

Failure Modes

Philip P Gill

Principal Propellant Chemist

philip.gill@roxelgroup.uk.com

Nov 2024

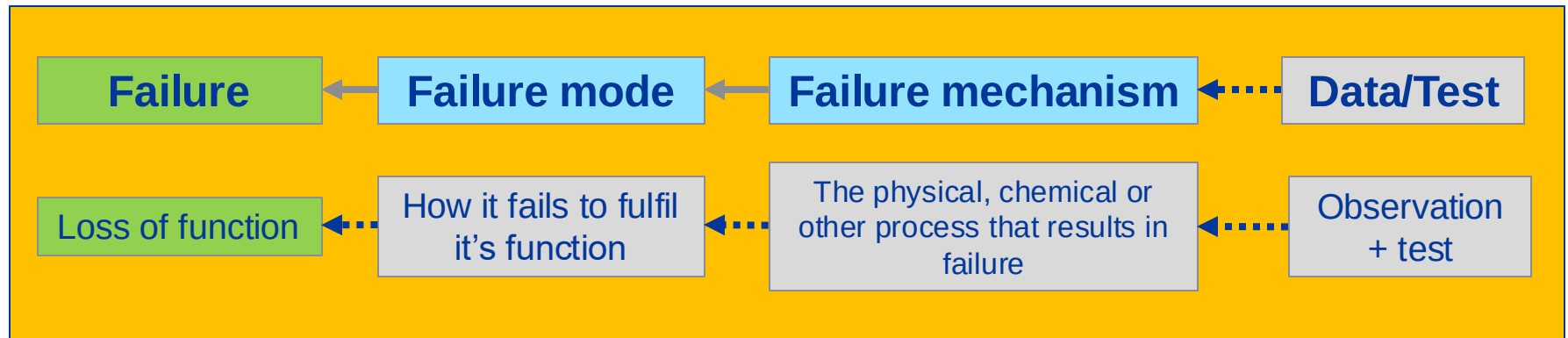


AOP 46 - THE SCIENTIFIC BASIS FOR THE WHOLE LIFE ASSESSMENT OF MUNITIONS

- *Discusses design assessment using Failure Modes and Effects Analysis (FMEA)*

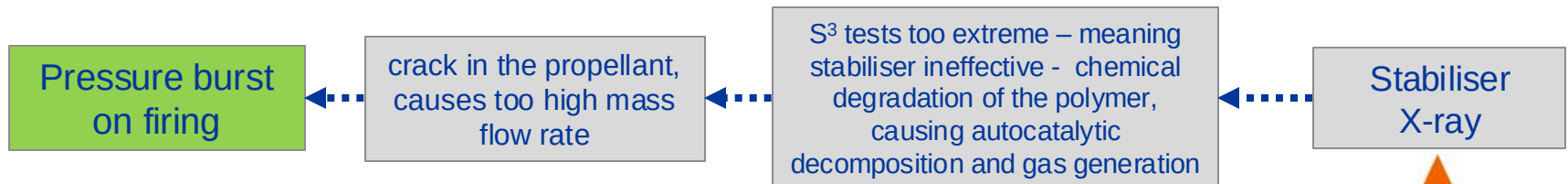
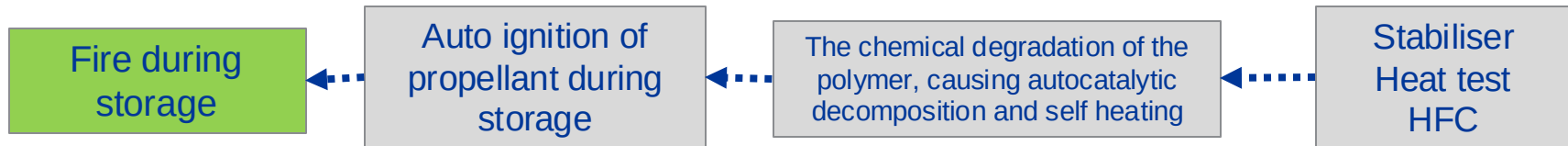
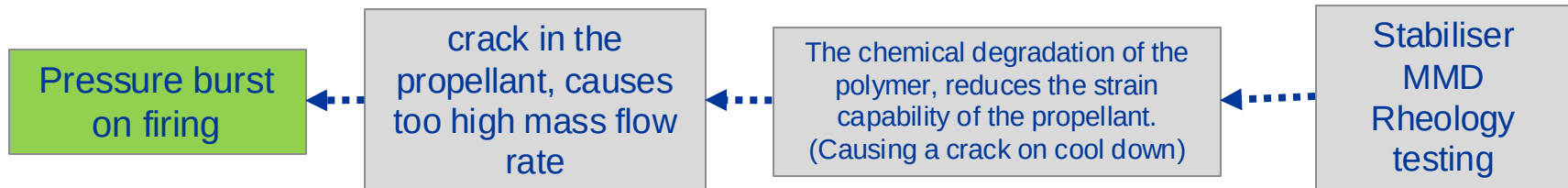
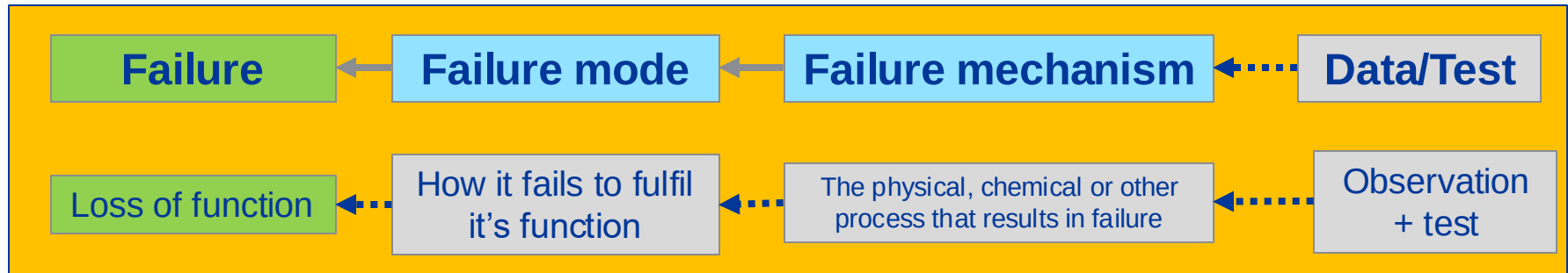
FMEA terminology

https://en.wikipedia.org/wiki/Failure_mode_and_effects_analysis



- a. **Margin of Safety too low initially or mechanical properties deteriorate on ageing faster than projected Knock-down Factor**
 - Binder breakdown, oxidative cross linking
 - Migration Effects (into or out of propellant)
 - Incompatibility with other explosives or components e.g. resins
- b. **Debonding**
 - Bondline chemistry can be more complex than Propellant Chemistry
 - Should be demonstrated by pre-programme Research
- c. **Chemical Instability (stabiliser depletion or gas crack)**
- d. **Ignition too violent or insufficiently reliable**
- e. **Ballistic Drift (Burning rate slows or speeds on ageing)**
- f. **Propellant sensitises to inadvertent ignition (impact, friction)**
- g. **Acoustic Instability (Longitudinal, Transverse Modes)**

LIFE ASSESSMENT OF MUNITIONS - definitions



There are two very distinct stages in the operational life of a propellant grain:

1.the stage before firing:

- this includes manufacturing followed by various transportation and storage phases. The duration of this stage varies, and could last from a few months to several years.

2.the firing,

- which lasts from a few milliseconds to several seconds

Operational Life

Safe storage life
"Chemical Shelf Life"

Safe life "Mechanical/
Rheological life"

Functional life
"Ballistic/ operational
life"

Chemical ageing of
explosive

Diffusion/migration with
matrix

Debonding

Chemical ageing of
explosive-binder

Phase changes

Cracking/deformation

- 1. Identify candidate Design Failure Modes**
 - Failure modes at hot, different than cold
 - 2. Model design response to ERS and calculate requirement**
 - Finite element analysis
 - 3. Add safety factors (1.5 Boosters, 1.3 Sustain)**
 - 4. Add knock down factors (errors, uncertainty, ageing)**
 - 5. Calculate safety margins**
-
- 6. Test and quantify (e.g. Uniaxial testing)**
 - 7. Specify for materials meeting requirements**
 - 8. Meet requirements 😊**

There are two very distinct stages in the operational life of a propellant grain:

1. The stage before firing: this includes manufacturing followed by various transportation and storage phases. The duration of this stage varies, and could last from a few months to several years.
2. The firing, which lasts from a few milliseconds to several seconds, depending

- Case bonded

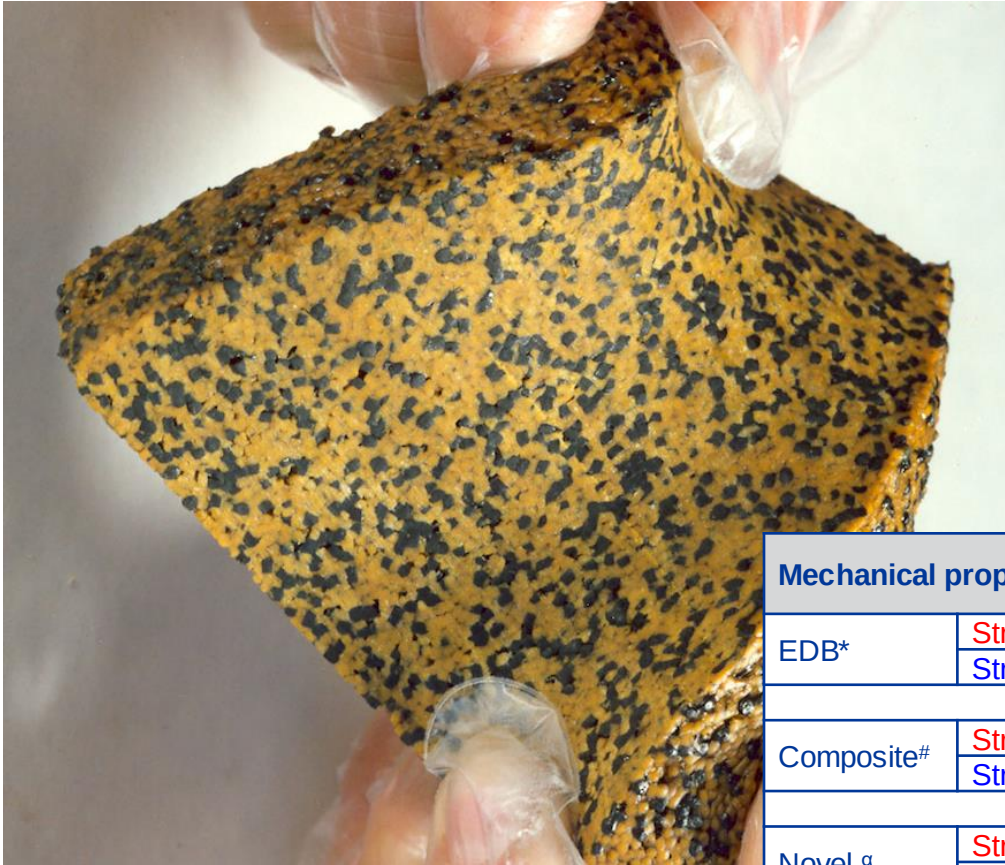
- Temperature changes
 - Thermal expansion coefficients (manufacture and service)
- Force of gravity
 - Slumping
- Pressure rise at firing
 - Strain in propellant and bond line

- Free standing

- Temperature changes
 - Uneven thermal expansion coefficients
- Pressure rise at firing
 - Increase in gaps
 - Oscillating in gaps

- a. **Margin of Safety too low initially or mechanical properties deteriorate on ageing faster than projected Knock-down Factor**
 - Binder breakdown, oxidative cross linking
 - Migration Effects (into or out of propellant)
 - Incompatibility with other explosives or components e.g. resins
- b. **Debonding**
 - Bondline chemistry can be more complex than Propellant Chemistry
 - Should be demonstrated by pre-programme Research
- c. **Chemical Instability (stabiliser depletion or gas crack)**
- d. **Ignition too violent or insufficiently reliable**
- e. **Ballistic Drift (Burning rate slows or speeds on ageing)**
- f. **Propellant sensitises to inadvertent ignition (impact, friction)**
- g. **Acoustic Instability (Longitudinal, Transverse Modes)**

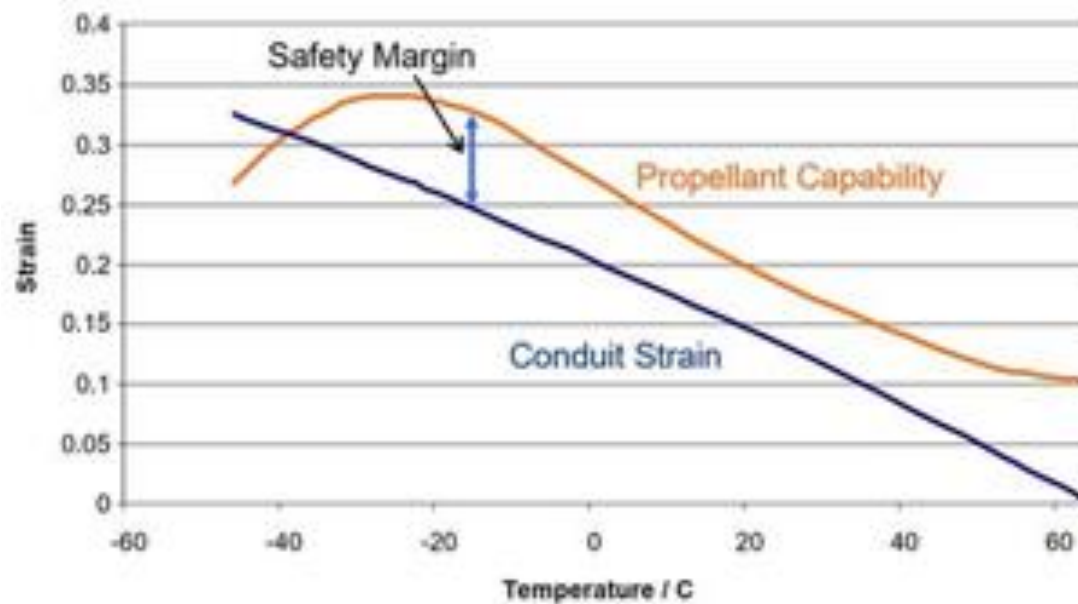
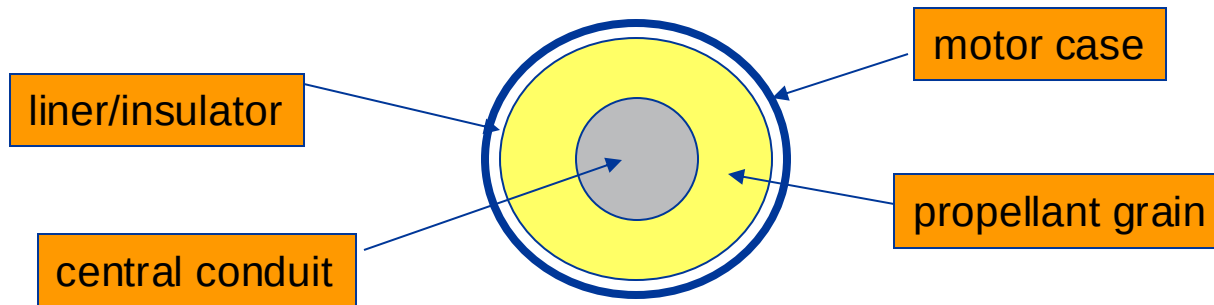
(a) Mechanical properties



- Modulus/Stress - hot
- Elongation/Strain energy - cold
- Damage/Cracking

Mechanical properties		-40 °C	20 °C	+60 °C * / +70 °C#
EDB*	Stress (MPa)	51	11	2
	Strain (%)	2.8	2.5	8
Composite#	Stress (MPa)	4.0	1.5	1.0
	Strain (%)	50.5	56.5	54.5
Novel ^α	Stress (MPa)			>0.5
	Strain (%)	>10		
* EDB data taken from Davenas; # Composite average data taken from Sutton; α Novel taken from Fossey				

(a) Propellant Strain Capability Vs CTE



(a) Mechanical properties- HTPB oxidative cross linking

QinetiQ Proprietary

HTPB Binder System

HTPB binder system includes a curing catalyst

Samples open to air
at right hand end
after cure

Discolouration due to
oxidation of
Calco2246 in
presence of catalyst

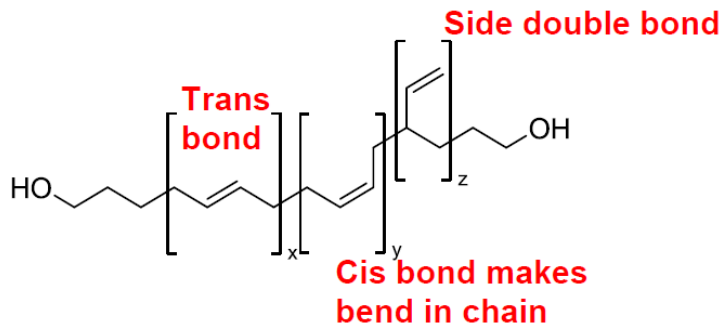


Post Cure (N2)

0.9 days

2 days

5 days



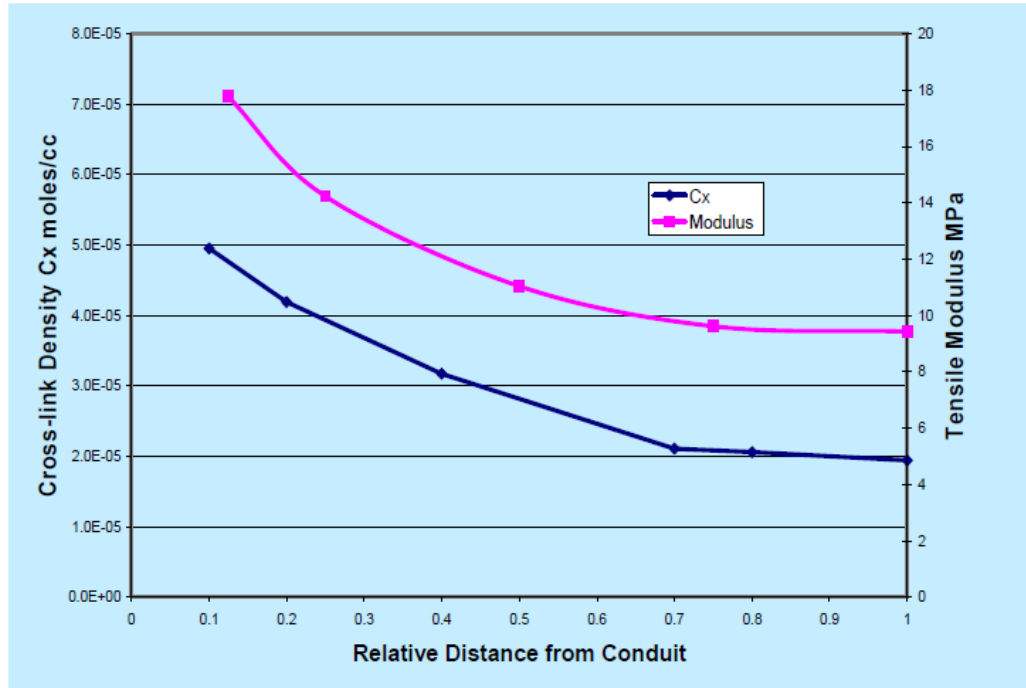
www.QinetiQ.com

Copyright QinetiQ limited 2006

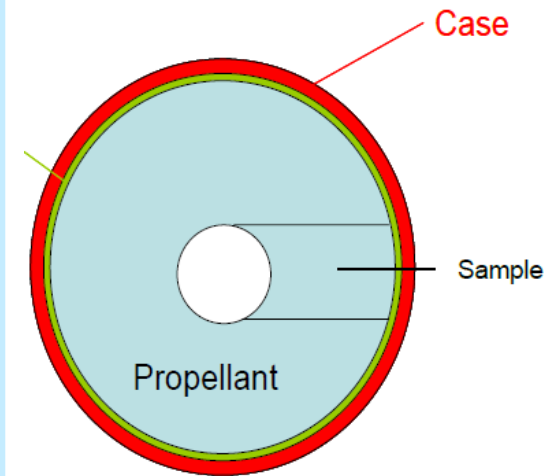
In any manner whatsoever without prior written consent of QinetiQ. © QinetiQ 2020
Page 12

(a) Mechanical properties- HTPB oxidative cross linking

Cross-link Density & Modulus Across the Web



Sustain Section
Cutting Diagram



Naturally Aged Motor, Propellant A

QinetiQ

www.QinetiQ.com

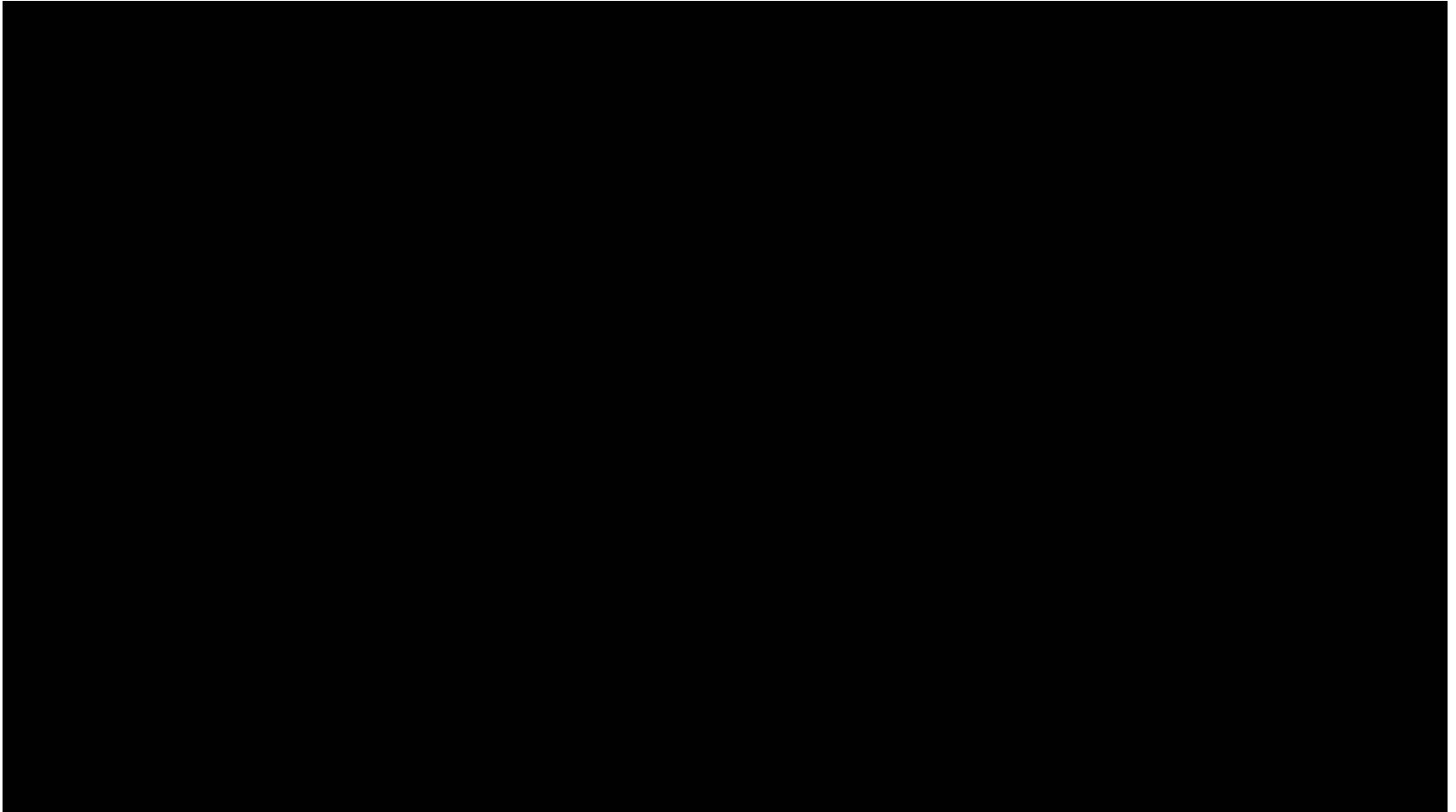
© Copyright QinetiQ limited 2006

24

- **Limiting temperature extremes**
 - Limiting low temp will reduce storage and ignition failure since the propellant is more extensible
 - Limiting high temp will reduce gas cracking and slumping
- **Reducing loading density**
 - Reducing hoop strains on grain
- **Reducing length to diameter ratio**
 - Reducing strain
- **Rounding off sharp corners**
 - Limiting areas of stress concentrations
- **Stress relief devices**
 - Slot inhibitor flaps, End stress relief bellows
- **Improving propellant mechanical properties**
 - **Most effective method**

- a. Margin of Safety too low initially or mechanical properties deteriorate on ageing faster than projected Knock-down Factor
 - Binder breakdown, oxidative cross linking
 - Migration Effects (into or out of propellant)
 - Incompatibility with other explosives or components e.g. resins
- b. Debonding
 - Bondline chemistry can be more complex than Propellant Chemistry
 - Should be demonstrated by pre-programme Research
- c. Chemical Instability (stabiliser depletion or gas crack)
- d. Ignition too violent or insufficiently reliable
- e. Ballistic Drift (Burning rate slows or speeds on ageing)
- f. Propellant sensitises to inadvertent ignition (impact, friction)
- g. Acoustic Instability (Longitudinal, Transverse Modes)

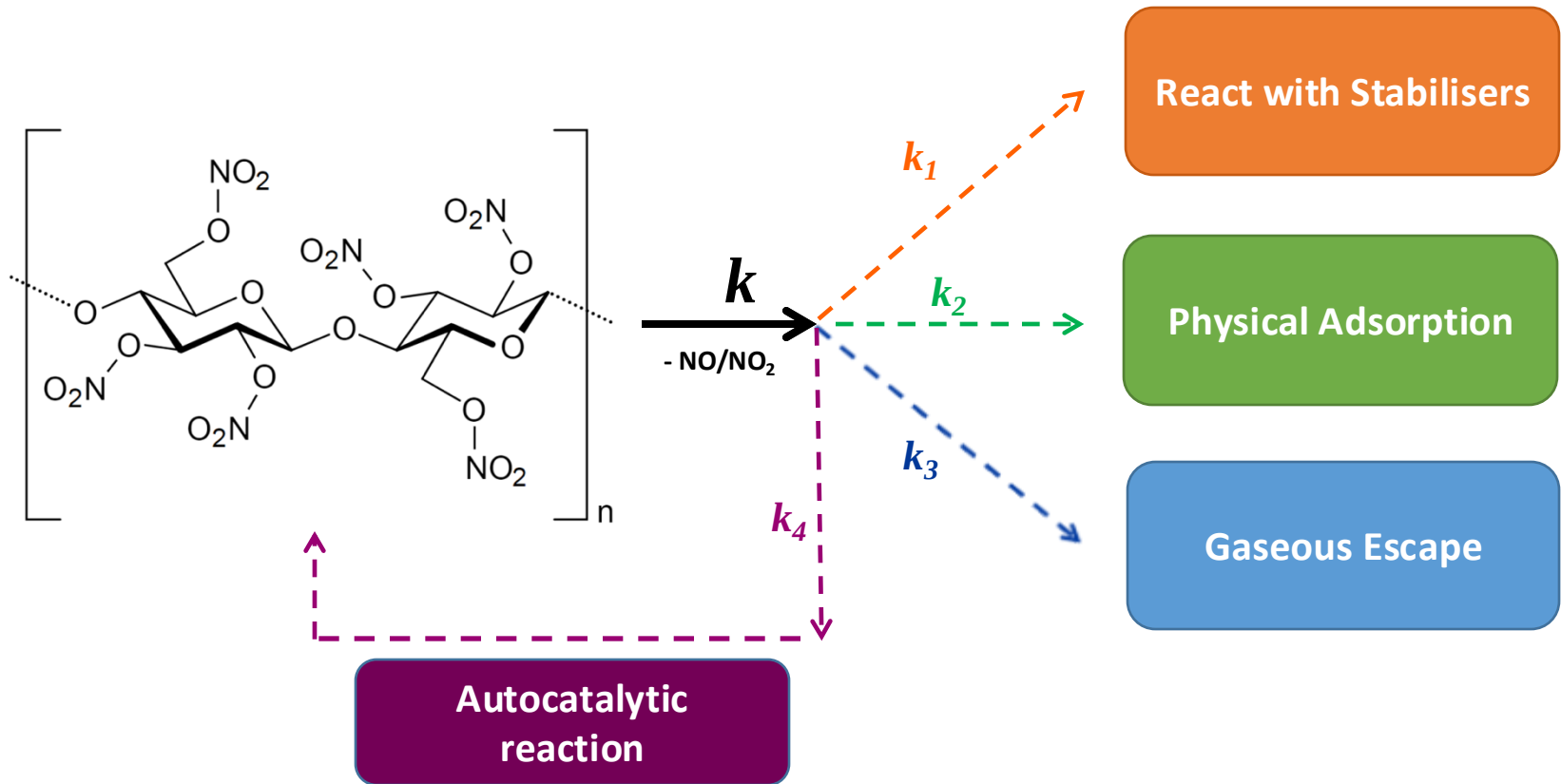
CASE BONDING FAILURE





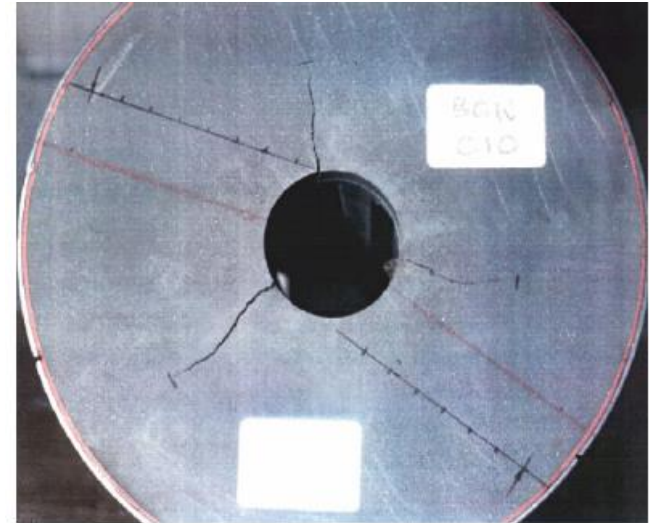
- a. Margin of Safety too low initially or mechanical properties deteriorate on ageing faster than projected Knock-down Factor
 - Binder breakdown, oxidative cross linking
 - Migration Effects (into or out of propellant)
 - Incompatibility with other explosives or components e.g. resins
- b. Debonding
 - Bondline chemistry can be more complex than Propellant Chemistry
 - Should be demonstrated by pre-programme Research
- c. Chemical Instability (stabiliser depletion or gas crack)
- d. Ignition too violent or insufficiently reliable
- e. Ballistic Drift (Burning rate slows or speeds on ageing)
- f. Propellant sensitises to inadvertent ignition (impact, friction)
- g. Acoustic Instability (Longitudinal, Transverse Modes)

(c) Chemical instability - Nitrocellulose



(c) Chemical instability – NC Gas cracking

- Cracking of propellants is extremely significant in that any extra surface area created may or probably will cause system failure
- Minor surface flaws etc not a problem as they will burn away before the motor realises they are there.
- However imperfection can act as stress raiser during further environmental testing



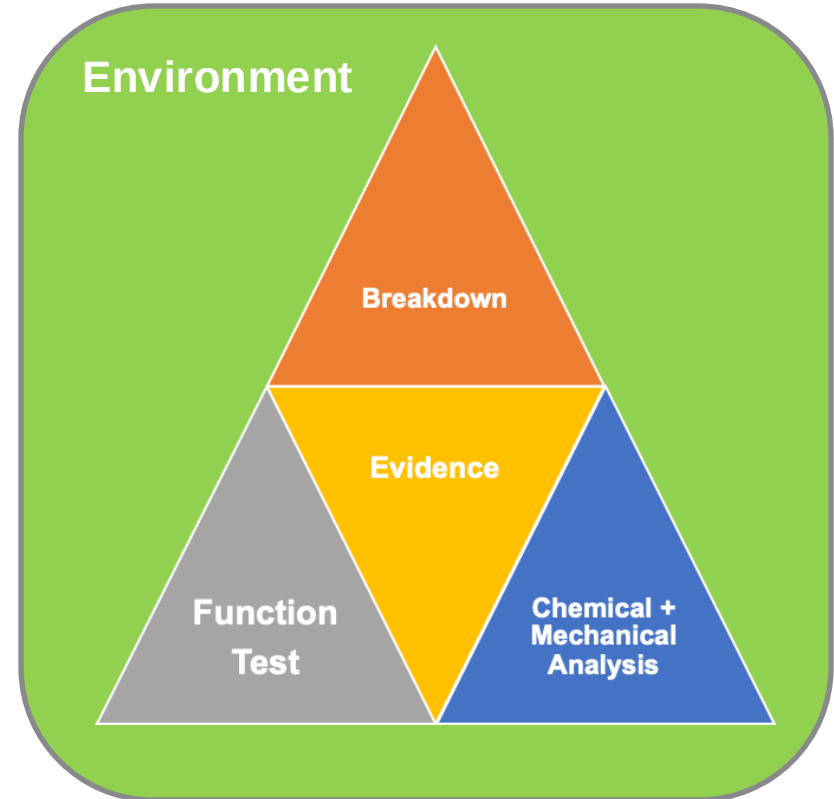
- a. Margin of Safety too low initially or mechanical properties deteriorate on ageing faster than projected Knock-down Factor
 - Binder breakdown, oxidative cross linking
 - Migration Effects (into or out of propellant)
 - Incompatibility with other explosives or components e.g. resins
- b. Debonding
 - Bondline chemistry can be more complex than Propellant Chemistry
 - Should be demonstrated by pre-programme Research
- c. Chemical Instability (stabiliser depletion or gas crack)
- d. Ignition too violent or insufficiently reliable
- e. Ballistic Drift (Burning rate slows or speeds on ageing)
- f. **Propellant sensitises to inadvertent ignition (impact, friction)**
- g. Acoustic Instability (Longitudinal, Transverse Modes)

(f) Migration of Propellant Ingredients; Sensitising?



Two Motor Surveillance Programme – Implications for the Stock?

- **Characteristics relevant to its role**
 - Safety and Performance
 - Thermal, mechanical, ESD, rheology, physical properties
- **Effect of temperature**
 - Safety and Performance
 - Thermal, mechanical, ESD, rheology, physical properties
- Sequential testing will **give 7-8 years predicted life**. The models aren't accurate enough to predict further.
- No UK munition cleared for all climatic conditions



Understanding the Failure Mode(s) is Key

- **Different performance criteria for a missile**
 - Thrust – Effective Range, Engagement time
- **Most suitable type 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

Questions?

Dr Philip P Gill

philip.gill@roxelgroup.uk.com



Roxel
Propulsion systems