parameters subject to discussion during interpretation of test results

Interpretation of test results

Propulsion status changes a type V in Type IV reaction but:

- How is propulsion defined when you get 3 holes (BI or FI)? or measure an axial thrust during a HFI trial without any EM ignition
- Mil Std 2105 : *"A reaction whereby adequate force is produced to impart flight to the test item in its least restrained configuration"*
- French DGA instruction *"Réaction qui produit une force suffisante pour provoquer le départ de l'échantillon testé"*
- Test centres *"Displacement or gas flow through nozzle"*



[51] BI Type IV PROPULSION

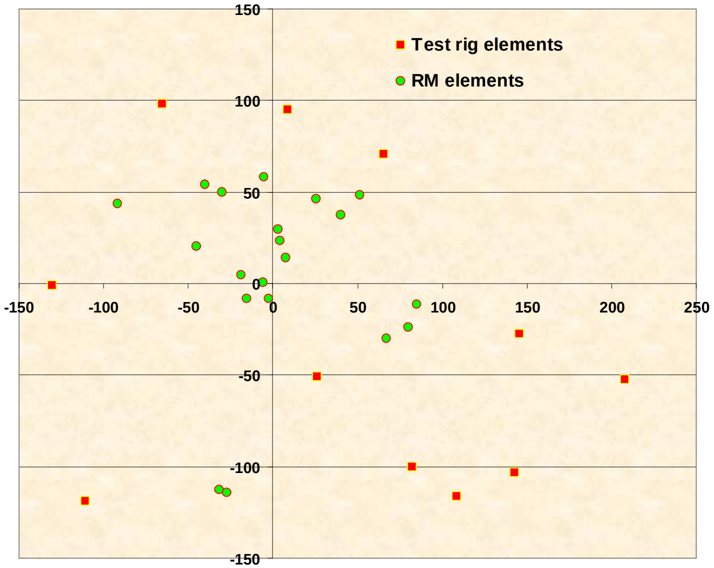
[27] Type IV ; BI PROPULSION NOT IN EVIDENCE SMALL FLOW OF GAS THROUGH NOZZLE

Interpretation of test results

Fragment and energetic material projection distances change a reaction from Type V to IV or III but

- Cartography of fragment position just used for distance (nb & origin, not lethality)
- Ejection of end caps, 3 parts (nozzle), and distance remains a problem for V, IV, III Types
- Origin (EM or Inert) of fragments and their energy is not always clearly identified (video evaluation)
- Scattering of material (risk of fire) is the same for Type III and IV reactions

[28] BI Type III



[27] SH Type II

[53] BI Type IV
(VIDEO DISTANCE EVALUATION OF PROPELLANT PIECES PROJECTIONS)

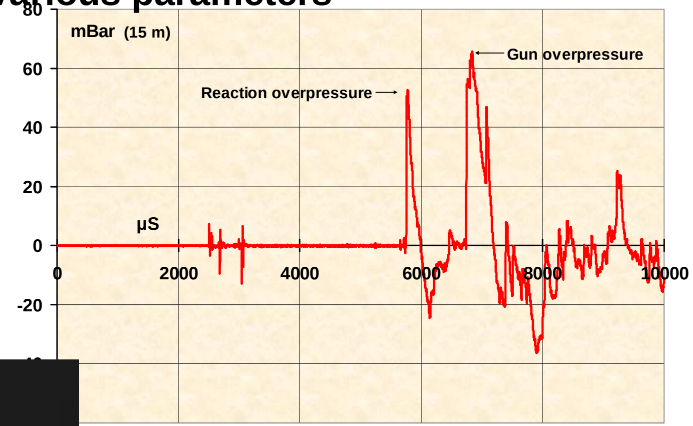
Interpretation of test results

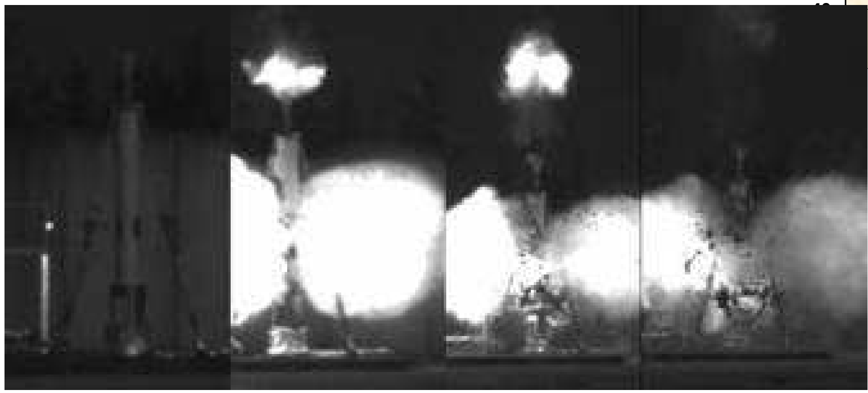
Blast pressure results and the measurement accuracy is influenced by various parameters

- Pressure gauge's positions and any directional or reflection effects
- Validity of threshold of 50 mbar at 5m and 15m

No Reaction statement for FI, HFI

- Analysis of a stopped reaction





[27] HFI : Type III OR STOPPED REACTION?

Fragment mass 252 g (sphere)
Fragment velocity 1813 m/s
Propellant stops burning immediately after impact
(More than 85% of the motor mass recovered)
No Propulsion ?
Several fragments
Overpressure 52 mbar at 15 m

↳ type III ?

TNT equivalent calculation method not specified

- Based on explosive pressure effect
- With TNT % equivalent interpretation for a partial detonation result of EM !

Heat flux never measured and used

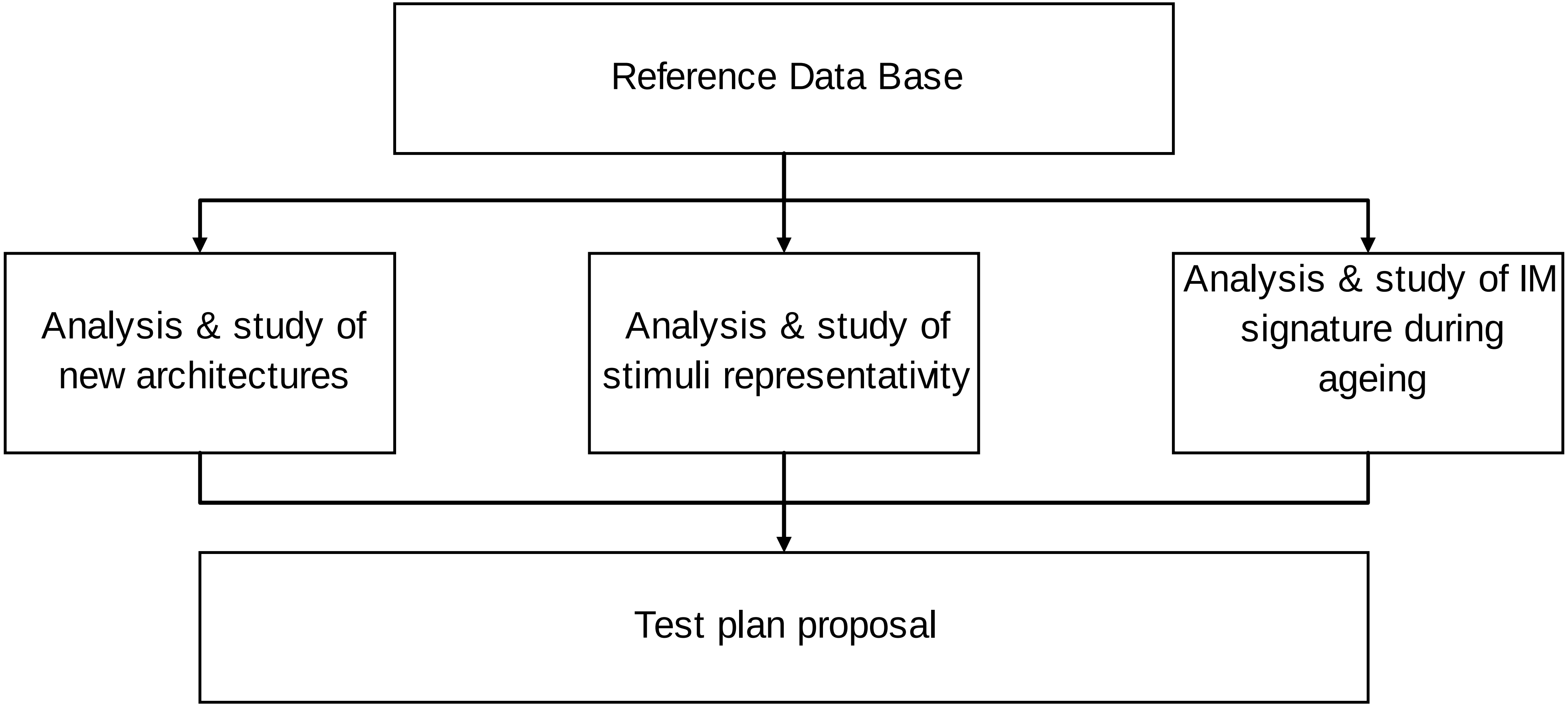
IM RM response assessment conclusions

- Test conditions and interpretation should not lead to discussions
- An IM RM response assessment should always be referenced to an accessible test report which must be seriously analysed even in the case of "no-test" situation.
- To reach an homogeneous and coherent IM response assessment then it seems necessary to ask for an "Expert Committee", able to state independently on the validity of test conditions, and propose the RM IM signature.
- RM should not be considered alone but at the munition level. For example the missile system's reaction of a RM can be changed by the warhead reaction or its configuration standard e.g. packaged system.
- It seems necessary to update STANAG & AOP39 procedures and tables of classification.

IM technologies gap, new research areas

- Case technology able to create sufficient venting in response to the SH stimulus.
- Improvement of passive PDI & LTI operation reliability.
- Development of acceptable active venting systems for FH & SH in field of smart RM.
- Development of generic, retrofittable, reusable concepts.
- Individual technologies providing full IM mitigation for a multitude of systems.
- Low cost composites cases.
- SCJ IM mitigation.
- Improvement of IM modelling response severity predictive capability.
- Investigate propellants IM ageing on IM response.
- Characterise FI IM response to rocket motor design to develop designer tool.

French MOD IM ARP “APTE” logic



Roxel

French MOD IM ARP "APTE'' test plan

Proposed ARP test plan 3 years work

PROGRAMME	TYPE		CASE				PROPELLANT		MITIGATION DEVICE						IM TEST							
DESIGNATION	**RM**	**Demonstrator**	**Steel**	**TBD**	**Composite**	**SSL**	**High Burning Rate HTPB**	**GAP & NEPE**	**Igniter**	**Membrane**	**Foam in bore**	**Weakness**	**Intumescent Paint**	**New**	**SH**	**SH* Heat rate**	**FH**	**BI**	**BI* Velocity & caliber**	**HFI**	**LFI**	**SCJ**
Ageing Effect	X														X		X	X			X	X
HBR & RM Temperature	X				X		X		X						X		X	X				
New Stimuli	X				X		X		X							X			X		X	X
New Technology	X		X	X			X		X					X	X		X	X				
New Propellant	X		X	X				X							X		X	X		X		
Representativity SCJ		X	X				X	X														X
Representativity FH		X	X				Inert										X					

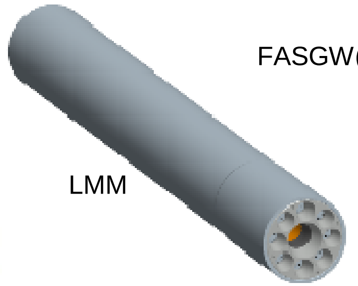
IM UK programmes

- Team Complex Weapons in the UK will require IM new products Loitering Munition (LM), Lightweight Multi-role Missile (LMM), Common Anti-air Modular Missile (CAMM), 50A and Future Air-to-Surface Guided Weapon (Heavy) (FASGW(H))
  - Low cost rocket motor
  - Roxel to address IM technology gaps

LM

CAMM

50A



LMM

FASGW(H) Sustain

FASGW(H) Boost

- Mechanical IM threats
  - UK-Energetics research programme (Foam bore)
  - FI mitigation techniques

- Thermal IM threats
  - Continuing the recent successful SH IM results (IM Python, IM RRPR, IM HVM, IM Brimstone)
  - Joint Anglo-French programme developing a low cost 2.75-inch IM solution

IM mitigation technology: is it an expensive addition?

Customers recognised that IM is a critical requirement. But IM products must be produced at a low cost - Roxel is continuing to develop its low cost IM design methodology.

1. Technology level:

- Current high performing solutions with low cost variants
- Current design features rather than proposing costly replacement solution
  - Roxel's bonded patch technology
  - Future IM technology developed to mitigate a number of IM threats through a single product or design
    - Proposed complete thermal and mechanical IM mitigation.

2. Rocket motor level:

- At component level understanding of the successful IM results previously obtained
  - Through modelling and sub-scale testing
  - Without adding extra mitigation devices as example, the excellent 2530 ms^{-1} FI response for JCM and Python

IM Low Cost Design Methodology

3. System level:

- THA to identify the most probable and critical system configuration and target **ONLY** this level to reduce the IM insertion costs to one product
- Establish the whole life costs according to a specified IM level
  - Additional costs & possible financial savings analyse ACB IMEMG or CBAM MSIAC softwares
- Produce technology which mitigates a number of munitions at once or a whole magazine

4. Productionisation level:

- Productionisation can be applied at any of the above levels to reduce the overall IM insertion costs
  - For example – a slight modification to the manufacturing tooling to improve the IM capability of a steel case with no additional recurring costs
    - IM improvement from a Type I to III

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Conclusion

- **IM rocket motor technology has progressed significantly** due to numerous tests and programmes funded over the last 20 years either by MOD's, missile primes and by Roxel's self funded research.

- However, a technology gap still remains:
  - **SH mitigation devices/cases and LTI & PDI reliability**
  - **FI, SR & SCJ behaviour**
  - **Ageing influence**
- STANAG and AOP need to be updated and improved:
  - IM signature sometimes difficult to establish due to test conditions and interpretation
- New programmes are in progress to improve knowledge and low cost technology.
- **Low cost IM solutions are the present challenge for the future.**

Acknowledgements & Questions

member of

Any Questions ?

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