Towards Environmentally Sustainable, High Performance Ammunition

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ABSTRACT

Ranges and training area (RTAs) are a key aspect to the training of military forces around the world. However, the use of ammunitions was shown to lead to the dispersion of Energetic Materials (EM) residues in RTAs. The use of sustainable ammunitions constitute a promising mitigation process by solving the issue directly at the source, thus reducing the unexploded ordnances production, the need for expensive RTAs cleaning or remediating as well as the necessity to develop site-specific range attenuation designs. A cost benefit analysis indicated that it is cost-effective to consider the long-term effects of the munitions on the environment right at the beginning of the weapon system development cycle.

Canada has initiated the development of environmentally sustainable ammunition in 2008 with a project aiming to prove that the environmental pressure on RTAs can be decreased and the health hazards for the users be minimized without reducing the ammunition performance. This was accomplished by performing significant improvements to a 105-mm army artillery munition (HE M1) currently using a M1 single-base propellant and Composition B as the main charge explosive. A near-zero dud rate was achieved by developing a self-destruct device for the fuse system. The potential of RDX contamination was eliminated by replacing Composition B with a melt-cast recyclable formulation made of an energetic thermoplastic elastomer, TNT and HMX, which meets the current performance criteria of in-use munitions, has better IM properties than Composition B and can be processed with conventional melt-cast equipment. The use of toxic and carcinogenic compounds in the propellant formulation was avoided by replacing the M1 propellant charges with a modular HMX-based formulation greener than M1, which is suitable for extended range applications and has better IM properties than current propellant formulations. A matrix of criteria was built to help select the appropriate candidates. The main selection criteria considered were the environmental and IM properties, the technical feasibility, the life cycle cost and the performance. The project was completed with a gun-firing demonstration.

The aim of this communication is to provide an overview of the project and to describe the properties of the chosen propellant and explosive formulations. This will help sustain military training while preserving our resources, as well as shaping the future of weapon system development.

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1. INTRODUCTION

Ranges and training area (RTAs) are a key aspect for the military forces around the world. However, the use of ammunition was shown to lead to the dispersion of Energetic Materials (EM) residues both in impact areas and at firing positions (Walsh *et al*, 2011 and 2013a, and references therein). Normally functioning munitions only spread a small amount of energetic residues in the environment. Most of the contamination in impact areas comes from unexploded ordnances (UXOs) that are cracked open by the detonation of an incoming round, by incomplete (low-order) detonations, by the destruction of duds and insensitive munitions (IM) and by the corrosion of UXOs. In fact, a single round which detonates incompletely (low order) spreads as much unburned explosives as 10,000 to 100,000 high-order rounds. In addition, UXOs pose safety problems for the troops, both in domestic training and in operations, and have to be removed from RTAs with a regular surface clearance. Unexploded or deflagrated RDX does not degrade in soil and, because of its solubility in water, migrates easily to groundwater and off military property. This may trigger a serious environmental problem and becomes a public health concern if the groundwater is used for drinking. Another health hazard arises from the incomplete combustion of gun propellant and from burning of excess gun propellant bags at firing positions. Propellants contain significant amounts of carcinogenic and toxic components, recently forbidden in Europe (EU, REACH), which could have a health impact on soldiers. Many RTAs firing points were contaminated with concentrations of energetic residues above the preliminary guidelines, sometimes by many orders of magnitude. This is an important issue because military personnel have to train to keep their state of readiness. Therefore protecting sensitive receptors of the fauna, flora and human populations by preventing contamination and hazards is essential to keep RTAs operational.

Range remediation and mitigation have been found beneficial to avoid unnecessary dispersion of EM outside range boundaries. Sustainable ammunitions constitute a promising mitigation process by solving the issue directly at the source, thus reducing the unexploded ordnances production, the need for expensive RTAs cleaning or remediating as well as the necessity to develop site-specific range attenuation designs. Canada initiated a Technology Demonstration Program (TDP) in 2008, aiming to prove that green and insensitive munitions (IM) will decrease the environmental pressure on RTAs and minimize the health hazards for the users without decreasing the performance of the munition. This five-year project, entitled Revolutionary Insensitive, Green and Healthier Training Technology with Reduced Adverse Contamination (RIGHTTRAC) was mainly funded by Director General Environment (DGE) of Canada's Department of National Defence (DND), led by Defence Research and Development Canada (DRDC), and performed with the collaboration of General Dynamics – Ordnance and Tactical Systems (GD-OTS) Canada, the *Institute national de la recherche scientifique – Centre eau, terre environnement* (INRS-ETE), the National Research Council (NRC) and the *Centre de recherche industriellle du Québec* (CRIQ). The goals of this TDP were to reach a near-zero dud rate and eliminate the potential for RDX contamination as well as the use of toxic and carcinogenic compounds. This was done by performing significant improvements to the fuzing system, the main explosive charge and the gun propellant. Once demonstrated, the technologies developed during this project are expected to be easily transferable to other types of medium and large calibres for the energetic formulations, and to other types of large calibre ammunition for fuzes.

A cost-efficiency analysis (CEA) was used to estimate the sustainable munitions' incremental economic costs, based on cost differences between green and conventional munitions (Sokri, 2011). This methodology was preferred to a full cost-benefit analysis because the feasibility of measuring all of the project's benefits (e.g., the value of training) was deemed low. In collaboration with subject matter experts, relevant cost categories were identified during the whole life-cycle of the munition, from its manufacture to its disposal either by live-fire or by demilitarization. Obtaining all the necessary data proved to be a huge challenge, because the information was often missing, partial, or very complex. For example, the RTA maintenance scenario may be as simple as performing a surface clearance to avoid UXOs, and cutting the bushes on a flat area, or as complex as performing an in-depth clearance, discarding the UXOs by blow-in-place, and cutting trees in a wooded steep area. Despite intensive research efforts, it was not achievable to obtain data for some cost categories. Therefore, simulated data obtained from a hypothetical training installation and a realistic baseline scenario were used for liability, remediation of impact areas, munitions conception, unit manufacturing cost, demilitarization and initial investment (e.g., PBX plant).

Results demonstrated that, on a 10-year basis, mean potential savings of several millions of dollars per artillery range could be reached by using sustainable ammunition in artillery impact areas. The status quo would thus be more expensive due to environmental hazard.

The aim of this communication is to provide an overview of the project and to describe the performance, IM and environmental properties of the chosen propellant and explosive formulations. A description of the selection criteria used to choose the final propellant and explosive formulations is also provided. Modifications to the fuzing system and the recycling process have already been previously reported (Brochu *et al*, 2011, 2014) and will not be further described in this communication.

2. RIGHTTRAC

As shown in Figure 1, the vehicle used for this demonstration was a 105-mm army artillery munition (HE M1), currently filled with Comp B and using a single base gun propellant (M1) formulation. The project tackled the three main components: the fuze, to add an independent self-destruct capacity to existing fuzes in order to significantly reduce or eliminate the UXOs; the gun propellant, to replace toxic or carcinogenic ingredients, to improve the IM characteristics of the propellant and to explore the concept of modular charges; and the explosives to replace the RDX in the main charge and to obtain an IM formulation. IM was a safety prerequisite, and a requirement to comply with international agreements. The development work on the fuze, main explosive charge and gun propellant ran concurrently during the first two years. Two explosives and six gun propellants candidates were evaluated by performing material characterization, sub-scale IM testing, and sub-calibre ballistic assessment. Work was also planned for the booster and primer, to ensure that both would effectively ignite the IM explosive/propellant charge (Brochu *et al*, 2011, 2014).

The final selection of an explosive and a propellant formulation was performed in fall 2011. A Green Insensitive (GIM) explosive, melt-cast, RDX-free formulation that was chosen to replace Composition B (Comp B) met the current performance criteria of in-use munitions, had a lower vulnerability than Comp B and was recyclable. Likewise, toxic components in the gun propellants (e.g., nitroglycerin, 2,4- and 2,6-dinitrotoluene, phthalates derivatives and diphenylamine) were replaced by more environmentally friendly products that resulted in a HMX-based Low Vulnerability (L320) recyclable formulation characterized by better Insensitive Munition (IM) properties than the current M1. Moreover, the charges were conceived as modular increments to avoid burning excess propellant artillery that would have resulted in significant contamination. Substantial enhancements were also planned for the

C32A1 Multi-Option Fuze for Artillery (MOFA), currently in use by the Canadian Armed Forces (CAF), in which a self-destruct device (SDD) was to be added. The SDD was planned as an independent fuze that would initiate the detonation in case of malfunction of the primary fuze, which can happen due to operator handling, impact on soft ground or age-related failures.

The technologies developed during this project are expected to be easily transferable to other types of medium and large calibres for the energetic formulations, and to other types of large calibre ammunition for fuzes.

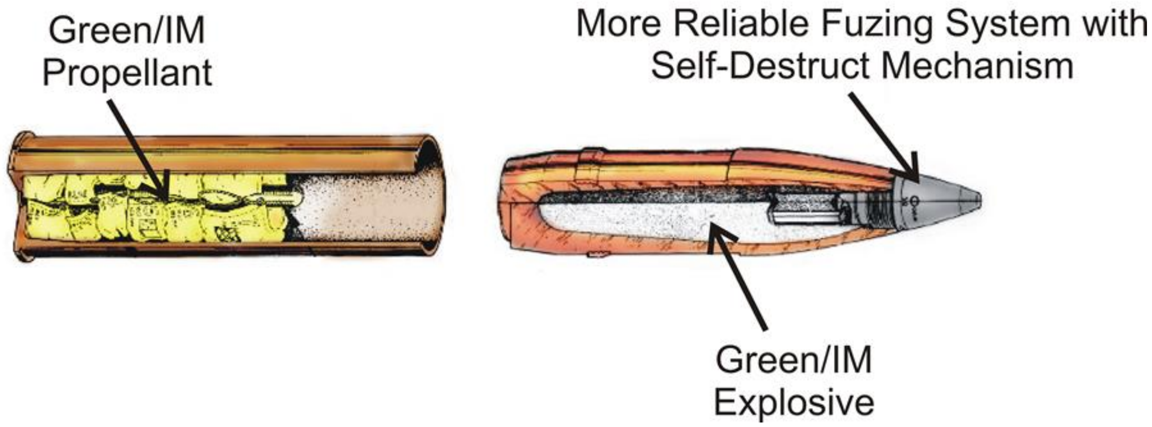

Figure 1: RIGHTTRAC concept

3. Results

3.1 Explosive Formulation

GIM, the selected candidate that was developed and patented by DRDC, is a melt-cast formulation made of TNT, HMX and an Energetic Thermoplastic Elastomer (ETPE) (Ampleman *et al*, 2002, 2003; Ampleman, 2011). Because of the existing large industrial base for the processing of melt-cast formulations, those are more common in North America than cast-cured formulations. Early in the project, the conformity of GIM to the performance prerequisite was verified using detonation pressures and velocities, as well as plate dent tests (Brousseau *et al*, 2010). As indicated in Table 2, the performance GIM was within 5% of Comp B's. GIM was thus judged qualified for further testing in RIGHTTRAC.

3.1.1 Performance – Gun Testing

The performance test and demonstration was conducted by GD-OTS Canada. The goals of this demonstration consisted in (1) testing the velocity uniformity by firing ten 105-mm M1 cartridges filled with High-Explosive Simulator (HES) and ten additional cartridges filled with GIM (XC179); and (2) testing the functionality of the GIM explosive by firing five XC179 cartridges. As the self-destruct device was not available for this demonstration, the GIM was tested with the current C32A1 fuze. Figure 2 shows the instrumented LG1 MKII

105 mm Howitzer employed by the CAF for direct and indirect fire that was used for the demonstration.

The velocity of the projectile was measured with an Infinition Radar using microwaves to track the projectile. The pressures were measured with piezo electric tranducer Kistler 6215 fitted with a 10 kHz filter. Results indicate that the velocity and pressure were as expected, and similar to that of current 105-mm M1 cartridges. In addition, as shown in Figure 3, all XC179 projectiles were successfully ignited by the C32A1 fuse.

Fragmentation testing was also conducted to determine the number and weight distribution, as well as the velocity and spatial distribution of fragments produced upon detonation. Results will be available soon.

Table 2. Performance of GIM Relative to Comp B.

Formulation	Density g/cm^3	Relative VoD % Comp B	Relative P % Comp B	Plate Dent % Comp B
GIM	1.67	97	94	96
Comp B	1.68	100	100	100

VoD: Velocity of Detonation; P: Pressure

Figure 2. Howitzer LG1 MkII Weapon

Figure 3. XC179 GIM explosion

3.1.2 Insensitive Munitions Testing (IM)

In preparation for the final selection of the explosive formulations, preliminary small- and full-scale IM tests were performed on GIM and Comp B, namely Shaped-Charge Jet (SCJ) attack, Bullet Impact (BI), Slow Cook-Off (SCO) and Sympathetic Reaction (SR) (Brousseau *et al*, 2010b). The goal of these IM tests was to compare the candidate energetic formulations to the reference formulations M1, and to discriminate between the candidates. Results are summarized in Table 3 for GIM and Comp B.

The reaction of GIM to BI was much better than Comp B's: GIM did not detonate upon bullet impact, but rather burned slowly, in contrast to Comp B, which detonated. Both Comp B and GIM exploded (Type III) during the SR but nonetheless they passed the test. GIM performed as well as than Comp B for the SCJ test. This level of reaction was not surprising, considering the severity of the threat. To our best knowledge, it is extremely difficult to obtain a milder reaction to the 84-mm shaped charge jet test with the military energetic formulations commercially available. Lastly, GIM performed as well as Comp B in SCO and passed the test.

Table 3. IM Tests Results for GIM and Comp B.

Formulation	BI	SCJ	SR	SCO
Comp B	I or II	I	III	V
GIM	V	I	III	V

NR: No reaction; NA: Not available.
Red: fail; green: pass

3.1.3 Detonation Residues

GIM explosive residues produced during live-fire and blow-in-place (BIP) operations were assessed by detonating six GIM-filled 105-mm projectiles on ice blocks at DRDC Valcartier experimental test site and collecting the residues on snow. Results, provided in Table 4, were compared to those of Comp-B filled 105-mm.

Table 4. Detonation Residues of Live-fire and Blow-in-place of GIM- and Comp B-filled 105-mm Rounds.

	Live-Fire		BIP	
	Munition outcome (%)	Residue	Munition outcome (%)	Residue
Comp B[1]	0.000007	RDX	0.0003	RDX
GIM[2]	0.0003	HMX	0.1	HMX

[1]Hewitt *et al*, 2003; [2]Walsh *et al*, 2013a

As expected for IM munitions (Walsh *et al*, 2010, 2013b, 2013c, 2014), the detonation residues of GIM-filled rounds are one to two orders of magnitude higher than Comp B's. However, GIM-filled rounds performed extremely well compared to other commercially available IM formulations, such as IMX-104, PAX-48 and PAX-21, for which deposition rates were one to two orders of magnitude higher (Walsh *et al*, 2010, 2013b, 2013c, 2014).

The laboratory dripping water tests as well as outdoor weathering tests performed on the explosive formulations candidates before the final selection indicate that GIM was much more resistant to dissolution than Comp B (Hawari *et al*, 2009, 2011; Côté *et al*, 2011). Comp B completely dissolves in a few months on contact with dripping water, releasing RDX and TNT. Under the same conditions, GIM did not fully dissolved in one year; it is not even expected to dissolve completely, as suggested by the dissolution kinetics. TNT was released from both formulations. In addition, HMX was released from GIM, and RDX from CX-85.

HMX is known to have a low toxicity (Sunahara *et al*, 2009) as well as a fairly low solubility in water (6 mg/L), almost one order of magnitude below that of RDX (40 to 60 mg/L) and TNT (130 mg/L). The toxicity of TNT is known to be below that of RDX, albeit above that of HMX. However, TNT decomposes rapidly to amino derivatives that bind to the organic material of the top soil. As a result, both HMX and TNT generally do not migrate into the groundwater. Their transport in sand was governed solely by dissolution, while both dissolution and sorption were observed in a more organic soil. TNT and HMX are considered environmentally friendly because of their low bioavailability and/or low toxicity. The K_{ow} data indicate that both HMX and TNT can potentially bioaccumulate in terrestrial and aquatic organisms.

An ecotoxicological assessment was built on each formulation under study by conducting terrestrial, aquatic, and benthic ecotoxicity assays (Refs 48-55). Three tests were included in the terrestrial ecotoxicity assays: ryegrass seedling emergence and growth inhibition, earthworm lethality, and earthworm avoidance behaviour. For the explosive formulations, the benthic assays were performed using amended artificial sediments and included four tests: mussel lethality and sub-lethal immunologic assays, as well as amphipod crustacean Hyallelaazteca lethality and growth inhibition tests. Microtox assays, as well as growth inhibition of algae and duckweed were also performed for aquatic receptors. Results reported in Table 6 indicate that GIM is as toxic as Comp B. The toxicity seems related to the concentrations of bioavailable TNT (Hawari *et al*, 2009, 2011).

3.2 Main Propellant Charge

The propellant charge of a 105-mm artillery munition is currently made of seven different types of bags, each containing a different charge weight and some using lead as a de-coppering agent. In addition, the shape, size and web dimension of the formulation of the first bag is different than the one of the six other bags. The range of the munition is fine-tuned in the field by removing the appropriate number of bags from the cartridge. The excess propellant bags used to be burned on the ground immediately after artillery exercises, which produced a significant amount of toxic and carcinogenic contaminants.

The concept of modular charges evaluated within this project consists in building identical charge weights bags for the 105-mm cartridge, which would be incorporated in the 105-mm cartridge during the firing event. The range would then be fine-tuned using an appropriate number of bags. The net advantage of this concept is a significant reduction in excess propellant bags burning, which can be retained for a future use. Similar modular charges already exist for the 155-mm artillery munition (M777), and are under study for the 105-mm calibre, albeit with the M1 propellant.

To be considered in the project, propellant candidates had to meet the current performance criteria of current artillery 105-mm propellant (M1). In addition, the potential candidates had to be free of NG, 2,4-DNT, 2,6-DNT, phthalates derivatives and DPA. The mechanical and ballistic performance, environmental and IM properties of L320, the selected candidate, will be discussed here.

3.2.1 Performance

3.2.1.1. Small-Scale Testing

The conformity and L320 to the performance prerequisite was verified using formulation ballistic properties (quickness, force and linear burning rate) (Richer, 2013). The performance of a propellant is measured by its burning rate as well as its quickness, which is defined in STANAG 4115 as the pressurisation rate, by its force, which corresponds to the maximum pressure applied at a specific loading charge, and by its vivacity, which is the ratio of quickness to force.

The quickness and force L320 are provided in Table 5 relative to that of M1-0.025. To find a suitable balance between pressure, burning rate, ignition delay and firing residues, several shape, size and web dimensions were tested (Petre *et al*, 2012). At the end of those tests, L320 was considered acceptable for an application in a 105-mm artillery munitions.

Table 5. Gun Propellant Performance at 21 ˚C and Mechanical Properties, Relative to Reference Formulation M1-0.025.

Formulation	Relative Young's Modulus %	Relative Quickness %	Relative Force %	Vivacity %
M1	100	100	100	100
L320	98	117	104	112

3.2.1.2 Gun Testing

The same instrumented LG1 MKII 105 mm Howitzer used for explosive testing was employed for this part of the demonstration. A total of 66 shots were fired by GD-OTS Canada to: 1) assess the best configuration; 2) optimize the low pressures zones; 3) verify the zones 1 and 7 characteristics; 4) the temperature sensitivity; 5) the uniformity; 6) the reduction or elimination of unburned residues at lower zones; and 7) test the modular charges concept.

The results clearly demonstrated that L320 was superior to the current propellant formulation and that modular charges could be very easily developed and implemented with the 105 mm munition.

3.2.2 IM Properties

As for explosive formulations, preliminary small- and full-scale IM tests were performed on propellant formulations to discriminate the candidates and compare them to M1, the reference formulation (Brousseau *et al*, 2010b). However, it has to be noted that BI, SCJ and SCO were performed on early batches of propellant formulations with a somewhat different composition than the final one, and that L320 is expected to better react than Modified L320 to IM testing, due to its composition. Results are summarized in Table 6.

Table 6. IM Tests Results for Modified L320 and M1.

Formulation	BI	SCJ	SCO
M1	V	II	IV-V
Modified L320	V	II	IV-V

NR: No reaction; NA: Not available.
Red: fail; green: pass

All formulations passed the BI test, but Modified L320 demonstrated a less violent reaction than M1. For the SCJ test, the gun propellants reacted similarly with a partial detonation (Type II). As for the IM explosive tests, this level of reaction was expected, considering the severity of the threat. No propellant formulations passed the SCO test: all the propellants candidates produced violent burning reactions similar to that of M1 at comparable temperatures (Type IV-V). The only exception was modified L320 that seems to be able to resist slightly higher temperatures.

3.2.3 Detonation Residues

The amount and distribution of unburned propellant residues produced by the firing of XC179 and M1 cartridges was evaluated by collecting the deposits in front of the gun using collection plates that were filled with water. High Performance Liquid Chromatography did not allow the detection of any residues, indicating that the deposition rate of XC179 was at least one to two orders of magnitude lower than that of M1 (0.08%).

As for explosive formulations, laboratory dripping water tests as well as outdoor weathering tests (Martel and Côté, 2009; Coté and Martel, 2010; Martel *et al*, 2010), were performed on the propellant formulations candidates before the final selection. M1 and L320 are very resistant to dissolution and were not expected to completely dissolve (Hawari *et al*, 2010, 2012). The order of dissolution seems to be related to the proportion of NC in the formulation, a higher NC content leading to a lower lixiviation. It was hypothesized that NC may swell in water and hence slow down the diffusion of the chemicals or act as potential adsorbent for the soluble components.

The ingredients leaching from the propellant formulations were DNT and DPA from M1, and HMX and a plasticiser from L320. As a matter of fact, up to 15% DNT and 1% DPA were released from M1 after 56 days of contact with water with dripping water, as compared with a little more than one third of the HMX content. The plasticiser is very soluble in water and tends to leach easily from the formulation.

The M1 reference propellant formulation was found to inhibit ryegrass and benthic amphipod growth. This formulation was expected to be toxic to earthworms because of 2,4-DNT. It was hypothesized that the low toxicity of 2,4-DNT to earthworms was due to its low bioavailability in the soil interstitial water, which can be explained by the presence of NC on which 2,4-DNT may be imbedded. L320 was not toxic to any of the receptors.

3.2.4 Combustion Residues

The particulate and gaseous residues were collected directly at the muzzle of the gun during a live firing event for M1 and L320 only. For M1 (Savard, 2009), the main combustion gases of the reference formulation were carbon monoxide (CO), carbon dioxide (CO_2), methane, ammoniac, sulphur dioxide and hydrogen sulphide. In addition, more than 100 Volatile Organic Compounds (VOC) were detected, most of them aromatic (benzene, toluene, etc); carbonyl sulphide, methyl isocyanade and ethane dinitrile were also detected in significant concentrations, as well as Semi-Volatile Organic Compounds (SVOC). In addition, particulate matter mainly composed of lead, potassium, sulphur, iron and copper, characterized by a mean particle size of 0.93 µm, were detected.

The combustion gases of L320 (Savard, 2014) were identical to those of M1, except for a slightly higher CO_2/CO ratio and smaller methane production. The firing of L320 also led to the production of less VOC and SVOC, although the main products were identical. The particulate matter was also identical in the two formulations, although the lead concentration was sensibly lower in L320.

3.0 CONCLUSION

This project has proven that it is possible to develop IM and green munitions that perform better than current munitions and that will help to ease the environmental pressures on RTAs. The test vehicle was a 105-mm M1 artillery round, but the technology aimed to be transferable to other calibres. The main outcomes of this project consist of a green and IM main explosive charge, and a greener, modular, extended-range and IM main propellant charge. Each of these outcomes can be exploited separately or as a whole, either for Army, Air Force or Navy munitions.

In contrast to the traditional approach, which consists in evaluating the environmental and health impacts at the end of the development cycle of a formulation, the candidate formulations were simultaneously tested for their environmental impacts as well as their ballistic, IM and mechanical properties. This approach had the benefit to avoid dedicating considerable efforts on the development of formulations that could be discarded at the end of the development cycle due to noxious environmental impacts (Brochu *et al*, 2013).

The end result is that military personnel will be able to train and fight with ammunition having comparable or better properties than current munitions, with the added benefit of decreasing the environmental pressure and the health hazards on soldiers, sailors or airmen. The technology developed under RIGHTTRAC will contribute to sustain military training and maintain troop readiness by minimizing long-term environmental impacts.

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