Comparison of four composite landfill liner systems considering leakage rate and mass flux

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ABSTRACT: Performance of four different municipal solid waste landfill liner systems, i.e., Subtitle D composite liner system, composite liner system with a geosynthetic clay liner (GCL) instead of low permeability compacted soil, Wisconsin NR500 liner system, and proposed four-component composite liner system that is a combination of the GCL composite liner system and the Subtitle D liner (with a 61 cm (2 feet) or 91.5 cm (3 feet) thick compacted clay liner), were evaluated in terms of leakage rate and mass flux. The leakage rate through circular and non-circular geomembrane (GM) defects was analyzed using both analytical and numerical methods. For the mass flux evaluation, solute transport analyses using GM defects and diffusion of volatile organic compounds through intact liners were conducted using one- and three-dimensional numerical models. Cadmium and toluene were used as typical inorganic and organic substances, respectively, in the analyses. The comparison shows that the proposed four-component composite liner system outperforms the other liner systems based on leakage rate and mass flux and is a viable choice for a liner system.

1 INTRODUCTON

Leakage rate has been commonly used to evaluate the performance of municipal solid waste (MSW) landfill liner systems. A liner system that allows the lowest leakage rate is deemed to exhibit the best performance. However, several studies suggest that the criterion of only leakage rate might not be sufficient for assessing the performance of composite liner systems (Crooks and Quigley 1984; Rowe 1987; Shackelford and Daniel 1991a and b; Foose et al. 2002) because advective flow is not the only mechanism of mass transport. Instead, solute transport should also be considered so the importance of volatile organic compounds (VOCs) is addressed to fully evaluate liner system performance (Foose et al. 2002). In this study, contaminant mass flux from the base of each liner system is estimated and compared with the flux from the other liner systems to evaluate the relative performance of each liner system.

The following three types of composite liner systems are commonly used in MSW landfills, the Subtitle D liner (the liner prescribed in Subtitle D of the Resource Conservation and Recovery Act, US EPA), the GCL composite liner (a popular alternative liner system to the Subtitle D system), and the Wisconsin NR500 liner (the liner prescribed in the Wisconsin Administrative Code Section NR500) and evaluated by Foose et al. (2002). The Subtitle D and the Wisconsin NR500 liners consist of a GM underlain by low permeability compacted soil with thicknesses of ≥61 and ≥122 cm, respectively. The GCL composite liner consists of a geomembrane (GM) underlain by a GCL. Foose et al. (2002) analyzed the performance of these three composite liners using estimates of leakage rate and mass flux. Cadmium and toluene were used by Foose et al. (2002) as typical inorganic and organic leachate constituents, respectively, in the landfill. The results indicate that the GCL composite liner exhibits the lowest leakage rate and lowest mass flux of the inorganic substances such as cadmium. However, the mass flux of organic substances such as toluene through the GCL composite liner is two to three orders of magnitude greater than that through the intact Subtitle D or Wisconsin NR500 liner systems owing to the small thickness of the GCL and thus small attenuation volume.

This study sought a more effective composite liner that not only possessed a low leakage rate but also a low mass flux for organic and inorganic substances. A four-component liner comprised of a GM/GCL liner and a GM/ low permeability compacted soil layer (61 or 91.5 cm thick), has been proposed for several new landfills or landfill expansions to protect important groundwater resources and facilitate permitting. This liner system is described in more detail below and was believed to exceed all performance requirements for a landfill liner and provide superior performance to the GCL composite liner, the Subtitle D liner, and the Wisconsin NR500 liner systems because it combines the benefits of these liner systems, e.g., two GMs, a GCL to reduce advective flow, and a thick layer of low permeability compacted soil liner to reduce diffusive flow. However, there was no published evidence to demonstrate the performance of this four-component composite liner system and its performance compared to the GCL composite liner, the Subtitle D liner, and the Wisconsin NR500 liner systems. As a result, this paper presents a procedure for demonstrating the effectiveness of the proposed four-component composite liner system. The proposed four-component composite liner system is compared to the GCL composite liner, the Subtitle D liner, and the Wisconsin NR500 liner systems using the following two performance criteria: (1) leakage rate and (2) mass flux from the base of the liner system. Analysis of leakage rate is estimated assuming defects in the GM. A solute transport analysis is performed to estimate the mass flux through the four-component composite liner system using a geomembrane with and without defects.

2 LEAKAGE RATE ESTIMATION

2.1 *Leakage rate model*

Foose et al. (2002) employed a finite difference numerical program, MODFLOW (McDonald and Harbaugh 1988), to estimate leakage rates through a composite liner with a defective GM. The numerical simulation is useful because it is usually difficult to conduct laboratory and field experiments on the performance of composite liner systems (Foose et al. 2001). In this study, an upgraded version of MODFLOW, MODFLOW 2000 (Harbaugh et al. 2000), was used to solve the three-dimensional governing equation for flow through the proposed double composite liner system assuming a steady-state condition. The conceptual flow model through two vertically coaxial circular defects in the GMs of a double composite liner system is presented in Fig. 1(a). In addition, the finite difference mesh used for the numerical analysis is shown in Fig. 1(b). The modeling of the composite liners and the boundary conditions were instructed by Foose et al. (2001, 2002).

Only one quadrant of a circular defect was modeled due to the axisymmetric geometry. Two layers of no-flow cells are modeled to simulate the two layers of GM. To model the worst situation, the two GM defects are assumed to be vertically coaxial. The upper defect was simulated using

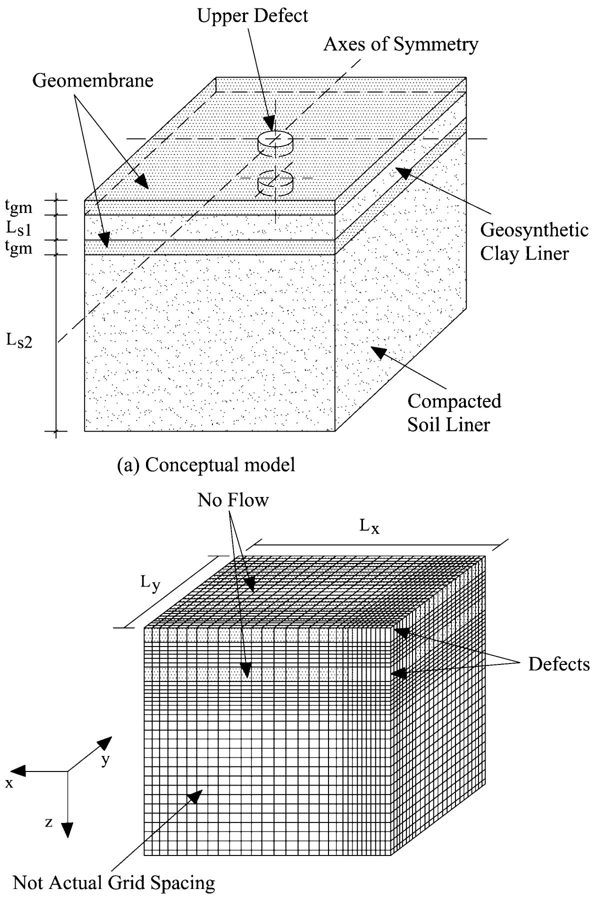

FIG. 1. Numerical modeling of flow through a circular defect in a double composite liner system

constant head cells. The constant head assigned to these cells is $h_t = 2t_{gm} + L_{s1} + L_{s2} + h_p$, where t_{gm} = thickness of the geomembrane, L_{s1} and L_{s2} = thicknesses of the GCL and the compacted soil liner, respectively (see Fig. 1 (a)), and h_p = 30 cm = depth of leachate in the landfill. It was assumed that the depth of leachate was constant due to the lack of data about the variation of leachate depth with time and to be conservative. The side boundaries were modeled as no-flux boundaries. The bottom boundary was modeled as a fully draining boundary with a constant head of zero. The geosynthetic and compacted soil liners were assumed to be saturated, homogeneous, and isotropic. The width of the model is 100 cm ($L_x = L_y$ = 100 cm), which is large enough for simulation of flow through defects (Foose et al. 1998).

Two numerical models were developed to consider cases of infinitely and finitely long defects. A two-dimensional numerical model with a unit length in the y direction is used to evaluate the leakage rate through the infinitely long defects in the geomembranes. Only half of the defect width is modeled due to the symmetric geometry. The mesh size in the *x*- and *z*-directions is identical to that of

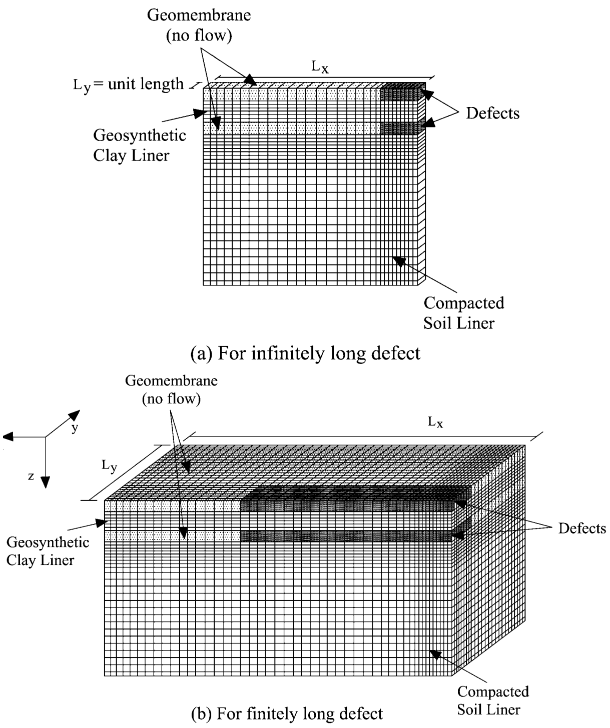

FIG. 2. Numerical models for flow through (a) infinitely and (b) finitely long defects in a double composite liner system

the three-dimensional model for circular defects (see Fig. 2(a)). A three-dimensional numerical model is developed to estimate the leakage rates through the finitely long defects in the double composite liners (see Fig. 2(b)). Only one quadrant of a long defect is modeled due to the symmetric geometry. The dimension is large enough for simulation of flow through the defect. Other conditions and parameters are the same as the three-dimensional model of the circular defect.

Leakage rates through a GM defect in the four composite liner systems considered and frequently used in practice are presented below and the four liner systems consist of:

1. Subtitle D liner system with 61 cm (2 feet) or 92 cm (3 feet) thick low permeability compacted soil liner overlain by a GM.

2. Wisconsin NR500 Liner which consists of a GM and underlain by low permeability compacted soil liner with thickness of 122 cm (4 feet).

3. GCL composite liner system with a GM underlain by a 6.5 mm thick GCL.

4. Proposed four-component composite liner system consists of four components from top to bottom of GM, 6.5 mm thick GCL, GM, and 61 cm (2 feet) or 92 cm (3 feet) thick compacted soil liner.

2.2 *Circular GM defects*

Leakage rates through circular defects in the GM of the composite liner systems were estimated

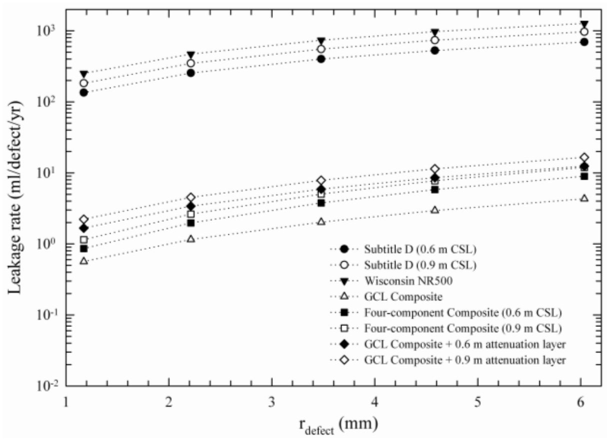

FIG. 3. Leakage rates through circular defects in composite liners with perfect contact

herein using MODFLOW 2000. In each analysis, the mass balance errors are less than 1%. Fig. 3 compares the leakage rates through circular defects in the four composite liner systems estimated using MODFLOW 2000. The four-component composite liner system with a 0.6 or 0.9 m thick soil liner yields significantly lower leakage rates than the Subtitle D liner system. Similar to the case of Subtitle D liners, the thicker the compacted soil liner in the proposed four-component composite liner system, the slightly higher the leakage rate. The leakage rates for the proposed four-component composite liner system range from 0.86 to 11.94 mL/defect/year for a defect radius of 1 to 6 mm. These leakage rates are comparable to those of the GCL composite liner system.

For comparison purposes only, the leakage rates for a GCL composite liner underlain by an attenuation layer of 0.6 and 0.9 m thick are compared with the proposed double composite liner system having the same compacted soil liner thicknesses. The attenuation layers have a hydraulic conductivity of 1×10^{-5} cm/s (Rowe 1998). Fig. 3 shows the leakage rates of the GCL liners with the attenuation layers are slightly higher than the proposed double composite liner, which shows that the proposed double composite liner system provides a superior performance to the other liner systems considered in terms of leakage rate.

2.3 *Long GM defects*

Leakage rates through infinitely long defects in the GM of the composite liner systems were estimated using MODFLOW 2000 and limiting mass balance errors to less than 1%. Fig. 4 compares the leakage rates through infinitely long defects in the four composite liner systems considered using the validated MODFLOW 2000 model. The leakage rates through infinitely long defects in the four-component composite liner system are 30 to 40 times lower than those for the Subtitle D liner. The

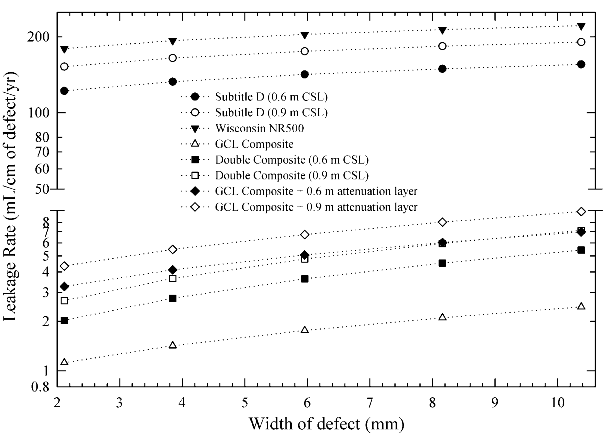

FIG. 4. Leakage rates through infinitely long defects in composite liners with perfect contact

leakage rates for the proposed four-component composite liner are slightly higher than the GCL composite liner, which is similar for circular defects. A GCL composite liner underlain by an additional attenuation layer of 0.6 or 0.9 m thickness, required to control diffusion, also shows higher leakage rates than the proposed four-component composite liner. Consequently, the proposed four-component composite liner system provides the lowest leakage rate for long defects of the liner systems considered except the GCL composite liner system which is slightly lower on the log-scale.

A series of simulations were performed to verify the relationship between leakage rate and defect length for the constant width of 2 mm. The three dimensional model shown in Fig. 2(b) was used for these simulations. The leakage rate of the GCL composite liner is higher than the proposed double composite liner when the defect length is relatively small, and there is a transitional value of defect length at which the GCL leakage rate becomes smaller than the proposed double composite liner (see Fig. 5). The transitional value for a defect width of 2 mm is estimated to be 0.65 m and 0.87 m for the proposed double composite liner with

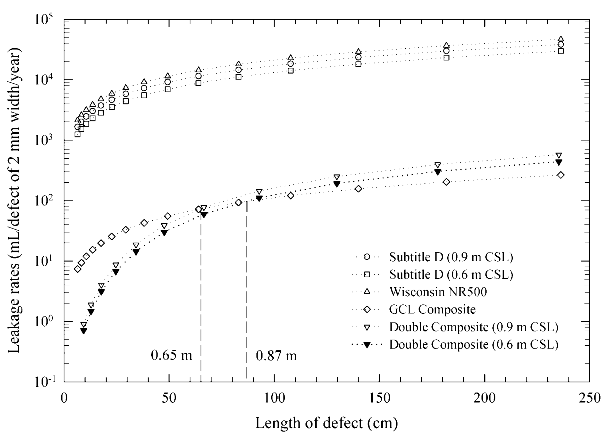

FIG. 5. Effect of defect length on leakage rates with defect widths of 2 mm

0.9 and 0.6 m thick compacted soil liners, respectively.

3 SOLUTE TRANSPORT

3.1 *Inorganic solute transport through a defective four-component composite liner system*

3.1.1 *Inorganic solute transport modeling and input parameters*

Adopting the flow or leakage rate solutions obtained from MODFLOW 2000, the inorganic solute transport through defects in the double composite liner system is simulated using MT3DMS (Zheng 2006). MT3DMS simulates the solute transport of multiple species in three dimensional groundwater flow systems. MT3DMS employs the implicit method in solving the governing equation, which is very time efficient. In this study, the cadmium transport through defects in the double composite liner is calculated and compared with the mass flux through the Wisconsin NR500, Subtitle D, and GCL composite liners. The finite-difference used for the flow solution in MODFLOW 2000 (see Fig. 1(b)) was also used in MT3DMS. In the numerical model, the lateral sides and geomembranes are modeled as zero solute flux conditions. The defect in the upper geomembrane and the bottom boundary are modeled as constant solute concentration cells. The constant solute concentration cells in the defect represent a constant solute source which is conservative because leachate solute concentration decreases with time during solute transport. The constant solute concentration of cadmium is fixed to be 100 μg/L. The input parameters can be found in Foose et al. (2002).

3.1.2 *Inorganic solute transport results*

To calculate the mass flux and cumulative mass of cadmium for one hectare of liner, the values obtained from MT3DMS for one defect are multiplied by 2.5 because Giroud and Bonaparte (1989) recommended the frequency of geomembrane defects is 2.5 defects/ha. The area of circular defects in the GMs of the double composite liner system is selected as 0.66 cm^2. The total simulation period is 100 years. Fig. 6 presents the results of the simulation of cadmium transport through defects in the geomembranes of the Wisconsin NR500, Subtitle D, GCL composite, and proposed double composite liner systems. The mass balance errors of the simulations are less than 1%. The three former liners are reanalyzed using MT3DMS with the same input parameters used by Foose et al. (2002) to verify the model develop herein. The MT3DMS results show good agreement with those in Foose et

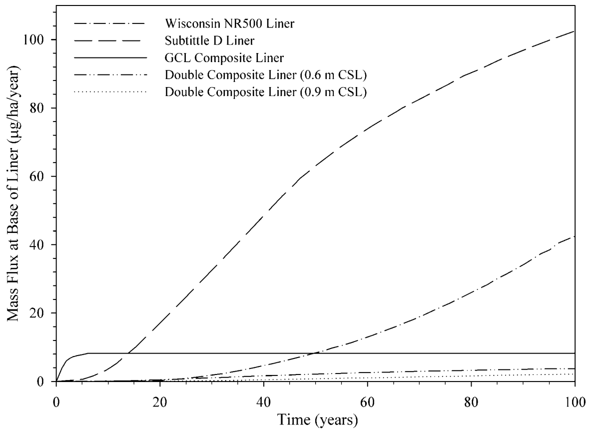

FIG. 6. Comparison of mass flux of cadmium transported through the four landfill liner systems considered

al. (2002). For the proposed double composite liner, the mass flux from the base of the liners is the smallest during the 100 year period for the four liner systems considered. For the proposed double composite liner with 0.6 m and 0.9 m of compacted soil liner (CSL), the mass flux after 100 years are 3.75 μg/ha/year and 2.12 μg/ha/year, respectively. The comparison shows excellent solute transport performance of the proposed double composite liner systems with extremely small mass flux of cadmium being transported through the liner system.

3.2 *Organic solute transport through intact four-component composite liner system*

3.2.1 *Diffusive transport modeling for organic solute*

The one-dimensional block-centered model of diffusive transport of toluene through intact double composite liners was developed to solve the governing diffusive equations for GM and soil liner layers. In the GM, the concentration of toluene and the coordinate in *z*-direction are normalized by $K_{d,gm}$ ($K_{d,gm}$ = partition coefficient for the GM and toluene) to account for the large difference between the concentrations of toluene in the GM and soil liner. The explicit method was employed in this model. This approach has an advantage that the interfaces can be handled without difficulty since there is no node on the interface. The bottom boundary conditions for the block-centered models were chosen as previously defined by Foose et al. (2002). The constant concentration at the bottom boundary was zero and the locations of it were at the base of the liner or 9 m from the base of liner. In addition, the time of simulations was also selected to be 100 years as in Foose et al. (2002).

3.2.2 *Diffusive transport results*

Fig. 7 shows that the double composite liners are the most effective liners in terms of the mass flow

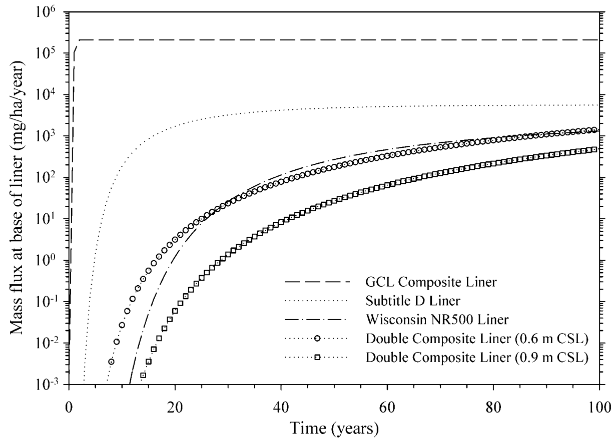

FIG. 7. Mass flux for transport of toluene with concentration at base equal to 0 μg/L

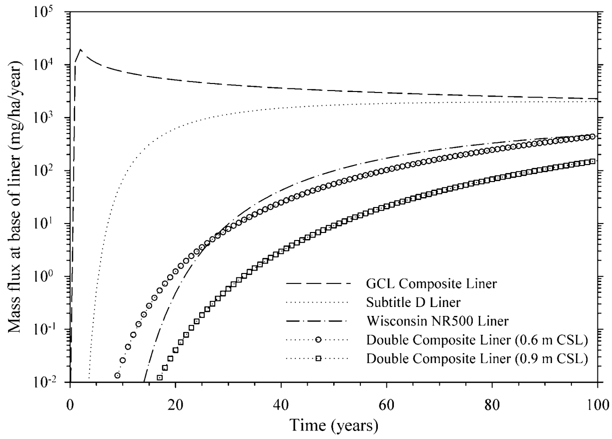

FIG. 8. Mass flux for transport of toluene with semi-infinite bottom boundary condition

rate of toluene at 100 years for the case of a constant concentration of zero at the base of the liners. The intact double composite liners permit minimum diffusion of toluene among the composite liners. The mass fluxes of toluene through intact double composite liners at the end of the simulation are 1432 and 489 mg/ha/year for the cases of the compacted clay liner layers having thicknesses of 2 and 3 feet, respectively.

For the case of the semi-infinite bottom boundary condition, which can be represented by the bottom boundary at the depth of 9 m from the base of the liner (Foose et al. 2002), the results also show that the double composite liners are most efficient for the landfill constructions (see Fig. 8). With the double composite liner of 2 feet of compacted clay liner, the mass flux after 100 years is almost equal to that for the Wisconsin NR500 liner. In this case, the mass fluxes at the end of the simulation are 445 and 153 mg/ha/year for the cases of the compacted clay liner layers having thicknesses of 2 and 3 feet, respectively.

4 CONCLUSION

The performance of the proposed four-component composite liner system was analyzed and compared to three other composite liner systems in terms of leakage rate and mass flux. The numerical models provide a useful means for evaluating the performance and protectiveness of these and other composite liner systems because there is limited field leakage rate and mass flux data published to date for these liner systems. The leakage rates through circular and long defects in the proposed four-component composite liner are lower than the Wisconsin NR500 liner and the Subtitle D liner and comparable to the GCL composite liner.

For the cadmium (inorganic compound) solute transport analysis, the proposed four-component composite liner exhibits the lowest mass flux and cumulative mass of the four liner systems considered. The mass flux and cumulative mass after 100 years of toluene (organic compound) transport through an intact four-component composite liner is also smaller than the amounts through the other three composite liner systems considered. Based on leakage rate, mass flux, and cumulative mass, the proposed four-component composite liner exhibits the best performance of the four liner systems considered.

The four-component composite liner with a 0.6 m thick compacted soil liner layer at the bottom has a lower leakage rate and equivalent mass flux for toluene than the Wisconsin NR500 liner, which consists of a GM and 1.2 m of compacted soil liner. With the above advantages, it may be concluded that the proposed four-component composite liner system represents a more protective design for MSW landfills than the other three composite liner systems considered. Transport analyses for other chemical species through the four-component composite liner system are being performed to evaluate the effectiveness of this system for a wide range of constituents.

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