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AD-E404 223

Contractor Report ARWSE-CR-18002

MEASUREMENT OF COMBUSTION PRODUCTS IN SMALL ARMS BLOWBACK GASES

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August 2020

U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT
COMMAND ARMAMENTS CENTER

Weapons and Software Engineering Center

Picatinny Arsenal, New Jersey

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-01-0188*

1. REPORT DATE (DD-MM-YYYY) August 2020	2. REPORT TYPE Final	3. DATES COVERED (*From - To*)

4. TITLE AND SUBTITLE Measurement of Combination Products in Small Arms Blowback Gases	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHORS Arnt Johnsen - Norwegian Defense Research Establishment (FFI), Kjeller, Norway Adam M. Jacob, Douglas Ray, and Daniel Cler - U.S. Army CCDC AC, Picatinny Arsenal, NJ	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army CCDC AC, WSEC Weapons Systems and Technology Directorate (FCDD-ACW-WF) Picatinny Arsenal, NJ 07806-5000 Norwegian Defense Research Establishment (FFI), Instituttvn 20, NO-2007 Kjeller Norway	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army CCDC AC, ESIC Knowledge & Process Management Office (FCDD-ACE-K) Picatinny Arsenal, NJ 07806-5000	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S) Contractor Report ARWSE-CR-18002

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

When a muzzle device, specifically a suppressor, is added to a small arms system, it typically has a tendency to increase the system's backpressure, therefore increasing the blowback. Different muzzle device designs result in different increases in backpressure, and thus different levels of blowback. If the pressure is high enough when the bolt opens, gas will escape from the barrel and into the operating mechanism. In this effort, electrochemical sensors were used to measure and quantify the combustion products of the blowback gases using suppressed and unsuppressed small arms systems by both a "Chamber Method" as well as a "Breathing Zone Method." While the combustion products consist of a variety of gases, the three primary toxic constituents are carbon monoxide, ammonia, and hydrogen cyanide. Results showed increased concentrations of gases with the use of suppressors. In addition to gaseous combustion products, metals are also aerosolized during combustion and firing of a round. Aerosolized metals, including copper, zinc, and bismuth, were measured. Results showed that some aerosolized metals become trapped in the suppressor during firing, resulting in lower levels of the aerosolized metals when a suppressor is used, while others are increased proportionally in the blowback gas when a suppressor is used.

15. SUBJECT TERMS

Small arms Blowback Toxicity Metal fever Suppressor Signature suppressor Breathing zone

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Adam M. Jacob
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U	SAR	23	19b. TELEPHONE NUMBER (Include area code) (973) 724-0535

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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INTRODUCTION

Toxic hazards of small arms weapon systems of the U.S. Army are currently measured using Test Operations Procedure 2-2-614, with measurement focus being on the entire toxicity of the system (ref. 1). There is no standardized method of measuring “blowback” in a small arms system, and, as such, there is a desire to develop one. “Blowback” is the term used to describe the gases and aerosols that emanate from a small arms system’s operating group and chamber area due to backpressure within the system, typically as a result of the addition of a suppressor or other muzzle device (such as a blank firing adaptor) to the weapon system. These gases are blown back toward the operator, thus the term “blowback.”

When a muzzle device, specifically a suppressor, is added to a small arms system, it typically has a tendency to increase the system’s backpressure, therefore increasing the blowback. Different muzzle device designs result in different increases in backpressure and, therefore, different levels of blowback. A suppressor traps high-pressure gas and blocks the flow from the barrel’s muzzle. Typically, organ piping occurs within the suppressor and barrel. This causes a cyclic effect in the pressure at the chamber that is dictated by the speed of sound in the gas and the overall length of the suppressor and barrel. If the pressure is high enough when the bolt opens, gas will escape from the barrel and into the operating mechanism.

Fundamentally, backpressure is caused by a reduction in flow rate at the muzzle of the barrel due to an increase in pressure at the muzzle caused by the suppressor. The suppressor, when added to the weapon barrel, operates in two phases relative to the type of gas flow. The first phase is a very dynamic, time varying, shock dependent flow as the blast wave strength is decreased coming from the weapon, and the sound levels are reduced. This typically occurs within the first couple of milliseconds.

After the flow starts to settle down in the suppressor, a more constant flow field is established and much of the dynamic change slows down. At this point, the suppressor acts more like a plenum attached to the muzzle, allowing the gas pressure to decrease much more slowly as it blows down. This second phase can last from 10 to 100 ms depending on the type of suppressor and level of restriction. During this second phase, organ piping, or time varying pressure, can cause pressure waves to move up and down the barrel. This can cause increases in the pressure at the chamber as organ piping occurs in the barrel/suppressor system.

It is during this second phase that the bolt starts to open (typically around 5 to 10 ms) and significant pressure can still be present in the chamber (50 to 2,000 psi). At this point, propellant gases escape from the chamber at the same time they are exiting from the muzzle. The pressure at the chamber at the time the bolt opens typically determines the amount of propellant gases that escape back into the operating group. In a gas-operated system, in addition to gas escaping from the chamber area, the pressure at the gas block tends to sustain a higher pressure for a longer period of time, thereby increasing the overall powering of the weapon system. This, in turn, increases the bolt velocity and subsequently the firing rate, unless the system is designed to accommodate the higher pressure.

While the total gases blown back as a result of the muzzle device are important to measure, it is also important to look at the system as a whole. More specifically, this means that measuring the total blowback gases only shows part of the issue, since it is important to also take into account where those gases go after they leave the chamber and operating group of the weapon. The blowback gases may bring about immediate operational effects on the weapon operator, such as burning eyes, difficulty breathing, or other immediate operational effects that could take the operator out of the fight and, therefore, put them in danger. Thus, both a “Chamber Test Method” (CTM) as well as a “Breathing Zone Test Method” (BZTM) are used.

EXPERIMENTAL SECTION

Blowback gases consist of combustion products that result from the burning primer and propellant from the ammunition cartridge within the small arms system as well as metal particles that are aerosolized from the primer, propellant, and projectile. These combustion gases consist of various toxic gases and aerosols, and a human can experience a variety of physiological effects as a result of exposure or inhalation. While the combustion products consist of a variety of gases, the three primary toxic gaseous constituents are:

- Carbon monoxide (CO)
- Ammonia (NH_3)
- Hydrogen cyanide (HCN)

Some of the primary metallic toxins of interest are:

- Copper (Cu)
- Zinc (Zn)
- Bismuth (Bi)
- Lead (Pb)

The effects of these toxins can vary. The CO typically impairs the blood's ability to transport oxygen; this is normally a long-term exposure issue but also important for short-term exposure at high concentrations (ref. 2). The effects of NH_3 are typically immediate at the onset of exposure and consist of eye, nose, and throat irritation. It is typically believed that the NH_3 constituent causes the most significant operational issues in blowback gases, due to these physiological effects (ref. 2). Short duration exposure to HCN can cause eye irritation, breathing difficulty, headache, nausea, and vomiting (ref. 2).

The test procedures focus on the measurement of concentrations of the three primary constituents within the blowback gases (CO, NH_3, and HCN). In contrast, TOP 2-2-614 is used to measure the concentrations of the total gases produced by combustion, both blown back as well as blown forward out the muzzle (ref. 1). Additionally, since TOP 2-2-614 is used to measure the concentration of a wider variety of toxins within a given system, the concentrations of the three primary constituents measured here can be used to estimate the concentration of any other constituents that may be of interest. This is due to the combustion being largely the same with and without a suppressor or other muzzle device. While the combustion products may be slightly different due to the percent completion of the burn as a result of the effect imparted by the muzzle device or suppressor, the difference in these combustion products is typically minimal.

In addition to the toxic gases present in the combustion products, metallic aerosols are also present and can also cause short-term onset of health issues, most commonly called “metal fume fever” (ref. 3). Metal fume fever typically results in flu-like symptoms. Metals are aerosolized from the primer and propellant as well as the projectile as it travels down the barrel and the outer layer of the projectile ablates. Again, while there are a wide variety of metallic aerosols produced during the firing event, this test, using lead-free ammunition, focused on the measurement of:

- Cu
- Zn
- Bi

The additional back pressure in the system that results from the addition of a muzzle device or suppressor has a variety of effects on the weapon system itself, including the potential to affect the bolt velocity and rate of fire, increased need for cleaning, and the potential to prematurely wear out or damage the operating group. Often, these aspects are thought to be the primary disadvantages of the addition of a suppressor, and these aspects can easily be measured in the laboratory environment. Still, if a small arm were to be developed using a systems engineering approach, the gas system and operating group of that system could be designed to work in harmony with the muzzle device, even with the additional back pressure in the system. This leaves the operator with a system that works well, but that still causes operational issues due to toxic gases being blown back in their face. Thus, measuring only the bolt velocity of the system is not sufficient to assess toxic gas blowback.

A two-pronged approach at measuring blowback is proposed. First, blowback will be assessed from a “total blowback” standpoint, measuring the total gases and aerosols that are blown back out of the weapon’s chamber and operating group area. This is called the CTM. Next, blowback will be measured and assessed from the system level, taking into account the directionality of the event, and measuring the blowback gases that reach the operator’s breathing zone. This is called the BZTM.

All of the tests described are intended to be comparative tests. In other words, the blowback should always be compared back to a baseline system. If a test is being done to assess the increase in blowback resultant from the addition of a suppressor or muzzle device, the baseline system should always be the same weapon system with the standard muzzle device, typically a “birdcage” style flash hider. If the test is being done to assess blowback in a weapon system with an integral suppressor, the baseline system should be a comparable standard issue system and/or a comparable standard issue system with similarly performing muzzle device. For instance, if an M4A1 system with an integrally suppressed upper receiver were to be tested, the baseline system would be a standard M4A1 with a birdcage flash hider and/or an M4A1 outfitted with a suppressor that achieves a similar level of signature reduction. These are all referred to as the “baseline” systems. In the case of this test, the “baseline” was an unsuppressed carbine weapon system, and the “modified” system was the same weapon with a specific suppressor added. These details are intentionally left out of the report.

Background and Methodology

The two evaluation methods detailed are the CTM and the BZTM. The CTM measures the total gases blown back and assesses only the direct effect caused by the addition of the suppressor or muzzle device. The CTM also includes measurements of the total gases produced by the system, which can be useful for various other analyses but is not necessary for the comparison of one suppressor to another or to assess the percent increase in blowback resultant from a given suppressor. The BZTM focuses on the measurement of blowback from the system perspective and accounts for other system attributes or features that may affect the amount of gas that reaches the operator’s breathing zone.

Data was collected following design of experiments (DOE) procedures and using the concept of a designed experiment. A designed experiment is a test in which purposeful, systematic changes are made to the input variables of a process or system so that one may observe and identify the reasons for changes in the output response variable. This is often done to quantify the impact of inputs on the response, quantify how input variables interact to affect the response, and to use this information to provide insight in how to improve the product or process.

Strategic data collection through a systematically designed experiment provides a gateway to answer questions about what input variables (Xs) are driving changes in the output (Ys) of a system, product, or process and to establish traceability. The key advantage of using designed experiments is that the experimenter controls which combinations of inputs are explored, which allows control over which ranges to explore as well as the establishment of relationships between inputs and outputs. It is the direct opposite of observational data, over which the user has no direct control and there is no active manipulation of inputs.

The DOE and thorough test planning facilitates the management of statistical risk in achieving test objectives and ensures test matrix balance and test execution robustness to support meaningful, valid, statistically defensible results.

The test matrices in tables 1 and 2 for each test method were designed using DOE best practices, leveraging analysis from past test data to inform the prospective power and sample size analysis, assuming 95% statistical confidence, 80% minimum threshold for statistical power, standard deviation [root mean squared error (RMSE)] determined from within-group variations in previous analysis [peak CO = 124 parts per million (ppm)], and factors and factor-levels of interest (firing mode, inlet side, and configuration). The 32-run matrices provide approximately 80% power to detect effects equal to or greater than the within-group standard deviation (RMSE) for all main effects and two-factor interactions, 98.3% power to detect effects equal to or greater than 1.5 x RMSE, and 99.97% power to detect effects equal to or greater than 2 x RMSE for all main effects and two-factor interactions, at 95% statistical confidence.

Table 1
CTM sequence

Run	Block	Firing mode	Muzzle inside or outside chamber	Configuration
1	L1	Burst	Outside	Standard
2	L1	Single	Outside	Standard
3	L1	Burst	Outside	Modified
4	L1	Single	Outside	Modified
5	L1	Single	Outside	Standard
6	L1	Burst	Outside	Standard
7	L1	Single	Outside	Modified
8	L1	Burst	Outside	Modified
9	L2	Burst	Inside	Standard
10	L2	Single	Inside	Standard
11	L2	Burst	Inside	Modified
12	L2	Single	Inside	Modified
13	L2	Single	Inside	Standard
14	L2	Burst	Inside	Standard
15	L2	Single	Inside	Modified
16	L2	Burst	Inside	Modified
17	L3	Burst	Outside	Standard
18	L3	Single	Outside	Standard
19	L3	Burst	Outside	Modified
20	L3	Single	Outside	Modified
21	L3	Single	Outside	Standard
22	L3	Burst	Outside	Standard
23	L3	Single	Outside	Modified
24	L3	Burst	Outside	Modified
25	L4	Burst	Inside	Standard
26	L4	Single	Inside	Standard
27	L4	Burst	Inside	Modified
28	L4	Single	Inside	Modified
29	L4	Single	Inside	Standard
30	L4	Burst	Inside	Standard
31	L4	Single	Inside	Modified
32	L4	Burst	Inside	Modified

Table 2
BZTM sequence

Run	Block	Firing mode	Inlet side	Configuration
1	L1	Burst	Left	Standard
2	L1	Single	Left	Standard
3	L1	Burst	Right	Standard
4	L1	Single	Right	Standard
5	L1	Burst	Left	Modified
6	L1	Single	Left	Modified
7	L1	Burst	Right	Modified
8	L1	Single	Right	Modified
9	L2	Single	Left	Standard
10	L2	Burst	Left	Standard
11	L2	Single	Right	Standard
12	L2	Burst	Right	Standard
13	L2	Single	Left	Modified
14	L2	Burst	Left	Modified
15	L2	Single	Right	Modified
16	L2	Burst	Right	Modified
17	L3	Burst	Left	Standard
18	L3	Single	Left	Standard
19	L3	Burst	Right	Standard
20	L3	Single	Right	Standard
21	L3	Burst	Left	Modified
22	L3	Single	Left	Modified
23	L3	Burst	Right	Modified
24	L3	Single	Right	Modified
25	L4	Single	Left	Standard
26	L4	Burst	Left	Standard
27	L4	Single	Right	Standard
28	L4	Burst	Right	Standard
29	L4	Single	Left	Modified
30	L4	Burst	Left	Modified
31	L4	Single	Right	Modified
32	L4	Burst	Right	Modified

Randomization, replication, and blocking are fundamental to the DOE. Randomization is used to minimize the risk of nuisance variables, such as temporally correlated error sources, corrupting the test results. Some modifications can be made to statistically ideal full randomization for practicality and test execution reasons (as was done with this test matrix), though at some risk. However, it is imperative that the test be run in the order specified in the test matrices rather than re-ordering to simplify test execution, as re-ordering will result in significant reduction to test statistical power.

While the measurements of gases CO, HCN, and NH_3 as well as the metals Cu, Zn, and Bi are the focus of this study, it is important to consider that the true intent is to measure suppressor blowback. Further, while current small arms propellants have the primary toxic combustion products of CO, HCN, and NH_3, future or developmental propellants may contain different toxins. Thus, it is important to tailor the measurements to the toxins that are of interest for the particular system being assessed. In the case of current small arms systems, the toxins of interest are CO, HCN, and NH_3 and certain metals, depending on the ammunition being fired.

In addition, in most cases, the full system toxicity (weapon and ammunition) has previously been measured through the use of TOP 2-2-614, and the ratio of each gaseous constituent is already known (ref. 1). As such, much can be gained simply from measuring the concentration of only a single gas, called an “indicator gas,” and then estimating the concentrations of other gases based on the known ratios to that indicator gas. In the case of current propellants, CO is the most prevalent toxic gas and also the easiest to measure, making it a good choice for an indicator gas. While the addition of a suppressor to the system could have some small effect on the combustion as compared to the unsuppressed system, this effect would be negligible.

All firing was performed to replicate operationally relevant firing. For the M4A1, single shots and three-round bursts were used. A handheld gas analyzer with the following specifications was used for all gas measurements (ref. 4):

- Minimum sampling rate one sample every second (1 Hz)
- Electrochemical sensors
    - CO
        - Detection range – 0 to 10,000 ppm
        - Resolution – 5 ppm
        - Detection limit – 10 ppm
        - Response time – T90 – 25 se
        - Sensitivity - +/- 2% of measured value
    - NH_3
        - Detection range – 0 to 300 ppm
        - Resolution – 1 ppm
        - Detection limit – 4 ppm
        - Response time – T50 – 10 sec
        - Sensitivity - +/- 3% of measured value
    - HCN
        - Detection range – 0 to 50 ppm
        - Resolution – 0.5 ppm
        - Detection limit – 3 ppm
        - Response time – T50 – 10 sec
        - Sensitivity - +/- 5% of measured value
- Sampling pump with flow rate of 0.5 L/min

In addition to measurement of gases, metal aerosols were also measured during the CTM. Metals were collected by passing air from the chamber through an Isopore™ membrane filter with a 0.4-µm pore size produced by Millipore (HTTP type). The filter used a three-piece, 37-mm cassette, with the end cap remover to allow the whole filter face to be exposed to the gas inside the chamber. The air was sucked through the filter at a flow rate of 2 L/min by an AirChek XR5000 pump from SKC, and the sampling time was 3 min. Thus, the total amount of air that passed through the filter was 6 L.

Chamber Test Method

The objective of the CTM is to measure the direct effect that the addition of a specific suppressor or muzzle device has on the amount of gases and aerosolized metals blown back toward the operator. The chamber method is performed by measuring the concentration of the total amount of toxic gases (CO, NH_3, HCN) and the mass of filtered metallic aerosols blown backward into a chamber of known size with the suppressor or muzzle device in question installed. These gas concentrations and metal aerosol masses are then compared to those blown back by the baseline weapon as well as to the total gases and aerosols produced by the weapon (both blown back and expelled through the muzzle). The chamber is used to isolate whether the total gases or just the blowback gases are being collected. These measurements differ from the BZTM in that all of the blown back gases are measured, regardless of whether these gases reach the operator's breathing zone. Primarily, the CTM is intended to measure the total difference in gas blown back toward the operator. Firing was done in accordance with table 1. The chamber design follows closely with previous work in toxicity measurements (ref. 5). Test chamber is shown in figure 1.

(a)
Total propellant gas

(b)
Blowback gas only

Figure 1
Chamber with weapon muzzle inside (a) and outside (b)

Since the chamber volume can vary depending on the weapon, scenario, and configuration being tested, reporting only the gas concentration can be misleading when comparing test results. As such, calculating the mass of gas produced will eliminate the effect of chamber volume on the numbers reported. If the number of moles present and the molecular mass of a gas are known, the mass of that gas can be calculated using equation 1.

$$m_{gas} = n \times M_{gas} \tag{1}$$

Where:

M_{gas} is the mass of the gas in grams (g),
n is the number of moles, and
M_{gas} is the molecular mass of the gas in grams per mole (g/mol).

The ideal gas law can be used to calculate the number of moles (n) of each gas using equation 2.

$$n = \frac{P \times V_{gas}}{R \times T} \tag{2}$$

Where:

P is the pressure in Pascals (Pa),
V_{gas} is the volume of gas in cubic meters (m^3),
R is the ideal gas constant in Joules per Mole Kelvin (J/mol*K), and
T is the temperature in degrees Kelvin (K).

Since the volume of the chamber is variable, and the measured characteristic is concentration of each gas in ppm, the total volume of each gas can be calculated using equation 3.

$$V_{gas} = V_{chamber} \times C_{gas} \tag{3}$$

Where:

$V_{chamber}$ is the total volume of the chamber (m^3), and
C_{gas} is the concentration of the gas (ppm).

Equation 3 can then be substituted into equation 2 to get equation 4.

$$n = \frac{P \times V_{chamber} \times C_{gas}}{R \times T} \tag{4}$$

Assuming that the gas pressure is approximately atmospheric and that the temperature is room temperature as well as using the molecular mass of each gas, conversion factors (k_{gas}) can be calculated for each gas in order to calculate the mass of each gas in milligrams (see table 3). Equation 1 can then be simplified to equation 5 to calculate the mass of gas in milligrams.

$$m_{gas} = k_{gas} \times C_{gas} \times V_{chamber} \tag{5}$$

Table 3
Conversion factors for mass calculations

Gas	Conversion factor (k_{gas})
CO	1.16
HCN	1.12
NH_3	0.71

To analyze for metals, each filter was digested with 10 mL of aqua regia (mixture of HCl and HNO_3) at 175 °C for 30 min in a MARS 6 microwave instrument from CEM Corporation. After digestion, the sample was transferred to a 100-mL bottle and diluted to 100 mL with ultrapure water. The diluted sample was analyzed by inductively coupled plasma - sector focusing mass spectrometry, inductively coupled plasma – atom emission spectroscopy), and atomic fluorescence spectroscopy at the ALS Scandinavia AB in Luleå, Sweden. The following elements were analyzed: iron, arsenic, barium, cadmium, chromium, Cu, mercury, manganese, nickel, lead, Zn, tin, strontium, Bi, antimony, titanium, cobalt, potassium, sodium, aluminum, calcium, molybdenum, and vanadium.

Breathing Zone Test Method

The objective of the BZTM is to assess blowback from a system level by measuring concentrations of toxic gases (CO, NH_3, and HCN) in the location of the weapon system operator's breathing zone during firing with a suppressor, muzzle device, or other accessory of interest. This is accomplished by obtaining gas concentration measurements during various live-fire scenarios at the operator's breathing zone location in a highly controlled environment. Metals were not filtered or analyzed during the BZTM.

The required test conditions for the BZTM are intended primarily to ensure that the environment is free of airflow, wind, and obstructions during data collection, as well as to ensure that all other test conditions are controlled to the maximum extent possible. It is critical that the conditions are closely controlled, since the BZTM requires that the blowback gases leave the weapon and begin to mix with the environment before they are measured.

Testing was performed in an indoor range. A 4 by 8-ft sheet of plywood was used as a blast wall between the muzzle and the rest of the weapon, including the gas block. The blast wall had a hole cut in the center, sized to allow the muzzle to pass through, with any gaps around the barrel minimized or closed with a thick rubber gasket. For firing, the weapon was hard mounted with its muzzle placed through the center of the blast wall. The intent here was to prevent muzzle gases from mixing with blowback gases during measurement.an example of this test setup is shown in figure 2.

Figure 2
Weapon and sampling setup for BZTM, left inlet

A 4-in. air inlet funnel was affixed at the location of the operator's breathing zone, as measured from an approximate 50% operator shouldering the subject weapon system. This location was carefully documented. The consistency of placement was critical. Since the air inlet is moved from left to right and vice versa throughout the test, the weapon was marked to ensure that the funnel was placed at the same location prior to each shot. Testing accounted for both left and right-handed operators, per table 2.

RESULTS AND DISCUSSION

Chamber Test Method

Gas Measurement Results

The results from the CTM showed consistent and repeatable results. Quantities are reported in milligrams of gas, using equations 1 through 5. Figure 3 shows each data point (shown as points) as well as the mean for each configuration tracked by the blue tracking line. Figures 4 and 5 show the analysis of variance (ANOVA).

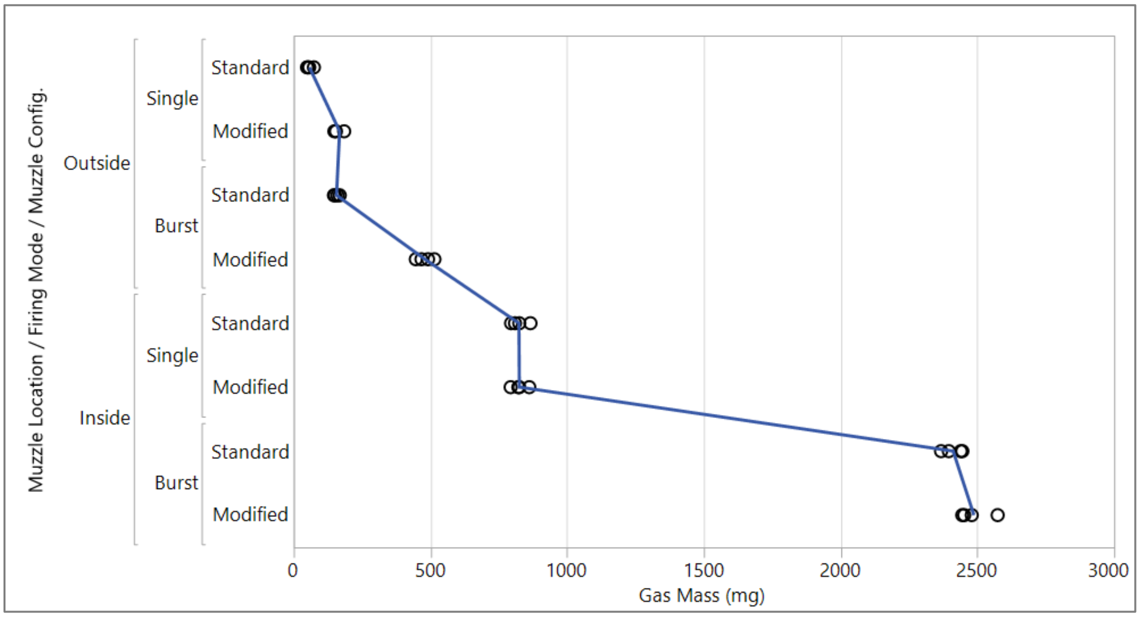


Figure 3
Mass of CO produced - all shots

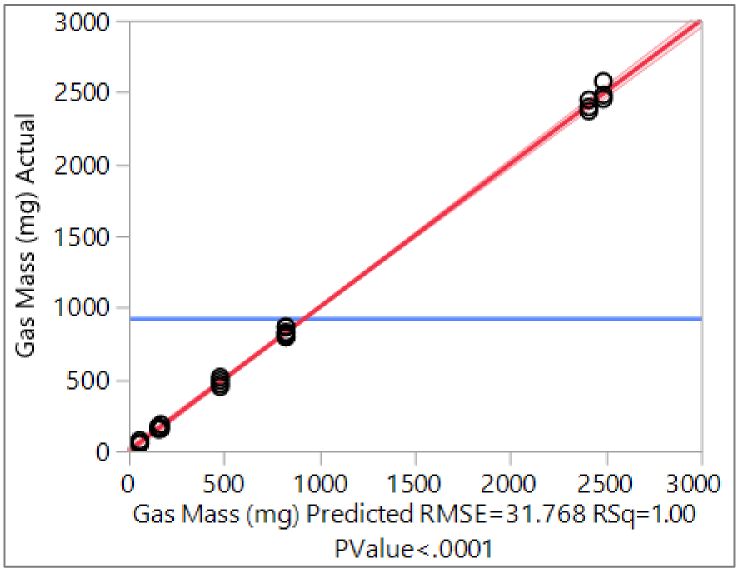
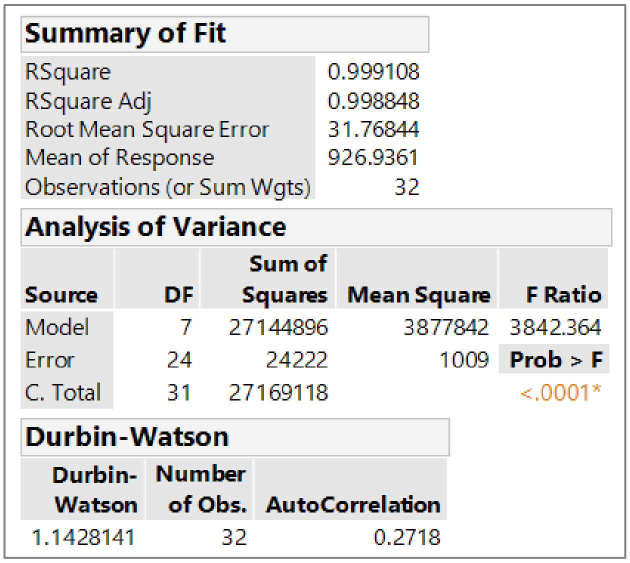


Figure 4
Actual versus predicted mass of CO



Summary of Fit

RSquare	0.999108
RSquare Adj	0.998848
Root Mean Square Error	31.76844
Mean of Response	926.9361
Observations (or Sum Wgts)	32

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	27144896	3877842	3842.364
Error	24	24222	1009	**Prob > F**
C. Total	31	27169118		<.0001*

Durbin-Watson

Durbin-Watson	Number of Obs.	AutoCorrelation
1.1428141	32	0.2718

Figure 5
Summary of fit and ANOVA - CTM

Using statistical methods, it is also possible to look at the interaction between each variable. Figure 6 shows these interactions.

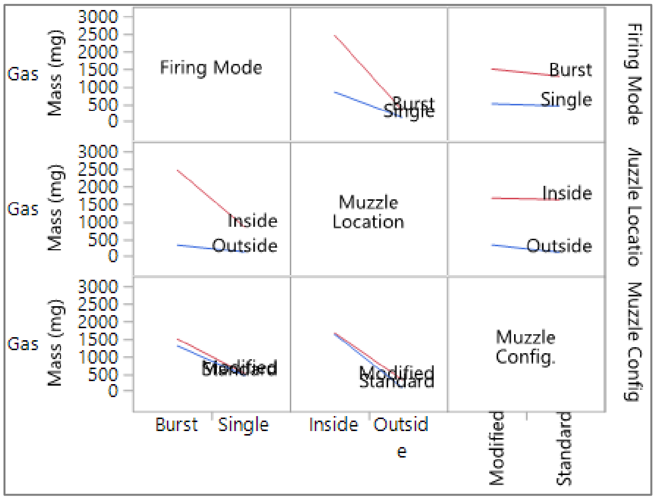


Figure 6
Interactions between variables - CTM

While the results from the CTM are very repeatable and consistent, they measure only the total blowback gases and do not give any insight into where those gases go after they leave the chamber and operating group of the weapon. Thus, the blowback was also measured and assessed from the system level, taking into account the directionality of the event and measuring the blowback gases that reach the operator's breathing zone using the BZTM.

Metallic Aerosol Measurement Results

The primary metallic aerosols measured were Cu, Zn, and Bi. The Pb was not measured because lead-free ammunition was used for the test; however, lead would also be of interest in ammunition with lead content in the primer, propellant, or projectile. Results of metallic aerosol measurements for the muzzle inside and outside the chamber, respectively, are shown in figures 7 and 8.

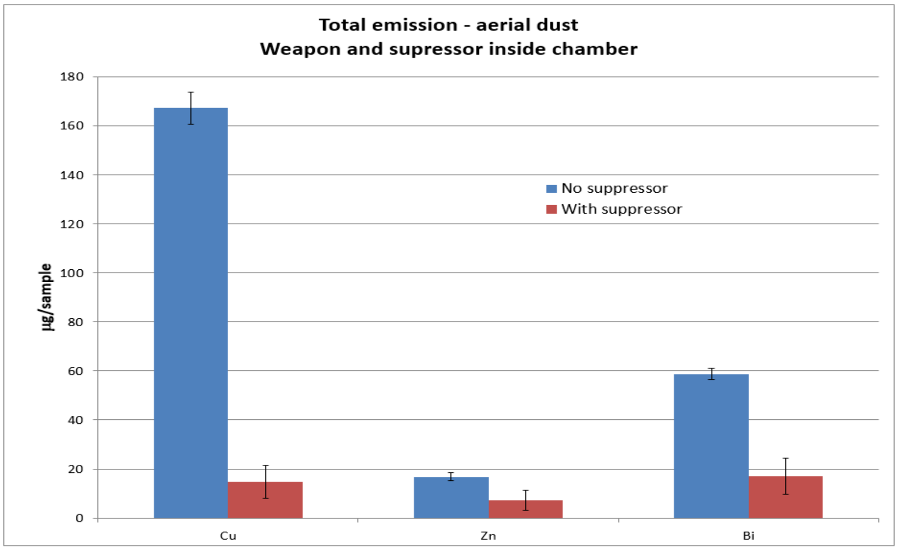


Figure 7
Mass of aerial dust produced – full weapon inside chamber (total dust)

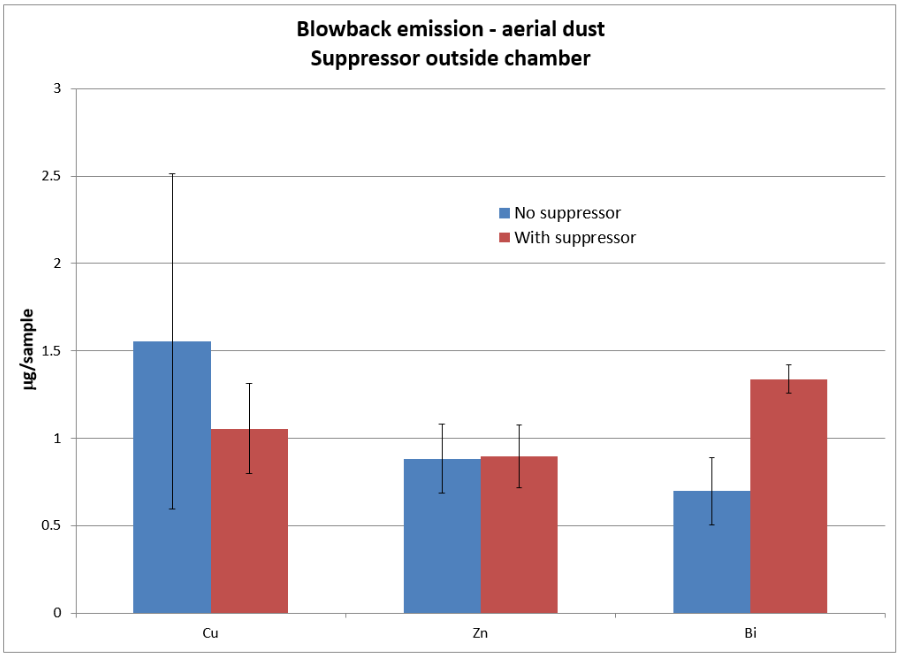


Figure 8
Mass of aerial dust produced – muzzle outside of chamber (blowback dust only)

Note that there is an overall reduction of Cu, Zn, and Bi from the full weapon when a suppressor is added. This indicates that these metals are, to some extent, deposited inside the suppressor when a suppressor is installed on the weapon. The Cu, in particular, is significantly reduced when a suppressor is added. This reflects previous testing that has shown a suppressor to gain weight after extended firing.

When the suppressor is placed outside the chamber, Cu is still reduced with a suppressor; however, Zn remains relatively unchanged and Bi increases. This is likely due to the fact that the primary source of Cu is the projectile, and these particles substantially leave the muzzle during firing. In contrast, the primary source of Bi is the propellant, and when the gases are blown back, the Bi particles that are aerosolized are then blown back as well, increasing the total amount in the blowback gas.

Breathing Zone Test Method

The results from the BZTM were not as consistent or repeatable but showed insight and basic trends into what happens with the gas after it leaves the chamber and operating group of the weapon in a given configuration. Quantities are reported in concentration of gas in ppm and are reported in 45-sec time weighted average. Peak, 15, and 30-sec time weighted average were also calculated but not reported here. Figure 9 shows each data point for a 45-sec time weighted average (shown as points) as well as the mean for each configuration tracked by the blue tracking line. Figures 10 and 11 show the ANOVA.

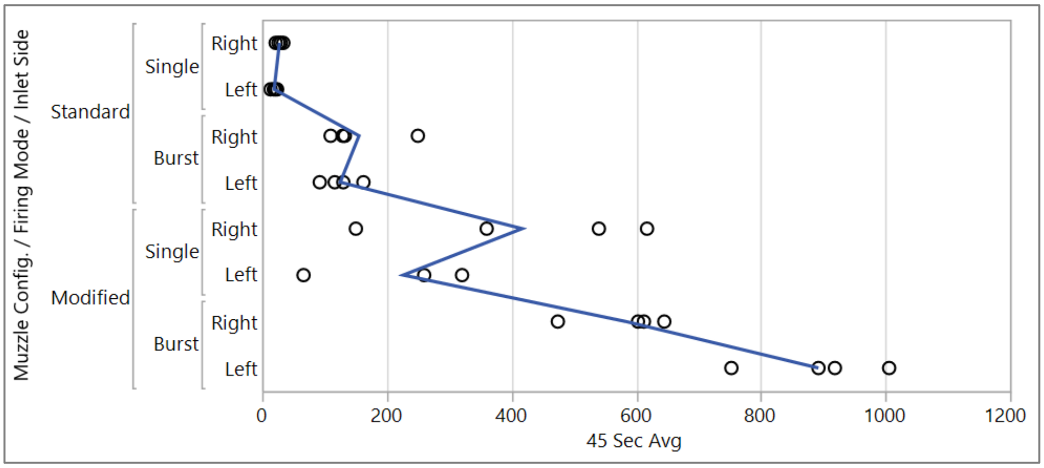


Figure 9
Concentration of CO produced – 45-sec time weighted averages – all shots

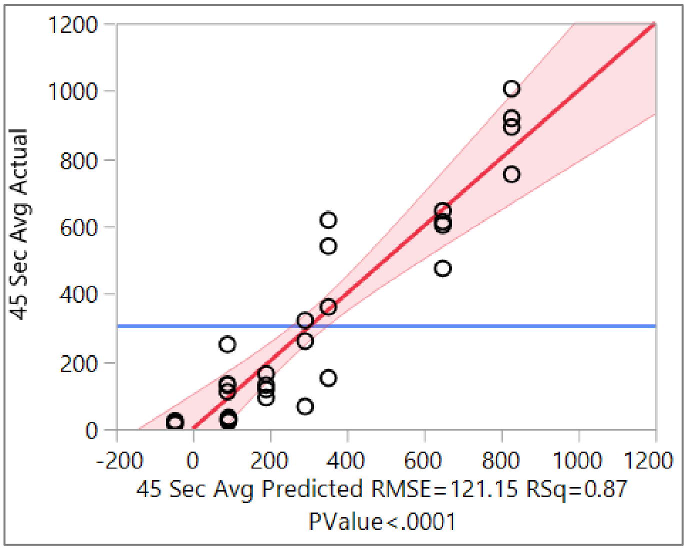
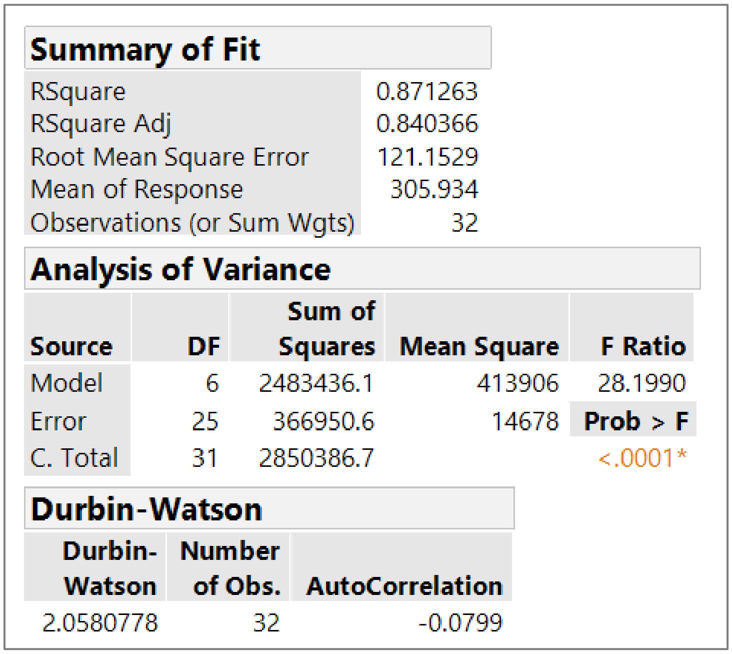


Figure 10
Actual versus predicted concentration of CO



Summary of Fit

RSquare	0.871263
RSquare Adj	0.840366
Root Mean Square Error	121.1529
Mean of Response	305.934
Observations (or Sum Wgts)	32

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	6	2483436.1	413906	28.1990
Error	25	366950.6	14678	**Prob > F**
C. Total	31	2850386.7		<.0001*

Durbin-Watson

Durbin-Watson	Number of Obs.	AutoCorrelation
2.0580778	32	-0.0799

Figure 11
Summary of fit and ANOVA - BZTM

Using statistical methods, it is also possible to look at the interaction between each variable. Figure 12 shows these interactions.

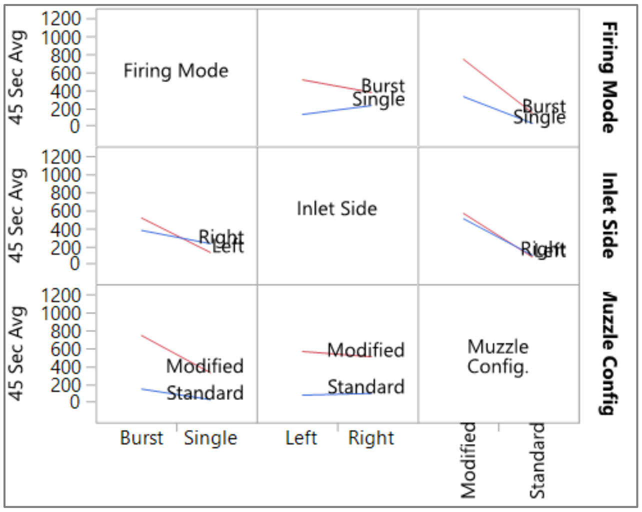


Figure 12
Interactions between variables – BZTM

CONCLUSIONS

The addition of the suppressor to the weapon system results in measureable differences of blown back gases using the methods described. The Breathing Zone Test Method is less repeatable but shows different results that would not be observed with the Chamber Test Method (CTM) alone. Particularly, there are a variety of aftermarket components for weapon systems that are intended to “reduce blowback” when used with a suppressor. Further research has shown that the actual design of these components does not “reduce” blowback at all, but rather, they attempt to redirect the gases away from the operator’s breathing zone. Data has shown that the method can measure differences in concentration at the operator’s face resultant of the use of devices that redirect the gas. This shows that the method can assess directionality, which plays a role in operational impact.

The CTM measures the total blown back gases, regardless of directionality after they leave the chamber and operating group. Since chambers of different sizes can be used to account for potentially different sized weapons or different amounts of gases produced, CTM results should always be reported in mass of gas in order to eliminate the effect of the chamber volume on the results. This allows appropriate comparison of results between different chambers, regardless of size. The CTM, in contrast to the BZTM, is very repeatable and consistent, but it does not take into account the system level effects, such as other changes to the weapon system to redirect the gas. This indicates that neither method alone is sufficient to assess the true operational impact of the blowback gas, and the best assessment is the combination of both methods.

The metallic dust filtering showed that, in general, metals that are aerosolized from the projectile are largely deposited within the suppressor. Metals that are aerosolized from the primer and propellant constituents tend to blowback proportionally with the rest of the blowback gases in the system.

Finally, it is important to consider that the order of testing is critical to randomize error. The order of testing was developed through the use of DOE methods, with the intent to randomize error within the test. The important consideration is that one cannot simply test all of one configuration and setup, then switch to next, and so on. Even if that is easier or quicker, it could result in potential systematic error that must be randomized.

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