CO_2 sequestration monitoring and verification technologies applied at Krechba, Algeria

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The In Salah project in Algeria is an industrial-scale CO_2 storage project that has been in operation since 2004. CO_2 from several gas fields, which have a CO_2 content of 5–10%, is removed from the production stream to meet the sales gas-export specification of 0.3% CO_2. Rather than vent that separated CO_2 to the atmosphere (as was normal industry practice for such gas plants), BP and its joint venture (JV) partner, Sonatrach, invested an incremental US$100 million in a project to compress, dehydrate, transport, and inject that CO_2 into a deep saline formation downdip of the producing gas horizon. Statoil then joined the JV at production start-up in August 2004.

CO_2 is being injected into the aquifer leg of the gas producing Krechba Field in central Algeria (Figure 1) for long-term storage as a greenhouse-gas reduction initiative as part of the overall In Salah Gas (ISG) development project. The site has been identified by the Carbon Sequestration Leadership Forum (CSLF) as one of three worldwide industrial-scale monitoring and verification demonstration sites. The In Salah JV derives no commercial benefit from the CO_2 storage at Krechba. Its value is derived from its role as an experimental and demonstration project to provide insights to CO_2 geological storage in deep saline formations. A joint industry project (JIP) was set up to monitor the CO_2 storage process using a variety of geochemical, geophysical, and production techniques over an initial five-year period.

Figure 1. Location of In Salah gas project.

Objectives

The objectives of the JIP were set in 2005:

1) Provide assurance that secure geological storage of CO_2 can be cost-effectively verified and that long-term assurance can be provided by short-term monitoring. (For the purposes of this discussion, short term is considered to be 10 years or less while long term is considered to be hundreds of years.)
2) Demonstrate to stakeholders that industrial-scale geological storage of CO_2 is a viable GHG-mitigation option.
3) Set precedents for the regulation and verification of the geological storage of CO_2, allowing eligibility for GHG credits.

Currently, there are three long (1500–1800 m), horizontal, state-of-the-art injectors at Krechba, injecting up to 50 mmscfd of CO_2 (Figure 2). These were drilled using geosteering technologies to maintain the wells within the formation and perpendicular to the maximum stress field, and, therefore, the dominant fracture orientation, to maximize the injection capacity. Over the life of the project, it is planned to store up to 17 million tons of CO_2, while to date, almost 3 million tons of CO_2 have been injected, principally with the two northern injectors, KB-502 and KB-503 (Figure 2).

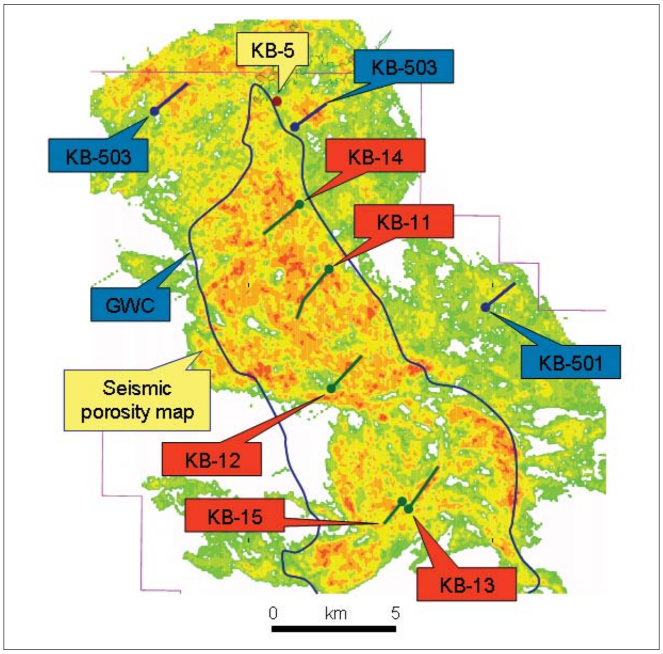

Figure 2. Location of Krechba injectors and producers.

The CO_2 is injected into the aquifer leg of a 20-m thick, fractured Carboniferous sandstone reservoir from which the Krechba Field produces CO_2-rich gas (Figure 3). The

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reservoir has porosities ranging from 13–20% and permeabilities averaging around 10 mD, while the injection depth is between 1850 and 1950 m underground.

The injection reservoir is sealed by around 950 m of a mixed sequence of Carboniferous mudstones that are unconformably overlain by approximately 900 m of a mixed Cretaceous sequence of sandstone and minor mudstones. This latter sequence comprises the regional potable aquifer. A thin impermeable anhydrite at the top of the Hercynian unconformity, some 3 m thick, divides the Carboniferous from the Cretaceous over the whole region as a final top seal. Surface outcrop consists mostly of Cretaceous muddy carbonates.

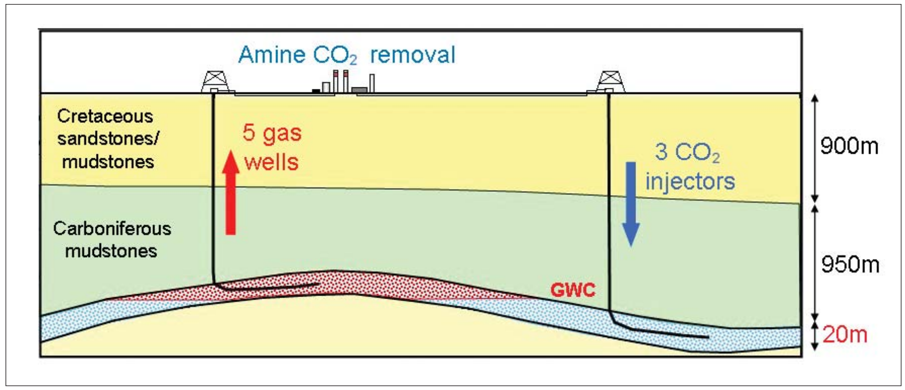

Figure 3. Schematic cross section of Krechba injection site.

A preinjection 3D seismic survey was acquired in 1997, but this was principally focused on imaging the reservoir section and not the overburden. These data were reprocessed in 2006 but did little to improve the imaging of the overburden section. Initial interpretations of the 3D seismic data suggested no major faults present at or above the injection horizon, with the strata being principally flat lying with little visible structural disturbance (Figure 4).

More recent detailed reviews of the reprocessed and original 3D seismic data sets have confirmed minor faults at the Carboniferous level and the immediately overlying cap rock but none at the Hercynian unconformity level. It is also is known that fracturing is present in the Carboniferous and lower overburden, based on information from image logs and mud losses sustained while drilling this section. It is thought these are due to deeper-lying structures over which the Carboniferous section is flexed, causing NW-SE oriented fractures.

In 2007, high concentrations of CO_2 were measured in the northerly KB-5 well (an old appraisal well drilled in 1980 into the Carboniferous aquifer and not cemented across that interval when suspended), which lies 1.4 km northwest of

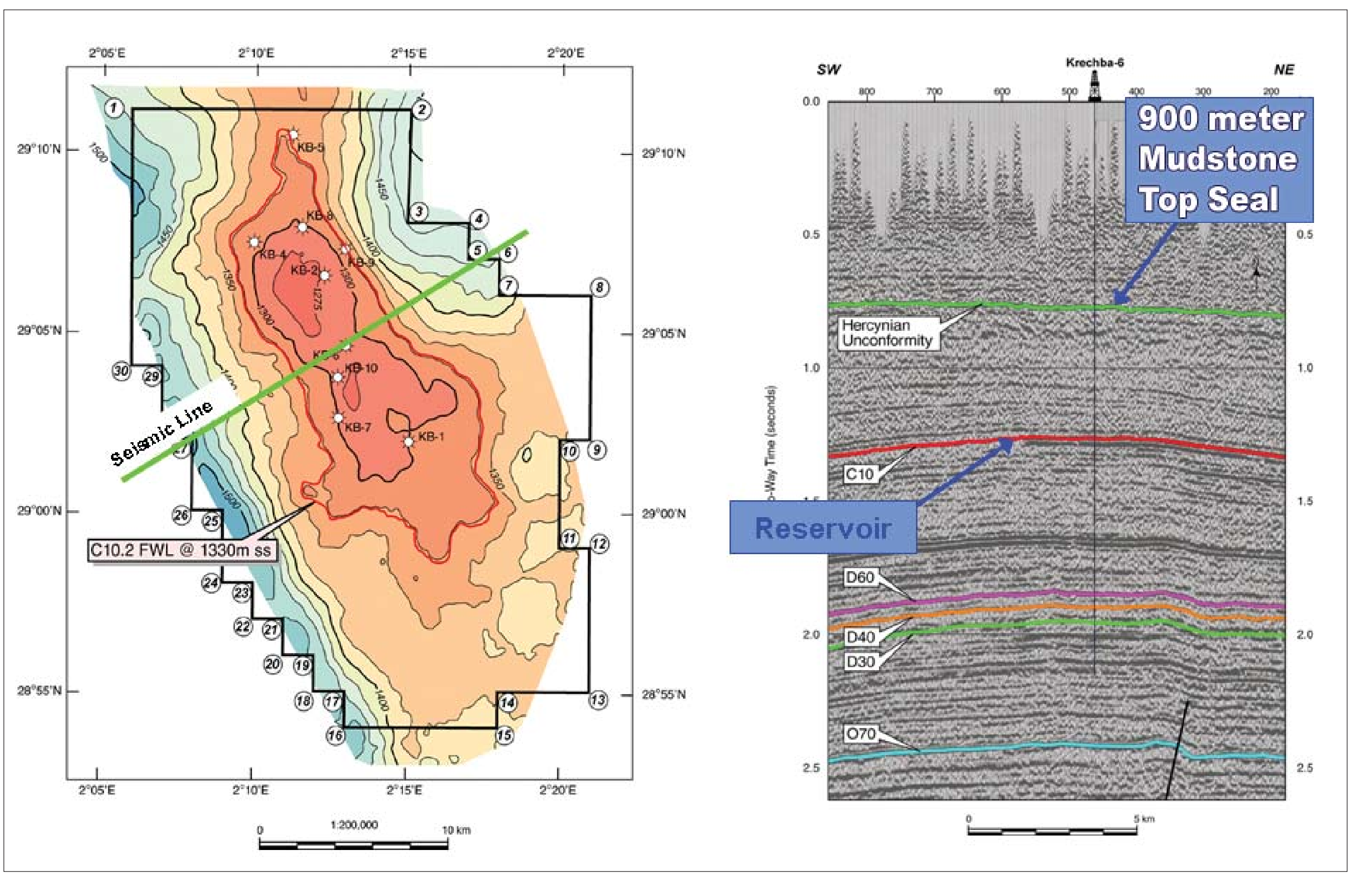

Figure 4. Original Krechba seismic data.

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Key risk	Monitoring technologies
Injection well problems	Ongoing pressure monitoring, through casing logging
Early CO_2 breakthrough	Modeling, tracers, seismic imaging, observation wells, fluid sampling, wellhead and annulus monitoring
Vertical leakage	Seismic imaging, microseismic, shallow-aquifer monitoring, soil-gas sampling, surface flux, gravity, tilt-meters, satellite imagery
Wellbore leakage	Annulus monitoring, soil-gas sampling, through casing logging
Old wellbore integrity	Annulus pressure monitoring and CO_2 surface flux monitoring

Table 1. *Key risks and monitoring technologies—Krechba.*

the KB-502 injector. Tracer analyses confirmed that the CO_2 detected at KB-5 came from KB-502. KB-502 was shut in until the well was remediated, which has been completed successfully; injection will restart imminently.

Reservoir modeling and history matching of the CO_2 breakthrough, pressure data, and satellite deformation data (to be discussed below) have allowed us to build up a detailed picture of the CO_2 plume around injection well KB-502. Wellhead-pressure monitoring on both the KB-5 and KB-502 wells indicated that the pressure stayed steady in both wells, confirming the CO_2 is being contained in the subsurface and not leaking off into the overburden.

Key risks versus monitoring

A preinjection risk register was prepared as part of the initial assessment of the injection site, which was used to design the original monitoring program. The key risks were identified,

Monitoring technology	Risk to monitor	Action
Wellhead/annulus sampling	Wellbore integrity Plume migration	• Twice-monthly sampling since 2005
Tracers	Plume migration	• Implemented 2006
Wireline logging/sampling	Subsurface characterization	• Overburden samples and logs collected in new development wells
Soil gas/surface flux	Surface seepage	• Preinjection surveys in 2004 • Repeat survey in 2009
3D-4D seismic	Plume migration	• Initial survey in 1997 • High-resolution survey acquired in mid-2009. Provides feasibility evaluation for 4D
Deep-observation wells	Plume migration	• Not planned at present due to cost
Microseismic	Cap rock integrity	• Test well drilled mid-2009 above KB-502 injector • Depth 500 m, 1500 m above injection zone, 50 geophones array (10 three-component) • Recording ongoing
Electromagnetic surface and wellbore	Plume migration	• Not useful at Krechba due to subsurface architecture and logistics • Wells too widely spaced
Gravity	Plume migration	• Modeling suggests surface response negligible • May be tested in 2011 • Borehole gravity possible if suitable access available
VSP	Cap rock integrity Plume migration Fracture evaluation	• Modeling results inconclusive • Decision pending 3D VSP into microseismic array
Shallow aquifer wells	Contamination of potable aquifer Cap rock breach	• Seven shallow aquifer wells drilled • Sampling twice per year
Microbiology	Surface seepage	• First samples collected in late 2009
Eddy covariance flux towers and LIDARs	Surface seepage	• Reviewed, but weather conditions and potential equipment theft ruled this out • Reviewing potential for deployment in 2011
InSAR monitoring	Plume migration Cap rock integrity Pressure development	• Used extensively, contributions and commissioned work from several providers • Images captured every 28 days
Tiltmeters/GPS	Plume migration Cap rock integrity Pressure development	• To calibrate InSAR deformations • 70 tiltmeters deployed around KB-501 in late 2009

Table 2. *Monitoring technologies, risks, and status.*

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and the associated monitoring technologies are shown in Table 1.

Four years after injection start up, a quantitative risk assessment was undertaken that identified wellbore integrity and potential migration of CO_2 out of the licensed storage area as the key risks, which resulted in further changes to the forward-monitoring program.

Preinjection data acquisition

A data-collection program was initiated prior to the start of injection in August 2004. This included extensive sampling and logging (including image logs) programs in the new development wells, saline-aquifer sampling, and headspace-gas sampling throughout the overburden. A soil-gas survey was also conducted around each of the new wells, and samples were collected from the shallow aquifer water wells at the accommodation camp and the central processing facility (CPF).

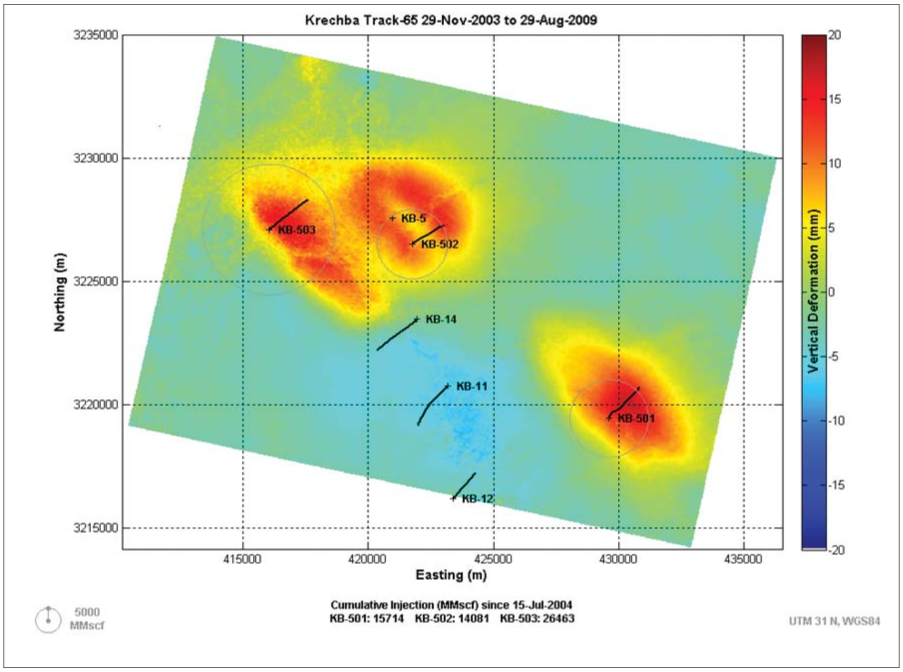

Figure 5. Satellite image of surface deformation at Krechba due to CO_2 injection (courtesy of MDA/Pinnacle Technologies).

Initial monitoring and verification program—Boston Square

Given the subsurface architecture, initial modeling work suggested that monitoring the movement of the injected CO_2 in the reservoir would be difficult using anything other than observation wells drilled through the injection horizon. However, it was initially considered (and still is) that monitoring of the overlying Carboniferous and Cretaceous sequences would be just as important, if not more so, than the reservoir. An initial suite of monitoring technologies was placed on a Boston Square to assess the cost benefit of each technology for use at Krechba. The Boston Square decision chart (Figure 6) has been critical in comparing the value of quite diverse technologies. The method has been used as a simple communication tool to contrast the relative merits of different monitoring technologies and help reach consensus with regulators and governments. It should be noted that each Boston Square assessment is unique to any given site.

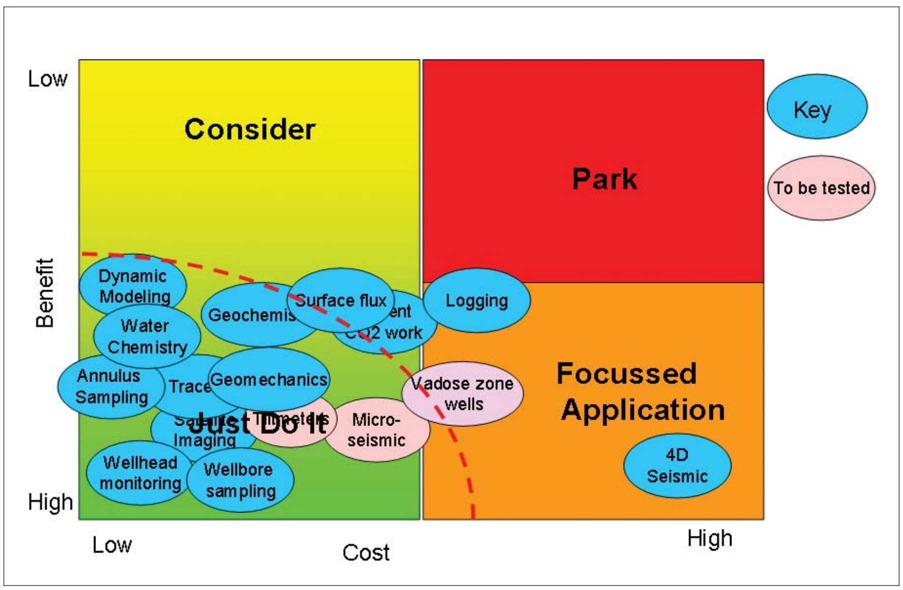

Figure 6. Current JIP monitoring and verification technologies at Krechba.

Monitoring and modeling studies/reviews: 2005–2009

A number of monitoring-technology reviews have been conducted over the last five years, and the results of the assessment of all initial technologies considered are shown in Table 2.

Satellite imaging

Perhaps the most valuable, and initially surprising, monitoring method so far has been the use of satellite-based interferometric synthetic aperture radar (InSAR) to detect subtle ground-deformation changes by comparing phase differences from successive satellite passes. There are several sophisticated signal processing methodologies such as permanent scatterer interferometry (PSInSAR), which is a multi-interferogram, image-processing approach developed by Tele-Rilevamento Europa (TRE) of Italy, and "network inversion" and "persistent scatterer interferometry" developed by MDA. These provide the

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means to compare multiple passes to enhance the deformation and suppress the influence of multiple noise sources due to atmospheric effects. These provide an accuracy of around 5 m/year and up to 1 m/year for a longer term average. In Salah has provided an excellent opportunity to evaluate the different approaches from the evolving satellite technologies and the signal processing from TRE, MDA, and JGI/Japex. Satellite data were and are being collected and interpreted continuously using Radarsat2, Envisat, and TerraSAR-X by MDA/Pinnacle Technologies and TRE on behalf of the JIP.

Surface uplift has been detected over all three of the In Salah CO_2 injection wells (with corresponding subsidence also observed over the gas-production area). Figure 5 shows one of the recent deformation images from MDA/Pinnacle (Envisat data) based on the surface deformation observed since the period before injection started up to August 2009. The red areas indicate uplift, while the blue areas denote subsidence. The observed surface uplift rate is around 3 mm/year. While not significant in terms of the local environment, the rate and pattern of surface deformation is being evaluated to provide an understanding of both the geomechanical response to subsurface movement of the injection of CO_2 at Krechba.

Using the satellite observations, it is possible to detect the surface changes resulting from the subsurface plume propagation effects. The "doughnut" shaped deformation around KB-502 is considered to be due to a single fault linking the KB-502 and KB-5 wells.

Forward and inverse modeling of the subsurface pressure increase due to CO_2 injection demonstrates that the surface deformation is consistent with measured geomechanical prediction and is caused by the geomechanical response to subsurface pressure increases caused by CO_2 injection. The JIP, working with the U.S. Department of Energy (DOE) Lawrence Livermore National Laboratory, has commissioned an extensive geomechanical and geochemical research program to model and integrate the InSAR data with geomechanical models, together with the seismic and fracture data to determine plume migration direction. Additional inversion work has been carried out at the DOE's Lawrence Berkeley National Laboratory, which will guide the forward-monitoring and data acquisition program.

Current monitoring program

The current and proposed JIP monitoring and verification program technologies are shown on a Boston Square in Figure 6. The number of technologies initially considered in the Boston Square has now been essentially reduced to the high-benefit, low-cost portion of the square, with the exception of 3D seismic and logging. The recently completed 3D seismic program provides high-resolution imaging of the overburden. This survey will also be compared to the original 3D survey and help assess whether detectable differences can be extracted from time-lapse comparison.

Monitoring results to date

To date, with the exception of the CO_2 encountered in the old KB-5 appraisal well, there has been no indication of any CO_2 moving out of the injection target zone.

The greatest risk of CO_2 leakage for any geological storage project is that associated with old wells. A valuable constraint to the In Salah subsurface CO_2 plume development was gained from detection of CO_2 breakthrough at the KB-5 monitoring (suspended appraisal) well.

Reservoir modeling and history matching of the CO_2 breakthrough, pressure data, and satellite deformation data have allowed us to build up a detailed picture of the CO_2 plume around injection well KB-502. Inversion of the deformation data with an updated geomechanical model suggests that existing vertical faults extending about 100 m into the immediate caprock between KB-5 and KB-502 have provided a conduit for the injected CO_2.

Conclusions

The suite of technologies to be deployed at any CO_2 storage site for monitoring and verification purposes is readily available and uses mainly standard oil field techniques and practices. However, each site will require a specific suite of cost-effective and focused technologies to provide the maximum benefit. There is no "cookie cutter" approach when it comes to designing a monitoring and verification program.

Our experience at Krechba to date is only in the early phases of a program that could extend for 20 years. So far, lessons learned about the various technologies and how best to integrate them into a coherent model of the subsurface and the CO_2 plume development for verification of long-term storage have proven invaluable. Key conclusions so far are as follows:

1) Each storage site is unique, and the monitoring and verification program is specific to the risks at each site.
2) Cost-effective technologies such as wellhead and annulus monitoring have proven to be very useful in the verification of long-term storage.
3) CO_2 plume development is far from homogeneous and requires high-resolution data for reservoir characterization and modeling.
4) InSAR data have proven highly valuable to monitor millimeter-scale surface deformation related to subsurface pressure changes caused by injection and production. This has resulted in major changes to the originally planned monitoring program.
5) Rock mechanical data and fractured rock characterization efforts are more important than initially anticipated, and current efforts are focused on acquiring further geomechanical data from cores of the overburden and logs in future development wells.
6) Five years of CO_2 storage at this site has been successfully demonstrated, and longer-term storage continues to be guided by a comprehensive, cost-effective, and fit-for-purpose storage monitoring programme.

We recommend, "*A technical basis for carbon storage,*" a Carbon Capture Project publication found at *http://www.co-2captureproject.org/reports.html*. TLE

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