MSIAC
Munitions Safety Information Analysis Center

Supporting Munitions Safety

O-215

September 2019

A BETTER USE OF INSENSITIVE MUNITION AND HAZARD CLASSIFICATION TEST RESULTS

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Presented at

IMEMTS, Seville, Spain, 21 - 24 October 2019

Parari, Canberra, Australia, 5 - 7 November 2019

ABSTRACT

During the 2018 MSIAC Improved Explosives and Munitions Risk Management (IEMRM) workshop, it was recognized by the community that low violence reaction types such as a burn on one side, and high violence reactions such as detonations on the other side, are relatively well understood. However, a number of insensitive munitions and energetic materials react in a sub-detonative regime when subjected to mechanical or thermal threats as defined in Insensitive Munition (IM) & Hazard Classification (HC) standardized tests. Based on recommendations from the 2018 IEMRM workshop, it was then proposed to revisit experimental data from IM & HC tests, and especially the ones that led to intermediate reaction types (Types II to IV). The aim is to make better use of the data recorded during these tests in order to better understand sub-detonative regimes and their effects.

In this context, MSIAC has started to work on two new projects in 2019 that are related to data collection during IM and HC tests:

- Guidance on Instrumentation for IM and HC Tests. This project will review the use of existing instrumentation and will seek to share and develop best practice.
- Collation and Analysis of IM and HC Test Data. This project will analyse existing IM blast, thermal and fragmentation test data to gain a better understanding of the explosive effects for sub-detonative munition responses.

Both projects rely on available information from the open literature but also from test centres and other organisations. A questionnaire was sent to the MSIAC member nations and the results received so far were analysed during the summer of 2019. This paper provides the first outputs from both projects and presents the steps forward for the next year on this topic.

The ultimate goal for this study is to provide recommendations for improved and harmonized test procedures as well as recommendations for the characterization of munition responses and their use for safety distances and risk analysis.

Keywords:

Insensitive Munitions, Hazard Classification, instrumentation, best practices, sub-detonation, TNT equivalent

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TABLE OF CONTENTS

FIGURES

TABLES

ABBREVIATIONS

EM	Energetic Materials
FCO / FH	Fast Cook-Off / Fast Heating
HC	Hazard Classification
IEMRM	Improved Explosives and Munitions Risk Management
ICP®	Integrated Circuit-Piezoelectric
IM	Insensitive Munitions
MEMS	Micro-Electro-Mechanical Systems
PVDF	PolyVinyliDene Fluoride
RTV	Room Temperature Vulcanizing
SCO / SH	Slow Cook-Off / Slow Heating
UN	United Nations

INTRODUCTION

During the 2018 MSIAC Improved Explosives and Munitions Risk Management (IEMRM) workshop, it was recognized by the community that low violence reaction types such as a burn on one side, and high violence reactions such as detonations on the other side are relatively well understood. However, a number of Insensitive Munitions and energetic materials react in a sub-detonative regime when subjected to mechanical or thermal threats as defined in Insensitive Munition (IM) & Hazard Classification (HC) standardized tests. Based on recommendations from the 2018 IEMRM workshop [1], it was then proposed to revisit experimental data from IM & HC tests, and especially the ones that led to intermediate reaction types (Types II to IV). The aim is to make a better use of the data recorded during these tests in order to better understand sub-detonative regimes and their effects.

Two new projects have started at MSIAC in 2019, one on “Guidance on Instrumentation for IM and HC Tests” [2] and one on “Collation and Analysis of IM and HC Test Data” [3]. Both projects rely on available information from the open literature but also from test centres and other organisations. A questionnaire was sent to the MSIAC member nations and the results received so far were analysed during the summer of 2019.

This paper provides the first outputs from both projects, and presents the steps forward for the next year on this topic. In the first part, we review the instrumentation requirements in IM and HC tests and the difficulties encountered in getting suitable measurements to classify an item. The second part focusses on the instrumentation required for blast pressure measurements, as the interest for this instrumentation was given as priority by the respondents of the survey. Finally, the last part describes the IM TNT tool developed at MSIAC which calculates TNT equivalencies from the blast output of any detonative or sub-detonative event, including a measure of uncertainty.

The ultimate goal of this study is to provide recommendations for improved and harmonized test procedures as well as recommendations for the characterization of munition responses and their use for safety distances and risk analysis.

1 INSTRUMENTATION REQUIREMENTS IN IM & HC TESTING

When assessing the reaction type or hazard division of a munition or energetic material, systematic tests are required. For Hazard Classification (HC), one has to follow the decision trees provided in the UN Manual of Tests and Criteria [1]. For the vulnerability assessment of Insensitive Munitions (IM), one has to refer to the test procedures described in the IM NATO standards in references [5] [6] [7] [8] [9] [10].

A review of IM & HC tests was conducted at MSIAC in relation to two new projects that have started in 2019; “Guidance on Instrumentation for IM and HC Tests” and “Collation and Analysis of IM and HC Test Data”. We have listed the instrumentation required for each of the tests detailed in the IM standards and the UN Manual of Tests and Criteria[1]. The result of this review is provided below in Figure 1.

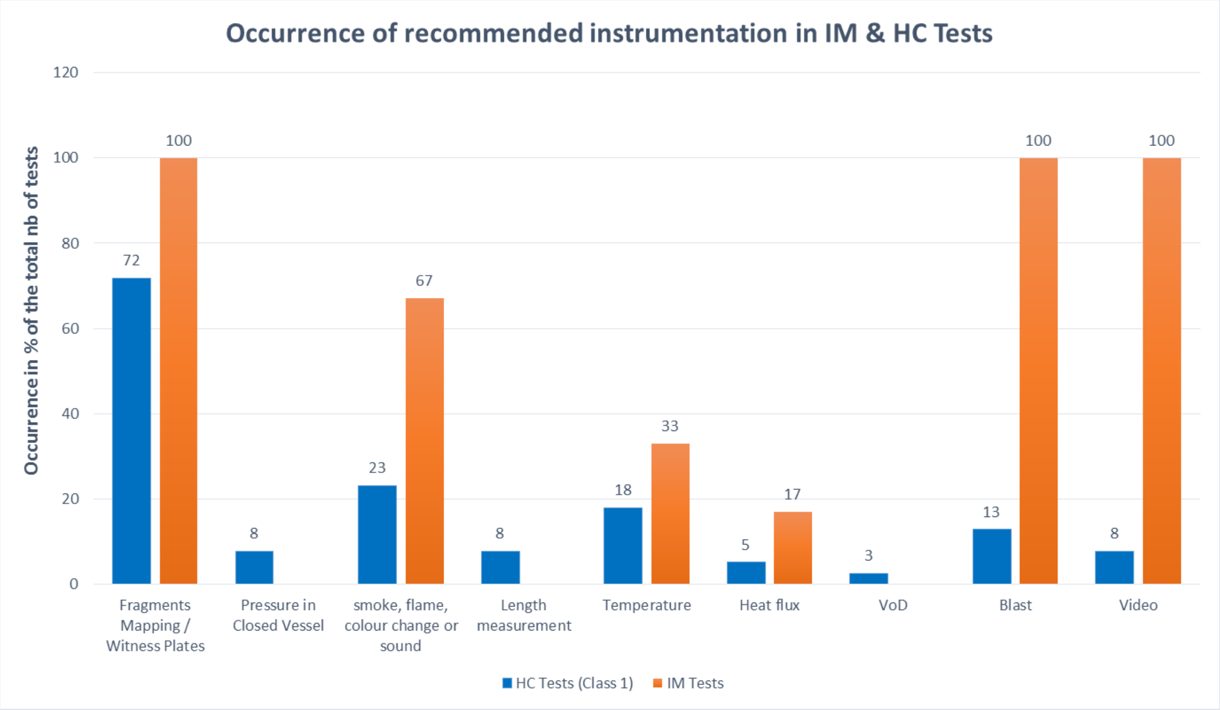

Figure 1: Instrumentation required in IM & HC Tests

This graph makes it clear that fragments mapping / recovery, which implicitely covers visual inspection after the test, is by far the most common method of assessing the results in IM and HC tests. Indeed, these methods are usually straightforward (hole or no hole in a witness plate, for instance) and cheap as they do not require any complex electronic device and post-analysis of data. However, they usually do not provide any granularity in the result (only go or no go), hence they are not sufficient to assess the reaction type of a munition from IM tests.

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[1] Only those HC tests for inclusion of energetic materials in Class 1

This is the reason why IM tests systematically require additional measurements by means of blast gauges and video cameras. In Slow and Fast Heating tests (SH and FH), the use of thermocouples and heat flux measurements is also required. All these measurement devices require suitable and well calibrated electronic devices associated to a data acquisition chain, and should be able to record the desired parameter with a relevant spatial and time resolution, and a good signal-to-noise ratio. In short, they require much more expertise and time.

The data generated by these more complex measurements give valuable information on the behaviour of the EM or the munition during the test. Indeed, the same data could also be used to develop safety distances and models for consequence/risk analysis. To date, IM test data has however not been consistently used for this purpose.

A survey was set up by MSIAC in January 2019, in order to get the feedback from the end users concerning the instrumentation of IM & HC tests. It was also asked to the respondents to share blast data from sub-detonative and detonative events recorded during previous IM tests. The questions of the survey are listed below:

1. In which one(s) of the categories below would you be the most interested by getting more information / best practices about instrumentation techniques? (multi choice)
    - Blast pressure; Heat flux; Temperature; High speed video; Velocity of detonation; Burning rate; Internal pressure; Others (open field)

For each instrumentation technique mentioned above, the responders had to answer questions 2 to 7:

2. Do you perform measurements in this category?
3. Please specify here the brand, type, model of device(s)
4. Which procedure or guideline or best practice document(s) do you use?
5. Have you already conducted uncertainty analysis on the measurement chain for your instrumentation devices in this category?
6. Have you already conducted comparison / benchmarking study(ies) between instrumentation devices in this category?
7. Would you agree to share documents in this category (partially or in totality)?

Finally, the respondents were requested to help out in reviewing the final MSIAC reports of the two projects, and to share releasable test reports or test data that contain measurements of blast, thermal radiation and fragmentation for sub-detonative munition responses.

In total 23 answers from 12 countries were received from this survey. The answers received for the first question highlighted the priorities for the instrumentation techniques:

- **65%** of respondents requested information on **blast pressure**
- **52%** on **high speed video**
- **43%** on **Heat flux**, **Temperature**, and **Velocity of detonation**
- **30 %** on **Burning rate** and **Internal pressure**
- **Others**: 3 respondents requested information on **fragments mapping** and 1 on **measurement of wind velocity near a fire plume**

These results clearly show that the community is most interested to get information on **blast pressure**, and this is the reason why the new MSIAC project on “Guidance on Instrumentation for IM and HC Tests” started with the blast measurement techniques, see Section 2. Furthermore, the project “Collation and Analysis of IM and HC test data” focused on the analysis of blast measurement data and the development of the IM TNT Tool for calculation of TNT equivalency. So far only one respondent, DGA Missile Testing from France, provided blast data from tests with sub-detonative responses. This is further described in Section 3.

2 BLAST MEASUREMENT TECHNIQUES

As it can be observed in Figure 1, blast is required in 100% of IM Tests and 13% of HC tests. Blast overpressure measurements are also a major contributor in comparing munitions' and explosives' performance or determining Quantity Distances (QD) in storage and transportation safety. The blast parameters of interest are usually the **peak overpressure**, noted P_p or P_{max} (the maximum differential pressure in the air blast relative to the ambient pressure) and the **positive impulse**, noted I+ (the area under the curve where the pressure is higher than ambient pressure), see Figure 2.

However, there is no international guidance on the best way to measure these blast parameters although their determination requires strong skills in a large variety of specialties (high speed phenomena, electronics, data post-processing, mechanics and sometimes optics).

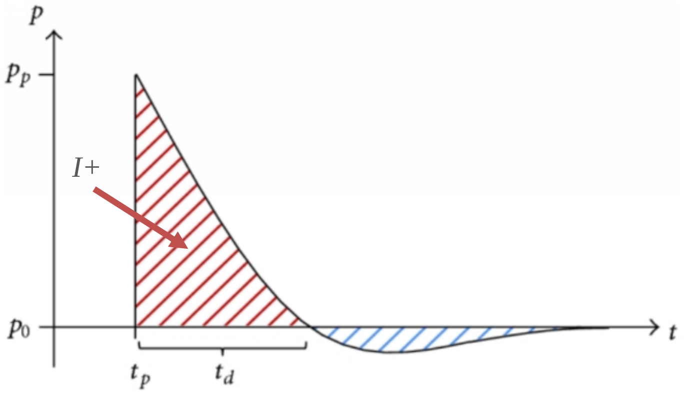

Figure 2: Typical blast pressure-time curve also known as the Friedlander curve

The review that has been conducted at MSIAC during summer 2019 aimed to gather the different techniques used by the community to record blast measurements, and the difficulties experienced during this process. From this state of the art, it was possible to make recommendations that will hopefully help the scientists in the determination of blast parameters for any safety or performance purpose. The limited report L-253 further details the outputs from this study. It is now in a review process and will soon be shared within the MSIAC community [2].

2.1 THE DATA ACQUISITION CHAIN

Any electronic sensor placed in a test range is part of a data acquisition chain which comprises the sensor itself, a voltage amplifier/conditioner, a readout instrument and cables connecting together these electronic elements, see Figure 3.

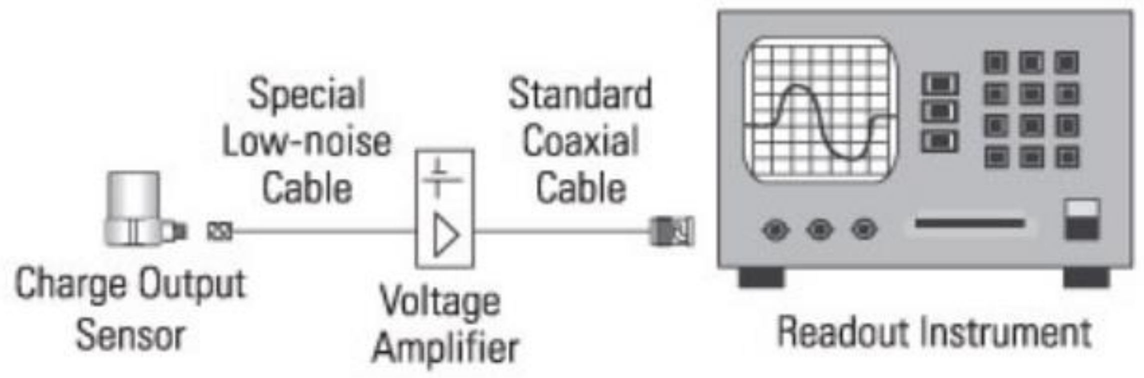

Figure 3: A typical data acquisition chain for electronic sensors

All the elements of this chain were reviewed during this study. However, only the state of the art on electronic transducers will be presented in this document, as we believe this is the most critical part of the blast instrumentation.

2.1.1 State of the Art on Blast Transducers

Measuring the blast from an explosive event implies measuring the overpressure as a function of time, as shown in Figure 2. To do so, the most direct method is to use transducers to convert the blast effect into an electronic signal that can be recorded by a readout instrument such as an oscilloscope. Post-processing the pressure-time curves provides all the blast parameters, including P_{max} and I+.

2.1.1.1 Existing Electronic Blast Transducers

The most commonly used blast transducers are probably the piezoelectric and the piezoresistive ones. They are typically composed of a sensing element protected by a diaphragm and a transduction element. A signal condition device can be also included to the sensor design.

Piezoelectric transducers

The sensing element of piezoelectric transducers is a natural crystal, historically quartz or tourmaline but it has readily given way to ceramic materials which can be a hundred times more sensitive than natural crystals. These kinds of material react when they are constrained by pressure. They deliver an electrical voltage which is proportional to the strain: this is the piezoelectric effect [11].

This pressure transducer has a very high frequency response (depending on its height), it can withstand high pressure shock waves, and it shows a linear behaviour over a wide range of applied pressure [12].

However, most of the time, the voltage signal is very low, therefore, an amplifier is needed to get the final result. That is why some manufacturers are designing built-in amplifiers in their piezoelectric transducers. Besides, piezoelectric transducers' crystals only react when they are constrained, which means that only dynamic pressure measurements can be done with this type of transducers.

Piezoresistive transducers

Piezoresistive transducers rely on the piezoresistive effect which occurs when the electrical resistance of a material changes in response to applied mechanical strains [11]. The piezoresistive resistors are linked with a pressure sensitive diaphragm which is usually directly connected to a Wheatstone bridge. Hence, the resistance change due to the pressure can be directly converted into a voltage output which is proportional once again to the applied pressure.

Several kinds of piezoresistive transducers exist. Semi-conductor transducers are among the most sensitive ones but they may also be sensitive to light (including radiation produced by the munition or explosives) and significantly affect the results.

Piezoresistive transducers are widely used by experimenters because they are simple to use, they can measure both dynamic and static pressure and have a high accuracy. However, they are quite expensive and have a limited frequency response [13]. Besides, as they are passive devices, they need an external source of power to operate.

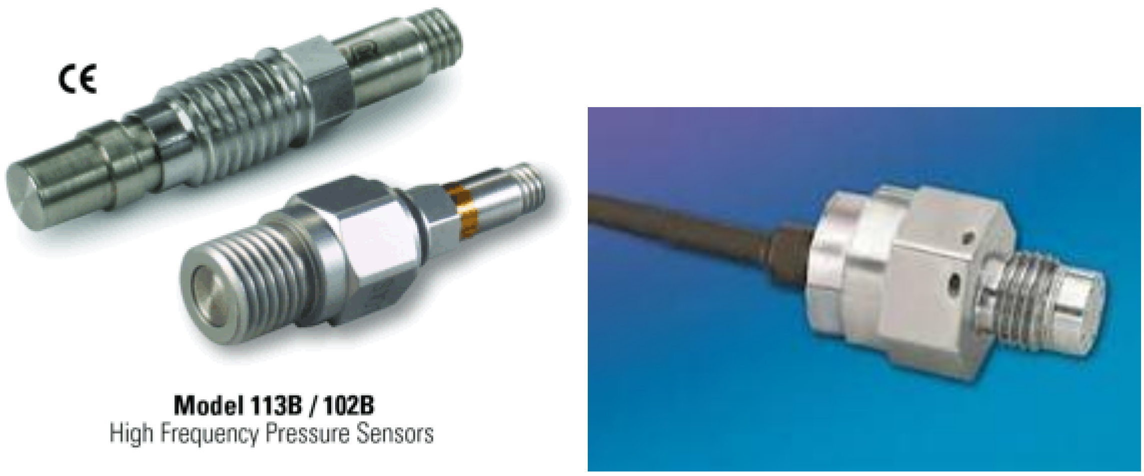

Figure 4 Left side: Integrated Circuit-Piezoelectric ICP® pressure transducers [9] – Right side: A piezoresistive Kulite HKM 375 Pressure Transducer [10]

Other electronic transducers

Other electronic blast transducers exist which are more or less used, depending on some advantages they may have over the piezoelectric or piezoresistive ones: PVDF, capacitive transducers, microphones, and Micro-Electro-Mechanical Systems (MEMS).

Their respective advantages and drawbacks are gathered in Table 1.

Table 1: Blast transducers – Pros and Cons

Transducer name	**Typical Brand**	**Advantages**	**Drawbacks**
Piezoelectric transducers	PCB Piezotronics	High frequency response Linear over a wide pressure range Quite robust Works well in thermally active environments	Low noise cables needed Need very high input impedance Only dynamic pressure measurements Sensitive to acceleration (if no compensating masses are present)
Piezoresistive transducers	Enedvco, Kulite	Both dynamic and static pressure measurements Reliable Robust good signal over noise	Temperature dependent Limited frequency response Power supply needed
PVDF	/	High signal to noise ratio Wide pressure range Flat (can be sandwiched between two layers of material)	Sensitive to lateral strains Not linear response Need to integrate the resulting data
Capacitive transducers	Setra Systems	Good linearity, hysteresis and reproducibility Static and dynamic measurement possible	Sensitive to humidity Temperature of operation range is limited
Microphones	/	Microphone height do not have an impact on the pressure measurements Durable and robust Easy to operate	Not recommended for high pressure measurements Limited frequency response
MEMS	/	Small and cheap Shockwave disturbance minimized High bandwidth	External power required Sensitive to thermal transients Still not widely used, needs more user feedback

2.1.1.2 Orientation and Mounting

When mounting the pressure transducer in the test range, two configurations exist: the reflected (or face-on) pressure and the incident (or side-on) pressure. Figure 5 emphasizes the position of the pressure transducers for the appropriate measurements.

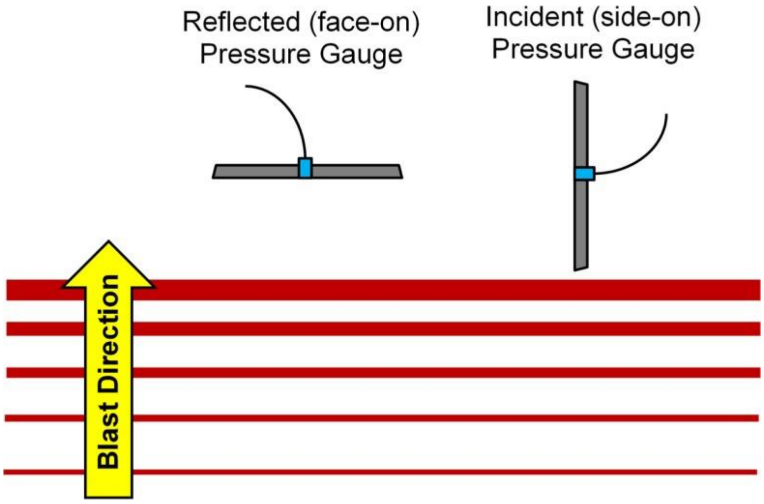

Figure 5: Pressure transducers position relative to the blast wave direction

Measurement of the side-on overpressure takes place by mounting the transducer parallel to the blast direction. This captures the actual pressure wave with the incident overpressure peak as it travels through the air. The reflected pressure is measured when the transducer is mounted perpendicular to the flow. In that case, the pressure signal is a combination of the incident overpressure and the dynamic one. Therefore, at the same distance from the source of explosion, the reflected pressure always has a higher overpressure peak than the side-on pressure. The “reflection factor” equals 2 in the acoustic limit of low overpressures (ca. < 10 kPa), but reaches up to 8 for high overpressures (hundreds of kPa). Dependent on the size of the perpendicular plane and the positive phase duration, the reflected overpressure may be “cleared”, and the reflection reduces to the side-on overpressure.

The side-on pressure is often measured to get the static overpressure peak value which is then analysed for the determination of TNT equivalency or for performance comparison. When the actual blast loading and structural response and damage of a structure is of interest, transducers may be mounted in walls.

The orientation of the sensor will then determine its mounting. Pencil, pancake (or lollipop) and bullnose probes will be preferred for side-on pressure. The shape of these probes are designed in order to disturb the blast wave as little as possible during its passage along the probe. The biggest drawbacks for these types of mounting are the misalignment issues [16] and the vibration of the stand.

For reflected pressure against walls, or side-on pressure measurement on the ground, the flush to ground/surface mounting will be used. With this mounting, misalignment is not a problem anymore. However, this mounting requires a smooth large surface free of obstacles. The vibrations may also affect the measurements, especially for ground mounting as the transducer will be subjected to Mach stems. It also requires to design specific boxes in which the sensors are mounted. This type of mounting is preferred for test ranges that are dedicated to air blast measurements as this technique is more time-consuming to be implemented.

The mountings mentioned above are presented in Figure 6.

			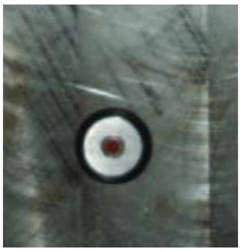
Pencil Probe	Bullnose Probe	Pancake/Lollipop probe	flush to surface mounting

Figure 6: Different types of sensor mounting

2.1.2 Recommendations and Best Practices

Accurate measurement of the incident or reflected overpressure in an air blast is extremely challenging. In addition to strong specific skills in various domains, it also requires a lot of experience and know-how which is not always possible to share. The following sections represent a summary of the recommendations and best practices found in the open literature concerning what we believe as the most critical questions to address on air blast measurements: calibration, fireball effects and frequency response. More details on other aspects such as the mounting, the cabling, the data recording system and the location of the sensors in the test configuration will be provided in the MSIAC limited report L-253.

Calibration

The calibration is the most important part of the test preparation as it ensures the good functioning of the sensor: its response to a trusted pressure level and its linearity and hysteresis over the desired pressure range. It is recommended to calibrate the sensors in the same end-to-end configuration (or the closest possible) as the one in which they will eventually be used. Ideally, pressure transducers must be calibrated each time there is a change in the data acquisition chain and before and after each test campaign [17].

Two types of calibration exist: the static and the dynamic calibration. For obvious representativity reasons, the dynamic calibration is preferred over the static one. Plus, it is useful to know that the static calibration stresses the transducer more than dynamic calibration.

Dynamic calibration can be done by the means of a shock tube, a shockless pressure step calibrator or a pulse generator, for instance. The pros and cons of each option, as well as the devices commonly used for calibration, will be further discussed in [2].

Fireball Effects

If the sensors are placed too close to the explosive charge (less than 2-4 m/kg$^{1/3}$, depending on the explosive formulation), air blast measurements may be strongly disturbed by thermal transients and electromagnetic effects due to the fireball which produces both light and thermal effects. Typically, the sensor is likely to sustain up to 2000°C for 10-20 ms [18]. This may result in an undesirable zero-shift of the signal and/or a distortion of the pressure-time curve.

The investigation done by the US National Bureau of Standards in 1978 [19] studied the influence of thermal transients on several transducers protected with different options. The most efficient techniques consist in adding one or several (up to three) layer(s) of electric black tape on the sensing element or applying RTV silicone rubber or vacuum grease on it. Figure 7 shows an example of a transducer protected by RTV and the resulted signal of an RTV-coated sensor vs an unprotected one (bare element).

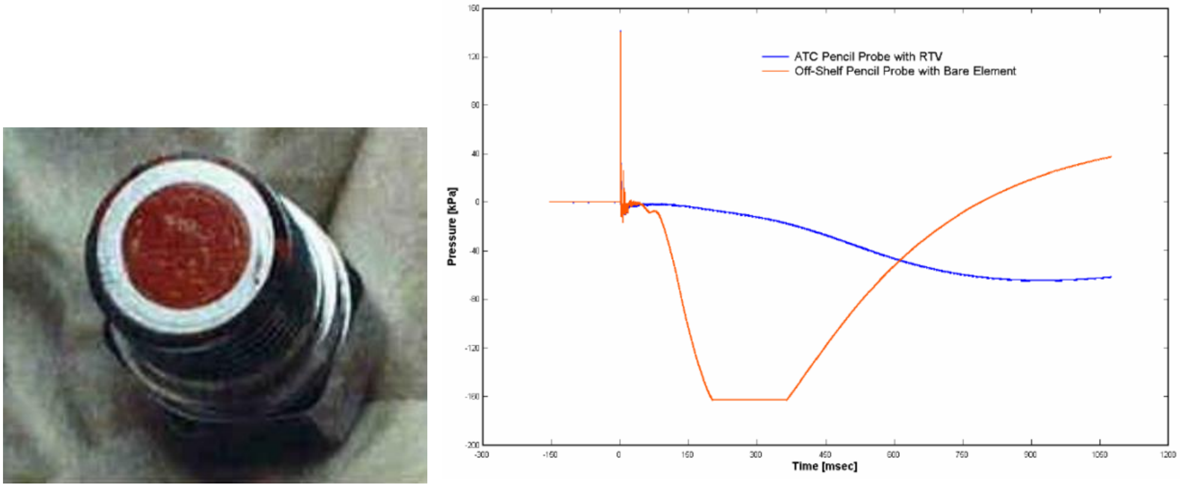

Figure 7: Pressure transducer protected by a layer of red RTV silicone rubber – Effect of the RTV coating on the recorded signal [18]

If a thermal protection can save the signals recorded in close-in regions, the extra layer onto the sensing element may also affect the recorded signal. The consequences are 1) an increase in the mechanical impedance of the pressure transducer, resulting in a slower rise-time, and 2) a lower transducer frequency response, resulting in a higher signal-to-noise ratio [19].

Frequency Response

Pressure transducers generally approximate a second-order low-pass model [18]. Their resonant frequency when exposed to a dynamic stimulus is sought to be the highest possible (above 100 kHz).

A rule of thumb is to limit the frequency response of the whole data acquisition chain to about 20% of the resonant frequency of the transducer. However, due to the mounting of the transducer it is the mechanical resonance once mounted that needs to be considered [17].

Adding protective coating on the diaphragm of a transducer can affect the frequency response of the transducer and thus, its resonant frequency. To take into account these changes the following formula gives an approximation of the expected resonant frequency f_r (in Hz) of the transducer after being protected.

$$f_r = \frac{0.471t}{R^2} * \sqrt{\frac{Eg}{w(1-\upsilon^2)}}$$

Where t is the diaphragm thickness (in m), R is the diaphragm radius (m), E the elasticity modulus (Pa), g the gravitational acceleration (m.s^{-2}), w the specific weight of the diaphragm material (N .m^{-3}), υ the Poisson’s ratio.

3 ANALYSIS OF IM AND HC TEST DATA

Within the project “Collation and analysis of IM and HC test data” the objective is to analyse existing IM and HC blast, thermal and fragmentation test data to gain a better understanding of the explosive effects for sub-detonative munition responses. A possible outcome could be a correlation between TNT equivalency and assigned munition response. In order to help finding this correlation the IM TNT tool has been developed which calculates several TNT equivalency values including a measure of uncertainty, based on blast measurements.

This section will describe the IM TNT tool including its application to a number of data sets in the scope of munition response. Also we will discuss the impact on safety distances and consequence analysis. The current report only describes a selection of the work done; a complete overview is available in MSIAC report [3].

3.1 THE IM TNT TOOL

The IM TNT tool has an input section where the following data can be provided with respect to the munition:

- Munition Type (name or description);
- Explosive Mass (kg);
- Assigned munition response (Type I, II, III, IV, V, or No Reaction (NR)).

After providing the number of measurements, columns are generated to input the distances, peak overpressure and impulses, including a measure of uncertainty. We note here that for sub-detonative responses the shape of the blast wave may differ substantially from a detonation (e.g. Figure 2). An example with more rounded pressure peaks is shown in Figure 8 [20] (note that some sensors failed after blast wave passage).

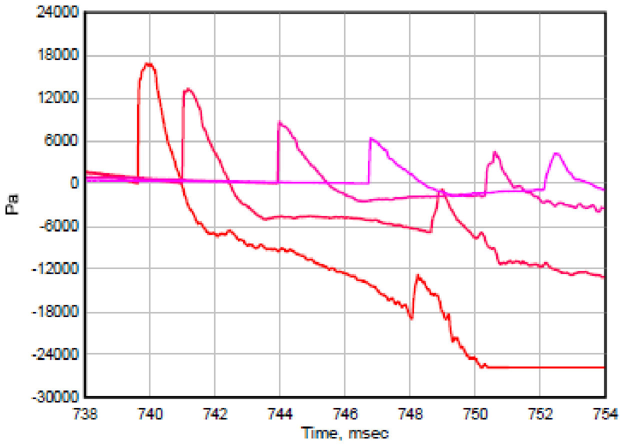

Figure 8: Blast wave from a sub-detonative event [20]

For the determination of TNT equivalency the user can make a choice between a hemispherical or a spherical TNT charge. During the development of the tool, differences have been observed in “standard” TNT curves reported in literature. The Blast Effects Computer (BEC-O) [21] was assumed to be the most reliable option and been selected for inclusion in the tool. More details are presented in MSIAC report L-248 [3].

Furthermore, the user can choose to carry out the data fitting procedure with an optimisation of:

- The sum of squared errors;
- The sum of relative squared errors (relevant when there are large differences between the measured values at different transducers);
- The sum of weighed squared errors (relevant when measurement errors are available).

The datafitting procedure varies the explosive mass, scaled distances, peak overpressures, and scaled impulses in an iterative process until an optimum is reached. An example is given in Figure 9, which shows test impulse values, a 100% TNT equivalency curve based on the munition’s explosive mass, and an optimised curve (in this case for 12%).

TNT equivalencies are determined for each measurement point individually, as well as one global for the combined set of (pressure or impulse) measurements.

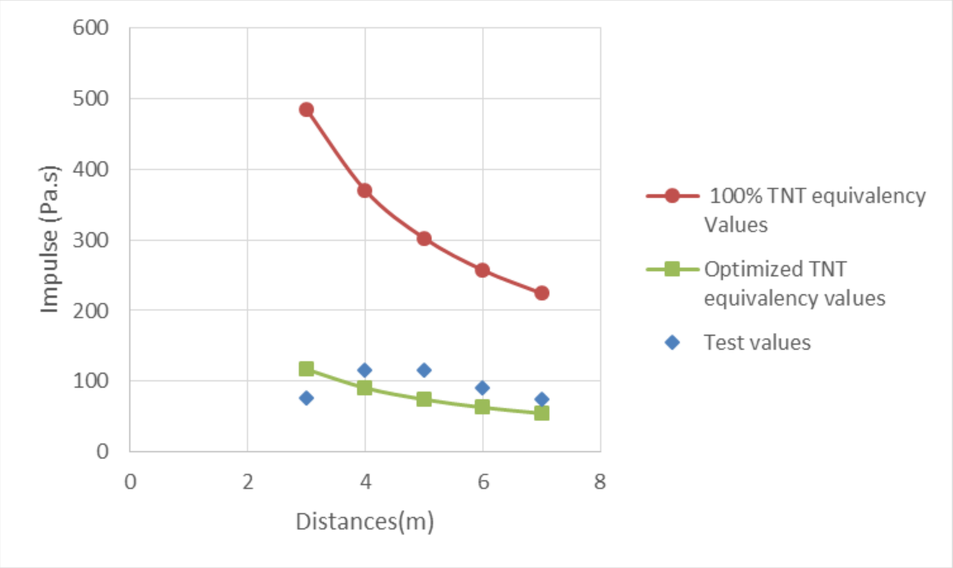

Figure 9: Illustration of datafit process

3.2 APPLICATION TO TEST DATA

Various datasets have been analysed with the IM TNT tool for validation purposes. Davies, et al. [20] from Cranfield University conducted tests with MTV compositions and calculated TNT equivalencies for each measurement. Figure 10 shows the presented values overlaid with results from the IM TNT tool. The calculated values could be very well reproduced, which gives confidence in the proper working of the tool.

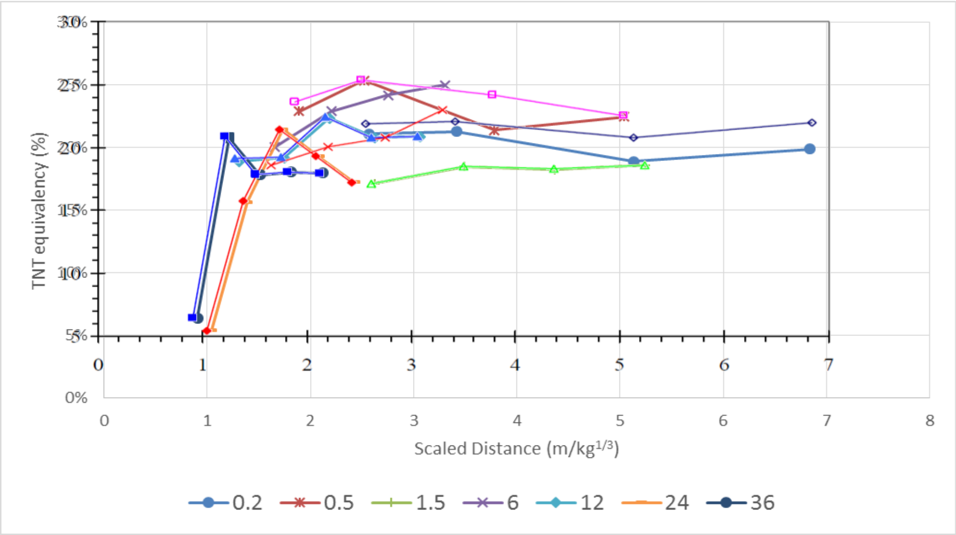

Figure 10: Comparison between TNT equivalencies calculated by Davies, et al. [20], and with the IM TNT tool.

The survey resulted in only one useable dataset from IM tests. This deals with German/French SCO and FCO tests for solid propellant rocket motors, Coutrey, et al. [22]. TNT equivalencies were determined and can be compared with the assigned munitions reponse in the tests as shown in Table 2. We conclude that much more (IM) test data is needed to identify trends between assigned munition responses and TNT equivalency. This will also be influenced by variability of test results.

Table 2: Results of SCO and FCO tests for solid propellant rocket motors together with TNT equivalency determined by IMT TNT tool.

Test	SCO1	SCO2	FCO1	FCO2
TNT equivalency	22%	118%	0.03%	1%
Assigned response type	III	II	IV	III

3.3 SAFETY DISTANCES AND CONSEQUENCE ANALYSIS

With respect to the storage of ammunition and explosive, NATO standards AASTP-1 [23] and AASTP-4 [24] provide safety distances, also called Quantity Distances (QD), as well as models for consequence and risk analysis. Although these standards address various Hazard Divisions, some of which exhibit “IM properties” such as SsD 1.2.3 and HD 1.6, they do not address the reduced TNT equivalency.

For illustration purposes, we have plotted peak overpressure curves for 100, 60, and 30% TNT equivalency in Figure 11. This figure also shows the curve for the FCO1 test in Table 2 (0.03%). This graph highlights the severe reduction of distances with a peak overpressure of 2 kPa (Vulnerable Building Distance), 5 kPa (Inhabited Building Distance) and 9 kPa (Medium Density Public Traffice Route Distance). It should be noted that QD and risk are not only determined by blast, but also by fragmentation and debris, which has not been further analysed in this project. It is of interest how these phenomena are influenced by sub-detonative munition response.

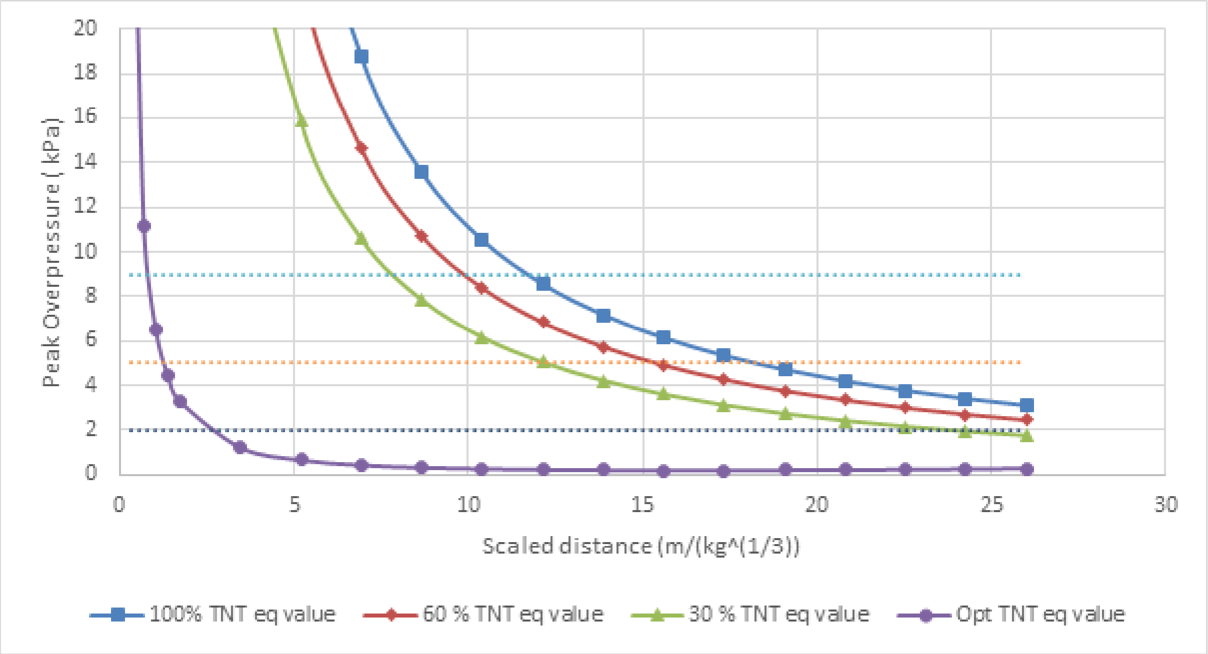

Figure 11: Illustration of reduction of blast distances in relation to QD and consequence/risk analysis

CONCLUSION

This paper provides the first outputs from two new projects at MSIAC, one on “Guidance on Instrumentation for IM and HC Tests” and one on “Collation and Analysis of IM and HC Test Data”. More details will be available in the limited reports associated to these projects: L-248 and L-253, respectively. The draft versions of these documents can be shared with experts for testing and feedback.

The review made on instrumentation techniques for air blast measurements provides a state of the art which covers all the elements of the data chain acquisition. It also provides guidance and best practices in order to improve the determination of air blast characteristics as requested in IM and HC tests.

The on-going work concerns the velocity of detonation and the future efforts will be put on thermal measurements: temperature and heat flux.

The IM TNT tool has been developed for analysis of IM and HC blast measurement data. The tool is capable of predicting TNT equivalencies, and has been validated for detonations and sub-detonative events. It takes into account measurement errors and also presents TNT equivalencies, including an error estimate.

During the development of the tool, differences have been observed in “standard” TNT curves reported in literature; the most reliable option has been selected for inclusion into the tool.

More IM test data is needed to find a correlation between munition response type and TNT equivalence. Results can be used to predict blast QDs as a function of response type (and TNT equivalency). The IM TNT tool is available as an Excel spreadsheet with documentation and benchmarks.

The ultimate goal of these studies are to provide recommendations for improved and harmonized test procedures as well as recommendations for the characterization of munition responses, whatever their reaction type, and their use for safety distances and risk analysis.

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O-215