

OME Design Rocket Motors and Propellants

Philip P Gill

Principal Propellant Chemist

philip.gill@roxelgroup.uk.com

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Ref.:

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- **Performance criteria for a rocket motor/missile**
 - Thrust – Effective Range, Engagement time
- **Suitable types of propellant for different applications**
 - Solid Double Base
 - Solid Composite
 - Solid min smoke composite
 - Liquid Mono propellant
 - Liquid bipropellants
- **Failure mode and effects analysis (FMEA) of rocket motors**
 - Cracks, Debonds, Auto-ignition, Ignition reliability, Ballistic Drift, Propellant Sensitisation, Acoustic Instability

1 – Introduction – Requirements

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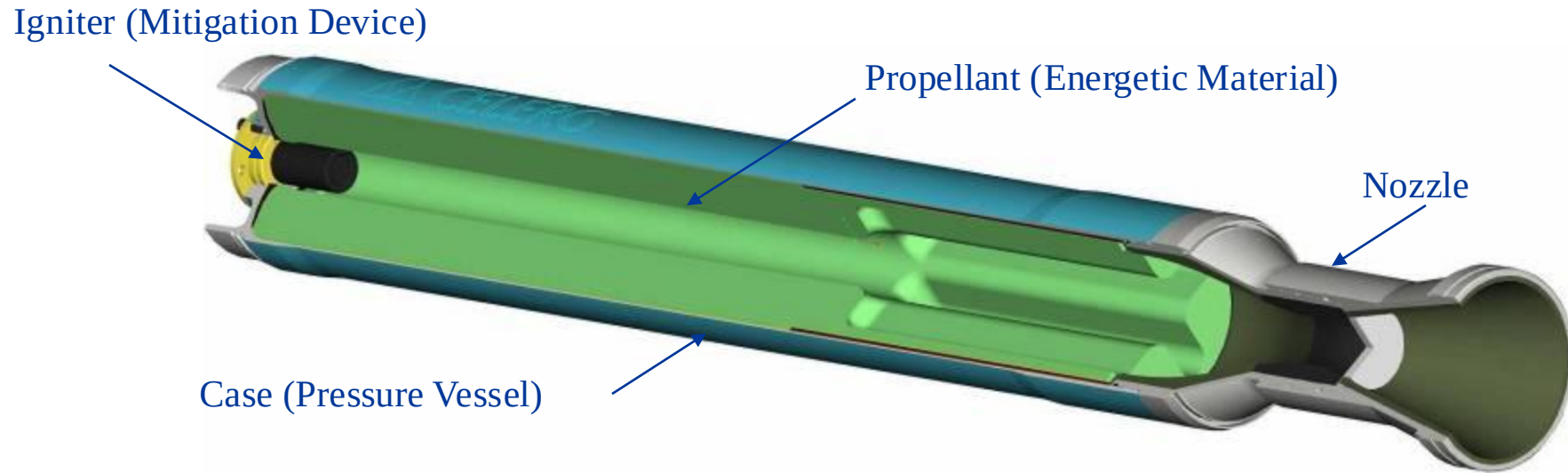
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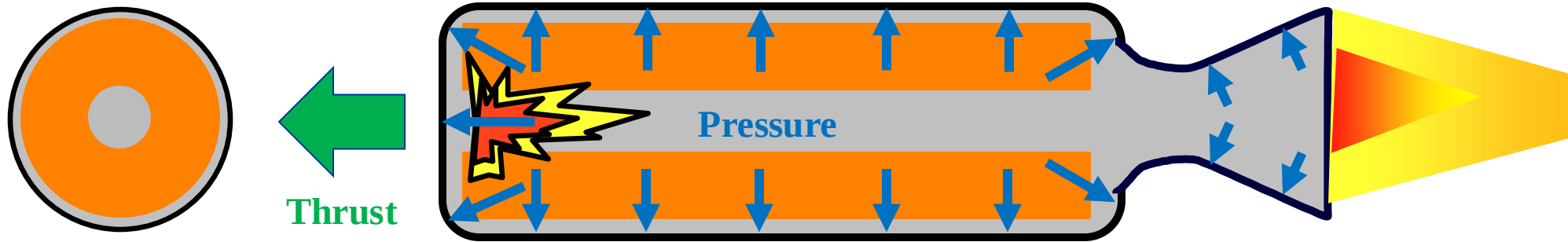


What is a Rocket Motor



- **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.

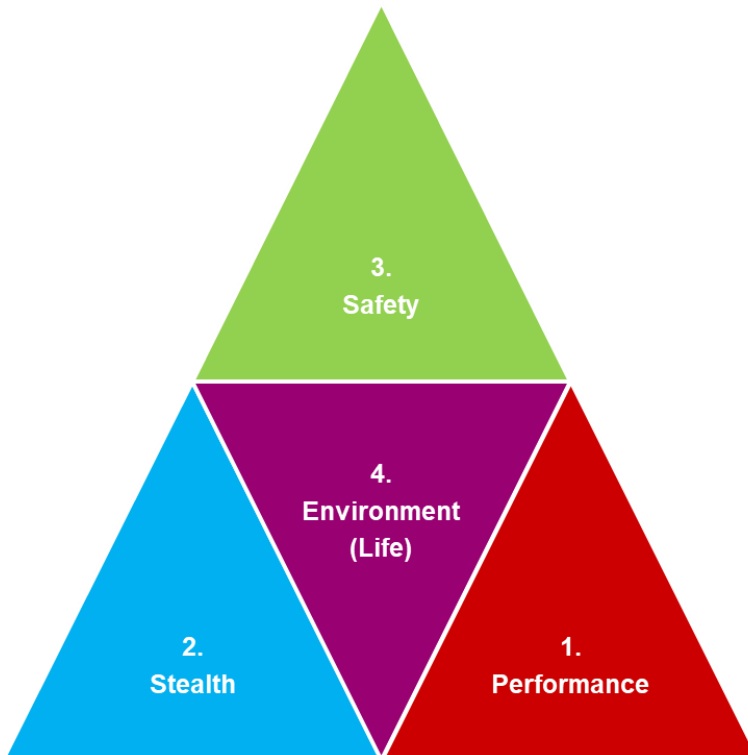
How Does a Rocket Motor Work



- Propellant charge ignited and burns on exposed surface area
 - Propellant rate of burn and surface area controls level of pressure generated
- Pressure acts on inside of case and is balanced except over nozzle hole (“throat”)
 - This is main contributor of the motor thrust (force) forwards
- Expansion of gases through nozzle provides additional thrust
 - Propellant gas sub-sonic inside case
 - As the gas passes through the nozzle throat it is at Mach 1
 - Gas accelerates to super-sonic speed as flows through nozzle expansion cone

A stealth fighter jet is shown in flight above a cruise missile. The jet is a dark, angular aircraft with a single visible cockpit. The missile is a large, cylindrical weapon with a black nose cone and various markings, including a yellow warning symbol and text. The background is a cloudy sky.

REQUIREMENTS?!



1. Performance

- Thrust, Range, Time

2. Safety and Reliability

- Including Insensitive Munitions

3. Stealth

- Combustion signature, toxicity

4. Operational environment/life

- Temperature, Vibration, Chemical safe life

5. Cost

- Development, Manufacture, Life, Disposal

$$\text{Thrust} = I_s \times m$$

$$= c^* \times C_F \times A_s \times r \times \rho$$

To increase thrust:

- Increase c^* and/or density, ρ
- Increase burning rate, r
- Increase burning surface area, A_s (i.e. build bigger rocket!)



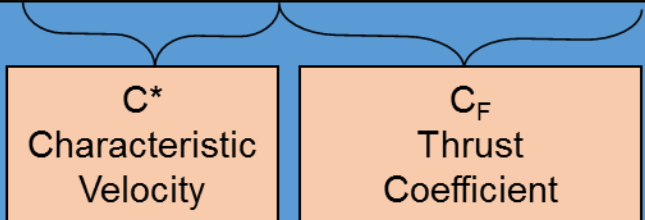
Jet or Rocket Engine	Thrust (kN)	Time (s)
Concord (take off)	676	120
Concord (cruise)	120	18,000
Saturn 5	35,100	168
SLS Block 1	36,786	480
Medium Tactical Missile Boost	5-50	1-2

1) Specific Impulse (N s kg^{-1})

$$I_{sp} = C^* \cdot C_f$$

- a) Oxygen balance, Ω
- b) Calorific Value, Q_p
- c) *density*

$$I_s = \left\{ \frac{2\gamma RT_c}{(\gamma - 1)M} \left[1 - \left(\frac{P_e}{P_c} \right)^{\frac{\gamma-1}{\gamma}} \right] \right\}^{1/2}$$



2) Burning rate, r (mm s^{-1})

r = burning rate (mm/s); p_c = combustion pressure (MPa);
 a = empirical constant (influenced by T_p) (mm/s/MPa); n = burn rate exponent

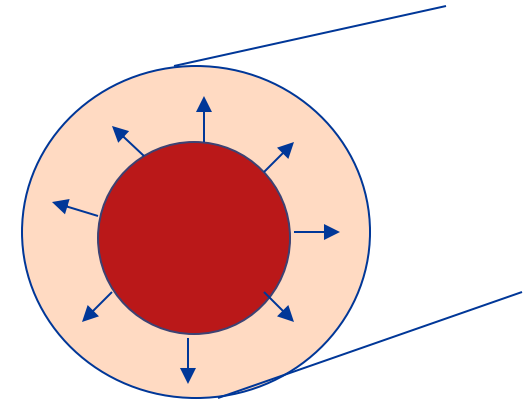
- a) Pressure index/exponent, n
- b) Temperature Coefficient, π_k

$$r = ap_c^n$$

Vielle's Law

Piobert's Law

Burning is in a direction normal to the burning surface at every point



Vieille's Law

Rate of regression of burning surface, r , depends on pressure:

$$r = ap_c^n$$

where: r = burning rate (mm/s); p_c = combustion pressure (MPa);
 a = empirical constant (influenced by T_p) (mm/s/MPa); n = burn rate exponent

Performance - Range

Breguet range equation (cruising) $R = v \frac{I_{sp}}{g} \frac{L}{D} \ln \frac{m_o}{m_f}$

Annotations for the Breguet range equation:

- v : Increase Velocity? (orange arrow pointing up)
- I_{sp} : Propellant Performance (green arrow pointing down)
- $\frac{L}{D}$: Reduce Drag (green arrow pointing down)
- $\ln \frac{m_o}{m_f}$: Reduce Unburnt Mass (green arrow pointing down) and Increase Propellant Mass (green arrow pointing down)

$C_d \frac{\rho V^2}{2} \times Area = Drag$

Annotation for the drag equation:

- ρV^2 : Reduce Velocity? (orange arrow pointing up)

High energy propellant

High volumetric loading

Light weight case/nozzle

Low drag

Nomenclature:

F - Thrust

I_{sp} - Specific Impulse

c^* - Characteristic Velocity

c_f - Thrust Coefficient

r - Burn Rate

A - Burning Surface Area

ρ - Propellant Density

v - Velocity

g - gravity

m_o - Wet mass

m_f - Dry mass

L - length

D - diameter

C_d - drag coefficient

Thrust: Four main types of motor

$$\begin{aligned}\text{Thrust} &= I_{sp} \times \text{mass} \\ &= c^* \times C_F \times A_s \times r \times \rho\end{aligned}$$

To increase thrust:

- Increase c^* and/or density, ρ
- Increase linear burning rate, r
- Increase burning surface area, A_s (i.e. build bigger rocket!)

(1) Blip/ eject/ gas generator
(for soft launch/ manoeuvring)

(2) Boost
(to accelerate to max speed)

(3) Sustain
(to maintain speed)

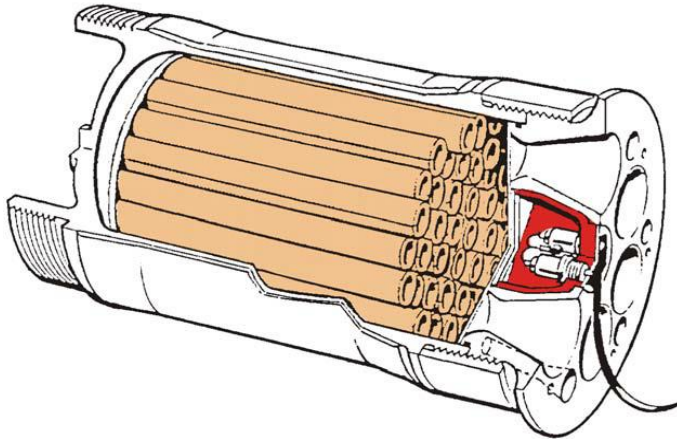
(4) Terminal boost
(to accelerate in terminal phase)

Boost Motor (blip)

- Higher thrust required

$$\text{Thrust} = I_s \times \underline{A_s} \times r \times \rho$$

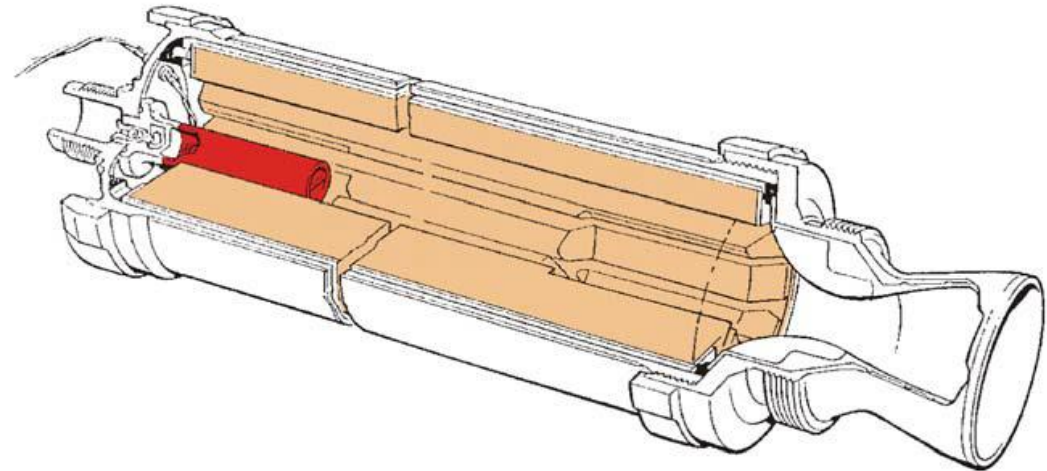
- Increase thrust by increasing surface area (A_s)



The Propellant Charge consists of 36 split tubular sticks (0.54 kg) is all burnt before the missile leaves the canister, in approximately 17.5 ms.

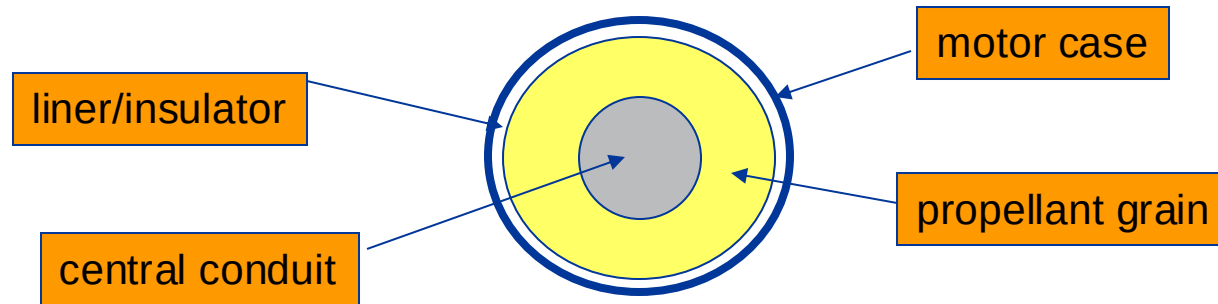
Sustain Motor

- Lower thrust requirement
- More space inside motor is taken up by propellant grain (volume fraction)

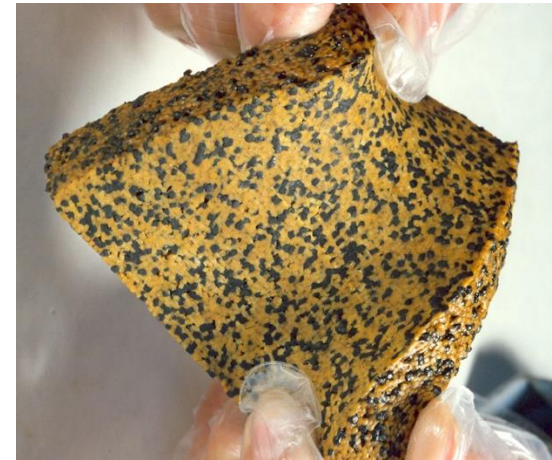


The Double Base SRS137/D76 Propellant Charge is 5 kg. The Propellant is totally burnt after 590 ms.

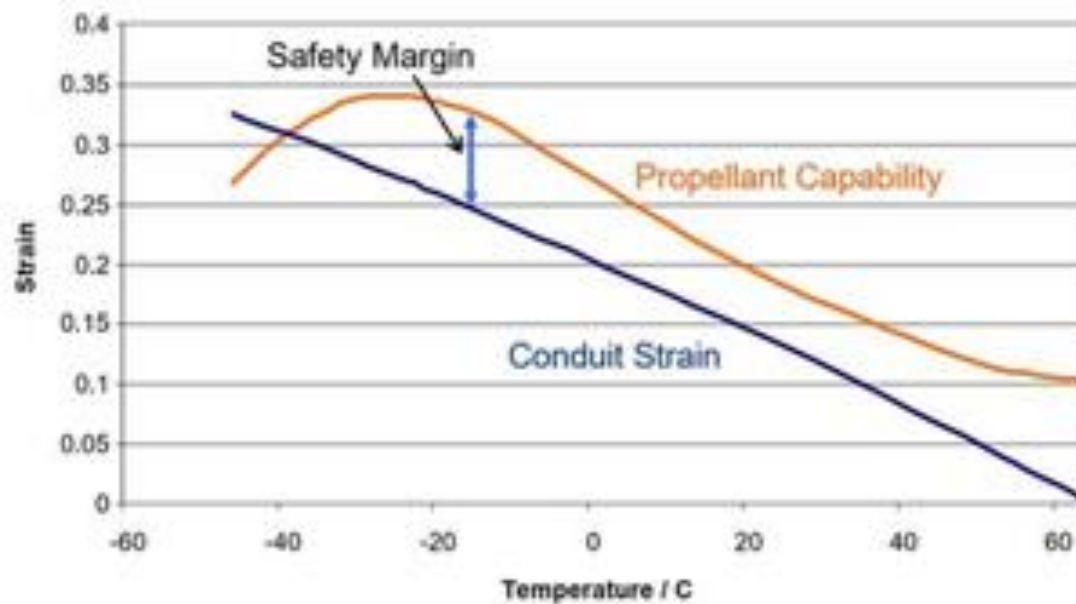
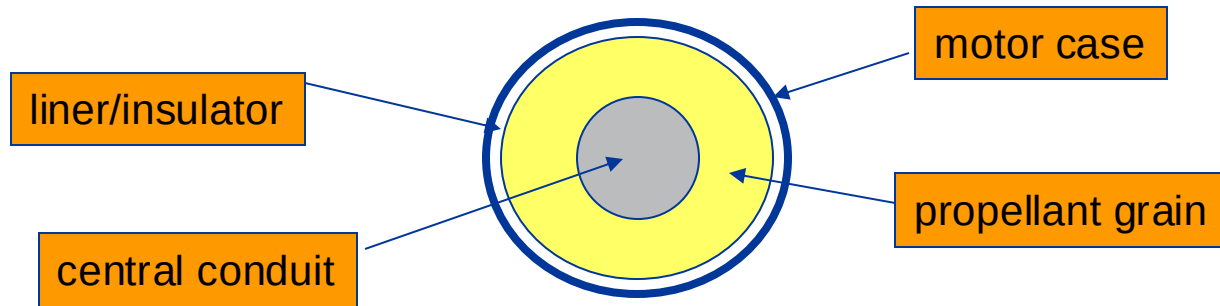
High Volumetric Loading - Case bonding



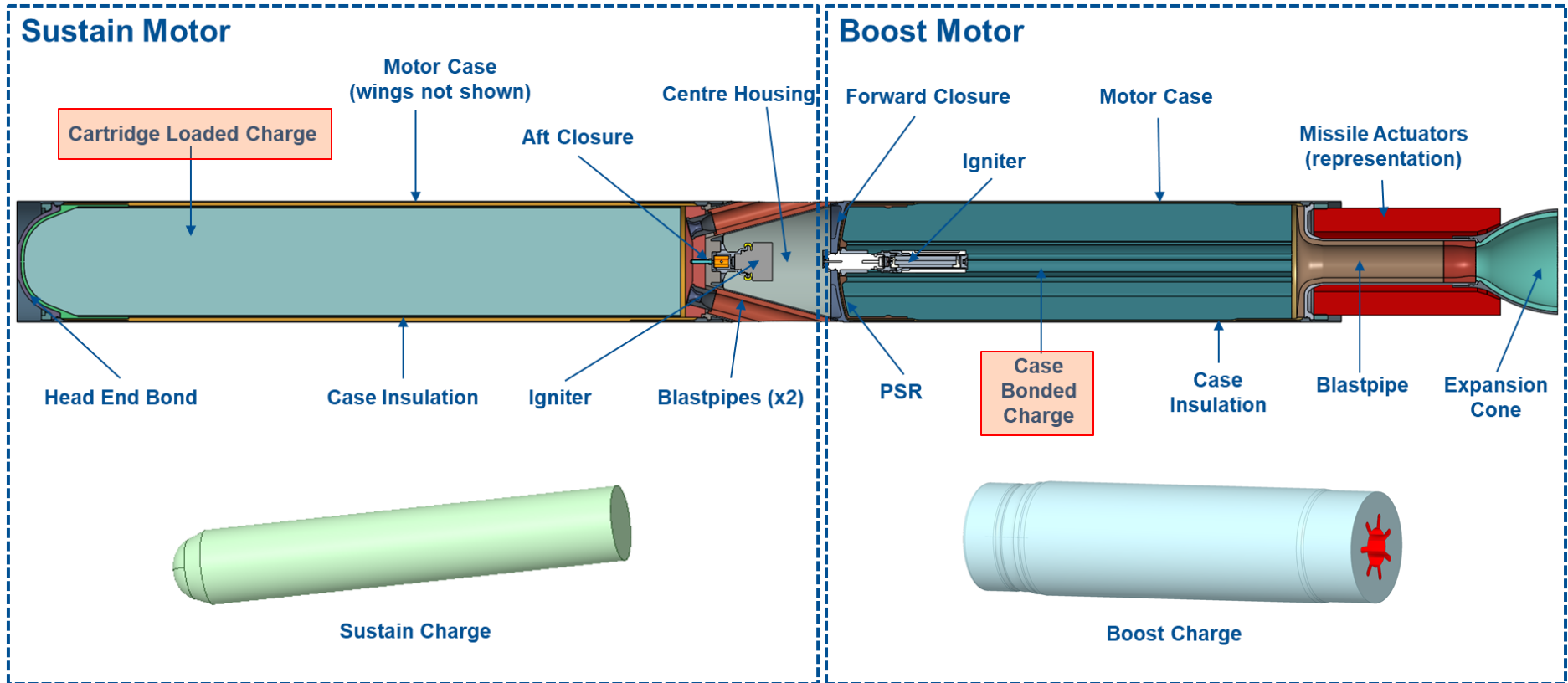
- More space inside motor is taken up by propellant grain being case bonded (~10% increase in volume fraction)
- Grain must have good mechanical properties (rubbery not brittle)
 - *Chemical Incompatibility and de-bonding a major failure mode*



Strain Capability Vs Coefficient of Thermal Expansion (CTE)



Concept Design: Boost/Sustain



Combustion Signiture: Stealth and Smoke

TWO TYPES:-

Primary (aluminised propellants,
 Al_2O_3)

Secondary (HCl and Additives)

AGARD Definition (STANAG 6016)

AA = minimum smoke

AC = reduced smoke

CC = smokey

Increasing Primary Smoke ↓	Increasing Secondary Smoke →		
	AA	AB	AC
	BA	BB	BC
	CA	CB	CC

HTPB/AP



HTPB/AP/AL



Ground firing of PBAN/AP (CC Class)



PBAN/AP (CC) at Max. Altitude (150 000ft)



STS-51-L (28-JAN-1986) SPACE SHUTTLE CHALLENGER DISASTER



- R.P. Feynman: Appendix F,
- “It appears there are enormous differences of opinion as to the probability of a failure...estimates range from roughly 1 in 100 to 1 in 100000. The higher figures come from the working engineers, and the very low figures from management”.
- “With special care in the selection of parts and in inspection, a figure below 1 in 100 might be achieved but 1 in 1000 is probably not attainable...”

SPACE LAUNCH SUCCESS %

Launcher	Total	Successful
A / Semiorka (Soviet-era)	1,446	94.19%
Kosmos C	462	94.81%
Proton	416	90.87%
Atlas	401	90.52%
Soyuz (Semiorka) (Russia-era)	378	98.02 %
Delta	377	95.23%
Chang Zheng	252	94.84%
Thor	244	87.03%
Ariane	239	95.61%
Tsyklon	235	95.74%
Total	4,450	93.20%

STANDARD MISSILE (SM) 2

4 failures in public domain

> 2700 firings



2009	July 2015	June 2018	2019/20?
USS Pinckeney (DDG91)	USS Sullivan (DDG-68)	FGS Sachsen (F 219)	DST (Australia) Test Stand

Cost: Rocket Motor

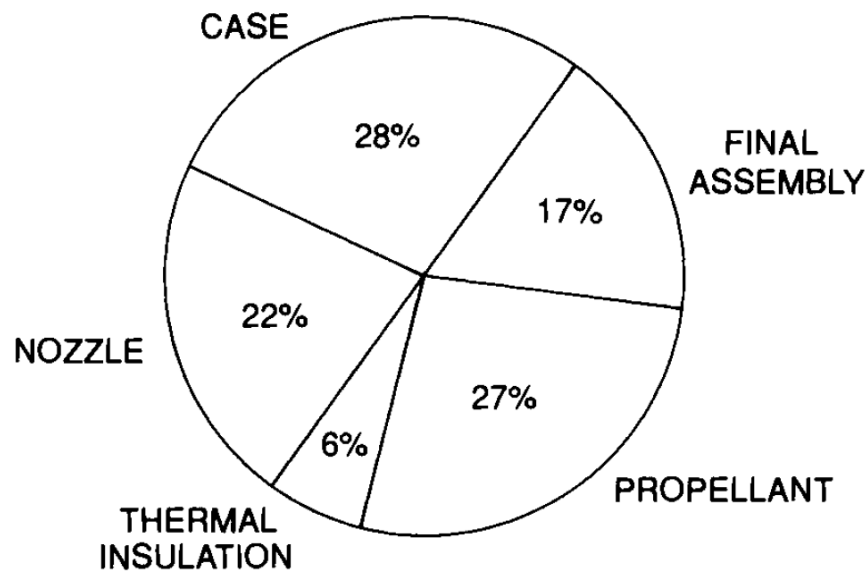
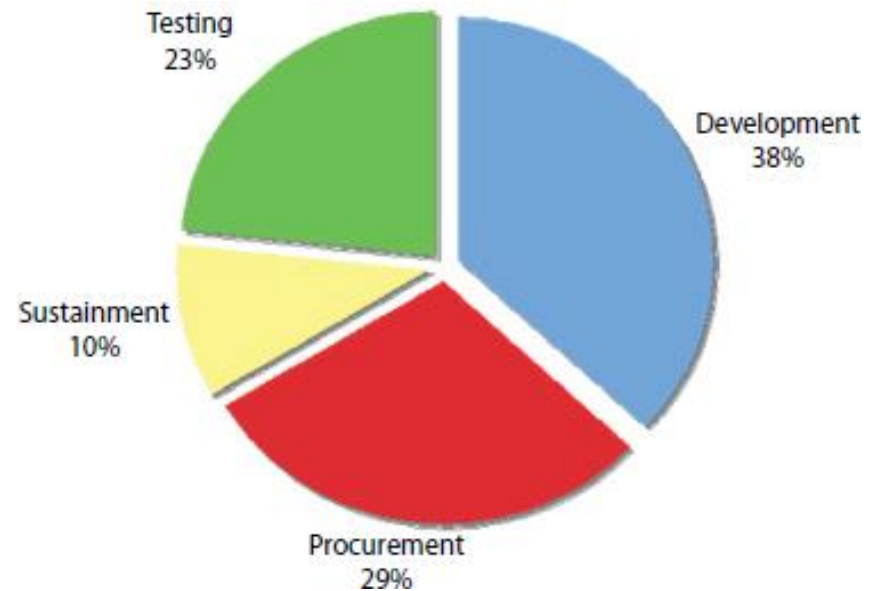
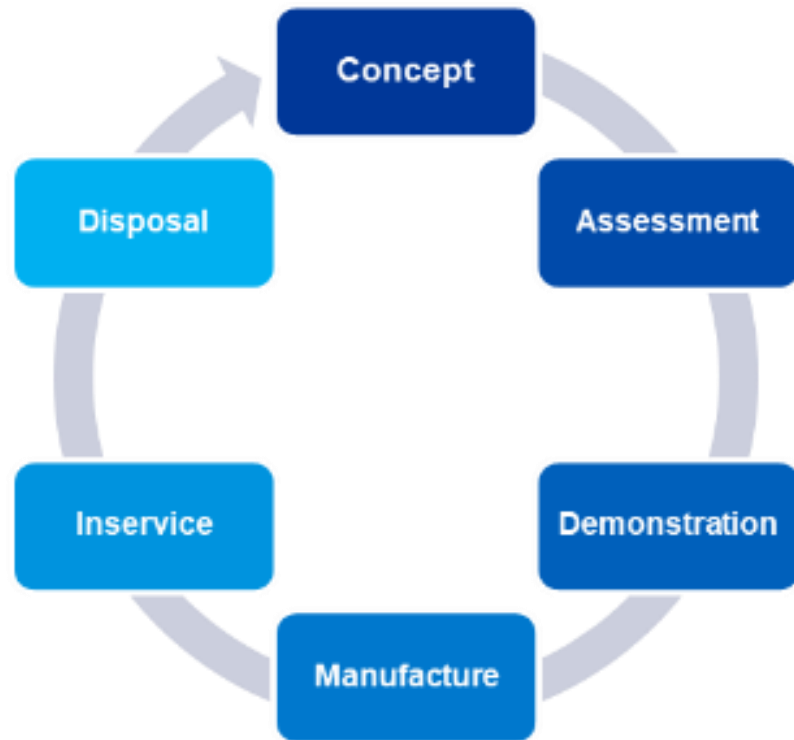


FIG. 8.9. Breakdown relative costs for a large motor.

Davenas 1993



<https://nap.nationalacademies.org/read/13189/chapter/13#202>



- Concept to Inservice 13 years
- CAD- 7 years
- MI- 6 years
- Missile is qualified for 20-25 years use

MOD - Roxel UK

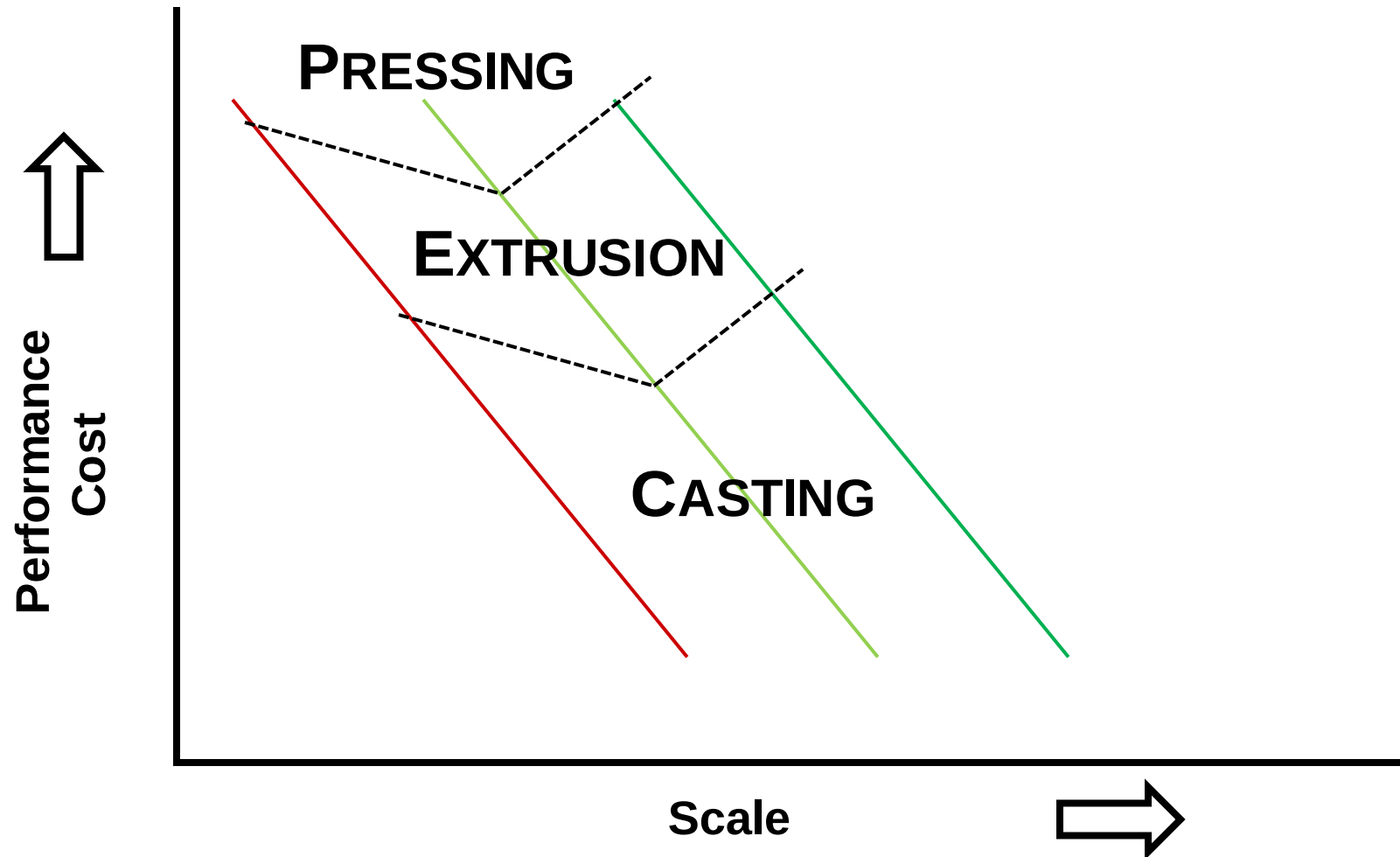
- 2003 Smokeless Large Insensitive Munitions (SLIM) demonstrator programme
- 2007 IM Brimstone requirement from MBDA
- 2010 Brimstone 2 (SPEAR 2) contracted awarded
 - The Demonstration and Manufacture contract increased the missile's performance "significantly", and converted the warhead and rocket motor to use insensitive munitions.
 - Brimstone 2 has an improved seeker, a more modular design and improvements to airframe and software for "an overall increase in performance with improvements in range and engagement footprint", including a "more than 200% increase" in maximum range.
- 2016 Brimstone 2 into service
- Brimstone 3 ... in qualification... in-service 2024
- Brimstone 4....in development



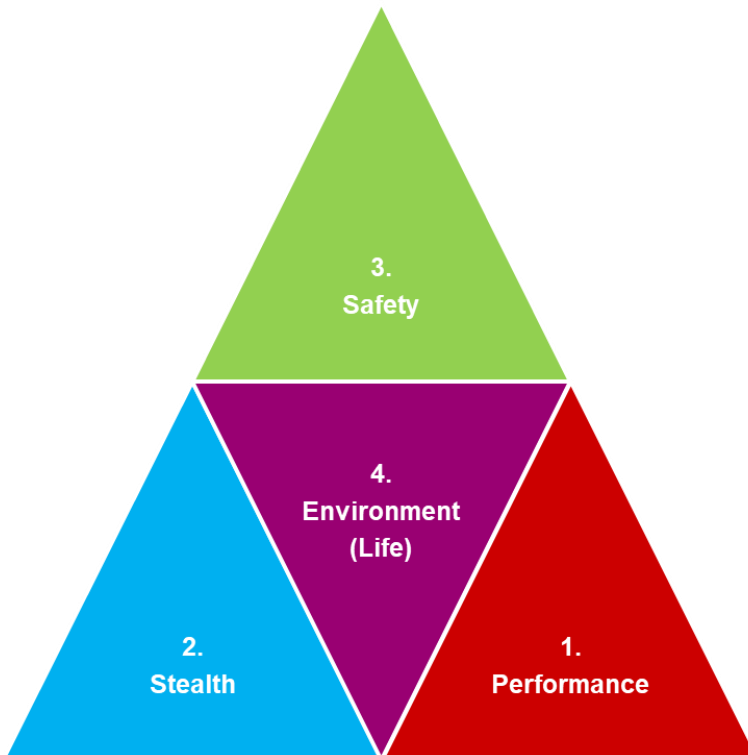
<https://www.thinkdefence.co.uk/brimstone-guided-missile/>

Solid Propellants – 4 main types

	Double Base (Min Smoke)	AP/Composite (Smokey)	Reduce Smoke Composite	Min Smoke Composite
Binder/Polymer	Nitrocellulose	Polyurethane	Polyurethane or	Energetic Binder
Oxygen/Filler	Nitroglycerine	Ammonium Perchlorate	Ammonium Perchlorate	Nitramine (RDX)
Others	Nitramine (RDX)	Aluminium	Aluminium	Ammonium Perchlorate
	Inert Plasticiser	Inert Plasticiser	Nitramine (RDX)	Inert/Energetic Plasticiser
	Burn rate modifier(s)	Burn rate modifier(s)	Inert/Energetic Plasticiser	Burn rate modifier(s)
		Processing aids	Burn rate modifier(s)	Processing Aids
			Processing Aids	



- **Key design factors**



- 1. Performance**

- Thrust, Range, Time

- 2. Safety and Reliability**

- Including Insensitive Munitions

- 3. Stealth**

- Combustion signature, toxicity

- 4. Operational environment/life**

- Temperature, Vibration, Chemical safe life

- 5. Cost**

- Development, Manufacture, Life, Disposal

Rocket Motor Applications

Application	Suitable propellant	Thrust Profile	Duration
Space launcher	Packageable or cryogenic liquid bipropellant	Variable	~ 8 mins
Anti-tank GW	Double base solid	Constant	0.2 - 3 s
Satellite attitude control thruster	Liquid monopropellant	Multiple restarts	Cumulative total of 1 h
Air launched guided missile	Rubbery composite solid	High boost, low sustain	2 s boost 30 s sustain
Long range ICBM	Rubbery composite solid or packageable liquid	High boost, low sustain	Up to 2 min each

Questions?

Dr Philip P Gill

philip.gill@roxelgroup.uk.com



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Propulsion systems