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DESIGN INSIGHTS RESULTING FROM THE COMPARISON OF U.S. NUCLEAR POWER PLANT COMPONENT BIRNBAUM IMPORTANCE MEASURES

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SUMMARY/ABSTRACT

The ability of a nuclear power plant to reach and maintain a safe shutdown condition is influenced by many factors, including those associated with a plant's operation, maintenance and design. Due to the confluence of these factors, coupled with variations in probabilistic modeling techniques, it is difficult to gain design insights as to the effectiveness of the designer's choice for a particular system or component configuration when comparing one power plant design to another. However, significant insights are obtainable if one can limit the operation, maintenance and modeling variations through the use of the U.S Nuclear Regulatory Commission (NRC) – sponsored Standardized Plant Analysis Risk (SPAR) models and focus on specific system functions through the use of component Birnbaum importance measures. These standard insights can then be validated through reviews of licensee probabilistic risk assessments (PRA).

This paper describes the significant technical insights resulting from the comparison and grouping of components by attributes that have been shown to influence a component's risk importance.

The attributes were determined through the investigation of the SPAR model cut sets in support of the implementation of the Mitigating Systems Performance Index. The investigation proceeded by selecting a component type and an associated failure mode (e.g., emergency diesel generator (EDG) fails to run), which typically equated to several basic events per plant (e.g., EDG A fails to run, EDG B fails to run, etc.) and investigating the resulting basic events for the fleet of U.S. plant designs. Each SPAR model was reviewed to determine the critical attributes influencing the component's importance. This was an iterative process. Often the number and type of attributes changed as the investigation progressed. Basic events having similar attributes were grouped and a resulting Birnbaum importance measure distribution was determined to validate the effectiveness of the grouping. This process was repeated for several component types. Once the initial grouping was completed, refinements were made based on limited reviews of licensee PRAs.

The focus on Birnbaum importance helped to reveal plant design elements that were otherwise obfuscated by the complex interactions of a plant's systems. Technical insights associated with the influence of system configurations, including component redundancy and diversity, system interactions and recovery actions, were seen.

INTRODUCTION

The Mitigating Systems Performance Index (MSPI) is formulated as a simplified linear approximation of the change in core damage frequency (CDF) attributable to changes in the reliability and availability of risk-significant elements of the system during internal events with the reactor operating at power [1,2].

The Birnbaum *importance* of a basic event is the partial derivative of the CDF with respect to the basic event probability. While other importance measures such as Fussell-Vesely (F-V), Risk Reduction Worth (RRW), and Risk Achievement Worth (RAW) are more often used in risk rankings, the Birnbaum provides more of an *absolute* measure of risk sensitivity for our purposes. It can be shown that, given identical basic event probabilities, two redundant components with the same Birnbaum values have identical F-V, RRW, and RAW values. Furthermore, the four measures are mathematically related so that higher Birnbaum implies higher F-V, RRW, and RAW given the same basic event probability.

The Birnbaum importance measures of the monitored components are critical inputs to the MSPI calculation and are determined by the licensee using their probabilistic risk assessment (PRA) models. An important aspect of PRA quality for MSPI implementation is the comparison of Birnbaum values within different classes of plant design. One should expect the Birnbaum values for like components modeled in the PRAs for two plants of similar design to be relatively close. For example, two 4-loop pressurized water reactors (PWRs) of the same thermal rating, with similar numbers and ratings of emergency diesel generators, auxiliary feedwater system pumps, and emergency core cooling system components should generally have Birnbaum values for like components that agree to within about a factor of 3 based on our reviews. Where there are greater differences, these can be attributable to the following:

- Important differences in balance-of-plant design, particularly electrical power and cooling water dependencies, or plant back-fits that have resulted in two otherwise similar plant designs to have divergent values.

- Differences in operating procedures and plant equipment performance: Some plants may have implemented off-normal or emergency operating procedures to address risk-significant scenarios. In other cases, the plant equipment performances might differ, and these are reflected in differing PRA model inputs and outputs.

- Finally, differences in PRA modeling assumptions and methods: The PRA models for two sister plants may have been prepared by two different organizations, using different software and databases, and/or modeling to differing levels of detail.

It is the first item, insights resulting from differences in plant designs, that is the topic of this paper. In this regard, the Standardized Plant Risk Analysis Risk (SPAR) models representing all 103 operating plants have proven useful in establishing a benchmark for this effort [3]. Because the SPAR models use identical industry-averaged failure rates, and similar modeling techniques, two of the three elements contributing to differences in plant Birnbaum values can be eliminated. Theoretically, any differences that exist for Birnbaum values for like components in a group of sister plants would be owing to differences in plant design. In many cases, very subtle differences such as the DC power dependencies or the installation of a non-safety pump can account for an order of magnitude or more difference in Birnbaum values. When combined with comparisons made by the authors between SPAR and the licensees' own PRA models, these insights can be useful in improving the safety of current and new designs. The insights for six key systems monitored by the MSPI are described below. Note that the cooling water system discussion addresses systems typically referred to as component cooling water and service water.

From a design perspective, it would be desirable to have a risk profile with low and symmetric Birnbaum values for major components within the system. Low Birnbaum values imply less sensitivity of the CDF to changes in overall equipment performance. All other things being equal, the Birnbaum values for the independent basic events of redundant components within a 3-fold redundant system (e.g., three emergency diesel generators) would be less than those for a 2-fold redundant system). This is because the cut sets in the former case contain an additional factor that reduces the overall contribution to CDF from the failure of the component in question.

Symmetric (i.e., nearly identical) Birnbaum values for similar components implies a balanced risk design. Where there is asymmetry, a greater dependence is placed on the component with the higher Birnbaum value (and correspondingly higher RRW and RAW) than the component with the lower value. Design is optimized from the risk perspective and often the cost-effectiveness perspective when further efforts are made to reduce high Birnbaum values for redundant components rather than already low ones.

EMERGENCY AC POWER SYSTEMS

Onsite electrical power at U.S. plants is typically provided by emergency diesel generators but can also be supported by gas turbine generators or hydro-electric generation. The focus of the emergency AC discussion is on the emergency diesel generators (EDGs). A logical premise is that the more EDGs available to a plant the lower the Birnbaum importance of the diesels. It would also be logical to expect that plants with similar nuclear steam supply system (NSSS) would have similar EDG importances. Both of these relationships were found to be not well correlated.

In the U.S., the number of EDGs per plant varies from two to eight. However, the importance of the EDGs is not only driven by the number of EDGs, but also by the degree of dedication of the EDG (dedicated or swing), the functions supported, and the availability and type of backup power given failure of the EDG. For single unit sites with two EDGs, and no alternate AC, for which there are about a dozen sites, the variations are minimized. The single failure criterion drives these plants to a very symmetric arrangement with two electrical safety divisions supporting like sets of safety equipment. At each site, these redundant EDGs have similar Birnbaums and are among the EDGs with the highest Birnbaums. However, some plants that have more than two EDGs also have one or more EDGs with high Birnbaums. Other EDGs at these plants are considerably lower in importance. This variability challenges the premise that increasing the number of EDGs reduces their importance. As the number of EDGs and alternate power sources increase, the variability due to items like function and backup power become more significant. Investigating the reasons for the variability in importance of the EDGs has yielded some interesting insights.

Significance of EDG Loads

This review found that the significant diesel loads driving the Birnbaum importance values are associated with heat removal and cooling water. The heat removal loads include auxiliary feed water (AFW) motor-driven pumps for PWRs and long term AC or DC power support for high pressure core injection/spray or reactor core isolation cooling for boiling water reactors (BWRs). The typical cooling water loads of interest are the cooling water pumps and occasionally valves associated with the isolation of non-critical loads. EDGs supporting these loads typically had higher Birnbaum values than those that did not. Consider as an example, a three EDG PWR plant that has two motor-driven AFW pumps. Each motor-driven pump is typically supported by an EDG leaving the remaining EDG without a supported AFW pump. This disconnect in the degree of redundancy between the AFW pumps and EDGs results in asymmetry of design. The EDGs supporting heat removal have higher Birnbaums. A similar impact holds true for cooling water. If the allocation of EDG support to the cooling water pumps varies per EDG, then those EDGs with greater support would be more important from a PRA perspective.

Alternatives on EDG Failure

The failure of an EDG in response to a loss of offsite power event can result in the loss of key safety equipment unless recoveries are available. The Birnbaum importance for a failure of an EDG in a two EDG plant is among the highest when there are no alternate AC options such as cross-connecting the impacted bus to another available bus or AC source. Multiple units typically have the flexibility to cross-tie buses between units. Other plants have non-safety class alternate AC sources. An EDG with an effective cross-connect will have a significantly lower Birnbaum than those without. However, not all recoveries are equally effective. Recoveries that require an assessment of availability of the opposite unit in a multiple unit site results in reduced availability from that of a dedicated alternate AC source. Recoveries that can not be employed immediately due to the complexity of the startup or alignment process are significantly less valuable than those that can be quickly and reliably aligned. The quick alignment is necessary to support the immediate and critical loads. A delay in alignment significantly reduces the effectiveness of the alternate AC source. Such delayed actions result in the AC source used for recovery being modeled as only maintaining battery capacity as opposed to supporting heat removal or cooling water pumps. Although battery support is an important function, it is considerably less important than the support of immediate and critical loads. A low human error probability for the alignment of the backup source is also important. Human error probabilities ranging from 0.3 to 1E-3 were observed.

Air Cooled versus Water Cooled EDGs

This review expected to find higher Birnbaums for air cooled EDGs then those of water-cooled EDGs due to the independence of air-cooled EDGs from support systems. This independence should result in a greater EDG availability and therefore a more robust ability to mitigate loss of offsite power events. However, loss of EDGs due to the failure of their associated cooling water was not observed in the dominant cut sets. Cooling water pumps are typically more reliable than EDGs and often there are redundant pumps available for cooling. As a result, the opposite impact of the EDG failures impacting cooling water was observed. This is discussed in the cooling water system section below.

HEAT REMOVAL SYSTEMS

The systems supporting the heat removal function are unique to their associated BWR or PWR reactor type. For BWRs, our review was limited to the importance of the turbine-driven reactor core isolation cooling (RCIC) pumps. Design features associated with isolation condenser plants were not investigated due to the small population of plants. The variation of the Birnbaum values for the 30 RCIC pumps reviewed was slightly larger than one order of magnitude and as such indicates that the importance of this pump is relatively independent of BWR type. For PWRs, motor-driven and turbine-driven auxiliary feedwater pumps (AFW) were reviewed including emergency feedwater system pumps which are considered for this discussion to be within the scope of AFW pumps. Our review noted a large variation in Birnbaum importances for these pumps even for plants with similar NSSS design and number of pumps. These variations are discussed below.

PWR Heat Removal – Base Configuration

Most PWR plants in the U.S. have redundant motor-driven auxiliary feedwater pumps, a turbine-driven pump, and feed and bleed capability. But even with these similarities, the effectiveness of the heat removal function varies significantly between units. This difference can be often traced to the degree of support system independence between these components. The motor-driven pumps are typically powered by independent safety-related diesel-backed AC buses. The turbine-driven pump often has a DC bus dependency that is ultimately powered by a safety-related diesel-backed AC bus. The power-operated relief valves that support the ability to feed and bleed are typically DC powered and again supported by a safety-related AC bus. Most plants require two PORVs for successful heat removal with either two or three available. For plants with two emergency diesel generators each providing an on-site power source to a safety-related bus, the dependency between these heat removal components is high. A two EDG configuration essentially results in five components (two motor-driven pumps, one turbine pump and two PORVs) or six components (when there are three PORVs available) supported ultimately by two electrical buses. If the failure of a safety bus results in a plant trip, then such a trip will significantly challenge the heat removal function. For example, assume a plant trip occurs as a result of the failure of the safety bus that supports the turbine-driven pump. This is typically the more significant bus for a two safety bus plant. This trip would result in the long-term loss of the turbine-driven pump, the failure of one the motor-driven pumps, and the lost of the ability to feed and bleed. In this example, the only remaining heat removal capability would be a single motor-driven AFW pump. As would be expected, plants with this configuration have many dominant cut sets associated with the loss of an AC bus.

Our review noted a large variation in the design of electrical distribution systems for U.S. plants, including the plants with the above heat removal components. These variations include electrical distribution systems where alternate power feeds are available to the turbine-driven pump, plants with no modeled turbine-driven pump electrical dependency, plants with electrical distribution systems that have alternate power feeds (typically DC power) to the PORVs, and plants with an increased number of safety buses and associated emergency diesel generators supporting these heat removal components. Some of the electrical distribution flexibility can be traced to battery charger arrangement. Batteries with a single battery charger provide minimal flexibility because the failure of a single on-site AC source or the associated AC bus will result in the loss of the DC bus. Batteries with two chargers each ultimately powered form a different on-site AC source yield much greater flexibility and are often the source of the alternate DC power feeds discussed above. It should be noted that our review found plants with redundant chargers that were powered from the same AC bus significantly reducing the benefit of the additional chargers. There are also plants that, because of high-head high capacity injection pumps and/or large capacity PORVs, only require one PORV for successful feed and bleed. The primary benefit of the one PORV feed and bleed configuration is reduced dependence on electrical supports.

Whatever the design configuration used, as the power sources are diversified, the overall system capability is increased and the individual importance of the heat removal components decreases.

Feed and Bleed

It would be reasonable to believe that plants with feed and bleed capability would have a more robust heat removal function than plants with a similar number of auxiliary feedwater pumps and no feed and bleed capability. This review found that the Birnbaum importances do not correlate well with this belief. That is not to say that there is no benefit associated with feed and bleed, for there clearly is. What it does indicate is that differences in the electrical system configurations need to be considered. As discussed above, a plant that trips due to a safety bus failure that impacts a motor- and turbine-driven pump is not as robust as a plant that is not impacted by a safety bus trip. Our review observed a plant without PORVs and not subjected to safety-related bus initiating events (plant does not trip on loss of a safety electrical bus) to have lower auxiliary feedwater importances than plants that are subjected to safety-related bus failures and that have feed and bleed capability. Other electrical configuration issues discussed in the previous section would also influence these importances.

Benefit of Additional AFW Pumps

Additional motor-driven pumps are only effective from a risk reduction perspective if they are able to recover the cut sets of concern. For example, a start-up AFW pump that does not have diesel backed power is not very valuable to a plant whose failures are dominated by the loss of offsite power. However, plants that have an additional motor-driven pump supported by dedicated or emergency diesel generator result in very low component Birnbaums for the remaining heat removal pumps. A few plants in the U.S have more than one turbine-driven pump. The turbine-driven pumps play a significant role in the mitigation of the loss of offsite power and safety bus initiating events. These plant challenges are typically important and therefore plants with additional turbine-driven pumps obtain significant benefit.

HIGH PRESSURE SAFETY INJECTION SYSTEMS

Like the heat removal systems, the systems supporting the high pressure injection function are unique to their associated BWR or PWR reactor type. For BWRs, we reviewed the turbine-driven high pressure coolant injection (HPCI) pumps, and the motor-driven high pressure core spray (HPCS) pumps and its dedicated diesel generator. For PWRs, motor-driven high pressure injection pumps and charging pumps, if applicable, were reviewed. Our review noted a large variation in Birnbaum importances for these pumps even for plants with similar NSSS design and number of pumps. These variations are discussed below.

BWR High Pressure Injection Function

BWR designs with high pressure coolant injection systems using a turbine driven pump, on average, exhibited smaller Birnbaum importance measures than designs with HPCS systems using a motor driven pump with a dedicated diesel generator. The HPCS designed plants, in general, employ a dedicated diesel generator to provide alternate AC power to the pump. This dedicated diesel generator typically supports the Division III electrical bus. At a few plants the HPCS diesel generator can be cross tied to the Division I or II electrical buses. The models reviewed included several variations to cross-connecting the HPCS diesel including only crediting the cross tie on failure of the HPCS pump or only crediting the cross tie on HPCS success. Because of the limited number of plants with this feature, the relative benefits of these two variations were not fully assessed.

The contribution to core damage frequency from HPCS diesel generators, albeit relatively low, is significant when compared to the contribution from the HPCS pumps. The contribution to risk from the failure of these dedicated diesel generators range from 2% to 7% of CDF, while the contribution from the HPCS pumps range from 0.01% to 0.2%. Plants with HPCI designs using a turbine driven pump, on the other hand, usually employ multiple diesel generators with considerable cross tie capability. This illustrates the disadvantage of a component having a unique function, the HPCS diesel generators, compared to a component capable of multiple functions, the emergency diesel generators. For example, the emergency diesel generators have the ability to provide support for SPC and provide electric power to a battery charger for station blackout mitigation, thus significantly reducing overall risk.

PWR High Pressure Injection Function

PWR designs examined included two pump, three pump and four pump configurations. As expected, the high pressure injection (HPI) pumps in the two pump designs typically have the highest Birnbaum values with a narrow uncertainty distribution. PWRs that incorporated three pump designs exhibited a high degree of variability in their importance measures. This high degree of variability is primarily a result of the way the third pump is installed and operated. The least benefit in terms of risk reduction was found in those plants that generally used the third pump as an installed spare. Although the use of an installed spare provided benefits in terms of test and maintenance unavailability, and a slight decrease in overall risk, the overall configuration had cut sets that were similar to the two pump configuration. The maximum risk reduction was generally observed with those plants that have installed and operate the third pump as a true redundant pump. There are other major design features that also contributed to the variability is the configuration of the support systems. Cooling water to HPI pump seals and bearings can be designed such that more than one pump is aligned to a single cooling water train resulting in multiple pumps being unavailable on the loss of that train. Other designs have the pumps supported by common headers and are therefore independent of a single train failure. Loss of AC bus initiating events that disable multiple pumps due to the loss of power were also found to be significant. Therefore, the more the third pumps behaves like a true redundant pump and the more flexible the cooling water and /or electrical plant alignment, the lower the pump's Birnbaum.

Many of the four pump configurations reviewed had two normally operating charging pumps and two high pressure injection standby pumps. A significant variability associated with this configuration is the success criteria used for the ability of the charging pumps to mitigate a loss-of-coolant accident (LOCA). Some plant models require both pumps for success while others only require a single pump. The two pump requirement significantly reduces the injection capability primarily as a result of requiring redundant and independent support systems. These support systems add reliability during normal charging operation but reduce the reliability during LOCA mitigation.

In general, four loop PWR designs with separate high and intermediate head designs exhibited the smallest median Birnbaum value for HPI pumps. In contrast, PWR designs without separate high and intermediate head designs and with feed & bleed capability exhibited the largest median Birnbaum importance value.

RESIDUAL HEAT REMOVAL SYSTEMS

The residual heat removal (RHR) systems are similar between BWRs and PWRs; however each reactor type has unique features that warrant separate discussions.

BWR Residual Heat Removal Systems

The BWR designs that have been reviewed consist of 3 or 4 RHR pumps and 2 or 4 heat exchangers (with one or two exceptions). These designs span a spectrum of reactor and containment designs (e.g., Mark I/II/III). In most cases, not all pumps are designed to be capable of suppression pool cooling. For example, in a three pump system design, it is likely that only two pumps are capable of providing suppression pool cooling while the third is relied upon primarily for low pressure coolant injection. In many PRAs, the residual heat removal function of the pumps has often been found to be more risk-significant than the low pressure injection function. This is because for many plant designs there are a limited number of ways to remove long-term decay heat, whereas there are numerous emergency core cooling system (ECCS) pumps (plus alternative injection sources). For transients with loss of condenser heat sinks, as well as LOCAs, loss of suppression pool cooling is often a dominant sequence. Numerous cut sets are found with combinations of RHR pumps, RHR service water pumps, and emergency diesel generators (for loss of offsite power events) contributing to overall CDF. The RHR pumps that provide suppression pool cooling are found to have significantly higher (one or more orders of magnitude) Birnbaum values than the pumps that do not. In effect, the pumps that do not provide suppression pool cooling are underutilized in comparison to the pumps that do.

Even with the allowance for common-cause failure contribution, the capability of the third (and fourth) pump to provide suppression pool cooling would tend to diminish the cut set contribution from these and similar sequences, thus reducing the Birnbaum values of the highest pumps and eliminating the gross asymmetry. All other things being equal, designing in the ability for the third (and fourth) pumps to provide more than one risk significant function would be risk beneficial.

PWR Residual Heat Removal Systems

A somewhat different situation has been found for some PWR designs. Here, our reviews have found tendencies that offer interesting insights. The situation arises with regard to the designs for long-term core cooling via containment sump recirculation. One class of plants provide containment sump recirculation primarily through one ECCS pump in each train, usually the high pressure safety injection (HPSI) pumps. A second set of plants require the so-called piggy-back mode of operation whereby the RHR/LPSI pumps take suction from the sump, and provide suction to HPSI pumps. In such latter designs, all other things being equal, the RHR pumps tend to have higher Birnbaum values because additional cut sets in small and medium LOCA sequences are found, such as

LOCA * RHR-PA * RHR-PB *...

that are not found in the designs where the HPSI pumps draw directly from the sump. In effect, the more equipment needed to mitigate a LOCA in the recirculation phase, the more cut sets can be found, resulting in additional contribution to CDF.

COOLING WATER SYSTEMS

There is a tremendous variation in the cooling water configurations used in the U.S. plants. Our review focused on those safety systems that cool the EDGs, high pressure safety injection pumps, and heat removal components including residual heat removal. Cooling water systems whose failure would result in a plant trip typically were the most important. They have both an initiating event and mitigation Birnbaum importance contribution. However, even within this set, there is a large variation in the component Birnbaum importance. For PWRs, for which most have an initiating event contribution, their importance is influenced by the design of the system interfaces, the safety functions supported and the available recovery actions. From an internal events perspective, systems that are aligned by trains, e.g., Component Cooling Water (CCW) Train A supported by Service Water Train (SW) A and CCW Train B supported by SW Train B, tended to provide less flexibility and lower reliability. Cut sets for this configuration include many cross-term basic events of failed CCW Train A and SW Train B resulting in total loss of cooling. Systems configurations that allow flexible train alignment or that have common piping connecting the discharge of redundant cooling pumps and heat exchangers tend to have greater resistance to support system failures. The impact of cross-term basic events for this more flexible alignment is significantly reduced. It should be noted that the negative side of this more flexible configuration is that passive pipe failures could result in the loss of the entire system.

PWR cooling water system components that provide both RCP seal cooling and high pressure safety injection pump cooling typically have high Birnbaums unless there are effective recovery actions available. Note that the type of RCP seals and the associated RCP seal LOCA model is an additional variable that can have a significant impact on the Birnbaum values. Many modeled recoveries were observed including alignment of swing pumps and/or swing power sources and the use of alternate cooling such as the fire protection system. Some plants had diverse high pressure safety injection cooling whereby one or more pumps were independent of RCP seal cooling. Plants with highest cooling water Birnbaum values were those that have cooling water initiating event contributions, limited or no recoveries and functioned to provide RCP seal cooling and high pressure safety injection pump cooling.

Number of Cooling Water Pumps

A correlation between the number of cooling water pumps within a system with their importance was not found. This is in part due to the variation of functions and recovery actions possible as discussed above. It is also related to the configuration of the electrical design of the plant. Our review found that many important cooling water cut sets are associated with one or more EDG failures. In many cases, the number of EDGs is less than the number of cooling water pumps. This results in multiple pumps being supported by each EDG. Therefore, an EDG failure can result in the loss of multiple pumps significantly reducing the cooling water system's redundancy and, when combined with other cooling water system failures, can result in the complete loss of cooling water. Cooling water systems that are shared between units often benefit from the increase level of onsite AC power redundancy that is afforded from multiple units. This reduces the number of EDGs per cooling water pump and therefore minimizes the impact of an EDG failure on cooling water. Lastly, two plants were found to have diesel-driven cooling water pumps. These are typically standby pumps and are effective at removing the support system failures but have lower reliability than motor-driven pumps.

CONCLUSIONS

The focus on Birnbaum importance helped to reveal plant design elements that were otherwise obfuscated by the complex interactions of a plant's systems. Our review found that the typical categorization of plants by high level attributes such as, NSSS type, number of EDGs, and feed and bleed capability is not completely effective in understanding the drivers of component importances. We found that EDGs are completely independent of NSSS type including whether the plant is a BWR or PWR. Our review found that a significant contributor is the design of the interfaces between systems. This includes the mapping of the diesel-backed AC buses to the critical loads and the design of the interfaces between cooling systems and their loads. A final critical feature is the availability of alternate systems and credited operator recovery actions. It should be noted that some NSSS design features do play significant roles. These include whether RCIC or AFW systems are employed, the type of RCP seals, and the use of the RHR piggy-back function.

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