

ANNEX IV – INVESTIGATING ENVIRONMENTAL EFFECTS OF WAVE AND TIDAL DEVICES THROUGH INTERNATIONAL COOPERATION

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ABSTRACT

The pace of development for marine energy projects worldwide continues to be hindered by uncertainty surrounding potential environmental effects of wave and tidal devices and the balance of system. In response to this continued uncertainty, member nations of the Ocean Energy Systems (OES) developed a collaborative project – Annex IV – to increase collection and sharing of knowledge, research collaborations around high priority environmental interactions, and relevancy of the information to permitting (consenting) processes. The culmination of Annex IV Phase 1 is a searchable database of current literature and reports on environmental effects of marine energy development, and an analysis of three key interactions of devices and the marine environment.

The initial phase of Annex IV concluded in 2013 with an examination of three priority environmental concerns: 1) interaction of aquatic animals with turbine blades; 2) effects of underwater noise from tidal and wave devices on marine animals; and 3) effects of energy removal on physical systems. Each priority interaction (or “case study”) examined published literature,

compliance and investigative reports, and information and metadata gathered directly from device developers and researchers. This information was used to: reach preliminary conclusions on the importance of each interaction to the environment; assess the level of certainty surrounding each interaction; and highlight key research gaps that hinder a deeper understanding of the interaction. This paper will present the findings of each case study and discuss the importance that each of the three priority interactions continue to play in permitting wave and tidal devices.

INTRODUCTION

Commercial development of wave and tidal energy sites around the world has been slow, hampered in part by continued uncertainty surrounding the potential risk to marine animals and habitats from the installation and operation of the devices. Although demonstration and pilot scale prototypes of numerous wave and tidal energy converters have been deployed in Europe and to a lesser extent in North America, a lack of clear and efficient pathways to permitting (consenting) has not ensured the large scale private sector investment needed to launch a large commercially viable industry. There is a need to

share the pool of information and research findings that highlight interactions of marine energy devices with the environment to clearly delineate the risks to marine animals and habitats, to ensure that valuable research and monitoring funds are wisely and effectively spent, and to appropriately apply gained knowledge and experience to other marine energy developments. At this early stage of permitting marine energy developments, there is a need for close cooperation among developers and regulators to ensure that useful information is attained with each deployment; by using an adaptive management approach to monitoring of device interactions, a path forward can be developed that supports development of the industry while protecting critical marine resources. Reduction in the uncertainty needed to accelerate the permitting processes will help to bring confidence to investors and stakeholders, easing the way to a sustainable global industry.

In 2009 the Ocean Energy Systems agreement (under the auspices of the International Energy Agency) recognized the need to share information, leading the group to establish a collaborative project titled Annex IV. Focused on aggregating information on environmental effects of marine energy development, Annex IV distributes information to a broad audience of stakeholders, provides analyses that inform the establishment and expansion of the industry, and provides a collaborative space for discussion among researchers. The initial phase of Annex IV was completed in 2012. Feedback from users of the Annex IV information indicates that the products are being used by several discrete groups: 1) device developers use the information to create and operate effective energy converters that pose little risk to the environment; 2) government regulators consult Annex IV products to assess the safety of the deployed devices and to establish monitoring requirements that are proportionate with the risk, consistent from one marine energy farm to another, and do not unduly burden the emerging industry; and 3) researchers access information and connect with other professionals working in similar fields to move the state of science forward.

The culmination of Annex IV Phase 1 is a searchable database of current literature and reports on environmental effects of marine energy development, and an analysis of three key interactions of devices and the marine environment: 1) interaction of aquatic animals with turbine blades; 2) effects of underwater noise from tidal and wave devices on marine

animals; and 3) effects of energy removal on physical systems[1][2]. Through these analyses and others like them, a greater understanding of the environmental effects and monitoring methods should help to foster public acceptance and advance marine energy technologies. This paper discusses the results of those analyses.

METHODS

Three topics that describe key interactions of marine energy devices and the marine environment (called “case studies”) were chosen for analysis, with the intent to survey, compile, and analyze the best available information in one coherent location. Only information readily available in the public domain was used. Case study topics were chosen to meet the following criteria: 1) the topic must be a common environmental concern or question among at least two nations; 2) the topic must be raised as a significant issue in permitting (consenting) of marine energy sites in more than one nation; and 3) there must be sufficient information available to make an assessment.

Scientific papers and technical reports comprise the majority of the material for the case studies. In many instances, however no published reports or papers are available. Additional information from deployed wave and tidal projects was gathered by querying project and device developers, researchers and other practitioners, and the results organized as metadata forms hosted as part of the Annex IV collection on the public website *Tethys* (tethys.pnnl.gov).

Each case study begins by defining the problem addressed, presents available evidence from marine energy monitoring and/or research studies, and concludes with a discussion of the lessons learned and data gaps. References used for each case study are cited and can be accessed through the Annex IV Final Report [1] and the *Tethys* website.

RESULTS AND DISCUSSION

The analysis for each case study was based on environmental effects information from full-scale tidal device deployments when available, followed by information from smaller scale devices deployed in open water, testing in laboratory flumes and tanks, and outputs from numerical models. Each information source was examined to determine whether the outcome informed the case study, and information was compared among projects and research studies. Significant gaps in

data needed to better understand the interaction of interest were identified.

Case Study #1 – Interactions of Marine Animals with Tidal Turbine Blades

Direct observations of marine animals interacting with turbine blades are restricted to locations where deployments of tidal devices have occurred; to date these have consisted of small-scale devices and/or single devices, most often in the water for relatively short periods of time, in comparison with commercial-scale development. Marine animals could potentially be at risk from turbine blades through a variety of mechanisms that include: blade strike that could result in death or significant injury; collision between an animal and other parts of the device such as the foundation; changes in animals behavior due to the presence of the device that could negatively affect the animal and the population; avoidance of an array of devices that displace animal populations from critical feeding or breeding grounds; or attraction of groups of animals to a device that could increase predation or competition. The strands of evidence collected under Annex IV provided limited and inconclusive proof that any of these risks are substantial or likely, but some insight was gathered from specific projects and studies.

Lines of Evidence for Marine Animal Interactions with Turbines

The strongest evidence of interactions of marine animals with tidal turbines comes from:

- Observations of seals around the SeaGen tidal project (Siemens - Marine Current Turbines) in Strangford Narrows, Northern Ireland [3];
- Acoustic tracking of fish interacting with the TideGen turbine (Ocean Renewable Power Company) in Maine, US [4].
- Video observations of fish around an OpenHydro turbine at the European Marine Energy Center in Scotland [5];
- Acoustic measurements of fish and birds around the Verdant turbine in the east river of New York [6];
- Experimental passage of fish through a hydrokinetic turbine (HydroGreen) on the Mississippi River [7];
- Laboratory experiments of fish passage near a hydrokinetic turbine in a river flume (Conte Laboratory, Massachusetts US) and in a laboratory flume (EPRI and Alden Laboratory, Massachusetts US) [8];
- Modeling encounters of harbor porpoise and herring with turbines (Scottish Association of Marine Science) [9];

- Modeling fish encounter with river turbines (Oak Ridge National Laboratory US) [10].
- Modeling potential interaction of a killer whale with a tidal turbine (Pacific Northwest National Laboratory and Sandia National Laboratories, US) 0.

Knowledge Gained from the Evidence

The limited information available provides no evidence that direct interaction of marine mammals, birds, or fish with tidal turbine blades causes harm to the animals, particularly from blade strike or collision. Evidence from the SeaGen project suggests that seals (SeaGen) tend to avoid the turbine structure when moving in and out of Strangford Lough. The SeaGen turbine has been shut down in the presence of marine mammals through most of its operation; new information from continuous operation of the turbine will become available in the near future. Movement of fish around the TideGen turbine (coastal Maine) and in flume studies at the Conte and Alden Laboratories indicate that many fish pass through the turbine without harm, while some choose to spend time in the wake of the turbine.

Changes in animal behavior including avoidance and attraction to tidal turbines are difficult to estimate due to the limited number of small deployments that have occurred to date. Video data from the OpenHydro turbine at EMEC indicate that fish vacate areas with fast moving tidal currents when velocities approach the cut-in speeds for turbines. Other studies have also shown that fish reduce their movement through areas where turbines are present and that the deterrent effect is increased with current speed 0[11]. Most other interactions of marine animals with underwater objects must be surmised from other sources.

Scaling Effects to Commercial Arrays

Scaling interactions of animals with tidal turbines from the limited number of deployed devices to large-scale commercial developments lasting many years is challenging. Limited acoustic data collected around the six-machine Verdant RITE (Roosevelt Island Tidal Energy) deployment in New York indicate that the indigenous fish perceived the array as a collection of separate objects, aligning themselves between the turbines. The SAMS (Scottish Association of Marine Science) modeling effort addresses the longer-term interaction of harbor porpoise and herring with tidal arrays over periods of months and years, indicating the potential for a cumulative impact on populations; however, the SAMS researchers caution that their model overestimates encounters

because it does not allow for avoidance behavior or consider that each encounter may not be injurious or lethal.

Significant Data Gaps

In order to determine the risk posed to marine animals around tidal turbines, additional observations around deployed tidal devices are needed, around single devices, and eventually around large arrays, with a particular focus on behavioral effects of marine mammals, fish and sea turtles. Investigations are also needed to link these behavioral changes to deleterious effects on the individual animals and on populations. Interpretation of animal behavioral reactions observed in the field can be gleaned from continued laboratory and flume studies. Modeling studies are needed that explicitly simulate the physics and biological interactions of animals with turbines, as these will provide predictive power and insight into the design of laboratory and field experiments. There is a need for studies that examine the interactions of marine animals with a range of tidal devices and operating parameters to help clarify the potential risk to those animals, and to support development of appropriate mitigation strategies.

Case Study #2 - Effects of Underwater Noise from Tidal and Wave Devices on Marine Animals

Underwater sound is used by many marine animals to navigate and communicate, as sound travels better than light underwater, rendering eyesight and optical cues less important. The underwater sound generated from tidal and wave devices has the potential to interfere with basic communication and navigation of certain marine animals, most notably marine mammals and some fish species ([12],[13]). Little is known about the hearing or use of underwater sound by sea turtles or diving birds. Understanding the effects that sound from wave and tidal devices may have on animals requires accurate measurement of the amplitude and frequency of the sound from the devices, as well as extensive observations to understand potential changes in animal behavior.

Measuring underwater sound is a well-developed science, dating back over a century [14], however, these measurements are seldom made in areas of high flow or significant wave activity. Sound waves are received by marine animals in different ways; cetaceans detect the pressure component of sound waves, while pinnipeds appear to detect particle motion and vibration with their facial whiskers, in addition to detecting pressure with their ears [15].

Depending on the fish species, fish can detect particle motion, pressure, or both components. Understanding the various sensory systems of marine animals and the physics of underwater sound is necessary to understanding potential risks to animals from marine energy development, and also to developing effective mitigation strategies to protect key species. It is equally challenging to understand the effects that sound from marine energy devices may have on the behavior of indigenous animals.

Lines of Evidence for Underwater Sound Effects on Marine Animals

The strongest evidence of effects of sound generated from tidal and wave devices on marine animals comes from:

- Monitoring for ambient noise, noise generated during construction (pile driving) and operation, and how noise is perceived by marine animals, around the SeaGen tidal turbine (Siemens- Marine Current Turbines) in Strangford Lough, Northern Ireland [3];
- Acoustic monitoring during construction (pile driving) around the TideGen tidal turbine, and monitoring during operation of a smaller scale barge-mounted turbine (Ocean Renewable Power Company) in Maine, US [16];
- Acoustic monitoring during operation of the Verdant tidal turbines in the East River of New York [6]; and
- Acoustic monitoring of an operational 1/7 scale Columbia Power Technology wave energy converter in Puget Sound, US [17].

Other lines of evidence contributed to understanding the environment that marine animals may face from development of marine energy, including:

- Examining the ambient sound field at a tidal site in Puget Sound, US, by University of Washington investigators ([18]-[20]);
- Laboratory flume studies that measured tidal turbine noise by University of Newcastle upon Tyne investigators in the UK [21]; and
- Laboratory exposure of fish to simulated tidal turbine noise by Pacific Northwest National Laboratory investigators in the US ([22] [23]).

Numerical models have also contributed a framework for understanding how underwater sound may be propagated and affect marine animals, including:

- Modeling the acoustic signature of Pelamis wave energy converters in Portugal [24];
- Modeling the effects of sound from arrays of tidal and wave devices Scotland [25];

- Developing an acoustic signature for a hydrokinetic turbine by investigators at Pennsylvania State University, US [26];
- Field calibration of acoustic models for noise prediction by investigators at the University of Algarve in Portugal [27]; and
- Modeling acoustic deterrence to develop mitigation for marine mammals by investigators at Oregon State University and Pacific Energy Ventures, US.

Knowledge Gained from the Evidence

Relatively few tidal and wave devices have been deployed to date and even fewer datasets of underwater sound measurements collected or measurements of animal response documented. The few sound measurements we have from operating devices indicate that single devices are probably almost indistinguishable from ambient noise. Although we may be able to accurately measure the sound output from devices in the next few years, conclusive information about the risks of sound from marine energy devices will only be gained from many years of data collection and observations of marine animals around arrays of tidal turbines and wave energy converters. This information may be augmented by *in situ* field studies, laboratory experiments, modeling outputs, and the opinions of experts in the field of marine animal behavior.

Improvements are needed to characterize the acoustic environment into which marine energy devices will be deployed, as well as the ability to accurately measure the amplitude and frequency spectrum of sound from these devices, as they vary over time and space. Measuring the acoustic environment is a well-developed methodology; experience has been gained by sub-bottom profiling for oil and gas exploration [28], naval operations [29], and other oceanographic investigations [30]. However, only a few of these investigations have been carried out for purposes of marine energy siting ([19] [20]). The ability to observe marine animal reactions to these new sound sources is hampered by a lack of instrument packages and data analysis procedures, as well as interpretations of how sound received by the animals affect their behavior and health [31][31]. Even a fundamental understanding of whether the sound output from tidal and wave devices falls within the auditory range of many species is lacking [31]. Measurements of effects of acoustics on marine animals have been developed, with varying degrees of completeness and applicability, to help bridge the gap between real world observations,

laboratory findings, and indirect evidence of behavioral change in animals ([33]-[36]).

Existing evidence indicates that operational noise from individual marine energy devices or small arrays is unlikely to have large-scale effects on animal behavior or survival. Intuitively, marine mammal experts believe that the sound of the device will warn animals to avoid the hazard, but there is no clear evidence of this around tidal or wave devices to date [37]. The sound from the SeaGen turbines appears to be below the level at which effects on the animals' hearing is expected ([3][38]). In addition, observers noted that the marine mammals spent little time in close proximity to the installation when the turbines were turning, further limiting their exposure to harm. Alternately, observers saw seals and harbor porpoises routinely within the region where behavior changes such as avoidance might be expected.

Regulators and stakeholders may have concerns about possible effects from the noise of large numbers of devices, added to that of other human activities such as shipping. There is a need for measurements of the frequency and amplitude of sound that may be generated by large tidal or wave arrays, as well as measurements of the cumulative effect of sound from multiple arrays within a waterbody. Greater concerns are likely to arise, however, from underwater sound generated during relatively short periods of device installation that may include pile driving and intensive vessel traffic around marine energy sites; these activities will require mitigation and careful observation to ensure that they do not cause long-term harm to marine animals.

Laboratory experiments have found relatively low levels of harm (the equivalent of tissue bruising) from the exposure of fish to tidal turbine sound [23], if the fish were to spend large amounts of time in close proximity to a tidal turbine. This behavior is unlikely for most fish, unless they are attracted to the noise of the device [39], indicating that the direct effect of sound output appears to be of little environmental concern. Challenges remain however, in estimating the effect of sound signatures from multiple turbines in an array and extrapolating the results to other turbine designs, to other fish species, and to marine mammals.

Efforts in Portugal to model underwater sound at levels that may affect marine animals from marine energy devices have compared sound levels from portions of a wave energy convertor

(Pelamis) to the hearing range and sound levels at which harbor porpoise are thought to be affected, and have allowed for calculating the distance from devices at which animals might be affected for single devices and arrays [24]. Researchers in Scotland modeled the acoustic output of arrays of tidal devices, at levels at which animals are believed to suffer temporary or permanent hearing damage, and were able to estimate the distance and exposure levels at which concerns for specific animal groups might occur [25].

Scaling Effects to Commercial Arrays

The limited number of marine energy deployments to date indicates that the sound signatures from single or small numbers of operating tidal and wave devices are unlikely to cause substantial harm to animals. However, the complex propagation of sound through seawater makes it very difficult to predict possible additive or synergistic sound effects that might be generated from large arrays. Long term monitoring around arrays is needed to inform these effects. Modeling outputs may assist in understanding acoustic effects of multiple devices arrays, but field data will be needed to validate the models.

Significant Data Gaps

As each tidal and wave device or array is deployed, a full suite of acoustic and behavioral studies is needed, including measuring the ambient sound field and propagation potential of the waterbody prior to deployment of the marine energy device; documenting the sound of installation; accurately measuring the sound of the operational device; and observing species of interest around the device using multiple tools such as observers, active acoustics, and remote sensing capabilities like satellite tags and aerial surveys. A wide range of device types and indigenous animals must be observed to establish the unique sound signature of each device and the individual reactions of animal groups. With sufficient observations, new devices and future deployments will be able to extrapolate and mitigate the acoustic risk to animals.

In order to understand thresholds at which noise from marine energy devices may pose a risk to marine species, laboratory experiments are needed to establish dose/response relationships for the amplitude and frequencies of sounds that elicit reactions in animals of concern. These studies can only be carried out with fish and invertebrates due to ecological concerns, necessitating extrapolation to marine mammals and sea turtles.

Case Study #3 - The Environmental Effects of Marine Energy Development on Physical Systems

Introduction of marine energy converters into a water body has the potential to affect the natural processes of that water body and all the essential marine ecosystem functions that depend on the system. Effects may be caused by changes in water flow, as well as the effects of removing energy from the system in the form of electricity through a power cable [5]. Environmental concerns that may arise include changes in water circulation, sediment transport, and alterations throughout the marine food web. However, these changes are likely to result only from the extraction of very large amounts of energy from a system (0 [37],[40] [41]). Understanding and modeling how energy extraction may disrupt tidal flows and wave trains requires a thorough understanding of how tidal and wave systems work. Oceanographic measurements are not commonly taken in very high-energy systems; these studies will require adaptation and invention of oceanographic instrumentation to measure tidal flows, turbulence, and changes in wave energy. Numerical models are sophisticated enough to simulate the natural conditions, as well as the flow blockage and energy removal from the system; however field measurements are vital to validate and ground the models in reality. Modeling potential effects of flow and energy removal is the most practical means to predict future changes, and will support the design of cost-effective monitoring programs for large commercial marine energy arrays.

Lines of Evidence for Environmental Effects of Marine Energy Development on Physical Systems

A limited number of field studies have measured changes in water flow and water quality around tidal devices; no such studies have taken place around wave devices:

- Water velocity measurements around the SeaGen turbine in Strangford Lough, Northern Ireland [3]; and
- Measuring water velocity around tidal turbines, New York, US [6].

Most modeling studies of wave energy converters have focused on changes to the wave trains themselves and have not provided simulations of the effects on the marine environment. The best evidence for changes to the marine system include:

- Simulation of the propagation of sinusoidal waves of different amplitudes, periods, and

directions with and without wave farms, in Portugal [42];

- Effects of a wave array on the incident waves and the impact on the shoreline, under present and future climate change scenarios, off the coast of Cornwall, UK [43];
- Modeling effects on the physical and biological environment, including waves, currents, and sediment distribution, for a proposed deployment of WaveDragon devices off the coast of Wales [44];
- Changes in sediment transport caused by arrays, changes in benthic organisms and habitats, in Sweden ([45] [46]);
- Effects of wave energy removal, through modeling and wave tank tests by US researchers at Columbia Power Technology and Oregon State University; and
- Effects of wave arrays on the nearshore wave field in Hawaii and effects on the nearshore waves, currents, and sediment transport off the coast of California ([47][48]).

Like wave modeling, most tidal modeling has focused on changes to tidal flows and to a lesser degree on changes to the marine system; the best evidence for changes that may affect the environment include:

- UK researchers examined the effects of an array of tidal turbines with 10-m-diameter blades in the Severn Estuary and Bristol Channel ([49] [50]);
- UK researchers simulated alterations in the circulation patterns of the sea shelf caused by the development of a tidal turbine farm in a simulation of the eastern Celtic Sea, including the Bristol Channel [51];
- Investigators examined the effect of energy removal and flow changes around Verdant tidal turbines on water level elevation and flow in the east river of New York [6];
- Canadian researchers examined the effects of tidal energy extraction on the available energy, near the sea bottom and over the entire water column in Minas Passage, the Bay of Fundy and the Gulf of Maine [52];
- US researchers examined the effect of tidal turbines on flow in an estuary like Puget Sound ([53] [54]); and
- US researchers modeled the interaction of tidal turbines in a river channel (Mississippi River) and in two tidal channels (Maine and California) ([55] [56]).
- Simulations of water quality changes from tidal energy extraction in an estuary like Puget Sound [57].

Knowledge Gained from the Evidence

Measurements of water flow and water quality in areas of tidal energy development have shown no apparent changes from the presence of the devices ([3] [6]); however no large arrays have been deployed to date.

There is some indication from modeling studies of wave energy converters that moderate effects on shorelines and coastal currents may occur near wave arrays ([42] [43] [44]), and moderate to severe changes in sediment transport and water quality may occur in the vicinity of large wave arrays nearshore [48].

Tidal modeling studies have shown that changes in water flow will occur with the operation of moderate to large arrays ([49]-[51] [6] [52] [54]-[56]). By modeling changes in water quality from large numbers of tidal devices, it appears that competing forces in the water column (vertical stability and turbulence) may buffer changes [57].

Significant Gaps to Support Modeling Studies

Collecting data from the natural environment for model validation is currently the largest barrier to accurately modeling the effects of flow changes and energy removal from marine energy devices. There is a need to collect: field data on the effects of large arrays; oceanographic measurements that describe turbulence around high energy tidal and wave energy extraction sites; and data specific to different types of tidal turbines and wave energy converters. There is also a need to develop better models that examine and couple effects in the nearfield (within a few device lengths of an energy converter) and the farfield (up to the scale of the waterbody)[11]. Finally, better modeling solutions are needed to simulate cumulative effects of many marine energy arrays in a waterbody that will include interactions among and between devices and arrays.

CONCLUSIONS

Information gathered from the three case studies under Annex IV provides insight into the state of knowledge of potential environmental effects from the deployment and operation of wave and tidal devices.

Information from case study #1 indicates that: there is no direct evidence to date of adverse interactions between marine animals and rotating tidal turbine blades; changes in behavior of animals near turbine blades will require ongoing monitoring to determine effects on individuals

and on populations; and that additional information on interactions must include interactions between a wide range of tidal turbine designs and multiple animal species indigenous to potential tidal energy development areas.

Information from case study #2 indicates that: the sound from pilot scale projects is unlikely to have widespread negative effects, however there is a need to collect sound data and observe animal behavior around commercial scale arrays of tidal and wave devices to determine potential effects of sound; the noise from construction activities, including pile driving and excess vessel traffic, are more likely to be of concern to marine animals than operational noise from devices; measurements of ambient amplitude and frequency of sound is needed in waterbodies prior to deployment of marine energy devices; and correlations of the level and frequencies of underwater sound and behavioral reactions of marine animals should be developed through laboratory and field studies.

Information from case study #3 includes the knowledge that: changes in physical oceanography and water quality are unlikely to be seen at the pilot scale and may or may not be significant at commercial scale array development; numerical models can be a useful tool for siting and predicting future changes at the ecosystem level in a waterbody; and there is a need to collect data from pilot and commercial scale developments to validate and refine numerical models. Data from pilot projects will most likely yield information about interactions of individual animals interacting with marine energy devices, while commercial scale arrays will be necessary to provide useful information on other effects, such as energy removal.

The two clearest outcomes from the three case studies are that: there continues to be a dearth of quantitative environmental information from tidal and wave devices that have been deployed in coastal waters; and there are inadequate research and modeling data to characterize the potential effects of marine energy devices, particularly at the large commercial array scale. In response to these needs, many regulators and developers have recognized the need to take an adaptive management approach (“learning by doing”) to the design and implementation of monitoring data collection pre- and post-installation of marine energy devices. In this respect, the indications thus far that pilot-scale deployments have few environmental impacts may allow other projects to move forward more

quickly and successfully utilize adaptive management approaches for characterizing and assessing risk. Future Annex IV activities will continue to support and analyze these outcomes.

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