Demonstrating munitions insensitivity through simulation: the IMEMG compendium dedicated to cook-off scenarios

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Abstract 24074

The Experts Working Group "computer modelling" of IMEMG (Insensitive Munitions European Manufacturers Group) built up a map where computer models would be of assistance to design munitions, to demonstrate their safety by assessing insensitive munition labels, to evaluate collateral damage, to design ignition trains, to improve processing and manufacturing technology, to propose innovative packaging and to study ageing of the systems.

One could be confident on numerical predictions if the models and codes have previously been compared to known experimental data. Unfortunately in our scientific community, there is no systematic collection of data –agreed to by the community– to reach this goal.

In the context of cook-off insults, this paper details (1) the survey of the open literature made by the Group, (2) how some papers were reviewed and selected or not, and (3) an example of a well-documented experiment. Fifteen international papers plus experiments provided by the IMEMG teams themselves have been gathered in the IMEMG compendium. This compendium will be used to benchmark European manufacturers' codes and models.

Introduction

European manufacturers involved in the design of munitions participate in the IMEMG association to promote insensitive munitions. The IMEMG Expert Working Group (EWG) "computer modelling" builds up a map where computer models would be of assistance to design munitions and to demonstrate their intrinsic insensitivity.

Models are used in the manufacturer community to design and develop new systems to, demonstrate their safety and for the assessment of insensitive munition labels, evaluate collateral damage, design ignition trains, improve processing and manufacturing technology, propose innovative packaging and study ageing of the systems. The group is focused on high explosives, propellants and pyrotechnics.

Among the loading scenarios, the detonation of a munition to a violent impact could be predicted using the Thor formula [1,2] to deduced the residual velocity of the projectile, and the shock-to-detonation threshold. Semi-analytical softwares are available to run fast simulations in 1D and 2D configurations (for example, the TEMPER software from NATO MSIAC using the Jacobs-Roslund initiation formula).

For low velocity impacts, not only the energetic part but also the metallic case have a crucial influence. Impacting such a structure could yield no reaction for low velocity, a deflagration-like reaction at intermediate velocity, an inert impact if the velocity is increased above the previous value, and a detonation in case of a high velocity. This non linear evolution of the violence with the velocity of the projectile is not intuitive for the engineer. Due to finite strain, non linear materials behaviors and complex friction conditions between parts, finite elements simulations are required to understand the localization of the mechanical energy into the energetic material and its ignition.

However, when the question was asked to IMEMG members, cook off loading was highlighted as the most important condition to be modeled. Works of the EWG shown the lack of knowledge on the parameters which are needed as input for the different constitutive models, equation of state or reactive models. Data is available for few models and the testing to gain such data for models requires considerable effort and complex test facilities. The group investigated two open software tools to be shared among the insensitive munition (IM) community: TEMPER (NATO MSIAC, thermal loading module) and Fire Dynamic Simulation (NIST) [3-4]. Group members also used other commercial softwares such as FLUENT, ABAQUS, COMSOL [5-7].

In order to increase the confidence of designers, managers and customers on numerical predictions, models and numerical softwares must be benchmarked using experiments. Among all the physics involved in insensitive munition assessment, thermal threats are of great concern for the IM industrial community. A long time ago, dedicated test procedures were proposed (NATO STANAG 4240 for liquid fuel/external fire and NATO STANAG 4382 for slow heating). These procedures could be applied to munition, which possible responses to these threats are detailed in NATO AOP 39. The results yield the munition Insensitive Munition label. Unfortunately, only few data are collected during the tests. It does not allow engineers and researchers to improve their knowledge and their models describing the physical mechanisms at work from ignition to the final level of reaction. On the other hand, sharing data on system scale experiments could be impossible due to national and industrial restrictions.

Therefore, IMEMG mandated the Expert Working Group to build a compendium of experimental data dedicated to models validations. The technical specifications were the following ones:

1. Focus on experimental data obtained on «unclassified» systems.
2. Find well-documented experiments which could be simulated with confidence, i.e. the geometry of the test set-up is given, the boundary conditions are detailed as well as the materials (not only the energetic one) and the results (ignition time, location, violence of the reaction, size/mass of the fragments...). These experiments could be useful to benchamark the numerical tools.
3. The compendium must deal with explosives, propellants and pyrotechnics.
4. The aim of the compendium is not to standardize the numerical tools and models but to provide data each company could use to validate its own tools.

The process used to build the compendium is detailed below. To illustrate how papers were selected, two examples will be detailed. The conclusion will draw our future work.

Selection of the tests

IMEMG funded two studies (one in UK and one in France) for the first stage of this work. The goal was to make a largest as possible survey of the open literature of thermal loadings on energetic materials. Fifteen documents, reporting tests made from the gram-scale up to ten kilograms, were selected. It was interesting to see how the two studies yield a different list of experiments. Unpublished experiments provided by IMEMG companies were also added to the first list, yielding a collection of approximately twenty papers.

In a second stage, each paper was reviewed by the Expert Working Group members. The following criteria were screened:

- *Energetic material*: name, constituents, proportions, at least references to be used. If not, data to determine the parameters of the chemical decomposition, at least references to be used (Y/N), data to determine the burn rate, at least references to be used (Y/N)
- *Dimensions, shapes*: EM sample (Y/N), the whole set-up (Y/N), the environment (oven…) (Y/N), mass of the EM sample (lab < few g; intermediate < few 100g; large kg; system), the heating system (type, dimensions, position) (Y/N)
- *Materials*: of the vessel, between the vessel and the sample.
- *Position and type of sensors*: temperature (Y/N), pressure (Y/N), wires (propagation of the combustion) (Y/N), strain gauges or method to determine the deformation of the vessel (Y/N)
- *Simulations-Results*: thermal boundary conditions applied to the set-up are well known and measured or there is thermocouple located ot the wall (Y/N), the temperature is given into the EM sample with time (Y/N), the propagation of the combustion is recorded, the deformation of the vessel is shown, the violence is recorded (pressure blast, fragmentation of the vessel…)
- *References*

All the papers were submitted to at least two experts of the Group. Each reviewer provided its decision in a table as below:

Thermal load	Time to ignition	Location of ignition	Response level
1 to 3	1 to 3	1 to 3	1 to 3

The table indicates if the paper deals with thermal load (fuel fire, gas fire… and thermal flux applied to the set-up), time to ignition of the energetic material and the location of ignition in the sample, and if the paper describes the level and the type of violence.

Each of the four topics were scored:

- 1: data is not useable for simulation benchmarking,
- 2: a qualitative comparison with data could be possible,
- 3: quantitative comparisons are possible with future numerical results.

Papers yielding only note 1 on all the four topics were definitively rejected from the compendium.

The last stage of the process was to write short datasheets to sum-up the test conditions and the main results. It will enable a quick selection of a test depending on the targeted application.

Main trends of the compendium

The selected tests cover the gram to kilograms-scales. The compendium is about the following materials:

- Explosives: Comp-B(3), PBXN-110, PBXN-111, HMX-based (HMX/HTPB, HMX/NC/K10), RDX-based (RDX/AP/Al/HTPB), IMX-104, cast-cured HMX-based explosives, RDX/TNT/wax
- Propellants: AP-based, HTPB/Al propellant

These materials are embedded in cylindrical or spherical case made of aluminum or steel.

Heat is applied by fuel-fires, electric heaters or ovens. Thermocouples are put around the set-up or on the surface of the latter to determine the thermal loading. Many of the experiments show measurements made into the energetic part itself.

Probably motivated by the authors themselves to simulate their tests, the final selection of the papers are based on recent ones published during the last two decades.

Slow cook off on a cast-cured HMX based explosive

The paper published in 2019 by Narboni and coworkers [8] has been selected. The decision of the two reviewers were the following one:

Thermal load	Time to ignition	Location of ignition	Response level
3 / 3	3 / 3	3 / 3	1 / 1

This paper describes gram-scale to kilogram scale cook off experiments made on a cast-cured HMX-based explosive. Among these tests, let us here give some details of the ten-kilogram scale ones. For the latter, the explosive sample is put into a 10 mm-thick steel casing. The casing helps to homogeneously heat the bar (fig. 1). The position of the thermocouples are given in figure 1. Thermocouples are located at the casing surface, in the middle of the bare radius or on its center.

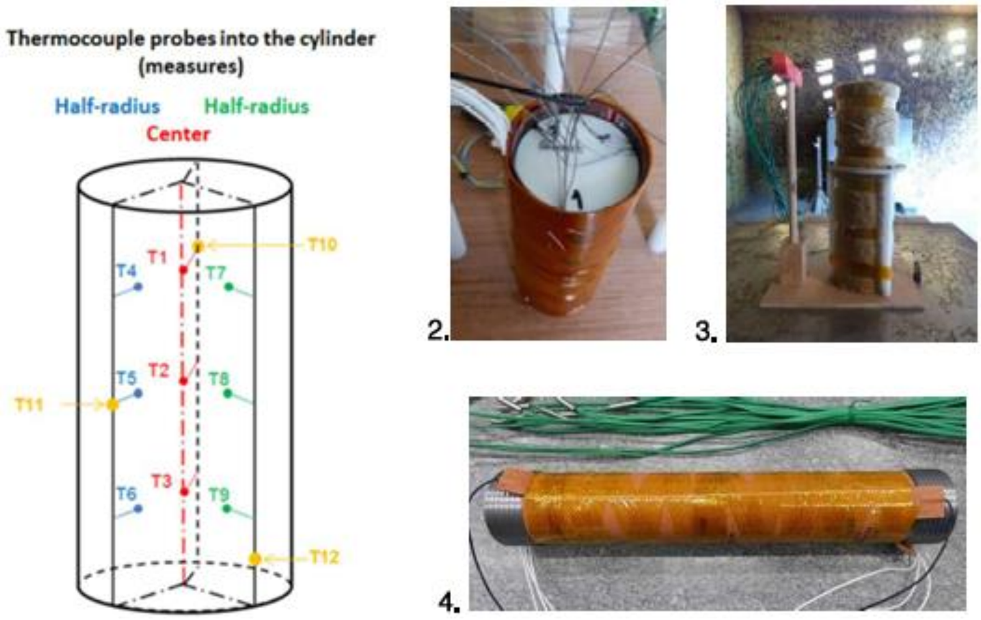

Figure 1. Thermocouples probes set-up on the left. (2.) kilogram scale bare test. (4.) Four kilogram scale test. From [6].

Temperature evolutions are given for all the thermocouples. Unfortunately, the violence of the reaction is not accurately measured. A photo shows the fragmented casing after the tests (fig. 2).

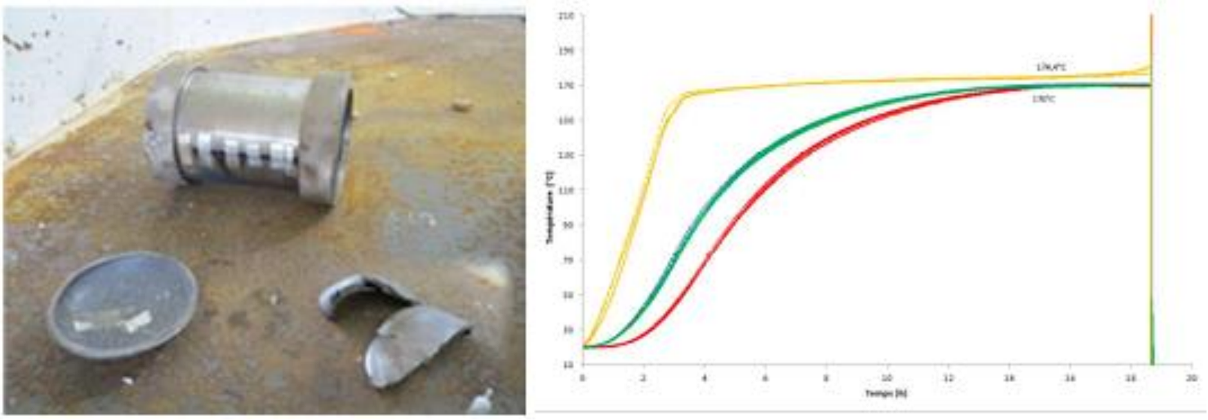

Figure 2. Casing after reaction for the 10 kg-scale test (left) and thermocouples (right) (from [6]).

DSC data are detailed which enables modelling the kinetic decomposition of the material when heated. Different heat rates are applied, from 0.2 to 2°C/min, and the heat flow is recorded (fig. 3). The exothermic peaks recorded during these tests were used to fit a model (AKTS).

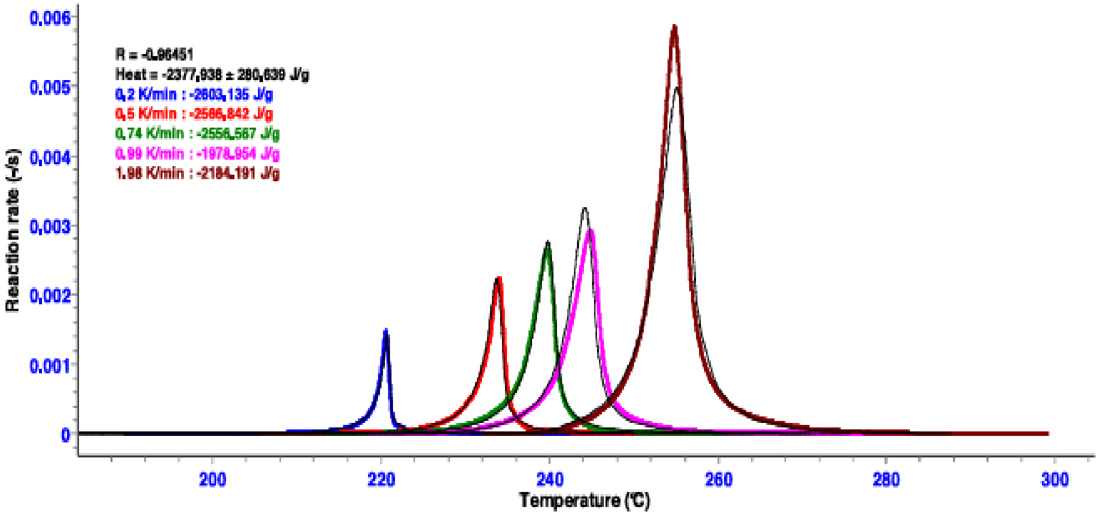

Figure 3. Reaction rates and isoconversional fitting (black lines) from [6].

All the DSC data gives the opportunity to compare time to ignition during the kg-scale tests to numerical predictions. A good accordance is obtained.

RDX/HTPB explosive

The paper published in 2016 by Graswald and Gutser [9] has been selected. The decision of the two reviewers were the following one:

Thermal load	Time to ignition	Location of ignition	Response level
3 / 3	3 / 3	1 / 1	2 / 3

This paper describes the cook-off vessel developed at TDW for cast-cured or pressed high explosives. The energetic material is put into a cylindrical thick metallic case closed by two end caps. Approximately 300-400 grams of explosive is used per experiment (fig. 4).

Temperature is recorded at the charge center and at the inner radius of the steel cylinder. The latter is interesting as it gives the loading directly experienced by the high explosive during slow cook-off. Simulations do not need assumptions on the far-field thermal loading set-up, nor the material of the case nor the thermal parameters for convection or radiation heat transports. However, seven other thermocouples are used to record the oven temperature, air temperature around the set-up, and the surface of the vessel.

Reference [9] describes four experiments, each of these made on a different high explosive (RDX/AP/Al/HTPB, HMX/HTPB and HMX/Si). Temperature records are given in figure 5 and the fragmentation of the vessels could be compared in figure 6.

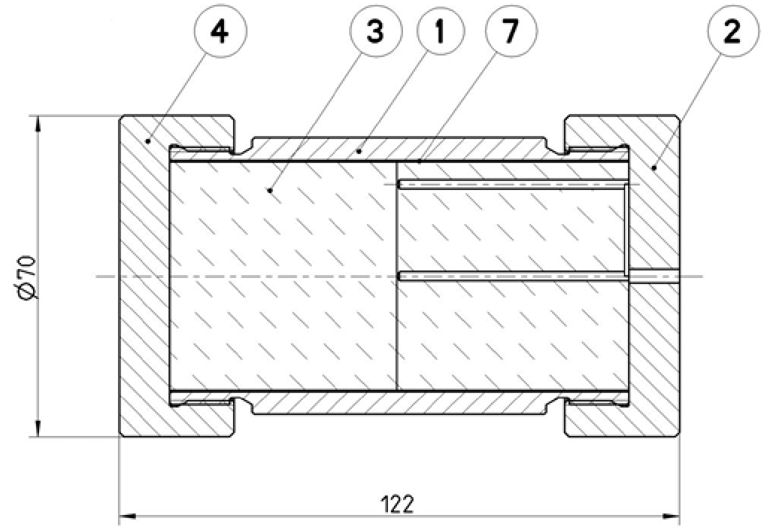

Figure 4. TDW vessel for cook-off response characterization of high explosives (from [9]). The energetic part (3) is glued (7) into the casing (1). The two thermocouples are located at the vessel center and close to the outer radius of the high explosive part.

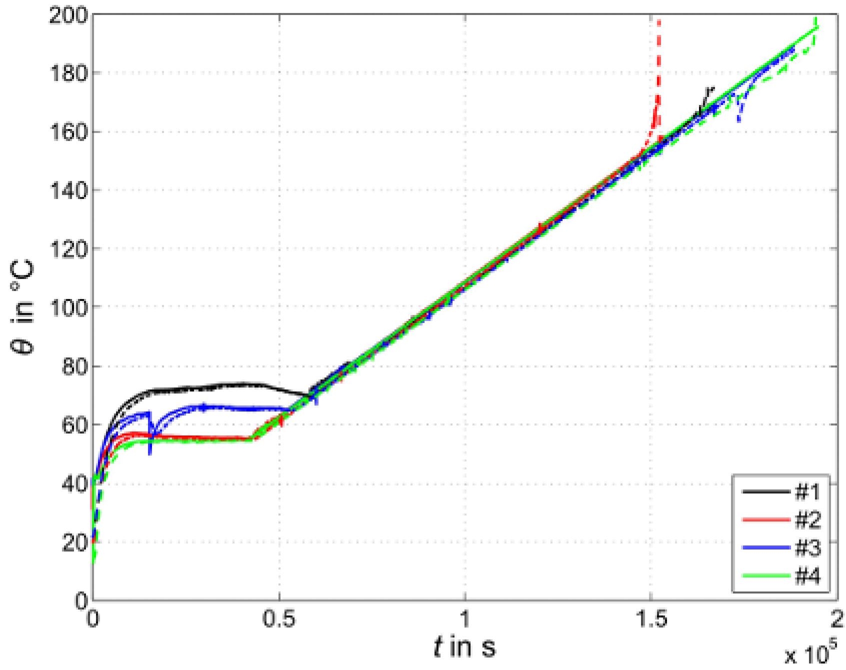

Figure 5. Temperatures recorded in the oven (solid black line) and using thermocouples at the center of each charge (dashed lines).

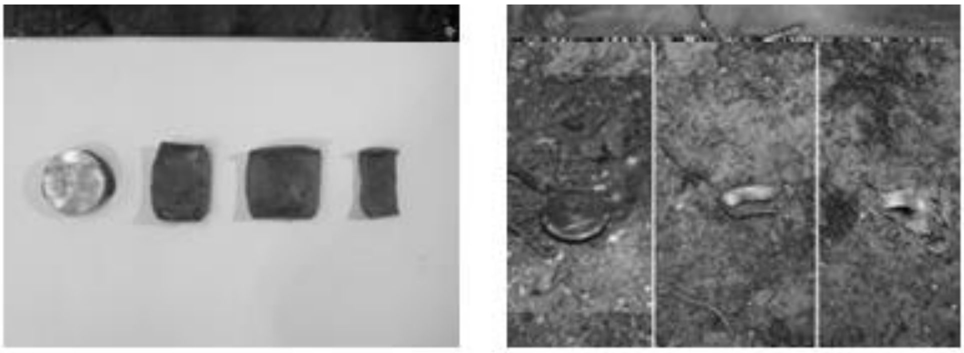

Figure 6. Vessel fragments for composition KS57 (top left), KS22d (top right), KS33 (bottom left) and P31 (bottom right).

The TDW authors to improve their models of thermal ignition, pressurization and failure of the vessel [10] use data reported in [9]. Internal pressure calculation is based on a perfect gas assumption and the rate law of solid-to-gas conversion. Figure 7 shows that the sudden increase of the pressure at the inner radius of the high explosive part. Unfortunately, pressure was not recorded during these experiments.

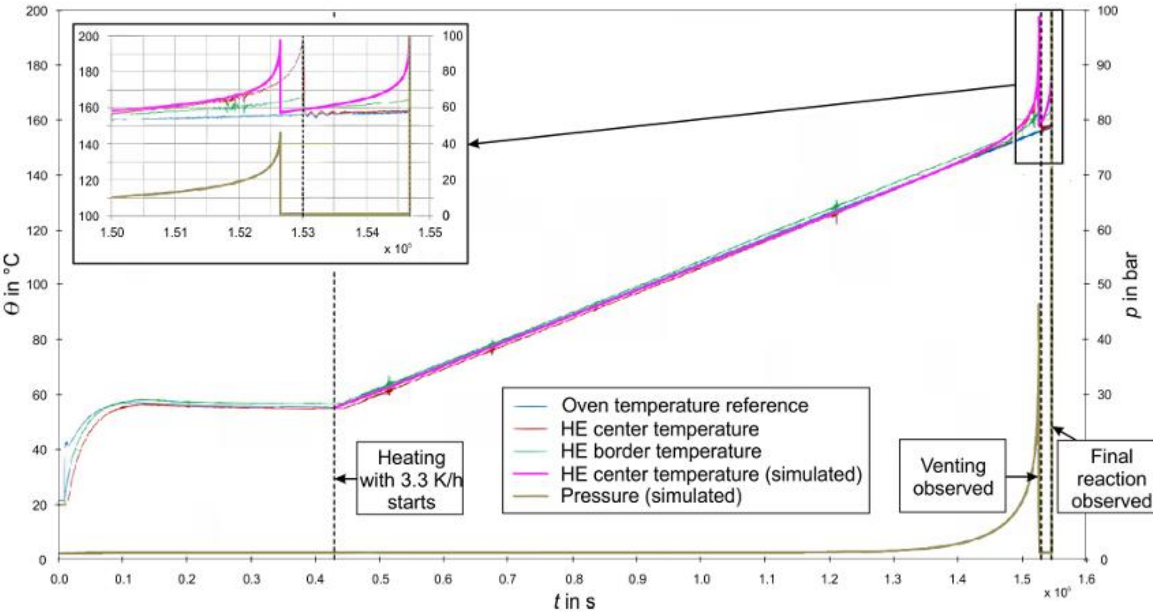

Figure 7. Evolution of the pressure at the high explosive center along time (brown line). For the moment, the number of generated gas moles is determined multiplying the solid-gas rate law by a fitted constant.

Conclusion

To give the possibility IMEMG companies to benchmark their own codes and models, the Expert Working Group of the association ran a survey of the open literature focused on cook-off experiments. Fifteen papers plus experiments shared among the participants brought together in the IMEMG compendium dedicated to cook-off scenario. These tests are available to the IMEMG community.

IMEMG experts will now can take advantage of the compendium to run crosscheck studies. It will give the opportunity to share the methods and numerical tools, to discuss model assumptions and to maintain a high level of expertise in the IMEMG companies.

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