Extended multi-physics model for slow-cook off events of warheads

Insensitive Munitions & Energetic Materials Technology Symposium

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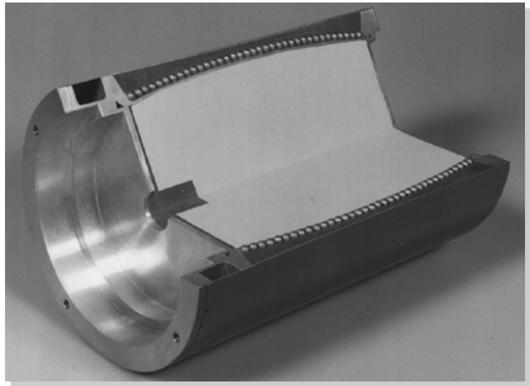
TDW an MBDA company

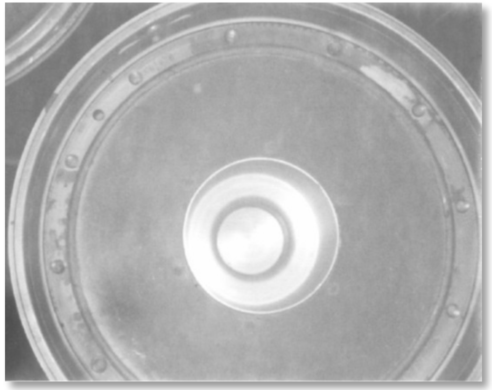
Member of IMEMG MURAT EUROPEAN MANUFACTURERS GROUP

TDW – a pioneer for insensitive lethal packages

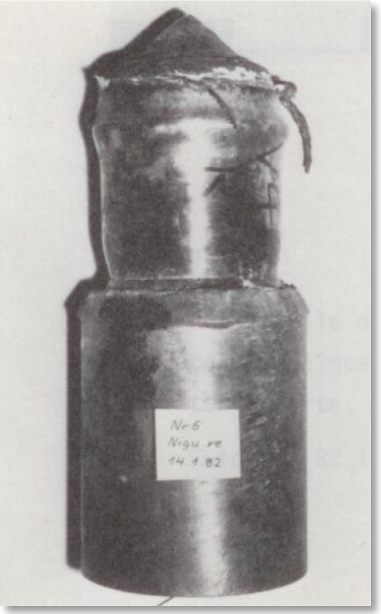
- ANS (D / FR)
  - One of the first programs using PBX in early 1980s
  - Studying, developing, and testing various PBX charges
- ALARM (UK)
  - Series production with a cast-cured PBX charge started in 1988



ALARM warhead with cast-cured PBX (1988)



ANS warhead with cast-cured PBX (1985)



Scaled ANS test vessel after an impact test (1982)

Requirements on modern lethal packages

- Defined IM threats und required response level according to STANAG 4439

Threat	Full Scale Test Procedure in accordance with	Requirement: No response more severe than
Magazine/store fire or aircraft/vehicle fuel fire (Fast Cook-off - FCO)	STANAG 4240	Type V (Burning)
Fire in an adjacent magazine, store or vehicle (Slow Cook-off - SCO)	STANAG 4382	Type V (Burning)
Small arms attack (Bullet Impact - BI)	STANAG 4241	Type V (Burning)
Fragmenting munition attack (Fragment Impact - FI)	STANAG 4496	Type V (Burning)
Shaped charge weapon attack (Shaped Charge Jet - SCJ)	STANAG 4526	Type III (Explosion)
Reaction propagation in magazine, store, air-craft or vehicle (Sympathetic Reaction - SR)	STANAG 4396	Type III (Explosion)

TDWs systematic IM assessment approach for thermal stimuli

Material tests	Small-scale tests	Modeling & simulation (M&S)	Full-scale tests
• Small HE sample tests • Scale: <1 g of HE	• Standardized SCO / FCO vessel tests • Scale: ~350 g HE	• M&S supporting warhead and thermal mitigation measures design • Small-scale to full-scale	• Full-scale IM SCO or FCO tests • Lethal package or munition scale
• DSC tests • ARC tests • At different heating rates, i.e., SCO heating rate of 3.3 K/h and fast heating rates up to 80 K/min	• Tests according to AOP-39, STANAG 4439, and STANAG 4382 or 4240 whenever possible • Confined HE charge in standardized vessel with built-in venting mechanism allowing temperature measurements inside the HE charge	• Multi-physics modeling of self-heating behavior for predicting time to reaction and temperatures at reaction • Transient FE model including multi-physics thermal model predicting SCO or FCO responses of full-scale warheads	• Tests according to AOP-39, STANAG 4439, and STANAG 4382 or 4240
• Material characterization and self-heating behavior • Input for AKTS-Thermokinetics software	• Thermal sensitivity of HE charges • Physical properties at slow heating • Venting behavior	Thermal response of full-scale warheads including predictions of • Time to reaction • Temperatures at reaction • Spatial temperature profiles • Hot spot locations	IM compliance on • Subsystem level or • System level

Significant increase in effort, time, and costs

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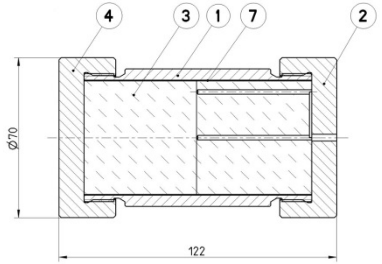
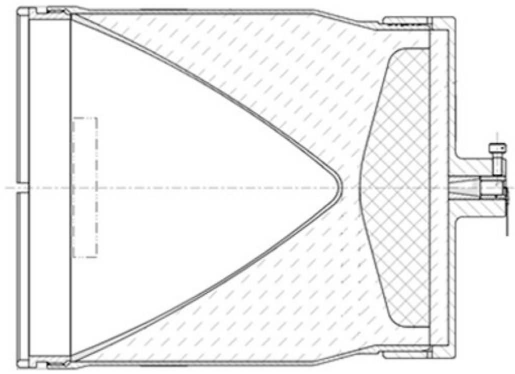
Relevant earlier publications on thermal experiments and simulations

- M. Graswald and R. Gutser. Thermal Modeling of Fast Cook-offs. In Proceedings of the Insensitive Munitions & Energetic Materials Technology Symposium, Portland, OR, 2018.
- M. Graswald, R. Gutser, and E. Waldner. Modeling of Thermal Reactions and Associated Events. In Proceedings of the 30th International Symposium on Ballistics, Long Beach, CA, 2017.
- M. Graswald and R. Gutser. Thermal Modeling of Slow Cook-off Responses. In Proceedings of the Insensitive Munitions & Energetic Materials Technology Symposium, Nashville, TN, 2016.

SCO test vessels

- TDWs standardized SCO test vessel
  - Cast-cured or pressed HE charges of ~350 g
  - Confinement with intrinsic venting mechanism
  - Two thermocouples integrated
- Shaped charge vessel
  - HE charge of approx. 3,000 g
  - Soft confinement through Al casing and end cap

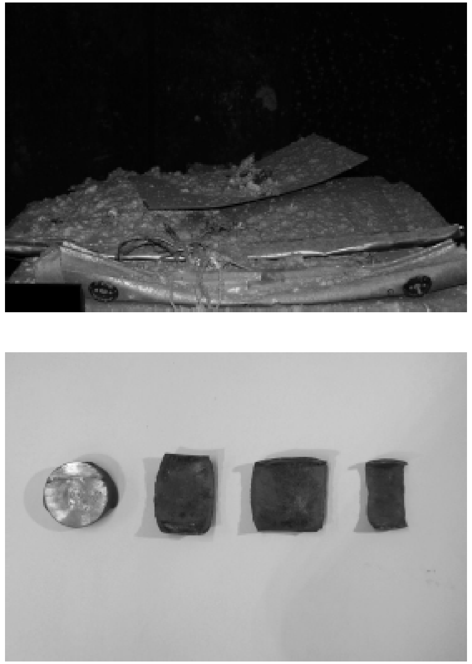




PBX	Type	Composition	Application
KS57	Cast-cured	RDX / AP / Al / HTPB (24 / 40 / 24 / 12)	Underwater
KS22	Cast-cured	RDX / Al / HTPB (67 / 18 / 15)	Blast / Frag, Penetrator
P31	Pressed	HMX / Si (96 / 4)	Shaped Charge

Test results showing oven remnants and vessel fragments

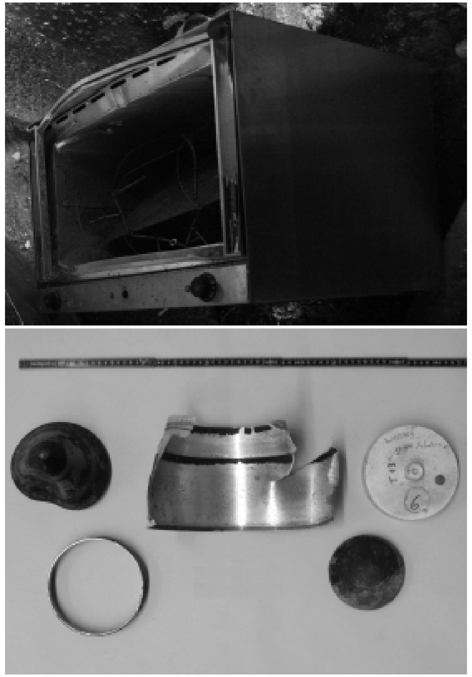
- Type IV response for SCO test vessel, Type V for shaped charge (SC) vessel



#1: KS57

#2: KS22

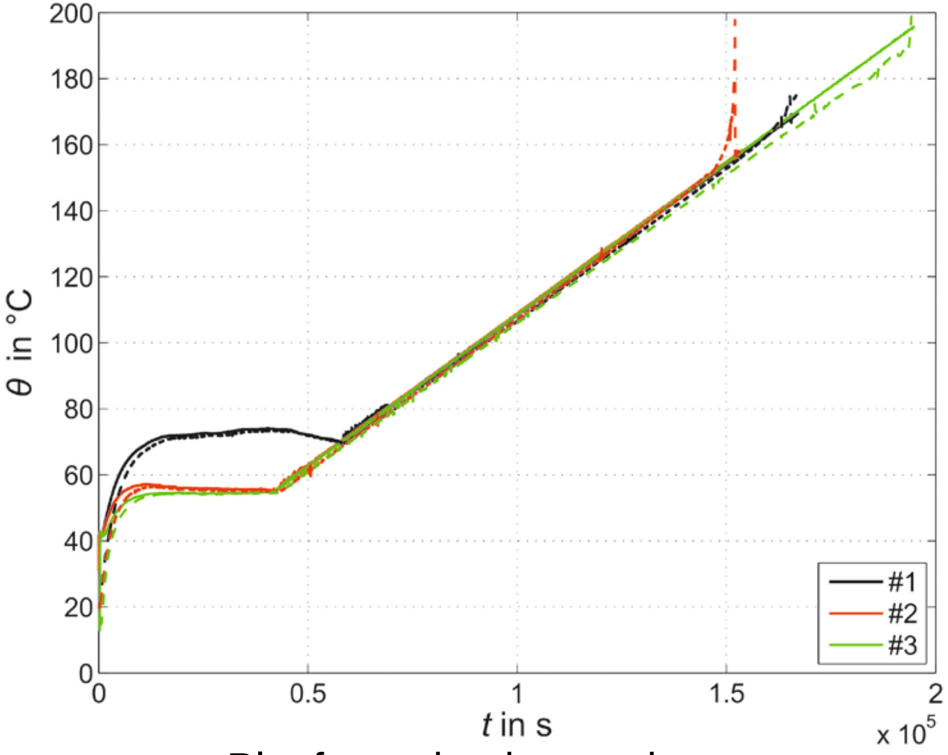
#3: P31



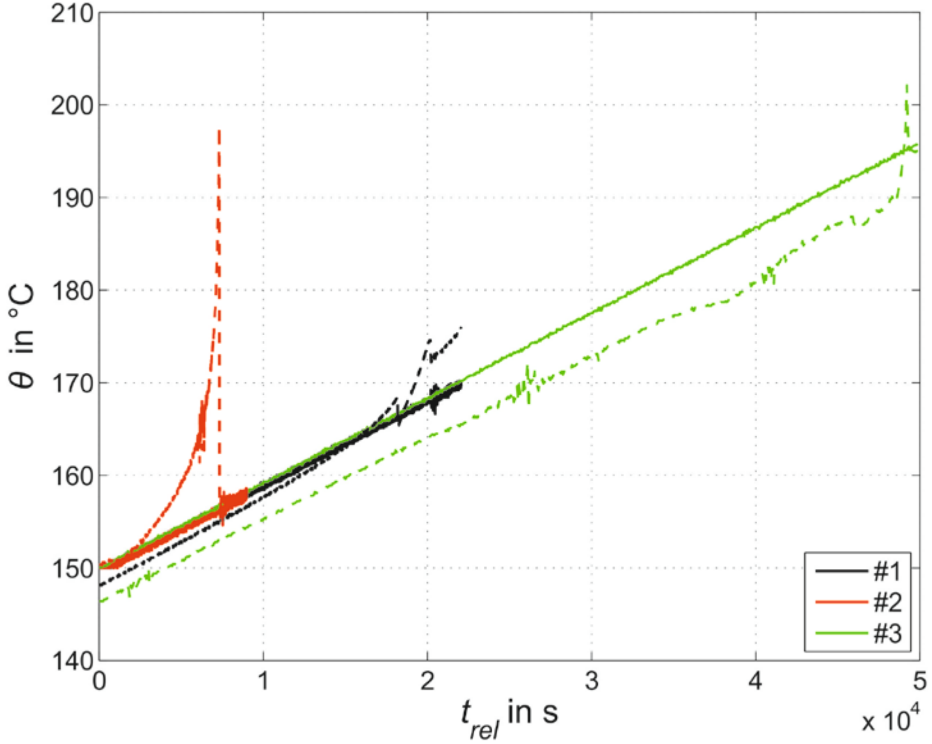
#4: P31 (SC)

Measured temperatures indicate self-heating and provide ignition data

- Oven reference (solid) and thermocouple at HE charge‘s center (dashed line)



Plot for entire time regime



Data shown above 150ºC oven ref threshold

Events observed by HS video recordings correlate with temperature curves

- Slow cook-off test #2 of a KS22 charge sample
- Evacuation of material and gases during self-heating followed by onset of reaction

Close view: venting effects observed

Site overview: onset of reaction

Modeling the heat transfer process into solid media

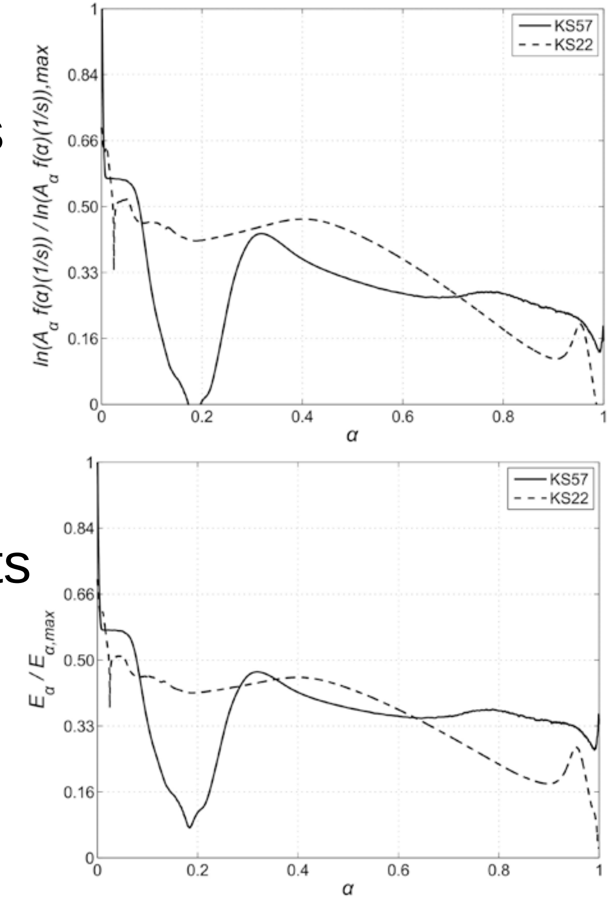
- Transient heat transfer equation in cylindrical coordinates

$$\rho c_p \frac{\partial \theta}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial \theta}{\partial r}\right) + Q\left(r,t\right)$$

- Multi-physics coupling of a model-free reaction kinetics with internal heat generation Q
- AKTS-Thermokinetics for $A_\alpha f(\alpha)$ and $E_\alpha(\alpha)$ from DSC tests

$$Q\left(r,t\right) = q\frac{\partial \alpha}{\partial t} = qA_\alpha f\left(\alpha\right)e^{-\frac{E_\alpha(\alpha)}{R\theta}}$$

- System of coupled PDEs solved numerically with MATLAB



AKTS input data

Modeling the heat transfer process into solid media

- Model extended for simulating pressures resulting from HE charge's self-heating

i) Isochoric heating of the air inside the completely closed test vessel

$$p(t) = \frac{\theta(t)}{\theta_a} p_a$$

ii) Period with increasing pressures resulting from gases produced by heat transfer in the oven and and self-heating of the explosive charge

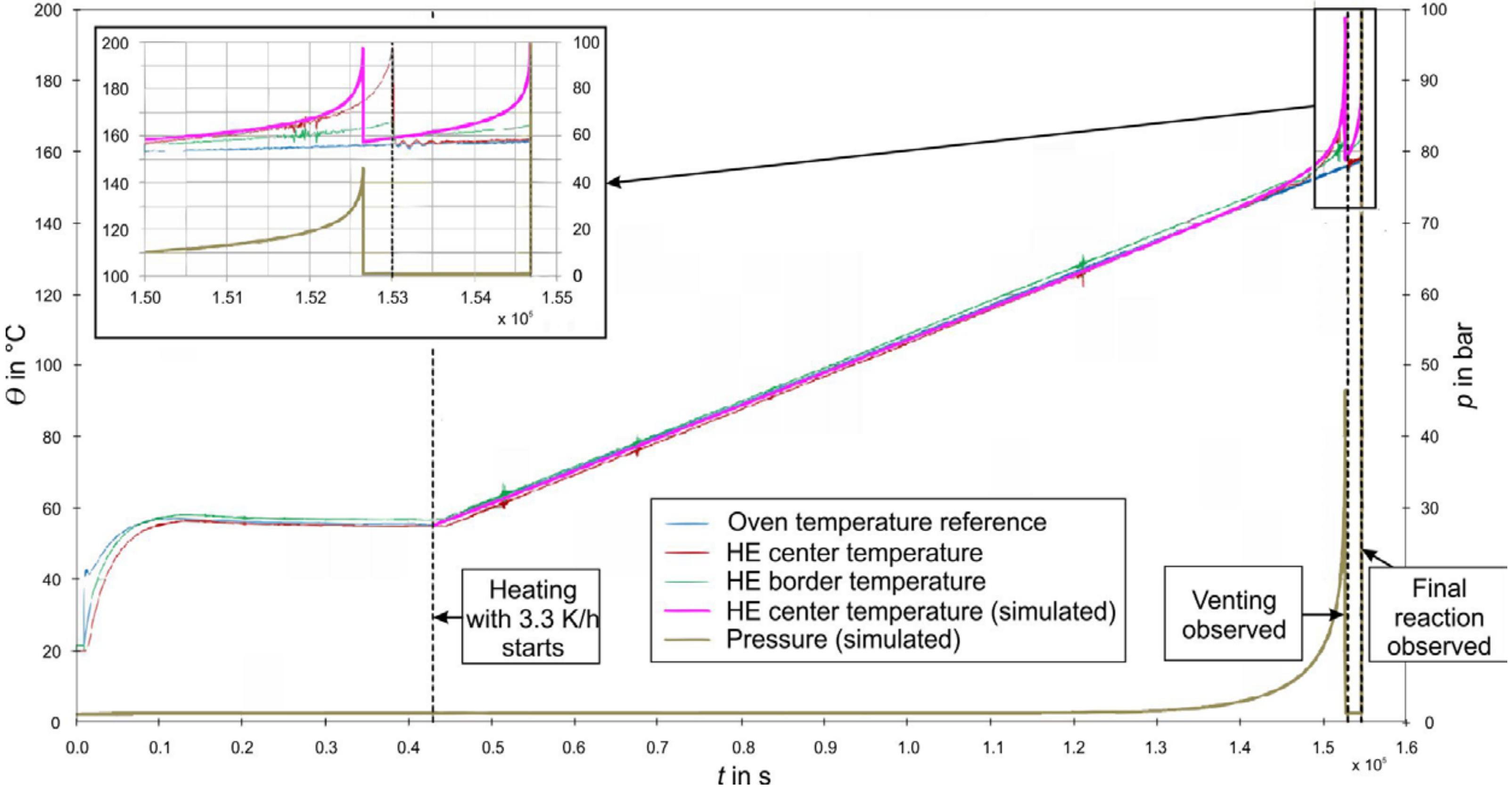
$$\frac{\partial p}{\partial t} = \frac{R}{V}\left(\frac{\partial n}{\partial t}\theta + n\frac{\partial \theta}{\partial t}\right) \qquad \frac{\partial n}{\partial t} = \beta \frac{\partial \alpha}{\partial t}$$

iii) Heat and pressure dissipation with temperatures and pressures relieved to ambient conditions as a result of gas venting

$$Q_v(r,t) = \frac{A_v \Delta p(r,t)}{c}\frac{c_p}{V}\gamma\theta(r,t) \qquad p_v(r,t) = \frac{A_v \Delta p(r,t)}{c}\frac{c_p}{V}\theta(r,t)$$

Simulating temperatures & pressures in KS22 for a complete heating cycle

- Measured curves are plotted for sensors located at oven, HE center, and border



M. Graswald, R. Gutser, and M. Schweizer: Extended SCO model (IMEMTS 2019)

Extended slow-cook off modeling and simulation study

- A standardized, confined SCO vessel is used to experimentally investigate thermal sensitivities of HE charges and provide valuable temperature data
- New modeling approach including reaction kinetics using MATLAB
  - Self-heating rates and times predicted with a thermal model match well experimental data
  - Simulating temperature and pressures curves for a complete heating cycle including period of gas venting through end cap’s hole of the test vessel
  - Allows design and evaluations of mitigation measures such as venting technologies
- Thermal models can be easily applied to other full-scale warhead systems allowing a prediction of their IM conformance

Potential future efforts

- Experimental verification and optimization of thermal simulation models through pressure and gas flow measurements at the casing and inside the HE charge

IM signatures of lethal packages made by TDW

- Continuously improving their insensitivity

Threat		ESSM	PRG A	PRG B	PRG C	PRG D	PRG E	PRG F	PRG G	PRG H	PRG I
		Blast / Frag	Blast / Frag	Shaped Charge + Frag	Penetrator	Anti-Ship Penetrator	Anti-Ship Penetrator	Shaped Charge	Blast / Frag	Blast / Frag	Shaped Charge
		KS33	KS32	KS33	KS22	KS22	KS22	KS33	KS33	KS32	KS33
Fast Heating	V	V	V	V	IV (Missile Level)	V	V	V	V	V	V
Slow Heating	V	V	IV (bare WH)			IV (bare WH)	IV (bare WH)	V	V (bare WH)	V	V
Bullet Impact	V	V	V	V (Missile Level IV bare WH)	better V	IV	V	V	better V	V	V
Sympathetic Reaction	III	better I (TDW ass. IV)		better V		IV	better V		better V	V	V
Fragment Impact	V	V (4 cubes 0.5" @ 2530m/s)				V (2530m/s)	better V (1830m/s)	V (2530m/s)		V (1830m/s)	V (1830m/s)
Shaped Charge	III										

M. Graswald, R. Gutser, and M. Schweizer: Extended SCO model (IMEMTS 2019)

TDW Gesellschaft für verteidigungstechnische Wirksysteme mbH

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