MSIAC
Munitions Safety Information Analysis Center

Supporting Munitions Safety

Application of Herd Immunity to Munitions Safety / Approaches to Lifing Algorithms

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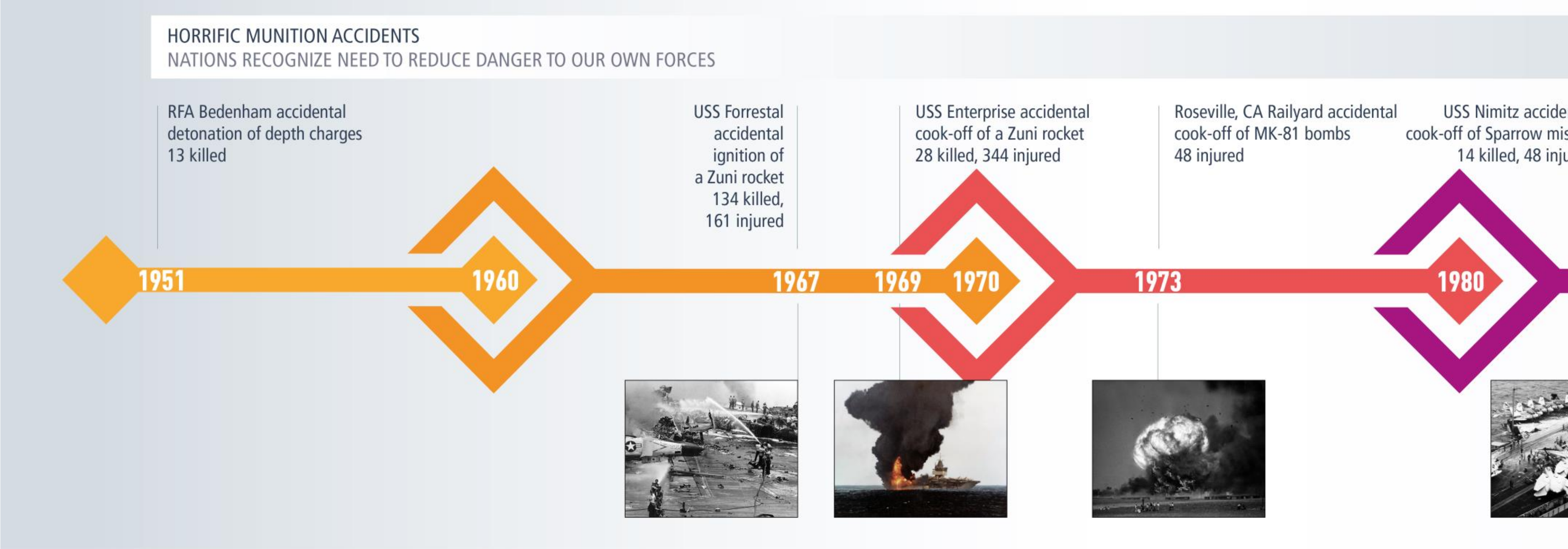
History

History of MSIAC is linked to history of Insensitive Munitions (IM)

- Need for IM arose from horrific accidents of 1960 and 1970s

History


HORRIFIC MUNITION ACCIDENTS
NATIONS RECOGNIZE NEED TO REDUCE DANGER TO OUR OWN FORCES
RFA Bedenham accidental detonation of depth charges 13 killed
USS Forrestal accidental ignition of a Zuni rocket 134 killed, 161 injured
USS Enterprise accidental cook-off of a Zuni rocket 28 killed, 344 injured
Roseville, CA Railyard accidental cook-off of MK-81 bombs 48 injured
USS Nimitz accide
cook-off of Sparrow mis
14 killed, 48 inju
1951
1960
1967
1969
1970
1973
1980

Our Organization

Technical Information Analysis Center Focusing on Munitions Safety

- NATO Project Office
- Independently Funded by its Member Nations (16 currently)

Areas of Expertise:

- Warhead Technology
- Propulsion Technology
- Materials Technology
- Energetic Materials
- Munitions Transport and Storage Safety
- Munitions Systems

Products & Services:

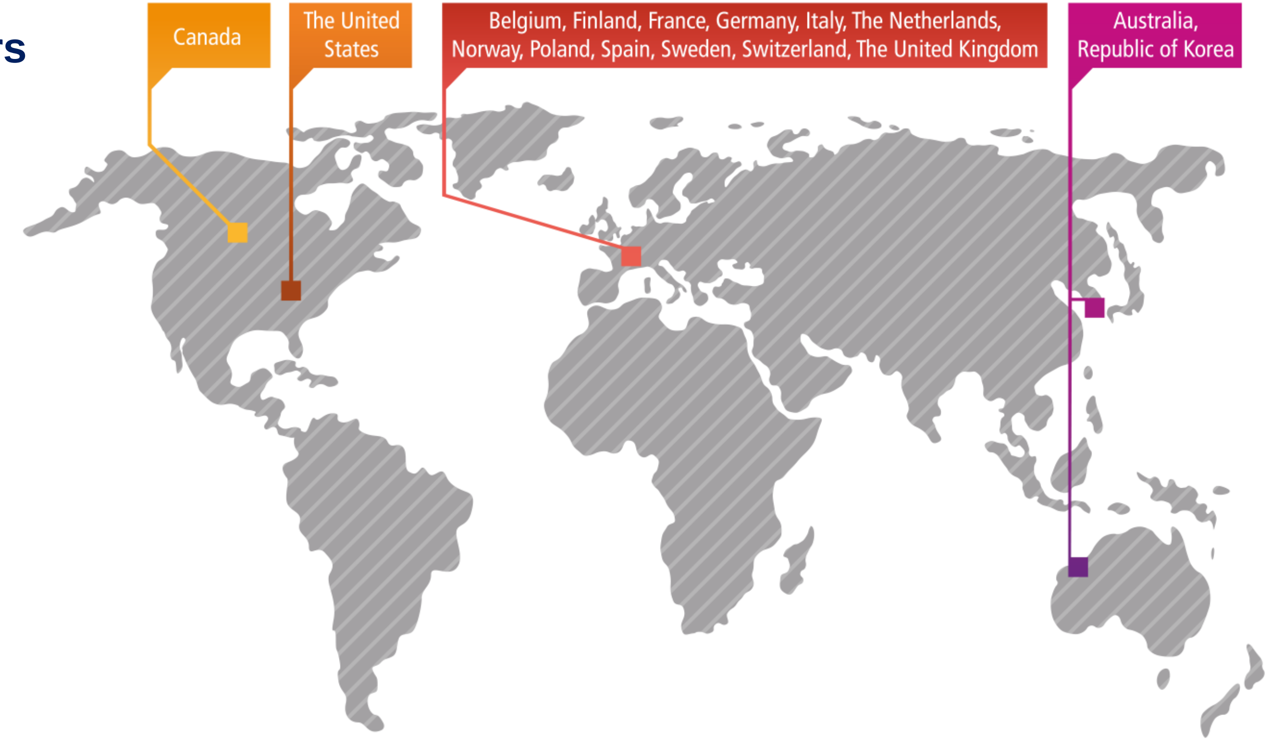
- Technical Questions
- Promotion/participation International Conferences
- Support to NATO WG activities
- Training and Workshops
- Technical Reports
- Repository of Technical Information

Eliminating Safety Risks from Unintended Reactions of Munitions and Energetic Materials throughout their Lifecycle

MSIAC Member Nations

- **MSIAC Strategies, Policies, & Work Efforts Defined by a Steering Committee (SC)**
  - 1 SC Representative per Member Nation, 1 Vote per Member Nation
  - 1 Elected Chairman (non-voting) from a Member Nation

- **16 Members**



Products and Services for the Technical Community

Supporting Munitions Safety

Application of Herd Immunity to Munitions Safety

Introduction & Objective

- Introduction of IM creates safety benefits – but replacement of conventional munitions by IM often occurs partially / in phases

- Is aggregate reaction of larger stockpiles lessened when only a portion of the stockpile is IM?

- Objectives of MSIAC study:
  - Assess implications of mixing IM / non-IM munitions in a stockpile
  - Develop theoretical methods to determine a critical quantity of IM
  - Explore concept of **herd immunity** as applied to munitions safety

Herd Immunity

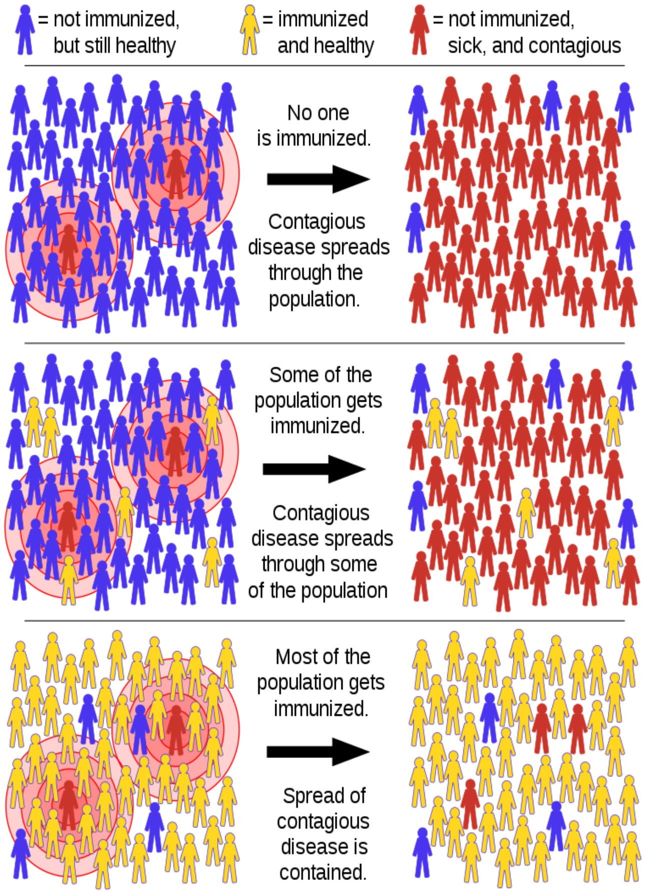
- If a sufficiently high proportion of individuals are immune to a disease, especially through vaccination, the spread within a population is restrained

$$R_e = R_0 \cdot S = 1$$

  - R_e Effective reproduction number
  - R_0 Basic reproduction number
  - S Proportion of population susceptible to infection

- Herd Immunity Threshold (HIT)

$$HIT = 1 - \frac{1}{R_0}$$



Wikipedia, 2021

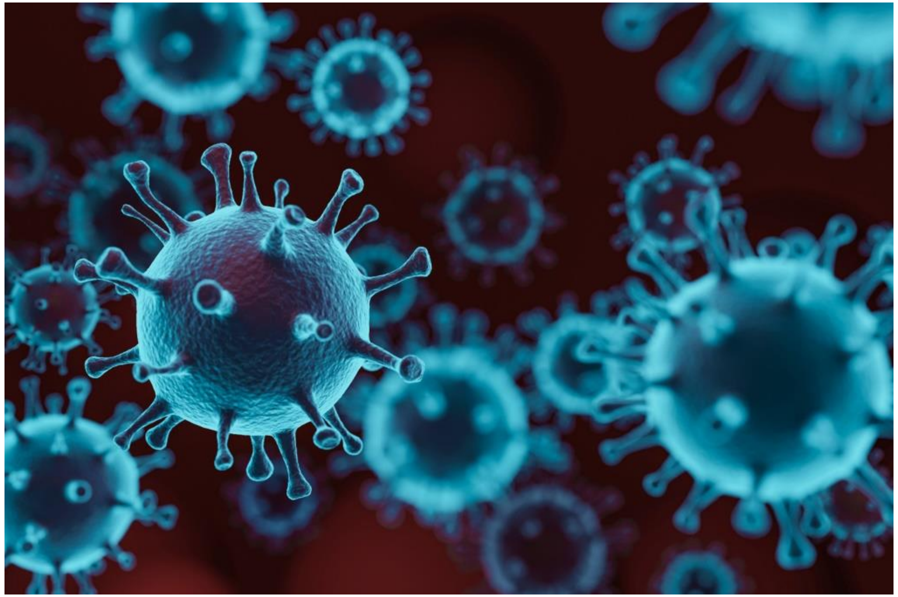
Herd Immunity

<table>
<tr><th>Disease</th><th>Transmission</th><th>R_0</th><th>HIT</th></tr>
<tr><td>Measles</td><td>Airborne</td><td>12–18</td><td>92–95%</td></tr>
<tr><td>Pertussis</td><td>Airborne droplet</td><td>12–17</td><td>92–94%</td></tr>
<tr><td>Diphtheria</td><td>Saliva</td><td rowspan="2">6–7</td><td rowspan="2">83–86%</td></tr>
<tr><td>Rubella</td><td rowspan="2">Airborne droplet</td></tr>
<tr><td>Smallpox</td><td rowspan="2">5–7</td><td rowspan="2">80–86%</td></tr>
<tr><td>Polio</td><td>Fecal-oral route</td></tr>
<tr><td>Mumps</td><td rowspan="3">Airborne droplet</td><td>4–7</td><td>75–86%</td></tr>
<tr><td>COVID-19 (2020 -</td><td>2.5–4</td><td>60–75%</td></tr>
<tr><td>SARS (2002–2004)</td><td>2–5</td><td>50–80%</td></tr>
<tr><td>Ebola</td><td>Bodily fluids</td><td>1.5–2.5</td><td>33–60%</td></tr>
<tr><td>Influenza (pandemics)</td><td>Airborne droplet</td><td>1.5–1.8</td><td>33–44%</td></tr>
</table>

Herd Immunity

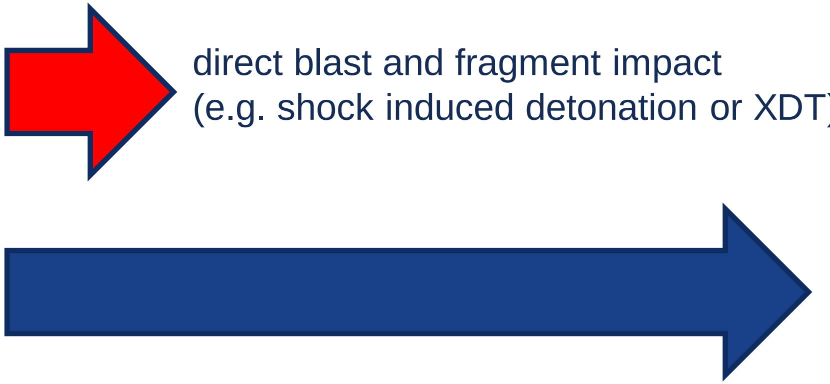
- Assumption: populations are homogeneous, or well-mixed, meaning that every individual comes into contact with every other individual

- Reality:
  - Heterogeneous populations, networks
  - Vaccine efficiency
  - Duration of vaccine effectiveness
  - Prevention of infection and transmission or only infection



Herd Immunity and Munitions Safety

- **Disease versus munition response**
  - “Contagious disease” = response of donor munition to initiating stimuli (e.g. accident or enemy action)
  - “Infection” of acceptor munitions, leading to further munition responses and further “infections”
  - The six munition response types (AOP-39) = different “diseases” or “disease severities”:
    - Detonation (type I)
    - Partial detonation (type II)
    - Explosion (type III)
    - Deflagration (type IV)
    - Burn (type V)
    - No reaction (type VI)



Herd Immunity and Munitions Safety

- **Vaccination versus Insensitive Munitions**
  - "vaccination" analogous to introducing munitions that do not exhibit violent response, i.e. Insensitive Munitions
  - The "vaccinated" (IM) munition does not cause any new infections
  - Important note: IM Compliance does not equate to Immunity!

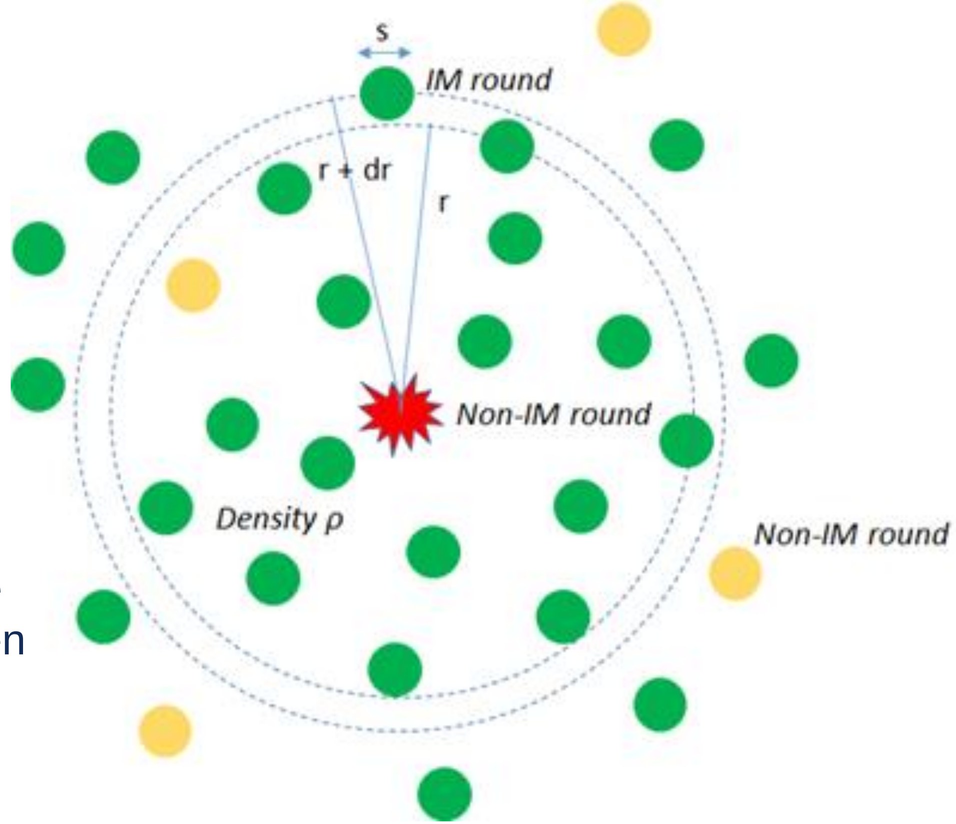
Test	Required Response for IM Compliance
Fast Heating (FH)	No worse than Type V
Slow Heating (SH)	No worse than Type V
Bullet Impact (BI)	No worse than Type V
Fragment Impact (FI)	No worse than Type V
Shaped Charge Jet Impact (SCJI)	No worse than Type III
Sympathetic Reaction (SR)	No worse than Type III

Herd Immunity and Munitions Safety

- **Mixing of Individuals vs Munitions**
  - Munitions transported and stored in configurations, in which IM and Non-IM is typically not mixed
  - During an accident munitions do not move around (proximity and line of sight are required for 'infection')

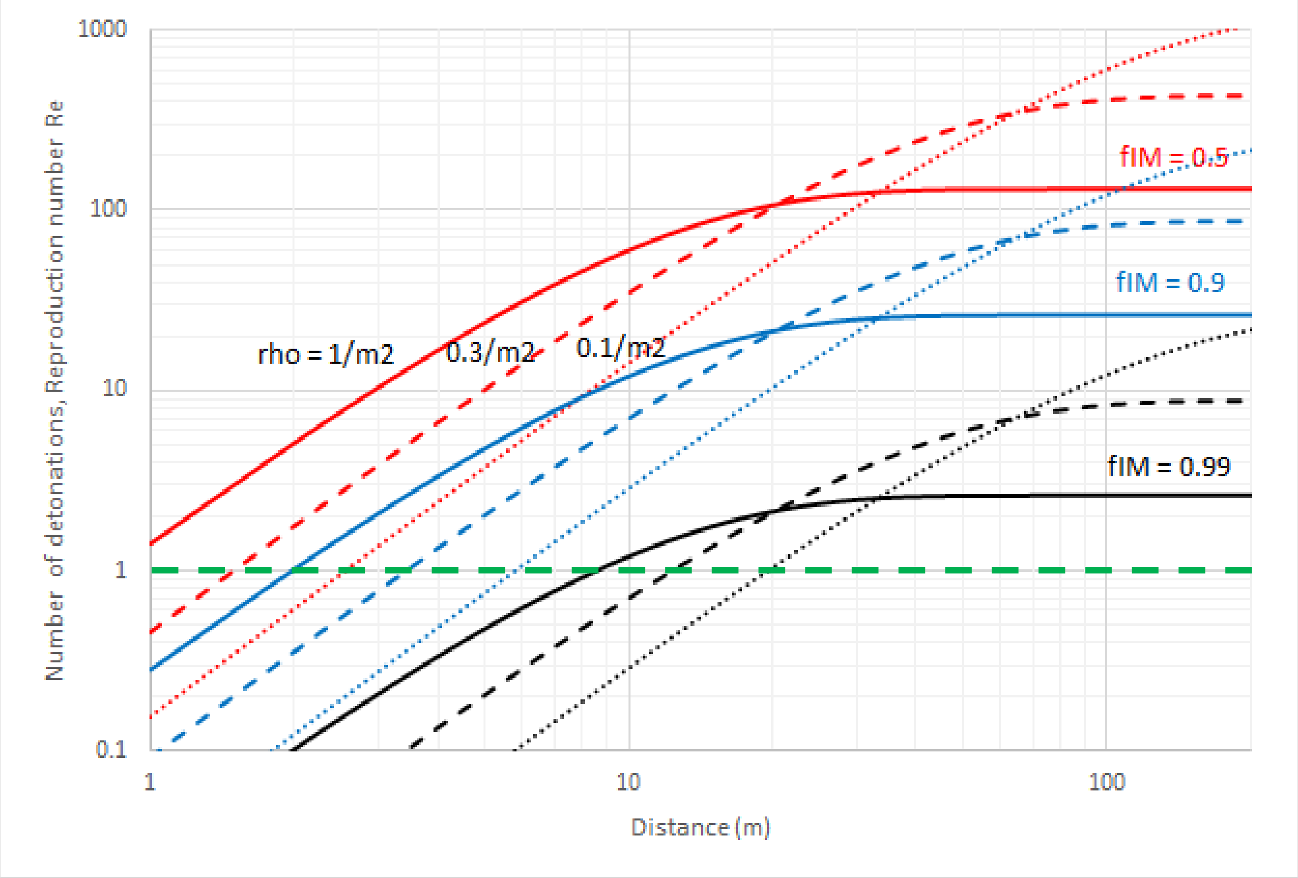
2D random distribution of munitions

- Assumptions:
  - 2D configuration with a random distribution of separate munitions, munition stacks or storage magazines
  - Propagation of reaction occurs by fragment impact
  - There are two types of acceptors, with variable proportions:
    - Non-IM – assumed to detonate if there is a line of sight with donor; resulting fragments can then initiate other munitions within line of sight
    - IM – do not detonate if line of sight with donor, i.e. they "block" the fragment. No further propagation of "mild" (Type V) response



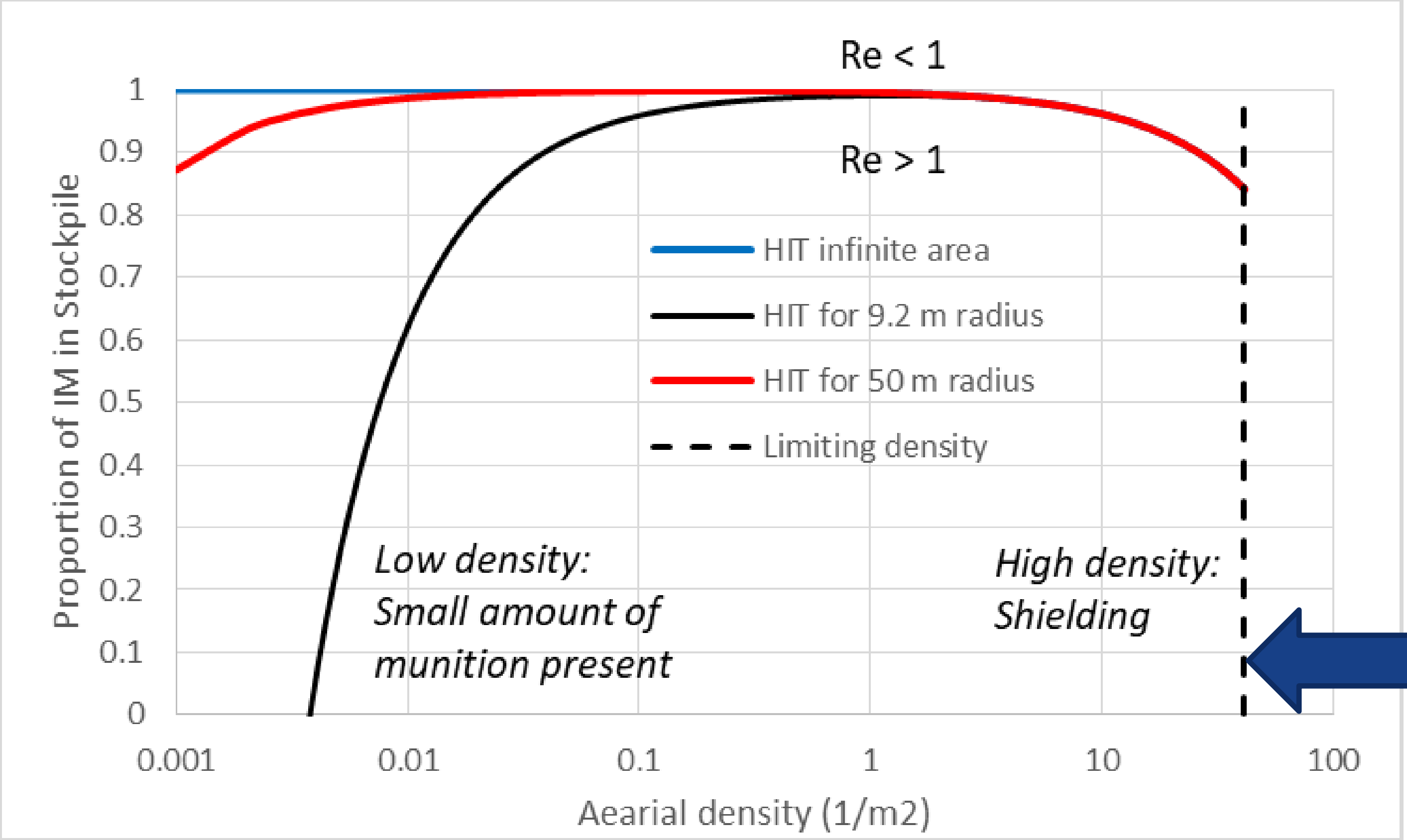
2D random distribution of munitions

- Mathematical derivation of number of detonations e.g. for 155 mm ammunition

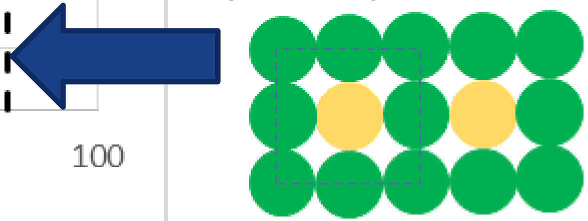


2D random distribution of munitions

- Herd Immunity Threshold as a function of aerial density and size of area

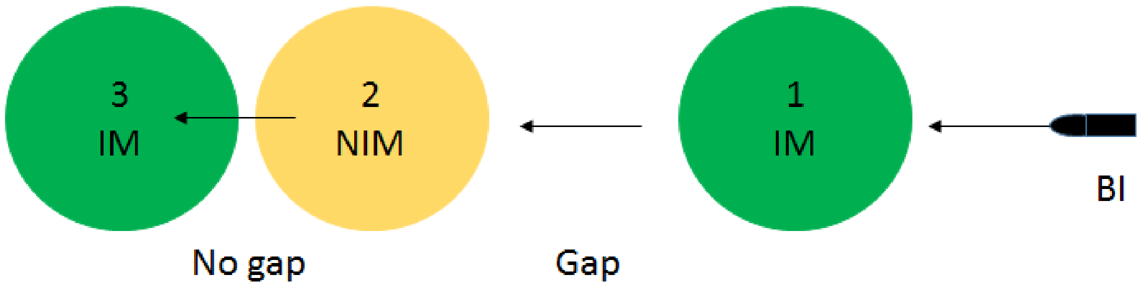


Square packing density
(41.6 /m^2)



Munition response in 1D configuration

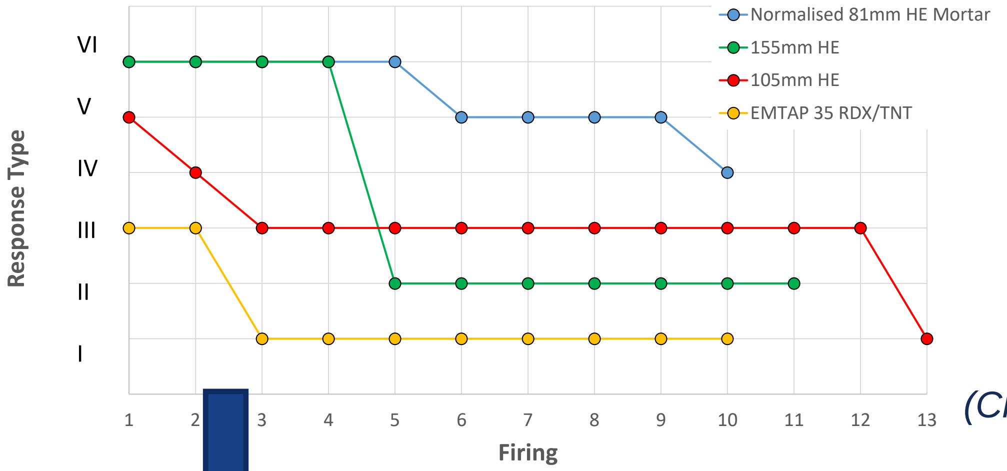
- Calculation method to predict probability of threats and responses based on test data and expert judgement

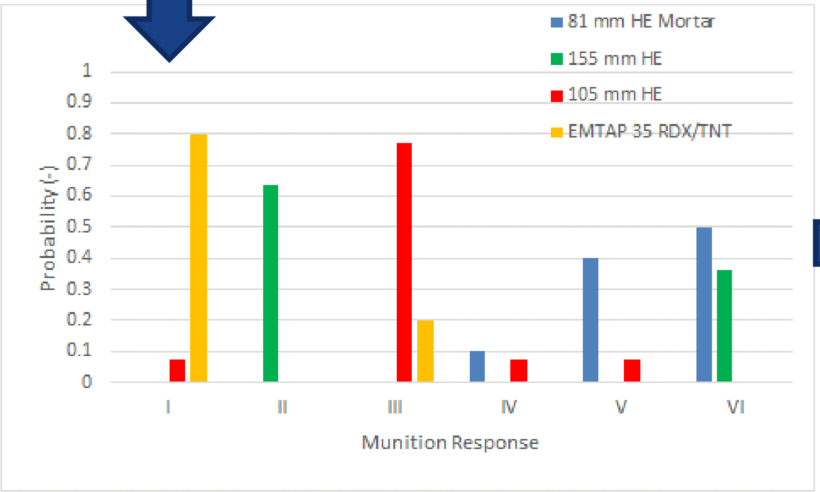


Threat (j)	SH	0
	FH	0
	BI	1
	FI	0
	SC	0
	SR	0

- Consists of:
  - Threat vector (T)
  - Threat-response matrix (TR)
  - Response-threat matrix (RT)
  - Response vector (R)

Munition response in 1D configuration





- Threat-Response (TR) matrix
  - To be filled based on test data
  - Response probability distribution
  - For each threat

(Cheese, Keefe & White, 2018)

		Threat (j)					
		SH	FH	BI	FI	SC	SR
Response (i)	I	0.01	0.01	0.01	0.01	0.01	0.01
	II	0.01	0.01	0.01	0.01	0.01	0.01
	III	0.01	0.01	0.01	0.01	0.5	0.5
	IV	0.01	0.01	0.01	0.01	0.25	0.25
	V	0.9	0.9	0.9	0.9	0.2	0.2
	VI	0.06	0.06	0.06	0.06	0.03	0.03

Munition response in 1D configuration

- Response-Threat (RT) matrix
  - What threat does a munition response pose to a next munition?
  - Based on expert judgment
  - E.g. detonation (I) or partial detonation (II) response
    - Leads to fragment (FI) threat when there is a gap, and SR threat when there is no gap.

		Response (i)					
		I	II	III	IV	V	VI
Threat (j)	SH	0	0	0	1	1	0
	FH	0	0	0.2	0	0	0
	BI	0	0	0	0	0	0
	FI	1	1	0.8	0	0	0
	SC	0	0	0	0	0	0
	SR	0	0	0	0	0	0

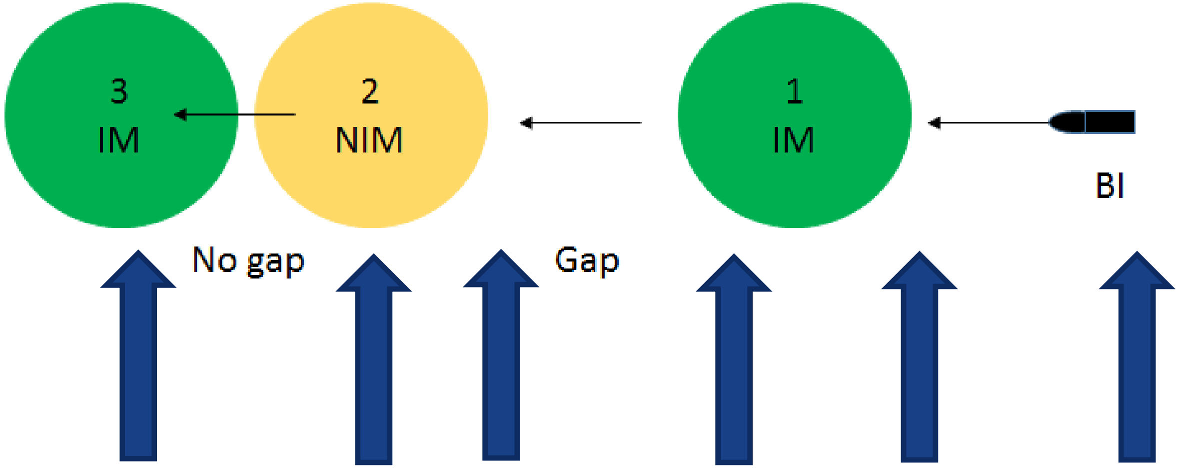
RT matrix for gap situation

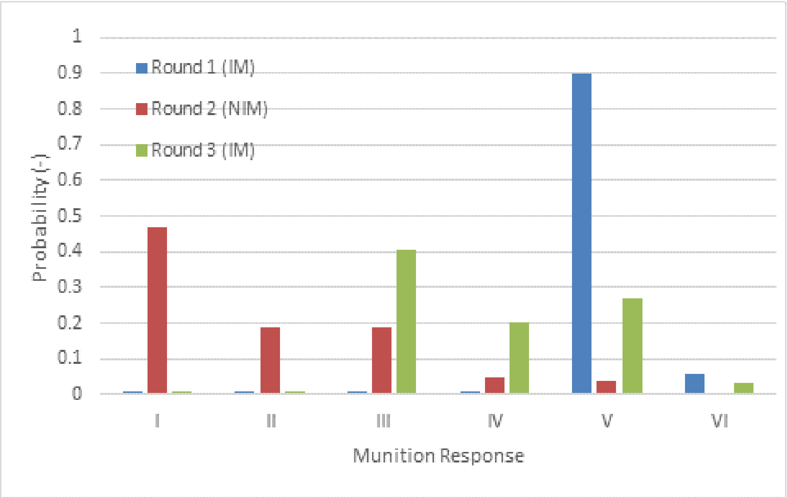
		Response (i)					
		I	II	III	IV	V	VI
Threat (j)	SH	0	0	0	0	0.5	0
	FH	0	0	0.2	1	0.5	0
	BI	0	0	0	0	0	0
	FI	0	0	0	0	0	0
	SC	0	0	0	0	0	0
	SR	1	1	0.8	0	0	0

RT matrix for no gap situation

Munition response in 1D configuration

- Calculation of the response vector of round 3





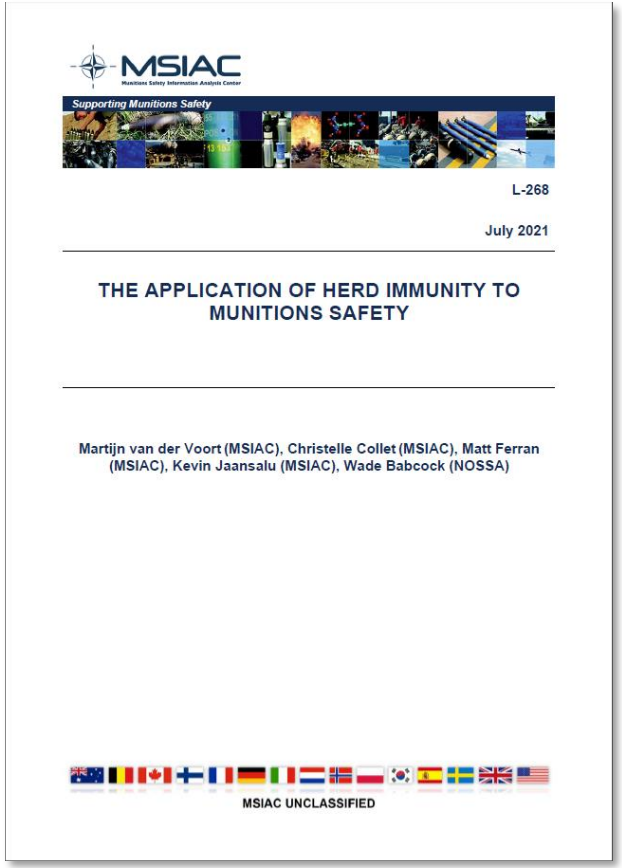
$$R_{3,i} = TR_{IM,ij} \cdot RT_{NG,ij} \cdot TR_{NIM,ij} \cdot RT_{G,ij} \cdot TR_{IM,ij} \cdot T_{0,j}$$

Conclusions

- The models illustrate the importance of careful planning and design of storage, including buffered storage and other mitigation options

- Models can be further improved by adding more realistic assumptions of propagation of reactions, including less violent reactions, more complex geometries, availability of data for mixed munition configurations etc.

- The associated report (MSIAC L-268) presents a theoretical basis that may help national authorities assess the interim benefits of IM investments, during the period when inventories are only partially converted


MSIAC
Supporting Munitions Safety

L-268

July 2021

THE APPLICATION OF HERD IMMUNITY TO MUNITIONS SAFETY

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MSIAC UNCLASSIFIED

Approaches to Lifing Algorithms

Outline

- Aim:
  - Describe the ageing of materials
  - Outline algorithms and requirements for capturing ageing processes of energetic materials
  - Basis for improved munition lifing predictions

- Part I: The System in which the Algorithm Operates
- Part II: Four Situations for Algorithms
- Part III: The Algorithms

Part I: The System

Influences:

- Information available as input
- Nature of output (i.e. what information it must give to be of use)

Must understand:

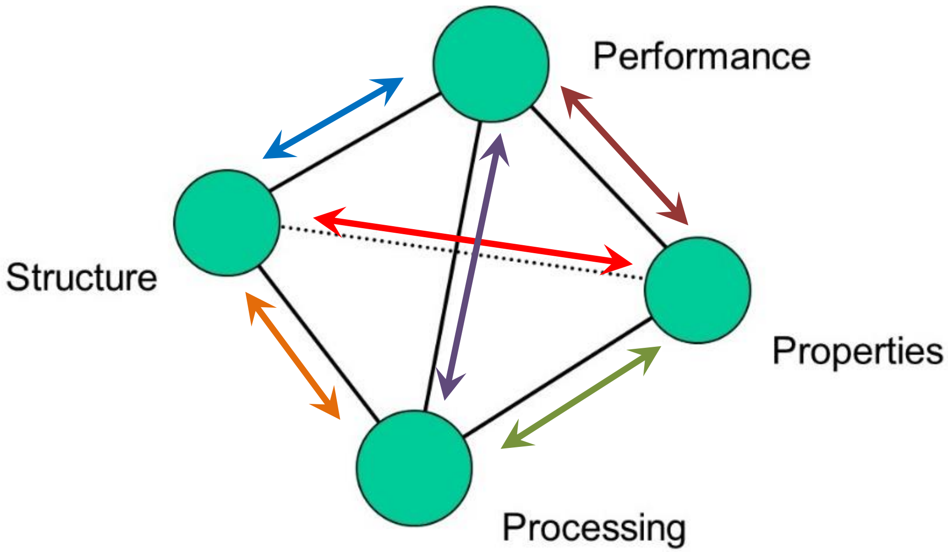
- What constitutes “end-of-life” for a munition / energetic material
  - Understanding of environment within which munitions operate
- National munition safety practices, inc.:
  - Approaches to life management
  - Procurement strategies
  - Environmental testing programs employed
  - In-service surveillance (ISS) practices, inc. munition health monitoring (MHM)

Part I: The System

- Munitions exposed to natural and induced mechanical and climatic environments

- Leads to mechanical and thermomechanical forces being imparted onto munitions
  - Chemical ageing
  - Mechanical damage

Part I: The System



- What is “End-of-Life”?
  - Point at which there is an adverse effect on performance or safety
    - Hazard properties
    - IM response
    - Burning rate / blast / pyro output etc.
  - Point at which material composition / structure or properties are out of tolerance
    - E.g. remaining stabilizer levels
  - Equivalent environmental exposure
- Material, system and application dependent

National munition safety practices:

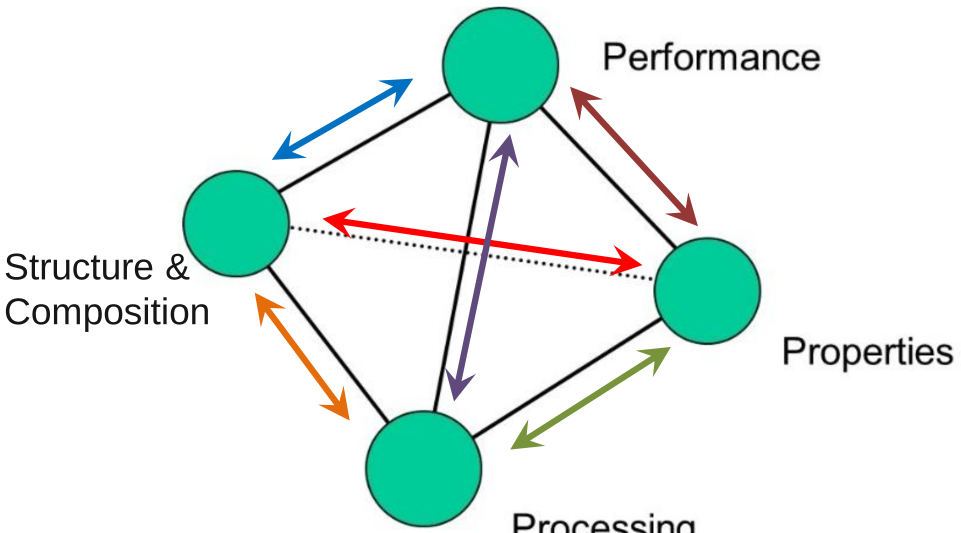
- Different national approaches to lifing:
  - **Definite Life:** end-of-life defined by environmental exposure or time – based on environmental testing undertaken
    - e.g. 10 years storage, 1,000 flight hours, 10,000 km road transport
  - **Indefinite Life:** end-of-life defined by a condition, as monitored through ISS
    - e.g. stabilizer remaining, strain to failure, observed cracking
  - Reflective of national risk tolerance (perhaps as legislated); also customary

Part I: The System

- Life Cycle Environmental Profile (LCEP)
  - Foreseen at the time of design and qualification vs actual exposure
- Environmental Testing Program
  - Use of time compression
- Procurement Scheme (e.g. MOTS, COTS, FMS)
  - Determines what information will be available

It is within this, sometimes ill-defined, context that a lifing algorithm is expected to function.

Part II: Four Situations for Algorithms



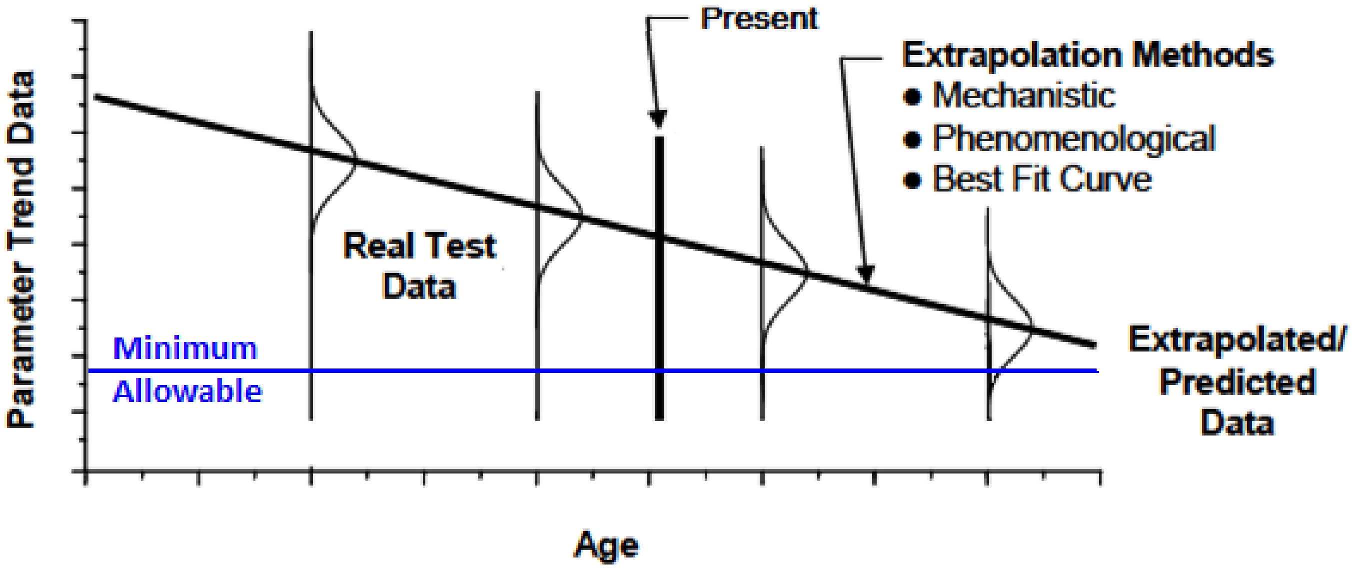
- Calculations that determine any or all of:
  - The end-of-life based on occurrences
  - Conditions for inspection interval / next inspection
  - Changes to material property and compares it to a defined value
  - Consequences on performance for different functions or roles

Part II: Four Situations for Algorithms

- Situation 1: Definite life after a set of occurrences (exposure)
  - Environmental qualification and service limits, service exposure, and models for equating processes
  - Differences in LCEP can cause issues.
- Situation 2: Material composition limits, there are suitable degradation models to predict next inspection / test
  - Situation with gun propellants
  - Manage life and prioritize use

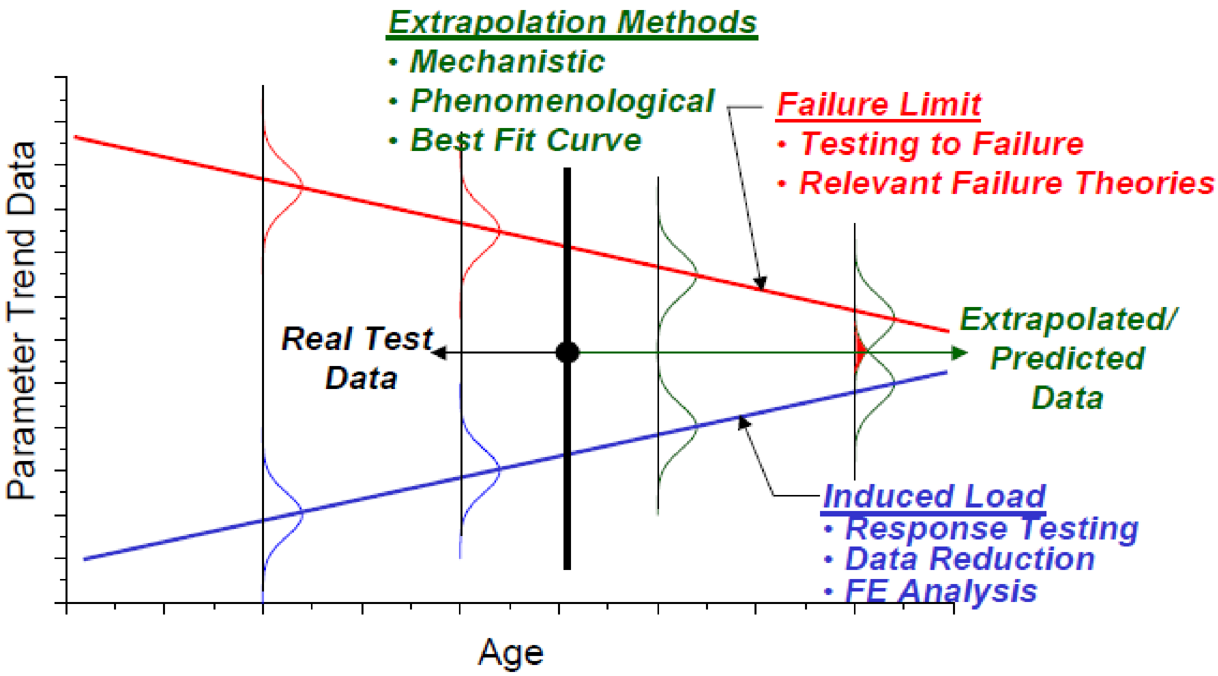
Part II: Four Situations for Algorithms

- Situation 3: Material property tolerances
  - Combines environmental service limits, material degradation modes and associated models, and actual service exposure



Part II: Four Situations for Algorithms

- <u>Situation 4:</u> Material Performance
  - complete engineering design data set, required material properties, tolerances, environmental service limits, material degradation modes and associated models, and actual service exposure.

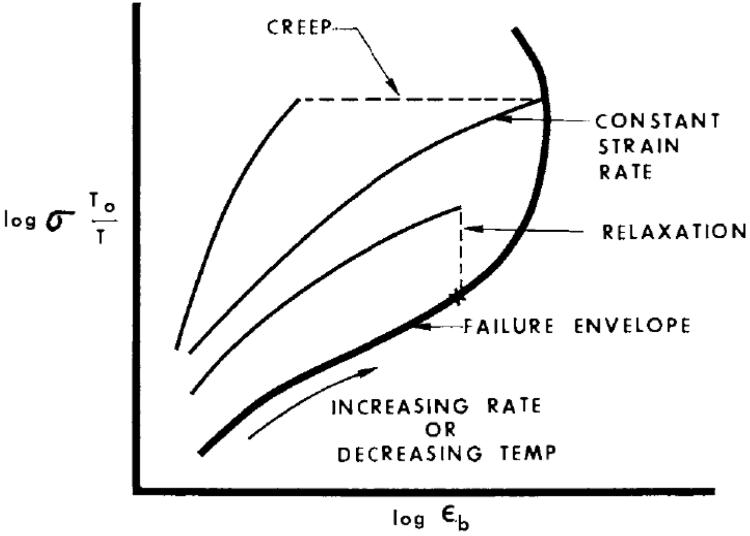


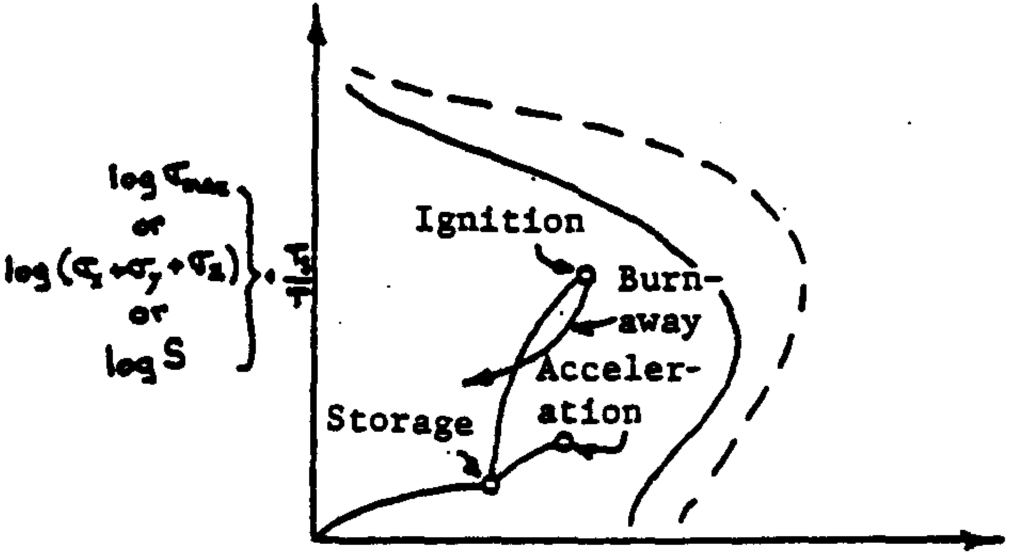
Part III: The Algorithms

- Work in progress
  - Rupture
  - Fatigue & Damage
  - Impact and Shock
  - Thermal Fatigue
  - Activated Process: Diffusion

Failure Algorithms: Rupture

- Rupture
  - Smith Failure Envelope – used for rubber components, some solid rocket motor formulations

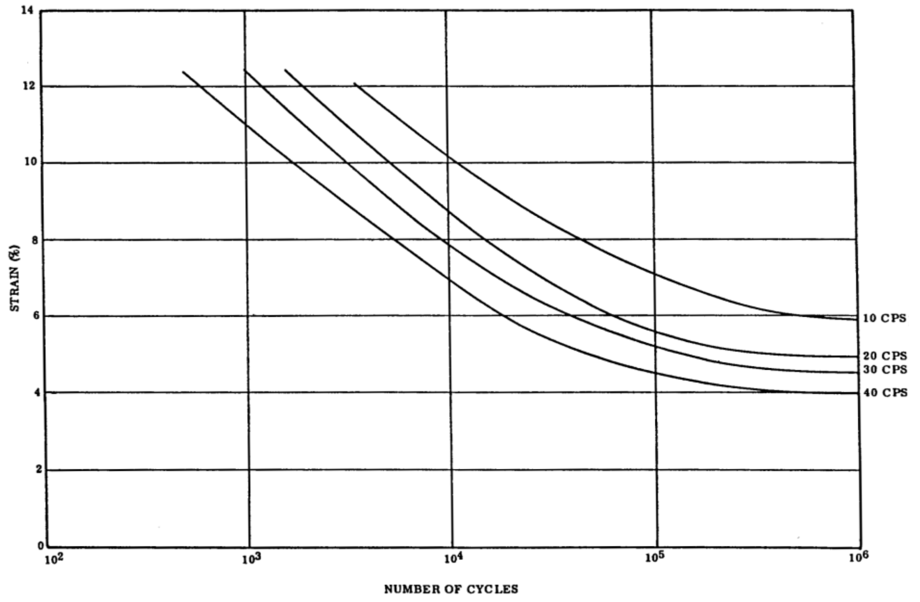




Failure Algorithms: Fatigue

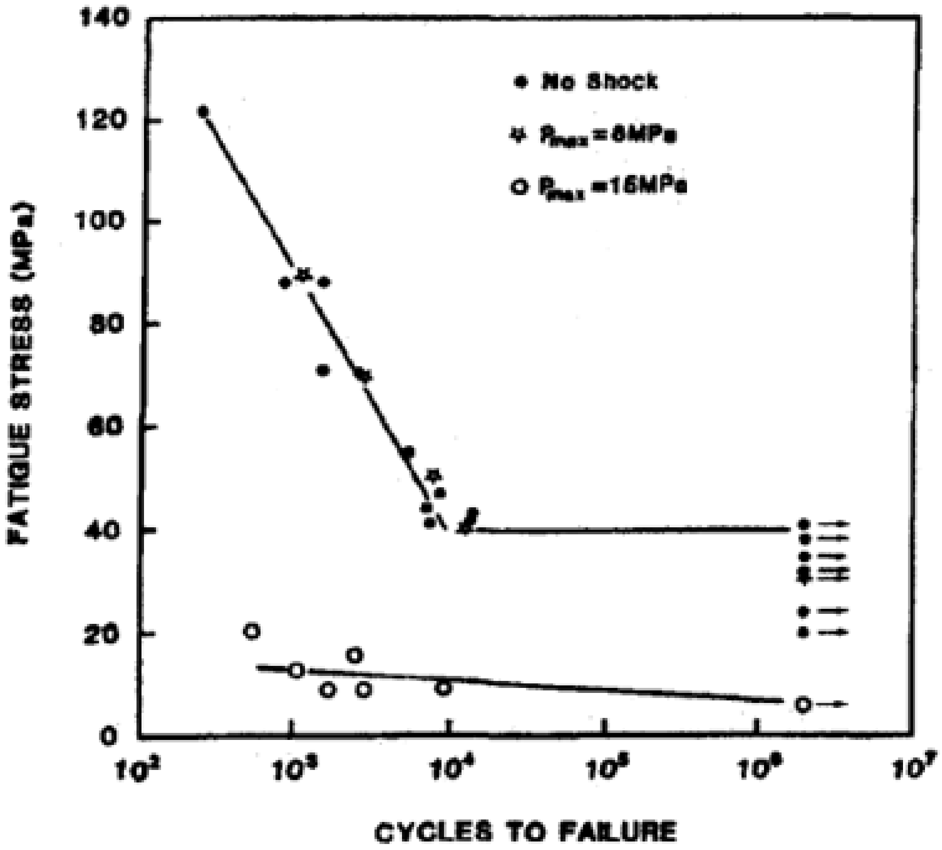
- Miners Rule: $C = \sum_{i=1}^{j} \frac{n_i}{N_i}$
- But order and frequency of loads affect count for polymeric materials
- Incorporate damage into constitutive models to account for effects of damage on strength

$$\sigma' = \frac{\sigma}{1 - D}$$



Failure Algorithms: Impact and Shock

- Account for effects of other events:
    - Here impact and shock on fatigue life of composite panels



Thermal Fatigue

- Over 100 different models in the literature
  - Most of these never in use
- Six popular categories in use:
  - Linear damage accumulation, frequency separation, ductility exhaustion, strain range partitioning, total strain – strain range partitioning, strain energy partitioning
  - No one model is the best
- In practice:
  - Model developed for a material and expected environmental conditions
  - Model validated by in-service monitoring

Activated Processes

- A general form for the reaction rate constant is:

$$k = A_0\, T^n e^{\left(-E_a/_{RT}\right)} e^{f(s)[C + D/_{RT}]}$$

- Reaction rate for consumption of, say, A:

$$\frac{dN_A}{dt} = -k\,[A]^\alpha [B]^\beta$$

- Similar dependency for diffusion and creep:

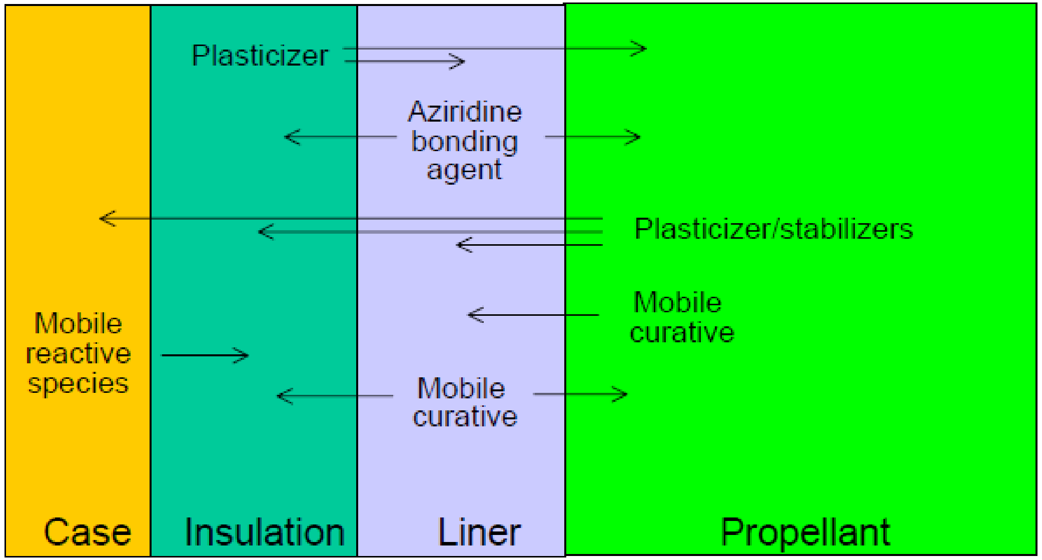
$\mathrm{D} = D_0 e^{\left(-E_a/_{RT}\right)}$ in $\frac{\partial\varphi}{\partial t} = D\,\nabla^2\varphi$ and $\dot{\varepsilon} = A_0\, e^{\left(-E_a/_{RT}\right)} 2\, sinh\left(\frac{w}{RT}\right)$

- Diffusion can be influenced by:
  - Stress
  - Other diffusing species

Diffusion: Rocket Motor Bond Integrity

- Six different groups across two to four materials
- Each material / species represents one differential equation
  - Two (or more) parameters to be fit for each equation
  - Each equation requires initial conditions

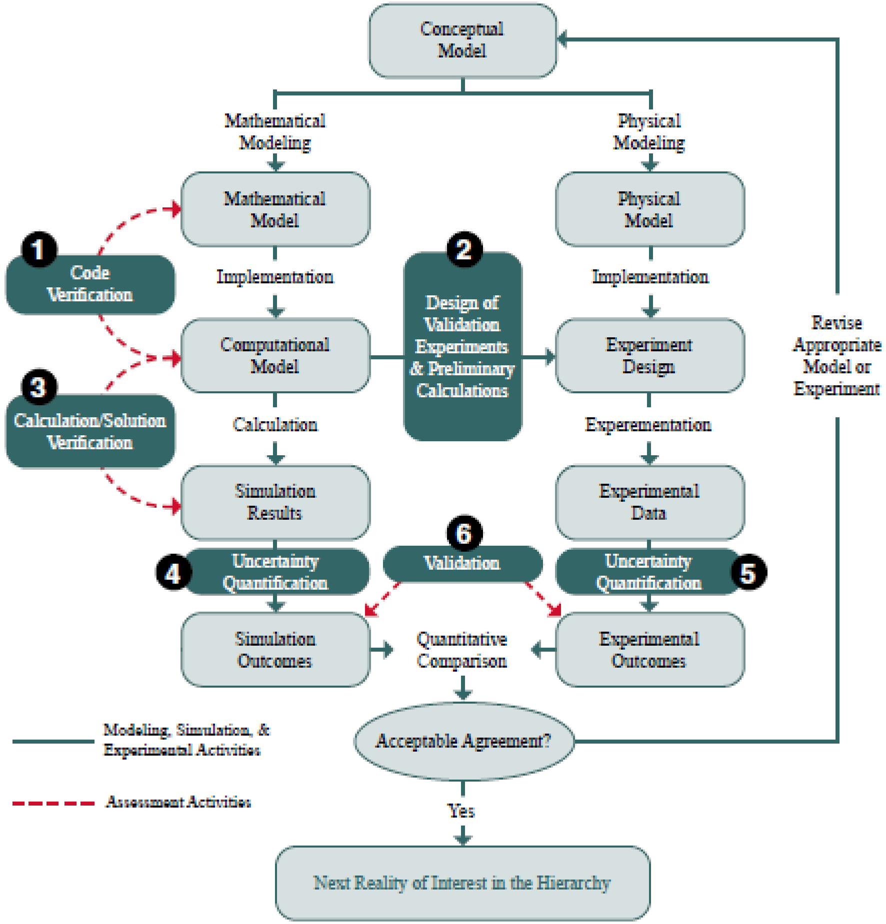
$$D = D_0 e^{\left(-E_a/RT\right)}$$



- Considering the arrows, have 24 equations
  - 48 parameters
  - 24 initial conditions starting ..
  - May need to account for stress
  - Diffusion cross coefficients
  - Uncertainty and error

Verification and Validation

- Continuous, ongoing process
- Not well covered in research and academia
  - Very few peer review articles
  - Includes uncertainty quantification
- It is a disciplined, rigorous, and often underestimated, process



Summary

- The System in which the Algorithm Operates
  - “End-of-life”
  - National munition safety practices
- Four Situations for Algorithms
- The Algorithms
  - Verification and Validation

- MSIAC developing technical report to collect the most common age-induced degradation mechanisms