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The Relationship Between Smoke Yields and Tipping Materials of the Cigarette

Young-Hoh Kim*, Young-Taek Lee, Sung-Han Kim, Chung-Ryul Kim, Jong-Yeol Kim, Chang-Ho Shin and Keun-Hoi Lee

Korea Ginseng and Tobacco Research Institute, Taejon 305-345, Korea

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ABSTRACT : In order to minimize the trial frequency in the new filter cigarette design, we studied the relationship between smoke yield and tipping materials of cigarette. A three levels full factorial design involving filament denier (X_1,2.5-3.3d), porosity of the acetate filter plug wrap (X_2, 3,500-16,000CU) and porosity of the tip paper (X_3, 400-1,200CU) was used. Three independent factors (X_1, X_2, X_3) were chosen for their effects on the various responses and the function was expressed in terms of a quadratic polynomial equation, $Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33} X_3^2 + \beta_{12} X_1X_2 + \beta_{13} X_1X_3 + \beta_{23} X_2X_3$ which measures the linear, quadratic, and interaction effects. Twenty-nine trial numbers were obtained as a results of using a three levels full factorial design and it was analyzed by the multiple regression analysis with backward stepwise in *STATISTICA*/pc under restricted conditions. Tar yields of the cigarette was affected by porosity of tip paper (0.66), filament denier (0.47) and porosity of plug wrap (0.28) in the decreasing order, and linear effect of tip paper porosity (β_3) and filament denier (β_1) were significant at a level of 0.01(α). The filament denier and tipping paper porosity interaction F ratio among three factors had a *P*-value of 0.000041, indicating higher interaction between these factors. Based on the analysis of variance, the model fitted for Tar (Y_1) was significant at 5% confidence level and the coefficient of determination (0.96) was the proportion of variability in the data fitted for by the model.

Key words : **Factorial design, Independent variable & factor, Linear & quadratic effect**

There is wide spreading interest in designing and predicting the degree of delivery of cigarette tar effected by ventilating the filter. It is recognized that tar delivery depends upon an interrelationship of numerous factors, involving not only the resistance to influx of fresh air presented through the micro holes of the tipping and plug wrap paper, but also the pressure drop of the filter plug by the filament and total denier of the acetate tow, itself(Selke, 1978). So many articles (Dwyer, 1986, Keith,1979, Parker,1979) try to derive a theoretic and empirical prediction model of the filter pressure drop and ventilation rate for the cigarette design. Ventilated filter cigarette design have been used for long term periods to reduce delivered tar amount while maintaining acceptable cigarette unencapsulated pressure drop. One concepts in selecting a specific design from many options available might be the variability of cigarette physical properties. Variation in tar delivery and filter ventilation arise from many sources including variation in tobacco column pressure drop, filter

* Corresponding author : *Korea Ginseng and Tobacco Research Institute, Shinsung-Dong, Yusung-Ku, Taejon 305-345, Korea*

tip pressure drop, tipping paper permeability, and plug wrap paper permeability (Selke,1979, Keith, 1978). For the purpose of designing a new cigarette, One should be find many combinations of filter tip pressure drop, tipping paper permeability and plug wrap permeability which are consistent with a target tar and ventilation level for a cigarette having a restricted tobacco column weight(PDM, 1995). Mathematical models which relate properties of cigarette components to tar delivery and filter ventilation level can be used to examine the relationships of component variability on the cigarette performance and to study the expected variability of alternative cigarette design. At the point of these mathematical calculation is a routine which uses a detailed understanding of the effect of tipping materials on cigarette ventilation level and tar delivery(Broune,1990, Kiefer,1980). Selecting the optimum cigarette design to achieve specific tar yield and filter ventilation requires the simultaneous solution of several complicated polynomial equations(Curran,1982). Therefore, this experiment was initiated to develop the relationships of ventilation parameters and tar delivery. The specific objective was to provide a means of estimating the effects tipping materials on the amount of air dilution and tar delivery. To accomplish this objective we had to determine the effect of the tipping materials involving filament denier and permeability of plugwrap and tip paper on the amount of cigarette ventilation and delivery tar.

MATERIALS AND METHODS

Wrapping materials. A ventilation materials study was also conducted to determine the effect of tipping materials on the ventilation level achieved. Variables included in the study were three levels of filament denier, tipping paper, and plug wrap permeability. Denier per filament for the filter plug were selected for three levels of 2.5, 2.9, and 3.3 denier. Permeability of tipping paper which were punched in 4 rows with 18 holes at each perforating line were selected at three levels of 400, 800, and 1,200 CORESTA unit(CU), and plugwrap porosities were also selected at three levels of 3,500, 9,500, and 16,000 CU. Because of any variation in the permeability of the plug wrap has a major impact on the uniformity of filter ventilation. The air permeability of porous plug wrap must not only specify to the target but must also be as uniform as possible. Air permeability of porous plug wrap and tipping paper was generally measured by the CORESTA method using $2Cm^2$ measuring head of Heiner Borgwaldt porosimeter.

Cigarette preparation. A 3*3 level factorial design was used for each filament denier and each porosities of wrapping papers. Dependant variables ($Y_{1,2}$) were selected as tar delivery and cigarette ventilation levels. Cigarette which was 84mm in overall length including 24mm filter section and was wrapped with cigarette paper at a permeability of 60 Cm/min. measured at one cbar was used in this study. The tipping paper had four rows of micro laser perforation at the position of 12.5mm from mouth and the width between rows of perforation was 1mm. In order to minimize the fluctuation of the analysis results, tobacco column weight (620mg/cig), total denier(40,000d), cigarette circumference(24.8mm) were fixed as a consistent factors. Filament denier of the tow ranged between 2.5d and 3.3d. Test cigarette were prepared for each denier per filament at three permeability

Table 1. Coded three independent factors with 3-levels for the tar delivery and cigarette ventilation rate experiment

Independent factors	code change	actual value
filament denier(FDT)	-1, 0, +1	2.5d, 2.9d, 3.3d
permeability of plugwrap paper(PWP)	-1, 0, +1	3,500, 9,500, 16,000
permeability of tipping paper(TPP)	-1, 0, +1	400, 800, 1,200

targets of plug wrap with three levels of permeability of tipping paper. Table 1 showed coaded three independent factors with three levels for the tar delivery and cigarette ventilation rate experiment.

Tar and ventilation rate measurement. A full three level factorial design was used to reduce the testing error. All hand-made cigarette were smoked by using standard CORESTA smoking method. The cigarette for tar delivery analysis ,that is, were smoked to a 32mm butt length; 3mm beyond the overwrap by tip paper. The calculation of delivered tar is the amount that sustracts the water content and nicotine content from cigarette total particulate matters trapped on the Cambridge pad. the calculation for delivered tar is : Delivered tar = cigarette particulate matter- delivered nicotine -delivered water. and the level of filter ventilation rate was measured using by *FILTRONA* ventilation rate tester.

Statistical analysis. Mathematical models which relate properties of cigarette components to tar delivery and filter ventilation were employed with a three levels and three factors full factorial analysis to study the expected variability of alternative cigarette designs. The lower significant data which was gained by statistical analysis with their interactions among 3 independent factors were pooled down to get a higher significant value(F,T values) used by backward stepwise. R-square value, polynomial equation coefficients and its accuracy were determined used by *STATISTICA*/pc statistical software.

RESULTS AND DISCUSSION

One needs to determine exactly which of the independent factors significantly affected the dependant variable of interest. It was desired to learn which of the factors involved in the tipping material, that is, permeability of plugwrap paper and tipping paper, filament denier for filter plug affected the level of tar delivery and cigarette ventilation rate(table 2). As expected reduction in tar delivery was directly related to the amount of filter ventilation. Reduction in tar delivery at constant filament denier and plugwrap porosity was also related to the level of ventilation, Maximum reduction occured when the permeability of tipping paper was the highest to code +1.2 at the center point of the independent factors. Each factor is at three levels arranged in a factorial experiment. This was a 3^3 factorial design, and the experimental layout and treatment combination notation were shown in table 2. The analysis of variance and the regression results were summarized in Table 3,4 for tar delivery. These table indicated that the filament denier, permeability of plugwrap and tipping paper significantly affected the level of tar delivery, and also filament denier and tipping paper porosity interaction *F* ratio(1Q by 3L) had a *P*-value of 0.000041, indicating higher interaction between both factors(Tab 3). Notice that one of three variables had negative

Table 2. Tar delivery and ventilation rate data following the code combination

code	vent	tar	code	vent	tar	code	vent	tar
-1 -1 -1	38	7.4	-1 -1 0	53	5.4	-1 -1 +1	55	3.8
-1 0 -1	39	7.2	-1 0 0	55	5.3	-1 0 +1	59	4.2
-1 0 -1	41	7.2	-1 0 0	56	5.0	-1 +1 +1	61	3.9
0 -1 -1	36	5.9	0 -1 0	51	4.9	0 -1 +1	54	4.5
0 0 -1	36	6.0	0 0 0	53	5.7	0 0 +1	58	4.8
0 +1 -1	37	6.5	0 +1 0	57	5.4	0 +1 +1	59	5.1
+1 -1 -1	29	9.4	+1 -1 0	47	6.7	+1 -1 +1	50	6.0
+1 0 -1	34	7.8	+1 0 0	50	5.9	+1 0 +1	52	5.4
+1 +1 -1	37	6.8	+1 +1 0	51	5.3	+1 +1 +1	55	4.7

Table 3. Analysis of variance for tar delivery data

Factor		SS	df	MS	F	p
(1) FTD	(L)	4.10889 *	1 *	4.10889 *	44.6189 *	.000003 *
FTD	(Q)	1.77852 *	1 *	1.77852 *	19.3131 *	.000350 *
(2) PWP	(L)	.93389 *	1 *	.93389 *	10.1412 *	.005134 *
(3) TPP	(L)	26.40222 *	1 *	26.40222 *	286.7049 *	.000000 *
TPP	(Q)	1.01407 *	1 *	1.01407 *	11.0120 *	.003823 *
1L by 2L		1.92000 *	1 *	1.92000 *	20.8495 *	.000239 *
1Q by 2L		2.35111 *	1 *	2.35111 *	25.5310 *	.000083 *
1Q by 3L		2.66778 *	1 *	2.66778 *	28.9697 *	.000041 *
Error		1.65759	18	.09209		
Total SS		42.83407	26			

main effects in table 4; that is, increasing the variable moves the average deviation from the tar target downward. The 27 treatment combinations had 26 degree of freedom. Each main effect has 2 degrees of freedom, each two-factor interaction had 4 degrees of freedom, and three-factor interaction had 8 degrees of freedom. The sums of squares have been computed by the usual methods. We knew that the three all factors were statistically significant at the level of 0.01. Two-factor interactions except X_2 by X_3 were also significant at 0.01. Linear and quadratic effect of tipping paper permeability seem be most effective in reducing tar delivery following the table 4. while in the case of ANOVA of ventilation, No significant interaction of those factors were shown from table 5. Tar delivery of the cigarette was affected by porosity of tip paper(0.66), filament denier(0.47) and porosity of plugwrap(0.28) in the decreasing order, and also cigarette ventilation rate of linear effect of tipping paper porosity (X_3, 9.77) and filament denier (X_1, 2.88), and plugwrap porosity (X_2, 2.88) were significant at a level of 0.01(α). Table 4,6 showed these linear and quadratic regression models for tar delivery and ventilation rate. The regression coefficients for each independent factors in this models were estimated using a standard linear and quadratic regression computed program. In this model, the variable $X_{1,2,3}$ were coded to the levels −1, 0, +1 as discussed previously, and We can be assumed the following natural levels for filament denier for tow, permeability of plugwrap paper and tipping paper. Regression equation and its interaction effects

Table 4. Regression coefficient and its significance in tar delivery

Factor		Regression Coeff.	Std.Err.	t(18)	p	−95.% Cnf.Limt	+95.% Cnf.Limt
Mean/Interc.		5.148148*	.130589*	39.42260*	.000000*	4.87379*	5.422505*
(1) FTD	(L)	.477778*	.071526*	6.67974*	.000003*	.32751*	.628049*
FTD	(Q)	.544444*	.123887*	4.39467*	.000350*	.28417*	.804722*
(2) PWP	(L)	.283333*	.123887*	2.28702*	.034522*	.02306*	.543611*
(3) TPP	(L)	−.666667*	.123887*	−5.38123*	.000041*	−.92694*	−.406389*
TPP	(Q)	.411111*	.123887*	3.31843*	.003823*	.15083*	.671389*
1L by 2L		−.400000*	.087602*	−4.56613*	.000239*	−.58404*	−.215956*
1Q by 2L		−.766667*	.151730*	−5.05282*	.000083*	−1.08544*	−.447893*
1Q by 3L		−.816667*	.151730*	−5.38235*	.000041*	−1.13544*	−.497893*

Table 5. Analysis of variance for cigarette ventilation rate

Factor		SS	df	MS	F	p
(1)FTD	L+Q	157.630 *	2 *	78.8148 *	38.1704 *	.000081 *
(2)PWP	L+Q	93.852 *	2 *	46.9259 *	22.7265 *	.000502 *
(3)TPP	L+Q	1970.074 *	2 *	985.0370 *	477.0583 *	.000000 *
1*2		3.037	4	.7593	.3677	.825360
1*3		4.148	4	1.0370	.5022	.735811
2*3		1.926	4	.4815	.2332	.912005
Error		16.519	8	2.0648		
Total SS		2247.185	26			

could be expressed in terms of a quadratic polynomial equation, $Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33} X_3^2 + \beta_{12} X_1X_2 + \beta_{13} X_1X_3 + \beta_{23} X_2X_3$ which measured the linear, quadratic and interaction effects. The regression equations were shown in tables 4(tar delivery) and 6(ventilation rate). Each regression equation was tested lack of fit. Based on the analysis of variance, the model fitted for tar delivery(Y_1) was significant at 5% confidence level and the coefficient of determination (r^2=0.96) was the proportion of variability in the data well fitted for by the model. A simple way to present 18 independent or interaction factors in this experiment is to review the Pareto chart of the effects to tar delivery. The ANOVA effect estimates are sorted from the largest absolute value to the smallest absolute value. The magnitude of each effect is represented by a horizontal column, and often, a vertical line going across the columns indicates how large an effect has to be statistically significant at the level of 0.05. Note that the plot shown here was stretched to accommodate the 18 factors along the vertical axis. For the eight independent factors including main three factors that were statistically significant at the level of 0.05(p), and permeability of tipping paper clearly had a much larger effect than the other effects; permeability of tipping paper parameter value was negative, thus, we could estimate the higher the permeability of the tipping paper, the less tar delivery to the mouse through the filter in figure 1. Figures 2, 3 and 4 represented the response surface contour plots of dependent delivery tar as a function of filament denier at X axis and plugwrap permeability for Y axis(fig.2), and filament denier at X axis versus tipping paper permeability for Y axis(fig.3), and tipping paper permeability at horizontal axis versus vertical axis (fig.4). These contour plots showed reveal considerable useful information about the performance of this reducing tar and so we can be used to

Table 6. Regression coefficient and its significance for cigarette ventilation rate

Factor		Regressn Coeff.	Std.Err.	t(20)	p	-95.% Cnf.Limt	+95.% Cnf.Limt
Mean/Interc.		53.48148*	.576399*	92.7855*	.000000*	52.27913*	54.68383*
(1) FTD	(L)	-2.88889*	.266821*	-10.8271*	.000000*	-3.44547*	-2.33231*
FTD	(Q)	-1.11111*	.462147*	-2.4042*	.026016*	-2.07513*	-.14709*
(2) PWP	(L)	2.27778*	.266821*	8.5367*	.000000*	1.72120*	2.83436*
PWP	(Q)	-.27778	.462147	-.6011	.554553	-1.24180	.68624
(3) TPP	(L)	9.77778*	.266821*	36.6455*	.000000*	9.22120*	10.33436*
TPP	(Q)	-6.44444*	.462147*	-13.9446*	.000000*	-7.40847*	-5.48042*

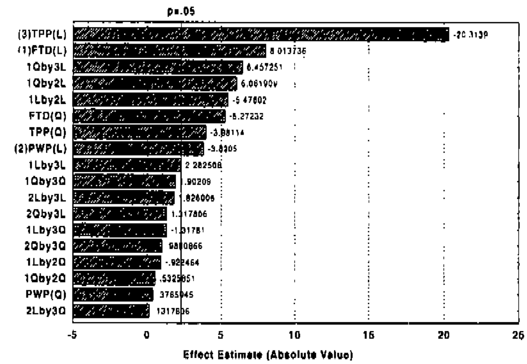

Fig. 1 Pareto chart of standardized effects for tar delivery.

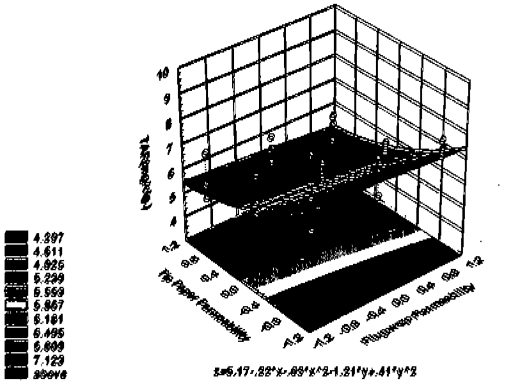

Fig. 3. A three-dimensional response surface showing the expected yield as a function of permeability of plugwrap paper(x) and tipping paper(y).

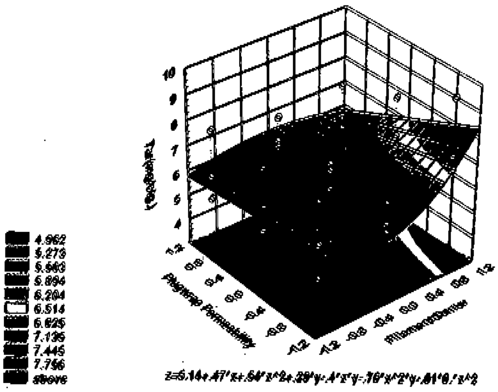

Fig. 2. A three-dimensional response surface showing the expected yield as a function of filament denier(x) and permeability of plugwrap paper(y).

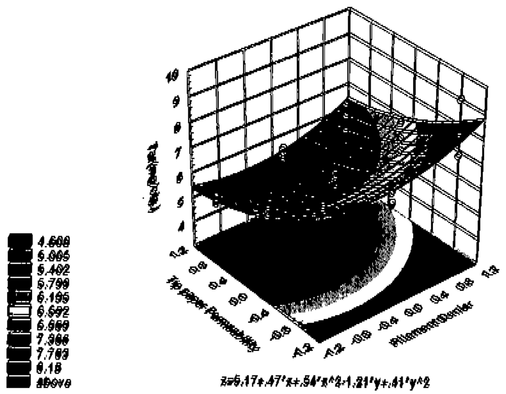

Fig. 4. A three-dimensional response surface illustrating the expected yield as a function of filament denier(x) and permeability of tipping paper(y).

minimize trial and error for designing new cigarette brand as a key information. According to these contour graphs, One variable should be maintained at the center point value(code 0) and then the level of tar delivery and ventilation rate was plotted as a function of the other two factors ranging from code −1.2 to +1,2. All three major factor variables affected the tar delivery simultaneously. Among of those factors, tip paper permeability especially had the highest impact to dependent variables. Since the effectivity of tipping paper permeability to tar delivery is highest, we came to the point that the air permeability of tipping paper must not only specify to the target but must also be as uniform as possible. Any variation, first of all, in permeability of the tip paper had a major impact on the fluctuation of tar delivery and filter ventilation rate. Note that these contour graph also contained the prediction equation in terms of the original metric of factors that produces the respective response surface on the bottom of the graphs. Fig. 5 illustrated the normal probability plot of the residuals for this model. the residuals were plotted as a cross symbol along a common solid line, and this was a technique how closely a set of observed values (residual in this figure) follow a theoretical distribution. In this plot the actual residual values were plotted along the horizontal X-axis; the vertical Y-axis shows the expected normal values for the respective values. Our experiment model gives very similar results for each factors. The plot revealed that there was much less scatter in residual at the low or high horizon axis position. The correspondence between observed and predicted value was graphically illustrated in figure 6. This graph was accomplished by using polyno-mial equation involving linear, quadratic and interaction effect with computed values of delivery tar. It appeared that they closely follow the normal distribution.

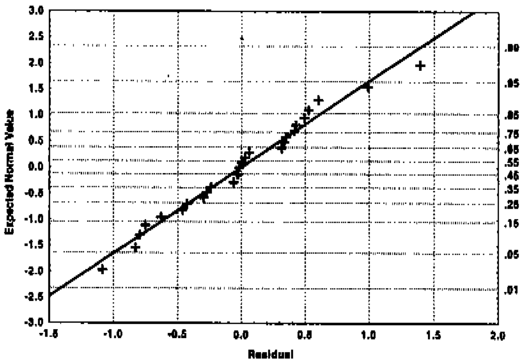

Fig. 5. Distribution of residual and expected normal values of the response following the changed conditions.

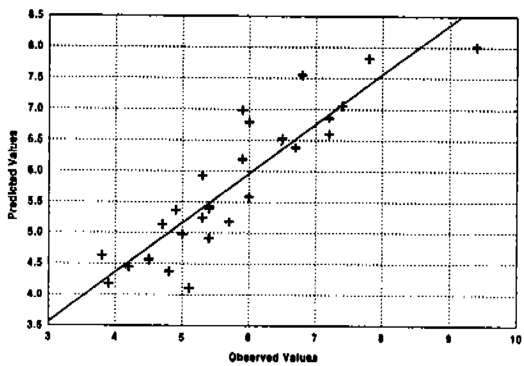

Fig. 6. Distribution of predicted and observed values of the response following the changed conditions.

The plot revealed that there was a good distribution the observed data as a plus symbol are plotted near around a predicted solid line and this experiment allowed us to represent a large number of factors for those that were significantly related to the dependant variables of interest. while, Figure 7 also represented the 2-dimensional response surface contour plots of constant ventilation as a function of filament denier, plugwrap and tip paper permeability for at X axis and Y axis in order. these contour plots illustrated the considerable useful information about the performance of the increasing filter ventilation. On account of the effectivity of tipping paper porosity to filter ventilation was the highest, the air permeability of tipping paper must not only be to target specification but must also be as uniform as possible.

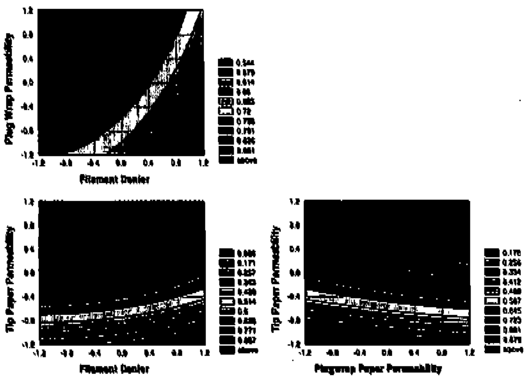

Fig. 7. A two-dimensional response surface contour graph illustrating the expected yield as a function of permeability of filament denier, plugwrap paper and tipping paper.

CONCLUSION

It should be emphasized that the major conclusion of this paper is not that any particular parameter is linear on any particular scale, but that there are highly significant relationships among factors involving linear, quadratic and their interaction and perhaps even linearity between and within factors. There is also quite strong evidence that filament denier and tipping materials are reverse relationship on this experimental model. Twenty-nine trial numbers were obtained as a results of using a three levels full factorial design and it is analyzed by the multiple regression analysis with backward stepwise in *STATISTICA* /pc under restricted conditions. On the basis of our results it can be concluded that The permeability of the tipping paper have a marked effect in reducing the level of tar delivery and ventilation rate. Tar yields of the cigarette, that is, was affected by porosity of tip paper (0.66), filament denier(0.47) and porosity of plug wrap(0.28) in the decreasing order, and linear effect of tip paper porosity (β_3) and filament denier (β_1) were significant at a level of 0.01(α). The filament denier and tipping paper porosity interaction F ratio among three factors has a P-value of 0.000041, indicating higher interaction both factors. Following to the analysis of variance, the model fitted for Tar(Y_1) was significant at 5% confidence level and the coefficient of determinat-ion(r^2=0.96) is the proportion of variability in the data well fitted for by the model.

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