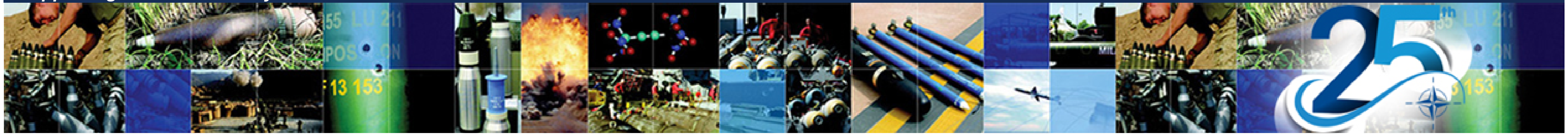
Supporting Munitions Safety



The influence of mechanical properties on the explosiveness of energetic materials

Stokes Fellowship Project

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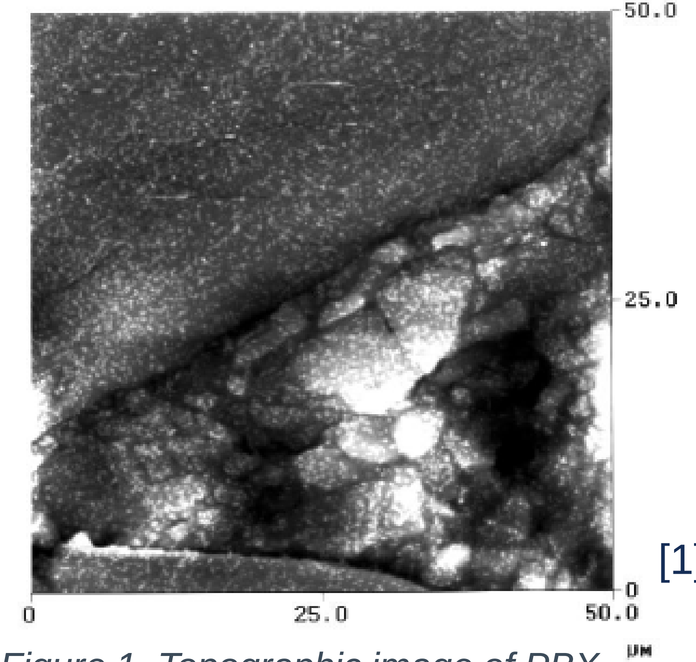
Content

Purpose of this work

- To understand effect of damage on the mechanical properties of an energetic material and on the behavior of the component
- Comparisons between pristine and damaged materials
- Link between material level and component level
  - Material level – change in mechanical properties
  - Component level – change in response to stimuli

Material selection

- PBX materials
  - Binder changes the mechanical properties of a formulation
  - Wide range of properties
  - Complex
  - Many uses



[1]

Figure 1. Topographic image of PBX

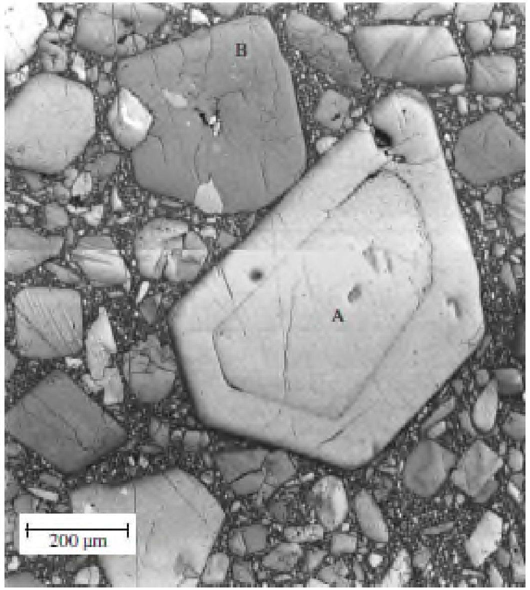


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Figure 2. Optical micrograph of PBX

Defining undamaged materials

- Lack of clarity and inconsistency with use of terms

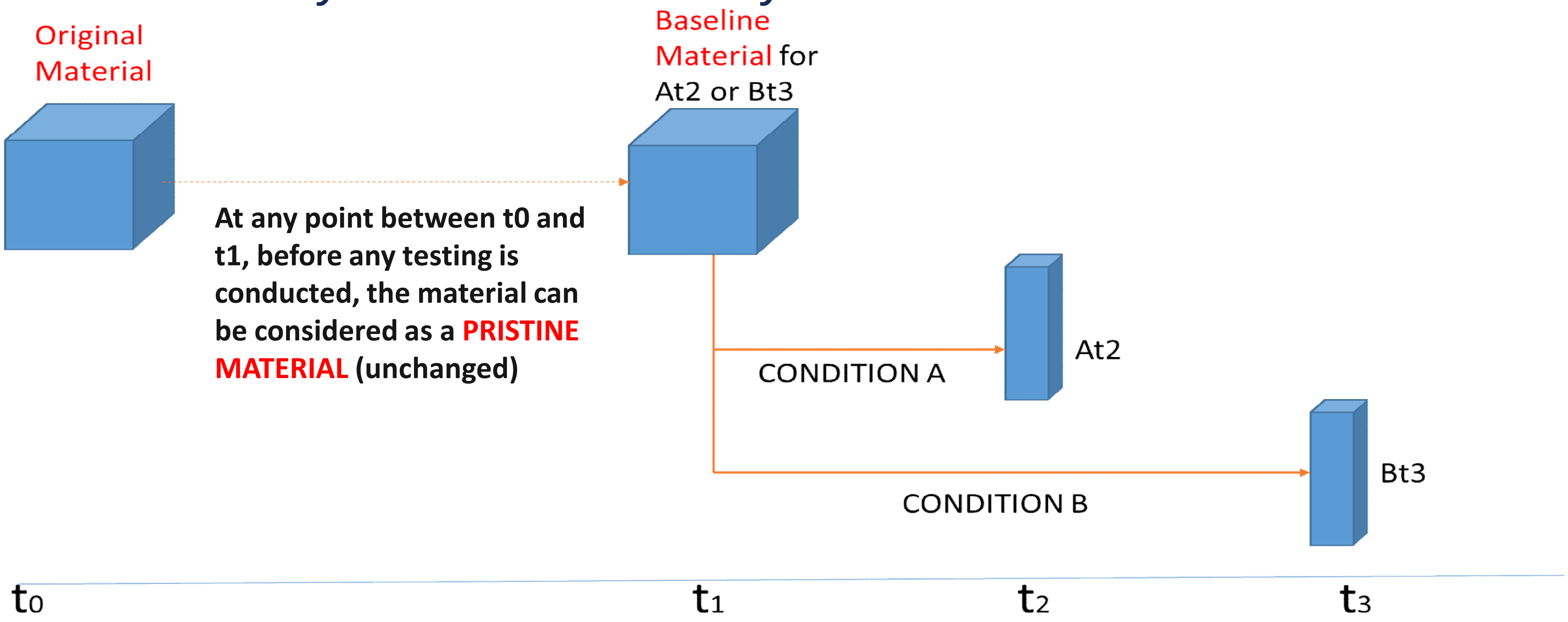
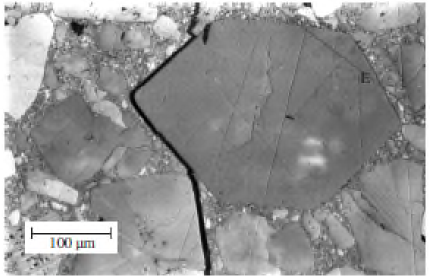


Figure 3. Visual Relationship between the definition for 'original', 'baseline' and 'pristine' materials

What is damage?

- Change from the original material
  - o Visible
  - o Measurable
- Can cause a change in performance
- Different sources of damage
  - o Mechanical
  - o Thermomechanical
- Damage at the material and/or component level
- Cracks, deformation and debonding, porosity and permeability



[2]

Figure 4. Interfacial crack

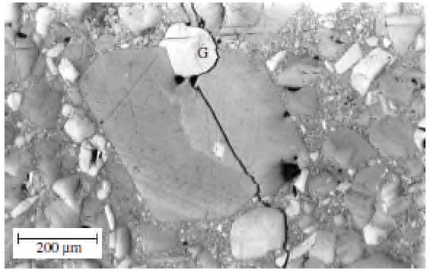


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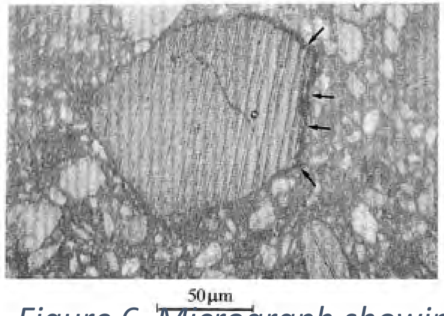
Figure 5. Internal crystal crack

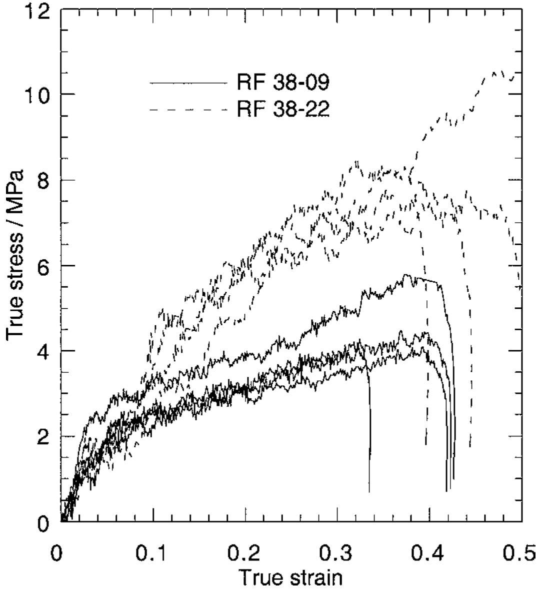


[3]

Figure 6. Micrograph showing debonding

Factors affecting damage

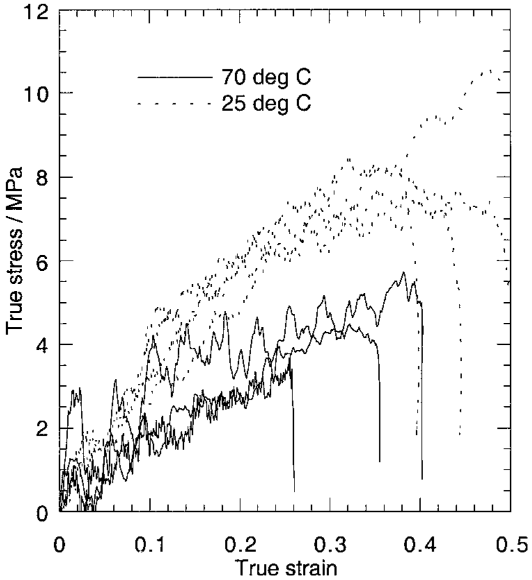
- Material factors
  - o Particle size and shape
  - o Composition
  - o Degree of adhesion



[3]

Figure 7. Stress vs. Strain Graph to show effect of particle size. RF 38-09 RDX 710µm, RF 38-22 RDX 159µm

- Environmental factors
  - o Atmospheric pressure
  - o Low and high temperatures



[3]

Figure 8. Stress vs. Strain Graph to show effect of temperature

Microstructural changes

- Visual
  - Longer the temperature insult, the bigger the crack
  - No quantification of amount, location, or distribution of cracks
- Mass and density
  - Greater mass loss at higher temperatures, and longer duration
- Porosity and permeability
  - Increases with temperature and duration of insult
  - Confined vs. unconfined
- Detonation velocity
  - Decreases with increasing temperature

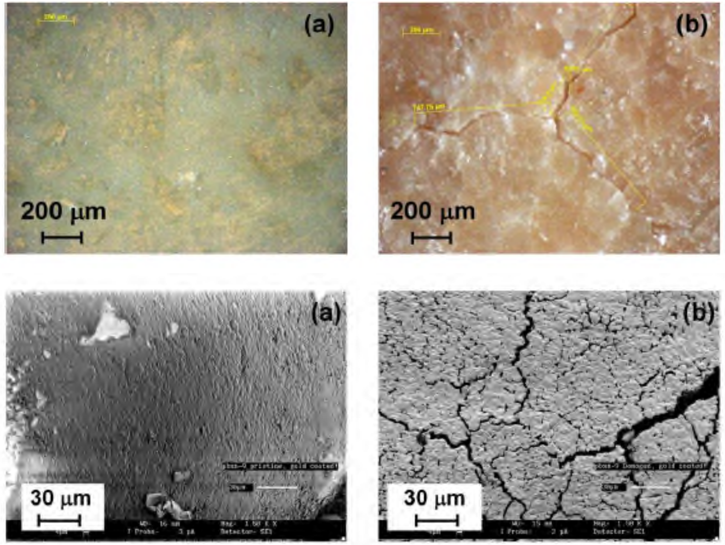


Figure 9. Microscopic images of PBXN-9 before and after damage at 180˚C for 3 hours [8]

Effects of damage - small scale tests

Table 1. Small scale sensitivity test results for thermally damaged PBX materials

PBX	Explosive Fill	Binder	Condition	Test	Result	Ref
LX-10	HMX 95%	Viton 5%	180 °C 4hr	Impact (Drop Hammer)	Increase 52cm (71cm pristine)	[9]
LX-14	HMX 95.5%	Estane 4.5%	180 °C 4hr	Impact (Drop Hammer)	Increase 75cm (94cm pristine)	[9]
LX-17	TATB 92.5%	Kel-F 800	190 °C 250 °C	Impact (Drop Hammer)	No change (no data)	[10]
PAX-2A	HMX 85%	BDNPA/F 9%	60 °C 12mths	Impact: ERL, type 12, 2.5kg	No change (no data)	[11]
PBX-9501	HMX 95%	Estane 5%	180 °C 4hr	Impact (Drop Hammer)	Increase 82cm (94cm pristine)	[9]
Rowanex-1440	RDX 66%	HTPB 12%	60 °C 12mths	Impact	Increase (no data)	[11]
PBXN-110	HMX 88%	HTPB	70 °C 6mths	Impact	No change	[12]

Effects of damage - sub scale tests

- Burn area
  - o Increases with temperature at which damage is induced
- Burn rate
  - o Increases with temperature at which damaged is induced

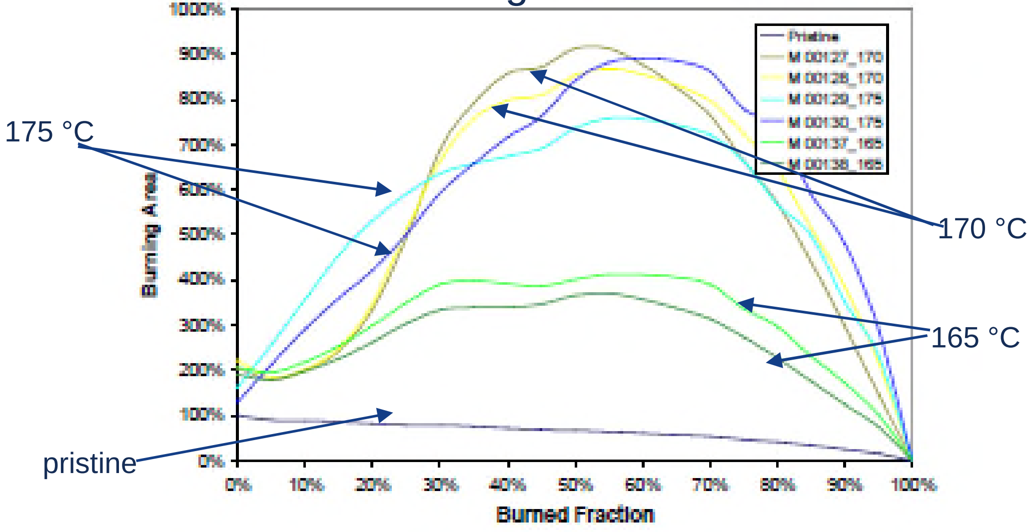


Figure 10. Burn area increase due to thermal damage of HMX-PBX samples [14]

Table 2. Burn rate of PBXN-9 and LX10

Temperature	Burn Rate for PBXN-9 [15] [16]	Burn Rate for LX-10 [9] [10]
90˚C	No change compared to pristine	
110˚C	Only slight acceleration	
150˚C	Approximately 21 times faster than pristine	Slightly faster than pristine
180˚C	2 to 3 times faster when damaged for several hours. 100 times faster	2 to 3 times faster than pristine. 4hours at 180 several orders of magnitude faster
190˚C		Self-ignited

- PBXN-9 – 92% HMX, DOA
- LX10 – 95% HMX, Viton
- HMX-PBX sample 85% HMX, HTPB

Linking porosity to burn rate

Table 4. Porosity and Burn Rate Results for Thermally Damaged PBX-9501 and LX-10 [17].

Composition	Damage Process	Porosity	Burn Rate
PBX-9501	150˚C for 134 minutes	3.8 %	10^1-10^3 mm/s
PBX-9501	174˚C for 75 minutes	6.5 %	10^4-10^5 mm/s (173˚C)
PBX-9501	174˚C for 227 minutes	6.7 %	
LX-10	150˚C for 134 minutes	3.1 %	-
LX-10	174˚C for 75 minutes	5.2 %	-
LX-10	174˚C for 227 minutes	6.4 %	-
LX-10	180˚C	-	10^3-10^5 mm/s

- LX-10 – HMX 95%, Viton
- PBX-9501 – HMX 95%, Estane
- Porosity increases with temperature and duration for both
- Increased porosity leads to increased burn rate, no clear pattern
- For burn rates the duration of insult was not stated

Effects of damage - confinement

Table 5. Effect of Confinement on Permeability and Porosity of PBX-9501 [18]

	Temperature and Duration	Permeability, m^2	Porosity
Sample glued to holder, radially confined	180˚C, 4 hours	8.3×10^{-15}	10 %
Unconfined	174˚C, 2 hours	1.4×10^{-13}	>12 %
Sampled glued to holder, radially confined	174˚C, 2 hours	1.4×10^{-15}	6 %

- PBX-9501 – HMX 95%, Estane
- Confinement has a greater effect than temperature and duration on the porosity
- Confinement provides a restraint to the formation of damage

Table 6. Effect of confinement on the Permeability of PBX-9501 [19]

	Permeability, m^2
Confined	2.89×10^{-16} (3 orders of magnitude larger than pristine)
Unconfined	6.88×10^{-14} (5 orders of magnitude larger than pristine)

Temperature and detonation velocity

Table 7. Table to show the relationship between temperature of insult and detonation velocity [20][21][22]

Temperature	Detonation Velocity of LX-04	Detonation Velocity of HU45 (85% HMX, HTPB binder), km/s
Pristine	8.5	8.3
165˚C	-	7.8
170˚C	-	6.8
175˚C	-	7.0
185˚C	7.7-7.8	

- LX-04 – HMX 85%, Viton
- HU45 – HMX 85%, HTPB
- Temperature causes a decrease in the detonation velocity
- LX-04 has less change over a greater temperature range than HU45
- HU45 detonation velocity increases at 175˚C slightly, suggestion temperature has no greater effect at 170-175˚C?

Crack size and critical pressure

- Crack size 2-20µm at 180°C, 30 mins
- Crack size 10-100µm at 180°C, 3 hrs
- Could use similar plots to highlight where acceptable limits for damage formation may lie if the acceptable limit for critical pressure is known

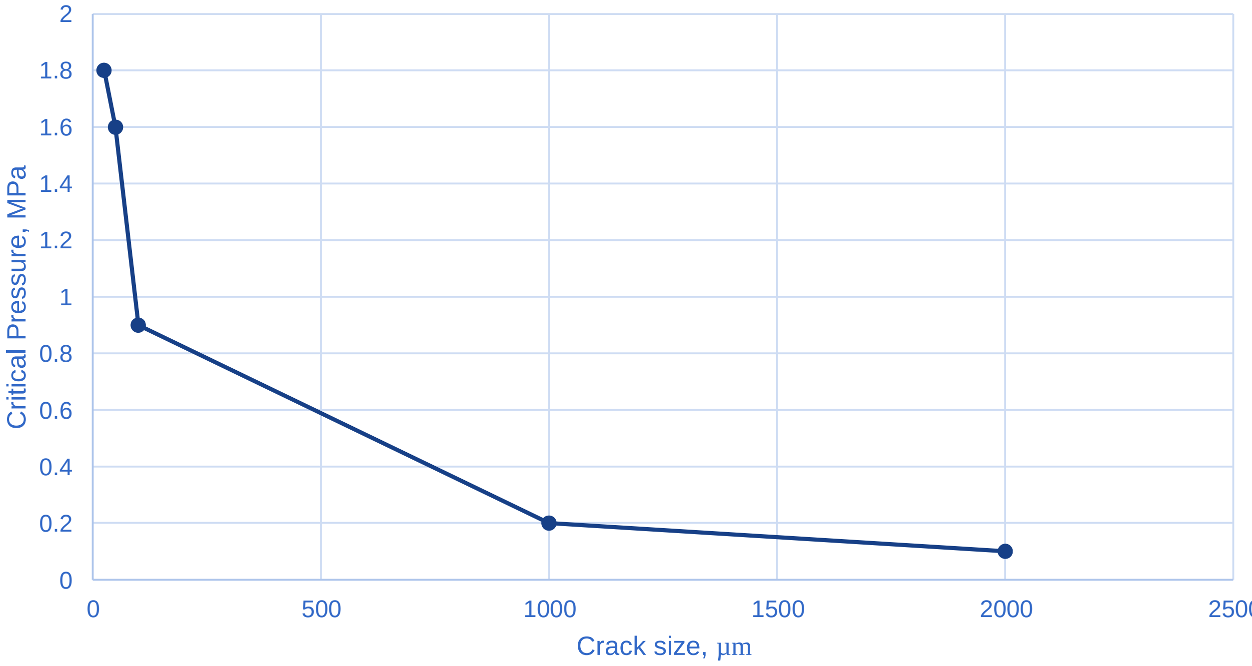


Figure 11. Graph to show the relationship between crack size and critical pressure for PBX-9501

Overview table for PBX-9501

	Test	Mechanical Damage Response	Thermal Damage Response
Characterisation	Visual	Cracks, 200-300 µm [26] [27] [28]	Cracks, 2-20 µm. pores increase with increasing temperature of insult [26]
	Density		1.53 g/cm^3 (1.81 g/cm^3 pristine) [28]
	Mass		0.7 % decrease [28]
	Permeability		Increased with increasing temperature of insult. Increased with duration of insult [30] [31] [32] [33] [34]
	Porosity		Increased with temperature of insult. Increased with duration of insult [66]
Small-scale Test	Impact test	Changes in sensitivity seen (both increase and decrease) [29]	Increased sensitivity[35][36] [37]
	Friction test		No change [25]
	Spark test		No change [25]
Sub-scale Test	Critical pressure	1.4 ± 0.4 MPa. Increase as crack size decreases [26]	9.2 ± 0.4 MPa. Decreases with porosity and permeability [26] [38] [39] [12]
	DDT tube test		• Porosity increases, run distance decreases • Temperature of insult increases, run distance decreases • Duration of insult increases, run distance decreases [40]
	Burn rate		Increases [25]
	Impact velocity	Decreases [27]	
	Run length to detonation	Decreases as the velocity of impact projectile increases [27]	

Multiple and combined aggressions

- Multiple bullet impacts
  - US bullet impact tests
  - 10 out of 28 change in response
  - Type V to Type IV
  - Limited details on progression from first impact to second/third
- Slow cook off and a fuel fire
  - Replicate worst case scenario
  - Slow cook off, Type V
  - Fuel fire ignition changed to Type III
- Heat cycling and vibrations
  - Investigation of a Paveway IV accident
  - Unintended burn witnessed in environmental vibration test
  - Cause: combination of prior heat cycling and vibrations

[41]

Figure 12. Photographs of the response of a warhead containing a PBX undergoing a slow cook off followed by a fuel fire. Left to right is the slow cook off, fuel fire ignition and explosion

[41][42][43]

Summary

- No in-depth damage studies conducted
- Little available data for multiple and combined aggressions but there is evidence of a substantial difference from single aggressions
- Further work
  - Publish experimental detail
  - Realistic damage insults
  - Quantification of damage
  - Links between damage formation and response

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