BLAST FRACTURING: INSTALLATION AND EVALUATION OF A FRACTURED BEDROCK ZONE WITHIN GRANITIC BEDROCK AT EDWARDS AFB

Mark Henkes (mark.henkes@earthtech.com), Sarah Grossi Ph.D., and
Doug Britton Ph.D. (Earth Tech, Inc. Long Beach, CA)
Patrice Hallman (U.S. Air Force 95th Air Base Wing Environmental Management Branch)

Abstract

A pilot study involving creation of two fractured bedrock zones (Northern and Southern FBZs) was conducted at Site 37, Edwards AFB, CA. Ground water occurs in discrete water-bearing zones within fractured granitic bedrock at low yields (<0.1 gallons per minute [gpm] and ~0.3 gpm in the two study areas) that limit remedial options. The objective for creating the FBZs was to evaluate whether blast fracturing could create a zone of highly interconnected fractures that would exhibit greater ground water connectivity, well yield, and pumping radius of influence than what is typically encountered at Site 37.

Between December 2004 and January 2005, three blasting events were conducted in which a total of 31 boreholes were loaded and detonated with packaged emulsion explosives vertically stacked in decks spanning a 60-foot blast zone (80 feet to 140 feet below ground surface). The decks, separated by stemming stone, were detonated sequentially, with a delay between decks and between blasting holes to allow for increased movement of rock within the blasting zone and to reduce vibrations (that could damage underground utilities) outside the blasting zone. The initial blasting event used a charge weight per deck of approximately 14 pounds and the two subsequent events used approximately 28 pounds per deck. In total, 2,200 pounds of explosives in the Northern FBZ and 370 lbs of explosives in the Southern FBZ were used to create blast-impacted areas of approximately 29,000 cubic feet and 4,300 cubic feet, respectively.

Boreholes that had been drilled and left open during the blasting events did not collapse (as had been expected), indicating that complete fracturing of the zone was not achieved. However, seismographic data indicated that further increasing the charge weight per deck would have created vibrations exceeding limits designed to be protective of nearby buildings and underground utilities. Ground water samples collected in the FBZ areas showed that post-blasting concentrations of several parameters (notably perchlorate and nitrate) increased by several orders of magnitude as compared to their pre-blasting concentrations.

To complete the evaluation, long-term pumping tests were conducted in one well located in each of the FBZs. Results from these pumping tests indicated that the blast fracturing did not achieve any significant increase in well yield or pumping radius of influence over what is typically encountered at Site 37. Ground water connectivity within the Northern FBZ was anisotropic with parts of the FBZ showing no greater connectivity to wells located inside the FBZ than those outside the FBZ.

298 to 311

Introduction

Edwards Air Force Base, located approximately 5 miles northeast of the city of Lancaster, California (Figure 1), was listed on the U.S. EPA's National Priorities List (NPL) in 1990. Site 37 is located within the northeast portion of Edwards AFB on the southeastern flank of Leuhman Ridge. Building 8595, the source area for the Site 37 ground water plume, was used between 1960 and 1996 for maintenance and repair of rocket components involving the use of tetrachloroethene (PCE). The release of PCE south of Building 8595 has created a ground water contaminant plume extending laterally approximately 6,000 feet south and vertically to depths greater than 250 feet (ft).
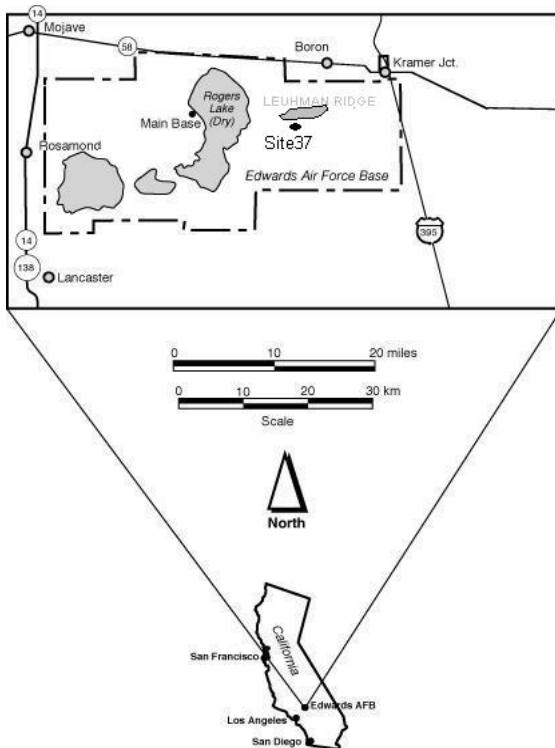

Figure 1 – Location of Site 37 at Edwards AFB, CA

A ground water extraction and treatment system (GETS), installed as part of a treatability study at Site 37, has been operating since January 1999 to evaluate the effectiveness of ground water pump-and-treat to hydraulically contain ground water with PCE concentrations in excess of 10,000 micrograms per liter (μg/L). The Site 37 GETS includes seven extraction wells and an aboveground treatment system that uses activated carbon to remove volatile organic compounds (VOCs) from the extracted ground water. As of June 2006, the long-term pumping rates in these wells ranged from 0.4 gallons per minute (gpm) to 0.01 gpm. The low and highly variable ground water yields are attributed to poor connectivity between ground water-bearing fractures in the granitic bedrock, which presents a major challenge to implementation of an effective remedial alternative for contaminated ground water at Site 37.

At other sites, blast fracturing has been used to overcome the remedial limitations imposed by a lack of connectivity among water-bearing fractures in various types of bedrock (Miller 1996, Lane et al., 1996, Roote 2000). Blast fracturing involves detonating explosives in boreholes (shotholes) to artificially create a fractured bedrock zone (FBZ). This technique has been shown to substantially increase permeability within the FBZ by comparison to bedrock that has not been blasted (Loney et al, 1996). Previous installations of FBZs, typically in shallower applications than described here for Site 37, have on average resulted in an order-of-magnitude increase in the well yield from a well installed within the FBZ over a well installed in the same bedrock without blast-enhancement (Loney et al., 1996).

The design, methodology, and location for the FBZ pilot study at Site 37, developed with help from Haley & Aldrich of New York, were selected with the intent to evaluate blast fracturing as a tool for enhancing groundwater recovery either for future groundwater extraction systems or to enhance delivery of remediation fluids (i.e. chemical oxidants or biological reagents). The FBZ design, consisting of two 25-foot long collection arms and a 15-feet by 10-feet treatment cell, was initiated with the intent to create an area of sufficient size to achieve the following objectives:

- Increase fracture connectivity.
- Increase the long-term yield substantially (at least 10-fold) above what is typically encountered at Site 37.
- Increase the pumping radius of influence (ROI) substantially above what is typically encountered at Site 37.

This paper describes the installation and subsequent evaluation of two FBZs at Site 37 to determine if the objectives were achieved.

Site Geology and Hydrology

Geology at Site 37 consists of quartz monzonite bedrock overlain in areas by a thin veneer of unconsolidated material. The overlying unconsolidated material grades into a thin zone of fractured, weathered bedrock below which fractured competent bedrock is encountered. Depth to competent bedrock in the area selected for the FBZ varies from 5.5 to 12 feet (ft) below ground surface (bgs). Based on observations of nearby outcrops and borehole logging, the crystalline bedrock is fractured throughout with discrete zones that are more highly fractured. It is not uncommon for these highly fractured zones to be completely weathered with varying percentages of clay. In surface exposures of the bedrock, steeply dipping fractures at approximately 70 to 85 degrees from horizontal predominate, with conjugate sets dipping at approximately 45 degrees from horizontal. However, sheeting or unloading fractures are thought to be present as well.

Ground water at Site 37 occurs under hydrostatic pressure within discrete water-bearing fractures in the competent bedrock. The depth to first ground water contact is highly variable, generally increasing in depth with distance from the source area at Building 8595. The first encountered ground water ranges from 32 ft bgs within 50 feet south of the building to 230 ft bgs near the leading edge of the plume, but has been observed to vary between 10 and 50 ft bgs in boreholes located 20 ft from each other. From previous pumping tests conducted at the site, the hydraulic conductivity has been calculated to range from 0.001 feet per day (ft/day) to 0.7 ft/day. Previously the pumping ROI was estimated at approximately 90 ft.

FBZ Design and Specifications

Due to the variability in depth to first ground water encounter, six exploratory boreholes were drilled to aid in selection among three potential study areas. The area

surrounding test borehole 37-FBZ2/3 was ultimately selected, based on its distance (more than 300 feet) from existing utilities or buildings, a relatively high water inflow rate (estimated at 0.7 gpm during drilling), and relatively shallow depth to ground water (first encounter between 85 and 135 ft bgs with a static level of 63 ft bgs).

To bracket the range of ground water encountered in the pilot study area, the FBZ was designed to span a 60-foot vertical zone, targeting depths between 80 and 140 ft bgs. The initial design (provided by Haley & Aldrich using elements of its patented Refractive Flow and Treatment [RTF] Process, Edwards et. al. 2001) included 20 boreholes arranged in a y-shape, with two 25-by-3 foot collection arms leading into a 10-by-5 foot central "treatment" zone (for post-blasting extraction of ground water and/or injection of amendments for in situ treatment). To achieve fracturing throughout the entire vertical span, closely spaced boreholes were to be drilled with a 3.5-inch diameter bit to a depth of 142 feet bgs. The design included two types of boreholes:

- Shotholes to be loaded with explosives and detonated; and
- Relief holes to be left open during blasting, allowing movement of the bedrock.

One FBZ Becomes Two

During drilling of the 11th borehole surrounding test borehole 37-FBZ2/3 (in what later became the Southern FBZ, refer to Figure 2), ground water was observed spouting from a previously drilled borehole located 3.5 feet away. This phenomenon indicated that the completed boreholes were likely to deviate from vertical, compromising the FBZ design. In response, the drilling method was modified to include the addition of larger diameter drill collars and thicker drill rods; this resolved the problem. A geophysical tool (FLEXIT smart tool) was used to measure the vertical deviation and direction of deviation for the completed boreholes. Based on results for the initial 11 boreholes, the pilot study team decided that the degree and random orientations of deviations in these boreholes was too great to fulfill the FBZ design; therefore, drilling was moved 35 feet to the north (in an area identified as the Northern FBZ).

After borehole drilling was resumed in the Northern FBZ location, it was observed that the ground water inflow rate (estimated at 0.01 gpm) was significantly lower than the rate (approximately 0.7 gpm) estimated for boreholes drilled in the Southern FBZ area. Thus the team decided to create a smaller, second FBZ (identified as the Southern FBZ) in the original pilot study area where the higher ground water yields were observed.

Characteristics of Explosive

For each of the FBZs, shotholes were loaded using an explosive identified as Dyno TX: a detonator- sensitive, high-energy, water-resistant packaged emulsion explosive specifically designed for trenching in very wet conditions where explosive charges are closely spaced. This type of explosive is not shock sensitive and will not detonate without a high energy trigger, such as a detonator. In addition, this explosive does not contain ammonium nitrate-fuel oil (ANFO). ANFO, which contains benzene,
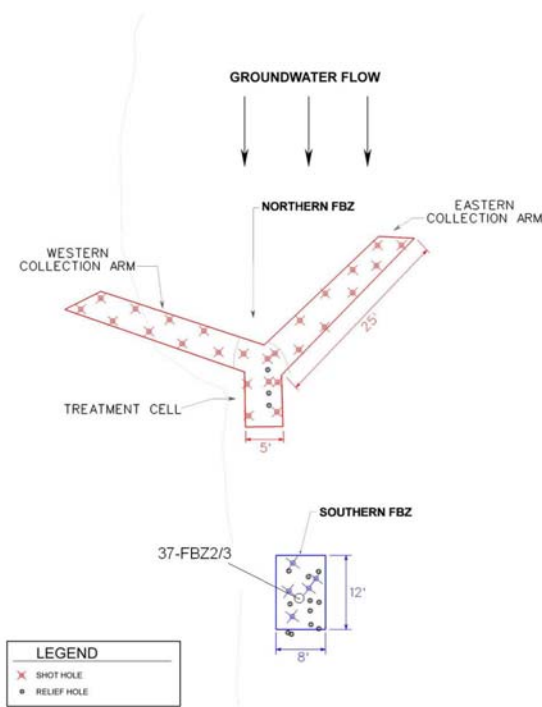
Figure 2 –Shothole Orientation for Northern and Southern FBZs

Shothole Design

In each shothole, 7 (for initial blasting event) to 14 (two subsequent events) cartridges of explosives were arranged into a series of decks, separated by 2-foot lengths of stemming (3/8-inch rock), that spanned the 60-foot blast zone (Figure 3). The uppermost deck was capped with stemming to the surface. A non-electric, high-energy detonator, which was attached to a length of shock tube of sufficient length to reach the ground surface, was inserted into the bottom cartridge for each deck. A weight was placed on the top cartridge and the entire deck was lowered into the shothole as one unit. This was done to minimize separation of the cartridges during loading. Above ground, a surface delay was attached to the shock tube for each deck. The firing sequence of the decks was

toluene, ethylbenzene and xylene (BTEX) components, an ingredient commonly found in emulsion explosives. Based on the material safety data sheet (MSDS) available prior to purchase, Dyno TX is composed of ammonium nitrate (60 to 80 percent) and sodium nitrate (10 to 18 percent) with a low percentage of heavy mineral oils and waxes. The Dyno TX explosives for the FBZs came in 55-pound (lb) cases with 25 to 27, 2-inch diameter by 16-inch long cartridges, each containing approximately 2.0 lbs of explosives.
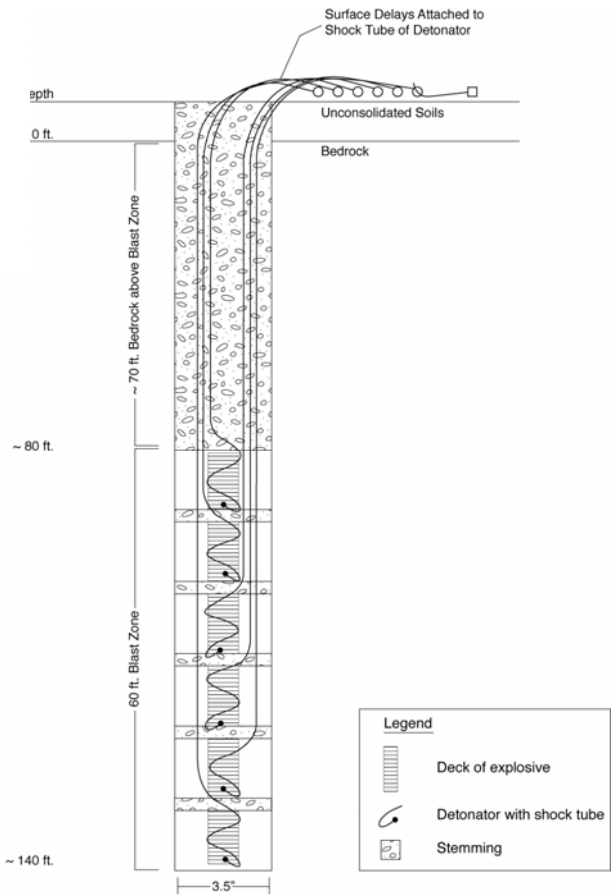

Figure 3 - Typical Shothole Design for FBZs

spaced so that none of the decks detonated at the same time. This created a series of detonations for each event. Though the decks were detonated only milliseconds apart, the delays allowed for larger volumes of explosives to be detonated in one event than could be safely used with one large detonation. The energy created from detonation of each deck in combination with the rotating firing sequence was designed to provide the energy to break up the bedrock.

The orientation of shotholes and relief holes for the two FBZs is presented in Figure 2. The "Y" shaped Northern FBZ, oriented with ground water flow gradient directed at the open part of the "Y", was designed with the intent that the collection arms would be of sufficient size to intersect a number of high yielding ground water producing fractures. The Northern FBZ was created using two separate blasting events: detonation of shotholes in the treatment cell area in the first event followed by detonation of shotholes in the two collection arms during the second event. The relief holes in the treatment cell, which were located in very close proximity to the first shothole detonated, were intended to provide open space along the 60-foot blast zone for any movement of the bedrock and opening of fractures. Table 1 presents a summary of the blasting specifications.

The design of the Southern FBZ was less structured. After the design team decided to attempt blasting in this area (because of higher groundwater inflow rates [relative to the Northern FBZ] observed during drilling). The results from the FLEXIT deviation survey were used to select placement of additional vertical shotholes. The Southern FBZ was created using a third and final blasting event per the specifications listed in Table 1.

Table 1. FBZ Blasting Specifications

	Northern FBZ		Southern FBZ
	Treatment Zone	Collection Arms	Treatment Zone
Number of Shotholes	8	18	5
Number of Relief Holes	5	3	9
Shothole Spacing	4-5 ft	4-6 ft	3-6 ft
Target Blast Zone	80-140 ft bgs	80-140 ft bgs	80-140 ft bgs
Stemming Between Decks	2 ft	2 ft	2 ft
Cartridges Per Deck	7	14	14
Charge wt. Per Deck	14 lbs	28 lbs	28 lbs
Number of Decks	6	3	3
Time Delay Between Deck	17 ms	25 ms	25 ms
Time Delay Between Shotholes	25 ms	17 ms	17 ms

Blast Vibration Monitoring

Blast-related vibrations, measured as peak-particle–velocities (PPV), were recorded during each of the blasting events from seismographs set up over the nearest utilities – an 8-inch diameter vitrified clay sewer line 250 ft to the east and a large diameter water line 225 ft to the west.   A design criterion limited the blast vibrations to a PPV of 2 inches per second (ips) during any blasting event. For comparative purposes, the US Bureau of Mines (USBM) considers a PPV less than 2 ips to be protective in preventing the

cracking of plaster walls in residential structures. The volume of explosives selected for detonation in each blasting event was selected to maximize the fracturing of the bedrock without damaging underground utilities.

Installation of FBZ Well Network

In order to prevent damage due to the explosives detonation, no wells were installed in the area of the FBZs prior to blasting. However, two months after the final blasting event, a total of nine wells were installed inside and surrounding the two FBZs (Figure 4). Each well was constructed with a 60-ft well screen spanning the approximate 60-ft blast zone (80-140 ft bgs). In the Northern FBZ, one well was installed in the eastern (Well 37-MW34) and western (Well 37-MW35) collection arm and one well in the center of the treatment cell (Well 37-EW09). Wells 37-MW37 and 37-MW38 were installed up gradient at distances of 28 ft and 62 ft, respectively from Well 37-EW09. Well 37-MW41 was installed halfway between the Northern and Southern FBZ, at a distance of 10 ft from each FBZ. Well 37-EW10 was installed inside the Southern FBZ. Wells 37-MW42 and 37-MW39 were installed 20 ft and 58 ft down gradient of Well 37-EW10, respectively.
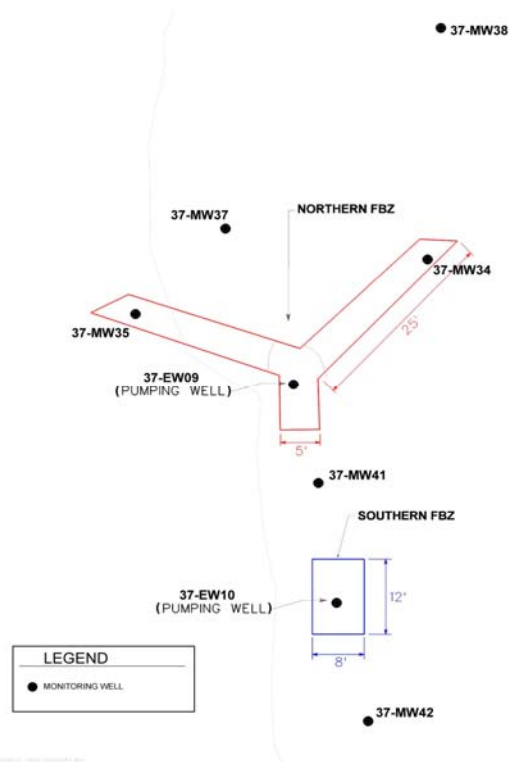

Figure 4 – Location of FBZ Well Network
(Well 37-MW39 is not shown)

Pumping Test Methods

Long-term pumping tests (lasting 133 days and 107 days, respectively) were conducted sequentially at Wells 37-EW09 and 37-EW10 located in the Northern and Southern FBZs. Objectives were to evaluate 1) the connectivity of wells within the Northern FBZ; 2) the long-term yields of wells inside both FBZs; and 3) the ROI from pumping within the FBZs. The pumping tests consisted of three phases: short-term constant rate pumping; long-term pumping; and rebound monitoring. Prior to initiation of each pumping test, pressure transducers were placed in the pumping well and five wells closest to the pumping well to monitor the ground water response to the pumping. Draw down of water within the wells located just outside the FBZ were used to calculate the pumping radius of influence.

Based upon variable pumping rate tests conducted a week prior to the long-term tests, flow rates of 0.2 gpm from Well 37-EW09 and 0.47 gpm from Well 37-EW10 were selected for the constant rate portion of the pumping tests. The pumping tests were initiated using an electric pump pumping at a constant rate (measured using a flow meter) until the ground water level reached the inlet to the electric pump. At this point, the electric pump was switched off and a pneumatic pump equipped with an in-line cycle counter was activated to initiate the long-term pumping test. The pneumatic pump worked cyclically: after ground water filled the 0.55-gallon chamber, compressed air pushed the water out through tubing to the surface. Thus flow from the well was not continuous but pulsed, removing ground water from the well as fast as it entered the well. At the conclusion of the pumping test ground water recovery was monitored.

Results

Between December 2004 and January 2005 three separate blasting events were conducted to create the Northern and Southern FBZs. Monitoring wells were installed during March and April 2005. Figure 5 shows a cross section of the FBZs.
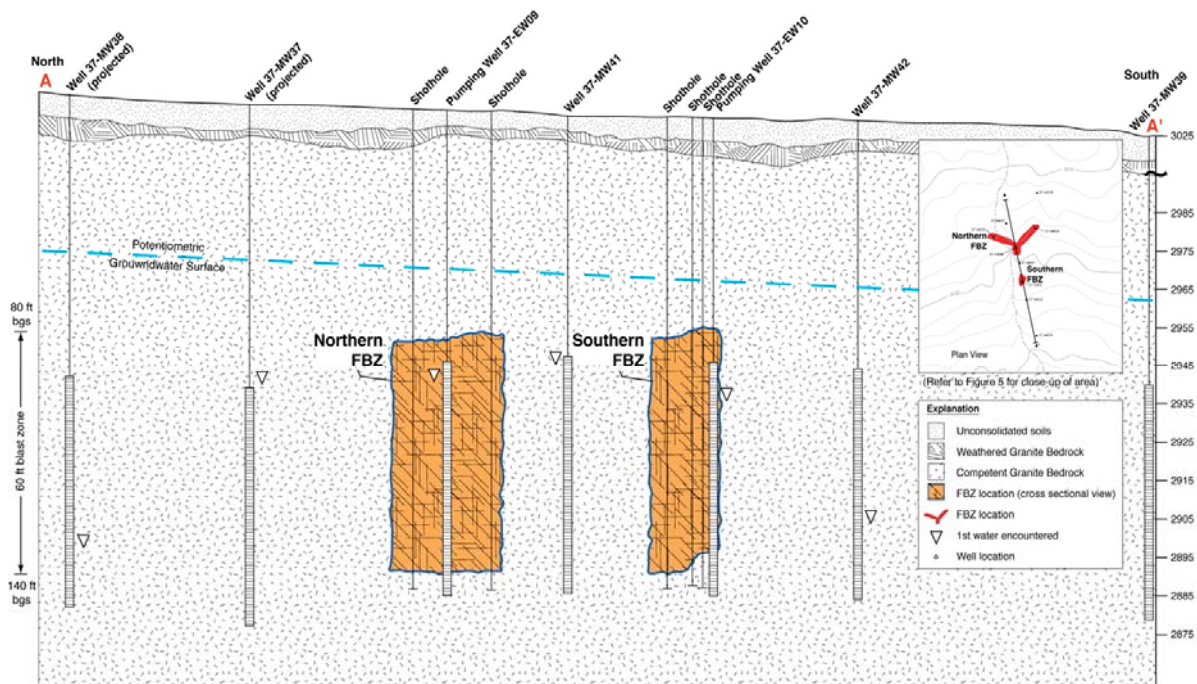

Figure 5 – Cross Section of Northern and Southern FBZs

Blasting and Well Drilling Observations

During the three blasting events, no surface heave was observed; however, gas venting and water spouting from the relief holes were seen, indicating communication between the shotholes was achieved. Unexpectedly, however, none of the blasting events induced all of the relief holes to collapse through the entire 60-foot blast zone. Some of the relief holes stayed open to their original total depth. Furthermore, estimated ground

water inflow rates at these open relief holes immediately following the blasting did not increase by comparison to rates measured when they were drilled, and in some cases inflow rates substantial decreased.

During the initial blasting event, the PPV from blast related vibrations measured 0.36 ips, well below the design limit maximum of 2 ips. Therefore, to increase the potential for fracturing during the two subsequent blasting events, the charge weight per deck was doubled (to 28 lbs). The increased volumes of explosive used for the second and third blasting events results in PPVs of 1.1 ips and 2.5 ips, respectively, the latter (in the Southern FBZ) exceeding the design threshold for acceptable blast vibrations. This result indicates that any further increase in the volume of explosives used per deck could present a risk of damage to underground utilities in the area.

Wells drilled within the FBZs were observed to emit a distinct odor of explosives within the 60-foot blast zone. Faster drilling rates were also encountered, and drill cuttings contained large, gravel-sized pieces. However the degree of fracturing through the blast zone was variable. In Wells 37-MW35, 37-EW09, and 37-EW10, an interval of competent, unfractured bedrock, approximately 5 ft thick, was encountered at a depth between 105 ft and 115 ft bgs. "Ponded" water was encountered on top of this unfractured layer, whereas drill cuttings immediately beneath this interval were dry. Below the unfractured layer, highly fractured bedrock was again encountered and drill cuttings again became wet, indicating interception of a water-bearing zone.

Ground Water Sampling

Ground water samples were collected from boreholes prior to and immediately following the blasting, and from wells installed after the blasting. Ground water sampling results showed elevated concentrations of perchlorate, nitrate, boron, and BTEX (primarily benzene and toluene) at locations inside and between the FBZs by comparison with samples collected from wells outside the FBZ area of influence. When comparing maximum pre- and post-blasting concentrations of these analytes, perchlorate increased from 18.3 µg/L to 6,550 µg/L, nitrate from 18.3 µg/L to 733 µg/L, boron from 1.5 mg/L to 30.3 mg/L, benzene from <100 µg/L to 340 µg/L, and toluene from <100 µg/L to 110 µg/L.

The likely source of the increase in these chemicals following the blasting was blast residue remaining in the ground water. In particular, the source for perchlorate is thought to be sodium nitrate used in the explosives (following the blasting events, the explosives manufacturer issued an updated MSDS that identified their source of sodium nitrate to be "Chilean Nitrate," which is known to contain naturally occurring perchlorate in concentrations between 50 and 350 ppm). Over the course of extraction from the FBZs, the perchlorate concentration in the area has gradually decreased.

Pumping Test

A summary of results from the long-term pumping tests is presented in Table 3. Wells 37-MW34 (eastern collection arm), 37-EW35 (western collection arm), and 37-MW37 (up gradient of the Northern FBZ) are all located at approximately equal distances (around 28 ft) from Well 37-EW09 (pumping well inside the Northern FBZ). However, during the pumping of 37-EW09, the response observed in Well 37-MW34 was faster and significantly greater than that observed in Well 37-MW35. By the conclusion of the pumping test, a greater drawdown was observed in Well 37-MW37 than in Well 37-MW35, indicating that ground water connectivity was anisotropic across the Northern FBZ and no greater in the western half of the FBZ than outside the FBZ.

Table 3. Summary of the Pumping Test Results

Pumping Wells	Observation Wells	Distance from Pumping Well (ft)	Total Pumping Duration (days)	Pumping Rate at Conclusion of Pumping test (gpm)	Maximum Drawdown (ft)	Radius of Influence (ft)
Northern FBZ						
37-EW09			133	0.02	76.7	105
	37-EW10	36			2.4	
	37-MW34	29			15.0	
	37-MW35	28			4.0	
	37-MW37	28			8.0	
	37-MW38	62			3.3	
	37-MW41	16			8.5	
Southern FBZ						
37-EW10			107	0.12	76.0 ft	70
	37-EW09	36			11.5	
	37-MW34	57			10.5	
	37-MW35	56			17.5	
	37-MW41	20			21.4	
	37-MW42	19			24.2	

During each of the pumping tests, the ground water extraction rate was monitored (Figures 6 and Figure 7). Extraction rates were low and observed to fall quickly once the pneumatic pump was activated. At the conclusion of the 133-day pumping test in Well 37-EW09, the pumping rate was 0.016 gpm. The rate at the conclusion of the 107-day pumping test in Well 37-EW10, the pumping rate was 0.12 gpm.

Figure 8 presents a semi-log plot of drawdown at the conclusion of the 133-day pumping test in Well 37-EW09 versus distance from the three wells (37-MW37, 37-MW38, and 37-MW41) located surrounding the Northern FBZ. An ROI of 105 ft was estimated based on the zero-intercept of a best fit line. Figure 9 presents a semi-log plot
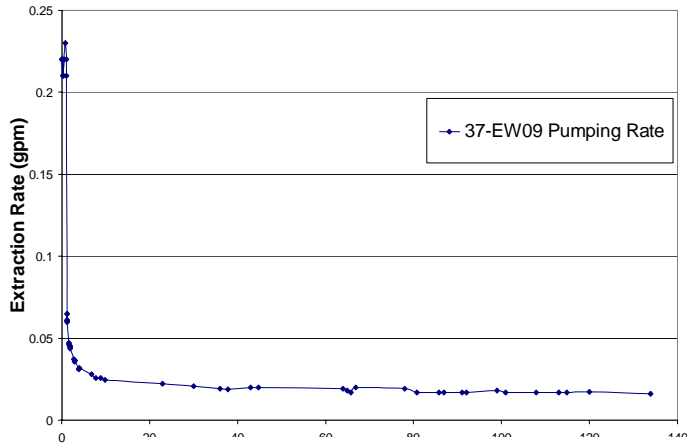
Figure 6 - Extraction Rates During Northern FBZ long-term pumping test at Well 37-EW09
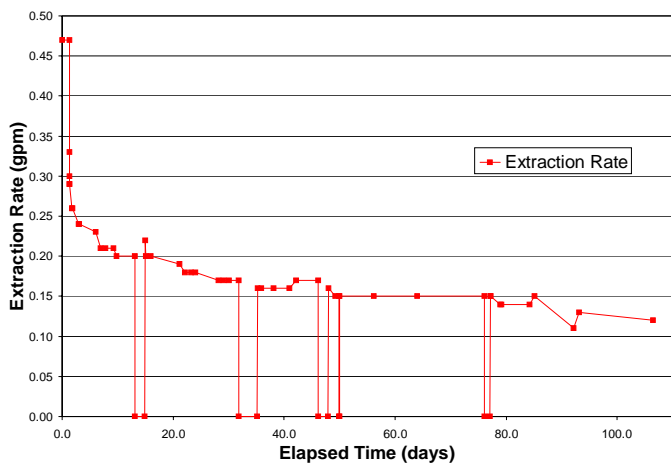

Figure 7 - Extraction Rates During Southern FBZ long-term pumping test at Well 37-EW10

new fractures to expand or propagate during the detonations. Also, the competent bedrock within the blast zone was observed (during drilling of shotholes and relief boreholes) to vary from very hard to soft. The soft zones may have dissipated the impact of the detonations by absorbing most of the energy. Should blast fracturing be attempted in a future pilot study at the site, we recommend the following design modifications to overcome these limitations:

of drawdown at the conclusion of the 107-day pumping test in Well 37-EW10 versus distance from the three wells (37-MW41, 37-MW42, and 37-MW39) located surrounding the Southern FBZ. An ROI of 70 ft was estimated based on the zero-intercept of a best fit line.

Conclusion

Neither of the FBZs showed increases in long-term yield or pumping radius of influences over non-blasted areas at Site 37. The connectivity within the Northern FBZ is anisotropic, with some wells showing a greater connectivity to wells located outside the FBZ compared to wells located inside the FBZ.

The failure of the FBZ to achieve any of the pilot study objectives is attributed both to design limitations and the challenging geology at Site 37. While the design relief holes provided an open space for the expansion of the bedrock, the thickness (65 to 75 feet) of competent bedrock above the blast zone may have limited the ability of
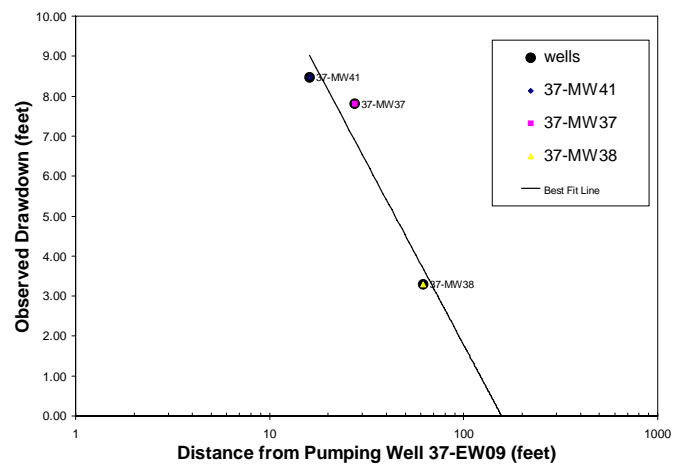

Figure 8 – Drawdown versus Distance at Conclusion of Pumping Test at Well 37-EW09 Located in Northern FBZ

1. Expand the blast zone to include the thickness of competent rock overburden overlying the targeted water-bearing interval.
2. Use a significantly larger quantity of explosives to overcome dissipation of energy within naturally-occurring soft zones.
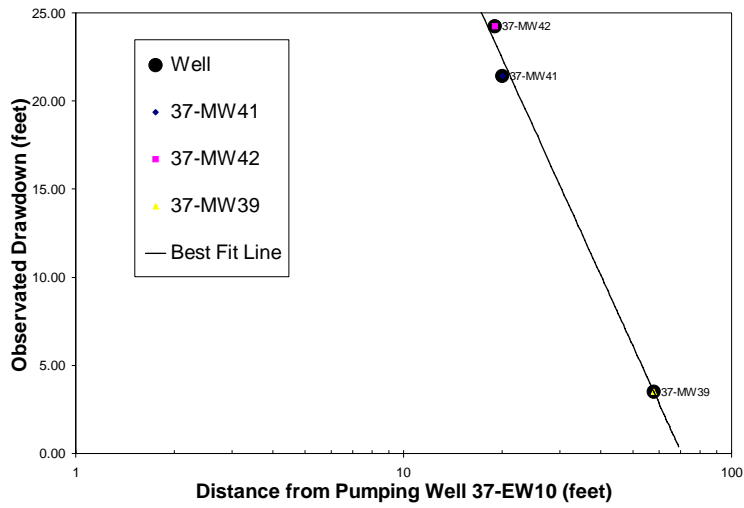

Figure 9 - Drawdown versus Distance at Conclusion of
Pumping Test at Well 37-EW10 Located in Southern FBZ

References

Edwards, D.A., Dick, V.B., Little, J.W., and Boyle, S.L. 2001, *Refractive-Flow and Treatment Systems: Conceptual, Analytical, and Numerical Modeling*, Ground Water Monitoring and Remediation, Vol. XXI, No 3, p. 64-70.

Lane, J.W., Jr., Haeni, F.P., Soloyanis, Susan, Placzek, Gary, Williams, J.H., Johnson, C.D., Buursink, M.L., Joesten, P.K., and Knutson, K.D., 1996, *Geophysical characterization of a fractured-bedrock aquifer and blast-fractured contaminant-recovery trench*, *in* Bell, R.S., and Cramer, M.H., eds., Symposium on the Application of Geophysics to Engineering and Environmental Problems, Keystone, Colo., April 28-May 2, 1996, Proceedings: Wheat Ridge, Colorado, Environmental and Engineering Geophysical Society, p. 429-441.

Loney, J.E., Edwards, D.A. and Little, J.E., 1996, *Ground water capture and remediation with engineered blasted-bedrock zones*, Northeastern Geology and Environmental Sciences, v. 18, No. 3, p. 195-200

Miller, R. R., 1996. *Artificially-Induced or Blast-Enhanced Fracturing*, Ground-Water Remediation Technologies Analysis Center, Technology Overview Report TO-96-01.

Roote, D. S., 2000. *Technology Status Report Hydraulic, Pneumatic, and Blast-Enhanced Fracturing*, Ground water Remediation Technologies Analysis Center, Technology Overview Report TO-00-01.

Smerekanica, J.R., Gheorghiu,F., Enachescu,C., Pedersen, M.C., *Hydrogeologic Testing in Blast-Shattered Heterogeneous Bedrock,* http://www.golder.com

Biographical Sketches

Mark Henkes obtained a BS in geology from Southern Oregon University in 1999. Following a year working in eastern Nevada within the exploratory division of a gold mining company, he began working for Earth Tech as a staff geologist. During the eight years at Earth Tech, he has worked primarily with investigation and delineation of large chlorinated contamination ground water plumes contained in granitic bedrock at the Air Force Research Laboratory at Edwards AFB. He is currently a project manager helping to manage activities to evaluate and investigate remedial alternatives.

> Address: Earth Tech
>   300 Oceangate Suite 700
>   Long Beach, CA 90802

Sarah Grossi obtained a BA in biology from Bellarmine College (Louisville KY) in 1976, an MS in Biology from the University of Southern California (USC) in 1979 and a PhD in Biology from USC in 1985. She worked as an environmental scientist at GSF Energy from 1986 through 1989, and has been at Earth Tech from 1989 to the present. She is a senior project director managing a number of task orders for ground water operable units at Edwards AFB.

Patrice Hallman obtained a BS in Industrial Engineering from the University of Texas at Arlington in 1986. She served as a Civil Engineering Officer in the United States Air Force until 1990. Since 1993, she has worked as an environmental engineer at the Air Force Flight Test Center at Edwards Air Force Base, California. She is currently a program manager for the Restoration Branch of the Environmental Management Division.