Using Composite Materials for Hybrid Propelled Ballistic Experimental Rockets

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Abstract

In order to reach higher altitudes and top velocities with ballistic experimental rockets two elements are required: 1) a lightweight launcher structure and 2) an efficient propulsion system.

On the one hand it is a state of art technology to achieving 1) by utilizing fiber-reinforced composite materials to construct optimized launcher structures. On the other hand 2) up to now is mostly achieved by using rocket engines based on a metallic lightweight design, due to heavy systems requirements and production restraints.

In the course of the project HyCOMET-1, conducted by the University of Applied Sciences Augsburg and described in the following, the use of fiber-reinforced composite material for structural components and the propulsion system is investigated. Due to the requirements this materials family are a promising solution to achieving a higher lift-off capacity.

HyCOMET-1 is a Hybrid-Composite Experimental-Rocket for high altitude ballistic flights and experimental purpose designed and built by students at the university. Project priorities are usage of composite materials for structural components and a new development of a mission optimized hybrid rocket propulsion system.

1. Introduction

The goal of the following paper is to present the usage of composite materials in the HyCOMET-1 hybrid rocket project. HyCOMET-1 is being conducted together with a student research group at University of Applied Sciences Augsburg (HSA). As one of its main focus areas HyCOMET-1 aims at evaluating to which extent it is feasible to exchange standard metallic components in the various subsystems of a rocket with new composite materials.

This project is incorporated into a research and technology background in “Lightweight Construction and Composite Technologies” at the department of Mechanical and Process Engineering at HSA. Together with several industry and research partners the HSA is working on developing new products based on composite materials. As part of the German Aerospace Agency’s (DLR) STERN program and funded by it HyCOMET-1 aims at designing, constructing, and flying a hybrid rocket in close collaboration between academic advisors and students. Combined with the research groups described background this creates new approaches in construction and design.

In order to reach higher altitudes (above 5000 m) and supersonic velocities with ballistic experimental rockets two elements are required: 1) a lightweight launcher structure and 2) an efficient propulsion system.

To achieve 1) it an established practice in Aerospace engineering to utilize fiber-reinforced composite materials for the construction of launcher chasses. On the other hand 2) in many cases is achieved by using rocket engines based on a metallic lightweight design. The HyCOMET-1 project focuses on investigating the feasibility of using fiber-reinforced composite material for propulsion systems as well as overall construction to a greater extent. Due to the extensive thermal, pressure, and structural load requirements, especially in the propulsion subsystem, these materials are promising candidate technologies for achieving higher launch capacity and thus more efficient rockets.

1.1 The STERN Program: Project Requirements

The STERN program, organized and funded by the DLR, aims at promoting rocket engineering skills and science in students at universities all over Germany. Therefore its main goal is to support and improve the academic education in the fields such as launch vehicle and propulsion systems design. All projects supported in this program deal with designing and testing small ballistic sounding rockets.

HyCOMET-1 (Hybrid Composite Experimental Rocket) is funded under the DLR project code 50RL1257 since November 2012. The STERN program has set the following overall requirements for the project:

- In a full flight conducted at ESRANGE in Kiruna, Sweden, the rocket is to reach an apogee of > 3000 m
- The rocket has to surpass Mach 1 and fly at supersonic velocities at one stage of the mission
- In-flight telemetry data has to be transmitted live to the ground during the flight
- Full recovery of all flight equipment has to be provided

1.2 Hybrid Rockets

Hybrid rockets are defined as propulsion systems with fuel and oxidizer in two different chemical phases (e.g. solid/liquid). A typical combination is solid fuel and liquid/gaseous oxidizer. By regulating the flow of the fluid reaction partner the combustion process can be controlled.

The pressurized oxidizer (self-pressurized or external pressurized) is stored in a tank and is released under controlled conditions before ignition. It flows through the feed system and evaporates partly within an injector unit, which sprays the gaseous/liquid mixture into the combustion chamber. To start the combustion process an igniter system or an exothermal chemical reaction is required to vaporize the solid fuel grain and allow combustion of fuel and oxidizer. The pressurized reaction products will be accelerated via the expansion nozzle to generate thrust.

Self-pressurized systems use the oxidizers saturated vapor pressure to generate pressure within the tank. External pressurized systems use an additional high-pressure tank with an inert gas to achieve the required pressure for fuel transport. As a result the feed pressure of a self-pressurized system will decrease over burn time as will the combustion chamber pressure. The externally pressurized systems work under a constant transport pressure. [1]

1.3 Tools

The projects design process is supported by various design tools. Some of these are commonly used within the field of rocket technology, others are custom-developed programs by students of the University of Applied Science Augsburg or other universities.

HyCAL
This is a custom-developed software to calculate basic parameters of new hybrid rocket motor designs. [2]

Open Rocket
This software is an open source flight simulation with design and flight envelope computation, which can be used up to velocities of Mach 1.5. [3]

NASA CEA
"Chemical Equilibrium with Applications" is a NASA-developed software, which allows calculating chemical equilibrium compositions and properties of various substance mixtures as they react in the combustion processes of rocket engines.

ANSYS
This state of art software solution is a multi purpose commercial finite-element-method for various problems such as structural mechanics, thermodynamics, fluid mechanics.

2. Mission Design

HyCOMET–1 is designed as a single stage modularized experimental rocket. Hence one single hybrid rocket engine will launch the vehicle up to the designated altitude.

Based on given requirements Figure 1 displays HyCOMET-1´s flight envelope. Supported by a rail structure at launch the vehicle will accelerate for the first 10 s in-flight and continue climbing to apogee until aerodynamic and gravity drag eliminates vertical velocity at approx. 5000 m. An immediately deployed small parachute will return the vehicle to an altitude of about 400 m. At this height a larger parachute will decrease drop-speed to 3 m/s till ground contact. On-board electronics transmit in-flight data continually during the whole flight to a ground station.

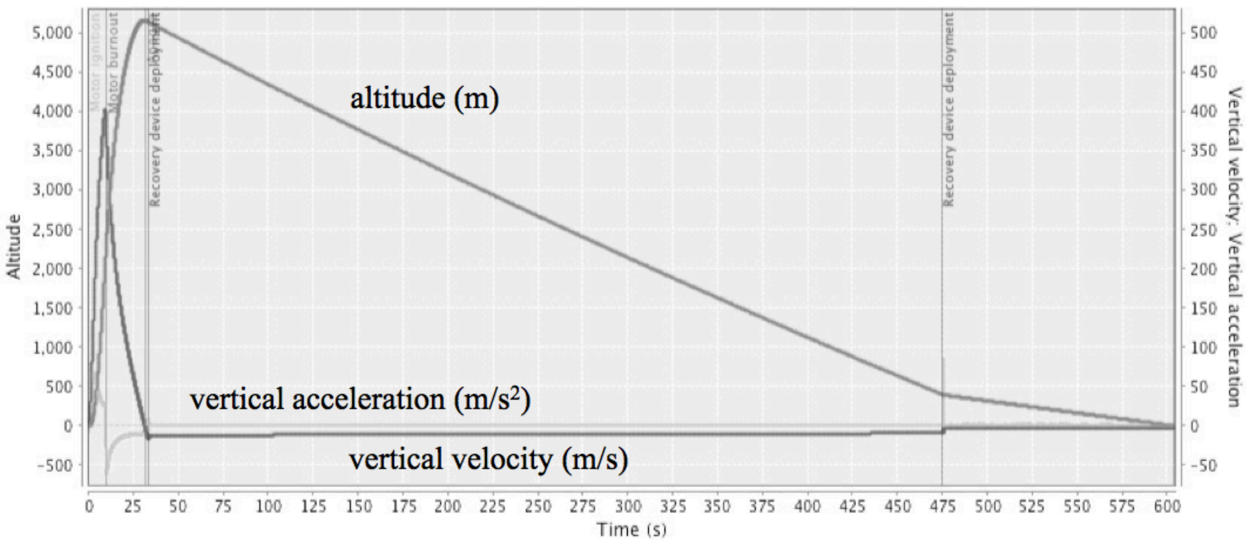

Figure 1: HyCOMET-1 flight envelope

3. Launcher Design

The vehicle itself is composed as a system of modular units with standard interfaces connecting the units to each other. The units are standardized in their diameter, materials, and loadbearing structure to form a rockets hull. Each unit houses a specific function or subsystem of the rocket, e.g. a recovery system or a telemetry unit. Each module is connected by a structural interface inside the hull. By this modular assembly it is possible to react easily to mission specific requirements or modifications and achieve optimized mission performance. For example it is simple to exchange different propulsion systems in the rocket. [4]

The launcher HyCOMET-1 consists of the following module types: propulsion system (PSYS), recovery system (RSYS), electronics/payload (EPAY), structural component (STCO).

The picture (Figure 2) below depicts the assembled launcher HyCOMET-1 with the different modules stacked.

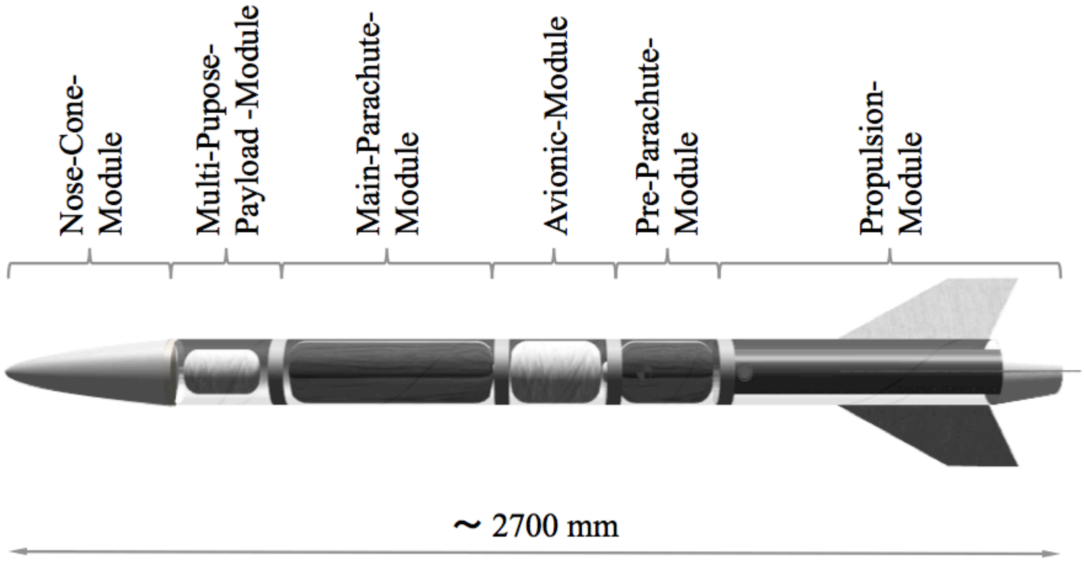

Figure 2: HyCOMET-1 layout

In order to fulfill the mission requirements the flight configuration of HyCOMET-1 consists of a six-module-setup.

Nose Cone Module

The front module has to largely account for the over-all drag of the rocket. Geometry as well as length-diameter ratio have to be specially designed for the planned flight velocity envelope. According to mission requirements the nose cone is an exchangeable structure-only module, which is able to house additional electronics. (STCO)

Multi Purpose Payload Module

This module is capable to house different payloads such as on-board cameras or a student experiment. The primarily empty module with multiple interfaces for the payload is mounted behind the nose cone module. (STCO)

Secondary Recovery Module (SRM)

This third module carries the main parachute and deployment equipment. It is part of the two-stage recovery system. Due to flight stability issues the heavier parachute is located in the section closer to the tip of the rocket. This parachute is deployed automatically in an altitude of about 400 m and will decrease decent speed to about 3 m/s. This secondary stage of the recovery system takes care of save landing the whole rocket. (RSYS)

Avionics Module

This module contains all avionics electronics for Telemetry/Telecommand and to activate automatically the two-stage recovery system as shown in Figure 3. The module is connected behind the SRM. On board avionics will record time-related acceleration, velocity, environmental pressure, as well as GPS data. The system also takes care of the transmission of data to a ground station. (RSYS)

The recovery systems controller consists of two redundant altitude determination electronic board, each of which can trigger two pyrotechnical actuators for the pre-parachute and the main parachute. The actuator punctuates a sealed CO_2 pressure vessel releasing the gas and “popping” open the respective parachute container modules. The parachute container modules are locked by shear-pins, which break at a defined interior pressure. The module then splits open and release the parachute. The smaller pre-parachute is released at apogee, the bigger main parachute at about 400 m height [5].

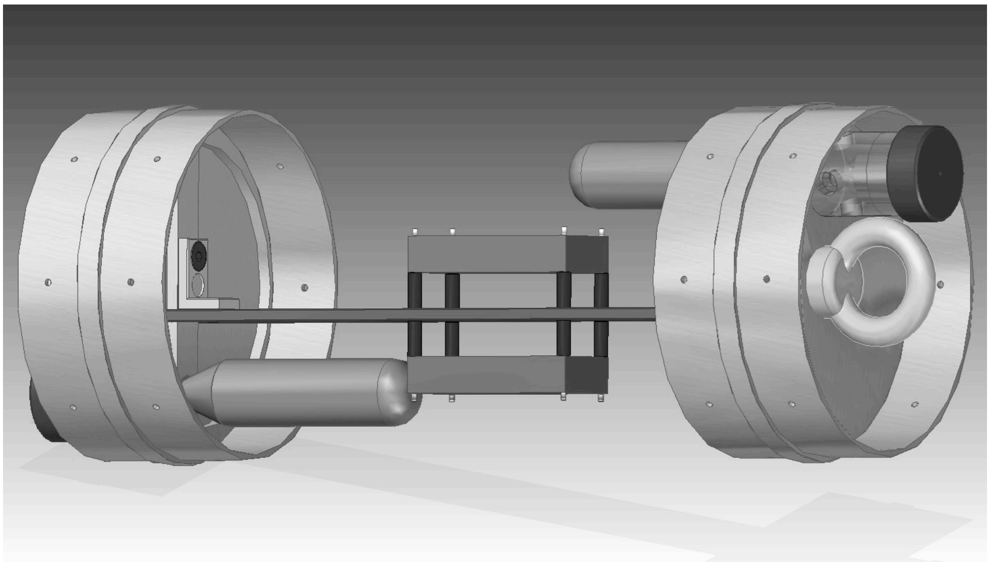

Figure 3: Avionic Module with actuators an CO_2 pressure vessel [5]

Primary Recovery Module (PRM)
This fifth module containing the smaller pre-parachute is connected behind the Avionics module. This parachutes main function is a fast decrease in altitude and in decent speed to a planned 20 m/s. The size of this parachute is kept minimal to reduce the wind-drift of the vehicle caused by strong high-altitude shear winds. (RSYS)

Propulsion Module
The last, aft, module houses the propulsion system of the vehicle. It mainly consists of an oxidizer tank, a supply-system, and a combustion chamber with injector, solid fuel, and nozzle. Thrust forces of the engine are guided into the propulsion modules structure via an aft-interface. The aero-dynamical fins are mounted on this module.

The rocket engine designed for the HyCOMET-1 launcher (HyER FM - Hybrid Experimental Rocket engine Flight Model) will utilize liquid nitrogen (N_2O) as oxidizer and a HTPB (Hydroxyl-Terminated Poly-Butadiene) solid grain as rocket fuel. N_2O, instead of liquid Oxygen (LOX), was selected due to safety and technical handling issues and addressing the fact that the project is mainly conducted by students. (PSYS)

4. Selected Elements of HyCOMET-1 in Carbon-Composite Design

Fiber-based (composite) vehicle structure design, especially with carbon fibers, is a major focus of the HyCOMET project. Utilizing these new materials will reduce the vehicles launch mass and improve its mechanical and thermal properties as well as capabilities. In the following two main fields of application for fiber-reinforced components are discussed: 1) vehicle hull structure and 2) propulsion system structure.

4.1 Hull Structure Design

A sounding rocket´s hull structure in ballistic flights is required to resist variable force, pressure and thermal loads. Therefore high performance materials and an optimized weight ratio are required to achieve high-altitude flights. Carbon fiber-reinforced materials offer high load and temperature resistance at minimal weight and can be applied various possible constructions and designs. For this reason carbon fiber-reinforced materials were chosen as constructive material for the hull structures of each rocket module.
The base structure for each module is provided as a carbon-fiber-reinforced-polymer (CFRP) tube segment composed of high tensile carbon fibers with a thermoset or thermoplastic polymer matrix. The exact matrix system will to be determined in manufacturing experiments and testing. [6]

Independent of the hull materials it is state of art to use metallic interface couplers to connect the different modules of a rocket to each other. When using CFRP as hull material thermally induced plastic-elastic strain at these connections is an issue, as the material properties of CFRP and metallic compounds in relation to their thermal behavior are very different. CFRP is far more thermally stable with metallic materials producing far higher expansion or shrinking rates in changing thermal conditions [7]. Especially during the low temperatures (-20 °C and lower) at the flights Apogee these possible frictions will result in the connectors requiring extra structural stability thus weight and size to the component. Therefore in the HyCOMET-1 these couplers will be designed as full CFRP parts [8]. For the for detachable connections between modules a screw/bolt and nut plate solution as depicted in Figure 4 with the nut plate adhesively attached to the coupler interface.

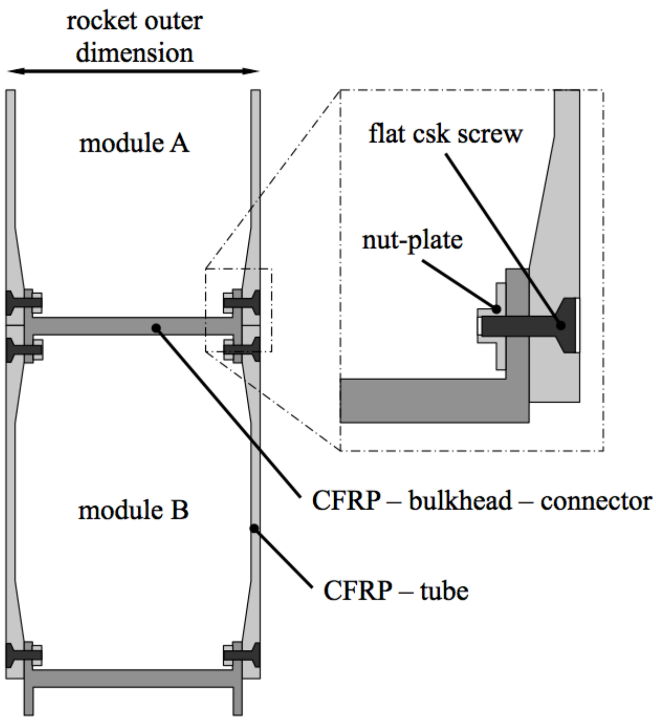

Figure 4: Detailed CFRP coupler interface

This design principle however makes an anticorrosive coating at any metallic/CFRP interface points necessary [7].

4.2 Propulsion Systems Design

The propulsion system of HyCOMET-1 is a central research and design activity in the project combining the application of composite materials with hybrid rocket propulsion. HyCOMET-1's rocket engine HyER FM is composed of four major components depicted in Figure 5 below:

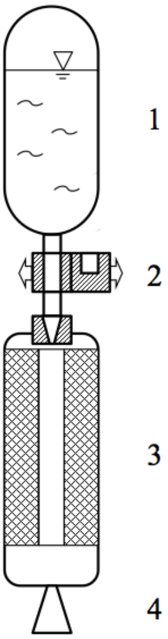

Figure 5: Major components of HyER EM

1) Pressure tank: liquid N_2O
2) Feed/supply system: transport N_2O in liquid form into the combustion chamber
3) Combustion chamber: with HTPB solid fuel
4) Expansion nozzle: provide propulsion for the rocket

Due to their high weight requirement as a metallic construction the pressure tank (1) and the combustion chamber (3) are implemented in lightweight fiber-reinforced design. The expansion nozzle (4) will be implemented in fiber-reinforced ceramics due to the high thermal and structural loads applying here.

Oxidizer Tank
The oxidizer tank contains liquid nitrogen at an approximate temperature of 25°C and an approximate pressure of 6.0 MPa based on the saturated vapor line. The system is self-pressurizing and feeds the combustion chamber with oxidizer. Additionally to the pressure load, leakage, and chemical resistance requirements a special requirement on thermal stability inside the pressure vessel has to be applied. As a result of an ambient temperature change while the rocket rests on the launch pad the temperature of the oxidizer might increase, subsequently creating higher pressures in the tank.

For HyCOMET-1 a filament winded pressure tank made of carbon fiber-reinforced thermoset polymer most probably is the optimal solution according to the requirements to manufacturing-effort. The pressure tank will be equipped with two inflows interfaces at either end-cone, providing re-fuel and vent capabilities.

Combustion Chamber
The thermal and structural requirements to this component require a quite sophisticated design approach to HyER FM´s combustion chamber. High temperature loads and gradients as well as structural loads and dynamic vibrations have to be coped with in this component. Additionally the combustion chamber is designed to be reusable. The chamber contains the solid fuel grain as a HTPB tube with the central burn channel milled out. On the forward interface bulkhead (connected to the pressure tank) the injector is positioned to disperse the liquid oxidizer at approximately 250 K. At the aft bulkhead the expansion nozzle is mounted taking up the hot combustion gases at temperatures between 2400 K up to 3300 K, according to simulation data. The combustion temperature varies with the oxidizer-fuel ratio with a stoichiometric combustion of N_2O and HTPB leading to maximum temperatures of 3300 K. To simulate the reaction products and temperatures inside the chamber NASA´s CEA is used. [9]

Protecting the chamber structure against the high-temperature gases is a quite challenging structural requirement for a reusable propulsion system. For HyER FM a multi-layer insulation interior liner based on Pertinax (composite material with phenol formaldehyde resin), CSic (carbon fiber reinforced silicon carbide) and ceramic foams possible candidate technologies. The outer structure to provide a pressure proof-container for the operational chamber pressure of 2.0 MPa is composed by a filament-winding structure.

In-depth experiments with the mentioned designs will be conducted by utilizing an engineering model of HyER (HyER EM). Additionally this model will be used to determine the engines parameters and properties. The design of HyER EM is depicted in Figure 6.

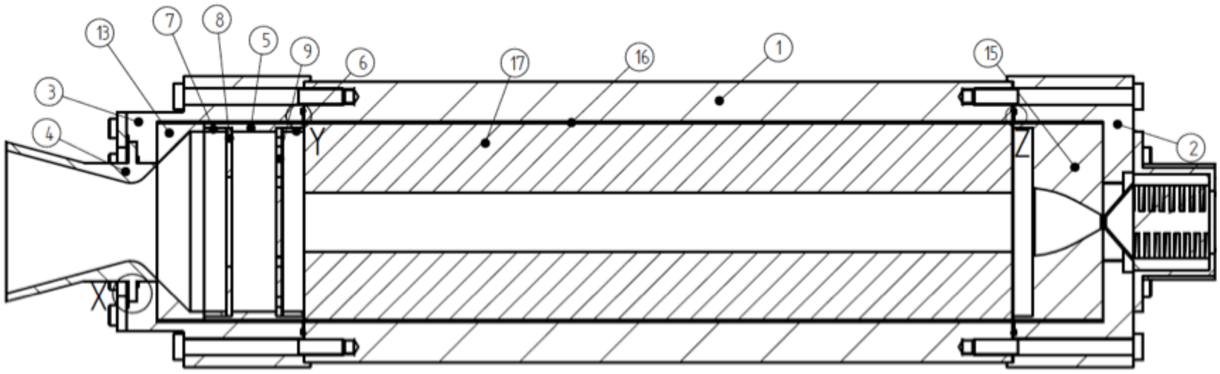

Figure 6: Cross section of HyER EM [9]

Expansion Nozzle
For this component due to the extreme temperature and high load and vibration requirements a Carbon-fiber-reinforced Silicon Carbide (CSic) is researched a candidate technology. This lightweight material is capable to handle high temperatures and forces due to its carbon fiber and ceramic structure. Additionally mechanical handling and adaptation, such as drilling or machining, of this material is more feasible than with oxide ceramics allowing a simpler contouring of the nozzle. [10]

4. Conclusion and Outlook

Composite materials are applicable for the design of various structural components due to their possibilities of modification such as fiber-typ, fiber-orientation or matrix systems. As described large parts of HyCOMET-1 are designed in composite materials making the rocket a technology test carrier. The data gathered during testing and flight will provide a better insight into the utilization of these materials.

The current design is still under development and will continuously improved by engineering methods until the conclusion of the detailed definition phase December 2013. The focus rests on the optimized application of composite materials. As a next step engineering models and small mock-ups will be built to verify the described principles and methods. A major milestone will be the hardware construction of the HyER EM.

5. Acknowledgment

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