Technology
Overview Report

TO-96-01

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Artificially-Induced or Blast-Enhanced Fracturing

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June 1996

Prepared For:

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FOREWORD

About GWRTAC

The Ground-Water Remediation Technologies Analysis Center (GWRTAC) is a national environmental technology transfer center that provides information on the use of innovative technologies to clean up contaminated groundwater.

Established in 1995, GWRTAC is operated by the National Environmental Technology Applications Center (NETAC) in association with the University of Pittsburgh's Environmental Engineering Program through a Cooperative Agreement with the U.S. Environmental Protection Agency's (EPA) Technology Innovation Office (TIO). NETAC is an operating unit of the Center for Hazardous Materials Research and focuses on accelerating the development and commercial use of new environmental technologies.

GWRTAC wishes to acknowledge the support and encouragement received for the completion of this report from the EPA TIO.

About "O" Series Reports

This report is one of the GWRTAC "O" Series of reports developed by GWRTAC to provide a general overview and introduction to a groundwater-related remediation technology. These overview reports are intended to provide a basic orientation to the technology. They contain information gathered from a range of currently available sources, including project documents, reports, periodicals, Internet searches, and personal communication with involved parties. No attempts are made to independently confirm or peer review the resources used.

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ABSTRACT

This technology summary report is an overview of information collected by the Ground-water Remediation Technologies Analysis Center (GWRTAC) on artificially-induced or blast-enhanced fracturing as applied to environmental remediation. Information provided includes an introduction to the principles and techniques associated with this technology, a general discussion of its applicability to remediation, limited data relating to results of its use, and advantages and limitations of use of this technology.

Artificially-induced or blast-enhanced fracturing is a technique used at sites with fractured bedrock formations to improve the rate and predictability of recovery of contaminated groundwater. The increased well yields, hydraulic conductivity values, and capture zones that result from use of this technique occur as a result of creation of a "fracture trench" or highly fractured area created through detonation of explosives in boreholes (shotholes). Blast-enhanced fracturing is distinguished from hydraulic or pneumatic fracturing in that the latter technologies do not involve explosives, are conducted in the overburden, and are performed within individual boreholes. In blast-enhanced fracturing, the numbers, locations, and spacing of shotholes are determined through interpretation of site characterization data, usually including aquifer testing (e.g., pump, packer, slug testing).

Blasting program design is determined by a qualified explosives contractor, considering rock strength, nearby structures (i.e., buildings and public and plant utilities) and vibration-sensitive processes, and integrating hydrogeological data and expected results. This technique has been used at sites underlain by various types of bedrock (i.e., sandstone, limestone, shale, granite, slate) and having elevated levels of LNAPLs and DNAPLs in groundwater. Advantages of using this technique include decreased numbers of recovery wells required (due to increased hydraulic conductivities) and decreased remediation times (due to increased well yields). To date, blast-enhanced fracturing has been used only with pump-and-treat methods, but it also may be useful in improving the performance of certain *in situ* technologies.

This document was prepared for distribution by GWRTAC. GWRTAC is being operated by the National Environmental Technology Applications Center (NETAC), under a Cooperative Agreement with the United States Environmental Protection Agency's (EPA) Technology Innovation Office (TIO).

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1.0 INTRODUCTION

1.1 BACKGROUND

Groundwater contamination in fractured bedrock aquifers is an important public health concern due to the frequent use of these aquifers for drinking water supplies. However, remediation of these aquifers can be very difficult due to the complex nature of fracture flow conditions. Additional complications to the capture of contaminated groundwater involve the often low and unpredictable well yields associated with these aquifers. Blast-enhanced fracturing addresses some of the complicating factors involved in groundwater remediation in fractured bedrock by increasing the predictability of flow paths and the rates of groundwater flow along these paths. Use of this technique, which involves the creation of an intensely fractured bedrock zone, provides a greater level of confidence for subsequent remediation/recovery and migration control efforts.

1.2 GROUNDWATER FLOW IN FRACTURED BEDROCK

In fractured bedrock formations, groundwater flow is complex and difficult to predict, being controlled by the nature, extent, and interconnectedness of the existing fracture network. Characterization of groundwater flow conditions at contaminated sites underlain by fractured bedrock is complicated by the often random occurrence and connections of fractures, with the common ideas of hydraulic conductivity, hydraulic head, and contaminated flow through porous media (e.g., “plume” concept) having little applicability to fracture-controlled flow. For example, aquifer testing may demonstrate little or no response in wells near the pumping well (due to lack to fracture connections), while responses in more distant wells may be much greater (due to fracture connections with the pumping well).

At sites with groundwater contamination in fractured bedrock, adequate removal, and subsequent treatment, of groundwater from all fractures transmitting contaminated flow, and the prevention of off-site migration can be time-consuming and expensive, and have limited success. In addition to the above site characterization problems, fractured bedrock aquifers often exhibit low hydraulic conductivities and low well yields, adding to the difficulties associated with remedial design (i.e., ensuring capture of sufficient groundwater and prevention of off-site migration) and making implementation of remedial/corrective measures expensive, with results uncertain and difficult to predict and monitor.

1.3 RATIONALE FOR BLAST-ENHANCED FRACTURING

To address the problems of groundwater remediation in fractured media, one or more localized areas with high fracture density can be created, through the controlled use of explosives, to enhance fracture interconnectedness and increase hydraulic conductivity. Detonation of explosives, in areas determined by hydrogeologic site characterization, creates an intensely fractured area of bedrock that is essentially “rubble.” Pumping/recovery wells installed into this area can capture greater quantities of groundwater, intercepting flow from fractures to which they did not previously have a hydraulic connection. The area containing this highly fractured rock, often referred to as a “fracture trench”, acts as a local groundwater sink, toward which groundwater flows. Groundwater can be captured in the fracture trench by the pumping of one or more recovery wells, allowing subsequent remediation and prevention of off-site migration.

Use of blasting to produce artificially-induced areas of high fracture density does not preclude the need for thorough characterization of the nature and extent of site contamination. The determination of site hydrogeological conditions is conducted thorough methods such as aquifer testing, fracture trace analyses, and surface and borehole geophysical techniques. This hydrogeological information is required to determine areas to be fractured and to monitor the effectiveness of the recovery well in capturing groundwater for treatment and containing groundwater to prevent off-site migration of site contaminants.

2.0 APPLICABILITY

2.1 CONTAMINANTS AND SITE CONDITIONS

Based on GWRTAC's limited literature survey, the blast-induced fracture technique has been used in sandstone, limestone, shale, granite, and slate formations. Contaminants at these sites included light non-aqueous phase liquids (LNAPLs, e.g., petroleum hydrocarbons) and dense non-aqueous phase liquids (DNAPLs, e.g., chlorinated solvents). Applications of this technique do not appear limited to specific contaminant categories, since blasting is utilized only to improve the efficiency of a subsequent remediation technology that is tailored to site-specific contamination.

To date, blast-enhanced fracturing has been used only with pump-and-treat methods, but it also may be useful in improving the performance of certain *in situ* technologies.

2.2 COMPARISONTO HYDRAULIC AND PNEUMATIC FRACTURING

In contrast to blast-enhanced fracturing, hydraulic and pneumatic fracturing techniques do not involve explosives, are conducted on unconsolidated materials (overburden), and are performed within individual boreholes. These techniques are utilized to enhance existing fractures or create new fracture zones in boreholes, usually for the purpose of increasing the efficiency of *in situ* treatment technologies such as vacuum extraction and bioremediation.

Hydraulic fracturing begins with the high-pressure injection of water into low permeability materials to create a starting point for further fracturing. This is followed by high-pressure pumping of a slurry mixture (water, sand, and thick gel) into the borehole, creating a fractures area (lens) filled with sand and exhibiting increased hydraulic conductivity compared to the original materials.

The pneumatic fracturing technique utilizes high-pressure air injected into low permeability overburden materials. This injection process expands existing fractures and creates additional small fractures extending from the primary fractures further into the area surrounding the borehole.

3.0 METHODOLOGY

3.1 HYDROGEOLOGY CONSIDERATIONS

Development of an effective and safe blasting program involves the integration of site-specific hydrogeological and contaminant distribution data with specialized information about the use of explosives. This coordination of information will allow design of a remedial program that effectively meets the objectives of contaminant recovery and containment. Hydrogeology data is used to determine the numbers, locations, depths, and orientations of fracture trenches required to achieve the appropriate groundwater capture/recovery. Trenches are generally located at or near source areas and are blasting patterns are configured so that trenches will intercept fractures in the primary direction of groundwater flow. Hydrogeological data, acquired from a comprehensive site investigation, may include:

- Geologic information such as thickness of overburden, bedrock/formation name and characterization of bedrock/formation to be blasted
- Nature and extent (horizontal and vertical) of groundwater contamination across the site
- Location(s) and extent(s) of suspected/known contaminant source area(s)
- Regional and site-specific groundwater flow directions
- Aquifer test results.

Proposed blasting configurations used to form fracture trenches generally involve shotholes at regularly spaced intervals and in a triple line, linear, or other blasting pattern, as determined by the explosives contractor.

3.2 BLASTING CONSIDERATIONS

A qualified explosives contractor, familiar with blasting in the rock underlying the site area, is needed to establish effective blasting procedures (based on rock strength) and to determine appropriate mitigation measures to prevent damage to nearby structures (based on utility company records, plant diagrams, nearby vibration-sensitive operations, etc.). Mitigation measures, implemented to prevent vibrations sufficient to damage nearby buildings and/or utility lines, are determined based on the following factors:

- Location, orientation, depth, and number of shotholes into which explosives are placed
- Total amount (weight) of charge in each hole
- Detonation delays (in milliseconds) between smaller packages of explosive charges.

Prior to full-scale blasting, a preliminary field test of the proposed blasting program is generally conducted to test the hydrogeological and explosives assumptions upon which the program is based. During this pilot test and full-scale program, monitoring of surface vibrations is accomplished through use of a seismograph placed near potentially susceptible structures. The effectiveness of blasting in achieving fracture interconnectedness is evaluated using data collected from the drilling of shotholes during pilot and full-scale blasting activities. Following blasting in the initial shothole, subsequent borings are drilled at proposed shothole locations to evaluate depth and degree of fracturing. Adjustments to shothole locations are made based on fracturing observed in these confirmatory borings.

The results of the pilot-scale blasting program, including vibrational and fracture information, are analyzed, and modifications are made, if necessary, based on this analysis. Design parameters of the full-scale blasting program can then finalized, using data from pilot tests to refine original estimates.

Blasting should result in the creation of a highly fractured area localized around each shothole, and completion of the blasting pattern should result in the creation of a continuous intensely fractured zone. Damage to well casings or open-hole cave-ins may result from blasting, and monitoring wells integrity should be confirmed following completion of blasting activities. Monitoring well data including aquifer testing results from an existing or new recovery/pumping well or wells are collected after blasting to confirm expected results.

4.0 RESULTS

This technique has achieved the following results:

- Increases in hydraulic parameters such as transmissivity (T) and hydraulic conductivity (K)
- Expanding capture radii of pumping/recovery wells
- Increased response to pumping (drawdown) in monitoring wells
- Increased well yields.

In addition, at one site, blasting was found to have accomplished a "hydraulic cleaning" of wells in the fracture zone, consisting of an apparent removal of fine-grained material from fractures (as determined from borehole video analysis). Table 1 presents general information and quantitative results of blast fracturing at sites described in the literature surveyed.

TABLE 1
BLAST-ENHANCED FRACTURING INFORMATION

	TRENCH DIMENSIONS (in feet)		CHANGE IN HYDRAULIC PROPERTIES (Well yield in GPM unless otherwise noted)	
ROCK TYPE	LENGTH	DEPTH	BEFORE BLASTING	AFTER BLASTING
Sandstone[1]	600	25	0.1	15
Sandstone[1]	600	25	0.1	40
Shale[1]	800	30	0.05	50
Sandstone[1]	300	25	1	30
Shale[1]	300	25	0.05	12
Shale[1]	300	60	0.1	10
Limestone/shale[1]	1,200	50	1	100
Sandstone[1]	300	30	0.1	15
Shale[1]	1,000	60	0.05	12
Limestone[1]	300	30	0.1	8
Sandstone[2]	300	25	3.4	20
Granite[3]	250	20	K = 0.27 ft/day (avg)	K = 20 ft/day (avg)
Limestone/shale[4]	15	8	Order of magnitude increase in fracture transmissivity	

[1] Smith, Davidson, and Loney
[2] Begor, Miller, and Sutch
[3] Barrett
[4] Lane *et al.*

5.0 ADVANTAGES

Advantages offered by blast-enhanced groundwater recovery include the following:

- Increased hydraulic conductivity can reduce the number of recovery wells required to be installed to achieve effective remediation and hydraulic containment. This will decrease well installation and operation and maintenance costs, including redevelopment and pump replacement.

- Increased well yield can shorten the time period necessary to achieve remediation objectives

- Verifying contaminant capture is easier since recovery well can be directly connected to fractures along entire cross section of fracture zone.

6.0 LIMITATIONS

Limitations associated with this technique involve the following factors:

- Thickness of overburden
- Proper positioning of explosives
- Ability of nearby buildings and other structures to withstand vibrational impacts.

7.0 REFERENCES CITED

Barrett, James K. "Interception of Contaminated Ground Water Bedrock Through Artificial Fracturing," Thermo Consulting Engineers/Normandeau Engineers, Concord, New Hampshire.

Begor, Kristen Franz, Michael A. Miller, and Rodney W. Sutch, 1989, "Creation of an Artificially Produced Fracture Zone to Prevent Contaminated Ground-Water Migration," Ground Water, Vol. 27, No. 1, January-February.

Gehl, Ronald W., P. E., Hydraulic Enhancement and Control Strategies for Remediation of a Contaminated Fractured Bedrock Aquifer," Caswell, Eichler and Hill, Inc., Portsmouth, New Hampshire.

Lane, J.W., Jr., *et al.*,Geophysical Characterization of a Fractured-Bedrock Aquifer and Blast-Fractured Contaminant-Recovery Trench."

Smith, Lawrence P., P. E., and Robert E. Heeks, Ph.D., 1992, "Innovative Remedial Technologies Applied to Chlorinated Solvents in Fractured Rock," Proceedings 5th Annual Hazardous Materials and Environmental Management Conference/Central, Chicago, Illinois.

Smith, Lawrence P., P. E., *et al.*, Linear Blasting for Migration Control in Low Permeability Rock Formations, Haley & Aldrich, Inc., Rochester, New York.

The Loring Air Force Base Installation Restoration Program (IRP), 1995, The Loring IRP, Fact Sheet, Vol. 2, No. 2, October.

U. S. EPA, 1995, In Situ Remediation Technology Status Report: Hydraulic and Pneumatic Fracturing, Solid Waste and Emergency Response, EPA542-K-94-005, April.