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ISOTOPE KILOWATT PROGRAM QUARTERLY PROGRESS REPORT
FOR PERIOD ENDING DECEMBER 30, 1971

A. P. Fraas and G. Samuels

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Reactor Division

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FOR PERIOD ENDING DECEMBER 30, 1971

A. P. Fraas, Program Director
G. Samuels, Associate Director

APRIL 1972

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FOREWORD

In 1968 the Oak Ridge National Laboratory started work on a program to evaluate various types of radioisotope energy conversion systems for the production of 1 to 10 kW of electric power for terrestrial and under-sea applications. This program is being carried out for the U.S. Atomic Energy Commission Division of Reactor Development and Technology and the Naval Facilities Engineering Command. The first phase of the program was a parametric and engineering analysis comparing the principal isotope fuels and the principal types of energy conversion system that have been proposed for applications of this sort, and the preparation of a set of conceptual designs for the more attractive systems. That work was completed in the summer of 1969 and was reported in Ref. 1. In October of 1969 ORNL was asked to proceed with a detailed engineering study of the three most promising systems selected from those covered in Phase I of the program. These three systems now under study are a 2-kW(e) thermoelectric system, a 3-kW(e) steam Rankine cycle system, and a 5-kW(e) organic Rankine cycle system.

The first step in the effort was to evolve a program plan for a three-year effort to be carried out in calendar years 1970, 1971, and 1972. The conceptual designs presented in Task I were reexamined and possible improvements were considered with particular attention to the difficult development problems. A variety of engineering tests was considered as a means of evaluating the technology, solving the principal technical problems, and investigating engineering uncertainties that should be resolved before settling on the design of a prototype power plant. In view of the limited funds and the desirability of narrowing the field to a single Rankine cycle system, particular attention was given to the relative merits of the steam and organic Rankine cycle systems.

The first quarter of 1970 was devoted to firming up reference designs for the three types of system, selecting the most crucial experiments required to evaluate the technology, and settling on a program plan for the three-year effort.² With this first quarter's work as a foundation, the second quarter was then devoted to firming up the details of the reference

designs, firming up details of the experiments to be conducted, and preparation of topical reports covering the three reference designs with their associated experiments.³ The subsequent quarters have been devoted to the design and construction of the most urgent experiments.^{4,5,6,7} The remaining period will be devoted to the design and construction of additional test equipment and to tests designed to investigate vital questions in the technology. As the results of these tests become available, the reference designs will be revised accordingly. The objective is to evolve by December 1972 a set of designs for two prototype power plants with a clear delineation of the development program required in each case including firm estimates of the cost and time for the various programmatic steps.

This is the eighth in a series of quarterly progress reports. Topical reports present the work carried out in particular areas when key tasks are completed. When a topical report is issued essentially concurrently with a quarterly report, to avoid duplication only a very brief summary of its contents is included in the quarterly.

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ISOTOPE KILOWATT PROGRAM QUARTERLY PROGRESS REPORT
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1.0 SUMMARY

In October four capsules were removed from the capsule decomposition test block after 7085 hr of operation at 600°F. All four of the capsules were glass containing stainless steel wires. Two of the capsules were exposed to a dose rate of approximately 55 rad/hr and two to a dose rate of about .0027 rad/hr. Visual examination showed no detectable change when compared to control samples. Preliminary results of the chemical analysis of the four capsules removed for examination after 7000 hr indicate that there was virtually no deterioration of the liquid and very little gas evolution with no statistically significant difference between the specimens with high and low radiation doses. The results indicate that a 5-yr unattended life should be attainable for the proposed full-scale organic Rankine cycle system.

The organic capsule decomposition test continued throughout the balance of the quarter without incident. The total operating time on the original capsules at the end of December was 8477 hr and the time on the new capsules was 1392 hr.

Fabrication of components for the quarter-scale organic fluid decomposition test loop was completed and assembly of the components for the loop was about 60% completed by the end of December.

The thermoelectric module continued to operate throughout the quarter to give 3156 hr at the end of December. Some evidences of degradation in the electrical output have begun to appear.

The design analysis and the design of the heat pipes for the full-scale heat block-shield test have been completed. The design analysis of these new heat pipes with a simpler construction indicates that, ideally, they should give sufficient output for all inclinations from normal vertical to an inclination of -19° (i.e., with the condenser below the evaporator region). The components for the first heat pipe for the shield block test have been fabricated, and preliminary test results are favorable.

Recent experience at Los Alamos with stainless steel-sodium heat pipes indicates that both cold trapping and hot trapping are required to make the performance of the heat pipe approach calculated values.

The thermal conductivity tests on the first combined aluminum screen-foil insulation were completed. Insertion of the foil in the screen matrix gave a marked improvement in the thermal radiation losses and thus the overall insulating value. The meltdown test of the combined aluminum screen-foil insulation specimen was then conducted. A preliminary analysis of the data and inspection of the screen following the meltdown indicate that the insulation will protect the fuel elements in the event that normal heat removal from the block is lost. This type of insulation was then chosen for the 1/4-scale thermal insulation test rig, and the system built. The system was placed in operation December 26 and thermal conductivity tests with a system nitrogen pressure of 15 psia were initiated.

The heat block-shield unit was received and set up for testing. A simulated fuel loading test was run by bringing the simulated fuel elements to temperature and then inserting them into the holes in the heat block-shield. No difficulties were encountered during the insertion of the seven elements.

The shipping and long-term storage tests were completed for both SrTiO_3 and SrF_2 fuel with maximum temperatures in the simulated fuel capsules of 1042°F and 979°F respectively. In a test simulating an accident in which the unit might fall off a truck it was found that, with the unit laying on its side and 110° of the surface covered with sand, the maximum fuel element temperature was 1161°F .

Detail design work on the full-scale organic system continued. About 60% of this work was completed at the end of December. A comprehensive analysis of the control system has been initiated.

2.0 ORGANIC FLUID EVALUATIONS

Capsule decomposition test

This test was shut down after 7085 hr of operation at 600°F to remove and check four of the capsules from the heat block. All four of the capsules were glass containing the ultra pure Dowtherm A and stainless steel

wires. Two of the capsules were removed from a hole located 1 1/4 in. from the radiation source (~55 rad/hr) while the other two were removed from a hole which was 8 in. from the source (~.0027 rad/hr).

Visual examination of the liquid in the capsules and the glass wires showed no detectable change when compared with a similar control sample which had been filled at the same time as the test capsule but had not been exposed to the radiation or elevated temperature. The four capsules were submitted to the Chemistry group for detailed analysis.

The preliminary results from the analysis of the fluid in the capsules are as follows:

- A. Sample No. 12, removed from hole in heat-shield block located 8 in. from the source, has been analyzed. Results showed an increase of 50 ppm (13 ppm initial and 63 ppm after exposure) of benzene. No appreciable increase in others. The gas volume taken from the tube amounted to 0.068 cc. Analysis shows it to be 86.5% H₂.
- B. The other three samples have been opened and the gas pumped off each sample. The gas volumes found were as follows:
 1. Sample No. 15 (other sample in hole 8 in. from source) had a total of 0.082 cc.
 2. Samples No. 23 and No. 27 (in hole 1 1/4 in. from source) had 0.054 cc and .067 cc of gas respectively.

No analysis has been made on the liquid from these samples.

While a detailed analysis of these results has not yet been carried out, it appears that there is no statistically significant difference between the deterioration in the capsules that were subjected to the maximum amount of irradiation and those that were subjected to a trivial amount. Further, there was virtually no deterioration in the liquid and the gas evolution was at such a low rate that there should not be a problem with non-condensibles in a properly designed organic Rankine cycle system of the type under development at ORNL, even for a five-year life. These tentative conclusions are, of course, subject to possible revision pending a thorough analysis. In any case the test data are very encouraging.

Four new capsules containing stainless steel wires and Dowtherm A material supplied by the Dow Chemical Company were installed in the holes

and heating of the block resumed. The block temperature again reached 600°F on November 2 and the test was continuing without interruption at the end of December. The test will be continued until the original capsules have had at least 10,000 hr of exposure to the radiation source and 600°F operating temperature. At the end of December the operating time since restarting the test was 1392 hr and the total operating time was 8477 hr.

Organic fluid decomposition test loop

The quarter-scale organic fluid test loop parts and equipment have all been delivered and construction is proceeding. The craft labor requirements to complete the system are estimated to be 900 man hr.

3.0 THERMOELECTRIC SYSTEM

Thermoelectric module

The heat pipe-thermoelectric module has continued to operate throughout this quarter, and at the end of December it had accumulated 3152 hr of continuous operation.

Figure 1 is a plot of the daily variation in some of the key heat pipe and thermoelectric parameters. The data relating to a current output of 5.673 amperes are plotted but have been disregarded as far as drawing the curves is concerned. These data were all taken for the conditions in the load cycle that prevail shortly after the battery bank begins to discharge. Prior to that time the battery bank is fully charged, the current output is about 4.7 amp, and the vapor temperature, hot junction temperature and voltage are at the high end of their range. When these particular data were taken, the system had not yet "leveled off." This is the reason that the output power also falls above its expected position.

The plot of temperature gradient along the nickel sleeve as a function of heat pipe vapor temperature that appeared in the September 1971 progress report is shown again with five new data points (see Fig. 2). Inspection of the new data seems to indicate that the temperature gradient along the nickel sleeve is diminishing with time. A likely explanation for this is that hydrogen gas that entered the heat pipe during the initial testing at 3M Company is gradually diffusing back out of the system. A vacuum has

Fig. 1. Daily variation of thermoelectric module parameters as a function of generator output current.

Fig. 2. Temperature gradient along nickel sleeve as a function of heat pipe vapor temperature.

been maintained in the shield can in an attempt to accomplish this removal. It was planned to continue to maintain the vacuum and monitor the temperature gradient.

On December 14, 1971 during a routine check of the flow switch in the TEM cooling water circuit, power to the heat pipe heaters was interrupted for about 20 min. During this period the system temperatures decreased several hundred degrees Fahrenheit. After power was restored and the system had returned to normal operating temperatures, it was noted that some of the internal instrumentation thermocouples had failed. As a result it will no longer be possible to monitor the temperature gradient along the nickel sleeve.

Before the thermal cycle was imposed on the thermoelectric module, the internal resistance had been exhibiting a steady increase. Measurements made immediately after the cycle showed that there had been a further sharp increase in the internal resistance. It continued to increase for two days and then began to decrease. Figure 3 shows the internal resistance as a function of time.

Heat pipes for the heat block-shield test

A series of computer runs were made to determine the optimum annulus width for the 12 heat pipes to be used in the heat block-shield test. The results of these runs are plotted in Figs. 4, 5, 6, and 7.

The plot of heat pipe capacity as a function of orientation in Fig. 7 indicates that the heat pipe will not meet the design requirement of 2.4 kW with the condenser below the evaporator by an amount greater than that given by an inclination angle of -19 deg, and that the maximum performance from the system can be achieved with the heat pipe in the vertical (evaporator down) position as called for in the reference design.

Recent experience at Los Alamos with stainless steel heat pipes indicates that both cold trapping and hot trapping are required to insure maximum performance of the system.

The first heat pipe for the heat block-shield test has been assembled, filled, and tested. First indications are that this heat pipe is capable of operation with the condenser end of the heat pipe below the evaporator end. This improvement in performance is attributed to the installation

Fig. 3. History of internal resistance of 3M thermoelectric module.

Fig. 4. Calculated performance envelope for phase II heat pipe as a function of potassium vapor temperature.

Fig. 5. Calculated performance envelope for phase II heat pipe as a function of annulus width.

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Fig. 6. Calculated performance envelope for phase II heat pipe as a function of pore diameter.

Fig. 7. Calculated performance envelope for phase II heat pipe as a function of orientation.

of an internal zirconium foil hot trap in the evaporator end of the heat pipe, a measure taken as a consequence of the Los Alamos experience.

4.0 THERMAL FUSE AND INSULATION

Small scale tests

Thermal conductivity tests on the combined aluminum foil-screen insulation test specimen have been completed. Data were taken at pressures of 0.012 mm Hg, 0.1 psia, 1 psia, and 15 psia with nitrogen as the gas present in the vacuum tank. As was discussed in the last quarterly report, two sets of data taken at 1 psia had appeared to form two separate curves. A third set of data was taken and these results were in close agreement with the curve formed by the lower values previously measured.

Preliminary results of the tests based on the thermal conductivity calculated using only one set of temperatures across the insulation are shown in Fig. 8. The operating conditions for the insulation in the organic system will be 0.1 psia and a mean temperature of approximately 450°F. The measured thermal conductivity at these conditions is 0.043 Btu/hr·ft·°F. The thermoelectric system will operate at a mean insulation temperature of 600°F and 1 psia. The thermal conductivity at these conditions may vary between 0.067 and 0.077 Btu/hr·ft·°F. The thermal conductivity values measured at 0.012 mm Hg were quite low and indicated that the aluminum foils are effective in reducing the heat transfer by radiation. The results for the insulation specimen without foils are shown for comparison in Fig. 9.

The insulation specimen was withdrawn from the vacuum tank for a visual inspection for the degree of oxidation of the aluminum screen. This revealed that the screen was bright and had not oxidized noticeably in the nitrogen environment.

The insulation was then reinstalled in the tank for the meltdown test. Temperatures at three elevations on the heater rod surface were recorded for about 30 hr after the test was begun. A plot of these temperatures is shown in Fig. 10 for the first 18 hr. There was essentially no change in the temperatures for the remainder of the time. The top thermocouple reached a peak temperature of about 1525°F in a few minutes,

Fig. 8. Thermal conductivity vs. mean insulation temperature at reduced pressures in nitrogen of combined aluminum foil-screen insulation.

Fig. 9. Thermal conductivity vs. mean insulation temperature at reduced pressures of aluminum screen insulation.

Fig. 10. Heater rod temperatures vs. time in the course of the meltdown of the combined aluminum foil-screen insulation operated in nitrogen at 0.1 psia.

dropped sharply, oscillated once, and then leveled off at about 1450°F. The center thermocouple reached a peak temperature of about 1445°F and leveled off at 1360°F.

The emissivity of the melting screen was calculated for two values of heater temperature and an assumed screen temperature of 1200°F. The resulting emissivity was 0.26 based on the peak heater temperature of 1525°F and 0.477 based on the heater average temperature of 1456°F. This range of values of emissivity would yield fuel cladding temperatures of 1900-2000°F in the isotope heat block-shield unit in the event all of the cooling from the power conversion system were lost.

The insulation specimen was removed from the vacuum tank for examination after the test was completed. The condition of the insulation after the test is shown in Fig. 11. About one-half of the thickness of the insulation had melted over most of the length. The next layer of aluminum foil had melted with three layers of screen ahead of it still intact, indicating that the lower melting point of the foil was allowing it to melt ahead of some of the screen layers. Areas were found where the foil had partially melted and had rolled up in patches with pieces of one or two layers of screen ahead of it torn and carried along with it. A black deposit was found on the inner portion of the screen and foil layers at the top end of the specimen, and it is believed that this stemmed from a residue from a petroleum wax left on the screen from the drawing and weaving process.

The series of tests in the small vacuum tank has been completed. The remainder of the testing will be done with larger insulation specimens in the 1/4-scale heat block insulation test rig.

One-quarter scale thermal insulation test rig

The 1/4-scale test rig is composed of a carbon steel heat block with a diameter of 8 in. and a length of 59 in. inside a vacuum tank with an OD of 18 in. and a length of about 75 in. A bundle of four electric cartridge heaters of 5000 W each fit into a 4.5 in. diameter central hole in the heat block. There are 24 fins 1 in. high welded to the outer diameter of the heat block. The aluminum insulation specimen fits around the heat block and has an ID of 10 9/16 in. and an OD of 17 1/4 in. The assembly

Fig. 11. Frozen puddle of aluminum from the melt-down test of the combined aluminum foil-wire screen thermal insulation.

is mounted on a structural steel frame so that it can be operated in either the vertical or horizontal position. A photograph of the components is shown in Fig. 12. This unit will closely simulate the heat transfer conditions that prevail in a full-scale heat block-shield-pressure vessel assembly.

The operating procedure and the projected test program are as follows:

1. The vacuum tank will be evacuated and back filled with nitrogen with the heat block at room temperature. This will be repeated three times for thorough air removal.
2. The thermal conductivity tests for the vertical position will be run as follows:
 - a. At 15 psia and four insulation hot-face temperatures from 500 to 1050°F.
 - b. At 1 psia and four temperatures from 500 to 1050°F.
 - c. At 0.1 psia and four temperatures from 500 to 1050°F.
 - d. Optional tests will be run at 0.02 mm Hg if time is available.
3. A meltdown test will be run in the vertical position. The system will first be brought to equilibrium at 0.1 psia and an insulation hot-face temperature of 1050°F. The power will then be increased in such a way that the block surface temperature will rise at a rate of about 75°F per hr until the heat flux on the block is equal to the heat flux on the large block at full power. The block and screen temperatures will be recorded continuously over a period of about two days or until it is determined that the melting of the screen has stopped.
4. The vacuum tank will be opened to remove the insulation specimen for inspection.
5. A new insulation specimen will be installed and the system evacuated and back filled with nitrogen. The thermal conductivity tests will then be run for the horizontal position:
 - a. At 15 psia and four temperatures from 500 to 1050°F.

Fig. 12. Photograph of (a) the one-quarter scale heat block-shield assembly and (b) the aluminum foil-wire screen thermal insulation ready for assembly.

- b. At 1 psia and four temperatures from 500 to 1050°F.
 - c. At 0.1 psia and four temperatures from 500 to 1050°F.
- 6. The meltdown test in the horizontal position will be run using the same procedure as for the vertical test.
 - 7. The vacuum tank will be opened to remove the insulation specimen for inspection.

Assembly of the 1/4-scale heat block thermal insulation test rig was completed in December. The heat block was heated in air for two days up to 750°F to oxidize the surface in order to increase its emissivity and then it was allowed to cool down. The aluminum insulation specimen and vacuum tank were then placed around the heat block. The system was leak-tested with an internal pressure of 10 psig nitrogen in the course of which leaks at thermocouple connectors were found and eliminated. The tank was then evacuated three more times, each time refilling with nitrogen. The system was placed in operation December 26 and thermal conductivity tests at 15 psia were initiated.

5.0 HEAT BLOCK-SHIELD TEST

The heat block-shield was received from the manufacturer on October 9 and installed in a sand box in preparation for the first test. Before installation the block was fitted with thermocouples on the outer surface. The seven heaters (see Fig. 13) were assembled and installed in the heat block-shield. The system was checked out the first week in November.

The first test was that for a simulated shipping accident. The test was run with the heat block-shield lying on its side in a sand box as shown in Fig. 14. Two tests were run with 60 deg of the block perimeter buried in the sand. One test was run with seven electric heaters supplying 34 kW to simulate SrTiO_3 fuel and the second test was run with six electric heaters supplying 34 kW to simulate SrF_2 fuel. The maximum heater can temperatures observed for these two tests were 1135°F and 1101°F, respectively. A third test was run for the SrTiO_3 case at 34 kW with 110 deg of the block in the sand. The maximum heater can temperature observed during this test was 1161°F.

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Fig. 13. Components used to simulate the isotope capsules for the full-scale heat block-shield test. The parts shown are the electric heater element (bottom), the shield plug (right middle), and the assembled heater (top).

Fig. 14. The full-scale heat block-shield assembly on its side in a sand box ready for a test simulating an accident in which the unit had rolled off a truck into soft dirt or sand.

A test to determine the feasibility of loading the fuel elements into the heat block-shield was performed. During this test the electric heater elements (see Fig. 13, were brought to full power outside the block and allowed to come to equilibrium with the surrounding air and then inserted into the block at an average speed of 6 ft/min. After each element was inserted into the block, the block was allowed to come to equilibrium before the next element was inserted. No difficulties were encountered during the insertion of the seven elements.

The shipping and long-term storage test for the heat block-shield were also completed. The test was run with the block upright as shown in Fig. 15. One test was run with seven electric heaters supplying 34 kW to simulate SrTiO_3 fuel and a second test was run with six electrical heaters supplying 34 kW to simulate SrF_2 fuel. The maximum temperatures observed in the simulated fuel capsule walls for these two tests were 1042°F and 979°F, respectively.

The temperature distribution of the heat block-shield taken through the "pinch point" between two of the six outer fuel element during the shipping and storage test is shown in Fig. 16 for the SrTiO_3 condition.

The test of the heat block-shield with the thermal baffle in place was started in December. Preliminary data from this test have been obtained and indicate that approximately a 500°F difference between the block surface and the heater can surface prevails up to a block surface temperature of 940°F.

6.0 FULL-SCALE ORGANIC TEST LOOP

The detail design of the full-scale organic test loop has been proceeding rapidly with four men on the job. About 60% of the drawing work has been completed.

Analysis of the control problems for the full-scale organic loop is underway. Several detail variations of the simple control system have been contemplated and are being examined. This work further confirms the feeling that a large increase in reliability can be obtained by rectifying the output of the generator and allowing it to ride on a battery bank, thus

Fig. 15. The full-scale heat block-shield unit being readied for test in its normal upright position.

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Fig. 16. Heat block-shield radial temperature distribution during shipping and storage. Ambient temperature = 80°F.

eliminating the need for close control of the turbine speed and reducing the control functions to maintenance of the proper voltage output from the generator.

The batteries required for the various anticipated needs for auxiliary and emergency electric power also can be employed to improve the quality of the plant power output. Similarities of this application to submarine installations led to telephone discussions with Mr. Albert Himy, Branch Head, Battery & Controls, Naval Ships Engineering Center, Hyattsville, Maryland. The discussion centered on the prospects for long-term unattended operation of lead-acid cells. Three major problems were pointed out by Mr. Himy: (1) the need to add water according to individual cell requirements, (2) the explosion hazard from hydrogen and oxygen continuously evolved during operation with the batteries floating on the line (~10 cc per cell-day), and (3) the need to adjust charge rates so as to maintain charge on cells with higher internal leak rates while not overcharging the remaining cells. Slow evolution of poisonous gases such as stibene (where antimony is used in battery construction) could also be troublesome over long accumulation intervals. Submarine practice permits operator attention to the water makeup and charge adjustment needs. Evolved H_2 and O_2 are collected and recombined; however, the recombined water must be further purified before reuse in the battery. Overall, Mr. Himy felt that a nickel-cadmium battery offered far better prospects than lead-acid batteries for this application and recommended that we contact manufacturers.

Further phone discussions were held with Mr. Robert L. Falzone, Editor of the General Electric Nickel-Cadmium Battery Application Handbook, currently serving with the G.E. Battery Products Section, Gainesville, Florida. The information provided by Mr. Falzone indicated that the hermetically sealed aerospace (Ni-Cd) cell would serve the proposed application very well. Within reasonable overcharge limits, the cell is not damaged by overheating and the gases evolved (mainly O_2 in the sealed cells) diffuse in the electrolyte and recombine. Such cells are relatively expensive, although not in relation to the overall project cost; for example, the 10 amp-hour aerospace cell, GE No. 42 B 010 AB 52, is about \$180 per cell in 100 cell quantities. The Ni-Cd cells are also small and lightweight, the unit just mentioned measuring 7 in. x 1 in. x 2 1/2 in. and weighing

1 1/4 lb. Excellent reliability is achievable; the main failure mechanism in commercial sealed cells, seal corrosion, is virtually eliminated by special materials and quality assurance methods for the aerospace batteries. Excessive overcharging or overheating will damage the plate separators as well as cause high internal pressures, hence this must be avoided. The relatively flat voltage versus charge characteristic makes it difficult to control the charge rate accurately on the basis of measured voltage, although a voltage rise does accompany charge completion. Consequently, it may be desirable for a fully automatic system to use current either as the main charge control parameter or to modify a voltage control scheme. In floated service, a rectifier can be applied to direct all charge current through a resistor bank which acts to limit the charge current. However, the Ni-Cd cell can stand continuous moderate excess charge, within overheat limits, and not sustain damage.

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