27th International Symposium on Military Aspects of Blast and Shock
MABS27, France, 2025

MEASUREMENT AND SIMULATION OF SMALL ARMS MUZZLE BLAST

J.K. Pennings[1], J. Verreault[1], R.M. van de Kasteele[1], E.P. Veldhuis[1], M.M. van der Voort[1], T.A.T. Westerhof[1], S. Ouellet[2], G. St. Onge[2]

[1]TNO, Personal Protection and Explosives Safety, Ypenburgse Boslaan 2, 2496 ZA, Den Haag, The Netherlands;
[2]DRDC Valcartier Research Centre, 2459 de la Bravoure Road, Québec, Canada

Key words: Muzzle blast exposure, small arms, measurement and simulation, system engineering, traumatic brain injury

ABSTRACT

Traumatic brain injury due to repetitive exposure to small arms muzzle blast is a growing concern for military forces. A reliable and standardized method to quantify the blast load on the human head is currently missing, let alone the link between the blast load and the injury. This study presents a combined measurement and simulation (CFD) system to measure / simulate the muzzle blast exposure from small arms. The system is developed such that measurements provide validation data to the simulation system, whereas the latter provides detailed pressure and impulse information at any desired location around the muzzle. The measurement equipment consists of various sensors and a data acquisition system as well as a database. The equipment was optimized based on test series with various weapon configurations including muzzle brake and suppressor systems. Testing was conducted both at the Knowledge Center of Weapons and Munition (KCW&M) in the Netherlands and at DRDC Valcartier Research Center, Canada. The simulation system is "powered" by the APOLLO Blastsimulator software (computational fluid dynamics solver dedicated to high-speed flows and blast waves). Furthermore, the simulation system ensures the proper pre-processing (convert the weapon scenario into input files for APOLLO) and post-processing (interpreting pressure profiles) tailored for the application of muzzle blast loading on a human head. Using a minimum amount of input information from the weapon configuration, the simulation system is able to predict the pressure (and impulse) profile at any desired location around the muzzle. This approach enables quantifying blast loads on the human head for various shooter postures and in any complex environment such as near (reflecting) walls and other infrastructure. A comparison for nine different weapon configurations shows that simulations are on average within 15% of the measured overpressures without calibration. The developed system provides a solid basis for standardization. To ensure the seamless integration of the measurement and simulation systems, a graphical user interface was developed, which also facilitates the interaction between the user and the different systems. This research has been conducted in a project funded by the Irregular Warfare Support Technical Directorate (IWTSD). Financial support by IWTSD does not constitute an express or implied endorsement of the results or conclusions of the project by either IWTSD or the U.S. Department of Defense.

INTRODUCTION

Traumatic Brain Injury (TBI) due to repetitive exposure to muzzle blast from small arm weapons is a growing concern for military forces [1][2][5]. Muzzle blast exposure is an example of Low-Level Blast (LLB), which is associated with (amongst others) cognitive problems, hearing problems, headaches, behavioral health conditions, anxiety, post-concussive syndrome and migraines [3]. In order to investigate (and eventually prevent) these injuries, the first step is to be able to quantify the load on the operator from firing these weapons. However, a reliable and standardized method to do so is currently missing. In this study, a system which is capable of determining these loads in a consistent manner is presented. First, an overview of the system is given in the first section. In the next three subsequent sections, the individual subsystems of the main system are discussed in more detail. Finally, in the last section, an example case study is given, where the application of the system for a specific weapon is discussed, as well as the results of all other weapons that have been examined so far.

SABOES SYSTEM OVERVIEW

The Small Arms Blast Overpressure Exposure System (SABOES) provides a methodology for characterizing the muzzle blast overpressure exposure to the operator resulting from firing small-arm weapons. Besides direct measurement of the overpressure, SABOES offers the capability to model and visualize (using CFD) muzzle blast wave propagation, allowing for predictions of (shock wave) pressures at various locations and for different weapon configurations. This modeling is validated through comparison to (and possibly calibration against) measured blast pressures. All generated data are systematically archived within the system's database.

The SABOES comprises three integrated subsystems (see Figure 1):

- SABOMS (Small Arms Blast Overpressure Measurement System): a measurement system for collecting muzzle blast pressure-time data.
- SABAS (Small Arms Blast Overpressure APOLLO Simulator): a CFD simulator for modelling the muzzle blast wave propagation.
- SABOD (Small Arms Blast Overpressure Database): a database for archiving data acquired from both SABOMS and SABAS.

All systems are connected by means of the SABOD Manager GUI, which is (amongst other functionalities) used to archive measurement data from SABOMS and simulation results by SABAS to the database (SABOD).

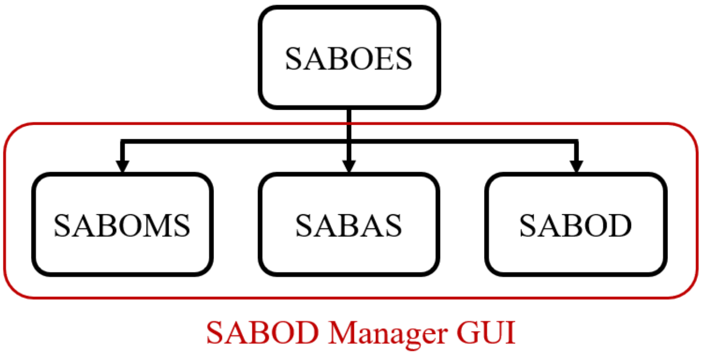

Figure 1: SABOES and subsystems which are connected by the SABOD Manager GUI.

In Figure 2, a schematic overview of the SABOES system is shown, which shows the setup and locations of devices. The subsystem SABOMS is deployed in a shooting range and control room. The SABAS and SABOD are located in an office environment. The physical component of SABOD is the network attached storage (NAS). The SABAS is software, which in turn consists of multiple software executables. The advantages of having a simulation subsystem (SABAS) in addition to a measurement system are (once validated with measurements):

- Access to field data (e.g. pressure) at arbitrary locations instead of at a limited amount of measurement locations.
- Visualization of the flow field for gaining insights in the muzzle blast propagation.
- Alleviation of the necessity to acquire additional measurements by simulating scenarios which are a (small) variation to validated scenarios.
- Allowing the possibility to obtain the reflected pressure on the (simplified) head of the operator.

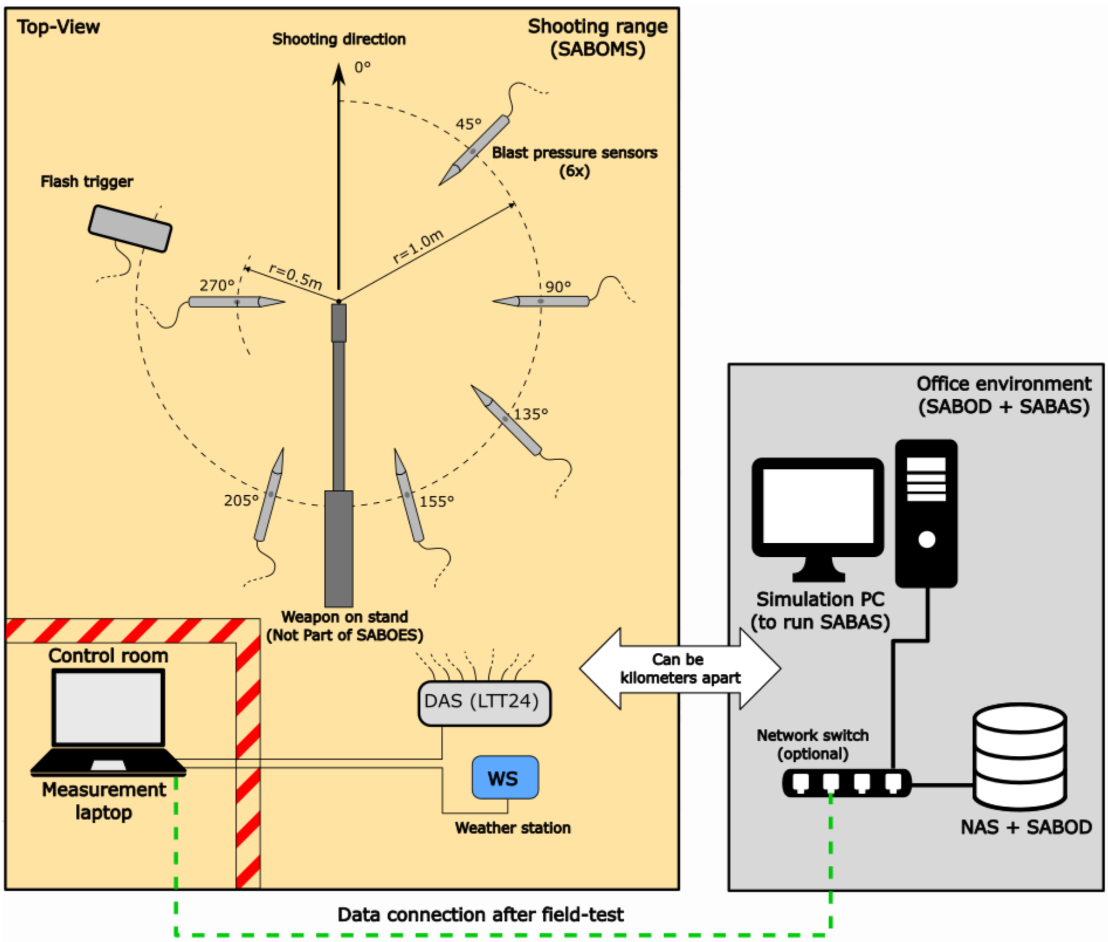

Figure 2: Schematic overview of the SABOES system. Software is excluded in this overview.

In the subsequent sections, each subsystem is discussed in more detail.

MEASUREMENT SUBSYSTEM (SABOMS)

In Figure 3, an overview of SABOMS is shown. The measurement system is designed with a total of six blast pressure sensors (blast pencils), P1 to P6. The sensors are connected with coaxial cables to a Data Acquisition System (DAS). The blast pressure sensors will be mounted on stands and have to be placed in pre-defined fixed positions around a weapon system. The sensor of the blast pencils is placed at 1 m from the muzzle (except for P6 which is at 0.5 m). If preferred, the sensors can be placed at other locations. A flash detector is used to measure the small flash just after the bullet leaves the barrel, which is defined as T-zero. Having a T-zero makes comparisons (in terms of arrival time of the shockwave) with SABAS simulations easier, because in SABAS T-zero is also at the moment the bullet leaves the barrel. To record the ambient temperature, humidity and pressure a small weather recording system is included to the measurement setup. The weapon needs to be placed on a stand (as in Figure 3) and should be fired remotely from a control room. The height of the (barrel of the) weapon above the ground can be chosen arbitrarily. The blast pencils need to be placed at the same height. The end of the barrel is the system's origin (i.e. the point x,y,z = 0,0,0). If an attachment is added, the end of the attachment becomes the new origin.

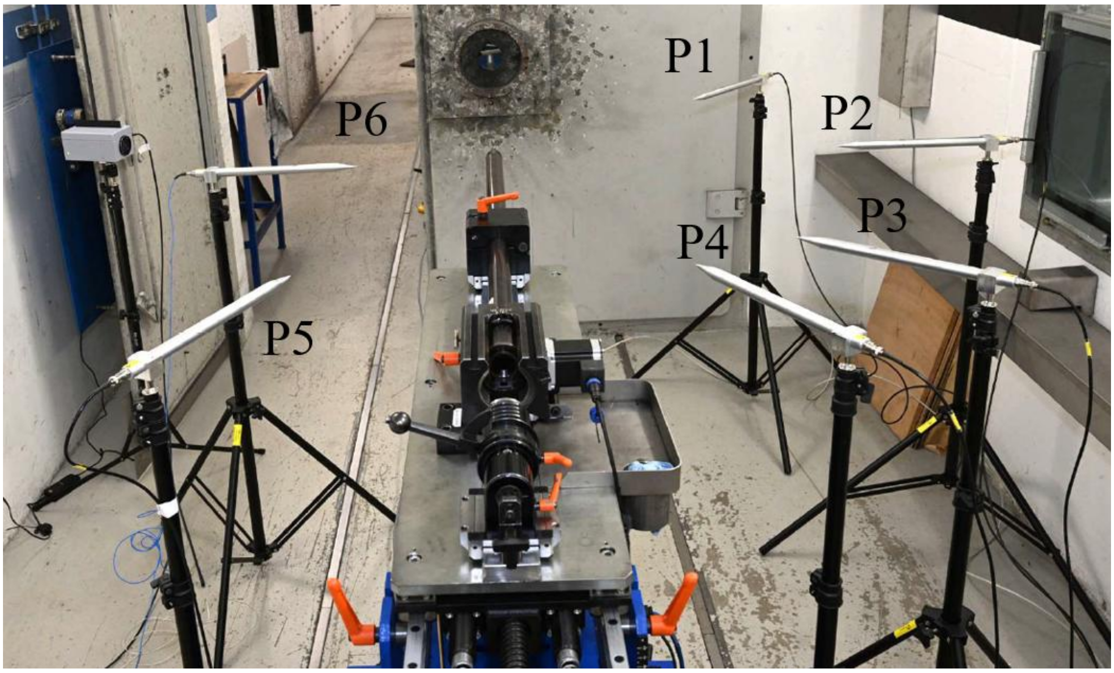

Figure 3: Overview of the SABOMS system with a lab barrel (instead of an actual weapon), blast pencils P1 to P6 and the flash trigger (left).

SIMULATION SUBSYSTEM (SABAS)

SABAS is a semi-automated CFD simulator for modelling the muzzle blast wave propagation. The entire simulation procedure can be performed from the SABOD Manager GUI, and requires minimal user intervention. It is designed such that non-CFD or simulation experts can run the analyses. In Figure 4, the data flow and interactions within SABAS are shown. It is divided into four sections: Input (green), Internal ballistics (yellow), Running CFD (orange) and Output (blue). From user-defined input, an internal ballistics analysis is performed, of which the output is used as input for the CFD solver. The results from the CFD analysis can be compared to the measurement data and, if sufficiently accurate, stored at the SABOD. If the accuracy is insufficient, a calibration procedure can be started by redefining the input and running SABAS again. In the subsections below, a description of each individual part of SABAS is given in more detail.

Input

Scenario

The user input specifies the scenario to be analyzed and is provided by the program user. In Table 1, the relevant input parameters for SABAS are given, where in Figure 5 a schematic with indication of the different relevant input parameters is given.

Table 1: Input parameters for SABAS.

Input relating to	**Input parameter 1**	**Input parameter 2**
Barrel	Internal length	Internal diameter
Cartridge	Case length	Case diameter
Internal ballistics	Propellant mass	Peak internal pressure
Projectile	Projectile mass	Muzzle velocity
Weapon position	Height of barrel center to ground	Elevation

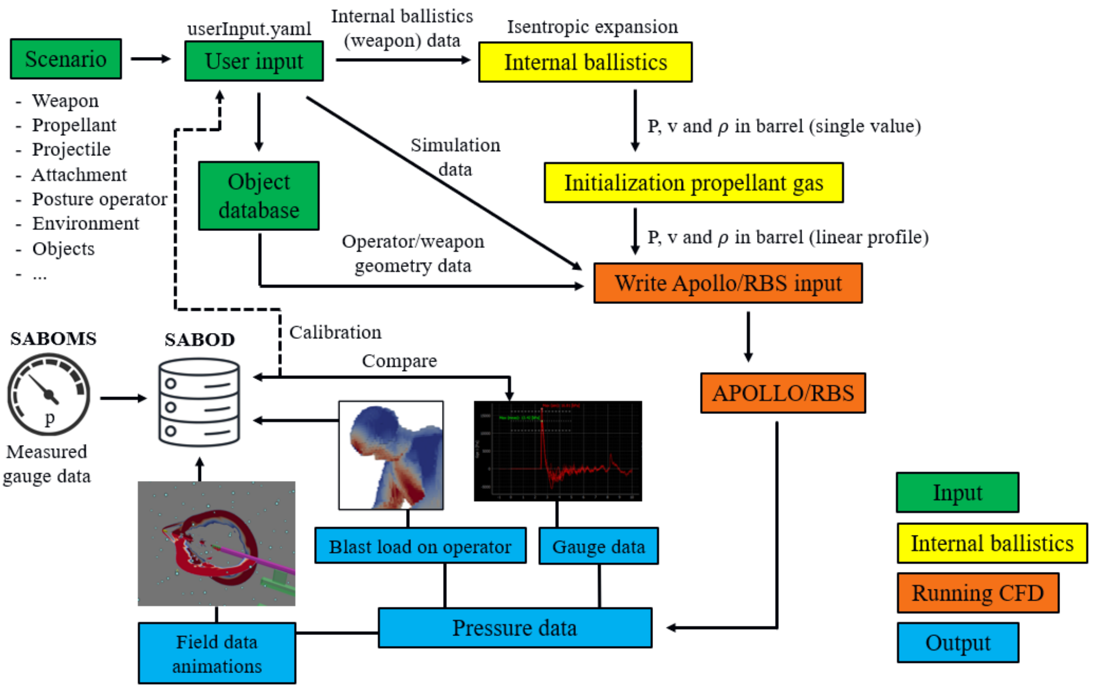

Figure 4: Overview of the SABAS subsystem (RBS = Rigid Body Solver).

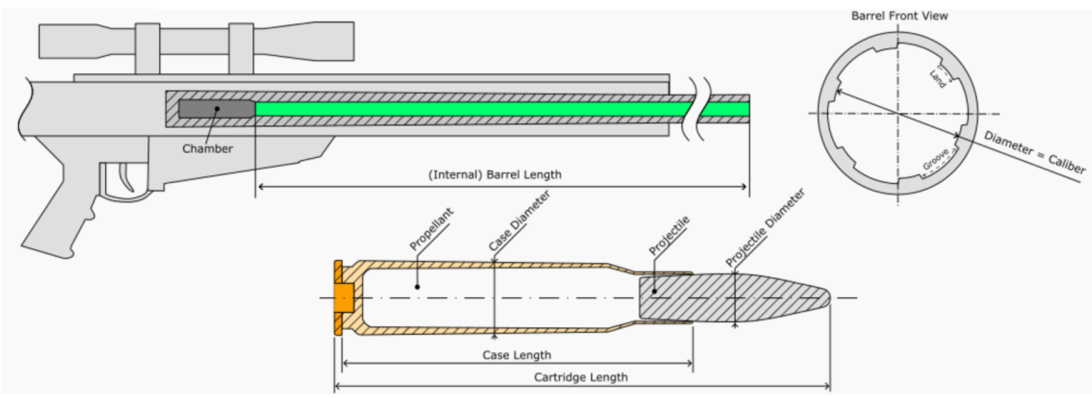

Figure 5: Definition of several relevant input parameters for SABAS.

CAD files for environment and weapon attachments

The environment (e.g. walls, shooting tunnel, cliff) as well as weapon attachments like suppressors and muzzle brakes can be included in SABAS. To this end, CAD (.step) files can be attached by the user. Note that in the simulation it is not necessary to model the complete weapon (external geometry or the triggering details). Only the internal geometry of the weapon suffices to generate the muzzle blast of the weapon. In Figure 6, some examples of typical weapon attachments are shown, where a cut is made in a vertical symmetry plane. Beside a bare muzzle configuration (top left), a situation with a muzzle brake (top right) and suppressor (bottom) is shown. SABAS is capable of modelling the reducing effect of an attachment on the muzzle blast. In Figure 7, an example of this is shown by visualizing the pressure field (left) and velocity field (right) from a SABAS run including a muzzle brake. The influence of the baffles of the muzzle brake can be clearly seen, especially in the velocity field where the gases expand sideways as well, as opposed to a bare muzzle where gases would expand mainly in the direction of the projectile.

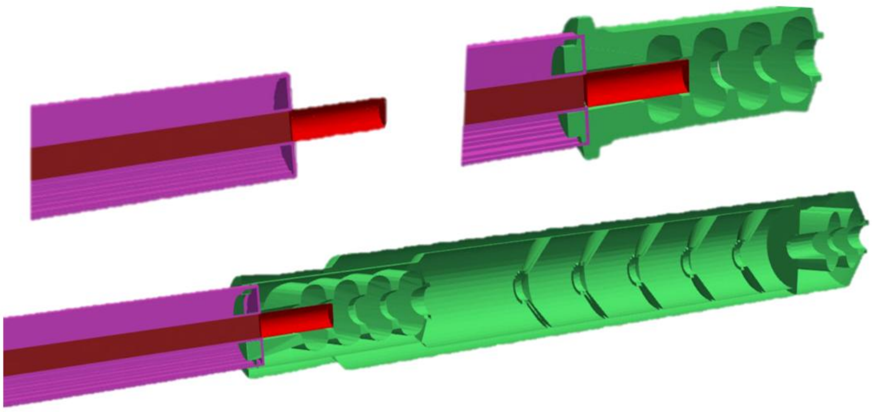

Figure 6: Examples of weapon attachments with a bare muzzle in the top left corner showing the barrel in purple and the projectile in red, a muzzle brake (green) in the top right corner and a suppressor at the bottom.

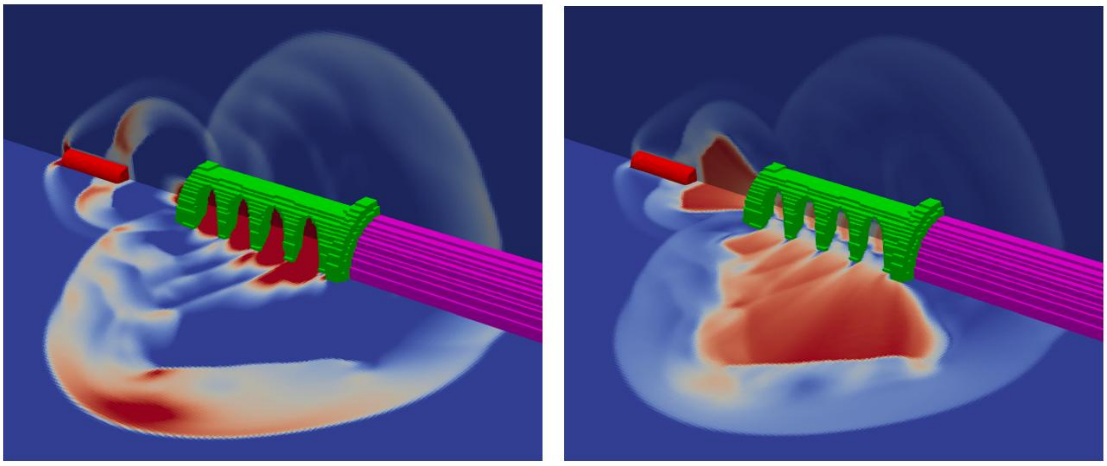

Figure 7: Example of effect of a muzzle brake simulated by SABAS showing contours of pressure (left) and velocity (right) and the barrel in purple, muzzle brake in green and projectile in red.

Gauge definitions
By default, 6 gauges are included in the SABAS simulation, of which the locations correspond to those from the blast pencils in SABOMS. This allows for a direct comparison of measurement and simulation data. In addition, the following gauge types can be included:

- Gauges in a sphere around the muzzle with user-defined radius and 3D grid spacing.
- Gauges at arbitrary locations defined by x, y and z-coordinates.
- Gauges at a head (modelled as a rigid sphere with radius 0.18 m), measuring the pressure applied to the head, accounting for the blast propagation around the head. This is automatically done when the user includes the head in the model. In Figure 8 an example of defined gauges around a head in SABAS is given.

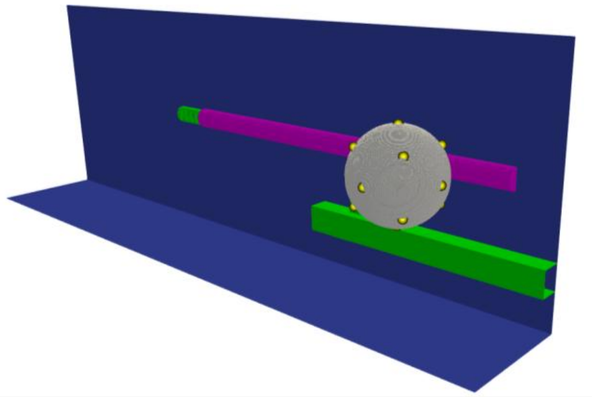

Figure 8: Visualization of the gauges (in yellow) around the head (represented by a sphere) where the pressure on the head can be measured.

Automatically starting analyses
With the specified user input, SABAS automatically sets up required files to run the internal ballistics and CFD analyses. This does not requires user intervention.

Internal ballistics
Before starting the CFD analysis, the gas properties within the barrel need to be determined, which are computed in the internal ballistics part of SABAS. For this, isentropic expansion of the gas is assumed, which is calculated based on the internal volume of the barrel and cartridge, mass of the propellant and the peak pressure in the barrel (all of which are user input). The calculation is started with the peak pressure and the initial volume behind the projectile (cartridge volume). Then, assuming the position of the projectile base to be at the end of the barrel, the isentropic relations are used to obtain the new pressure, temperature and density from this volume change, which are constant through the barrel. The flow velocity increases linearly from zero (breech) to the muzzle velocity (muzzle), which is an input parameter. This state of the (ideal) gas is provided as input for the CFD analysis.

Running CFD
The actual CFD simulation is done by using the commercial CFD program APOLLO Blast Simulator [4], which is a specialized CFD tool dedicated to the simulation of explosions, blast waves and gas dynamics by solving the conservation equations for transient flows of inviscid, chemically reacting, compressible fluids. It is important to

note that SABAS does not come with a license for the CFD program. The starting point of the CFD analysis is the gas initialization from the internal ballistics analysis. At this stage, the base of the projectile is at the muzzle end (as shown in Figure 6), corresponding to T-zero. The CFD solver is directly coupled with a Rigid Body Solver for the projectile motion. The analysis is divided into stages, where in the first stage the computational domain is relatively small with a high mesh density, allowing for accurately resolve the complex fluid flow near the muzzle (and possibly in attachments). An example of this complex fluid flow is shown in Figure 7. In subsequent stages, the computational domain is increased and the mesh density is decreased (since a high mesh density is no longer required), resulting in a computationally efficient simulation. The user can specify the number of CPUs that are used, the end time of the simulation and the use of symmetry (i.e. modelling only half of the domain for saving computation time) when this is applicable/allowed.

Output

Generated output

SABAS generates pressure data, and comprises the following:

- Gauge data: Pressure as a function of time at all the specified gauge locations. At least the data of 6 gauges are written, of which the locations coincide with the locations of the blast pencils during the experiments (SABOMS). These are shown in orange in Figure 9. Additional gauges are indicated by blue spheres.
- Field data: Animations showing contours of pressure in the domain (including the pressure on objects) are automatically written by SABAS. A screenshot of such an animation is shown in Figure 9. From this, the muzzle blast can be clearly seen, as well as the bow shock generated by the projectile.
- Blast load on operator (gauge data): A head (sphere) can be specified by the user at which the (reflected) pressure is measured (as shown in Figure 8).

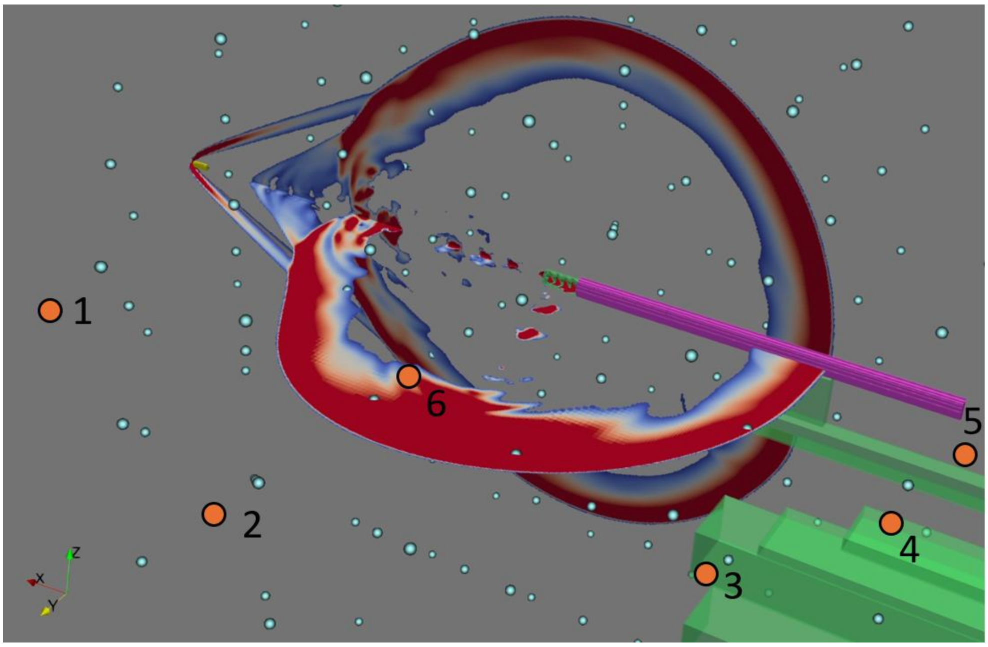

Figure 9: Screenshot of an animation generated by SABAS showing contours of pressure and gauges at the locations analog to those in SABOMS in orange. Overpressures below 1 kPa are now shown.

Writing to database (SABOD), accuracy and calibration

The gauge data from SABAS and SABOMS can be compared one-on-one to determine the accuracy of the SABAS simulation. If the accuracy is within a pre-defined limit, all SABAS data (input, gauge data and animations) can be stored to the SABOD. If the accuracy is outside the limit, a calibration procedure can be started where the input parameters are changed in such a way that the SABAS gauge data is within the accuracy limit. The input parameters of the internal ballistics part are most likely to be changed. If the calibration procedure is successful (i.e. a set of changed input parameters gives results within the accuracy limit), all results can be stored to the SABOD. The change of input parameters for the calibration procedure is done manually by the user.

DATABASE (SABOD) AND SABOD MANAGER GUI

The subsystem SABOD is a database for archiving data acquired from both SABOMS and SABAS. The physical component of SABOD is a Network Attached Storage (NAS). The subsystems SABOMS, SABAS and SABOD are all connected through the SABOD Manager GUI, from which the archiving can be controlled. The main functionalities are:

- Enabling storing data from SABOMS and SABAS to the SABOD in a consistent manner.
- Browse and plot stored data on the SABOD, including comparing measurement and simulation data.
- Running SABAS simulations.

In Figure 10 the main screen of the SABOD Manager GUI is shown. The GUI has several tabs and windows which can be easily accessed.

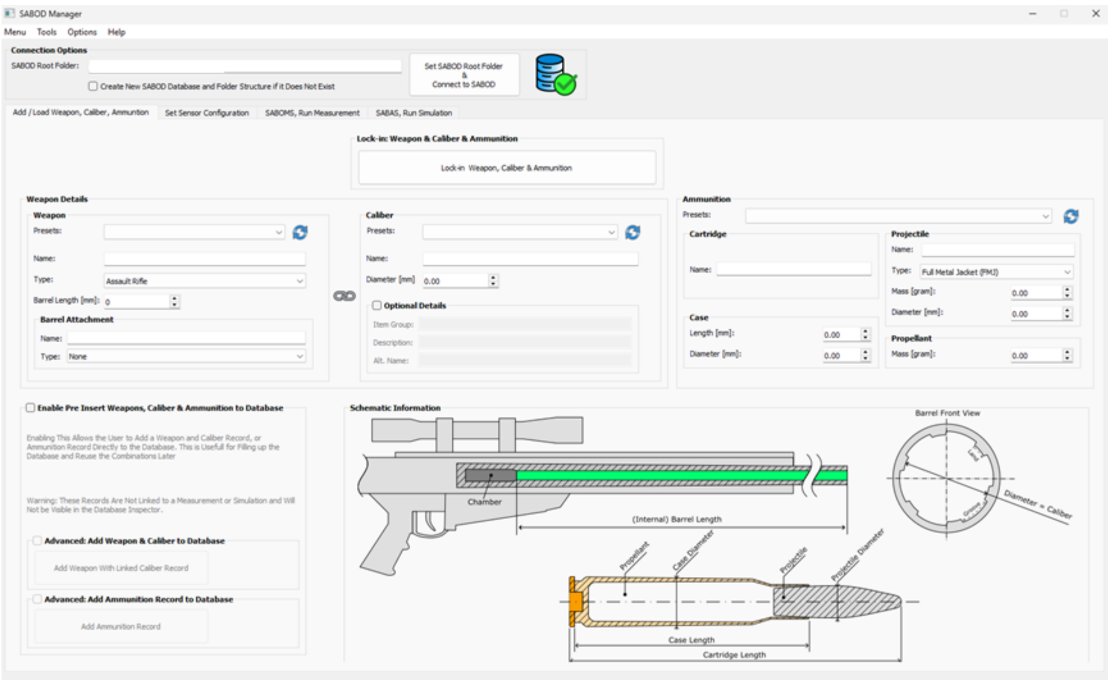

Figure 10: Main screen of the SABOD Manager GUI.

The SABOES is designed to operate in the field without internet connections. Any data generated during the field-test with SABOMS must be transferred to the SABOD at a later point in time. This can be done by directly connecting the SABOMS measurement laptop to the NAS or via a network switch. The SABOD Manager GUI has a specialized copying tool that enables this. Before the data is copied from the measurement laptop to the SABOD, the data resides in a local SABOD Lite on the SABOMS measurement laptop. The word "Lite" indicates that the local version is a lightweight version of the main SABOD, because it only stores measurements, which in turn may be deleted after they have been copied to the SABOD on the NAS.

When the data from SABOMS is stored in SABOD, typically a SABAS simulation follows. For running SABAS, the user has three options (simulation types):

1. Validation of a simulation of a scenario in SABOD
2. Variation on validated scenario
3. Free simulation

1. In SABOD, all scenario parameters are stored in addition to the results from SABOMS. The SABOD Manager GUI enables loading a scenario from SABOD and write this to an input file required for running SABAS without user-intervention. In this way, provided a scenario is in SABOD, a SABAS simulation can be launched very quickly. Since measurement data is available, a comparison between SABAS results and the measurement data is possible. In this way, the SABAS results can be validated. If not sufficiently accurate, a calibration procedure can be started as mentioned above.
2. A variation on a validated scenario can be simulated as well (e.g. adding walls or other objects, weapon position, including a head, etc.). This alleviates the need of acquiring additional measurements while the simulation model is still within the range of validity. The input parameters defining the scenario can be easily adjusted in the SABOD Manager GUI, after which a new simulation can be started.
3. A free simulation can be done without any measurement data from SABOMS (and thus no validation).

In Figure 11, the SABAS screen of the SABOD Manager GUI is shown, from which all aspects related to SABAS can be controlled. The main functionalities include starting and aborting a SABAS simulation, monitoring the progress of the simulation, checking and adjusting the input parameters and checking the specified scenario (SABAS writes images of the setup which can be opened from the GUI). After the SABAS simulation is finished, the results can be conveniently added to SABOD. Depending on hardware, a typical SABAS run takes approximately 24 hours.

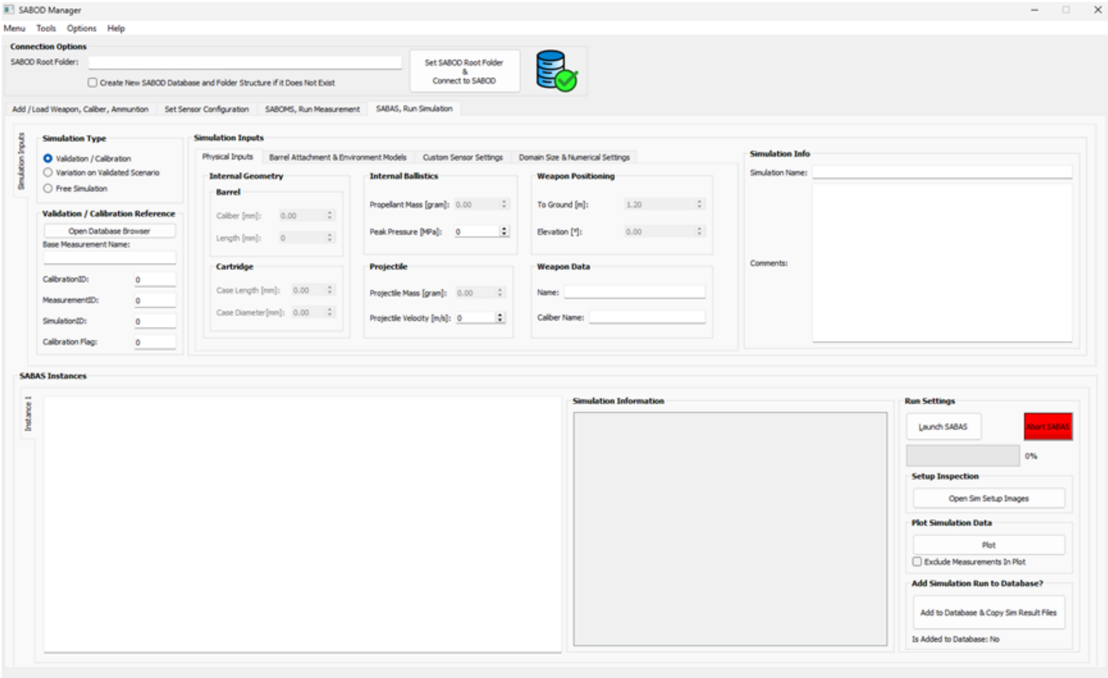

Figure 11: SABAS screen of the SABOD Manager GUI.

EXAMPLE CASE AND VALIDATION OF SABAS

In this section, the results of an example case (i.e. a single weapon) are discussed and a validation of SABAS results of all simulated weapons so far is provided. In total, three weapons (called weapon 1 to 3) with each three muzzle configurations (bare muzzle, muzzle brake and suppressor, see Figure 6) have been considered so far, leading to a total of nine scenarios. For classification reasons, all provided data are normalized. The weapons are existing weapons (like the muzzle brakes and suppressors), but are given anonymized names for the same reason.

For the example case, one of the nine configurations is chosen, which is weapon 3 with a muzzle brake. SABOES was applied to this weapon configuration, following the workflow as described in the preceding sections. In Figure 12, a plot created from the SABOD Manager GUI is shown, which shows a comparison between the normalized measurement pressure data (white) from SABOMS and the simulation pressure data (colored) from SABAS for the six gauge locations[1]. For the measurement results, the data of five shots are plotted per gauge location. In general, there is good correspondence, in terms of profile, peak pressure and arrival time. Since P6 is at 0.5 m from the muzzle (as opposed to all other gauges which are at 1 m), the pressure is significantly higher (a normalized pressure of approximately 4) compared to the other gauges. The plot from the SABOD Manager GUI is interactive, meaning the user can play with visualization settings on the fly. In addition, the data to plot can be directly imported from SABOD.

[1] During the development of the SABOMS system, the blast pencil positioning has been changed (optimized). During the recording of the data of the weapon currently considered, an old positioning was still used. Therefore, there is no data at the location of P5 of the current positioning.

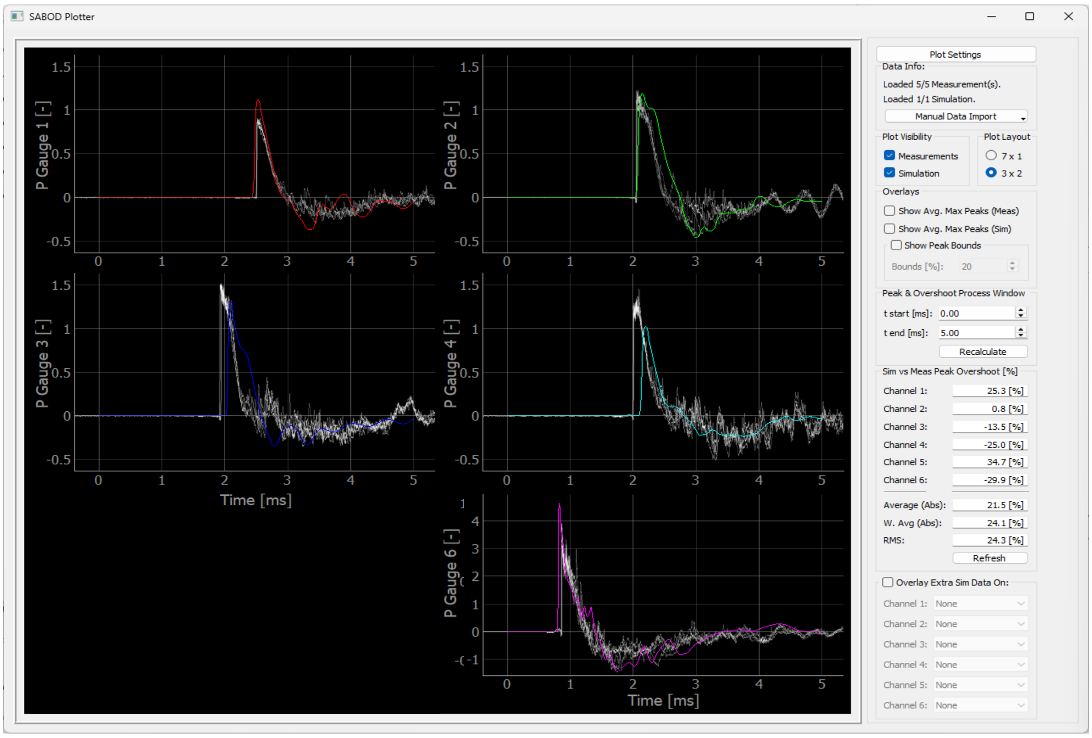

Figure 12: Plot from the SABOD Manager GUI where normalized measurement data (white) is compared to simulation data (colored) at the gauge locations.

A total of nine scenarios were analyzed with the SABOES system (three weapons with each three muzzle configurations). The measurements (SABOMS) where conducted both at the Knowledge Center of Weapons and Munition (KCW&M) in the Netherlands and at DRDC Valcartier Research Center, Canada. For each scenario, the accuracy and variability of the SABAS results were calculated, using the summary metrics averaged relative difference and averaged absolute relative difference, respectively. The averaged relative difference is calculated by averaging the relative difference in peak pressure between the measurement data and simulation results for each gauge (P1 to P6), as shown in Equation 1. Here, P_i is the peak pressure at gauge i and n the total number of gauges (which is 6). For the averaged absolute relative difference, the absolute value of the relative difference is taken, as shown in Equation 2.

$$\delta = \frac{1}{n}\sum_{i=1}^{n} \frac{P_{i,sim} - P_{i,meas}}{P_{i,meas}} \cdot 100\% \tag{1}$$

$$\delta_{abs} = \frac{1}{n}\sum_{i=1}^{n} \left|\frac{P_{i,sim} - P_{i,meas}}{P_{i,meas}}\right| \cdot 100\% \tag{2}$$

These two summary metrics are plotted in Figure 13, where the averaged relative difference is shown on the horizontal axis and the averaged absolute difference is shown on the vertical. The results provided in Figure 12 correspond to ‘Weapon 3 muzzle brake’. Repeated symbols indicate multiple test campaigns. As a criterion, an accuracy of 15% was taken, which is shown with the grey area on both the horizontal and vertical axes. Nearly all SABAS results for the average (horizontal) fall within the ±15%

accuracy, although most of the absolute average results (vertical) vary by more than 15%. Note that these results were obtained from the SABAS without any calibration procedure. A better accuracy could be achieved if desired by adjusting the SABAS input parameters. Such a decision to perform a calibration for improved accuracy is left to the future user of the SABAS system. Note that the open symbols refer to averaged measured overpressures of less than 1 kPa. At such weak compression waves, the accuracy of the SABAS (powered by the APOLLO Blast Simulator) is expected to be doubtful since compressibility effects of the gas no longer play a governing role. Furthermore, it is expected that such low overpressure levels are less relevant when it comes to traumatic brain injuries.

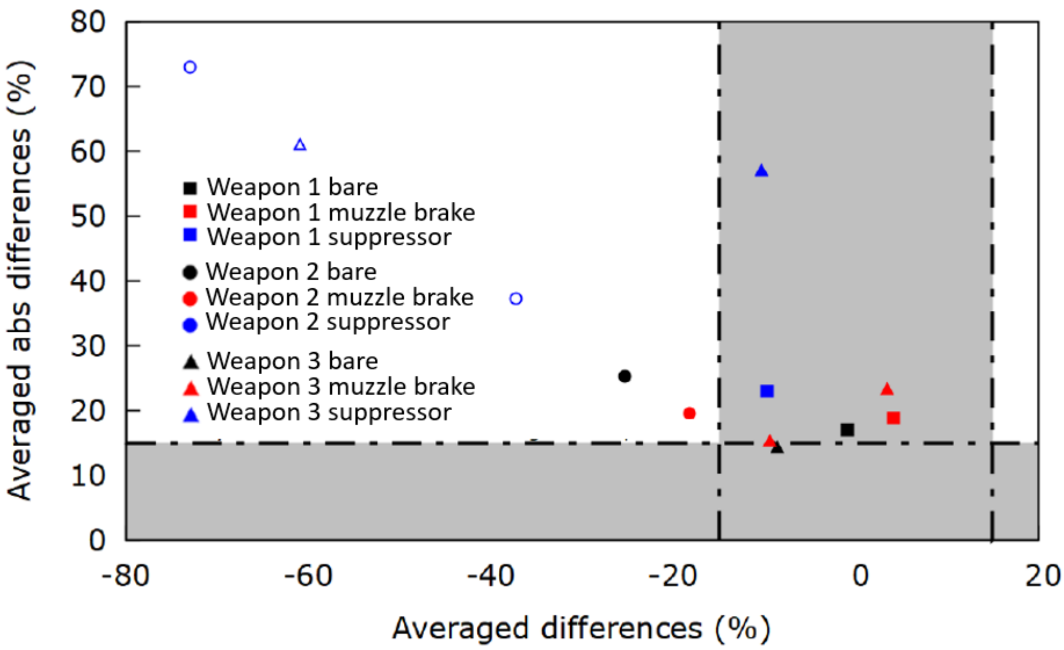

Figure 13: Accuracy (average differences) and variability (average absolute differences) of the SABAS results compared to all available measurements from SABOMS regarding three weapons with each three muzzle configurations.

CONCLUSIONS

The SABOES system is able to reliably and consistently quantify muzzle blast exposure from small arm weapons. After a description of the system and its subsystems (SABOMS, SABAS and SABOD) including the SABOD Manager GUI, the system was applied to nine different weapon scenarios (three different weapons with each three different muzzle configurations). The SABOMS subsystem successfully measured the pressure at the six defined locations around the muzzle, and the data were archived to the subsystem SABOD easily by means of the SABOD Manager GUI. The SABAS subsystem was able to simulate (predict) the muzzle blast of all scenarios with reasonable accuracy (without any calibration). Accuracy can be improved by performing a calibration procedure. All data from the simulations was written to the database SABOD using the SABOD Manager GUI (as was done for the SABOMS data). Besides providing the pressure profiles at the six measurement locations (allowing validation of the simulation by comparing to SABOMS results), SABAS allows for accessing field data (e.g. pressure) at any arbitrary location, visualization of the flow field, simulating scenarios which are a small variation to an already validated scenario and direct measurement of the (reflected) blast load on the head of the operator. With SABOES, these valuable insights can be obtained for any arbitrary small arm weapon, in a wide variety of environments.

ACKNOWLEDGEMENT AND DISCLAIMER

This research has been conducted in a project funded by the Irregular Warfare Support Technical Directorate (IWTSD). Financial support by IWTSD does not constitute an express or implied endorsement of the results or conclusions of the project by either IWTSD or the U.S. Department of Defense.

REFERENCES

[1] Belanger H.G., Bowling F., Yao E.F. (2020) *Low-Level Blast Exposure in Humans A Systematic Review of Acute and Chronic Effects*. In *Journal of Special Operations Medicine* 2020; 20(1): 87-93.

[2] Belding J.N., Bonkowski J., Englert R. (2024) *Traumatic brain injury and occupational risk of low-level blast exposure on adverse career outcomes: an examination of administrative and medical separations from Service (2005-2015). Frontiers Neurology* 2024; 15: 1389757.

[3] Belding, J.N., Englert, R., Bonkowski, J., Thomsen, C.J. (2021) *Occupational Risk of Low-Level Blast Exposure and TBI-Related Medical Diagnoses: A Population-Based Epidemiological Investigation (2005–2015),* in *International Journal of Environmental Research and Public Health*, 18, 12925.

[4] Klomfass, A., "*Apollo Blastsimulator*", Fraunhofer EMI, 2023. [Online]. Available: https://apollo-blastsimulator.de/.

[5] Warden, D. (2006) *Military TBI during the Iraq and Afghanistan Wars,* in *Journal of Head Trauma Rehabilitation*, Volume 21 - Issue 5 - p398–402.