A scientific review of the current state of IM mitigation devices for use with rocket motor systems and the future development outlook

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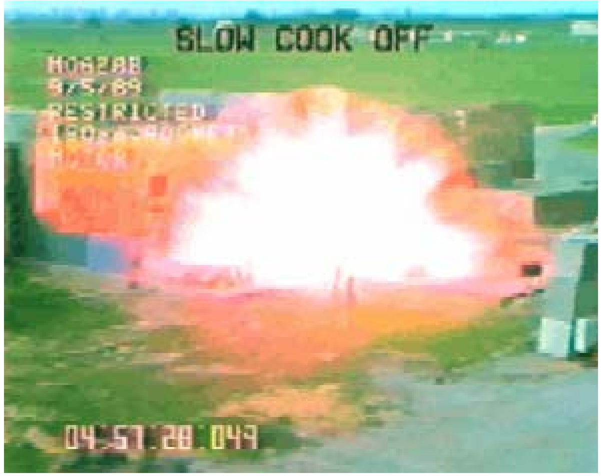
Roxel

Propulsion systems

Introduction

- As a system's IM response signature is becoming an increasingly important customer requirement the question remains as to what extent full IM compliance can be achieved



- No in-service RM design is fully IM compliant

- Some recent technical developments have closed gap
  - JCM, SLIM, amongst others

- Over many years mitigation technologies have been integrated into propulsion system designs

- The aim of this presentation is to present a review of the current state-of-the-art of IM mitigation technology (MT)
  - Including Roxel examples
  - Recommend areas and level of future development work

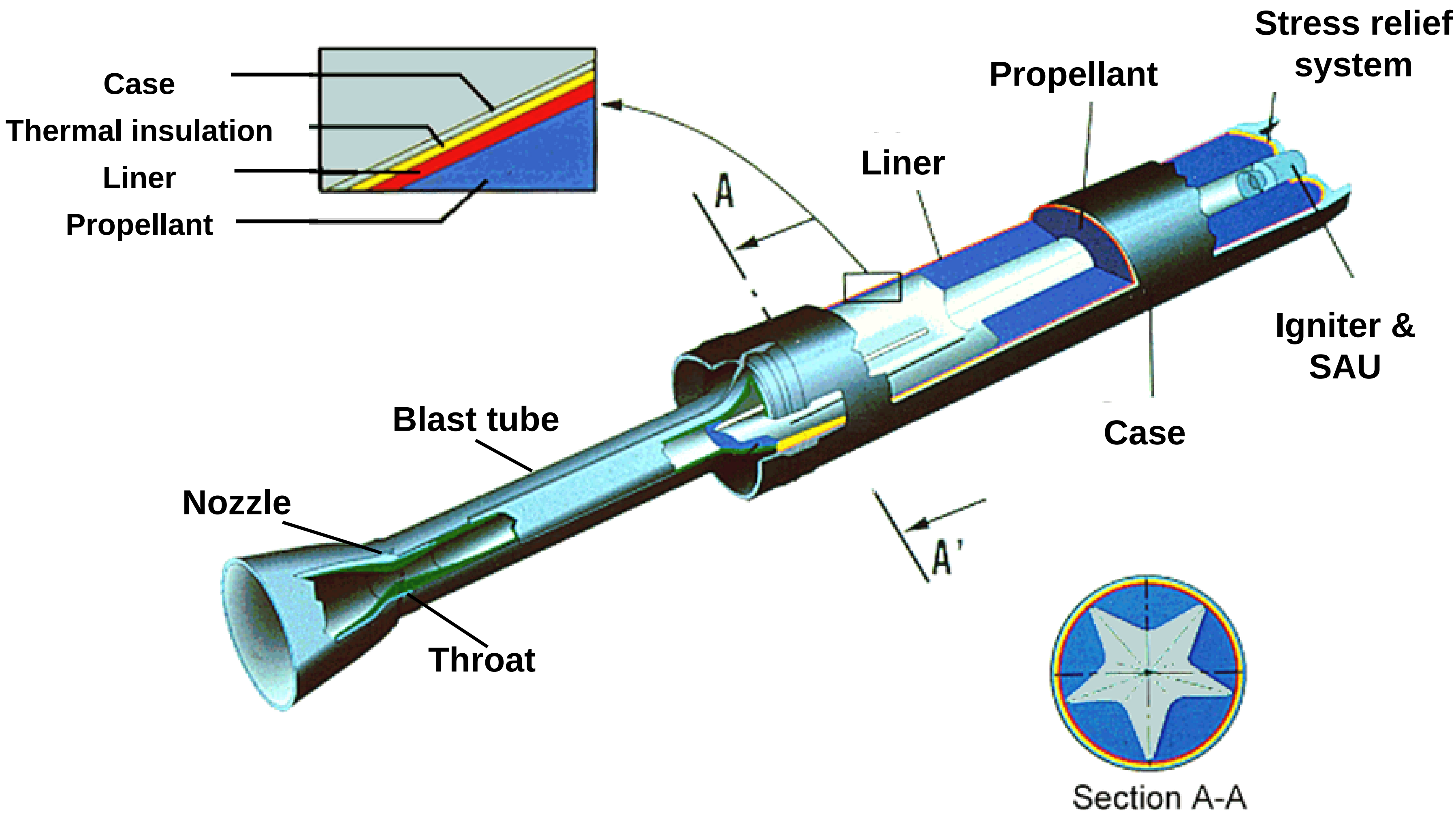
Documentation Background

- 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

Guidance on Interpretation of IM Response in AOP-39 (Annex I)

Propulsion System Overview



Current IM RM Design Methodology

- **Thermal threat: Fast Heat (FH) & Slow Heat (SH)**
  - Thermal barriers to delay reaction and possibly give orientation to a case failure (FH)
  - Venting devices, case technologies to decrease and control burst effects (FH & SH)
  - Pre-ignition of propellants at a temperature lower than the threshold of thermal decomposition (SH)
  - Modified propellants (SH)

- **Mechanical threats: Bullet Impact (BI) & Fragment Impact (FI)**
  - Less shock sensitive propellants (low card gap test and high velocity (> 600m.s^{-1}) shot gun test results)
  - External barriers, case technologies to absorb impact energy & increase venting at EM reaction or disrupt effectively upon impact (e.g. SSL)
  - Internal barrier, foam in the inner bore of the charge

- **Detonation threats: Sympathetic Reaction (SR) & Shape Charge Jet (SCJ)**
  - Less shock sensitive propellants
  - Appropriate storage barriers

IM Mitigation Review – Performance Criteria

Parameter Assessment Key	*Below desired reqs.*	*Close to desired reqs.*	*Meeting desired reqs.*
Type of device/technique	Active	N/A	Passive
Expected achievable IM response	< III	IV	V
Trial result attained	< III	IV	V
Requires combination of IM technology?	Y	N/A	N
No. of threats mitigated	1	2	>3
Maturity of device (TRL ranking)	1 - 3	4 - 6	7 - 9
Power demand for operation	H or M	L	Zero
Complexity level	H	M	L
Mass level	H	M	L
Technical risk level	H	M	L
Reliability level	L	M	H
IM ageing behaviour effect	H or M	L	Zero
Development cost level	H	M	L
Recurrent cost level	H	M	L
High or low pressure venting	H	N/A	L
Multi-directional or longitudinal venting	L	N/A	M
Pre-emption of reaction	H	M	L or Zero
Ease of Retrofittable	L	M	H
Generic design level	L	M	H
Reusable?	N	N/A	Y
No. of systems mitigated per device	1	2 - 5	> 5

- **Active systems** rely on the initiation of an energetic device to cut open the case or create sufficient weakness to allow a relatively benign separation at a certain pressure
- **Passive systems** rely on chemical or physical changes within specific materials to allow the creation of vent holes or the benign expulsion of end plates / closures

- **Low pressure**: A vent pre-prepared before propellant ignition that offers negligible resistance to the onset of attempted pressurisation after an IM stimulus
- **High pressure**: A vent, which is a region of deliberate weakness created prior to propellant ignition, that furthermore requires significant pressure to create full venting relief after an IM stimulus

IM Mitigation Review – Results

Type	Description	Ref.	Mechanism	Applications / Location	IM Threat Mitigation Criteria Compliance Evaluation (%)						Roxel Technology Experience
					FH	SH	BI	FI	SR	SCJ	
Pre-ignition	Pre-emptive device	[16]	Initiate the igniter pre-empting propellant reaching auto-ignition temperature	Internal	N/A	79%	N/A	N/A	N/A	N/A	Tested
	Low Temp. Igniter	[25]	Ignites propellant before main propellant reaches auto-ignition temperature		N/A	70%	N/A	N/A	N/A	N/A	Tested
Venting	SMA disengaging thread	[22]	Material properties intiate release of the closure retention	Within end closure	71%	65%	N/A	N/A	N/A	N/A	Studies
	SMA disengaging end ring	[27]			71%	60%	N/A	N/A	N/A	N/A	Studies
	LMA thread insert				62%	54%	N/A	N/A	N/A	N/A	Concept
	LMA locking wire				65%	57%	N/A	N/A	N/A	N/A	Concept
	LMA helix	[19]			63%	56%	N/A	N/A	N/A	N/A	-
	LMA disengaging end ring	[18]			60%	52%	N/A	N/A	N/A	N/A	-
	SMA buckle bars	[22]	Material properties intiate disruption of the case	Externally attached to case	79%	73%	N/A	N/A	N/A	N/A	Studies
	SMA cutter	[22]			76%	70%	N/A	N/A	N/A	N/A	Studies
	LMA case slots	[15]	Material properties of slots melt at set temperature	Within case structure	67%	59%	N/A	N/A	N/A	N/A	-
	Case patch		Resin material properties weakened/destroyed with temperature	Externally attached to case	73%	63%	N/A	N/A	N/A	N/A	Studies
	Closure resin weakening	[21]		Within end closure	70%	59%	N/A	N/A	N/A	N/A	Concept
	Shear closure	[24]	Material properties fail under extreme pressurisation		70%	68%	70%	N/A	N/A	N/A	Tested
	Stress grooves	[25]	Allows case to fail along thinner regions upon pressurisation	Within case structure	84%	75%	81%	78%	N/A	N/A	Tested
	Intumescent paint (partial cover)	[25]	Preferential failure along region of no paint	Externally applied to case	81%	N/A	N/A	N/A	N/A	N/A	Tested
	Internal insulation	[25]	To delay response	Internal	81%	N/A	N/A	N/A	N/A	N/A	Tested
	Case cutter	[29]	Thermal detection initiates detonation cord to disrupt case	Externally attached to case	67%	N/A	N/A	N/A	N/A	N/A	-
	TIVS device	[20]			68%	N/A	N/A	N/A	N/A	N/A	-
	Thermite patches	[17]	Exothermic reaction weakens case and ignites propellant	Internal or external	59%	59%	N/A	N/A	N/A	N/A	-
Case	Aluminium case	[7]	Lose mechanical strength with temperature and disupts effectively with impact threats	Casing	89%	N/A	89%	86%	83%	N/A	Tested
	SSL case	[7]			89%	N/A	89%	86%	83%	N/A	Tested
	KOA (no resin) case	[7]			89%	N/A	89%	83%	83%	N/A	Tested
	Composite case	[26]			87%	N/A	87%	84%	81%	N/A	Tested
	Hybrid aluminium/kevlar case (with resin)	[25]			89%	N/A	89%	83%	83%	N/A	Tested
	Hybrid steel/carbon slotted case (with resin)	[25]			87%	N/A	87%	81%	81%	N/A	Tested
Barrier	External impact protection	[14]	Reduces impact energy	External	86%	N/A	86%	86%	86%	79%	-
	Bore foam	[30]	Reduce propellant impact debris energy	Internal	N/A	N/A	82%	79%	N/A	N/A	Studies
Energetic material	Propellant (All types)	[1,4,7, 9,14]	Reduced sensitivity, decreased card gap, reduced reaction violence (avoiding XDT / DDT / SDT)	Internal	79%	79%	79%	79%	79%	72%	Tested

Values are extracted from Roxel's assessment of each MT evaluation (individual results beyond scope for discussion) against the performance criteria discussed previously

Roxel's IM Mitigation Technology Experience 1

- Roxel has an excellent pedigree with IM RM designs
  - ASRAAM RM is currently highest IM rating solid RM in service with UK MoD

  - Pioneers IM mitigation technology:
    - Manufacture of SSL cases
    - Pre-ignition SH mitigation device
    - Case grooves
    - Low temperature igniter
    - KOA and aluminium cases with GAP RDX propellant
    - Many more…

Response of a Alu. case to a BI IM trial

Response of a Composite case to a BI IM trial

Roxel's ASRAAM RM

Response of a KOA case to a BI IM trial

Response of a SSL case to a BI IM trial

Roxel's IM Mitigation Technology Experience 2

- Selection of Roxel's IM RM signatures:

Status	Technology Description				IM Characteristic of rocket motor (tested)					
	Calibre (mm)	Propellant	Case	Add. IM Technology	FH	SH	BI	FI	SR	SCJ
Qualification	128	Composite	Alu.	-	V		V			
Tech. Demonstrator	150	Composite	KOA	LT Igniter	V	IV				
In Service	160	Composite	Steel	Intumescent paint	V					
In Service	227	Composite	Steel	-	III	I				
Tech. Demonstrator	227	Composite	Steel 1	Grooves, LT igniter	III	III				
Tech. Demonstrator	227	Composite	Steel 2	Grooves, LT igniter	V	III	IV	IV		
Qualification	235	Composite	Alu.	LT Igniter	V		IV			
Qualification	150	CMDB	KOA	-	V		V			
Tech. Demonstrator	140	XLDB	KOA	-	V		N/R			
In Service	136	CDB	KOA	-	V		V			
Tech. Demonstrator	136	EDB	KOA	-	V		N/R			
Qualification	150	CDB	KOA	-	V		V			
Tech. Demonstrator	150	GAP Comp.	KOA	-	V		N/R			
Development	240	Composite	Alu.	-	V		IV			
In Service	70	EDB	Alu.	-	V	III	V	I		
Tech. Demonstrator	70	EDB	SSL	-	V	III	V	I		
In Service	70	EDB	Alu.	-	V	III	V		<III	
Tech. Demonstrator	70	EDB	SSL	-	V	V	V	II		
In Service	70	EDB	Alu.	-	V	V	N/R		I	
In Service	70	EDB	Alu.	In container	V	IV			<III	
Tech. Demonstrator	70	EDB	Alu.	-	V	V	V	N/R	<III	
In Service	127	EMCDB	SSL	-	V		V			
In Service	124	EDB	KOA	-	IV	IV	IV		V	IV
In Service	114	CDB	KOA	-	IV	III	IV		III	I
Tech. Demonstrator	180	CDB	CFRP	-	V		V	V	V	
Tech. Demonstrator	180	EMCDB	SSL	PID, shear closure	V	V	V	V	V	
In Service	160	Composite	SSL	LT Igniter	V	IV	V			

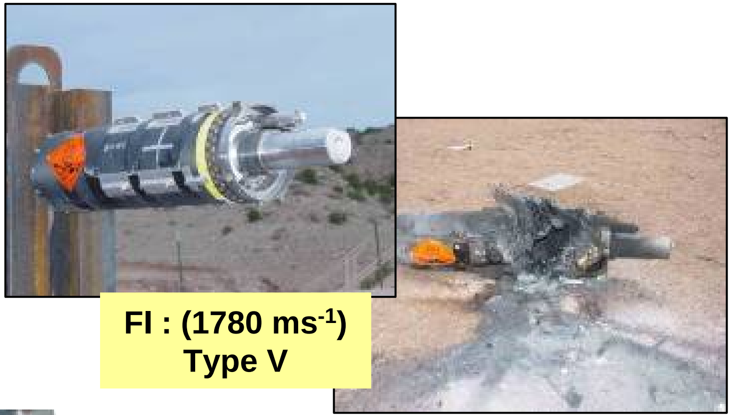
Roxel's IM Mitigation Technology Experience 3

SH : Type V

SLIM: SSL case, EMCDB propellant, pre-ignition SH mitigation device

BI : Type V

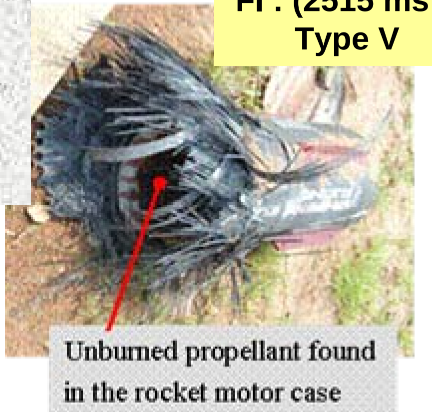
FI : (1948 ms^{-1}) Type V



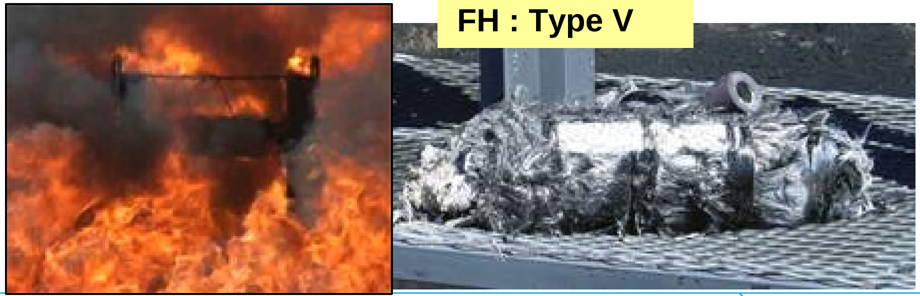
FI : (1780 ms^{-1}) Type V

JCM: composite case, CDB propellant

SR : Type V

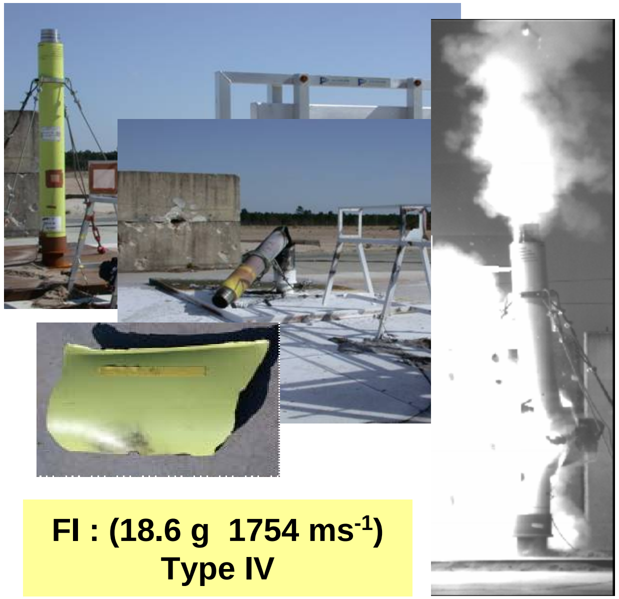


FI : (2515 ms^{-1}) Type V

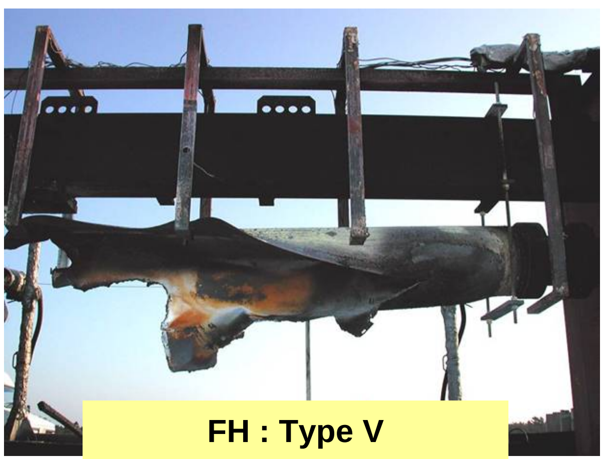


FH : Type V

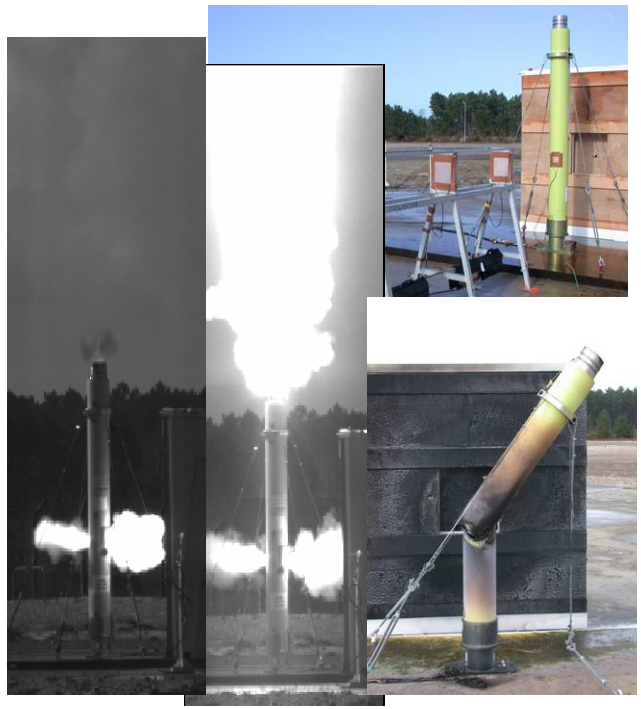
Steel case with grooves
Internal thermal protection
Low temperature igniter



FI : (18.6 g 1754 ms^{-1})
Type IV



FH : Type V



BI : (12.7 mm 857ms^{-1})
Type IV

SH : Type III

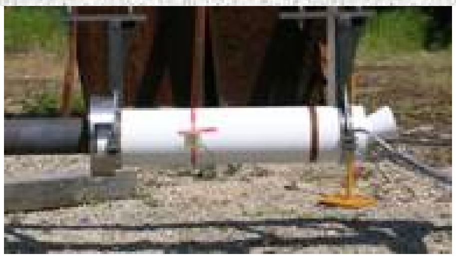
Roxel's IM Mitigation Technology Experience 5

Aluminium case 128 mm
HTPB HBR Propellant grain

BI : (12.7 mm 860 ms^{-1})
Type V

FH :Type V

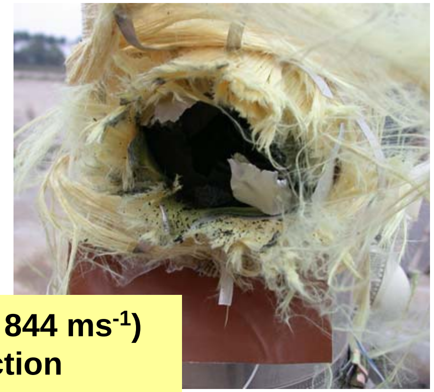
Aluminium case 235mm
HTPB HBR Propellant grain



BI : Type IV reaction
Due to overpressure at
15 m (12.7 mm 857 ms^{-1})

Hybrid case Motor (KOA) 150 mm
GAP RDX Propellant grain

FH :Type V at 240 s



BI : (12.7 mm 844 ms^{-1})
No Reaction

IM Technology Future Development Evaluation 1

Parameter	RM Venting					Pre-ignition	Case	Barrier	Energetic Material	Overall
	FH	SH	BI	FI	Overall					
Type of device/technique	L	L	L	L	L	L	L	L	L	L
Expected achievable IM response	L	M	H	H	M	M	L	L	L	L
Trial result attained	M	H	H	H	H	H	M	L	L	M
Requires combination of IM technology?	L	H	L	H	M	H	M	H	H	H
No. of threats mitigated	H	H	L	L	M	H	L	L	L	L
Maturity of device	M	H	L	L	M	L	L	L	L	L
Power demand for operation	L	L	L	L	L	L	L	L	L	L
Complexity level	M	M	M	L	M	L	L	L	L	L
Mass level	M	M	L	L	L	L	L	H	L	L
Technical risk level	H	H	M	L	M	M	L	L	L	L
Reliability level	M	H	H	H	H	M	L	L	L	L
IM ageing behaviour effect	M	M	L	L	L	M	L	L	H	L
Development cost level	H	H	H	H	H	L	H	H	L	M
Recurrent cost level	L	L	L	L	L	L	L	H	L	L
High or low pressure venting	M	M	H	H	H	N/A	L	N/A	N/A	M
Multi-directional or longitudinal venting	M	M	M	L	M	N/A	L	N/A	N/A	L
Pre-emption of reaction	L	H	L	L	L	H	L	L	L	L
Ease of Retrofittable	M	H	M	L	M	H	H	L	H	H
Generic design level	H	H	H	H	H	M	H	L	H	H
Reusable?	H	H	H	H	H	H	H	L	H	H
No. of systems mitigated per device	H	H	H	H	H	H	H	H	H	H
No. Reviewed	18	14	2	1	18	2	6	2	1	29

Summarised Overview of IM Mitigation Technology Performance Review Evaluating Areas and Levels of Future Development

Key for areas and level of future development

Requiring a high level of improvement	H
Requiring a medium level of improvement	M
Requiring a low level of improvement	L

IM Technology Future Development Evaluation 2

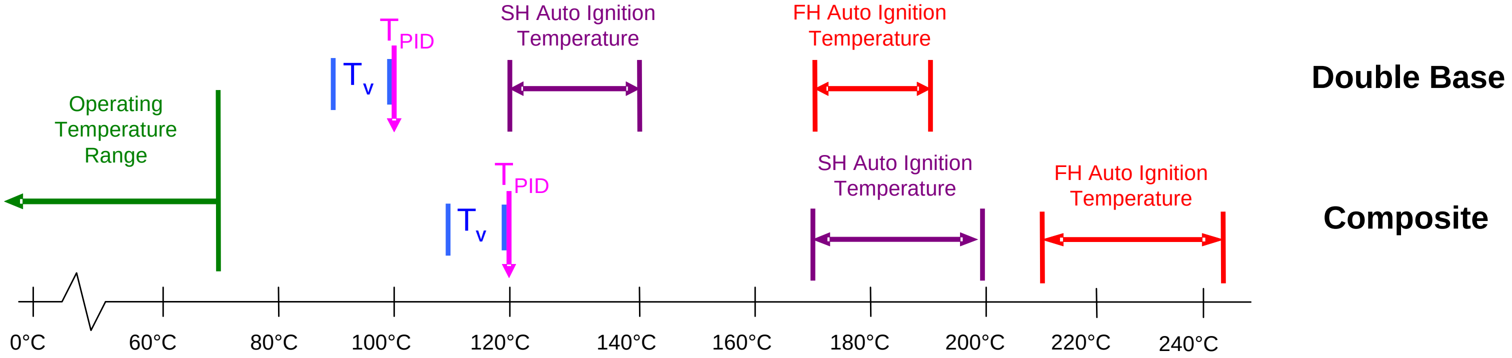
- General
  - Development of more generic, retrofittable, reusable designs
  - Single technologies mitigating full IM threat spectrum
  - Technology that can mitigate a multitude of systems at once

Courtesy of MBDA

- Barrier technology
  - More lightweight, low cost protective barrier solutions which mitigate a group of systems
  - Disruption fields
  - RM barrier technology
    - Flexible, lightweight and extremely high energy absorbing materials
  - Thermal protective barrier
  - Develop complete thermal and mechanical protective barrier on demand
    - Expulsion of a rapidly expandable material

IM Technology Future Development Evaluation 3

- Pre-ignition / pre-emptive technology
  - Conduct more IM trials testing the current state of the art
  - Reduce the pre-emptive qualities
    - Closer to auto-ignition temperature – may result in an increase in subsequent reaction violence



SH and FH Typical Response Temperatures

  - Investigate non-ignition techniques; substance which provides, for example:
    - A counteractive cooling element to thermal threats
    - Or renders EM inactive
    - Or ballistically modifies pressure / burn rate relationship
      - Subsequent ignition has a reduced gas generation flux or extinguishes propellant

IM Technology Future Development Evaluation 4

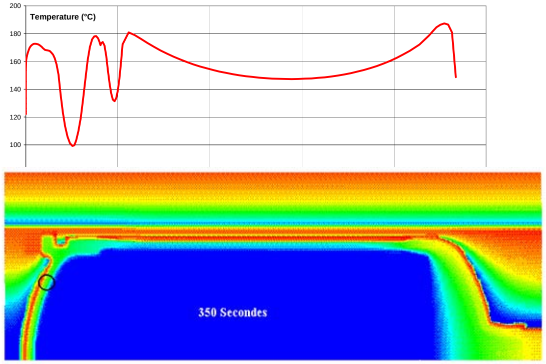
- Case technology
  - Ability to create venting under SH stimulus, for example:
    - Weaken structurally under the SH stimulus conditions
    - Or transfer SH response to a FH
  - Develop low cost IM cases

- RM Venting technology
  - Greatest responsibilities with SH IM mitigation
  - Maturity or demonstrated successfulness of these technologies lacking
    - Require more full scale IM testing of current / newly developed low pressure designs within a RM
  - Incorporate pre-ignition elements

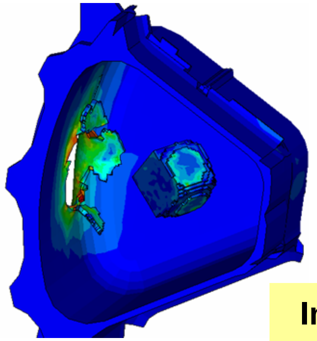
- EM Technology
  - Investigate propellant IM ageing effects and develop combative techniques or eliminate any deterioration

IM Modelling Evaluation

- Modelling of the IM phenomena and prediction of the subsequent reaction effects:
  - Will highlight problematic design features and further the design of IM mitigation technology
  - Assist in IM trial instrumentation and analysis
  - Requires reliable input data which is sometimes difficult to obtain in order to conduct accurate state modelling of the stimuli
    - e.g. wind, fire, positioning within trial, clamps and fixings, etc…
  - Challenging to predict the real reaction effects
    - e.g. distance of inert and EM projections, overpressure levels, number of fragments, etc…



FH modelling



Impact modelling

Modelling technique	**FH**	**SH**	**BI**	**FI**	**SR**	**SCJ**
Model of state	L	L	L	M	M	H
Prediction of severity of response	M	H	M	H	M	H

Areas and Level of Future Development for IM Prediction Modelling for the Propulsion System

Conclusion

- No in-service RM system is currently fully IM compliant
- Reviewed broad range of technologies providing mitigation across the IM threat stimuli
  - Emphasis on propulsion system aspects
- Facilitated subsequent recommendations for required areas and level of future research and development
  - Case technology able to create sufficient venting in response to the SH stimulus
  - Development of generic, retrofittable, reusable designs
  - Improvement of IM modelling response severity predictive capability
  - Individual technologies providing full IM mitigation and/or for a multitude of systems
  - SCJ IM mitigation
- Implementation and success of some or all of these improvements would considerably advance the capability for achieving fully IM compliant propulsion systems

Any Questions ?

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