IM warheads & rocket motors for tactical missiles: progress to date, future opportunities & challenges

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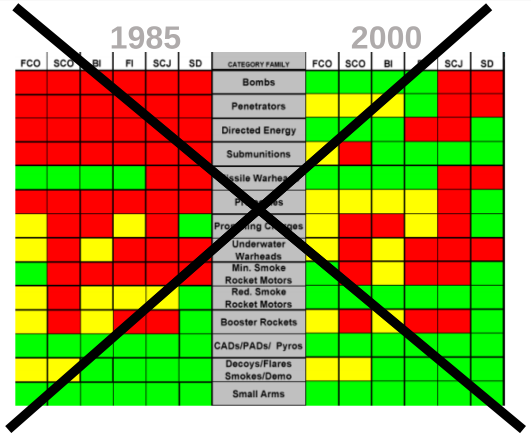
EMIMT Symposium, Sevilla, 21-24th October 2019

Abstract # 22168

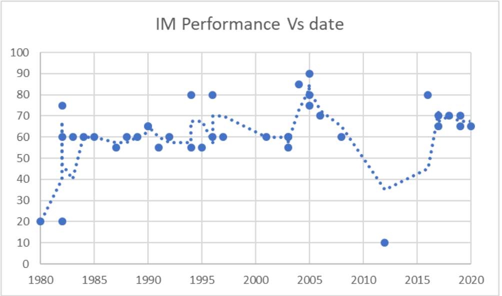
Issue 1d

1. IM status, costs & the route to IM

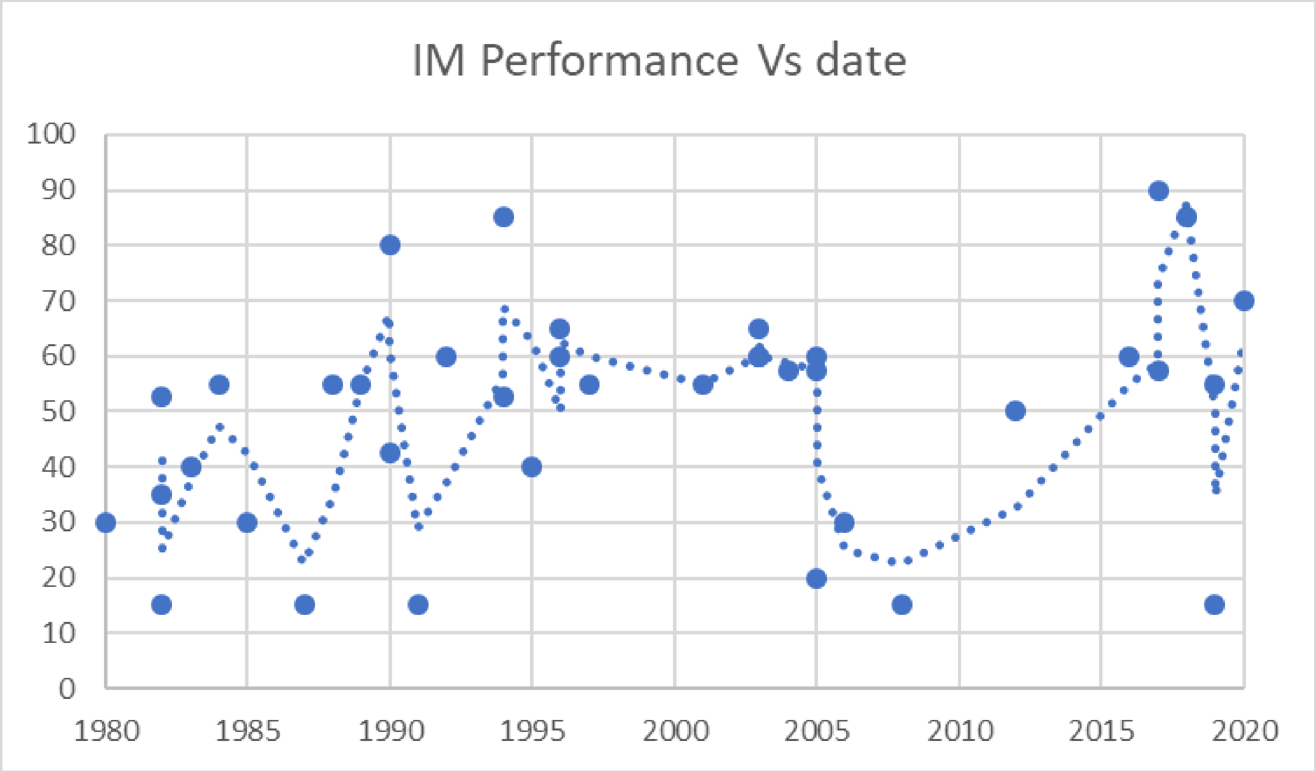
- Data is presented for IM ratings of SRM's & w/h's
- Focus is on what has been achieved for missiles & upgrades; the Start of the Art is presented subsequently
- The data is based on US, French, & UK tactical missiles with significant production since 1980 (most but not all such missiles)
  - 39 missiles & a further 6 variants
    - Six sectors but Ground to Air & Air-to-Air dominate
- Accompanying paper describes the methodology for establishing
  - IM Performance Indicator (PI) rating
  - IM score weighted, (IM_w) to take account of the number of each missiles in service with their Net Explosive Quantity (NEQ)
- Spend on IM, the steps to introduce it & the durations, to the Out of Service Date (OSD), are also considered



Aim in this section is to illustrate actual inventory status/evolution rather than best in class



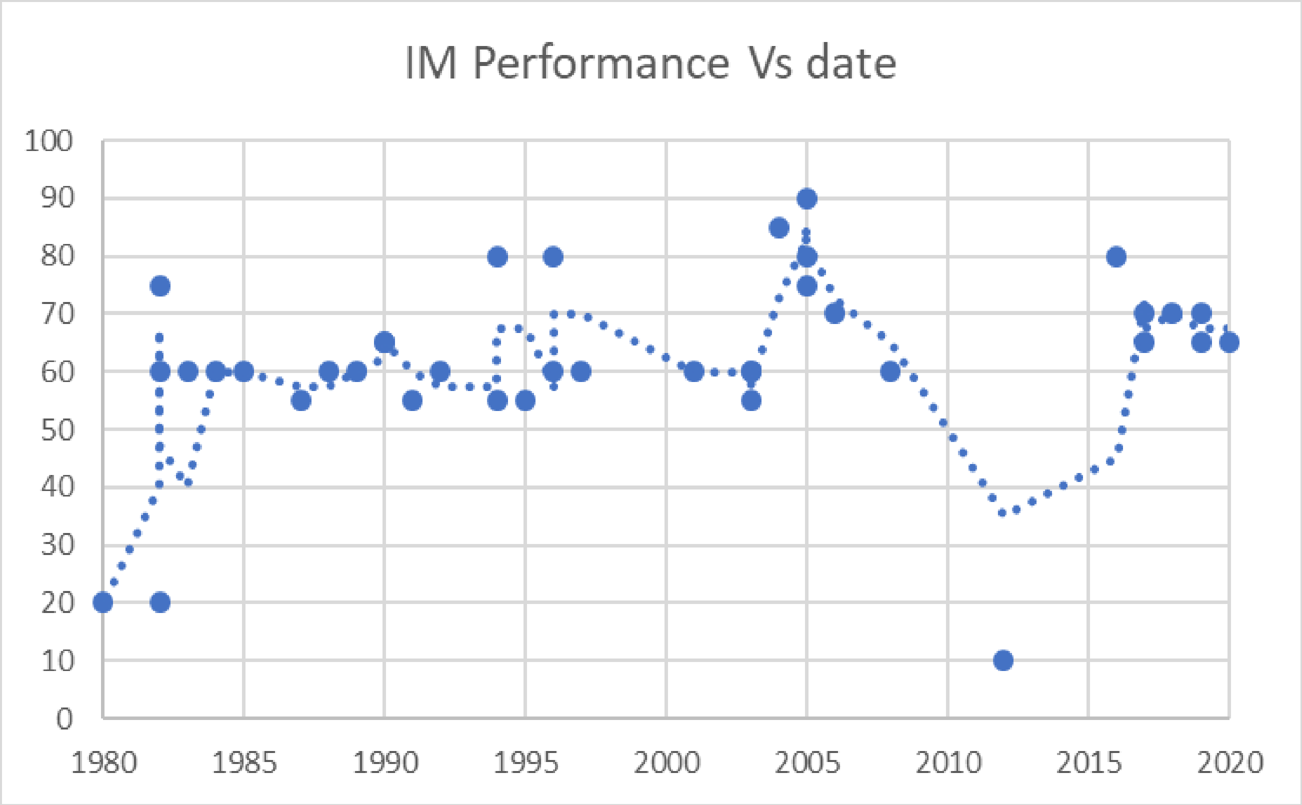
IM rating as missiles enter service: SRM's*



- From 1980, there has been a general increase in IM performance but a few missiles with poor IM motors continue to enter service, e.g.
  - JAGM, with Hellfire motor (2019)
- Some very high IM ratings, e.g. Brimstone2, VT1, etc
- Note: some deployed weapons may have better IM results due to packaging, missile containers, etc (applies to w/h also)

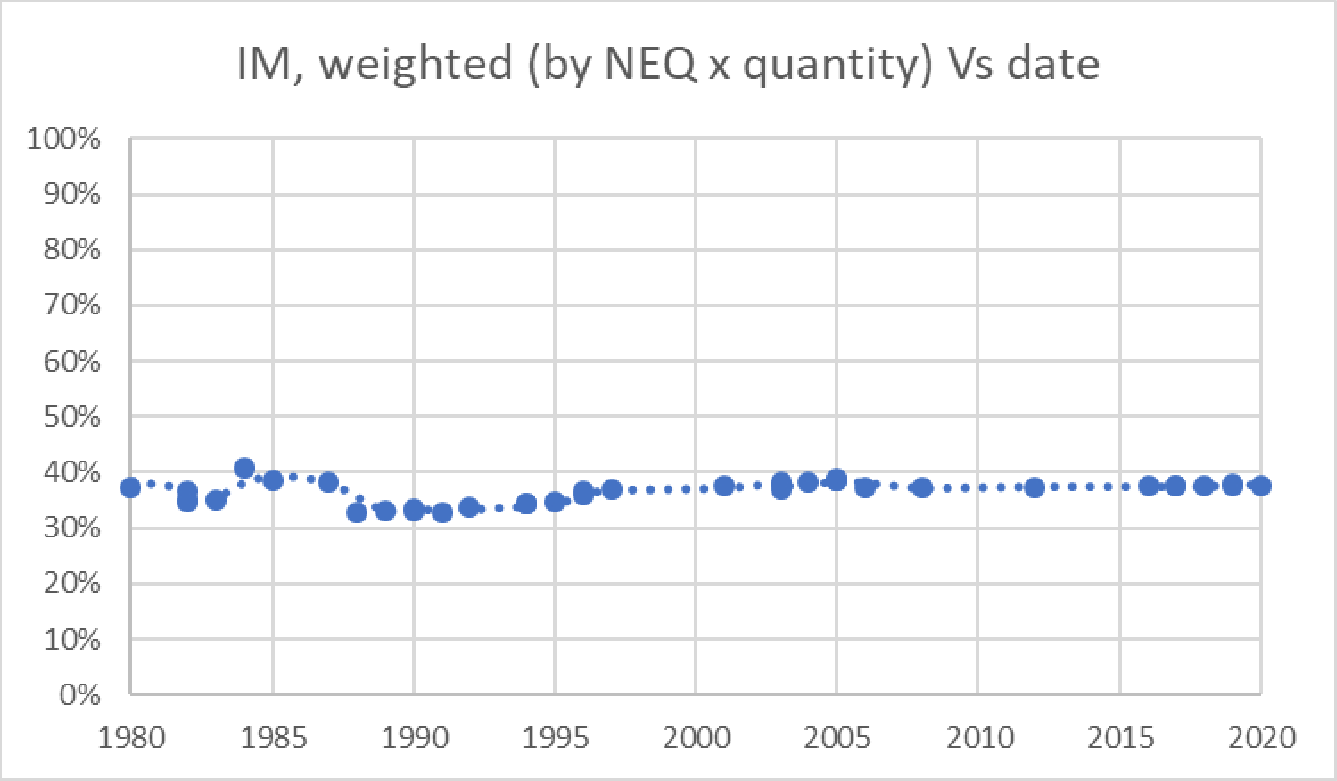
* Solid Rocket Motors (SRM's)

IM rating as missiles enter service: Warheads



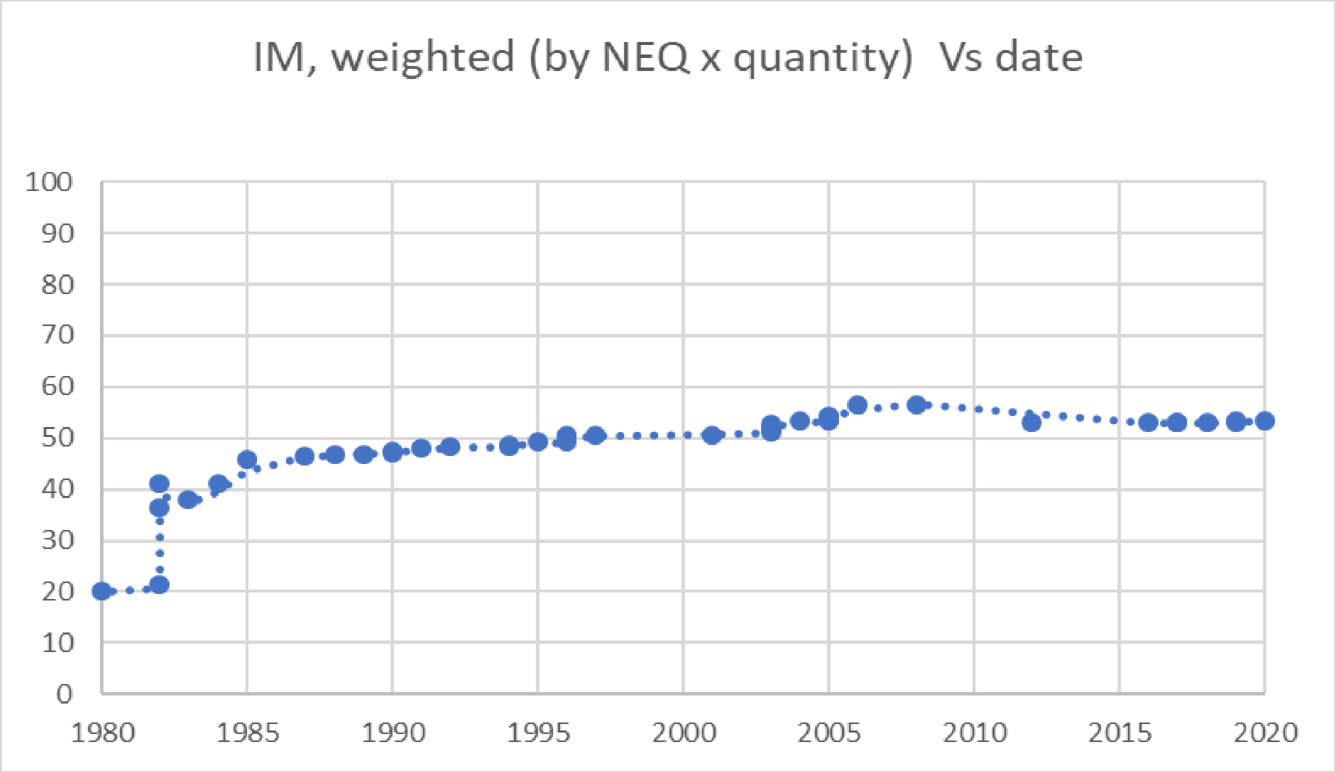
- Similar trend as SRM's
- Significant improvement from early '80's, coincident with move to improved PBX's

IM_w: SRM's



- The inventory (missile quantities x NEQ, remaining in-service) is dominated by several missiles with relatively low IM motors
  - e.g. AIM7M/P, GMLRS
- Only 1 high Q*NEQ missile retired
- Until now, the overall IM of the inventory has essentially remained constant

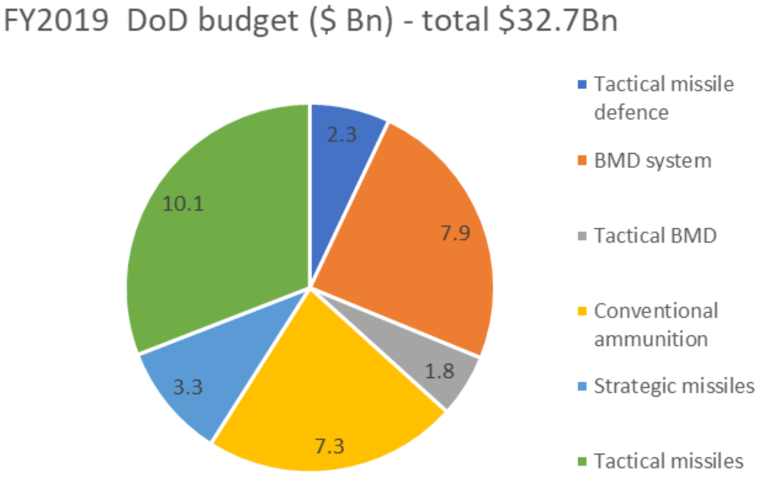
IM_w: Warheads

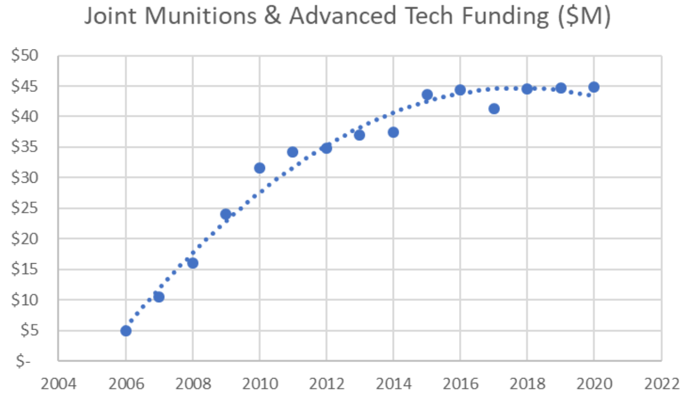


- Similar trend to SRM's, IM_w has remained nearly constant since 1995, but significant increase 1980 to 1985

IM spend

- The US Tactical missile market is ~$10 Bn (2019) with a further $15Bn for strategic & theatre defence
  - UK & FR tactical combined < $3 Bn
- Warheads & SRM generally each represent 5-15% of a missile's price, i.e. ~$2.5Bn total
- Current total RDT&E IM spend for US, FR & UK is estimated to be ~$55M/year (US recently $45M)
  - i.e. < 0.5% of missile spend
  - Estimate same again for Qualification & NRE
- Energetics typically cost <25% of warhead & <10% SRM





Extended development & deployment times, with or without IM

- Average, recently, 9 years from dev start to In Service Date (ISD)
  - No IM focus on missiles listed, but retrofits sometimes require similar timescales
- Surprisingly few IM insertions (retrofits)
  - US
    - Warheads: AMRAAM & Hellfire II (AGM-114K)
    - SRM's: only GMLRS
  - UK: Brimstone2, both the SRM & w/h
  - FR: Super 530D SRM (KFRP composite case)
- Duration ISD to OSD typically > 35 years

Missile	Dev Start	ISD	Current Variant
Sidewinder	1946	1953	AIM-9X
TOW	1963	1968	TOW-2B
Hellfire	1974	1982	AGM-114R
AMRAAM	1979	1988	AIM-120D
RAM	1976	1992	Block 2
GMLRS	1998	2006	GMLRS-IM

IM route to production: energetics & structures

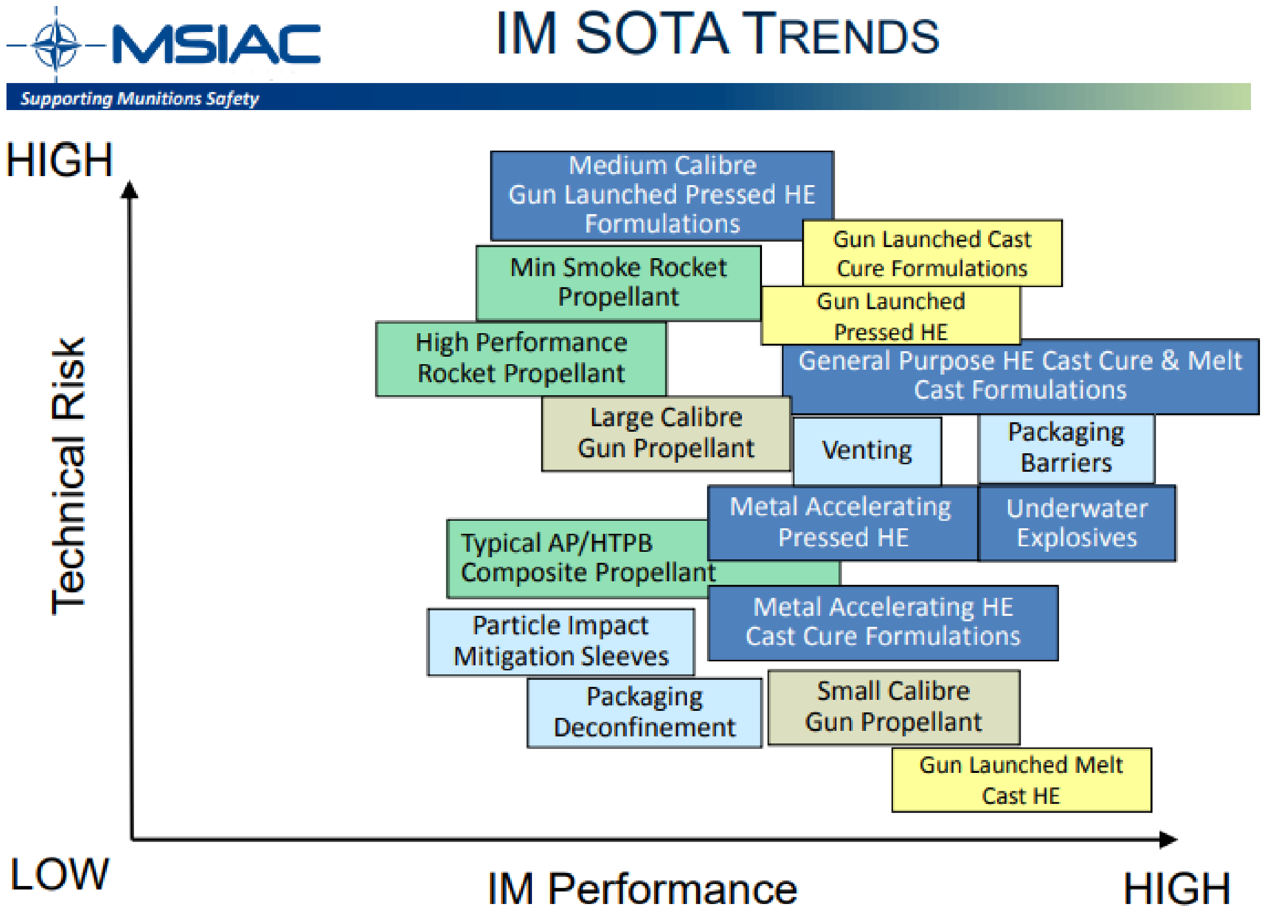
- Initial research followed by characterisation
  - Legacy molecules: Flow reaction, CONUS/equivalent, environmental
  - New molecules: Higher energy, REACH, etc
- New manufacturing methods, where required (e.g TSE, RAM, 3D printing, flow reaction, etc)
- Initial product development
  - Initial motor & warhead trials, ageing
  - Structures: impact of moisture, ageing, cumulative damage, etc
- Higher TRL tests & qualification
  - vibration, shock, IM sub-system
  - Full sequential qualification & flight trials, fatigue, lightning strike, etc
  - Certification (CofD, etc)

  } e.g. 9 years
- Production
  - Potentially new facilities &/or possibly higher UPP (at least initially)

2. Progress

- SRM's & warheads: comparison to other sub-systems
- Non homogenous cases & warheads
- Highlights of missile successes
  - Brimstone, ASRAAM, GMLRS, AMRAAM
- Implementation difficulties with energetic molecules
- Deployment not completed
  - JCM/JAGM, Sidewinder (C^4Q), PAC3 with HTPE

2.1 SRM's & w/h: comparison to other s-systems



- Some artillery shells with major IM improvements, e.g. M795 155mm (IMX 101)
- In many situations missiles have less associated (surrounding) protection; i.e. shoulder launched applications, aircraft mounted
- The IM rating of SRM's is particularly critical as, on average, they have 5 times the NEQ of the w/h
- State of Art: risks, or perception of these, result in reluctance to adopt IM

2.2 Non-homogenous cases & warheads

- Carbon fibre wound bomb bodies disintegrate instead of fragmenting
  - Introduced to lower collateral damage
  - SDB & BLU-129 in-service
- Rocket motors cases with Carbon & Kevlar (C/KRP)
  - Many produced for interceptors & ballistic missiles but significantly less for tactical
  - Tube launch/containerised mature; captive carry ?
- Steel Strip Laminate (SSL)
  - Particularly attractive for exposed air carriage applications
  - Reduced wall thickness: trade off with higher mass, c.f. CFRP
  - Roxel UK only is currently mfg but earlier Israeli & US efforts
- CFRP & SSL structures require consideration of the resin operating temperature that results from aeroheating

2.3 Successes

- GMLRS motor
- Brimstone2 motor & warhead
- ASRAAM motor
- AMRAAM warhead

2.3.1 GMLRS motor

- “March 2016 IM rocket motor contracts were awarded to ATK and AR, for ~$18M & $14M, respectively. The two 22-month contracts result in qualified IM rocket motor for GMLRS*”
- Previously considerable further time & money, mainly to (&/or) by ATK, to develop IM motor
- Qual costs small in relation to overall GMLRS budget
  - $500k RDTE & $11.5 Bn for Proc ($2003 FY); total 96,000 rockets
  - NRE for IM qual (of two designs) < 0.3% prog costs

IM Technology:
Motor:
Composite Case & aluminised HTPB propellant.
Warhead:
Insensitive PBX Expl Load, Preformed Frag, IM Venting

* https://www.esd.whs.mil/Portals/54/Documents/FOID/Reading%20Room/Selected_Acquisition_Reports/18-F-1016_DOC_32_Army_GMLRS_GMLRS_AW_SAR_Dec_2017.pdf

2.3.2 Brimstone2 motor & warhead

- Motor
  - IM now 90% but only 15% for Brimstone1 with Hellfire motor
  - Brimstone is an example of IM plus improved capability - for temp range & almost certainly Thermal Shock also
  - But several major issues in qual
    - Bondline features, conduit cracks, etc
  - Technology: EMCDB & SSL
    - EM/CDB powder process very different from slurry cast method used in USA for NEPE (XLDB)
  - Slow route to production: SLIM TDP started 10 years before ISD, IM Hellfire FCT >20 years
- Warhead
  - TSC with MEW type for Brimstone3: see separate presentation later in Session 8B (by Dr Ing Reiner Gleichmar)

2.3.3 ASRAAM motor

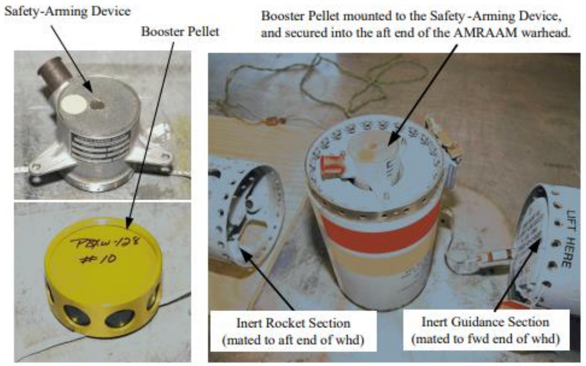
- SSL case with reduced smoke Composite propellant plus Motor pre-ignition (pyrogen igniter) for SCO mitigation
- 530D (KFRP) is the only other in-service non-homogenous rocket motor case for fixed wing air carriage
  - ISD 1994; new production run currently ongoing
- Structural tests passed included
  - 2000 hrs immersion at 60 ^{o}C followed by 400 hours air carriage at 85 ^{o}C fatigue life
  - Launch & Hangfire loads at +85 ^{o}C
  - Pressure bursts over temp range -51 to +85 ^{o}C
  - Free flight loads at 120 ^{o}C (simulating aeroheating)

2.3.4 AMRAAM warhead

- Legacy warhead had Type I-III responses to fast fragment & FH/SH Type IV
- Two concepts for IM mitigation were tested*
  - Composite closure plate: unsuccessful - no significant FCO or SCO mitigation observed at the system level
  - Alternate booster explosive: successful, concept implemented
    - Type V reaction achieved, at 2300 m/s
    - FCO & SCO maintained as deflagration
    - The revised warhead was introduced ~ 2003

	FCO	SCO	BI	FI	SD
WDU-41/B WHD (PBXN-110:~15 lbs.)	Defl	Defl	Burn	Expl / Det*	Pass

*Impact to CH-6 Booster



* The initial & qualification test programme is described in a paper at 49th Annual Fuze Conference (2005)

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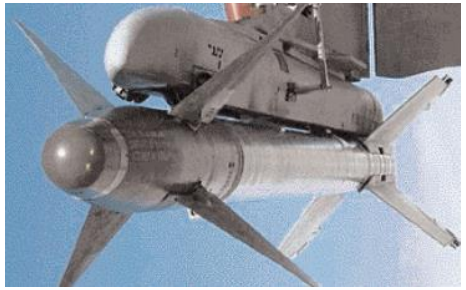
2.3.4 Deployment not completed

- JCM/JAGM Min Smoke motor
  - Composite case with cartridge loaded CDB charge with 15:1 TDR was demonstrated in 2006: IM rating of 90%
  - AUR funding cut twice, the second time terminally for the SRM; JAGM is entering service (Block I) in 2019 but with the Hellfire IM motor (IM rating only 15%)
- Sidewinder (C^4Q)
  - De-risked many aspects of CFRP cases for air carriage; trials conducted in 1998-2001
  - No CFRP case has entered service for fixed wing air carriage (ASRAAM SSL, Super 530D with KFRP)
- PAC3 with HTPE
  - The IM improvement was not demonstrated at full scale: not implemented

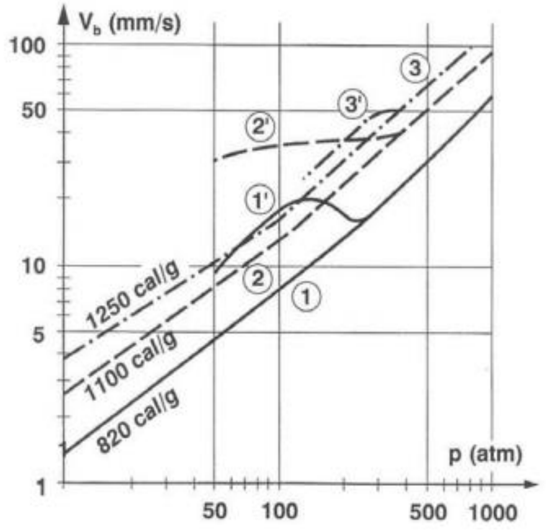


2.3.5 IM implementation

- Important to have representative but demanding early testing for IM upgrades
  - Must not reduce Margins of Safety
  - Qualification isn't the time to find basic issues
  - But also need to consider "like for like" testing for non-IM requirements (e.g. Thermal Shock Cycling): does legacy pass same tests
- Government & prime contractor support is critical
  - Although performance must be "owned" by the suppliers, with a strong incentive to complete to cost & time
  - Continuous funding, not stop/start

3. New propellants: “*n*” & temp coeff (π_k)

- Fundamental requirements include: stability, suitable range of burn rates (including *n* and π_k), energy level (ρ x Isp), Tg, Ti, bonding, insensitiveness, suitable melting point, no phase transition issues, smoke, availability, environmental footprint, etc
- However, in particular for air launched weapons, *n* & π_k can be very important as minimum thrust required at lowest operating temperature
    - Lower Isp of double base propellants compensated; see table
    - DB B/S dual burn propellant grains can give increased missile range due to the range of burn rates; especially at high L/D
        - Avoids mass & cost of Pintle, etc
        - Relatively benign efflux, simplified thermal insulation plus reduced pressure/case mass; no HCl (with Minimum Smoke)



	Smokey	Reduced Smoke	Minimum Smoke		
			XLDB	EMCDB	New Gen
density x Isp KNs/m3	4362	4100	4060	3745	3578
Charge Mass		3%	4%	8%	0
Max pressure, 71 C	Ref	0%	3%	-12%	1%
Velocity Increment		-2%	1%	-2%	-1%

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3.1 New energetics: recent developments include

- ADN type propellants
  - Attractive molecule but various issues including
    - HD 1.1, in some or all cases
    - Low melting point
    - High "*n*"
    - Incompatibility
  - Limited apparent progress since FOI's firing of a motor with 3 kg propellant in 2010
- Nitramine/GAP propellants
  - Nammo has qualified motor for Thales' LMM missile (Φ 76 mm); entering service 2020
  - Card Gap high but good IM results
  - Limited range of burn rates & relatively high *n*, c.f. EM/CDB
  - REACH compliant
- (others: CL-20, Poly GlyN/NiMMO, FOX7 & 12, HNF, LLM-105, etc, etc)

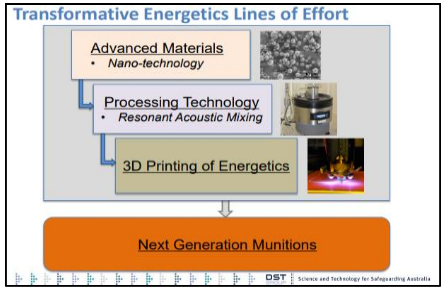
3.2 New energetics: ageing

- Potentially reduced life compared to their conventional equivalents; in any case limited real life storage data (compared to legacy products)
- Due to their energetic nature, often they combine the conventional composite propellant failure modes (oxidative ageing, hydrolysis) with the double base stability issues
- Potential issues due to hygroscopicity of some ingredients
- HTPE motors have not been implemented, except for ESSM, despite the manufacture of “over 1000 HTPE propellant mixes of various sizes”
  - Lifecycle issues associated with aging of the propellants?
    - Further U.S. investment in HTPE has largely been abandoned and other mitigation methods pursued

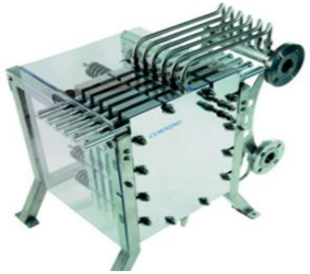
4. Challenges

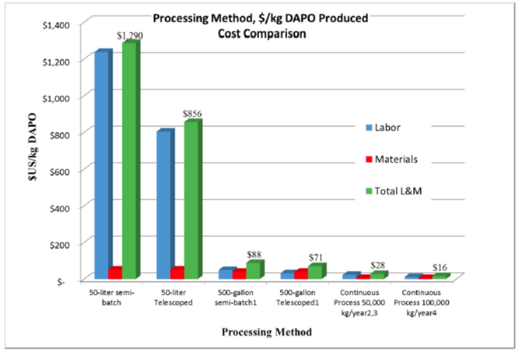
- Min Smoke SRM's generally had low IM rating
  - But recent successes: Brimstone motor (EMCDB/SSL) & LMM (GAP/RDX)
- Logistics/manufacture
  - Supply Chain issues: reduced number of suppliers, poor QA, etc
- Cost & duration
  - Production is required over >20 years with re-starts: obsolesences
  - Surge production can be a solution to both cost & duration
    - TSE & RAM
  - Double base can have similar costs to composite propellants
- Customers & missile primes are sometimes unwilling to consider implementing IM due to risks (perceived or actual) associated with IM products

5. Future Trends & Opportunities



- Future predicted trends with IM relevance
  - GAP/Nitramine propellants increasing in next 15 years
    - But legacy likely to remain important for new production also
  - Increased IM venting for both warheads & motors
  - More composite structures (w/h’s & motors)
  - Acceptance of higher energetic raw material costs
  - Increasing IM implementation on legacy systems?
- Variable composition radially via 3D printing
  - Internal diameter for more sensitive
- Source/security of supply
  - flow nitration allowing back-sourcing, new formulations & cost effective production





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6. Conclusion

- IM performance, for warheads & SRM’s, has improved in last 30 years
  - Legacy systems, generally with limited IM performance, currently dominate inventory
    - As IM is implemented & legacy systems retire from service, the average IM for the inventory will gradually improve
  - Retrofits for IM are unusual despite the technology being available
  - IM investment is estimated to be <1% of tactical missile spend
  - Significant effort on energetic molecules but limited IM benefits to date
  - Legacy energetics, with high performance, can give sub-systems with high IM ratings
  - Less progress on SRM’s than w/h’s despite motors typically having ~5x NEQ of w/h’s

- New manufacturing technologies give opportunities; supply chain issues present a number of challenges