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Rummy High-Altitude Pressure Measurements and Analysis

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John R. Banister, William V. Hereford

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Rummy High-Altitude Pressure Measurements and Analysis

John R. Banister
Ground Motion and Seismic Division 1111

William V. Hereford
TM Development and Evaluation Division 1582

Sandia National Laboratories
Albuquerque, NM 87185

Abstract

Five pressure-measurement canisters equipped with parachutes were deployed from an A7C aircraft on the Rummy test. Their altitudes above Yucca flat were over 8.5 km when the pressure pulse arrived. Three successful measurements were obtained. These time histories showed a more complicated behavior than histories obtained on Pahute Mesa tests because the Rummy event developed double spall closures over a large area. Excellent agreement was obtained between the observed pressure histories and those calculated from surface acceleration measurements. The Yucca Flat terrain was so level that pressure pulses were not appreciably changed or weakened by elevation differences.

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Rummy High Altitude Pressure Measurements and Analysis

Introduction

The air-pressure pulse radiated from the moving surface above an underground nuclear test disrupts the ionosphere.¹ Monitoring the changes in the electron distribution of this part of the atmosphere may provide a method for detecting clandestine tests. Sandia National Laboratories instigated a program to measure the time history of this pressure pulse for two reasons. The observed history can be used as the starting conditions for nonlinear calculations that specify the development of the wave as it propagates upward to the ionosphere.² A second and more compelling purpose is to determine whether or not we can accurately calculate the pulse-time history from observed ground motion in the quasilinear regime. Establishing the validity of such calculations allows examining other cases with reasonable confidence.

The second full set of high-altitude pressure measurements were obtained on the Rummy event. Rummy was an intermediate yield test conducted by the Los Alamos Laboratory on September 27, 1978. The shot was located in Yucca Flat (U4au); the burial depth was ~ 640 m.

Five instrument packages were deployed from an A7C Navy aircraft to be positioned ~ 8.5 km above the valley floor at signal arrival. The parachuted canisters were spaced over a wide range to document the pulse at fairly large polar angles.

Ground-motion measurements were obtained by both Los Alamos and Sandia. The Los Alamos measurements were situated relatively close to surface zero, while the Sandia instruments were placed on a line toward the northwest from surface zero (roughly parallel to the drop aircraft course).

As we shall see, the analysis of Rummy data is extremely straightforward because Yucca Flat is, indeed, flat. The agreement between the observed pressure histories and those calculated from ground motion show remarkable agreement in both waveshape and amplitude.

Air-Pressure Measurements

We designed the canister instrumentation system to be independent of the power-control interface commonly used for aircraft delivery operations.³ Each canister was activated immediately before the carrier aircraft left its parking ramp. The aircraft, a Navy A7C was operated from Naval Weapons Center (NWC), China Lake, CA, to minimize system operating time and the effect of subzero temperatures on the instrumentation. Takeoff was approximately 1 h before the 1020 PST shot time to allow for input after the last weather briefing. This permitted sufficient time to complete two practice runs. We obtained air clearance to fly the aircraft on a 328° true course, using an ~ 11 -min left-turn racetrack pattern.

Personnel at the Tonopah Test Range (TTR) controlled the aircraft position. The position was skin-tracked with the MPS-36 and MPS-25 radars. The tracking data was then presented on the TTR control-room plotting board. Operational requirements precluded dropping the canisters prior to 2 min before shot time because of the remote possibility of a free-fall canister hitting the control trailer or the cable run before shot time. The first canister was not released until 43 s before shot time—approximately a minute later than planned. The operation plan called for positioning canisters at 0, 900, 1800, 2700, and 4500 m from ground zero.

Deployment of the parachute, timed for 6 s after release from the aircraft, turned on the telemetry package installed in each canister. This also turned on the C-band beacons in canisters 1 and 5; these were tracked by two TTR radars. The positions of the remaining canisters were then interpolated at the time of shock arrival.

Telemetry data from each of the canisters was received and recorded at the Control Point, the TTR Station 24, and at the Monastery Station at the Nevada Test Site. The data from the recording station with

the least noise was digitized by Data Reduction at Sandia Laboratories. Because the canisters were released later than planned, the pressures had not stabilized. This required additional data processing to remove the slope caused by the rapid filling of the ballast tank.³ The release was delayed by a temporary loss of communications between the TTR aircraft controller and the aircraft that resulted in the aircraft making the turn late on the downwind leg. Also, the aircraft velocity was 75 knots less than the requested release velocity of 350 knots. This abnormality has been investigated; however, no plausible reason has been determined. The actual flight course was 313° rather than the requested 328°.

Wind balloons with radar reflectors were released from the Nevada Test Site at 3, 2, and 1 h before shot time. These were tracked to ~3000 m MSL by the weather station at NTS and above 3000 m by one of the radars at TTR. These runs were made to extrapolate the winds at shot time, to allow for proper positioning of the canisters at shock arrival time, and to predict the impact areas of canisters for safety considerations.

Immediately following canister impact, a radio-sonde was launched from TTR to obtain atmospheric speed of sound, density, and pressure information.

We obtained good data from the first three of the five canisters. Data was obtained for only 1.5 s on the fourth canister. The transmitter malfunctioned a short time later; a postmortem did not reveal the cause of the failure. The pressure from the fifth canister had not stabilized sufficiently to obtain data at shock arrival because of the late release.

The locations of the canisters relative to ground zero (GZ) and effective GZ (EGZ) are given in Table 1. The shot-day winds were light with a direction approximately normal to flight path of the delivery plane. The horizontal displacement of the effective GZ from the true was small (200 m on an 81° bearing). The EGZ is, as before, defined as being displaced from the surface GZ by the amount the normal sound ray is displaced by winds on reaching the pressure measurement altitude. Meteorological information for shot time is listed in Table 2.

The pressure-time histories of the three successful measurements are displayed on Figures 1 through 3. The character of the pressure wave at two of the inner stations is quite different than that observed on the Pahute Mesa experiments.^{4,5} The duration of modified "N" wave for Rummy is about twice that for Backbeach and Farm (2 s vs 1 s) and the rarefactions of both Rummy traces are partially filled with a pressure spike. Another difference is the marked interference (between the signals from the ground under

the canister and the signal from near GZ at a polar angle of 11° on Backbeach) is not apparent in the Rummy measurement at a somewhat smaller polar angle from EGZ (12.6° vs 13.2°). This is not surprising because the ground motion of the Yucca Flat shot has a lower frequency content. After the primary pulse has passed, the inner pressure measurements of Rummy show only weak pressure fluctuations as did the Pahute Mesa results.

Table 1. Pressure Measurement Canister Locations Relative to True and Effective Ground Zero at Signal Arrival

Parameter	First Canister	Second Canister	Third Canister
Altitude Above True GZ (km)	8.64	8.71	8.76
Horizontal Range From True GZ (km)	0.99	1.75	2.84
Azimuthal Angle From True GZ (deg)	213	275	289
Polar Angle From True GZ (deg)	6.5	11.4	18.0
Horizontal Range From EGZ (km)	1.13	1.95	3.02
Azimuthal Angle From EGZ (deg)	221	274	287
Polar Angle From EGZ (deg)	7.5	12.6	19.0

Table 2. Meteorological Conditions

Parameter	First Canister	Second Canister	Third Canister
Average Speed of Sound From Surface to Canister (m/s)	324.5	324.5	324.3
Speed of Sound at Canister Altitude (m/s)	303	302	302
Ambient Density at Canister Altitude (kg/m ³)	0.437	0.434	0.431

Figure 1. Pressure-Time History of the First Measurement Canister

Figure 2. Pressure-Time History of the Second Measurement Canister

Figure 3. Pressure-Time History of the Third Measurement Canister

The third unit of the Rummy experiment, which was situated at a polar angle of 19° , shows a remarkably complex interference pattern caused by interactions of the pressure signal from the surface beneath the canister and the signals generated by the stronger motion near GZ. The peak amplitude is, as expected, less than in the central core of the acoustic pulse (0.6 vs 3 mb). The coda of weak waves that follow the signal from near GZ has about the same initial amplitudes as those at the inner stations.

Ground-Motion Measurements

Ground-motion acceleration histories of the Rummy event were obtained by Los Alamos Laboratory and Sandia Laboratories.⁶ The Los Alamos measurements were taken fairly close to surface GZ while the supplementary Sandia measurements were taken on line with a bearing of 338.5° out to surface range of 4572 m (15 000 ft).

The records were checked for pathological symptoms such as the velocity not returning to zero at the end of the motion history. Corrections were made for accelerometers that overranged to force final velocities to zero. Some accelerometers seemed to be damaged by the spall closure spike or the records indicated serious recording problems. These were not used for the calculations of the air-pressure pulse. The accelerometer records that were used are listed in Table 3. The acceleration records are displayed in Figures 4 through 15. The acceleration histories displayed on Figures 11 through 13 were derived from velocity records. It was necessary to truncate these histories after spall closure to avoid severe drifts.

Table 3. Rummy Ground-Motion Stations

Station Code	Horizontal Range From GZ (m)	Azimuth With Respect to True North	Elevation Relative to GZ (m)
Los Alamos			
GM1-A	15	150	0.0
GM2-TP	357.5	174	-2.6
GM6	381.0	103	-1.8
GM4	487.7	10	2.1
GM11	609.6	340	4.9
GM9	640.1	283	3.1
GM10	877	352	5.6
Sandia			
JRB-1	914	338	6.8
JRB-2	1372	338	10.5
JRB-3	1829	338	13.9
JRB-5	2774	338	21.3
JRB-7	4572	338	36.7

Many of the records near surface zero show double spall spikes. It is apparent that both of these spikes are sufficiently coherent and wide spread to register on the observed pressure record at the closest station (Figure 1). Two pressure spikes, although weaker, are also evident on the record taken at second canister position. As we shall explain later, the inputs for the spikes are more complicated.

Figure 4. Vertical Acceleration-Time History at a Surface Range of 15 m (GM-1-A)

Figure 5. Vertical Acceleration-Time History at a Surface Range of 357.5 m (GM-2-TP)

Figure 6. Vertical Acceleration-Time History at a Surface Range of 381 m (GM6)

Figure 7. Vertical Acceleration-Time History at a Surface Range of 487.7 m (GM4)

Figure 10. Vertical Acceleration-Time History at a Surface Range of 887 m (GM10)

Figure 8. Vertical Acceleration-Time History at a Surface Range of 609.6 m (GM11)

Figure 11. Vertical Acceleration-Time History at a Surface Range of 914 m (JRB-1). This record has been truncated to reduce velocity drift.

Figure 9. Vertical Acceleration-Time History at a Surface Range of 640.1 m (GM9)

Figure 12. Vertical Acceleration-Time History at a Surface Range of 1372 m (JRB-2). This record has been truncated to reduce velocity drift.

Figure 13. Vertical Acceleration-Time History at a Surface Range of 1829 m (JRB-3). This record has been truncated to reduce velocity drift.

Figure 14. Vertical Acceleration-Time History at a Surface Range of 2774 m (JRB-5)

Figure 15. Vertical Acceleration-Time History at a Surface Range of 4572 m (JRB-7)

The spall zone extends out to an approximate surface range of 1800 m. The double spall is not evident near the spall zone perimeter. The usual pattern of the final spall closure appearing at this limit and progressing in toward GZ is evident.

Peak initial velocities were again used as the index for smoothing data for the input-to-pressure history calculations. The peak velocity is a better index than the peak acceleration if a large sector of the annulus is contributing to the pressure pulse.⁴ These peak initial velocities are plotted vs the slant range on Figure 16. These experimental values show more scatter than did those of Farm, but the data are still fairly smooth. The power law, which is the best least mean square fit to the data, is also shown on this figure.

Figure 16. Peak Initial Vertical Velocities vs Slant Range

The peak initial velocities of Rummy exceed those of Farm by a factor of about 1.5 at a slant range of 1 km. The decrease in peak velocity with slant range is also somewhat slower for Rummy. The higher initial upward velocity of Rummy is responsible for the greater displacement and the greater time span before the final spall closure.

The arrival time vs surface range is given on Figure 17. The curve shows a marked break in slope because signals that travel in part through the deep Paleozoic rocks arrive first at stations beyond 1 km. This curve was used to calculate the acoustic radiating areas since the behavior is too complex for a simple analytical treatment.

Figure 17. Ground Motion Wave Arrival Times vs Surface Range

Pressure History Calculation

The pressure-time history is calculated by the integration

$$p(t) = (\rho_0/2\pi) \int_S \frac{a(t - h/\bar{c})}{h} dS \quad (1)$$

where

$p(t)$ = air pressure history

ρ_0 = air density at the ground surface

$a(t - h/\bar{c})$ = retarded vertical acceleration

h = distance from the point where the pressure is specified to the surface element dS

$\bar{c}$ = average speed of sound.

The pressure history is multiplied by the correction factor $(\rho c/\rho_0 c_0)^{1/2}$ to conserve energy in the earth's atmosphere (Fuch's Scaling). The symbol ρc designates the acoustic impedance at the altitude the pressure is calculated. The details of this method and a program for computing pressure histories from ground-motion data are discussed in an earlier report.⁷ The sound velocities and air densities used in these calculations were those measured by a sounding balloon released after the Rummy test.

As usual, two methods were used for inferring the vertical acceleration at the individual grid elements from the field data. We used the power-law interpolation method discussed in Appendix C of the Farm report for the entire calculation for grid points outside the spall region.⁵ This method was applied for grid points within the spall zone for the first second. After the 1 s, direct linear averaging was invoked for these grid points. The slope of the regression equation (-1.59, Figure 16) was used to set up the power-law interpolation procedure.

For the bulk of the calculations, we used 299 rings ($M = 2, N = 300$). The outer edge of the last ring was set at the outermost ground-motion station; i.e., 4572 m from surface GZ. The characteristic dimension of the grid (r_0) was defined by

$$(r_0/2)[(N-1)(N+2)]^{1/2} = 4572 \text{ m} \quad (2)$$

giving r_0 a value of 30.43 m.

We have calculated the surface area limits through which signals pass and reached the canister position at several times after signal arrival using the method described in the program report.⁷ The results for the three canister positions are shown on Figures 18 through 20. The time of arrival curve (Figure 17) was used to generate these curves rather than assuming a constant longitudinal seismic-wave velocity. With the extended ground-motion measurement, we are able to specify the air-pressure histories with more confidence. The acoustic signals reaching the first two canisters originate from the area where ground motion is measured for more than 2 s after the signal arrival. The signals arriving at the third canister come from the instrumented area for the first second and while a relatively small fractional area is outside that area during the next second.

The location of ground-motion measurement stations are also plotted on these same three figures. We can see that the combined results of the drop plane flying off course and arriving late at the first drop point has displaced to some extent the canisters away from the area where the vertical acceleration measurements were obtained.

Figure 18. Surface Area Through Which Signals Travel to the First Canister at Various Times After the First Signal Arrival. The dashed curve indicates the outer radius at which ground motion was measured.

Figure 19. Surface Area Through Which Signals Travel to the Second Canister at Various Times After the First Signal Arrival. The dashed curve indicates the outer radius at which ground motion was measured.

Figure 20. Surface Area Through Which Signals Travel to the Third Canister at Various Times After the First Signal Arrival. The dashed curve indicates the outer radius at which ground motion was measured.

Comparison of Calculated and Observed Pressure Histories

Since the shot area for Rummy is remarkably level, we would not expect the pressure history to be significantly affected by the small differences in elevation. This expectation was checked with a calculation; the details of the calculation and terrain description are discussed in Appendix A. The signal changes introduced by the terrain are indeed minor and the pressure-time histories calculated from Eq (1) can be used for comparing the observed and calculated air pressures. The three calculated pressure histories with the corresponding measurements are displayed on Figures 21 through 23. The standard deviation for points in these calculated curves were derived by the procedure described in Appendix B of the Farm report.⁵ The standard deviation is an index of the variation we may expect in the calculated curve because our ground-motion measurements used as input for the calculation may not specify the true average at a particular time.

Figure 21. Comparison of Observed and Calculated Pressure-Time Histories at the First Canister Position

Figure 22. Comparison of Observed and Calculated Pressure-Time Histories at the Second Canister Position

Figure 23. Comparison of Observed and Calculated Pressure-Time Histories at the Third Canister Position

We find the comparison of the calculated and observed pressure histories for these three cases is quite satisfying. The agreement at the first position is remarkably close with wave shapes almost identical and peak amplitudes of nearly the same value. The tendency for the observed minimums to lag behind the calculated and the opposite behavior for positive pressure excursions is readily evident. The phenomenon has been noticed before and is the result of nonlinear propagation because the signal amplitudes are a small but appreciable fraction of the local atmospheric pressure.^{4 5}

The inputs from the various area annuli representing individual ground-motion measurements have been examined to establish the origin of prominent features of time history at this first station. The results are the expected; the first spike is caused by initial upward motion and the first minimum is associated with the free-fall. The second positive pulse is caused by the intermediate spall closure spike that appears at several ground-motion stations, while the last positive pressure excursion is associated with the final spall closure.

The comparison of the calculated and observed pressure-time histories at the second position is not quite as satisfactory. The agreement between the traces is excellent in later portions of the wave, but the observed pressure exceeds the calculated on the first positive excursion. The observed negative pressure of the first trough is less than the calculated. The agreement between the observed and calculated traces is improved somewhat if the departures from a flat terrain are accounted for (Appendix A). The remaining differences are probably caused by variations of the ground motion under this station from that of the region where ground-motion measurements were made (Figure 19). We note that differences between the two records is about a standard deviation.

The records at the first and second stations show considerable resemblance, but the pressure excursion at about a second after signal arrival is not caused by the intermediate spall closure at the second station. A check of the pressure inputs associated with the various ground-motion measurements shows this pressure

excursion is caused by signals from the final spall closure at the outer part of the spall zone. The last positive excursion at about 2 s after the signal arrival is caused by the final spall closure near the surface GZ.

The comparison of the observed and calculated air-pressure histories at the third station is again satisfactory. There is no precise agreement in the first part of the wave when relatively high-frequency acoustical signals are interfering but the overall "character" is proper. The long period wave that is caused by input from the strong motion near GZ shows again remarkable agreement between the calculated and observed pulses.

Other Results

The amplitude of the pressure waves of Rummy exceeded those of Backbeach; these measurements were taken about the same altitude above the surface. The differences are caused by two factors: the ground motion was somewhat stronger for Rummy; and the terrain is different (the region around Backbeach was sufficiently rough to weaken the pressure signal appreciably). The differences in range and Fuch's Scaling factor also reduce the predicted Backbeach pressures by 15%.

The calculated peak-to-trough pressure excursion on an arbitrary scale at a fixed range (50 km) are plotted vs the polar angle on Figure 24. This curve differs considerably from similar plots for Farm.⁵ The Rummy peak-to-trough values show a rather steady decline with increasing polar range; the Farm results showed a plateau out to 10° with an abrupt decrease for larger polar angles. At 30° the peak-to-trough value for Farm is decreased nearly two orders of magnitude from the central value, while the decrease is only one order of magnitude for Rummy. The calculated result suggests that Rummy, with its more complex ground motion and lower frequency content, radiated a less directional acoustical pulse than did its counterpart on Pahute Mesa.

We have calculated pressure histories at several altitudes to examine the attenuation of the peak-to-trough pressure swing with this parameter. A uniform atmosphere was used in these calculations since we are interested in relative values. The results are plotted on Figure 25 for polar angles of 6° and 10°. The variation of the peak-to-trough pressure range with altitude is more complicated than that obtained when Pahute Mesa ground-motion records were used for the program input. A virtual-source depth of about 10 km is required for an inverse decrease of the pressure with range at 6° while the vertical source of the 10° ray is located near the surface. In part, this different result

Figure 24. Peak to Trough Pressure Amplitudes vs Polar Angle at a Range of 50 km (calculated for a uniform atmosphere)

Figure 25. Peak to Trough Pressure Amplitudes vs Altitude for Two Polar Angles (calculated for a uniform atmosphere)

is probably caused by the interference of the two spall spikes at the greater polar angle.

The concept of an emergent pulse discussed in the Backbeach report was checked out again with calculations based on the Rummy ground motion.⁴ The central idea of this concept is to establish an altitude above which the relative pressure-pulse history becomes nearly steady and thus suitable for input to a nonlinear code. The calculated pressure histories are relatively stable above 10 km at a polar angle of 6° for Rummy (Figure 26). The two spall closure spikes

persist to 100 km; we see some shifts in relative heights of the three positive excursions. The histories at polar angle of 10° show somewhat more variation with a tendency for the first minimum to fill with a reduction of the second positive pulse at the higher altitudes (Figure 27). The final spall closure becomes more prominent at greater heights. These histories are time-shifted so the first pulse from near GZ coincides on all records.

We have suggested the criterion that the parameter $R_0^2/2cZT_0$ should be much less than 1 for the relative pressure history to stabilize. In this case, it seems suitable to assign R_0 as the spall limit radius (2000 m) and pulse duration (T_0) as 2 s. The symbol c designates the speed of sound in air, while Z is the altitude above the surface. Values of this parameter are 0.67, 0.27, 0.13, and 0.067 for the altitudes of 10, 25, 50, and 100 km, respectively. The general degree of stabilization of the relative pressure history seems reasonable. The fluctuations we see are features with a high-frequency content (small T_0) that show appreciable phase shifts with changes in altitude. On the whole, one would judge that the emergent pulse is established at a relatively low altitude for Rummy at these polar angles.

Figure 26. Relative Pressure Histories for a Polar Angle of 6°

Figure 27. Relative Pressure Histories for a Polar Angle of 10° . (These curves have been matched at principal pulse arrival.)

Summary and Conclusions

The pressure waves generated by the Rummy experiment were more complicated than those observed on the Pahute Mesa experiments. The Rummy ground motion showed two spall closures that were both extensive and coherent enough to cause prominent positive-pressure pulses at smaller polar angles.

The peak pressure levels for Rummy also exceeded those of Backbeach; these measurements were made at about the same height above the surface. In part, this is the result of terrain. The area around Rummy was nearly level so less destructive interference of acoustic waves developed. The ground motion was stronger for Rummy as well.

We find excellent agreement between the observed pressure histories and those calculated from the ground motion at the three stations. This is a striking confirmation for the efficacy of the summing of simple acoustic sources to predict pressure histories over buried nuclear tests or similar disturbances. The measurement at the smallest polar angle shows some minor distortion because of nonlinear processes.

The ground motion of Rummy had a more complex character and lower frequency content than Backbeach and Farm. Relatively stronger acoustical

waves were radiated into large polar angles. The variation of calculated peak-to-trough excursions with altitude does not suggest a unique depth for the virtual source of the explosion. The calculated relative pressure histories stabilize at a relatively low altitude (~ 10 km).

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⁶Letter from R. S. Fitzhugh J-8 to E. Jones J-9, *Rummy Event - Ground Motion Measurements - Presentation of Data* (Los Alamos, NM: Los Alamos Laboratory, December 22, 1979).

⁷J. R. Banister, *A Program for Predicting Ground Motion Induced Air Pressures*, SAND78-2361 (Albuquerque, NM: Sandia Laboratories, March, 1979).

APPENDIX A

Rummy Terrain Calculations

The area surrounding the Rummy GZ is quite level but a check calculation was made to examine the effect of minor elevation variations. This calculation was run for the second canister position.

Examination of the topological map reveals the Rummy GZ is near the bottom of a gentle swale. The drainage is down toward an azimuth of 170° from north; the gradient is 0.008. The elevation increases at somewhat greater rate to the east and west with a gradient of 0.014.

The terrain can be approximated by two intersecting planes. The mathematical description of the local elevation above that of GZ (Y) is

$$Y = -0.008R\cos\phi + 0.014R|\sin\phi| \quad (\text{A-1})$$

where R is the surface range from GZ and ϕ is the angle that is set to zero at an azimuth of 170°. This description of the area around the Rummy GZ was dubbed the butterfly terrain model.

The results of the calculation using this terrain model are displayed on Figure A-1. The modification in the calculated pressure-time history caused by terrain is quite minor. Some slight improvement between the calculated and observed traces is achieved but the changes are a small fraction of the standard deviation of the calculated traces. The elevation variation of the terrain is not important.

Figure A-1 Comparison of the Calculated Pressure-Time Histories Using the Butterfly and Flat Terrain Models at the Second Canister Position. The observed pressure history is also displayed.

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