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Low Global Warming Potential (GWP) Agent Testing

Author(s):

Joshua Fritsch

Steve Hodges

Steve McCormick

James Slemons

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U.S. Army Combat Capabilities Development Command
Ground Vehicle Systems Center
Detroit Arsenal
Warren, Michigan 48397-5000

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TEST REPORT

Low Global Warming Potential (GWP) Agent Testing

1.0 Executive Summary

Since the cessation of production of high ozone depleting substances such as halon 1301, the US Army (USA) has relied on hydrofluorocarbon (HFC) extinguishing agents for many of its fire suppression applications. However, production of HFCs is being phased down due to their high global warming potentials (GWP). Therefore, the Army initiated a research program to evaluate potential environmentally-friendly low-GWP chemicals as candidate extinguishing agents used to protect the crew of Army vehicles against fire and explosions caused by combat threats. The current effort is a continuation of research conducted for ground and aviation weapon systems [1]. This report addresses the investigation of the suitability of additional alternative agents. Specifically, we present evaluation results regarding TF-1, a proprietary gaseous chemical available in research quantities only, and KSA, a proprietary finely ground sodium bicarbonate dry chemical developed as a potential replacement for halon 1301 in civil aviation fire protection systems. These tests exhibited enough potential of the blend of TF-1 and KSA (TF-1 + KSA) to recommend continuation of testing including future vehicle-level fire suppression tests. Other candidate agents are also being investigated (e.g. aqueous solutions and other proprietary gaseous agents), and results for those agents will be reported separately.

2.0 Introduction

The Army relies on halon 1301 (bromtrifluoromethane), HFC-227ea (heptafluoropropane), HFC-125 (pentafluoroethane), dry chemical (sodium or potassium bicarbonate based), carbon dioxide (CO_2), and water with a freeze-point additive to provide fire protection for its ground and aviation weapon systems. Approximately two million pounds of these chemicals are installed in crew, engine, and auxiliary power unit (APU) compartment fire extinguishing systems and portable extinguishers of Army ground vehicles and aviation weapon systems. However, halon 1301 and HFC227-BC (HFC-227ea mixed with 5% - 10% sodium bicarbonate dry chemical by weight) are the only agents approved for use in automatic fire extinguishing systems (AFES) that protect the crew compartments of ground vehicles. These crew fire suppression agents, along with HFC-125 which is only used in a limited number of unoccupied applications due to it higher toxicity relative to its extinguishing concentration, have GWPs thousands of times greater than that of CO_2. GWP is a measure of how much heat a gas traps in the atmosphere relative to CO_2, and as such, these deployed agents will trap thousands of times more heat per unit mass. Due to international agreement, production of halon 1301 was eliminated in 1994 because of its high ozone depletion potential via the Montreal Protocol on Substances that Deplete the Ozone Layer [2]. Since then, the Army has relied on a strategic reserve of halon 1301 to support a very limited number of critical legacy applications while transitioning to HFCs or other alternatives (mainly sodium bicarbonate dry chemical) wherever possible. On 15 October 2016, Parties to the Montreal Protocol adopted the "Kigali Amendment" [3]. While this amendment does not restrict the use of HFCs, it calls for the gradual reduction of their consumption (production + imports – exports – destruction). The phasedown schedule for the US started with a 10-

percent reduction in 2019 and culminates in an 85-percent reduction in consumption by 2036 (Appendix A). As a result, alternative low-GWP chemicals for fire suppression are needed to satisfy these much more stringent environmental restrictions.

In response, the Army established the Low-GWP Alternative Fire Suppressants program. The focus of this effort is to evaluate the feasibility of commercially available and emerging chemicals to replace high-GWP fire suppression agents in its weapon systems. Results of this program will guide the direction of future research and procurement activities, as well as offer potential cost avoidance associated with reduced availability, and thus higher costs, of high-GWP agents after phase-down. If these low-GWP alternatives cannot satisfy the challenging military-unique performance requirements, including explosion suppression within occupied areas of vehicles, then the need for regulatory exemptions and/or establishment of a strategic reserve of HFCs may be investigated. This research was sponsored by the Army Combat Capabilities Development Command's (DEVCOM) Safer Alternative for Readiness (SAFR) Program, was managed by the Army Ground Vehicle Systems Center (GVSC) Fire Protection Team, and testing was performed at the Army Aberdeen Test Center (ATC) in Aberdeen Proving Ground, MD. To be considered a viable alternative to HFC227-BC, which is the Army's replacement for halon 1301 in vehicle crew AFES, the candidate must meet unique military requirements including the "Selected Crew Casualty Requirements" (Appendix B) that allow personnel to stay within the protected space for at least 5 minutes after fire suppression. The tests described in this report evaluated the effectiveness of the proposed alternative agents against a subset of these requirements. The toxicity thresholds are based on the findings published in the "Walter Reed Medical Evaluation of Nonfragment Injury Effects in Armored Vehicle Live Fire Tests" as summarized in Tables 1 and 2 below [4]. Chemical manufacturers of gaseous fire suppression agents provide Minimum Design Concentrations (MDC), and Lowest Observed Adverse Effect Levels (LOAEL), which, once vetted in independent evaluations, are, along with other properties, published in National Fire Protection Agency (NFPA) standards.

Table 1. Crew Casualty Criteria

Parameter	Requirement
Fire Suppression	Extinguish all flames without reflash
Toxic Gases	HF + HBr + $2COF_2$ < 746 ppm-min (5 min dose)
Oxygen	Levels at breathing locations of at least 16%
Overpressure	Lung damage <11.6 psi; Ear damage ≤ 4 psi
Agent	Concentration within occupational safety limits (LOAEL)

Table 2. Exposure Limits to Select Gases

Parameter	Requirement
CO + NO	< 37,250 ppm-min
NO_2	< 125 ppm-min
CO_2	1-min Time Weighted Average (TWA) < 3%
O_2	> 16%

The tests reported herein were the continuation of previous low-GWP fire suppression alternative agent testing [1], [5]. Eighteen potential fire suppression agents were reviewed against the Army ground vehicle performance requirements, and seven gaseous agents were down-selected for further testing and evaluation. Those previous tests identified Opteon 1150 (a hydrofluoroolefin (HFO) which is marketed primarily as a foam blowing agent) mixed with KSA, as a leading low-GWP candidate agent with potential to replace currently deployed HFCs. After these tests, the chemical manufacturer identified the minimum design concentration (MDC) needed to extinguish class B (liquid fuel) fires to be higher than the LOAEL of the agent. Based on this information, Opteon 1150 was removed from consideration as a candidate agent for occupied compartments. Two agent compositions were then selected as successor candidates for these tests, TF-1 combined with KSA dry chemical, and KSA dry chemical by itself. MDC and LOAEL values for the candidate agents are listed in Table 3, along with the values for halon 1301 and HFC-227ea for comparison. The goal was to collect enough data to determine those agents' viability as low-GWP fire suppressant alternatives, in order to move forward with future vehicle level testing. Vehicle level tests are required to optimize the distribution system, agent quantity and pressurization, and finally to confirm fire suppression performance in representative environments.

Table 3: Fire Suppression Agent MDC and LOAEL Values

Property	Halon 1301 [6]	HFC-227ea [7]	Opteon 1150 [8]	TF-1 [9]	KSA [10]
Class A MDC	5.0%	6.7%	5.6%	5.6%	90 g/m^3
Class B MDC	5.0%	8.7%	7.3%	6.9%	90 g/m^3
Class C MDC	5.0%	7.0%	6.3%	6.3%	90 g/m^3
LOAEL	7.5%	10.5%	7.0%	12.5%	TBD

TF-1 + KSA was originally tested as part of LGWP 16-01 [1] with encouraging results during small scale testing (cup burner and 8 ft^3 chamber), however, no further testing was conducted at the time due to an insufficient quantity of material available. The other alternative agent tested was KSA as a stand-alone dry chemical agent. However, concerns with the use of dry chemicals in occupied spaces remain, including inhalation toxicity, obscuration and the ability to prevent fire reflash (a sudden re-ignition of residual fuel due to insufficient suppression agent and/or inadequate distribution). These issues need to be examined further before the new agent could be fielded.

The testing consisted of simulating a crew compartment fireball within an enclosed instrumented chamber to analyze the effectiveness of proposed alternative agents. In general, for fire suppression performance in Army ground vehicles, all hatches closed with all personnel and stowage, and ventilation off would represent an optimal scenario to maintain agent concentration and thus an inert environment for the longest time. Therefore, this scenario was used as the starting point to evaluate the potential alternate agents. Chamber overpressures, oxygen levels, gaseous agent concentrations, and combustion byproduct levels were collected, along with high-speed video to determine fire durations.

3.0 Measurement Methods

The tests were conducted in a 200-ft^3 chamber shown in Fig. 1 and 2. The chamber was instrumented with two pressure transducers to measure blast overpressure (BOP), one on the left wall and the other on top of the center chamber stand. A temperature probe was also placed on the center stand, and air sampling lines were hung above it to measure gaseous agent and combustion byproduct levels using Fourier transform infrared (FTIR) instrumentation. Oxygen levels were also recorded via continuous emission monitoring (CEM). A high-speed camera was mounted outside the chamber to record the fireball, and a standard definition video on the top right corner of the chamber captured video of the entire test. An infrared (IR) sensor was used to document the start time and growth of the fireball, while a tactical wheeled vehicle AFES was used to release the extinguishers. The chamber had provisions for agent delivery via two extinguishers each with a single nozzle outlet located on the left chamber wall. Opposite of that was the fireball generator (FBG), which uses high pressure nitrogen, heated JP-8 fuel, and an atomizing nozzle to create a spray of fuel onto a spark plug to initiate the fireball, as shown in Fig. 3. The calculated K is a measurement of the fireball intensity, specifically growth rate, and is a variation of an industrial explosion protection parameter ‘K’, with units of bar-meter per second. K between 1.0 and 2.0 is targeted for each test to ensure the strength of the fireball is representative of ballistic events [7]. The fireball intensity, indicated by K, is held as constant as practical by using consistent fuel pressure, temperature and nozzle geometry. Formulas (Appendix C) applied within this report assumed 21°C for ambient temperature, with negligible variation in calculations due to actual ambient temperatures. Reflashes are detected by using a combination of high speed video footage and results from the chamber pressure transducers as shown in Fig. 4 and 5 below.

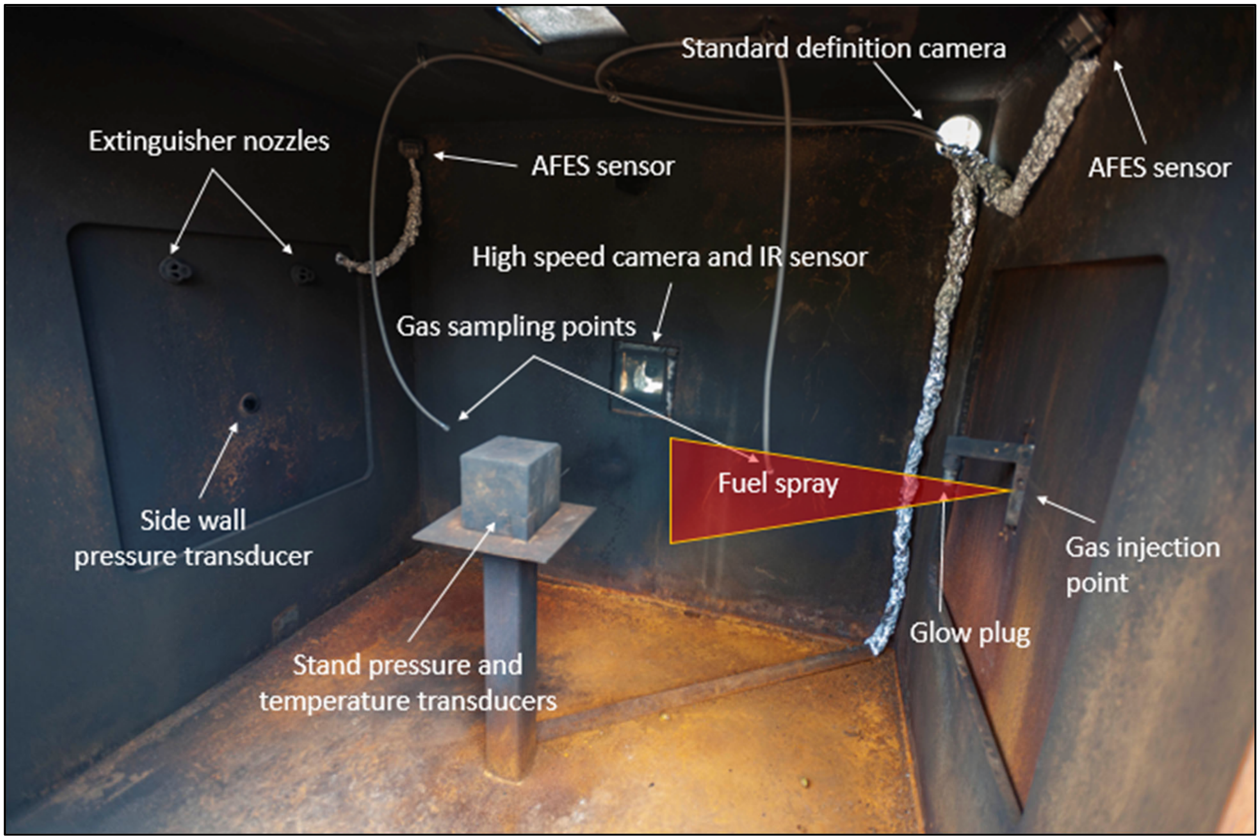


Figure 1: 200 ft^3 test chamber with no clutter (front panel removed)

Figure 2: Opened 148 ft^3 test chamber with clutter (ammo cans added to create obstructions)

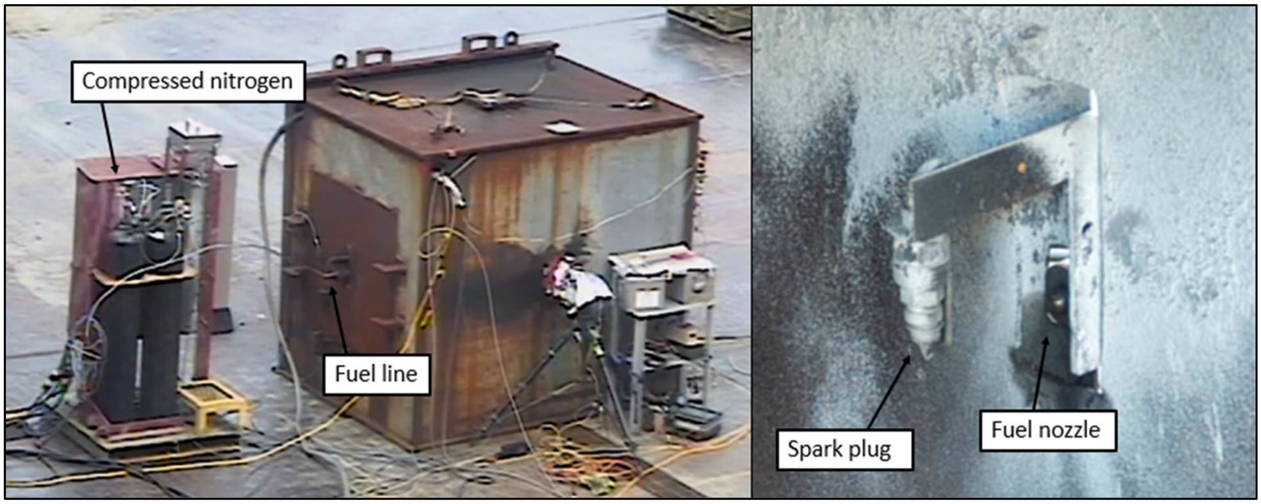


Figure 3: Fireball generator details

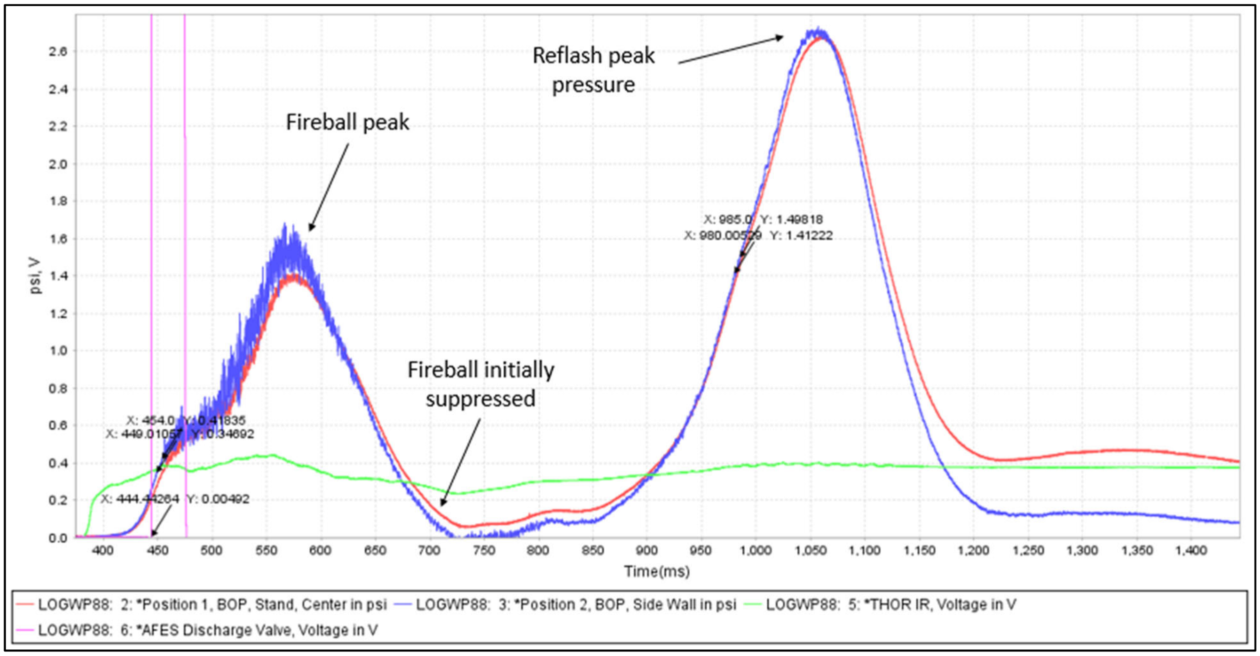


Figure 4: Example of reflash shown in pressure vs time plot – test #88

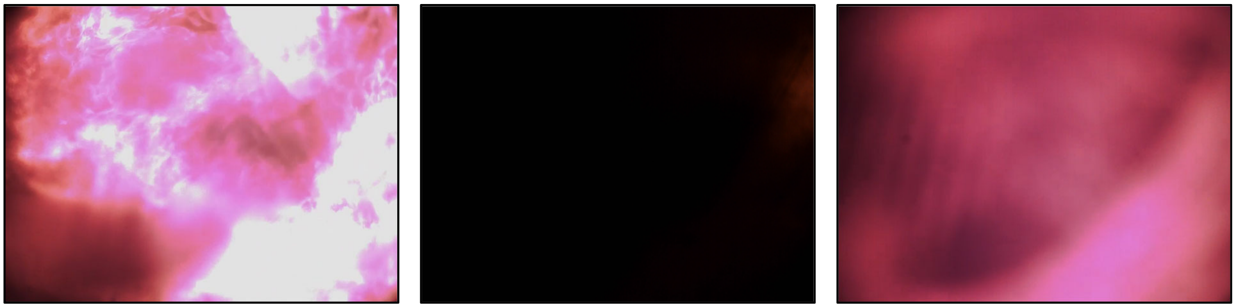


Figure 5: Images from chamber left to right – fireball peak, fireball initially suppressed, reflash peak

A total of 29 trials was completed, including daily FBG warm-up / calibration shots (tests 81, 84, 89, 95, 101, 103 and 106). The warm-up shots were conducted to introduce fresh heated fuel into the lines and verify the fireball generator was producing fireballs with sufficient K prior to testing with chemicals. Trials were conducted at a range of different concentrations, both with and without clutter in the test chamber, as described below.

4.0 Results

Table 4 shows a summary of the test results obtained for TF-1 + KSA. The concentration of KSA used for all tests with TF-1 was maintained at 92 g/m^3. As shown, three out of the four tests at 3.1% concentration of TF-1 failed, while all four tests at ~4.6% concentration passed. Good results were also obtained in test 100 where the average TF-1 concentration was 7.0%, close to the 6.9% MDC.

Table 4: Summary of Army TF-1 + KSA Test Results

Test Number	Agent	TF-1 Concentration (%)	Stored Energy (bar-L/kg)	K (bar-m/s)	Fire-Out Time (ms)	Peak Pressure (psi)	Reflash	Reflash Peak Pressure (psi)	Toxicity Level	Min Oxygen (%)
82	TF1 + KSA	8.6	31	2.5	255	2.72	No	N/A	Fail	15.6
83	TF1 + KSA	4.5	54	2.6	240	2.05	No	N/A	OK	17.3
86	TF1 + KSA	6.0	54	1.3	183	1.74	No	N/A	OK	17.4
87	TF1 + KSA	6.0	54	1.8	176	2.18	No	N/A	OK	16.9
88	TF1 + KSA	3.1	45	1.9	218	1.68	Yes	2.73	Fail	7.7
90	TF1 + KSA	3.1	100	1.2	183	2.12	No	N/A	OK	18.1
91	TF1 + KSA	3.1	100	1.6	193	1.34	Yes	3.98	Fail	9.4
93	TF1 + KSA	4.6	78	1.3	186	1.86	No	N/A	OK	17.5
94	TF1 + KSA	4.6	78	1.7	174	1.81	No	N/A	OK	17.4
97	TF1 + KSA	4.6	78	2.1	203	1.65	No	N/A	OK	18.0
98	TF1 + KSA	3.1	100	1.9	748	1.75	Yes	2.55	Fail	8.8
100	TF1 + KSA	7.0	73	1.9	167	1.60	No	N/A	OK	16.7

The results of Test #82 are an outlier in the dataset collected, as the byproduct and oxygen levels failed without an extended fire or a reflash. One factor to consider is the reduction in stored energy of the extinguisher cylinders, due to less volume of nitrogen over-pressurization, as compared to the other tests with successful results. All stored energy calculations within this report assumed 21 degrees Celsius. Another is the possibility that, in certain fire scenarios and unlike legacy agents, more combustion byproducts are produced by higher agent concentrations. Data from "ATC TF1 Toxic Fumes 2020" [11], Fig. 6 and 7, show that test #82 resulted in significantly larger amounts of carbonyl fluoride than Test #83, with the main difference being Test #82 contained twice the total TF-1 weight and thus a lower stored energy.

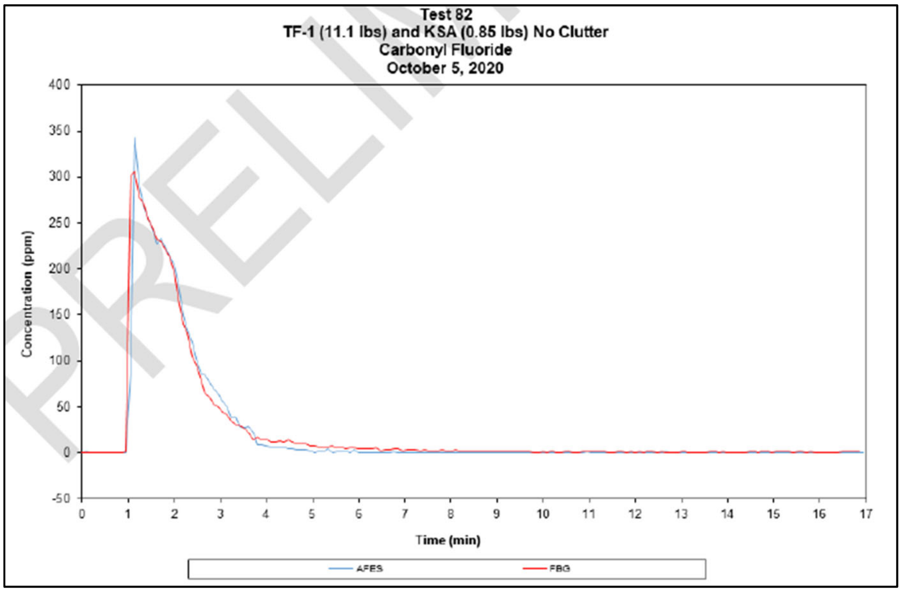


Figure 6: Test #82 carbonyl fluoride vs time

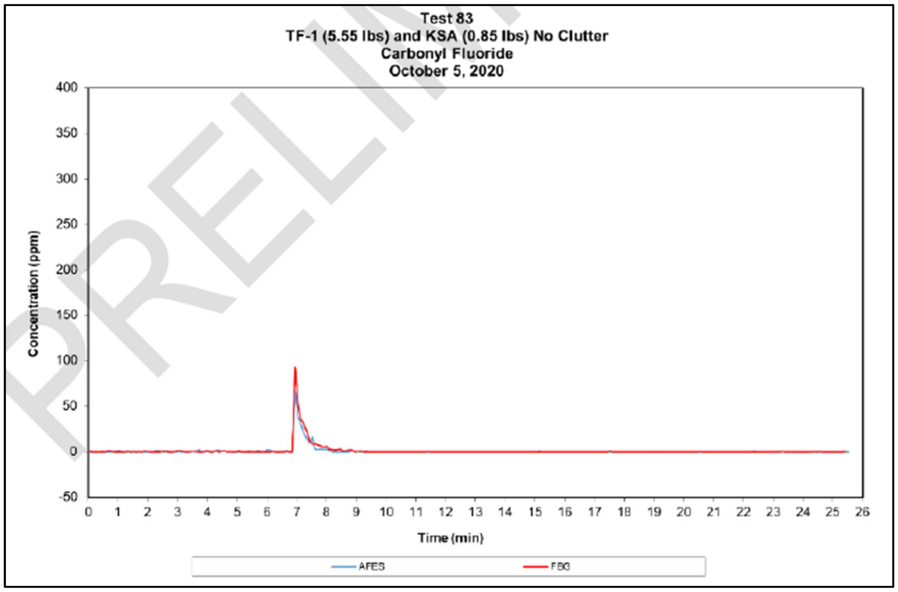


Figure 7: Test #83 carbonyl flouride vs time

As shown in Fig. 8, the effects of the high boiling point of TF-1 (30°C), can be seen on the test chamber walls. It appears as if the agent does not fully change to a gaseous phase during the extinguisher discharge as occurs with lower boiling point agents such as HFC-227ea or halon 1301. Also observed was a pattern of dry chemical residue at the extinguisher nozzles and against the opposite wall. This may indicate that a higher extinguisher over-pressurization and/or a more optimized distribution system may be needed to disperse the agent within the compartment effectively. Possible chemical incompatibility of TF-1 + KSA may also play a role and is being assessed via laboratory testing. The effects of low environmental temperatures should also be examined, as TF-1 may not be as effective at rapid evaporation and space filling in those conditions. The validity of these ideas will require further investigation.

Figure 8: Impact patterns of KSA when used with TF-1

Table 5 shows a summary of the test results obtained for KSA used alone. As shown, test #102 at 92 g/m^3 of dry chemical failed and one out of 3 tests at 141 g/m^3 failed. One out of two tests at 162g/m^3 also failed. All tests passed at 184 g/m^3. The stated MDC of KSA by the chemical manufacturer is 90 g/m^3, which failed on test #102, but may be due to inadequate distribution, quality of the KSA, or other reasons besides insufficient agent weight as mentioned below.

Table 5: Summary of KSA Test Results

Test Number	Agent	KSA Concentration (g/m^3)	Stored Energy (bar-L/kg)	K (bar-m/s)	Fire-Out Time (ms)	Peak Pressure (psi)	Reflash	Reflash Peak Pressure (psi)
85	KSA	182	136	2.2	159	1.80	No	N/A
92	KSA	182	136	1.2	205	1.23	No	N/A
96	KSA	141	151	1.6	204	1.61	No	N/A
99	KSA	141	151	1.7	226	1.18	No	N/A
102	KSA	92	218	2.4	232	1.46	Yes	1.27
104	KSA	141	151	2.1	231	1.20	Yes	0.94
105	KSA	141	151	2.5	214	1.50	No	N/A
107	KSA	162	131	1.8	1127	2.70	No	N/A
108	KSA	162	131	1.8	210	1.40	No	N/A
109	KSA	128	165	2.2	224	1.55	Yes	2.33

During previous testing with KSA [1], it was noted there was a product quality issue with the material received which is believed to have been the root cause of the unexpected clumping within the extinguisher valve during these tests [12]. This clumping could reduce the dry chemical's effectiveness, as some of the chemical does not get dispersed into the chamber and may not be distributed as evenly as intended, which reduces the effective KSA concentration. Fig. 9 shows examples of unacceptable clumping of the dry chemical observed in extinguisher valves, post discharge. In particular, note the large clumps of dry chemical visible in the valve outlet from test 91. On the other hand, Fig. 10 shows examples of fully emptied cylinders and valves, which is the design intent.

Figure 9: Clumping of KSA on test #91, #108, and #109, respectively

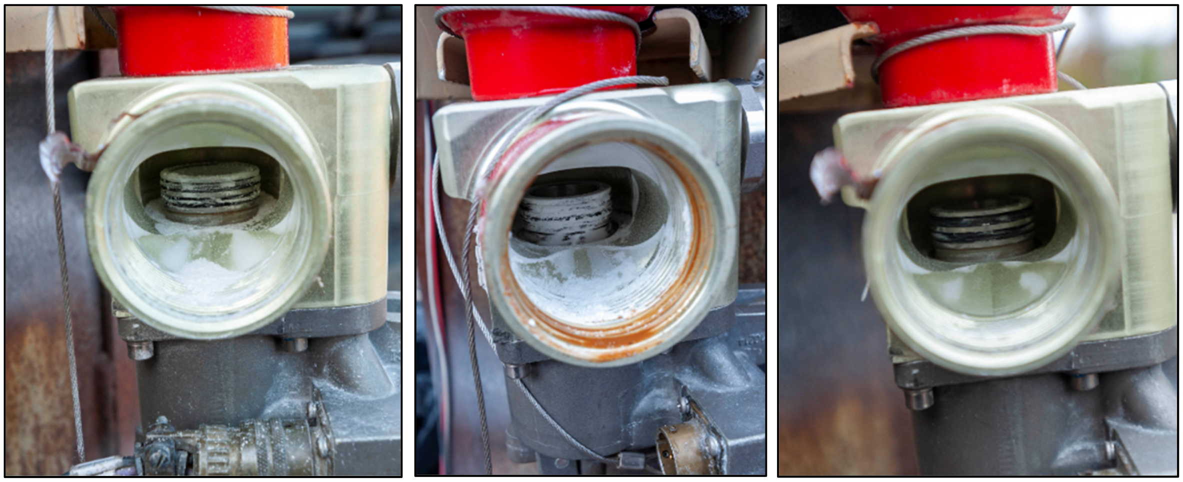


Figure 10: Emptied valves on test #102, #104, and #105, respectively

It was noted on tests with KSA only that the dry chemical coated most of the surfaces within the chamber, including the camera lenses. As such, it was not possible to assess the obscuration effect of the KSA within the chamber. Future testing would benefit from the development of a method to keep the camera lenses clean in the presence of suspended dry chemical.

The stored energies within the agent cylinders were much higher for KSA only tests when compared to tests using TF-1 + KSA. As noted by the chemical manufacturer, higher stored energy for KSA-only applications will increase the ability of the dry chemical to disperse within the chamber. The manufacturer noted high stored energies (150 bar-L/kg or greater) could lead to better dispersion and suppression performance. Maximum sound levels within the chamber were not recorded, but future testing should be conducted to verify that discharge impulse noise and discharge forces do not exceed the crew casualty criteria (Appendix B) with these higher stored energies.

Another metric to review when analyzing the ability of an agent to replace currently fielded AFES, is the potential concentration design margin of the agent. This is defined herein as the ratio of the minimum amount of agent required to extinguish fire events vs the agent's LOAEL. AFES with higher design margins are desirable. The minimum concentration shown to suppress 100% of fireballs generated without reflash was 4.6% TF-1 + 92 g/m^3 KSA, and 184 g/m^3 of KSA only. These values could likely be reduced further with optimized distribution systems. Our results indicate that TF-1 + KSA has a design margin of 2.7 which is similar to the currently fielded HFC227-BC design margin of 2.6, as shown in Table 6. This follows the published MDC vs LOAEL of TF-1 compared to HFC-227ea as shown in Table 3. The LOAEL of KSA dry chemical has not yet been determined, and as such, its design margin cannot be calculated. Concentrations that resulted in a 100% fire suppression success using halon BC (halon mixed with sodium bicarbonate dry chemical) and HFC227-BC as shown in Table 6 are taken from "Fire Extinguishing Agents for Protection of Occupied Spaces in Military Ground Vehicles" [5].

Table 6: Army Design Margin Test Results

Property	Halon 1301	*Halon BC	*HFC227-BC	TF-1 + KSA	KSA Only
LOAEL	7.0%	7.5%	10.5%	12.5%	TBD
MIN 100% Success	5.3%	2.0%	4.0%	4.6%	184 g/m^3
LOAEL Design Margin	1.3	3.8	2.6	2.7	TBD

* = Kiddex sodium bicarbonate dry chemical used

5.0 Conclusions and Recommendations

The analysis of these test results came to these primary conclusions:

1. TF-1 + KSA was confirmed to have successful fire suppression at and below the manufacturer recommended MDC of 6.9%, for TF-1 alone.

2. KSA as a sole agent was not confirmed to have successful fire suppression at the chemical manufacturer's stated MDC [10]. The tests were successful at higher concentration levels, which were still lower than the safe exposure values published for coarser grinds of the same dry chemical (sodium bicarbonate based) by the U.S. Army Public Health Center (APHC) [13].

3. Combustion byproducts are not significant concerns with KSA or other sodium bicarbonate dry chemicals when used alone, as they do not contain halogens (i.e. fluorine, bromine, chlorine, or iodine) that could lead to the production of acid gases and carbonyls.

4. The design margin for TF-1 + KSA fire suppression performance was shown to be comparable to currently fielded HFC227-BC systems.

Recommendations for future investigations are as follows:

1. The test results show enough potential of the candidate agents (TF-1 + KSA, KSA only) to recommend continuation of future vehicle level fire suppression tests.

2. Long term chemical compatibility of TF-1 and KSA should be evaluated for any interaction or degradation.

3. Testing of higher boiling point agents at lower temperatures is recommended to verify that dispersion of the chemical is unaffected or does not affect performance.

4. Testing with improved agent distribution should be performed on KSA, as well as TF-1 + KSA, to verify that dispersion of the dry chemical and agent is optimized, and will effectively protect cluttered volumes against fire reflash.

5. Due to its much finer particle size distribution, the inhalation toxicity of KSA needs to be further evaluated by APHC for final determination of safe exposure levels as compared to coarser grinds of the same dry chemical (sodium bicarbonate based).

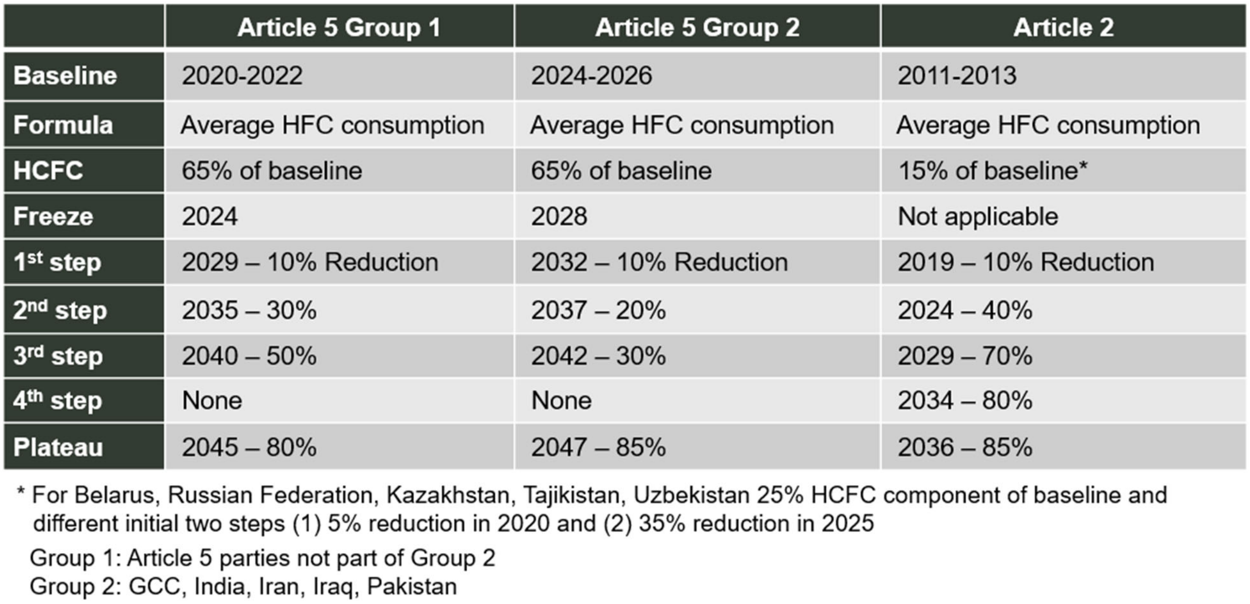
6. The effect of the product quality of the KSA on these trial results should be investigated further. Significant caking and clumping was observed during some trials, which was confirmed by the manufacturer to be due to a quality issue associated with the batch of materials received for this testing [12].

7. The potential correlation between fire suppression effectiveness and stored energy (due to nitrogen over-pressurization) of the low GWP extinguishers should be investigated further.

8. Additional testing of AFES using low GWP agents should be performed to assess operational effects, such as obscuration, discharge impulse noise, discharge forces, and long-term storage.

Appendix A. Kigali Amendment HFC Phasedown Schedule

On 15 Oct 2016, Parties to the Montreal Protocol adopted the "Kigali Amendment" that adds HFCs to the Montreal Protocol and gradually reduces their consumption (production + imports - exports - destruction)



	Article 5 Group 1	Article 5 Group 2	Article 2
Baseline	2020-2022	2024-2026	2011-2013
Formula	Average HFC consumption	Average HFC consumption	Average HFC consumption
HCFC	65% of baseline	65% of baseline	15% of baseline*
Freeze	2024	2028	Not applicable
1st step	2029 – 10% Reduction	2032 – 10% Reduction	2019 – 10% Reduction
2nd step	2035 – 30%	2037 – 20%	2024 – 40%
3rd step	2040 – 50%	2042 – 30%	2029 – 70%
4th step	None	None	2034 – 80%
Plateau	2045 – 80%	2047 – 85%	2036 – 85%

* For Belarus, Russian Federation, Kazakhstan, Tajikistan, Uzbekistan 25% HCFC component of baseline and different initial two steps (1) 5% reduction in 2020 and (2) 35% reduction in 2025

Group 1: Article 5 parties not part of Group 2
Group 2: GCC, India, Iran, Iraq, Pakistan

Appendix B. Crew Casualty Criteria

Parameter	Requirement
Fire Suppression	Extinguish all flames without reflash
Skin Burns[a]	Less than second degree burns (<2400°F-s over 10 sec or heat flux < 3.9 cal/cm^2)
Toxic Gases[a]	Acid Gases (HF + HBr + 2·COF2) < 746 ppm-min (5 min dose) Other toxic gases (eg, CO2, CO, NOX, HCN) are also measured
Oxygen[b]	Levels at breathing locations of at least 16%
Overpressure[b,c]	Lung damage <11.6 psi; Ear damage ≤ 4 psi
Discharge Impulse Noise[d]	No hearing protection limit: <140 dBP Single hearing protection limit: <165 dBP
Discharge Forces[e]	Not to exceed 8 g averaged over 30 milliseconds
Agent[f]	Concentration within occupational safety limits
Fragmentation[g,h]	Ejected non-agent particles <300 micrometers Non-Shatterable Cylinders (NONSHAT)

a) Ripple, Gary and Mundie, Thomas, “Medical Evaluation of Nonfragment Injury Effects in Armored Vehicle Live Fire Tests,” Walter Reed Army Institute of Research, September 1989.
b) Swanson, Dennis, “Fire Survivability Parameters for Combat Vehicle Crewmen,” Department of the Army, Office of the Surgeon General, 20 February 1987.
c) Rice, W. A., “Noise Specification for Automatic Fire Extinguishing Systems (AFES),” Dept. of the Army Memorandum, 14 Nov 2013.
d) “Hearing Conservation Program,” US Army Pamphlet 40-501, January 2015; similar criteria are found in “Design Criteria Noise Limits,” MIL-STD-1474, 1997.
e) Extrapolated from the 57 N-m limit given in reference (a).
f) Lowest Observed Adverse Effects Level per “NFPA 2001 Standard on Clean Agent Fire Extinguishing Systems,” (HFC-227ea) and “NFPA 12A Standard on Halon 1301 Fire Extinguishing Systems,” National Fire Protection Association (NFPA).
g) Section 3.4.1.3 in “VALVE AND CYLINDER ASSEMBLIES, HALON 13O1,” MIL-DTL-62547.
h) Section 3.3.9 in “CYLINDERS, STEEL, COMPRESSED GAS, NON-SHATTERABLE, SEAMLESS, 1800 PSI AND 2100 PSI,” MIL-DTL-7905.

Appendix C. Formulas and Definitions

Gaseous Agent Concentration

The predicted agent concentration (vol%) within the test chamber, where S_{agent} (cubic meters/kilogram) is the specific volume of the gaseous agent at the test temperature, W_{agent} is the weight of the gaseous agent (kilograms), and $V_{chamber}$ is the open-air volume of the test chamber (cubic meters).

$$Agent\ Concentration\ (\%)\ = \frac{100}{1 + \frac{V_{chamber}}{W_{agent} \times S_{agent}}}$$

Dry Chemical Agent Concentration

The predicted concentration for a dry chemical (grams/cubic meter) within the test chamber, where W_{powder} is the dry chemical weight (grams), and $V_{chamber}$ is the volume (cubic meters) of the test chamber.

$$Dry\ Powder\ Concentration = \frac{W_{powder}}{V_{chamber}}$$

Stored Energy

The stored energy (bar-liter/kilogram) within the charged cylinders, whereP_{fill} is the fill pressure (bar) of the cylinder, $V_{cylinder}$ is the cylinder's volume (liters), V_{agent} is the volume occupied by the agent, V_{powder} is the volume occupied by the dry chemical, W_{agent} is the weight of the gaseous agent (kilograms), W_{powder} is the weight (kilograms) of the dry chemical, and $W_{nitrogen}$ is the weight (kilograms) of the nitrogen. All stored energy values within this report were calculated at a temperature of 21 degrees Celsius.

$$Stored\ Energy = P_{fill} \times \frac{V_{cylinder} - V_{agent} - V_{powder}}{W_{agent} + W_{powder} + W_{nitrogen}}$$

K

A measure of the intensity of the fireball (bar-meter/second), where $V_{chamber}$ is the open-air volume of the test chamber (cubic meters), P is the chamber pressure (bar) and t is the time (seconds). The calculations within this report used $t_{initial}$ and $P_{initial}$ at 5 milliseconds after start of the AFES valve drive signal, t_{final} and P_{final} at 10 milliseconds after start of the valve drive.

$$K\ = \sqrt[3]{V_{chamber}} \times \frac{P_{final} - P_{initial}}{t_{final} - t_{initial}}$$

Minimum Design Concentration (MDC)

The minimum extinguishing concentration of an agent required to extinguish a flame (determined by the results of an approved underwriters laboratory test protocol) multiplied by a safety factor of 1.3

Lowest Observed Adverse Effect Levels (LOAEL)

The lowest concentration (% volume) at which there was an observed toxic or adverse effect in human clinical or experimental animal studies.

Appendix D. Test Matrix / Data

Test setup matrix:

Test #	Date	Time	Agent Type	Cylinder Size (in^3)	Total Mass Agent (lbs)	Total Mass DC (lbs)	Total Mass Agent + DC (lbs)	Agent Concentration Predicted at 70F	Charge Pressure (Psi)	Clutter?	Stored Energy (bar-L/kg)
81	5-Oct	14:44	Fireball Cal.	N/A	0.00	0.00	0.0	0	N/A	No	N/A
82	5-Oct	15:33	TF1 + KSA	204	11.1	0.85	12.0	8.6%	900	No	31
83	5-Oct	16:28	TF1 + KSA	144	5.55	0.85	6.40	4.5%	900	No	54
84	6-Oct	9:11	Fireball Cal.	N/A	0.00	0.00	0.0	0	N/A	Yes	N/A
85	6-Oct	11:05	KSA	72	0.00	1.70	1.70	180g/m^3	900	Yes	136
86	6-Oct	12:22	TF1 + KSA	144	5.55	0.85	6.40	6.0%	900	Yes	54
87	6-Oct	16:02	TF1 + KSA	144	5.55	0.85	6.40	6.0%	900	Yes	54
88	6-Oct	16:43	TF1 + KSA	72	2.78	0.85	3.63	3.1%	900	Yes	45
89	7-Oct	9:23	Fireball Cal.	N/A	0.00	0.00	0.0	0	N/A	Yes	N/A
90	7-Oct	10:16	TF1 + KSA	144	2.78	0.85	3.63	3.1%	750	Yes	100
91	7-Oct	11:00	TF1 + KSA	144	2.78	0.85	3.63	3.1%	750	Yes	100
92	7-Oct	13:50	KSA	72	0.00	1.70	1.70	180g/m^3	900	Yes	136
93	7-Oct	15:50	TF1 + KSA	144	4.16	0.85	5.01	4.6%	900	Yes	78
94	7-Oct	16:26	TF1 + KSA	144	4.16	0.85	5.01	4.6%	900	Yes	78
95	8-Oct	9:08	Fireball Cal.	N/A	0.00	0.00	0.0	0	N/A	Yes	N/A
96	8-Oct	9:44	KSA	72	0.00	1.30	1.30	140g/m^3	750	Yes	151
97	8-Oct	11:05	TF1 + KSA	144	4.16	0.85	5.01	4.6%	900	Yes	78
98	8-Oct	11:48	TF1 + KSA	144	2.78	0.85	3.63	3.1%	750	Yes	100
99	8-Oct	13:52	KSA	72	0.00	1.30	1.30	140g/m^3	750	Yes	151
100	8-Oct	16:11	TF1 + KSA	204	6.55	0.85	7.40	7.0%	900	Yes	73
101	27-Oct	15:01	Fireball Cal.	N/A	0.00	0.00	0.0	0	N/A	Yes	N/A
102	27-Oct	15:27	KSA	72	0.00	0.85	0.85	92g/m^3	750	Yes	218
103	30-Oct	10:00	Fireball Cal.	N/A	0.00	0.00	0.0	0	N/A	Yes	N/A
104	30-Oct	11:30	KSA	72	0.00	1.30	1.30	140g/m^3	750	Yes	151
105	30-Oct	14:00	KSA	72	0.00	1.30	1.30	140g/m^3	750	Yes	151
106	2-Nov	9:47	Fireball Cal.	N/A	0.00	0.00	0.0	0	N/A	Yes	N/A
107	2-Nov	10:11	KSA	72	0.00	1.50	1.50	160g/m^3	750	Yes	131
108	2-Nov	12:46	KSA	72	0.00	1.50	1.50	160g/m^3	750	Yes	131
109	2-Nov	16:02	KSA	72	0.00	1.18	1.18	130g/m^3	750	Yes	165

Test results matrix:

Test #	K (bar-m/s)	Valve Release Time (s)	Flame Out Time (s)	Peak BOP (psi)	Reflash?	Reflash Duration (s)	Reflash peak BOP (psi)
81	2.1	0.068	0.000	1.35	No	N/A	N/A
82	2.5	0.057	0.255	2.72	No	N/A	N/A
83	2.6	0.063	0.240	2.05	No	N/A	N/A
84	2.4	0.060	0.000	1.58	No	N/A	N/A
85	2.2	0.050	0.159	1.80	No	N/A	N/A
86	1.3	0.052	0.183	1.74	No	N/A	N/A
87	1.8	0.049	0.176	2.18	No	N/A	N/A
88	1.9	0.049	0.218	1.68	Yes	0.345	2.73
89	1.9	0.058	0.000	0.80	No	N/A	N/A
90	1.2	0.048	0.183	2.12	No	N/A	N/A
91	1.6	0.050	0.193	1.34	Yes	0.844	3.98
92	1.2	0.279	0.205	1.23	No	N/A	N/A
93	1.3	0.037	0.186	1.86	No	N/A	N/A
94	1.7	0.058	0.174	1.81	No	N/A	N/A
95	2.1	0.055	1.739	1.08	No	N/A	N/A
96	1.6	0.057	0.204	1.61	No	N/A	N/A
97	2.1	N/A	0.203	1.65	No	N/A	N/A
98	1.9	0.054	0.748	1.75	Yes	0.173	2.55
99	1.7	0.054	0.226	1.18	No	N/A	N/A
100	1.9	0.056	0.167	1.60	No	N/A	N/A
101	2.2	0.056	1.719	0.78	No	N/A	N/A
102	2.4	0.058	0.232	1.46	Yes	1.832	1.27
103	3.0	0.061	1.173	1.97	No	N/A	N/A
104	2.1	0.060	0.231	1.20	Yes	0.949	0.94
105	2.5	0.061	0.214	1.50	No	N/A	N/A
106	2.2	N/A	1.308	2.60	No	N/A	N/A
107	1.8	0.046	1.127	2.70	Yes	N/A	N/A
108	1.8	0.057	0.210	1.40	No	N/A	N/A
109	2.2	0.061	0.224	1.55	Yes	0.692	2.33

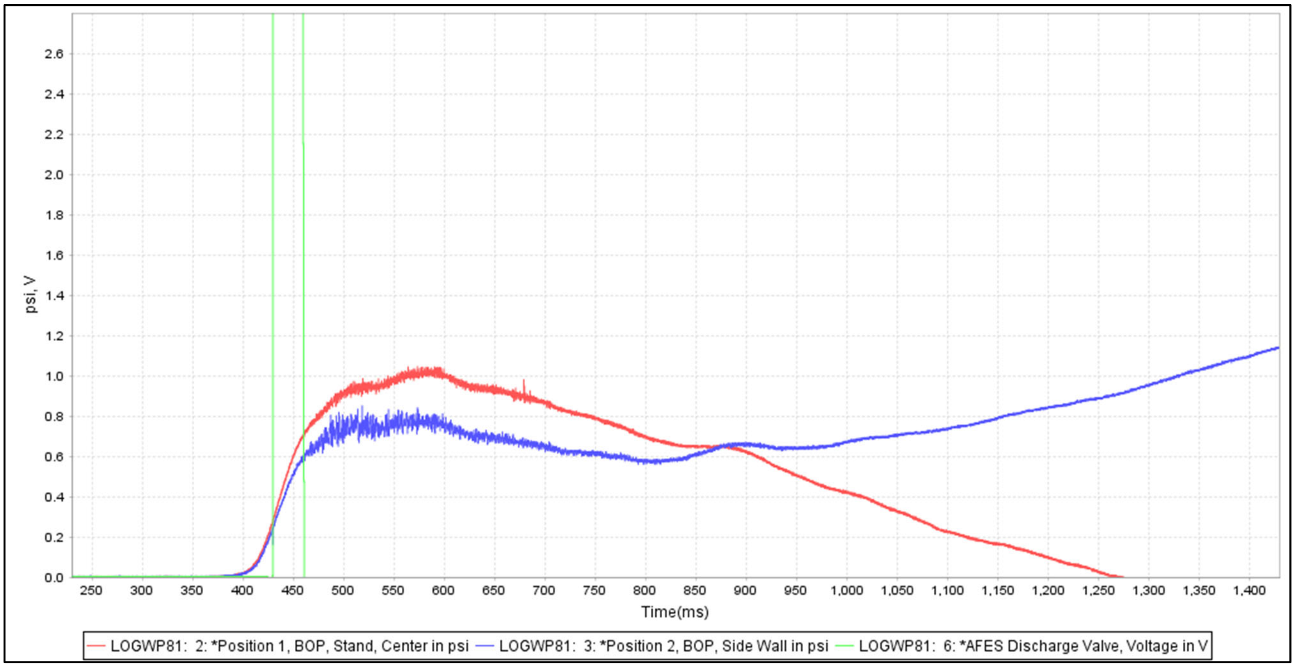
AFES cylinder fill weights first bottle:

Test #	Cylinder #	Valve #	Valve Weight (lb)	Cylinder Weight (empty, lb)	Total Empty Weight (lb)	Agent Weight (lb)	Dry Chemical Weight (lb)	Full Weight (no N2, lb)	Full Weight (with N2, lb)	Empty Weight (post test, lb)
82	N513917	ABS0651	4.572	8.470	13.042	5.550	0.425	19.020	19.410	13.050
	N513949	ABS0704	4.556	8.540	13.096	5.550	0.425	19.100	19.430	13.105
83	M755623	AAV9335	4.310	7.025	11.335	2.770	0.425	14.530	14.850	Not Available
	M755633	AAO0320	4.564	7.065	11.629	2.780	0.425	14.840	15.130	Not Available
85	4207904	AAN4900	4.554	3.130	7.684	0.000	0.850	8.540	8.670	7.685
	4207897	AAG4420	4.586	3.122	7.708	0.000	0.850	8.560	8.690	7.710
86	M755623	AAV9335	4.310	7.020	11.330	2.780	0.425	14.540	14.820	11.340
	M755633	AAO0320	4.560	7.060	11.620	2.780	0.425	14.810	15.110	11.645
87	M755623	AAV9335	4.310	7.025	11.335	2.770	0.425	14.530	14.820	11.340
	M755633	AAO0320	4.564	7.065	11.629	2.780	0.425	14.840	15.150	11.635
88	4207897	AAG4199	4.590	3.130	7.720	1.390	0.425	9.550	9.665	7.715
	4207904	AAG3992	4.540	3.130	7.670	1.390	0.425	9.510	9.610	7.680
90	4704231	AAO0303	4.564	7.130	11.694	1.390	0.425	13.510	13.775	11.750
	M755633	AAO0320	4.564	7.065	11.629	1.390	0.425	13.460	13.780	11.660
91	4512181	AAV9349	4.320	7.405	11.725	1.390	0.425	13.510	13.750	11.795
	M755623	AAV9335	4.310	7.025	11.335	1.390	0.425	13.150	13.465	11.395
92	4207904	AAG3992	4.544	3.128	7.672	0.000	0.850	8.520	8.645	7.675
	4207897	AAG4199	4.584	3.124	7.708	0.000	0.850	8.555	8.690	7.710
93	4512181	AAV9349	4.320	7.405	11.725	2.080	0.425	14.235	14.525	11.730
	M755623	AAV9335	4.310	7.025	11.335	2.080	0.425	13.845	14.185	11.340
94	4704231	AAO0303	4.564	7.130	11.694	2.080	0.425	14.210	14.480	11.705
	M755633	AAO0320	4.564	7.065	11.629	2.080	0.425	14.130	14.470	11.630
96	4207897	AAG4199	4.590	3.130	7.720	0.000	0.650	8.370	8.490	7.710
	4207904	AAG3992	4.540	3.130	7.670	0.000	0.650	8.330	8.450	7.675
97	4512181	AAV9349	4.320	7.405	11.725	2.050	0.425	14.190	14.480	11.735
	M755623	AAV9335	4.310	7.025	11.335	2.050	0.425	13.810	14.160	11.350
98	4704231	AAO0303	4.564	7.130	11.694	1.390	0.425	13.520	13.760	11.765
	M755633	AAO0320	4.564	7.065	11.629	1.390	0.425	13.430	13.700	11.670
99	4207897	AAG4199	4.590	3.130	7.720	0.000	0.650	8.370	8.485	7.715
	4207904	AAG3992	4.540	3.130	7.670	0.000	0.650	8.315	8.430	7.675
100	N513917	ABS0651	4.572	8.470	13.042	3.280	0.425	16.740	17.180	13.050
	N513949	ABS0704	4.556	8.540	13.096	3.280	0.425	16.800	17.300	13.100
102	4207897	AAG4199	4.590	3.130	7.720	0.000	0.425	8.135	8.250	7.720
	4207904	AAG3992	4.540	3.130	7.670	0.000	0.425	8.095	8.215	7.695
104	4207897	AAG4199	4.590	3.130	7.720	0.000	0.650	8.360	8.480	7.715
	4207904	AAG3992	4.540	3.130	7.670	0.000	0.650	8.325	8.440	7.680
105	4207897	AAG4199	4.590	3.130	7.720	0.000	0.650	8.370	8.475	7.715
	4207904	AAG3992	4.540	3.130	7.670	0.000	0.650	8.320	8.445	7.680
107	4207897	AAG4199	4.590	3.130	7.720	0.000	0.750	8.470	8.565	7.775
	4207904	AAG3992	4.540	3.130	7.670	0.000	0.750	8.420	8.540	7.675
108	4207897	AAG4199	4.590	3.130	7.720	0.000	0.750	8.470	8.570	7.725
	4207904	AAG3992	4.540	3.130	7.670	0.000	0.750	8.320	8.540	7.760
109	4207897	AAG4199	4.590	3.130	7.720	0.000	0.625	8.345	8.455	7.725
	4207904	AAG3992	4.540	3.130	7.670	0.000	0.550	8.220	8.345	7.680

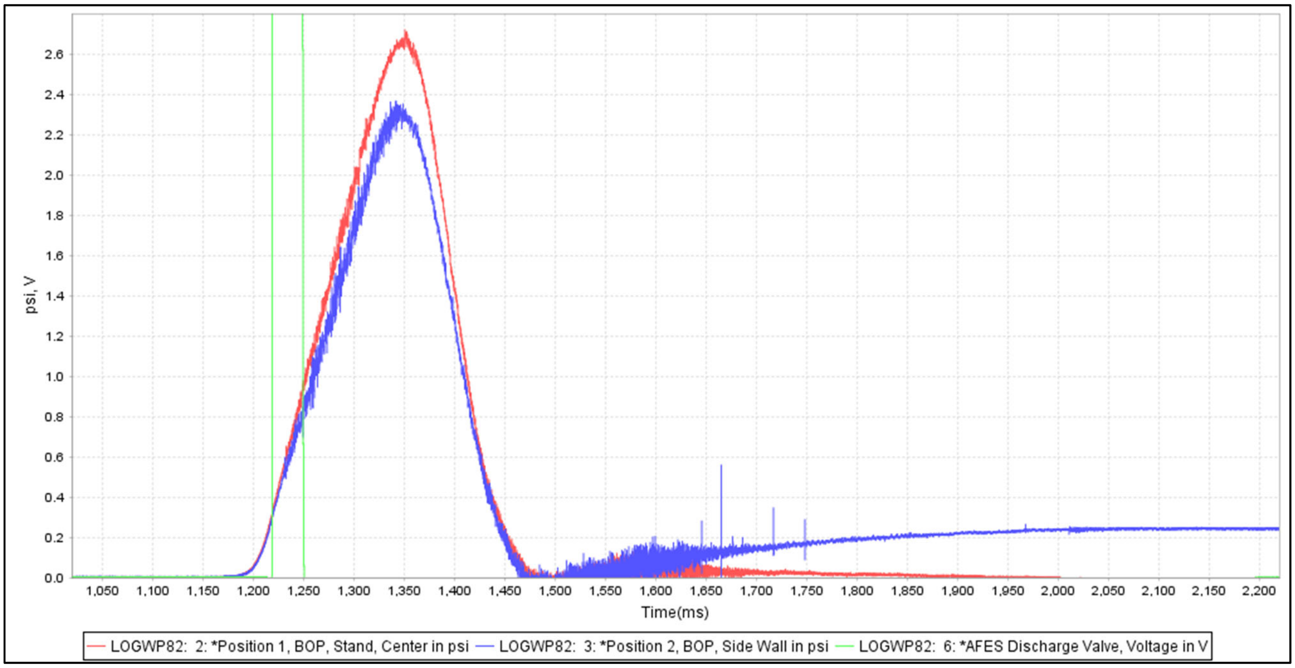
Appendix E. Pressure vs Time Charts

“AFES Discharge Valve, Voltage in V” = 30ms signal to extinguisher valve for agent release

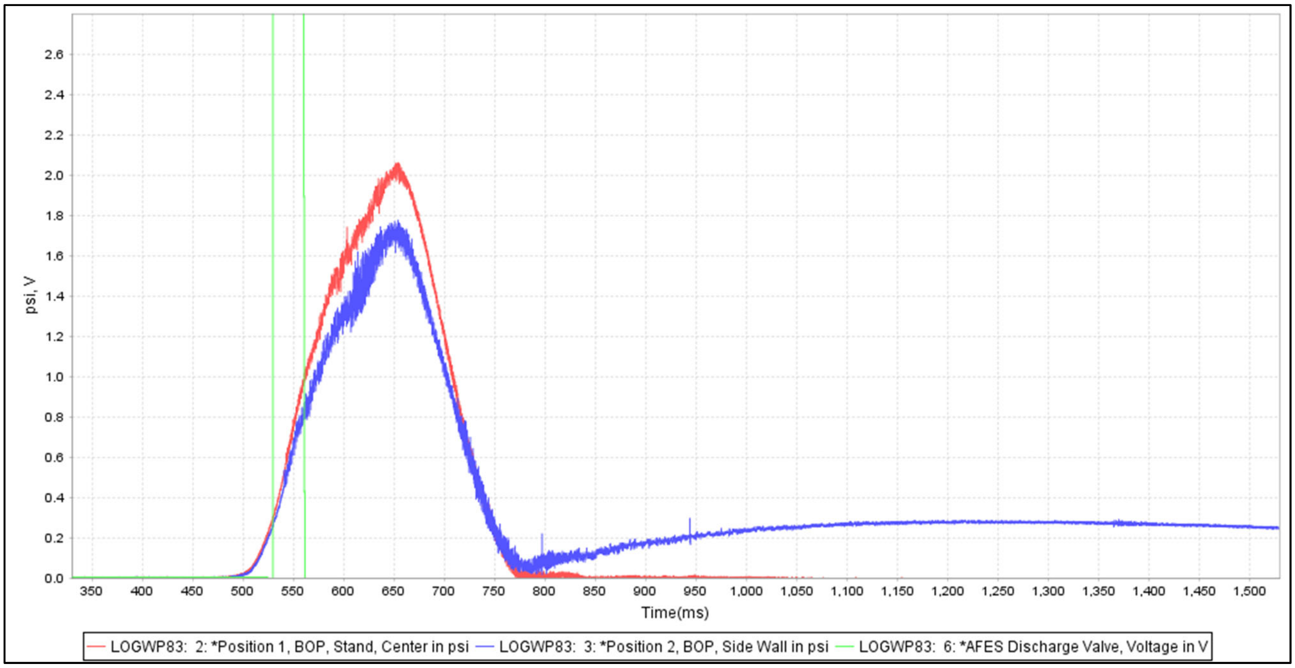
Test 81:



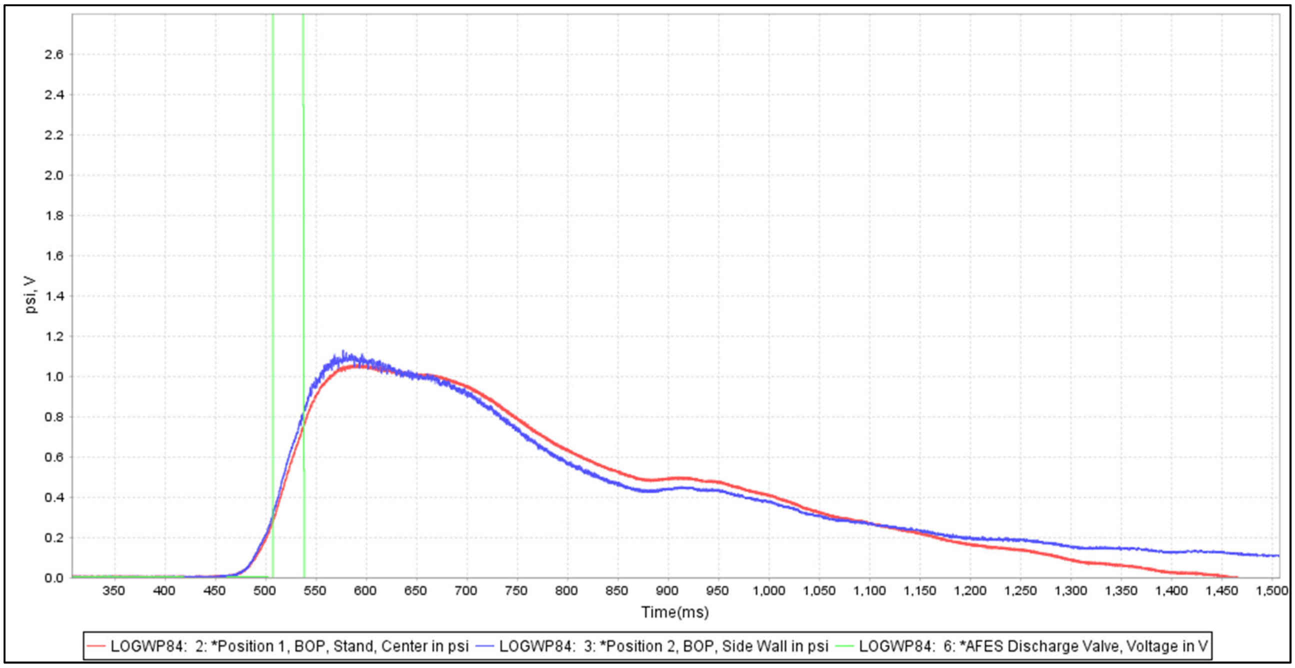
Test 82:


psi, V
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1,050
1,100
1,150
1,200
1,250
1,300
1,350
1,400
1,450
1,500
1,550
1,600
1,650
1,700
1,750
1,800
1,850
1,900
1,950
2,000
2,050
2,100
2,150
2,200
Time(ms)
LOGWP82: 2: *Position 1, BOP, Stand, Center in psi
LOGWP82: 3: *Position 2, BOP, Side Wall in psi
LOGWP82: 6: *AFES Discharge Valve, Voltage in V

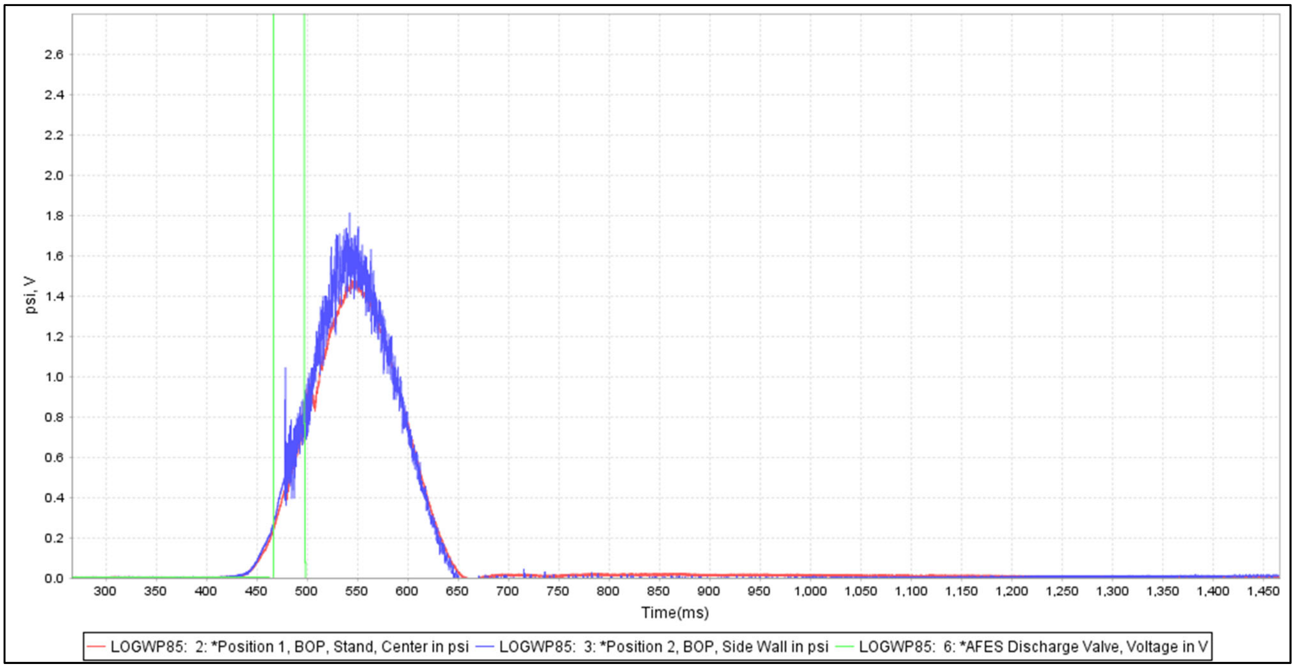
Test 83:



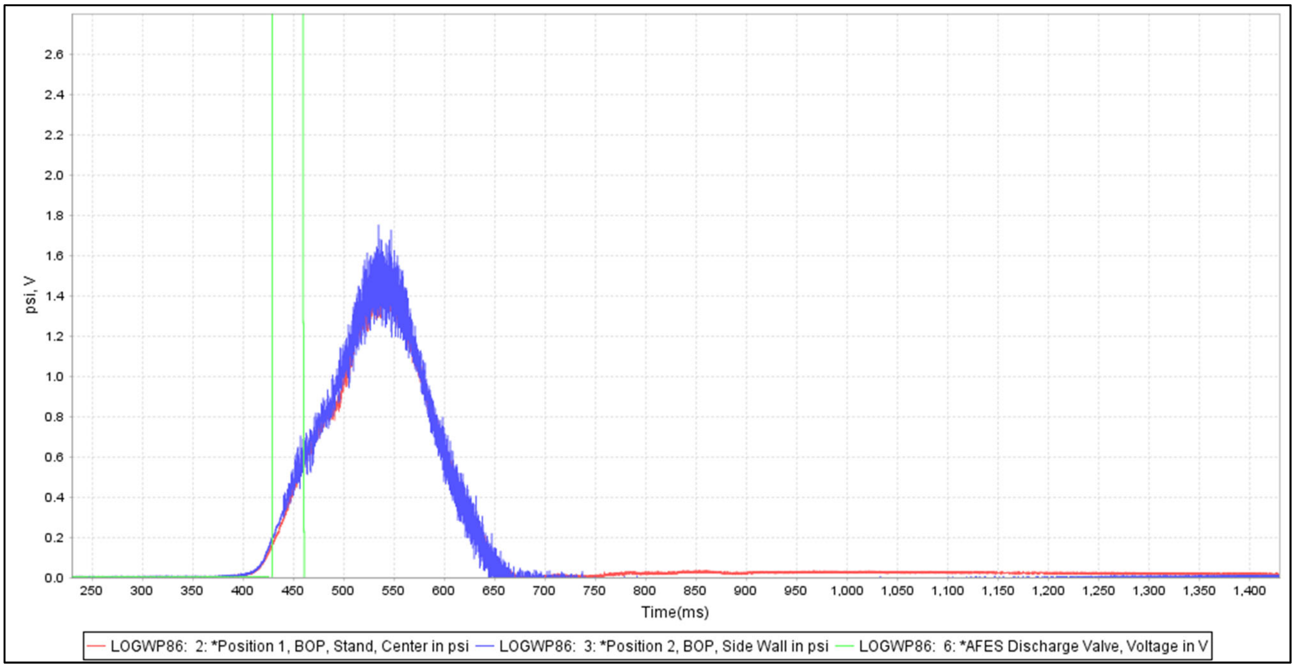
Test 84:



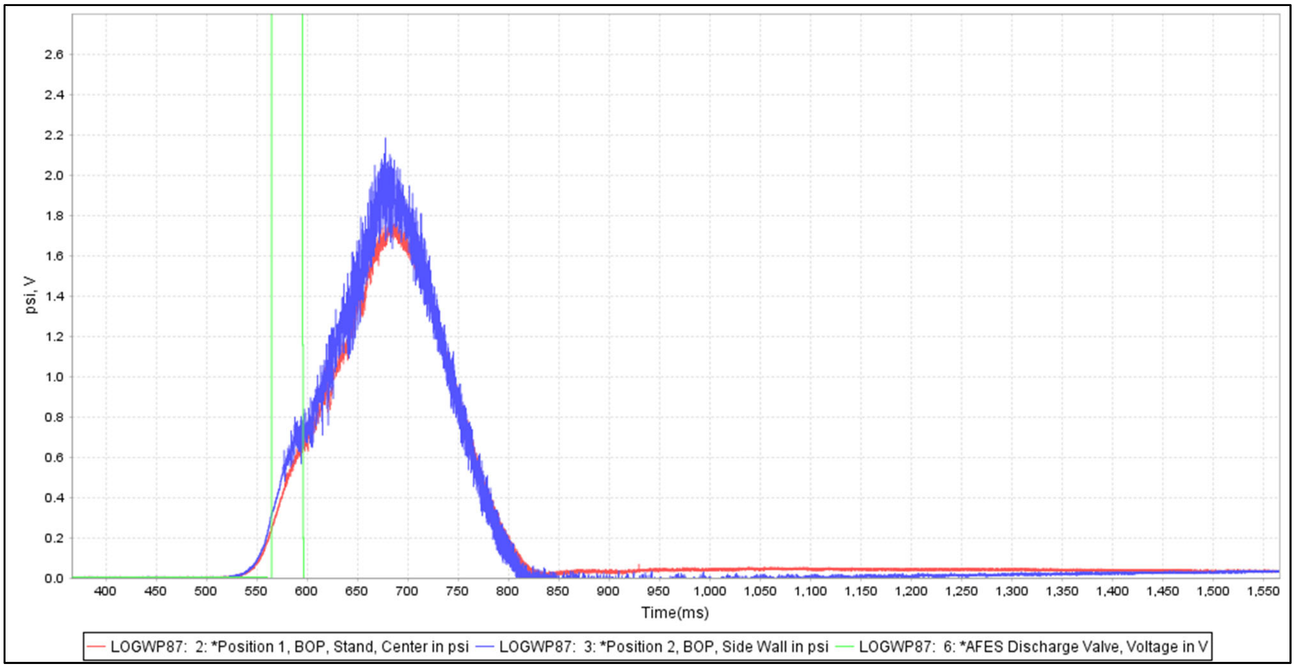
Test 85:



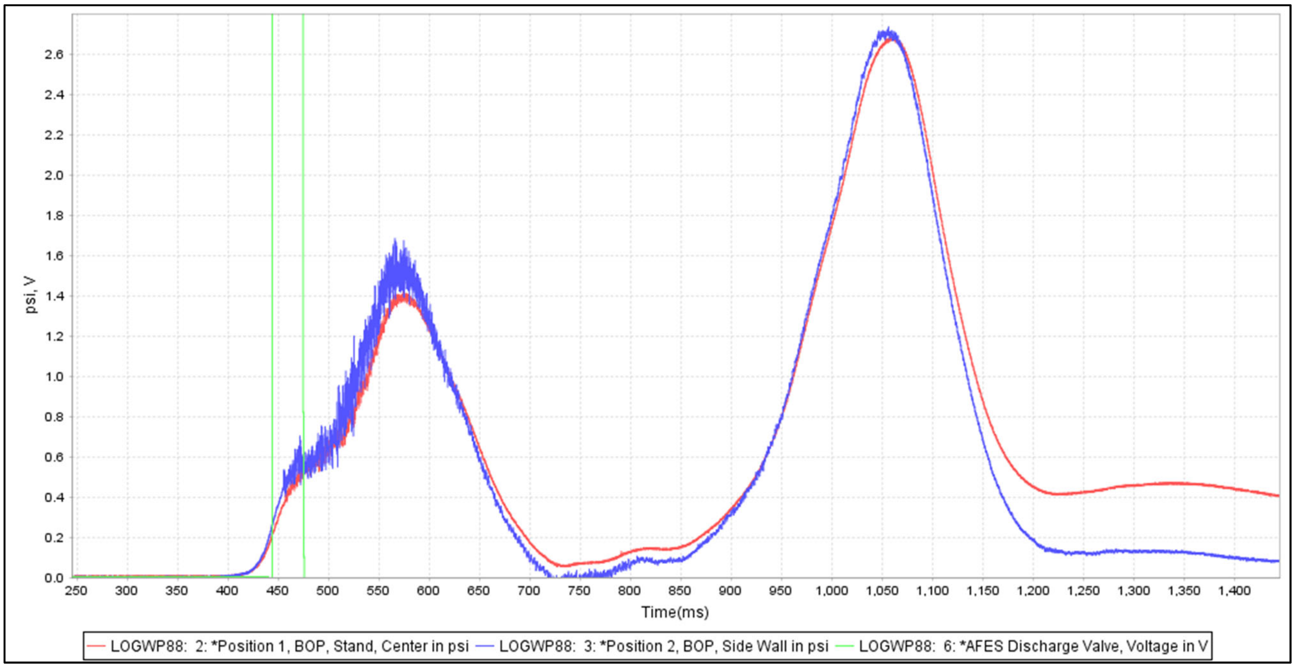
Test 86:



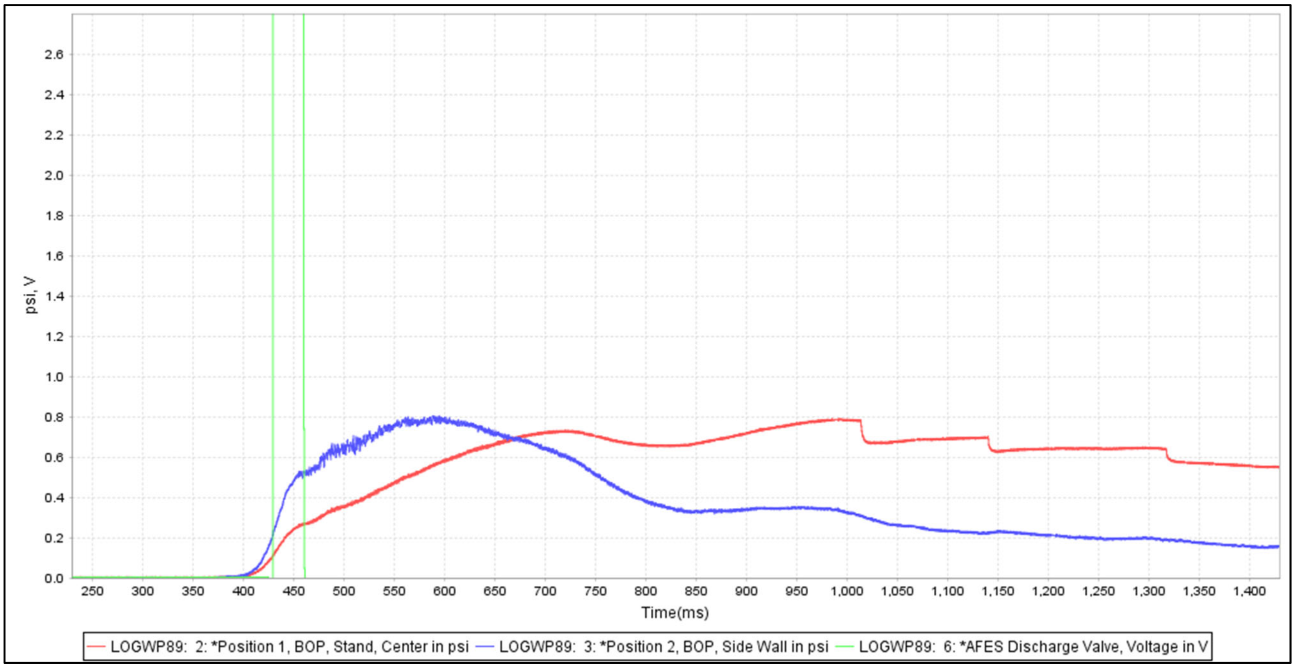
Test 87:



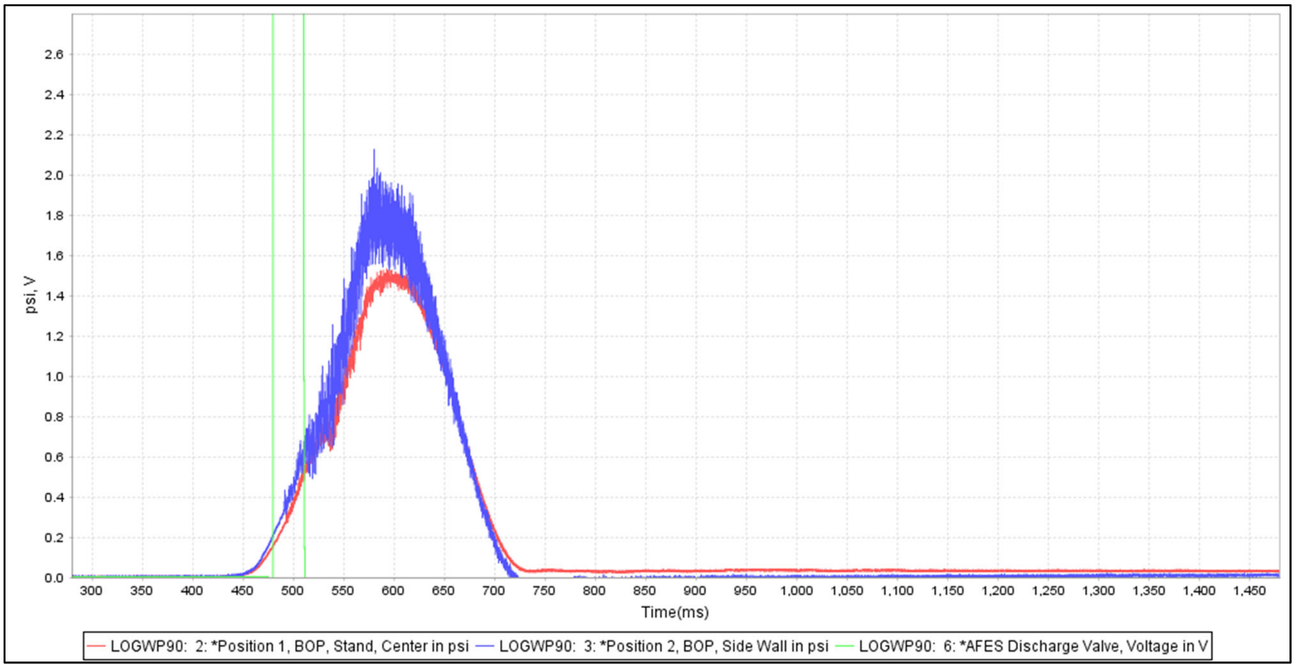
Test 88:



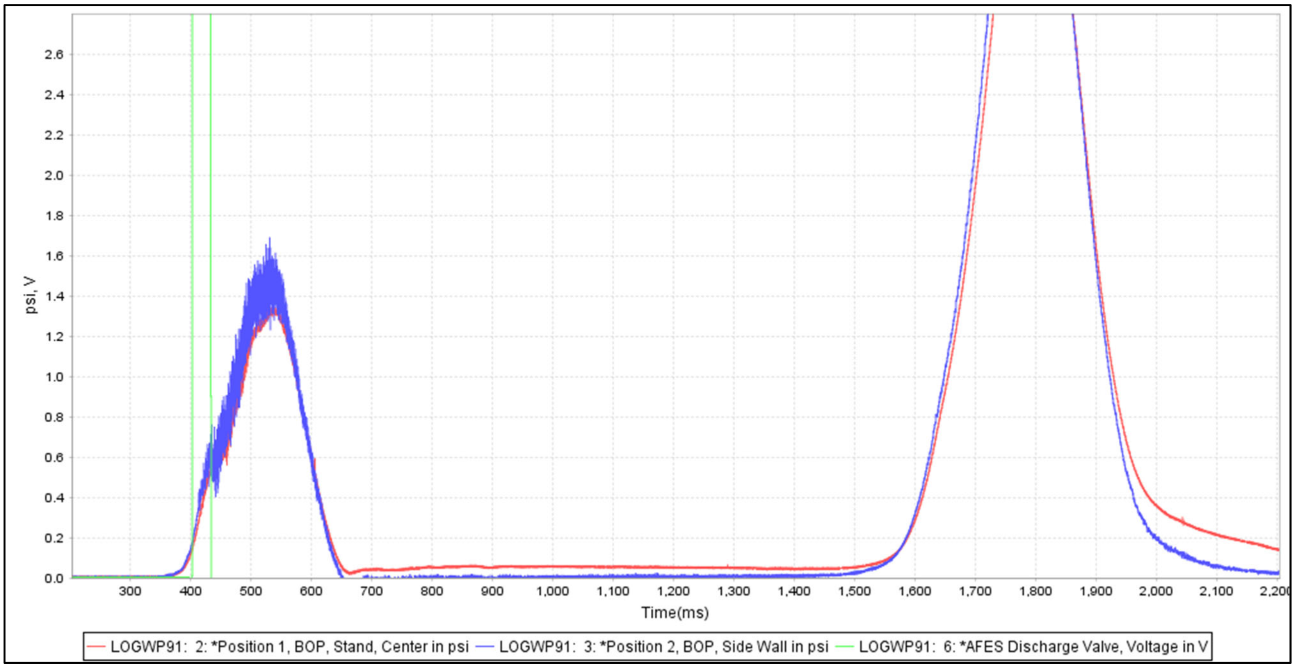
Test 89:



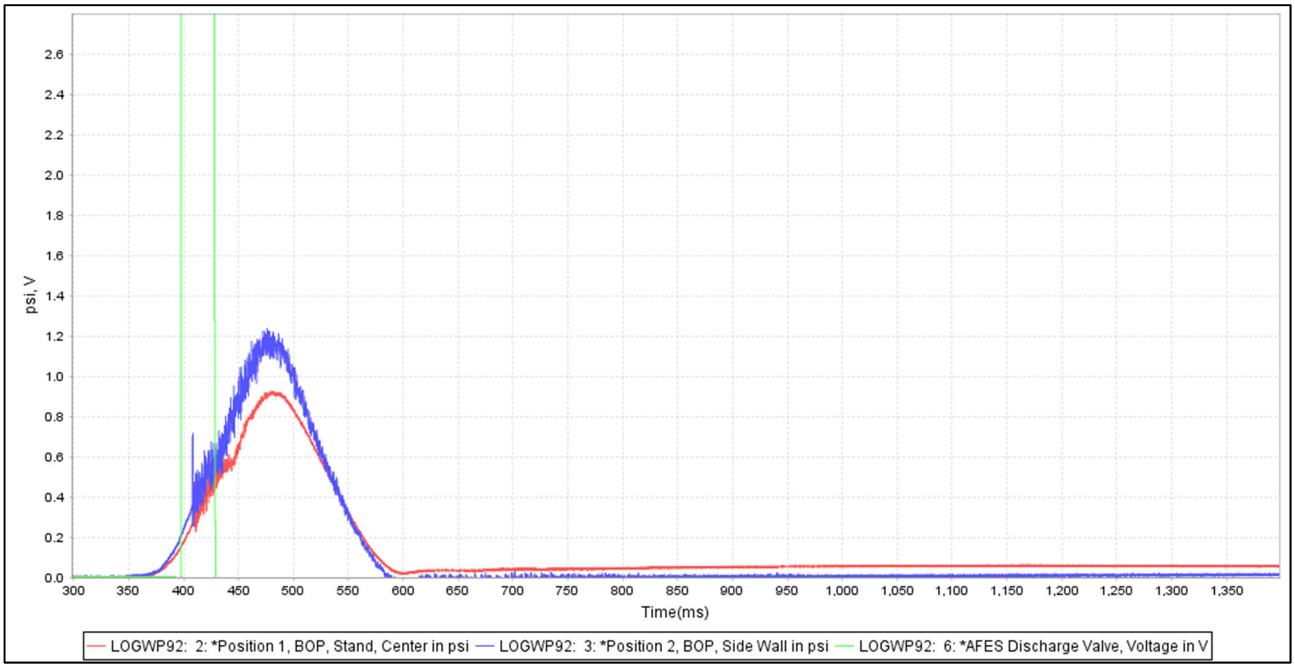
Test 90:



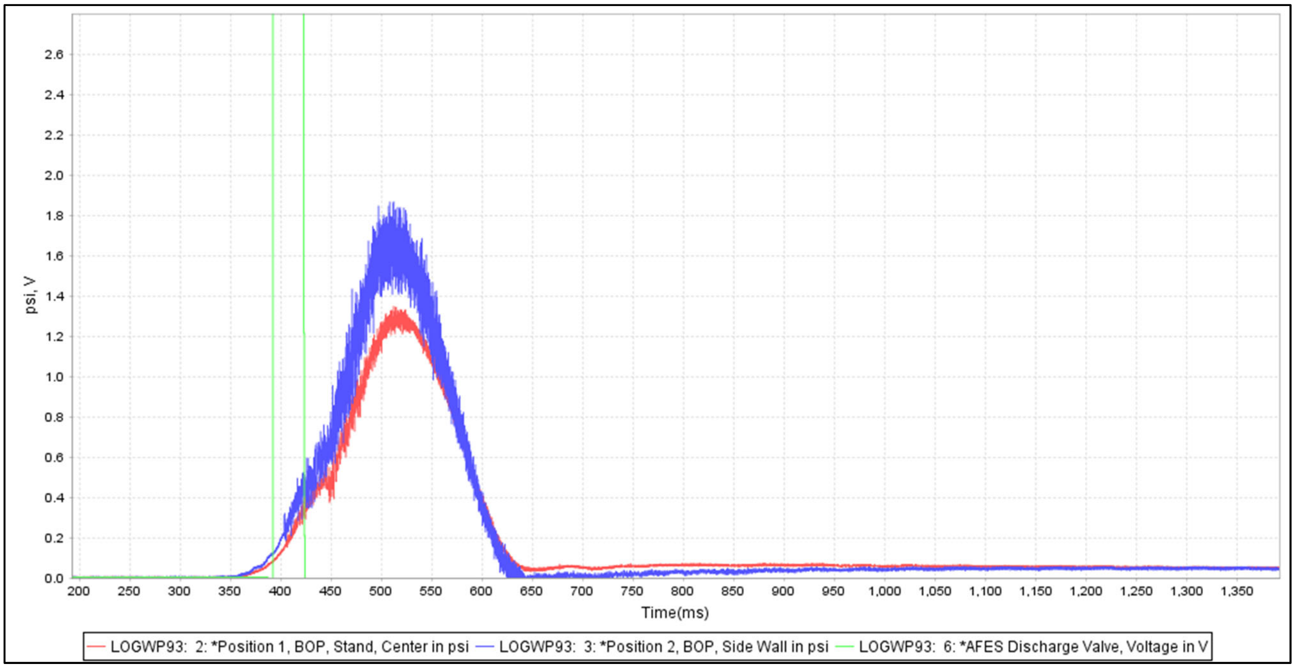
Test 91: Time scale adjusted to fit reflash pressure rise.



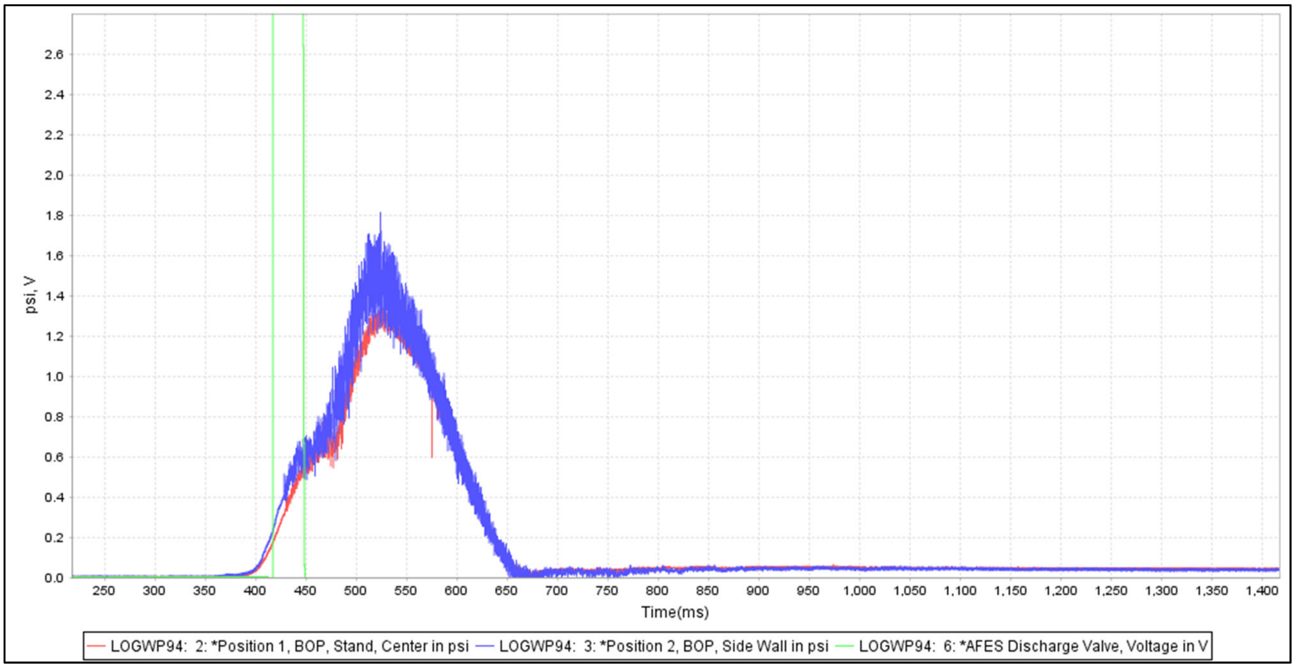
Test 92:



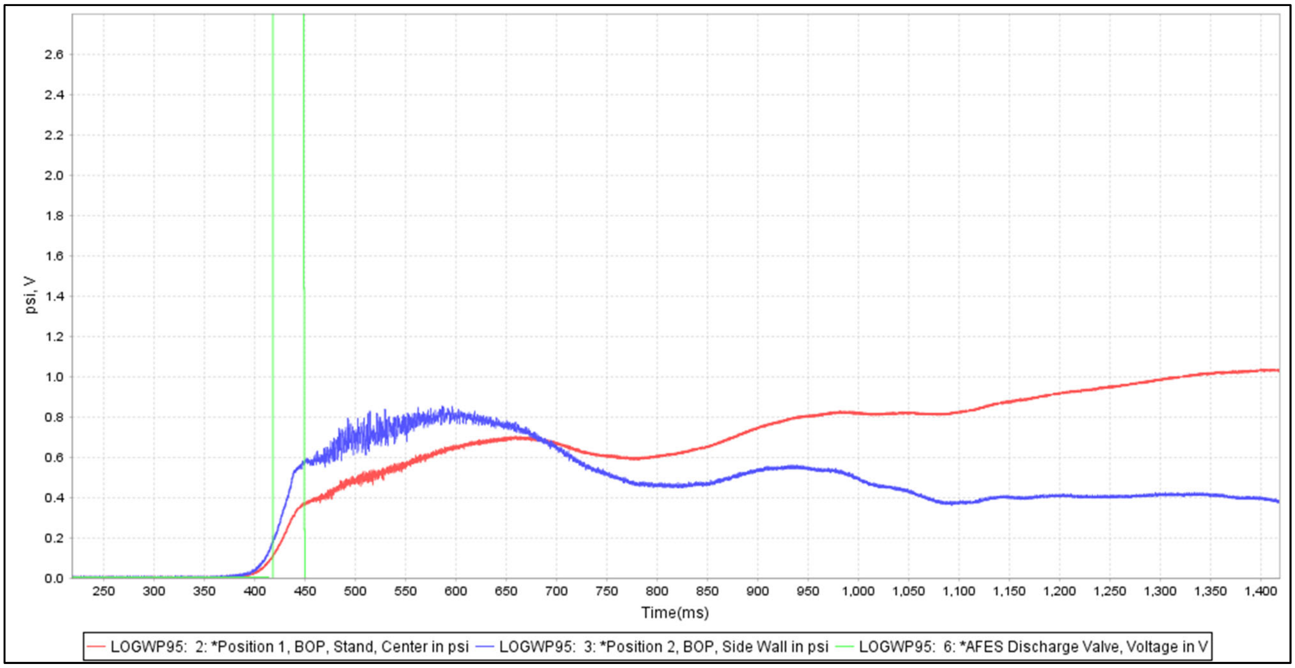
Test 93:



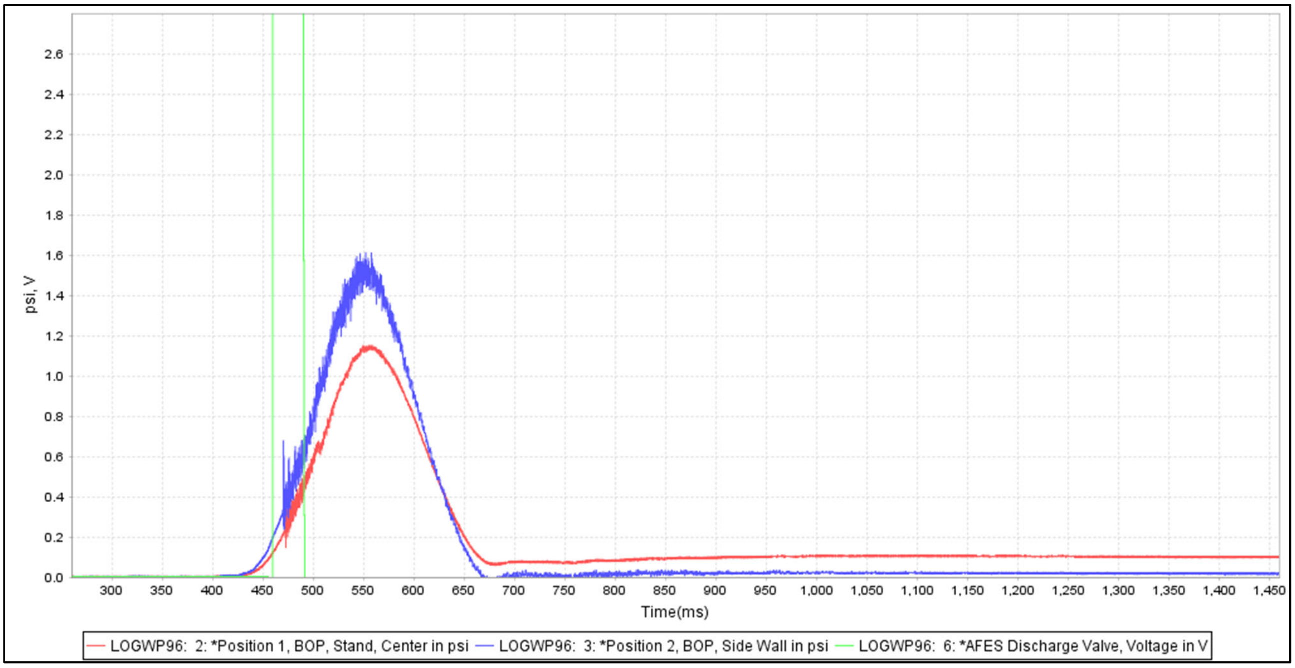
Test 94:



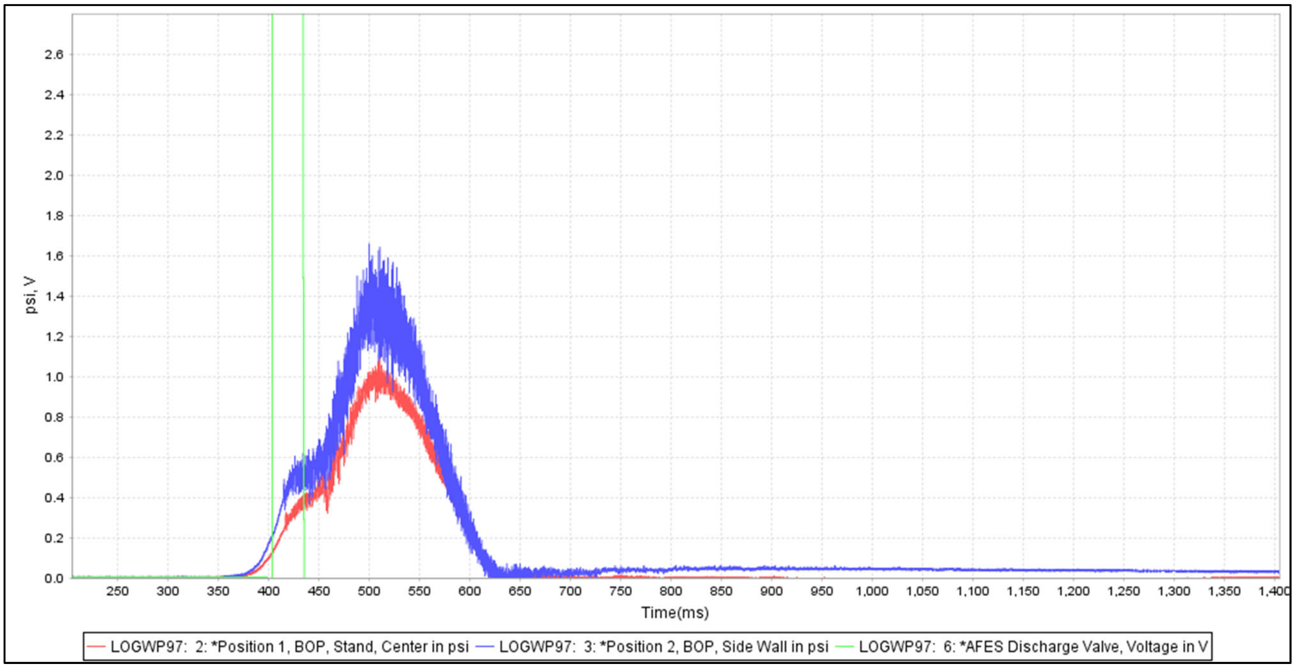
Test 95:



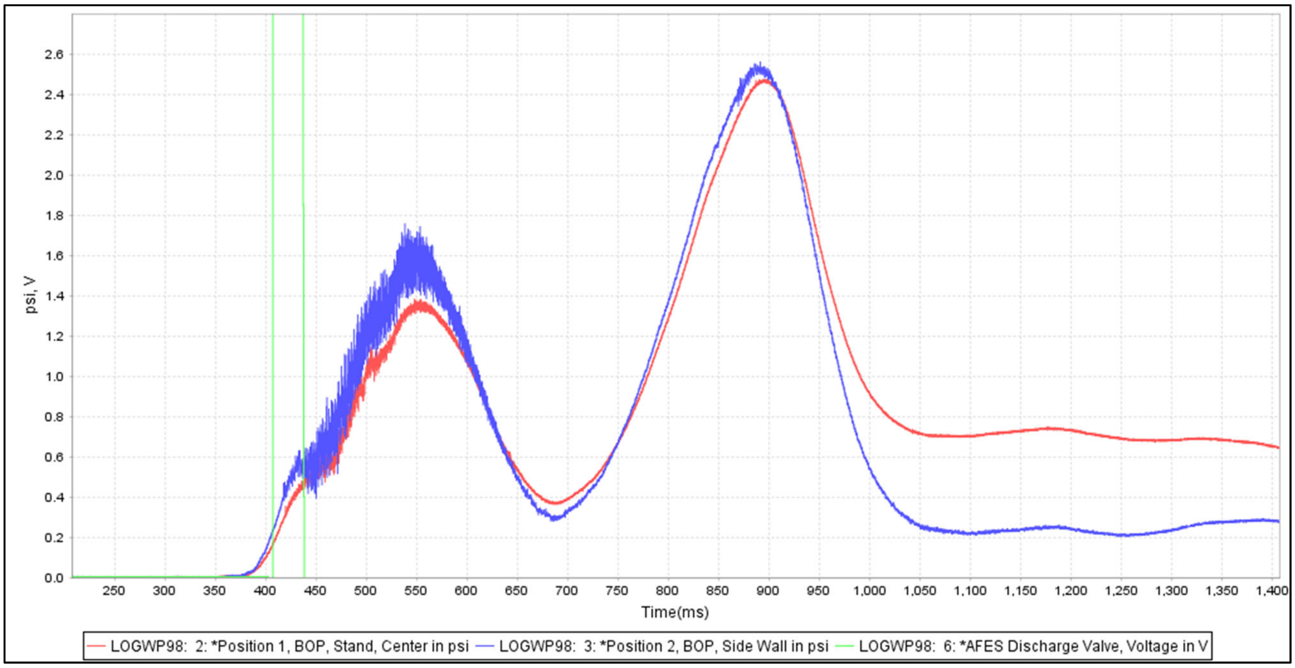
Test 96:



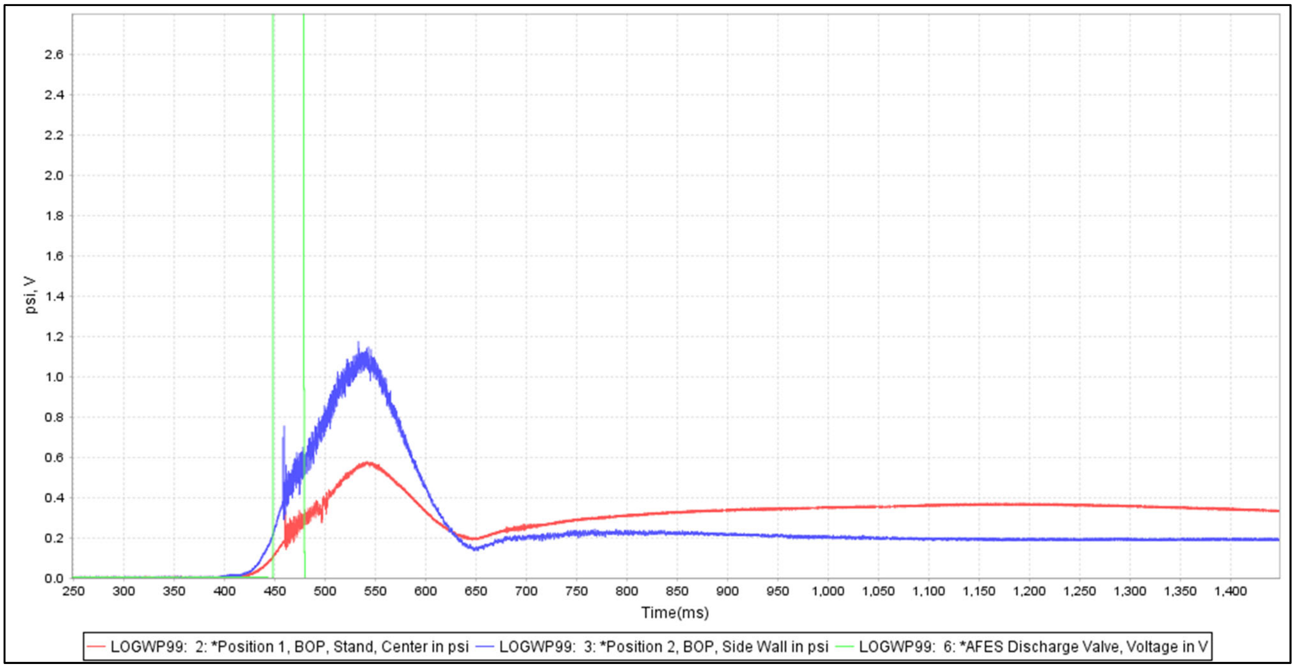
Test 97:



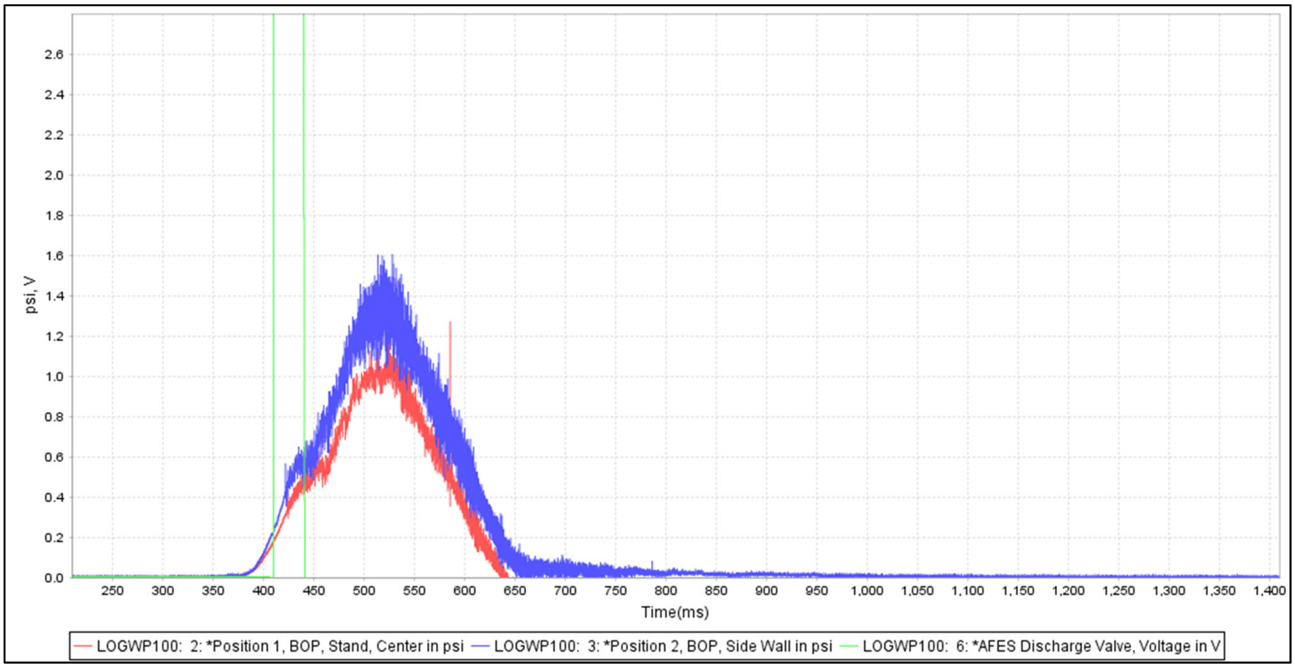
Test 98:



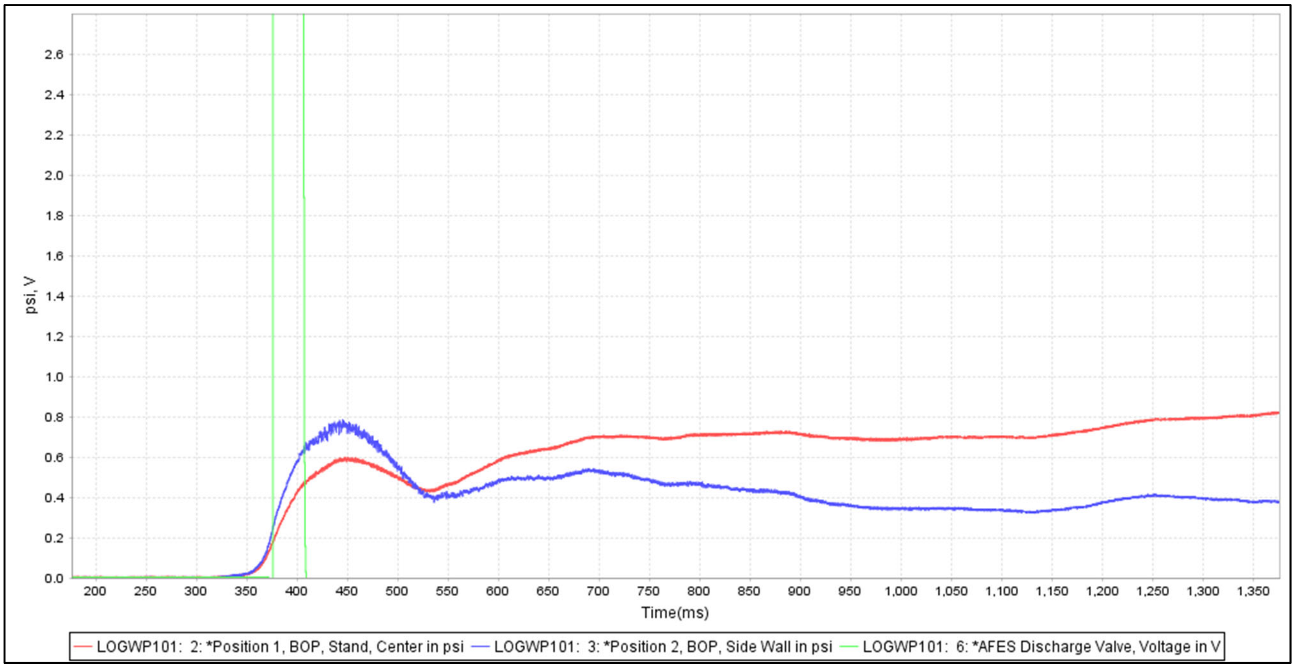
Test 99:



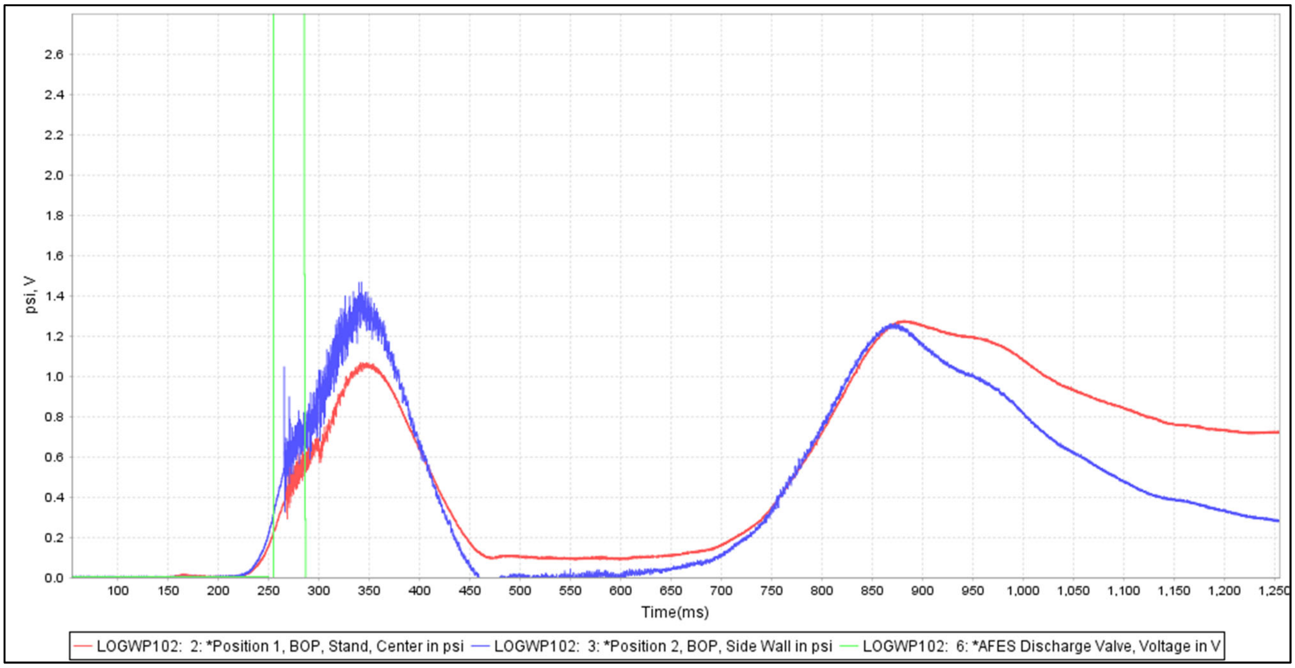
Test 100:



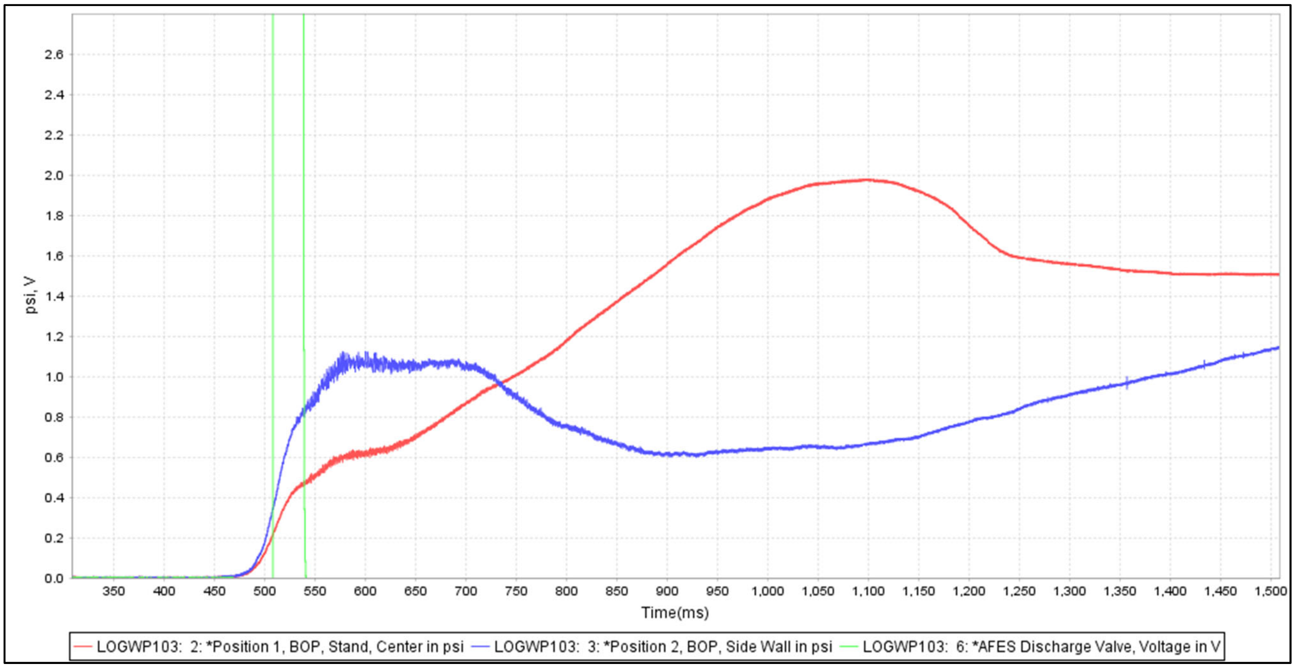
Test 101:



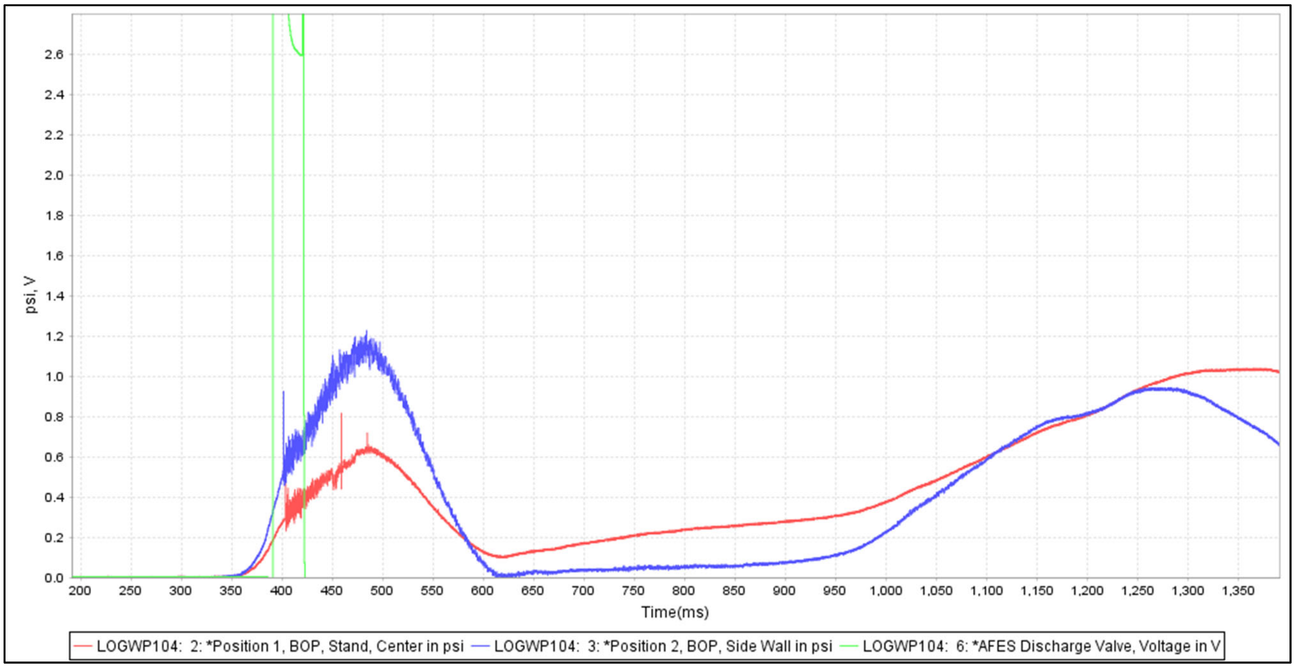
Test 102:



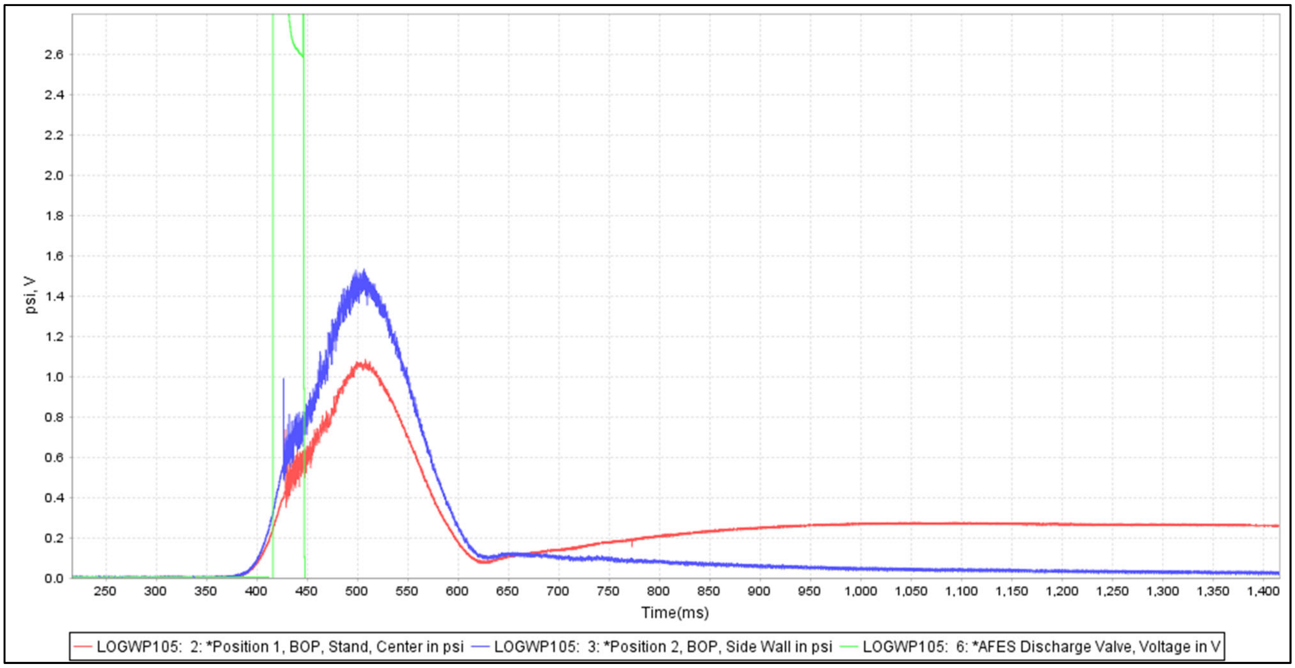
Test 103:



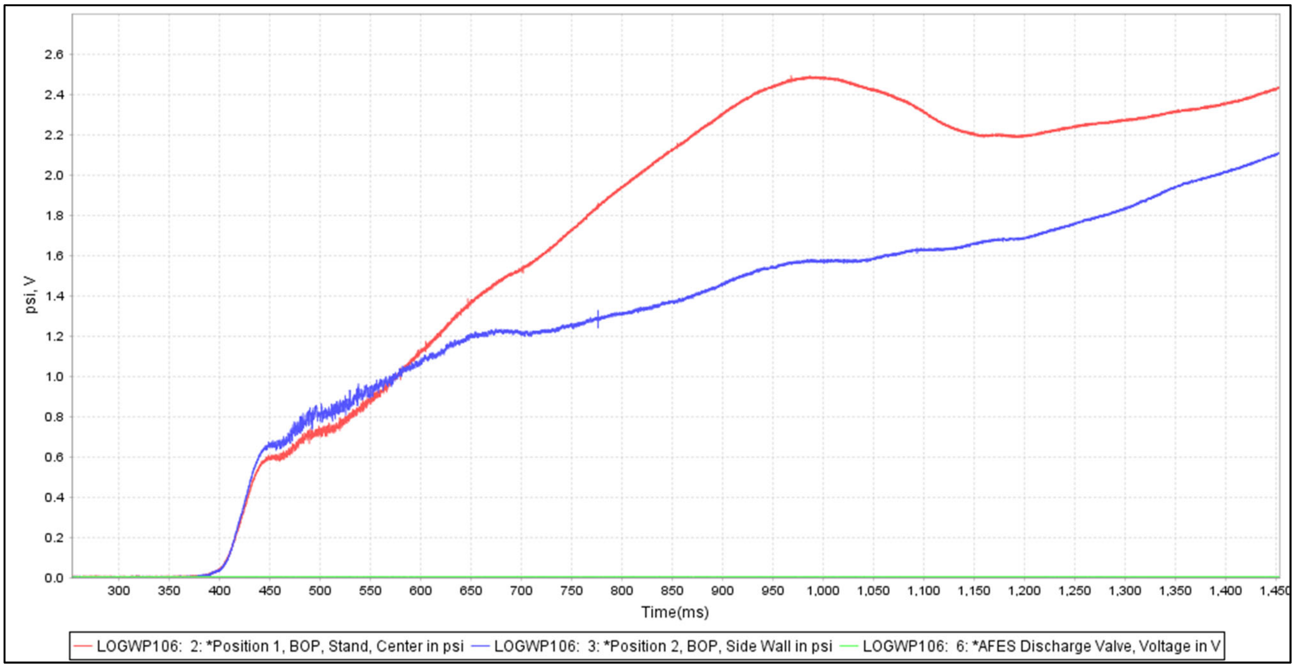
Test 104:



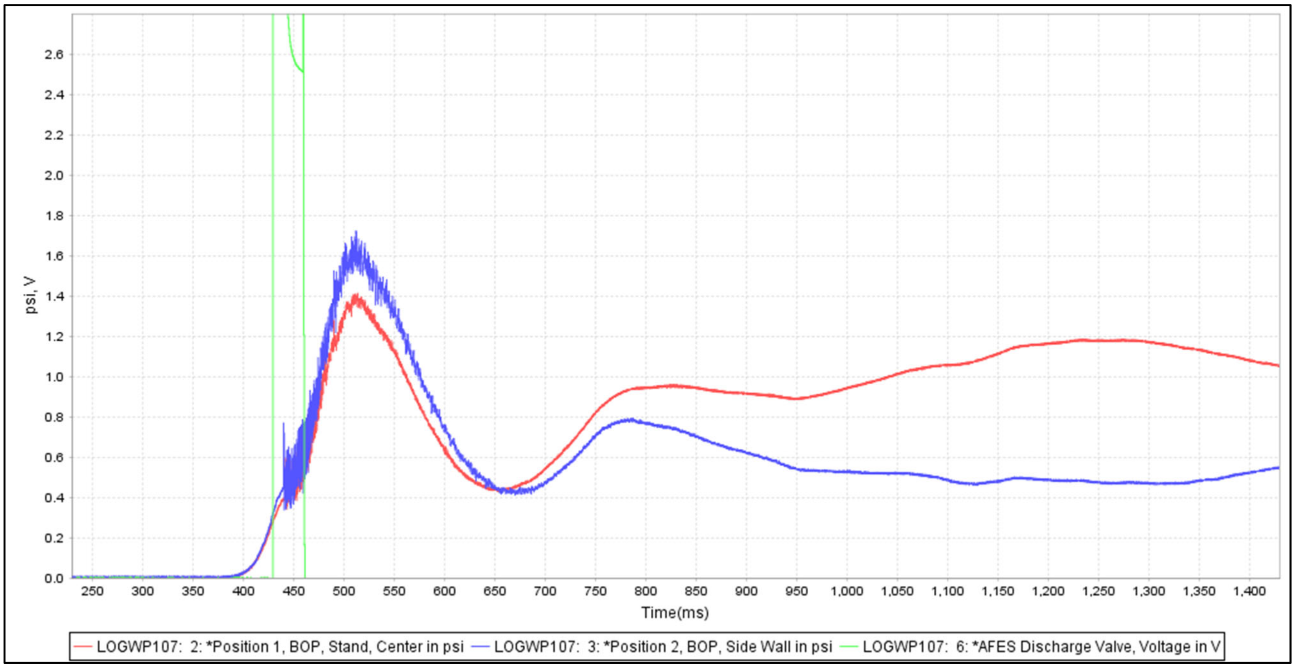
Test 105:



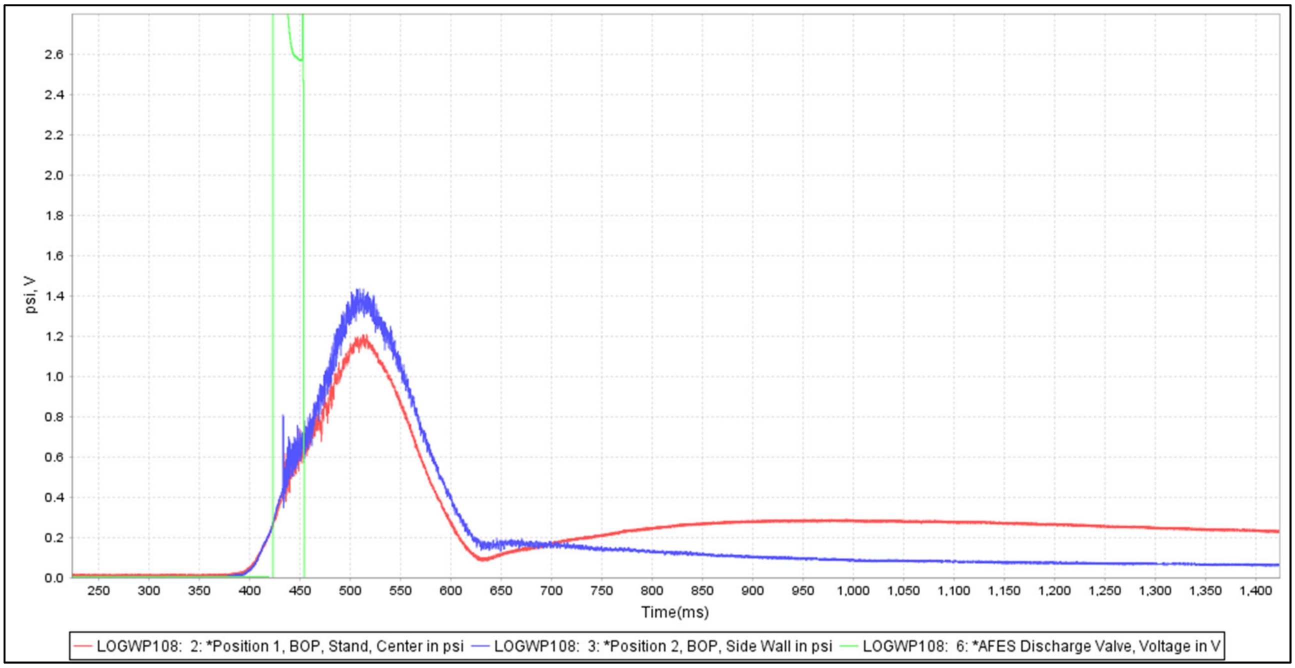
Test 106:



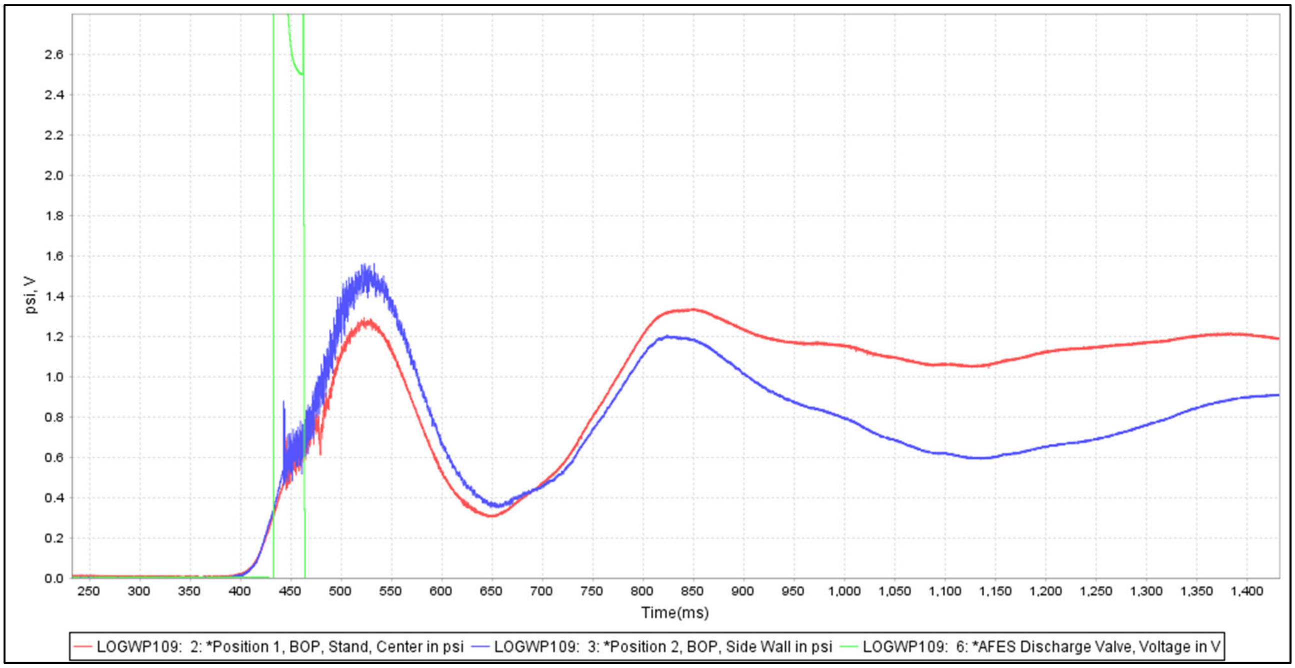
Test 107:



Test 108:

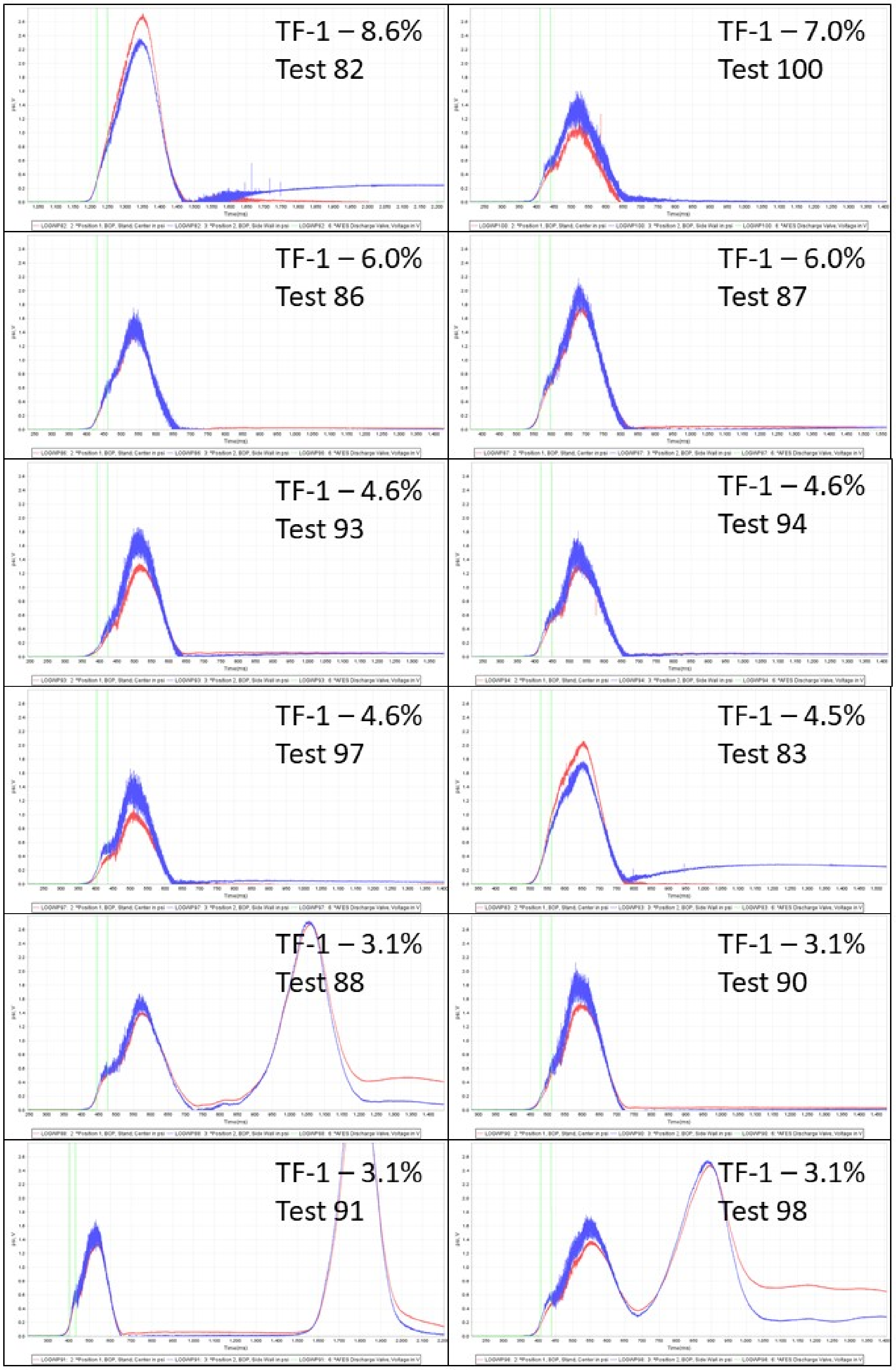


Test 109:

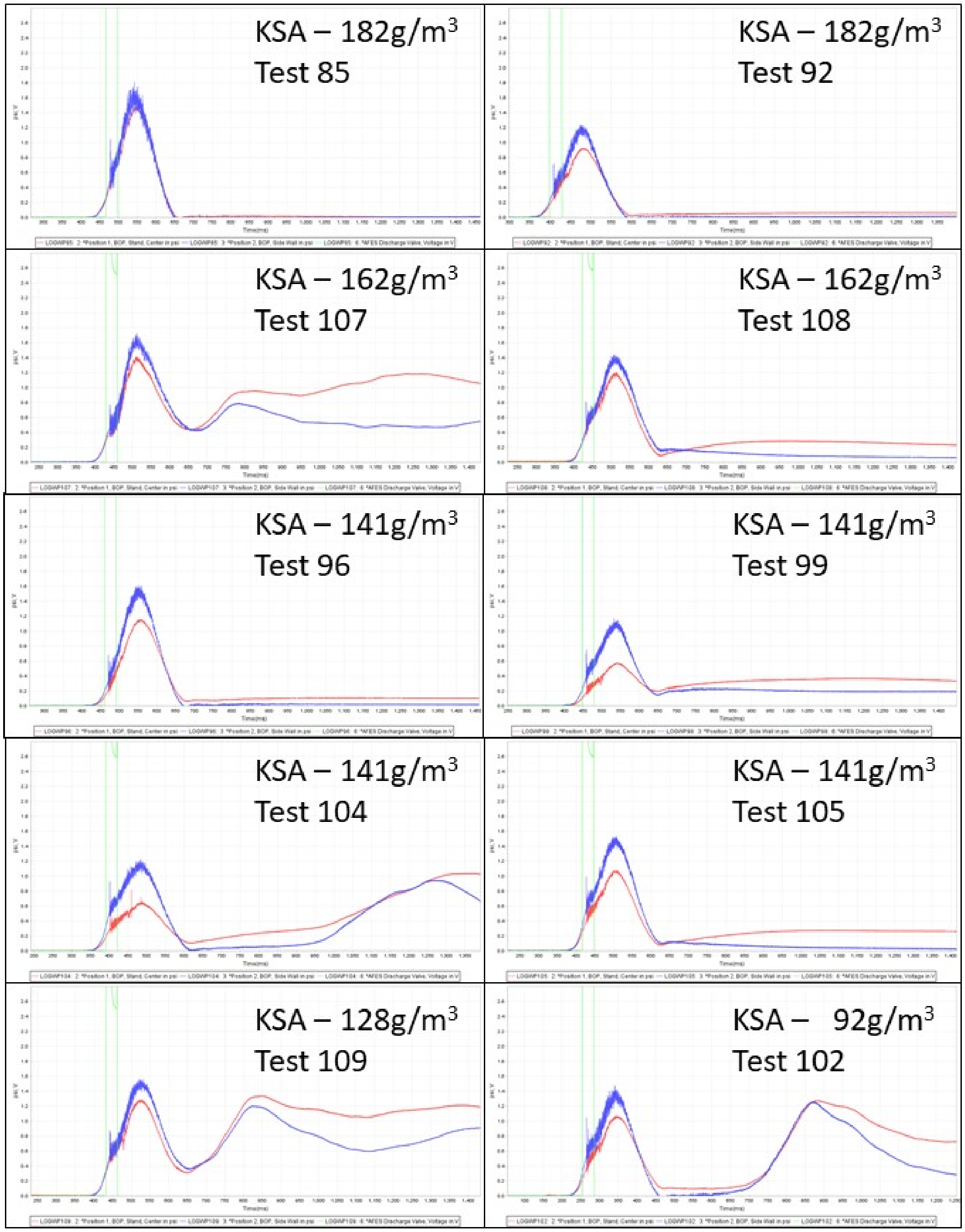


The following summary diagrams are a compilation of all pressure vs time charts, grouped together by test type (TF-1 + KSA, KSA only, and FBG warm-up / calibration). The TF-1 + KSA summary is shown descending by concentration (%), the KSA only summary is shown descending by concentration (g/m^3), and the FBG warm-up / calibration summary is shown ascending by test number. These diagrams were used to analyze the pressure vs time charts for abnormalities, as well as trends related to minimum successful concentration.

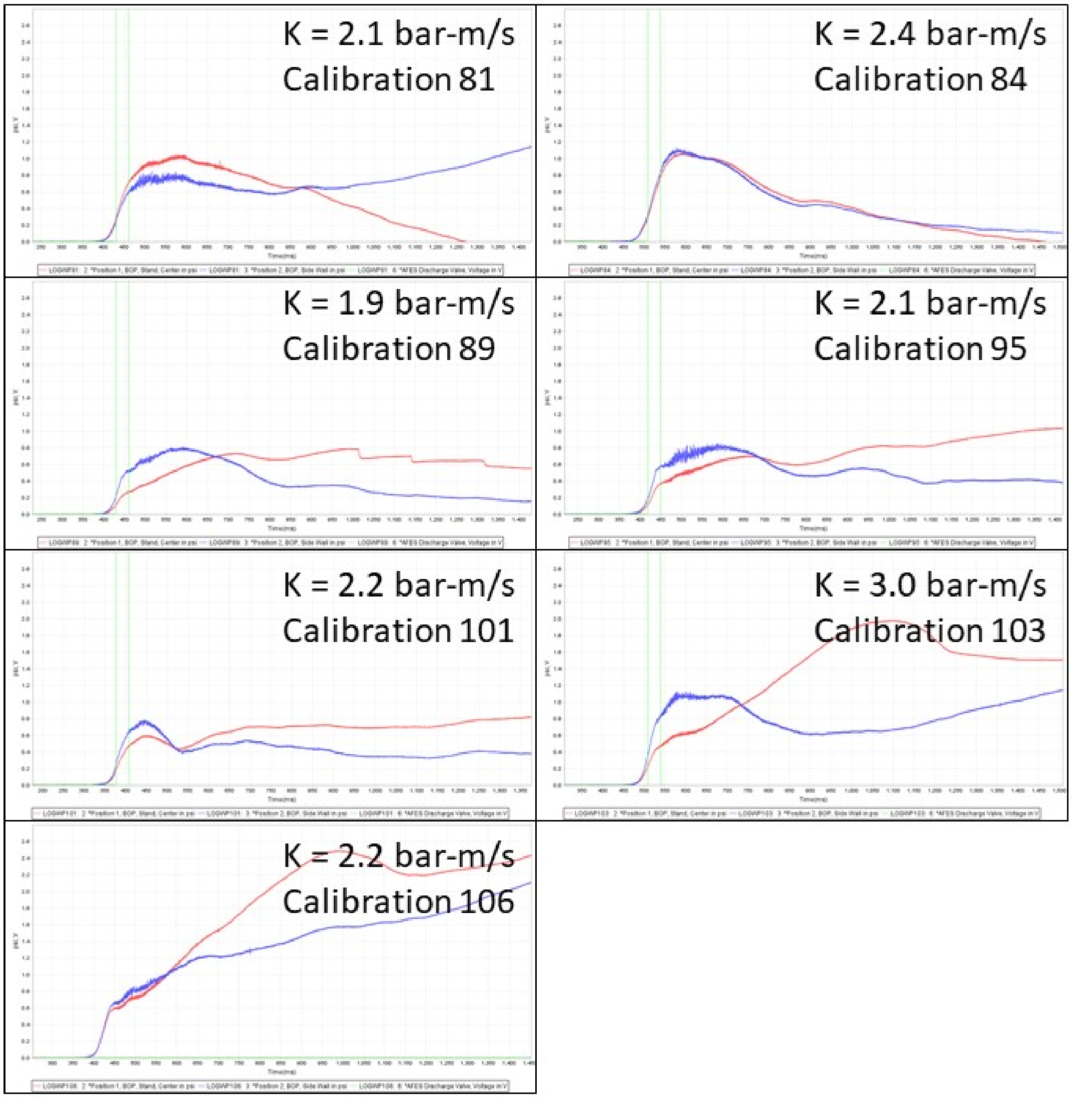
TF-1 Summary:


TF-1 – 8.6%
Test 82
TF-1 – 7.0%
Test 100
TF-1 – 6.0%
Test 86
TF-1 – 6.0%
Test 87
TF-1 – 4.6%
Test 93
TF-1 – 4.6%
Test 94
TF-1 – 4.6%
Test 97
TF-1 – 4.5%
Test 83
TF-1 – 3.1%
Test 88
TF-1 – 3.1%
Test 90
TF-1 – 3.1%
Test 91
TF-1 – 3.1%
Test 98

KSA-Summary:

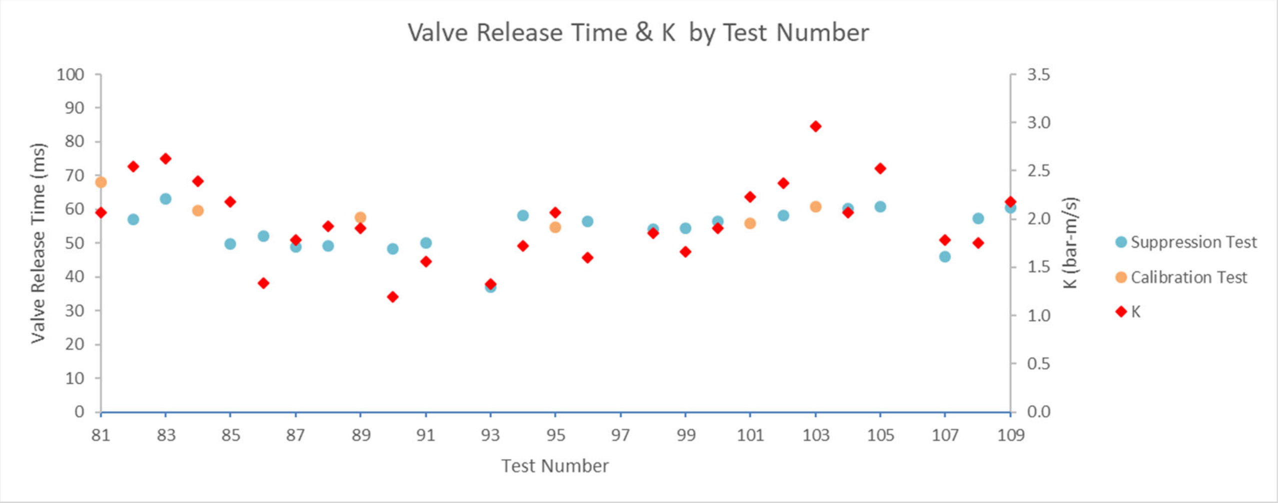

KSA – 182g/m^3
Test 85
KSA – 182g/m^3
Test 92
KSA – 162g/m^3
Test 107
KSA – 162g/m^3
Test 108
KSA – 141g/m^3
Test 96
KSA – 141g/m^3
Test 99
KSA – 141g/m^3
Test 104
KSA – 141g/m^3
Test 105
KSA – 128g/m^3
Test 109
KSA – 92g/m^3
Test 102

FBG Warm-up / Calibration Summary:



Appendix F. Sensor Response Time and K Summary

The following chart shows the AFES sensor response time and fire intensity (K) for each test. The variation gives a qualitative indication of the stability of the test conditions.



Appendix G. List of Acronyms, Abbreviations, and Initialisms

AFES	Automatic Fire Extinguishing Systems
APHC	Army Public Health Center
APU	Auxiliary Power Unit
ATC	Aberdeen Test Center
BOP	Blast Overpressure
CCDC	Combat Capabilities Development Command
CEM	Continuous Emission Monitoring
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COF_2	Carbonyl Fluoride
DEVCOM	Development Command
DOD	Department of Defense
FBG	Fireball Generator
FOUO	For Official Use Only
FTIR	Fourier Transform Infrared
GVSC	Ground Vehicle Systems Center
GWP	Global Warming Potential
HBr	Hydrogen Bromide
HCN	Hydrogen Cyanide
HF	Hydrogen Fluoride
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
IR	Infrared
LOAEL	Lowest Observed Adverse Effect Level
MDC	Minimum Design Concentration
NFPA	National Fire Protection Association
NONSHAT	Non-Shatterable Cylinders
NOx	Oxides of Nitrogen
SAFR	Safer Alternatives for Readiness
TARDEC	Tank-Automotive Research, Development and Engineering Center

Appendix H. References

[1] D. Kogut, “Final Report for the Fire Extinguishing Performance Test of the Low Global Warming Potential (GWP) Agents,” U.S. Army Aberdeen Test Center, Aberdeen, MD, USA, Jun 2019.

[2] United Nations Environment Programme, Montreal Protocol on Substances that Deplete the Ozone Layer — Final Act 1987, UNEP/RONA, Room DCZ-0803, United Nations, New York, NY, 10017.

[3] C. Newberg. “Update on Kigali Amendment to the Montreal Protocol.” EPA.gov. https://www.epa.gov/sites/production/files/2016-11/documents/newberg_kigaliamend_122016.pdf (accessed Nov. 30, 2020).

[4] Ripple, Gary and Mundie, Thomas, “Medical Evaluation of Nonfragment Injury Effects in Armored Vehicle Live Fire Tests,” Walter Reed Army Institute of Research, September 1989.

[5] S.E. Hodges and S. J. McCormick, “Fire Extinguishing Agents for Protection of Occupied Spaces in Military Ground Vehicles,” U.S. Army Tank-Automotive Research, Development and Engineering Center (TARDEC), Warren, MI, USA, 2010.

[6] “NFPA 2001 Standard on Halon 1301 Fire Extinguishing Systems 2018 Edition,” National Fire Protection Association (NFPA), Quincy, MA, 2018.

[7] “NFPA 2001 Standard on Clean Agent Fire Extinguishing Systems 2018 Edition,” National Fire Protection Association (NFPA), Quincy, MA, 2018.

[8] M. Robin, private communication, Jan 2020.

[9] M. Robin, private communication, May 2020.

[10] “UTAS-SAS-FPS Kidde KSA^{TM},” unpublished.

[11] D. Kogut, “Testing of Low GWP Agents,” Aberdeen Proving Ground, 2020.

[12] J. Porterfield, private communication, Sep 2020

[13] “Revised Toxicological Assessment of Sodium Bicarbonate Based Dry Powder Agents in Armored Vehicle Automatic Fire Extinguishing Systems,” official memorandum, Department of the Army - US Army Institute of Public Health, Aberdeen Proving Ground, MD, USA, Mar 2015.