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The State-of-the Practice of Characterization and Remediation of Contaminated Ground Water at Fractured Rock Sites

An analysis of the information provided during a workshop at Providence, RI, on November 8-9, 2000 and the Fractured Rock 2001 International Conference at Toronto on March 26-28, 2001

In cooperation with:

Ontario Ministry of the Environment
West Central Region

U.S. Department of Energy
Office of Science & Technology

Preface

The United States Environmental Protection Agency, the Department of Energy, and the Ontario Ministry of Environment, through the Smithville Phase IV Bedrock Remediation Program, sponsored a workshop of invited experts in Providence, Rhode Island, on November 8-9, 2000 to discuss the application of characterization and remediation technologies at fractured bedrock sites. These agencies also sponsored the international conference; "Fractured Rock 2001" in Toronto, on March 26-28, 2001. This summary is partially based on a draft report written by Bernadette Conant, Ontario, Canada, and substantial comments provided by Kathy Davies, EPA Region 3; Dick Willey, EPA Region 1; Al Shapiro, USGS; Susan Solyanis, Mitretek Systems and Carolyn Lepage, Lepage Environmental Services, Inc.; for EPA's Technology Innovation Office (TIO). Comments were also provided by members of the Fractured Bedrock Workshop Planning Group (Appendix 1).

The intent of this report is to provide; 1) a base line of the state-of-the-practice to help measure trends and directions, 2) a comprehensive view of remediation efforts to local, state and regional practitioners, and 3) suggestions of high priority needs of characterization and remediation to research and development laboratories. Suggestions or comments should be directed to Rich Steimle, EPA at 703-603-7195 or steimle.richard@epa.gov .

The State-of-the-Practice of Characterization and Remediation of Contaminated Ground Water at Fractured Rock Sites

Over the past two decades, there has been increasing recognition that geologic complexities pose some of the greatest challenges to site characterization and ground-water restoration. Fractured rock sites are among the most complex because of their considerable geologic heterogeneity and the nature of fluid flow and contaminant transport through fractured media. Relative to most unconsolidated deposits, characterization of contaminant migration in fractured rock usually requires more information to provide a similar level of understanding. The complexity of contaminant source conditions also make remediation more difficult. Therefore, there is a need to improve and augment current technologies applicable to these sites.

Professionals tasked with choosing technologies for contaminated ground-water in fractured rock need access to information from research and practical experience from the field. However, few forums exist for the sharing of this information. In addition, the development of a baseline of national experiences would be very useful in identifying future research planning needs. Consequently, U. S. Federal Agencies and the Ontario Ministry of the Environment through its Smithville Phase IV Bedrock Remediation Program, have initiated several efforts to help define the state-of-the-practice of remediation and characterization technologies in fractured bedrock sites. These efforts include a web site established in 1999, a workshop held on November 8-9, 2000 and an international conference held on March 26-28, 2001. The web site, http://clu-in.org/fracrock, contains literature references, workshop presentations, over 30 site profiles, and links to other web sites which contain fractured rock information.

The following sources of information were reviewed in the development of this summary:

- Summaries of fractured rock applications that others have placed on EPA's CLU-IN fractured rock web site (www.CLU-IN.org/fracrock).
- Poster abstracts that consultants, manufacturers, and others developed for presentation at an EPA-sponsored workshop in Providence, Rhode Island, November 8-9, 2000 (which are located on EPA's CLU-IN org/fracrock web site.
- Responses to questionnaires that attendees completed at the above-mentioned workshop (hard copies were reviewed but questionnaire summaries are contained in the Fractured Rock web site.
- Presentations at the Fractured Rock workshop (also contained on the web site).
- Reviews of oral and poster presentations at ***Fractured Rock 2001*** an international conference held in Toronto, Canada, March 26-28, 2001.

The Emerging State-of-the-Practice in Fractured Rock

Until the last few years, the state-of-the-practice for fractured rock has been essentially the same as that for all contaminated sites; it had not been differentiated from that for unconsolidated-deposits sites. Recently, new strategies to deal with fractured rock sites have been emerging, but there is a time lag in the widespread communication of new research and applications to both the practicing community and decision-makers.

Research, development, and more rigorous technology evaluations have previously focused predominantly on unconsolidated materials; particularly settings with relatively simple geology and shallow contamination. In addition, most contaminated sites distributed on a national scale are in unconsolidated-deposits; although, in some physiographic provinces the majority of the sites are in fractured rock. However, most practitioners have more familiarity with investigation and remediation of unconsolidated settings. The result is an industry that has been addressing fractured rock sites primarily drawing on experience, methodologies, and conceptual approaches developed in unconsolidated deposits, though at considerably greater expense and with generally less confidence about the results. Technology evaluations more specific to fractured rock sites are now emerging.

For hydrogeological studies in fractured rock, it is the discrete fracture pathways, rather than the total fracture network, which are important. To be of hydraulic significance, fractures must be both conductive and sufficiently interconnected to serve as part of a pathway. Only some subsets of open fractures will have active groundwater flow, and a small number of transmissive fractures may dominate. The challenge in application of characterization technologies is to locate the significant fractures and apply technologies in a way such that measurements properly reflect in-situ conditions.

Stakeholders must understand the importance of developing an accurate, conceptual model of the site. The complexity of the site will determine the necessary types of tools and testing. The results can be applied to a initial model so that the subsurface conditions become understood well enough to apply remediation. Understanding the site and the results of remediation efforts will be an iterative and inclusive process.

The distribution of contaminant mass in the subsurface, and the perceived need for short- or long-term controls, will determine the most appropriate remedial technologies and targets. Therefore, conceptual models must reflect the most likely distribution of contaminants as well as the transport processes controlling that distribution. This makes it possible to consider both current and future contaminant impacts under different remediation scenarios, and to identify the mass that is most likely to be limiting to cleanup. For example, dissolved contamination migrating with advecting ground-water in fractures typically represents the fastest pathway and primary transport pathway of concern. However, it may comprise only a very small portion of the total mass. Contamination may be sequestered within the rock matrix, on fracture coatings, in NAPL zones, or within poorly-connected fractures. Over the long term, such “sources” control ground-water contaminant conditions and the need for ongoing remediation.

Over the past 10 or 20 years, some technologies associated with definition and remediation of contamination in unconsolidated deposits have matured. A similar trend is now occurring in fractured rock settings, with increased recognition of the importance of discrete fracture pathways and matrix diffusion for contaminant fate and transport. Also, lessons learned in other disciplines such as petroleum and civil engineering, and from the evaluation of potential radioactive-waste disposal sites, are being increasingly re-evaluated to address questions of scale lithologies, structural features and geochemistry unique to environmental contamination problems. The state-of-the-practice for fractured rock as a distinct subclass of contaminated sites is being developed, although experience with characterization technologies is generally more advanced than that for many remediation technologies.

Site Characterization Technologies

Geological Characterization

Geological characterization at fractured rock sites includes use of conventional techniques such as outcrop mapping, fracture trace analysis, drilling, coring, and, more recently, increased use of borehole geophysics. Drilling boreholes remains the principal means of geological characterization and, because it is generally slow and expensive, contributes significantly to characterization costs. The majority of holes are vertical; inclined drilling is also used, albeit less frequently, to intersect and sample vertical or near-vertical features. In addition, there is concern that drilling activities may create a conduit for cross-contamination by drilling through previously isolated fractures and, at DNAPL sites, may risk mobilization.

Cores are collected to provide information on site geology and physical samples for laboratory testing. When core recovery is sufficient, fracture characteristics can be determined directly. However, it is very expensive to collect oriented cores to determine the dip and strike of the fracture features; it may also be very difficult to ascertain that the fractures are not caused by the drilling itself. The presence or absence of fracture oxidation and weathering, and fracture fill or coatings, can provide direct indications of likelihood of ground-water flow. However, fracture zones, which are of most interest to investigators, are poorly recovered from core samples. Zones of potential importance for ground-water flow frequently correspond to rubble zones or lost sections of core. Therefore, drilling and coring are often followed by use of geophysical borehole logging to provide more information on fracture zones.

Workshop discussions reflected a current debate over the cost-effectiveness of obtaining core during drilling. In response to the workshop questionnaire, almost all (94%) of respondents indicated they had used coring in characterization of fractured rock sites. The survey did not indicate how important they rated core analysis for characterization, the percentage of holes that were cored, or whether their reliance on it had changed over time. Other attendees indicated a preference for coring as the primary means of geological characterization and correlation, and to provide desired borehole conditions for subsequent hydraulic testing. Geophysical techniques were also recommended by those advocating the value of core, but as a supplementary, rather than primary, tool in support of fracture characterization.

Hydraulic Characterization

Hydraulic testing and measurements of hydraulic heads from monitoring wells are the most basic and most frequently used tools for characterization of ground-water flow in fractured rock. Hydraulic testing (injection tests, pumping tests) and vertical head profiling (packer isolation, cluster wells, sampling ports) have been used by 90% of respondents to the workshop questionnaire. In the EPA CLU-IN site profiles, hydraulic testing methods were not listed separately, but vertical chemical profiling (presumably conducted in conjunction with hydraulic head measurements) was the most frequently listed characterization technique.

Mapping of hydraulic heads (under both ambient and pumping conditions) is the most common method of inferring ground-water flow directions and fracture connectivity. Extrapolating hydraulic gradients between individual fracture zones or different monitoring wells requires a determination of whether monitoring reflects conditions in connected fracture pathways. Cross-hole pumping tests are also used to determine bedrock aquifer properties and fracture interconnection. Pumping test results are particularly applicable at sites where remedial response involves installation of pumping systems for hydraulic control. Workshop attendees reported the use of pumping tests in site investigations as part of standard practice.

Chemical Characterization

Collection and analysis of ground-water samples from monitoring wells is the most common method of characterizing the extent of contamination at fractured rock sites. Like hydraulic testing, chemical characterization of fracture pathways involves collecting samples from specific vertical intervals of the borehole. These intervals may be isolated using packer assemblies in open boreholes, completion of monitoring wells over specific intervals in well clusters, or installation of multi-level monitoring assemblies. Multi-level monitoring assemblies designed for dedicated use in boreholes are commercially available. Non-permanent (re-usable) systems with inflatable packers or continuous borehole liner/sampling systems are among the most recent developments and are in the early stages of real-site application. The use of such techniques as temporary monitoring assemblies, or chemical profiling during drilling, may help to optimize sampling location and monitoring well design and significantly reduce the capital costs of sample collection.

Geophysical Methods

Geophysical characterization represents an area where there has been considerable technology development and an increased application at fractured rock sites over the past decade. Conventional surface geophysics and borehole logging (wireline) methods have been applied in fractured bedrock environments for years (e.g. oil industry, water supply research). However, recent refinements for use in environmental investigations have been in response to different requirements of scale and resolution: from regional and site-level definition of fracture networks at 10's to 100's of meters, down to the level of individual fractures or fracture zones.

Surface Geophysical Methods

Surface geophysical methods (DC resistivity, electromagnetics, ground-penetrating radar, seismic) are typically used in conjunction with other remote methods early in the site investigation process to assist in locating and defining the geologic contacts, structural features, and location and orientation of fracture sets. Because they are non-intrusive, they avoid some of the risks of drilling, such as cross-contamination and DNAPL remobilization. However, they may be limited to fairly large-scale resolution. Also, their application can be hampered by cultural interferences, such as utilities, pipes, overhead wires, buildings and pavement. This provides a limitation which makes them inappropriate for some sites in urban areas and where active facilities are situated. In addition, their use can also be limited by the presence of significant unconsolidated deposits overlying bedrock.

Borehole Geophysical Methods

Conventional wireline logging methods, such as caliper, fluid logs (temperature, conductivity), EM conductivity, and gamma logs, are the most commonly used geophysical tools. They are used in combination with core logging or optical and acoustic imaging methods to assist in mapping of geology and fracture zones, and to extend geologic correlation between boreholes. Recently, borehole applications have expanded to include improved methods of imaging the borehole and identifying which fracture zones have active flow. More recent techniques are television/televiewer methods (acoustic and televiewer), of which over half of the respondents reported using, and flow meters (heat-pulse and EM).

Use of brine testing and borehole flowmeters capitalize on the vertical flow caused by head differences between fractures intersected by a single borehole. By measuring the direction and magnitude of this flow under both ambient and stressed (pumping or injection) conditions, it is possible to locate fractures or fracture zones where ground water is entering or exiting the borehole. This can assist in identifying fractures of potential significance for sampling and testing, as well as allowing estimates of hydraulic parameters. By helping identify the relative contribution of ground water from different fractures to the borehole, flowmeters are also useful in helping to interpret chemical sampling results. The main limitation of most flowmeters is their detection limits. Lower detection limits (e.g., approx. 0.01 gpm for heat-pulse flow meters) are insufficient to detect some low-flow fractures, which may be important for transport. Almost as sensitive as the heat pulse flowmeter, but with a higher range, the EM flowmeter may be used. For higher flow systems, it may be necessary to use spinner flow meters.

New Approaches

Newer technologies include digital borehole imaging methods which allow direct inspection of the borehole surface and viewing fractures in-situ. Orientation of the features as they intersect the borehole can also be determined. The possibilities of these methods are further enhanced by the advancement of software that constructs oriented "virtual cores" from the televiewer data. Interpretations using these methods are subject to the same limitations experienced by other borehole based techniques.

Other imaging methods, which represent promising new research areas, but are not yet used in common practice, are methods which allow extension of data collection beyond the constraints of measurements in boreholes. They allow extrapolation and interpretation between them, including borehole radar, seismic, and resistivity tomography. Two-and three-dimensional imaging methods require ground-truthing with physical/geological sampling, but offer the possibility of better siting sampling locations within complex fracture networks.

An interdisciplinary approach using multiple lines of evidence is recommended and is particularly important for characterizing fractured rock. The need to use a combination of different characterization tools was underscored by several workshop attendees. This approach has been borne-out by experience with geophysical methods in particular. The non-uniqueness of geophysical signatures and the need for parallel use of several methods has long been recognized. Side-by side comparison of geophysical logs is standard. Greatly improved analysis and interpretation of site conditions are possible; however, only if skilled, experienced geophysicists are conducting the interpretation. The importance of appropriate QA/QC programs for those personnel using these technologies were also stressed by the workshop.

TABLE 1

State-of-the-Practice on the Use of Characterization Technologies
n=53 sites

Technology	Number of Mentions in Workshop Questionnaires, CLU-IN Profiles and Conference Proceedings
Borehole Geophysics (total)	28
Single point resistance	6
Natural Gamma	9
Caliper	8
Borehole Televiewer (total)	32
Video Camera	9
Acoustic Televiewer	5
Fluid Loggings (total)	27
Temperature	12
Conductivity/Resistivity	11
Flow Meter (total)	23
Heat Pulse	5
Trace Brines	2
EM Flowmeter	1
Chemical Profiling (total)	39
Cluster Wells	13
Sampling Port Packer	6
Isolation	11
Surface Seismic Surveys (total)	14
Refraction	3
Reflection	3
Fracture Trace Analyses	22
Surface EM Conductivity Surveys	14
Surface GPR Surveys	14
Coring	35

Tracer Studies	15
Downhole Seismic Surveys	4
Measurement of Hydraulic Head	16
Hydraulic Testing	17
Outcrop or Geologic Testing	9
Borehole Radar Surveys	7
2D Resistivity Surveys	3
Modeling (water or solute transport)	13
Time Series Sampling	10
FLUTe with NAPL Ribbon	2

Remediation Technologies

Hydraulic Capture/Containment

Pumping and treating ground water is the most common technology (Table 2) for hydraulic containment. To the degree that contamination is contained within accessible fractures, the existence of discrete fracture pathways can be a positive factor for remediation. If the relevant fracture pathways are sufficiently permeable and connected, contaminated ground water can be readily extracted by pumping. Often without the need to apply large gradients or pump (and treat) huge volumes of water thus, migration of the contaminated ground-water plume can thereby be controlled. Conversely, the lack of fracture inter-connectivity is the major limiting factor to a successful pump-and-treat system.

Fracturing

Approximately half of the respondents who were using pump and treat technology also fractured the bedrock to improve well yield. Blast fracturing appears to be favored over pneumatic and hydraulic methods. The possible reasons include the widespread use in construction projects and broad knowledge base, greater number of service providers (local contractors experienced with area geologic conditions), simplicity, robustness and economic feasibility.

Vacuum Vapor Extraction

A significant number of respondents to the workshop survey (32%) indicated that they had used vacuum vapor extraction. It was not clear whether vapor extraction is being used primarily in unconsolidated deposits overlying fractured bedrock, in dewatered zones resulting from implementation of remediation systems, or whether vapor extraction systems had actually been used for removal of volatile contaminants from fractured bedrock vadose zones.

Other Remediation Technologies

Apart from pump-and-treat and its enhancements, there is very little experience with other technologies. Many of the innovative technologies being applied in unconsolidated deposits are now also under consideration and testing for application at fractured-rock sites. However, the primary concern with implementing test studies of innovative technologies is the uncertainty in having a sufficient monitoring network to adequately assess the success/failure of technologies implemented. There is concern that contaminant flow may move into previously uncontaminated fractures which are not being monitored or controlled. Confidence in the use of these technologies in unconsolidated settings, along with confidence that the fractured rock site is well characterized may help alleviate these concerns in the future.

Using monitored natural attenuation and engineered biodegradation have appeal for the same reasons as in unconsolidated deposits. Chemical oxidation and other abiotic strategies are of similar interest in that they have the potential for destruction of the contaminant in situ, rather than removal for above-ground treatment. There is current interest in further research to investigate the potential for biodegradation or oxidation of high dissolved-phase contaminant concentrations in the vicinity of NAPL sources to accelerate NAPL dissolution. Diffusive-delivery oxidation or biodegradation systems, as well as thermal methods, are also currently of interest because of their potential to address matrix contamination.

Engineered or enhanced bioremediation and chemical oxidation require the injection of nutrients or reagents. Pumping for hydraulic control, recycling of reagents, or treatment of breakdown products may also be required. Therefore, these strategies must address the same kinds of challenges encountered in unconsolidated deposits. These challenges can be more significant in fractured rock due to the level of heterogeneity. However, based on protocols already established for use in unconsolidated deposits, acceptance of monitored natural attenuation will likely require demonstration of a firm understanding of transport processes, pathways, and fate of contaminants.

TABLE 2

State of the Practice on the use of Remediation Technologies
n=53 sites

Technology	Frequency of Use*	Performance Experience
Pump and treat w/ enhancements including fracturing and flushing	51	Two purposes - containment of plume or removal of contaminant. Results often favor containment.
Dual Phase Extraction, Vacuum Vapor Extraction, and Soil Vapor Extraction	20	Coupled with fracturing and pump and treat in one instance. PCE concentrations after one year of shutdown were less than 200ug/l in one vacuum, hot air injection and vapor extraction system.
In-situ oxidation	10	
Natural attenuation	4	
Fracturing plus installment of permeable reactive barrier	2	One system installed above bedrock in Caldwell facility for TCE treatment
Pump and treat plus in-well stripping	1	
Bioremediation	1	An enhancement with sodium lactate reduced concentrations of TCE to MCLs.

*More than one technology was used at most sites

Research, Applied Research, and Technology Transfer Needs

1.) The factors and their relative significance affecting mass transfer of contamination from fractures to the matrix and from the matrix to the fractures (i.e. matrix diffusion and counter-diffusion) in fractured rock aquifers. Relevant factors could include, but not be limited to ranges of concentration gradients and magnitudes of permeability, contrasts between fractures and matrices for different rock types, short term changes from precipitation recharge, the impacts of mineral coatings present on the fractures, impacts of fracture size and flow rate, etc. Provide testing methodologies for identifying these factors. Provide an assessment of how these factors will ultimately affect plume development and subsequent cleanup to low risk-based levels.

2.) Determine the field studies needed to assess how any of the following concepts may be applied: discrete fracture network; dual-porosity medium or equivalent porous medium. Provide information on the extrapolation of fracture orientation, length and aperture measured on the local scale to those on the field site scale (hundreds to thousands of feet). Provide information on differentiating dual porosity behavior from nonlinear or convective flow near the borehole (e.g. from pump test data interpretation).

3.) Develop appropriate methods for aquifer test analysis for fracture flow systems. Assess the applicability of various methods used routinely in the evaluation of pump test data in unconsolidated formations to pump test data collected in a variety of fractured rock terrains.

4.) Assess the applicability of currently used models developed for porous media for fractured systems, especially in which the geometric characteristics of the fractures are unknown. Include an evaluation of the various methods using field data from sites in varied rock terrains. Evaluate the use of probabilistic methods in assessing the magnitude and extent of contamination and progress towards cleanup. Develop a unified federal agency approach to R&D concerning modeling.

The results of research in the above areas should be addressed by appropriate technology transfer products including especially guidelines, protocols, issue papers, etc.

1.) Guidelines for applying porous media flow and transport models to fractured rock settings. These guidelines should include the practical and appropriate limits of their application (by fractured rock setting, scale, etc.)as well as, applicable modifications to existing models to simulate unique fractured rock attributes.

2.) Documented case studies (including lessons learned) comparing whole well (no packers, purging, low flow sampling) and individual zone sampling results (packers-in-place, diffusion multi-level samplers or a FLUTe system) and their influence on the interpretation of the magnitude and vertical extent of contamination. Include borehole measuring methods to characterize the vertical distribution of contaminants, while minimizing investigation induced cross contamination and/or short circuiting in existing monitoring wells.

3.) Suggested studies (i.e., fracture trace, geophysics, structural) which should precede monitoring or test well locating.

4.) Documented case studies on the use of geophysical techniques and vertical chemical profiling. Selection of borehole geophysical tools by geologic terrain and contaminant type.

5.) Determination of the appropriate level of lateral and vertical detail needed to characterize (delineate contamination, determine risk), remediate (design, construct, operate) and monitor (remedial performance, compliance) contamination at fractured bedrock sites.

6.) Recommended borehole methods to characterize the vertical distribution of contaminants, while minimizing cross contamination and/or short circuiting within the monitoring well.

7.) Guidelines for the use of tracers to evaluate flow and transport of field site dimensions. Provide information on determining test set up (e.g. estimating length of test, location of monitoring points both horizontally and vertically, the use of pumping wells, etc.) Discuss uncertainties; present the merits/flaws of conducting the test under pumping conditions and natural flow gradients; and assess the influences of scale, adsorption, matrix diffusion, dead end fractures, flow velocity. etc., for various fractured rock terrains.

Appendix 1

Fractured Bedrock Workshop Planning Group
November 8-9, 2000

Skip Chamberlain, U.S. Department of Energy
Kathy Davies, U.S. Environmental Protection Agency, Region 3
Tom Early, Oak Ridge National Laboratory
Pete Haeni, U.S. Geological Survey
John Koutsandreas, U.S. Department of Energy (Alternate)
Bob Masters, National Ground Water Association
Ted O'Neill, Smithville Bedrock Remediation Program
Randall Ross, U.S. Environmental Protection Agency, Office of Research and Development
Damien Marie Savino, United Technologies Corporation
Rich Steimle, U.S. Environmental Protection Agency, Technology Innovation Office
John Vidumsky, Dupont Specialty Chemicals
Bill Wertz, New York Department of Environmental Conservation
Bernie Woody, United Technologies Corporation (Alternate)