Predicting Hazard Response Scenarios in Weapon Systems

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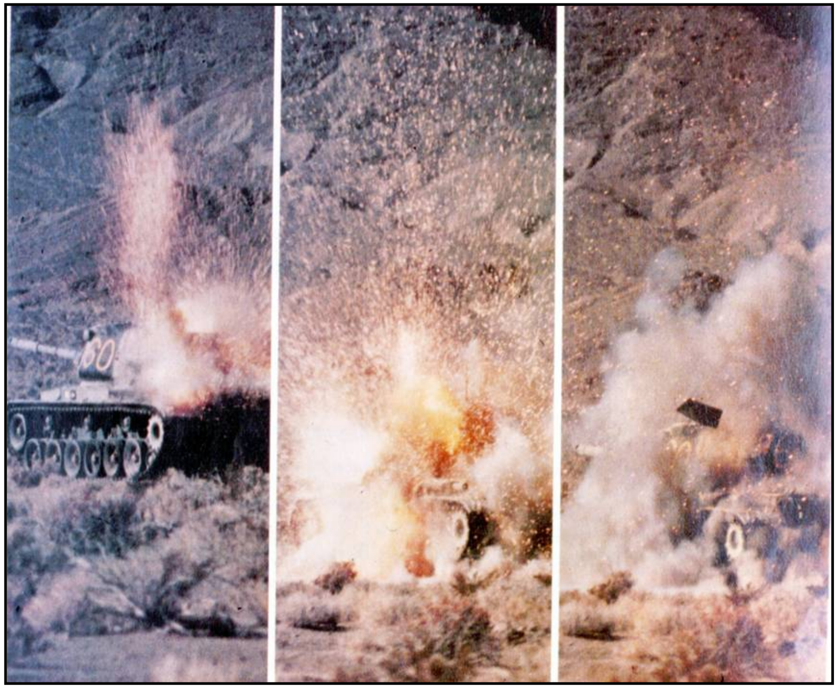
A presentation to: 24th International Symposium on Ballistics



Date: 22nd - 25th September 2008

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Contents

01 Background

The changes in the way the UK armed forces are being asked to deploy as part of Rapid Reaction peacekeeping forces and their long-term evolution into the Balanced Force concept demands the transport and store in forward ammunition dumps of different mixes of weapon systems and ammunition. An understanding of the associated hazard would allow this to be achieved with a minimum and well-defined risk factor.

It is an essential element of the MoD’s Duty of Care to the Armed Forces.

01 Background

Camp Falcon: US Army Ammunition Holding Area Iraq.

- 10th October 2006 Insurgent attack with 82mm mortars.
- Struck storage area for flares & illumination munitions. Started fire which spread to other stores.
- 7 EOD teams fully committed dawn to dusk
- Needed to secure area 1000ft radius.
- FIRE is an important hazard!

01 Background

Hazard Responses.

- Type 1: Detonation, characterised by a supersonic decomposition reaction.
- Type II: Partial detonation.
- Type III: Fast combustion of confined material (explosion) with a local pressure build up.
- Type IV: Combustion/deflagration characterised by a non-violent pressure release.
- Type V: Combustion.

Research Context.

- Need a fundamental understanding of the controlling physics and chemistry within energetic materials.
- This applies to ALL systems that contain an energetic material component.
- It provides a key component in establishing Through Life Cost of any munition procurement.

01 Background

Building Blocks

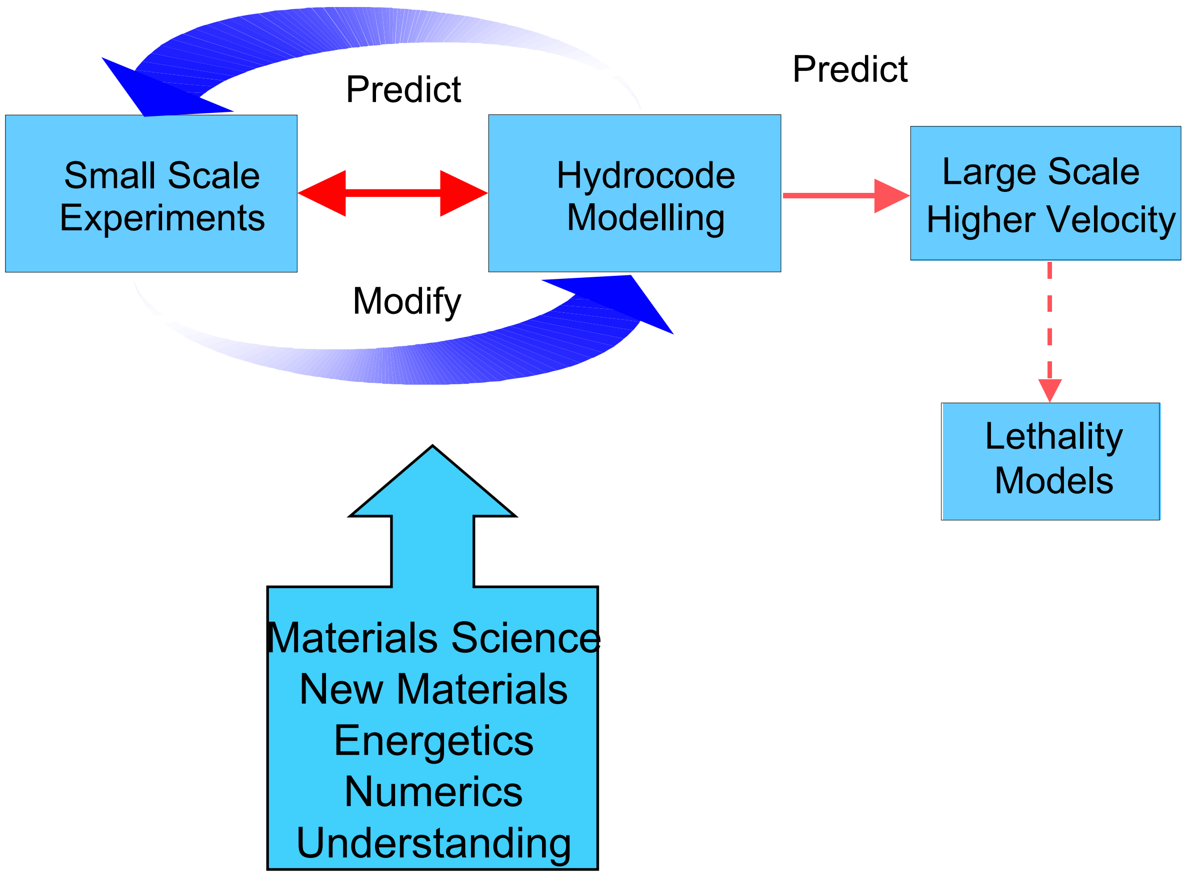
- Constitutive Response: deformation heating
- Chemical Response: ignition & growth
- Burning Response: deflagration, detonation

Needs

- Material models: EoS, constitutive, damage, fracture
- Ignition mechanisms and their description
- Link between constitutive response (damage) and ignition source term
- Burning models
- Experiments: characterisation, validation

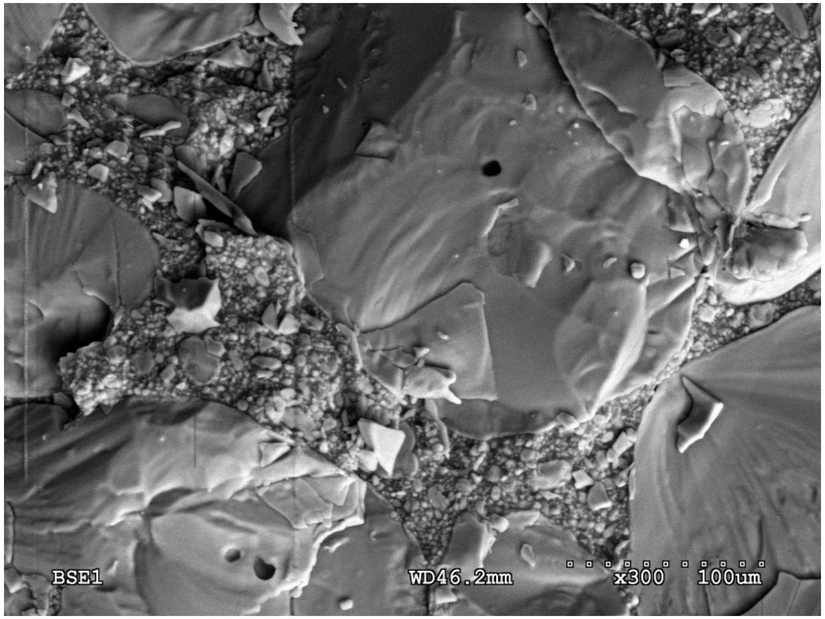
01 Background

Integrated Modelling



02

Material Model: Equation of State



02 Materials Models

Objective

To develop predictive Equations of State based on materials science with as few fitting parameters as possible – ideally none. Porter-Gould methodology, based on Group Interaction Modelling.

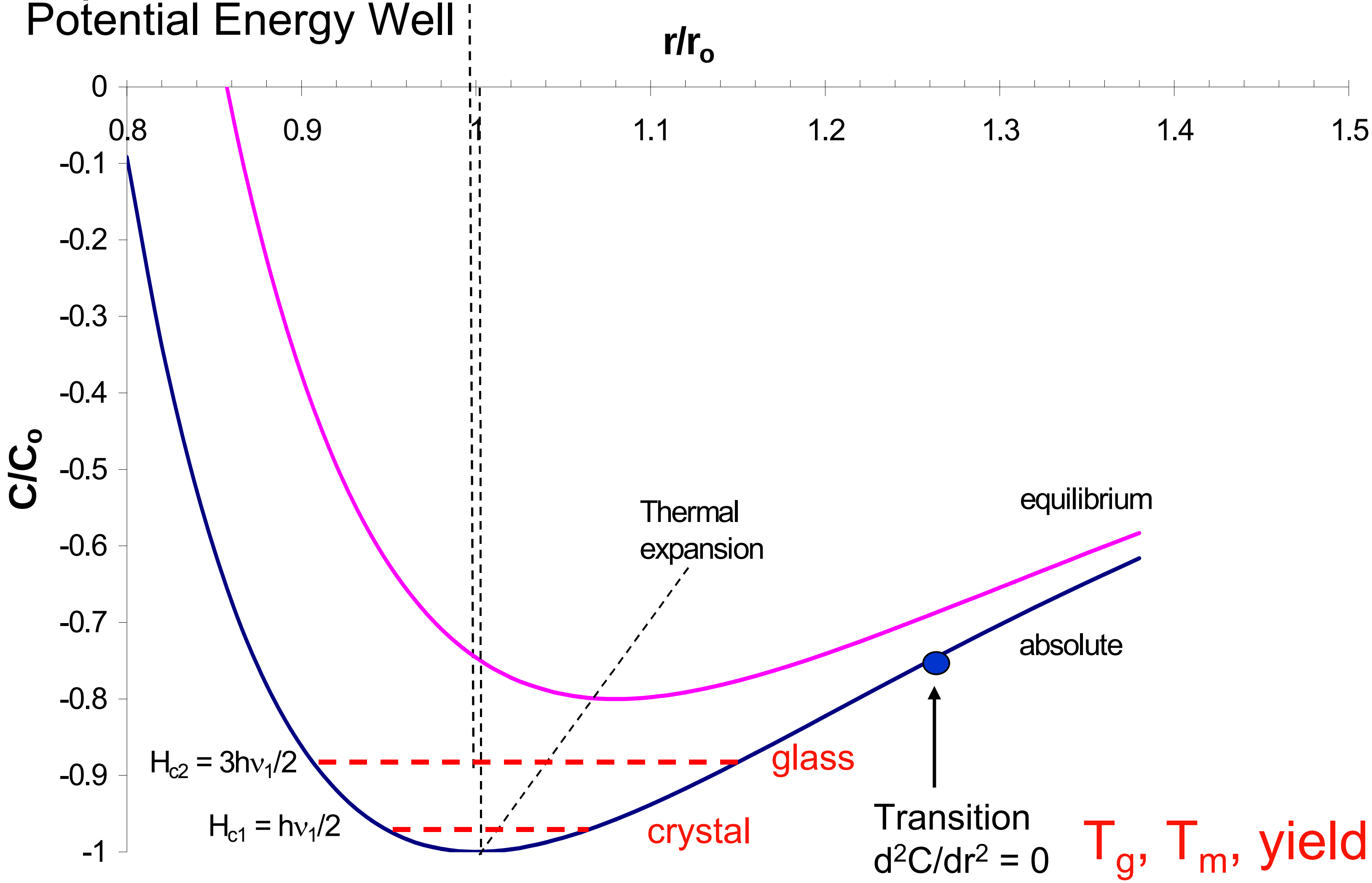
To develop predictive continuum based deformation and failure algorithms. These attempt to link the meso-macro scale and deal with anisotropic plastic deformation, failure and fracture.

Active strategy for the past 25 years – pioneered by Barry Goldthorpe, Philip Church.

Different approach to materials tests and models.

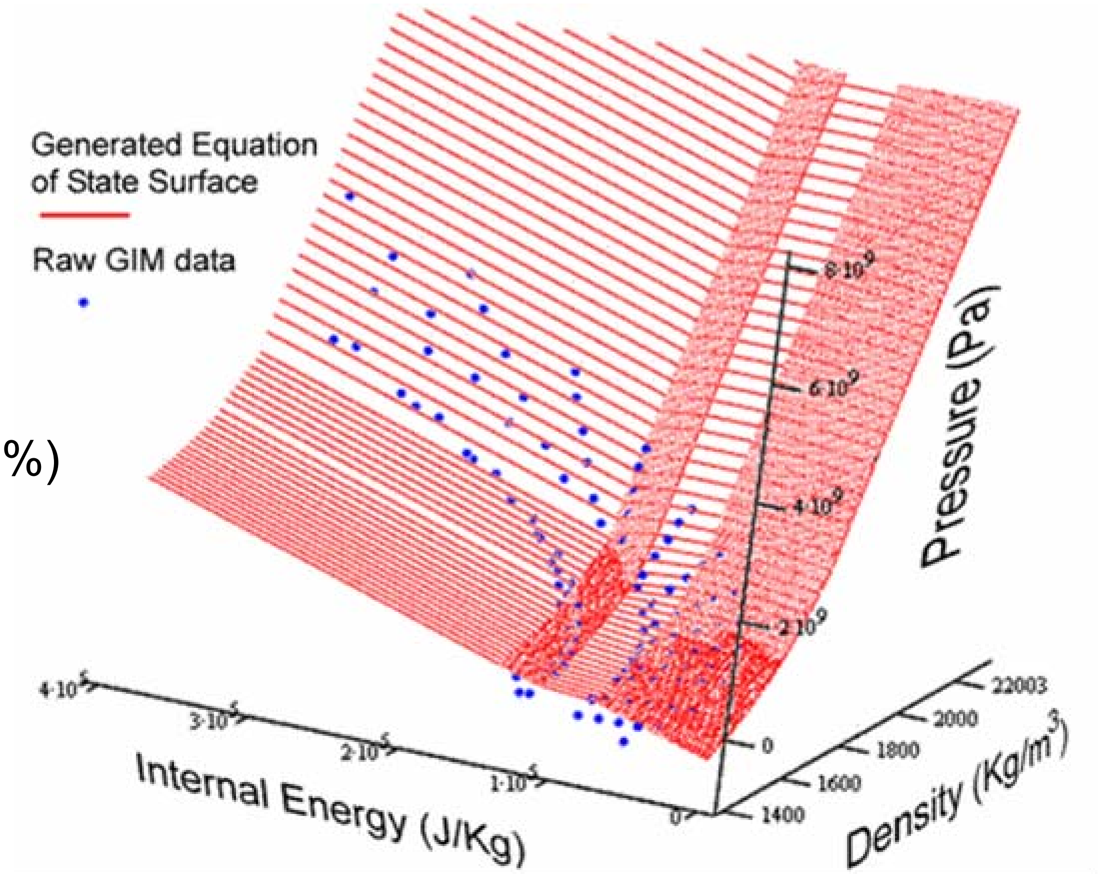
Predictive - within 5% of experiment or within experimental error.

02 Equations of State
Potential Energy Well



02 Equations of State

RX1100
(RDX:HTPB :: 88%:12%)



02 Equations of State

Specific Heat

Activation Model

Prediction of reaction properties: HTPB

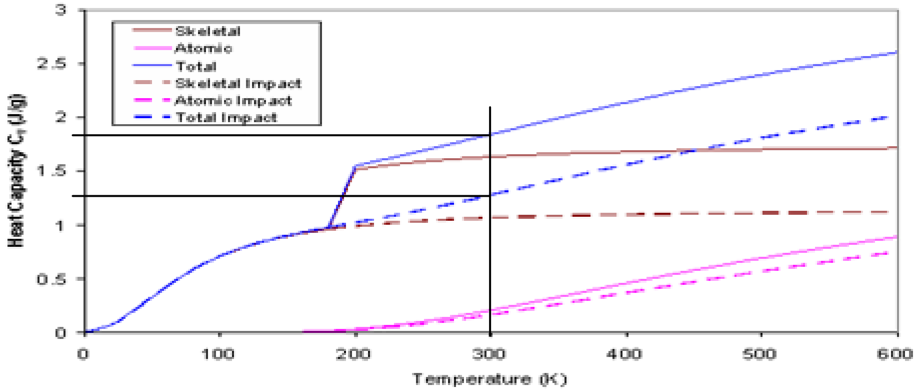
Experimental: C_p = 1.95 Jg^{-1} at 300K

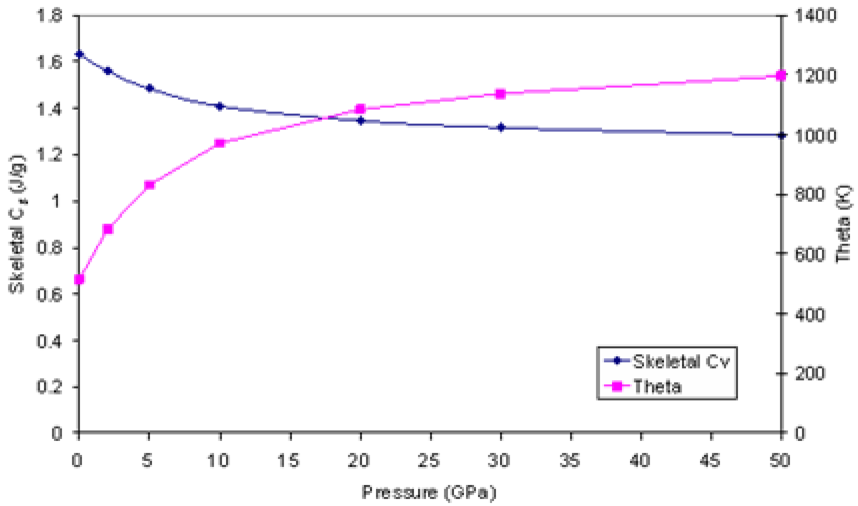
Model: C_v = 1.86 Jg^{-1} at 300K

Menikoff: C_p and C_v differ by only 5% for these materials

RDX: Cv = 0.96 Jg^{-1} compared with experimental Cp = 1.0 Jg^{-1}

Can also predict the dependency with pressure, a significant effect and crucial for hazard studies





03

Material Model:
Constitutive Response

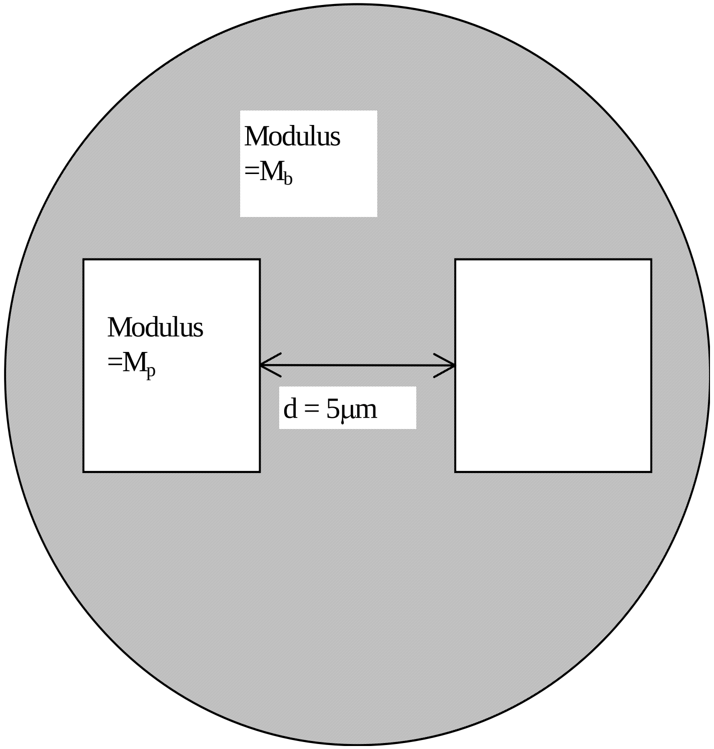
03 Constitutive Response

Binder properties

- Predicted from chemistry via Group Interaction Modelling
- Particle size distribution magnifies the binder effects
- Hierarchical model built up through multiple length scales
- Elastic material with an elastic limit
- Unique approach

03 Constitutive Response

Hierarchical model

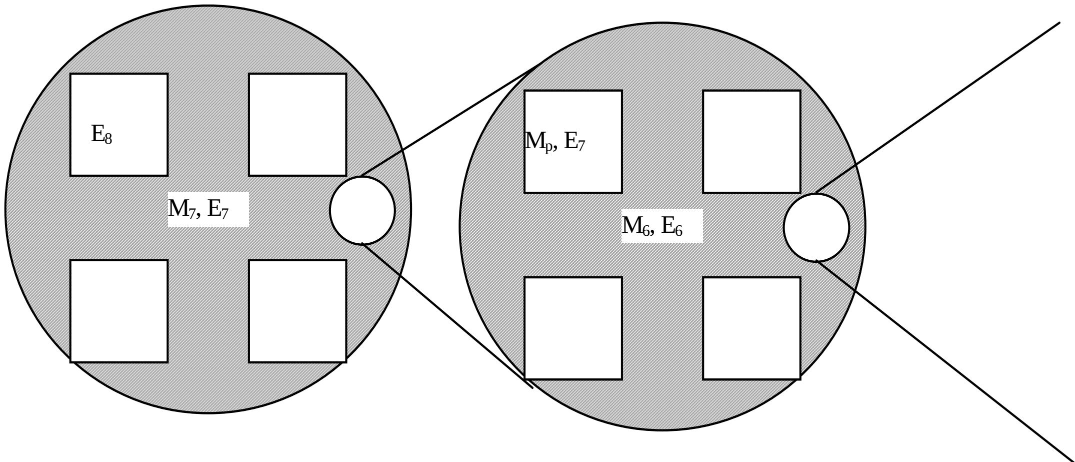


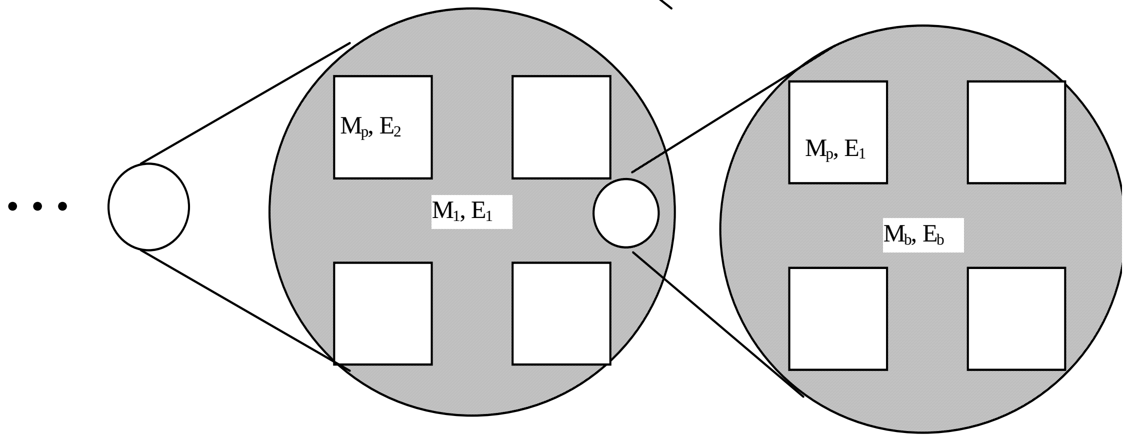
Local composite modulus

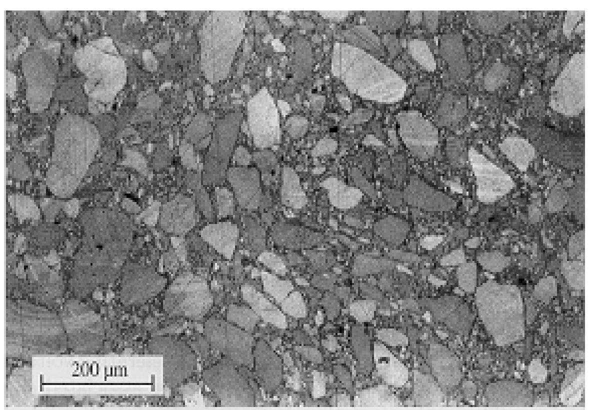
$$\frac{1}{M_{local}} = \frac{f_{V,particle}}{M_{particle}} + \frac{f_{V,binder}}{M_{binder}}$$

Schematic of smallest length scale within composite

03 Constitutive Response





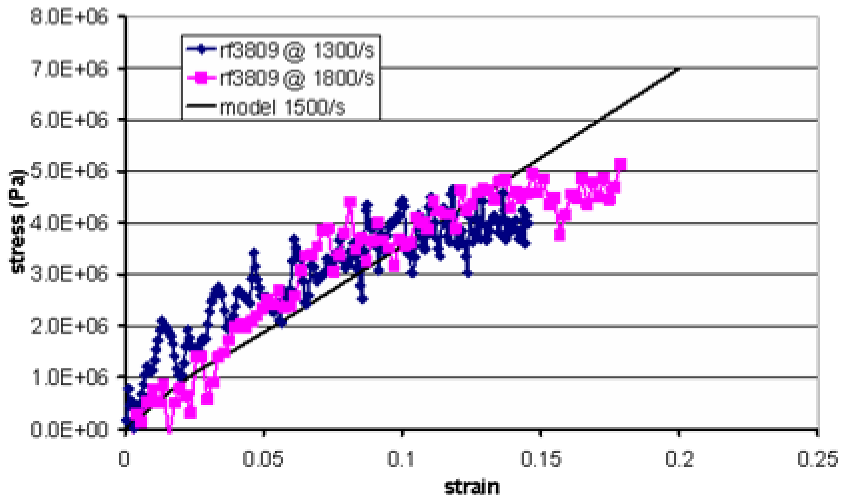


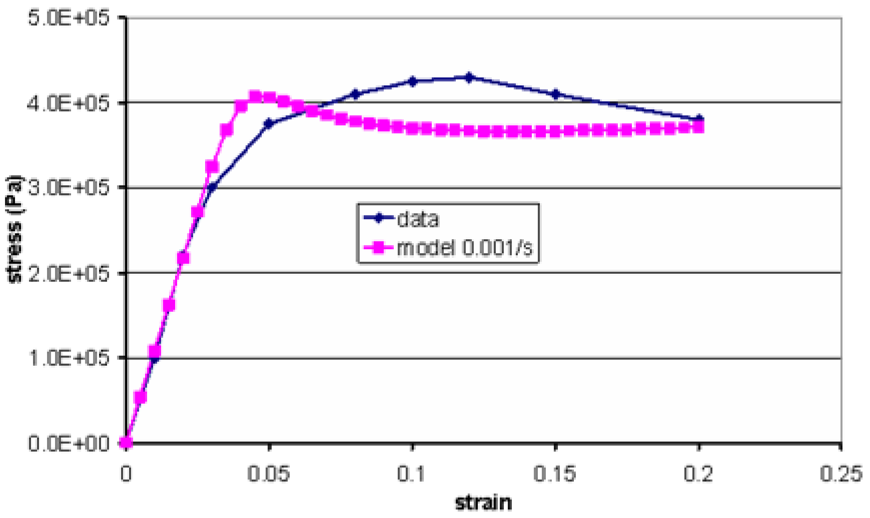
Micrograph from: PJ Rae, HT Goldrein, SJP Palmer, JE Field, AL Lewis, Proc. Roy. Soc. Lond. A**458** (2002) pp743-762

03 Constitutive Response

Basic Model

- Can predict stress – strain behaviour over a range of strain rates.





03 Constitutive Response

Two types of failure:

- damage
- fracture

Damage is local failure and may lead to hazard response

Fracture is complete failure - material can no longer support load

Need to quantify the effect upon deformation and upon hazard response

addressing specific microstructural events

03 Constitutive Response

Energy segregation gives most deformation energy in binder.

Work to fracture the binder is significantly lower than for interface or for filler particles.

Most likely damage is local brittle failure of binder leading to voids and removal of constraint.

Fracture of filler particles will lead to increased hazard.

03 Constitutive Response

Polymer properties calculated by considering the separation distance of polymer chains. (GIM)

Chain separation beyond a certain distance breaks the weak bond between chains on one side.

This relaxes any constraint on the polymer chain but still allows it to support load via bonds with chains on other sides.

On a continuum level we can introduce the concept of a “failed” state – a polymer chain that has been separated from some of its neighbours by a cavitation event. As crazing is a general nucleation of cavitation sites then in any particular volume, there will be a fraction of “failed” states that do not contribute to constraint – although they will contribute to modulus.

Crazes link to form planes.

03 Constitutive Response

Evolution of binder modulus can be determined as a function of damage.

$$M_b = 2.5 - 1.9 * f_f$$

$$f_f = \frac{2*\exp\left(-E_0 / E\right)}{1+\exp\left(-E_0 / E\right)}$$

We can predict:

- spacing of craze planes and thus surface area
- craze size and number of voids in each craze
- void size

- Craze planes close up on unloading
- Can predict conditions under which particles will crack

03 Constitutive Response

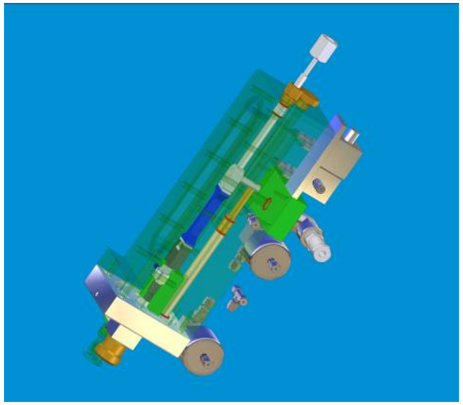
Material Damage

- Extensive research in polymers on this subject.
- Damage in composite due to debonding.
- Tomography provided validation. Can estimate created surface area caused by debonding.
- Implemented in GRIM and tested on different insults to ROWANEX1100.
- Basis for a variable hotspot density model in ignition and growth models.
- Ideas successfully being developed to describe cement composites.

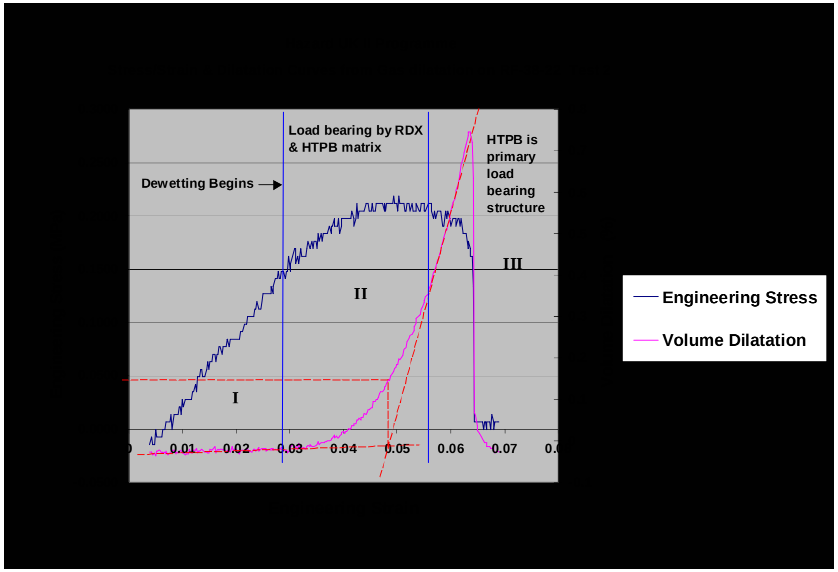
03 Constitutive Response

Gas Dilatometer

- Direct measurement of porosity and Poisson's ratio.
- Direct measurement of damage as a function of tensile strain.



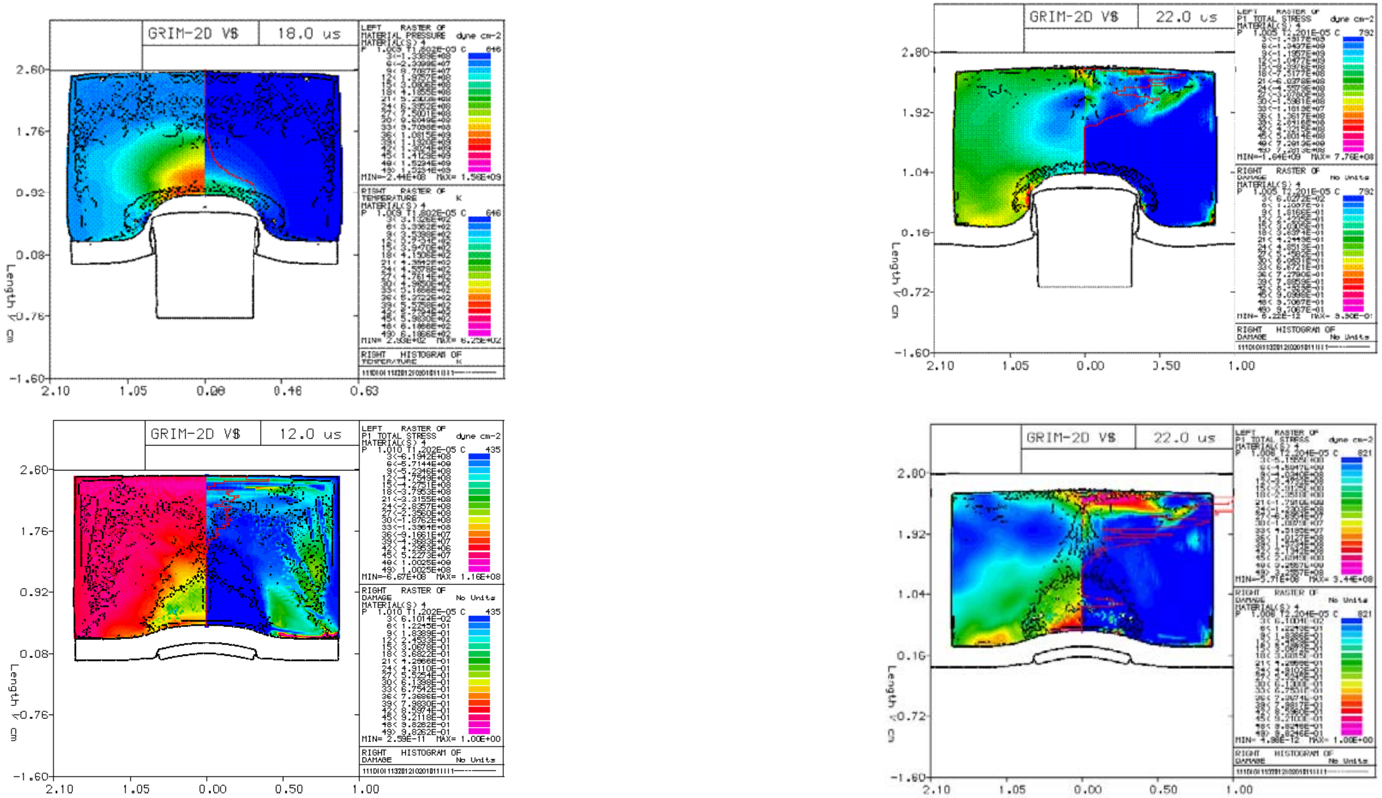
Dilatometer



Damage and stress histories

03 Constitutive Response

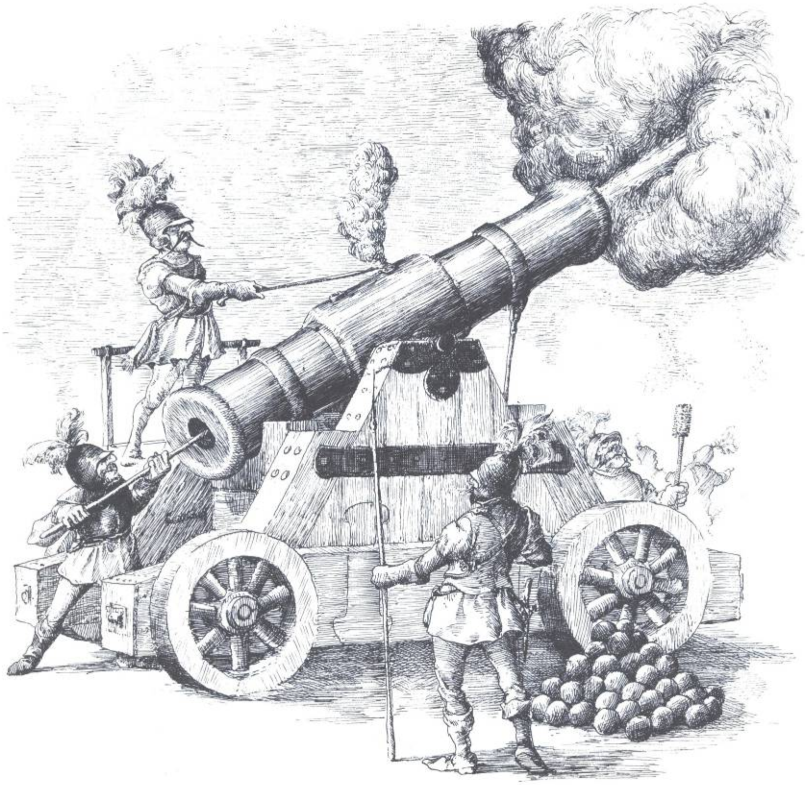
Material Damage



Fragment attack v=450m/s

04

CHARM



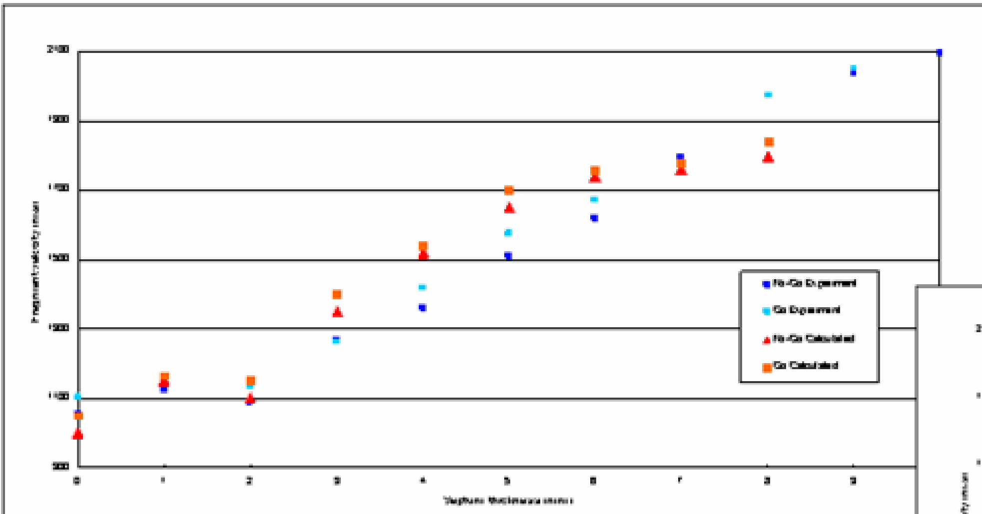
04 CHARM

CHARM Modelling

- Temperature driven 3-step Arrhenius chemistry to describe chemical reaction in solid to produce gaseous products and release of energy.
- Ideally fit the chemistry to ODTX.
- Predict fragment impact experiments (13.15mm diameter projectiles etc.)
- Adjust model to obtain best fit.
- Predict other diameter fragments
- Predict response of weapon.
- BUT, needs material data, needs ‘chemistry’ of explosive, often has to use literature data of ‘similar’ explosives.

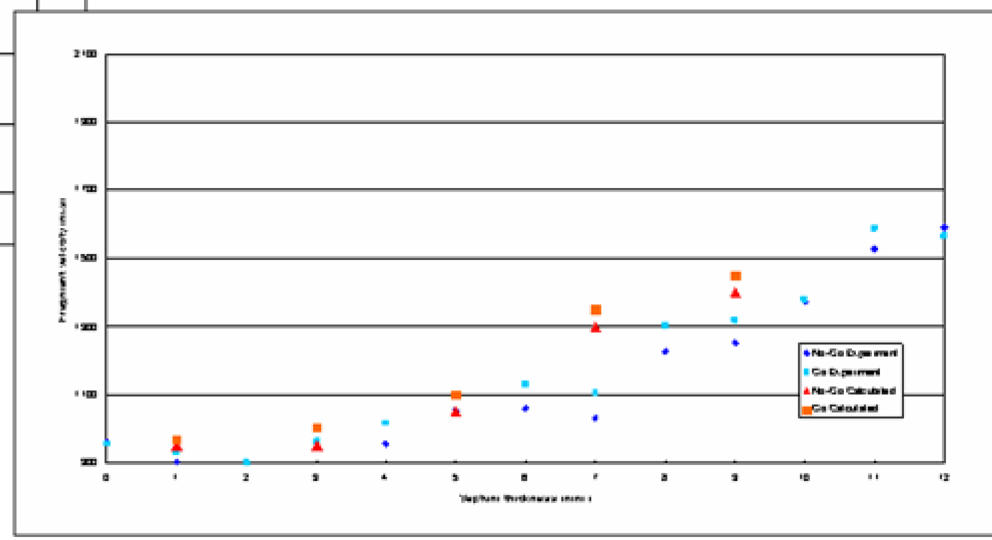
04 CHARM

CHARM: Rowanex 1001 fragment impact SDT Threshold data



13.15mm diameter projectile

20mm diameter projectile



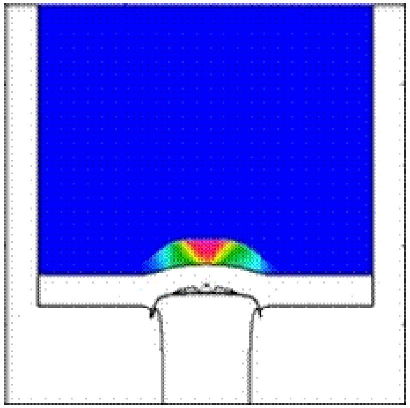
Experimental point: blue
Calculated: red

04 CHARM

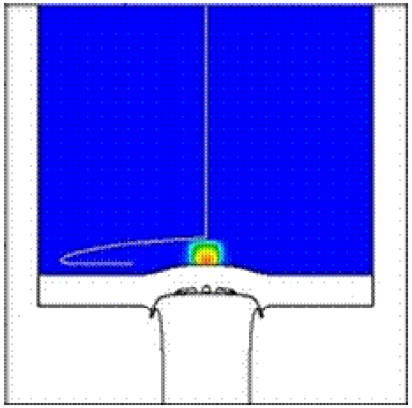
CHARM: Rowanex 1001 fragment impact SDT Threshold data

Pressure - Energy

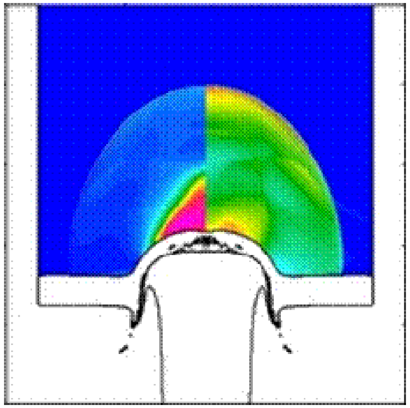
Gas Evolution



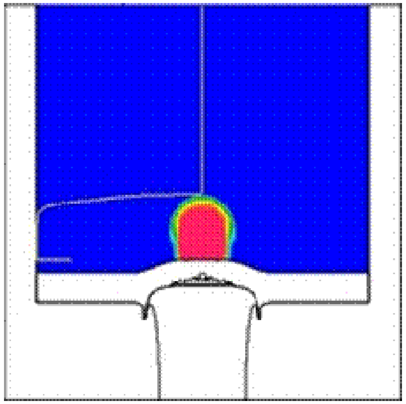
1.5µs



1.5µs



6.0µs



2.25µs

04 CHARM

Rowanex 1100 fragment impact SDT Threshold data

PG EOS

PG Constitutive Model

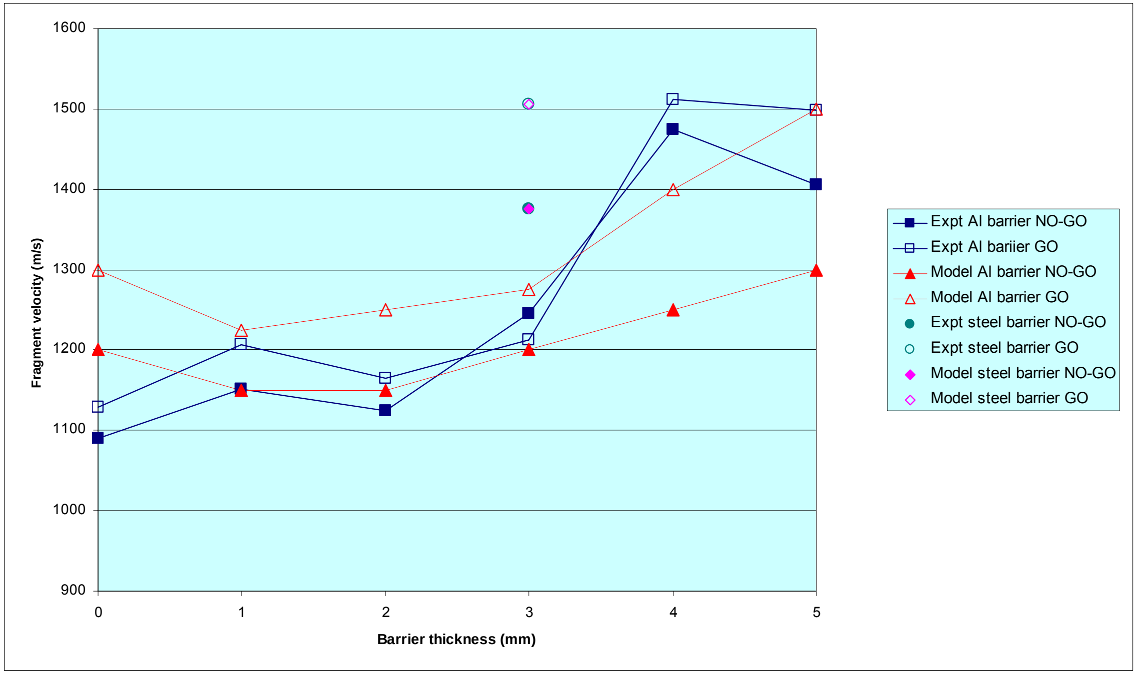
Pore number (size 5μm)

- $5.10^{10} m^{-3}$ in crystals
- $5.10^{10} m^{-3}$ due to debonding
- Porosity $6.5.10^{-6}$

Chemistry

- -1st step adjusted

Experimental point: blue
Calculated: red



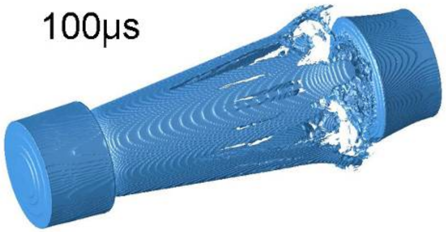
13.15mm diameter projectile

05
Munition System

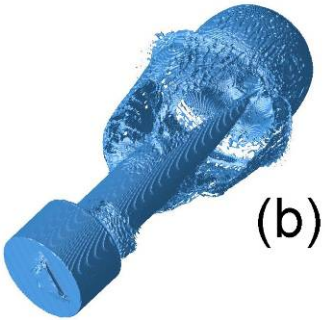
05 Munition System

Tube Test Explosiveness Levels

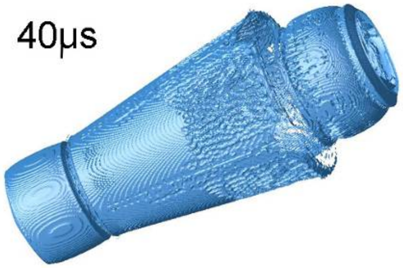
I – Pressure Burst



II - Deflagration



III - Explosion



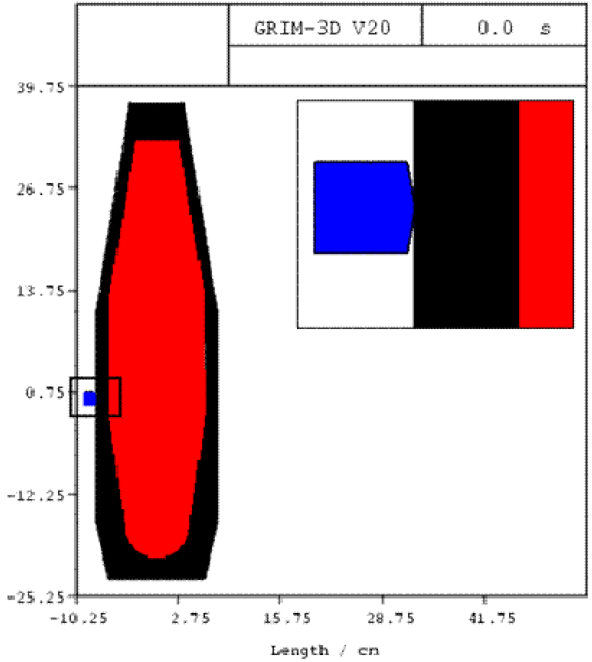
IV - Detonation

05 Munition System

Artillery Shell Fragment Attack Hazard

- CHARM, employing the advanced Equations of State (EOS), the Porter-Gould constitutive model and a physically based hotspot density distribution to predict the fragment attack experiments of an artillery shell.

STANAG Fragment v=2536m.s^{-1}

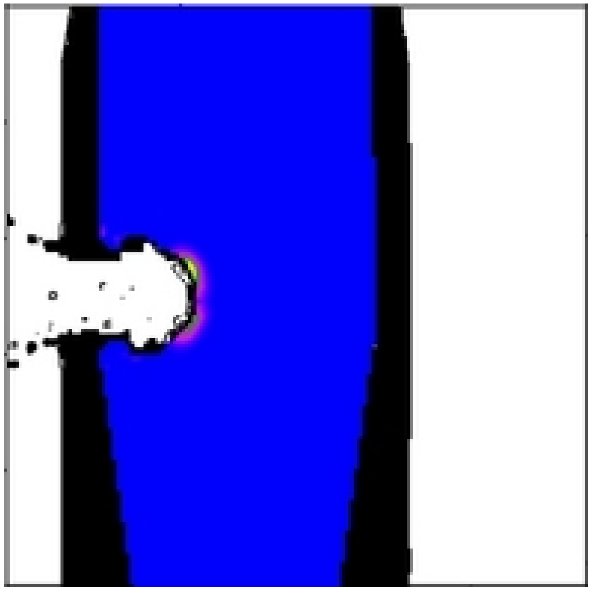


05 Munition System

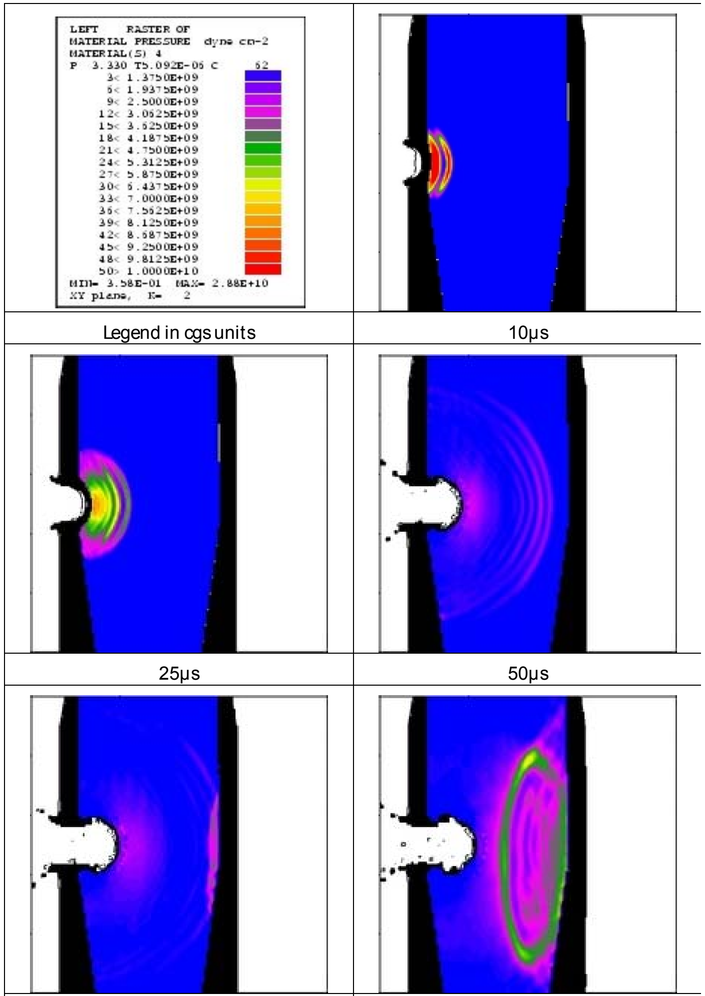
Artillery Shell Fragment Attack Hazard

Pressure field shows SDT not a mechanism

Gas evolution suggests low level BVR



Gas evolution 80μs

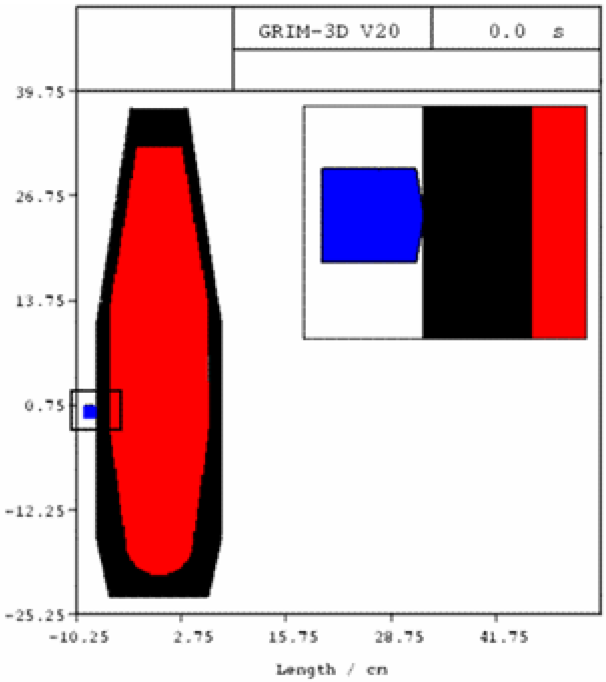


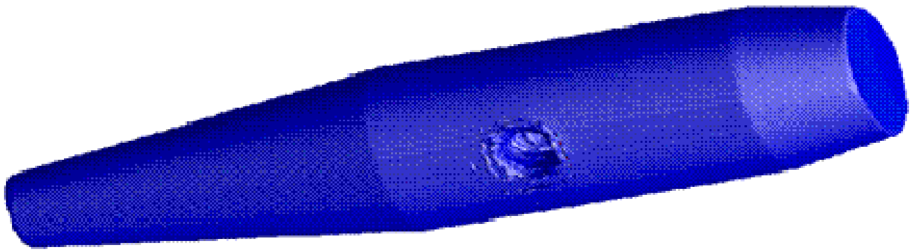
Legend in cgs units | 10μs | 25μs | 50μs | 60μs | 80μs

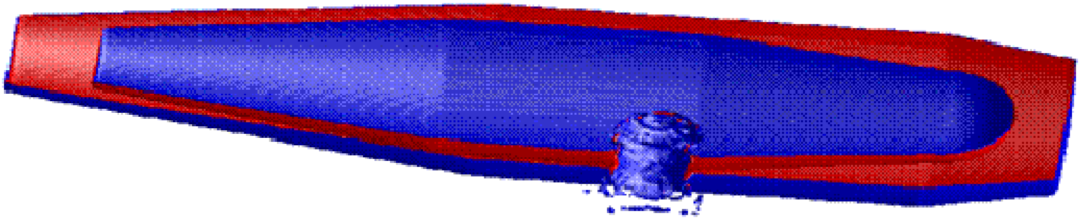
05 Munition System

Artillery Shell Fragment Attack Hazard

Comparison with experiment







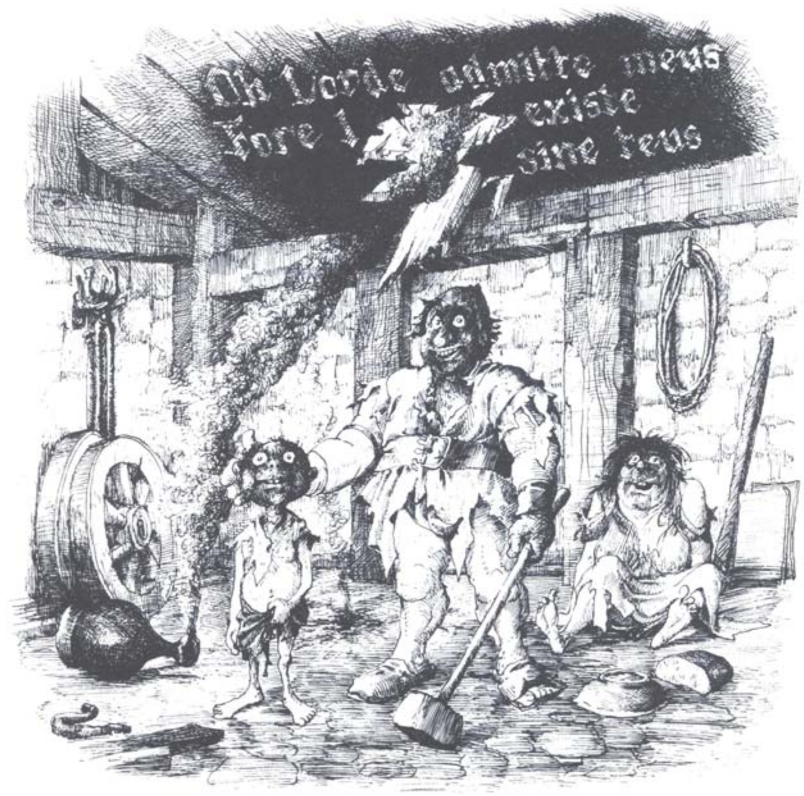
STANNAG Fragment v=2536m.s^{-1}

05 Munition System

Comparison with experiment.

- Modelling, in good agreement with the experiments, predicted that fragment attack of the artillery shell would not lead to an SDT event and that any subsequent reaction would be a BVR event.
- The size of the hole in the shell case and the destruction of the fragment were in excellent agreement with the experiment
- The model was able to show the generation of a small amount of gaseous reaction products around the cavity produced by the fragment in the shell filling.
- However, it was unable to predict how any subsequent reactions would grow.

06
Conclusions



06 Conclusions

The ability to predict the hazard response of a munition is an important requirement for the IM certification process of a munition.

Materials science can predict the basic behaviour of the mechanical response of a PBX:-

- Equation of State
- Constitutive response
- Damage and failure

Integration with an ignition and growth model can predict the SDT hazard response of munitions subjected to fragment attack.

A BVR model is required to predict non-SDT events and their resulting violence.

The long term UK objective is 'Certification by Simulation'

07 Acknowledgments

- Hazard UK II Consortium:
  - QinetiQ
  - BAESYSTEMS
  - Fluid Gravity Engineering
  - Cranfield University
- Defence Technology Innovation Centre, MOD for providing financial support.

Independent expertise where it matters most.

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