
Chapter 11. Conclusions

11.1. Lessons Learned

11.1.1. *Characterization*

The evolution of the wellfield and operational designs during the pre-treatment characterization phase of the Quarry, extending up to the beginning of operations, demonstrated the importance of understanding contaminant distribution and the hydrogeology of a remediation site thoroughly. Practical considerations, most notably the significantly greater cost required for effective characterization of a fractured rock site compared to an unconsolidated porous media site, make it particularly important that the greatest potential value must be extracted from characterization methods. A variety of characterization techniques were used at the Quarry, and while all of these provided information that was incorporated into the developing conceptual model of the subsurface, experience at this site showed a number of ways in which some relatively under-used techniques could be more effectively incorporated into future characterization efforts. Experience gained here also underscored the importance of other characterization techniques. In summary, some pertinent comments can be made:

11.1.1.1. Detailed Mapping

At this site, located in a former bedrock quarry with abundant three-dimensional exposure of rock, detailed mapping of structural geology of the site and surrounding areas had been conducted (e.g., Beane et al., 1998). This is a simple and cost-effective means of outlining the range and diversity of structures of potential hydrologic significance and of determining their possible history of development. Mapping of the site also provided a broad framework within which the subsequent characterization efforts could be accommodated. Wherever possible, mapping information from all sources, including large-scale site investigation mapping and small-scale academic, federal or state geologic maps, should be used, including fracture-trace analysis. This information should be analyzed and converted to a format suitable for direct integration with CADD plans used in subsequent characterization and wellfield design. Generating an effective base map will ensure consistent and comparable data representations.

At sites which do not offer abundant exposure of rock, a range of surface-based geophysical methods should also be considered as part of the baseline characterization effort. Surface geophysical techniques successfully used in site characterization include ground penetrating radar, electromagnetometry (EM) methods, electrical resistivity or conductivity methods, seismic refraction, and reflection methods. Electrical methods can include profiling (using a variety of array configurations) and sounding (using both linear and square-set arrays). The suitability of individual methods is dictated by the specifics of site and regional geology. A discussion of the theory and application of suitable methods is beyond the scope of this report; however, useful descriptions, case histories, and references are contained in publications such as those by EPA (1993; 2000) and USACE (1995).

11.1.1.2. Coring

At the Quarry site, a large number of wells were cored over their entire length. The high competency of the bedrock at this site ensured excellent recovery of most of the cored intervals, thereby providing a permanent record of structures intersected by boring that would be used for the remediation research project. The diamond drilling process used to collect the rock cores is relatively slow and expensive compared to other drilling methods, while the core itself is unoriented, requiring that the structures present in the core be correlated with similar structures of known orientation derived from direct mapping. In this research project, the need for coring was partly based on the need to recover material for rock matrix sampling (by the MERC method) and provided the additional benefit of smooth boring walls (in comparison to those produced by other drilling methods). The smooth boring wall allows a more effective seal to be maintained during straddle packer testing.

At sites where bedrock competency is lower or where direct sampling is not required, much of the utility of rock core can be achieved using borehole image profiling methods, which are able to directly measure the orientation of planar structures intersecting the boring, while producing “pseudo-cores” for conventional examination on computer monitors or printed images. These are discussed in more detail below.

11.1.1.3. Borehole Geophysics

At the Quarry as part of this research project, a suite of geophysical methods were used to profile each of the borings. These included caliper, fluid temperature, fluid resistivity and acoustic televiewer (ATV).

The combined caliper, fluid temperature and fluid resistance probes are commonly used borehole-logging tools. They provide a low-cost, simple measure of probable fracture locations in the borehole wall that can serve as a starting point for identifying features of interest to be correlated with visual logging methods, and which, in turn, serve as a framework on which to build an aquifer testing program. Fluid resistivity logging proved to be particularly effective at identifying features that subsequently were demonstrated to be hydraulically active. As such, this suite of probes should be used to profile all proposed operational wells as a matter of course as part of a general wellfield characterization program.

11.1.1.4. Acoustic Televiewer (ATV)

The ATV logs produced an effective record of the location and general orientation of those fractures that intersected the boring. However, no useful information could be gleaned regarding the nature or extent of fracture filling materials. Similarly, the ATV log failed to provide any detail of lithological variation or internal structure within the unfractured bedrock, such as sedimentary structures or systematic changes in mineralogy. Information of this type can be used to identify a stratigraphic sequence in core that can be correlated with adjacent borings and regional mapping, thereby serving as a tool to aid in structural analysis of bedrock. Borehole profiling methods that provide a photographic image of the boring walls, such as Optical Televiewer (OTV) or Borehole Image Profiling System (BIPS), provide greater detail (subject to potential limitations of poor color contrast in wall rocks and opacity of ground water), and are a more effective characterization tool in areas where interwell correlation is a requirement of characterization.

11.1.1.5. MERC Sampling

The methanol extracted rock chip (MERC) sampling method was originally developed for use at the Quarry (HLA, 1999c) as a means of providing fracture and location specific data on the distribution of contaminants. The procedures and assumptions used during this project are described in Chapter 4.1.2. This technique estimates the amount of contaminant mass that is extractable from the rock matrix, although it is known from the extraction of a subset of the samples that the one week extraction time used did not extract all of the contaminants from the rock matrix. In light of the very low porosity of the unfractured bedrock at the Quarry (<0.5 percent; ABB-ES, 1997), most MERC samples were collected from weathered fracture margins adjacent to a fracture with some samples (one per borehole) collected from the interior of long unfractured lengths of core.

The Phase II characterization (HLA, 1999c) had evaluated the use of MERC samples for estimating mass of contaminants in the system by considering the mass of contaminant distributed among fractures and the total potential mass contained in the impacted volume, as indicated by the average MERC mass data. It was found that the use of MERC samples, porosity, and organic carbon fraction in conjunction with the conceptual fracture model tended to underestimate the total volume of contaminant present in the rock mass, as compared to that calculated from the estimated total mass flux leaving the system in the dissolved phase. Thus, MERC sampling can only provide a qualitative means of assessing contaminant mass. However, it does provide a convenient indication of the location of contaminant within the rock mass sampled, which in turn, gives an indication of those fractures that acted as contaminant pathways, providing an understanding of contaminant transport in the system. Collectively, this provides an important piece of information that contributes towards the development of a conceptual model for any site, and its use is recommended for that reason. Contaminant distribution information is especially important for SER remediation as perimeter injection wells should be in relatively clean areas so that contaminants are not transported away from the target area by the injected steam.

11.1.1.6. Discrete Interval Ground Water Sampling

Ground water samples from completed wells within the target area were collected from short intervals of the wellbore that had been isolated by straddle or single inflatable packers. This allows particular features of interest to be sampled, thereby allowing the relative contribution to the contaminant load of a particular fracture (or group of fractures) to the contaminant concentration averaged over the length of the test interval to be determined. In conjunction with MERC sampling of matrix concentration, these data are important in developing a conceptual model of contaminant migration within the rock from an original source. It also serves to identify fractures of interest to target with steam injection, the hydraulic properties of which can then be assessed by subsequent aquifer testing.

11.1.1.7. Head Measurements

By simply recording the natural ground water head in all of the open wells at the site, three discrete zones of different head were apparent within the Quarry. This condition, lying within such a small area, was interpreted as meaning that each of the areas could be expected to contain wells that were relatively better connected to each other than were the wells of adjacent areas with significantly different head values. The discrete areas were assumed to be isolated from each other hydraulically, presumably by intervening areas of sparsely fractured rock. This model was subsequently confirmed by pulse interference testing. While the differences in head at the Quarry were relatively large because of the considerable topographic relief present across the site, the delineation of hydraulically isolated areas using such a simple method strongly recommends the use of this approach at all fractured rock sites.

11.1.1.8. Discrete Interval Transmissivity Testing

The straddle packer hydraulic testing conducted in 2001, as the first stage of aquifer testing at the site (Chapter 4.1.4), established a vertical profile of transmissivity for each proposed operational well. Each profile typically measured transmissivity in 3-meter (10-foot) increments from 3 meters (10 feet) bgs to at least 15 meters (50 feet) bgs. The deeper parts of the wells, which were generally more sparsely fractured, were more commonly isolated over longer intervals between packers or by using only a single packer. The establishment of a transmissivity profile in as many wells as practical should be regarded as a minimum standard for hydrogeological characterization in fractured rock settings. By establishing a record of transmissivity in the immediate vicinity of the boring or well, an initial correlation of aquifer properties to geological structures and geophysical anomalies can be made. This represents a first step in the hydrogeological characterization by allowing the identification of pairs of depth intervals to be investigated by pulse interference testing. In cases where more detailed pulse interference testing is beyond the project scope, the transmissivity profile alone can also serve as a template on which to select suitable injection and extraction intervals for the completed operational wells. However, it should be noted that there is no reason to assume that the optimum hydraulic connection between two wells will extend between the zones of highest transmissivity encountered in those wells. Thus, interconnectivity testing is to be strongly recommended.

11.1.1.9. Interconnectivity Testing

As discussed in Chapter 4.1.6, several phases of interconnectivity testing using pulse interference methods were employed during hydraulic characterization of the Quarry. In a wellfield of this extent with comparatively deep wells, the number of possible straddle packer-isolated intervals that could be tested is prohibitively large, and a limited number of well pairs must be selected. The characterization effort demonstrated that a longer packer interval, comparable to that used in the previous transmissivity profiling, should be used in order to reduce the total number of tests required and to allow a clearer comparison between the transmissivity profiles and the interwell connections. Size limitations of the straddle packer equipment used at this site were such that wells for monitoring could not be tested for interconnectivity. For example, the smaller diameter of well VEA-5, which had originally been intended for use as a geophysical monitoring boring, prevented straddle packer testing of interwell connections to this boring, in a part of the test site that early phases of characterization had shown to be suitable for injection. In the future when it is desirable that interconnectivity testing be conducted, all wells should be drilled at, or reamed out to, at least 0.15 meters (0.5 foot) in diameter.

The constant head pulse interference test, using pressurized injection (as described in Chapter 4.1.6), has the advantage of locating lower permeability interconnections by the injection of larger quantities of water. These lower permeability interconnections may also come into play during long-term steam injection remediations. However, logistical considerations at the Quarry, where water supply was problematic during testing, showed that in similar sites the slug interference method to be more practical than a constant head test.

In more general terms, in any fractured rock steam injection remediation site, interconnectivity testing should be regarded as an essential component of the hydrogeological characterization of the site. While all other components described above provide useful information and increase the understanding of the site beyond the level typically encountered in general characterization, only interconnectivity testing establishes the presence of real interwell fluid flow pathways and allows their transmissivity to be determined. The potential importance of this is demonstrated by the possibility of strong anisotropy in rock permeability over short distances, particularly in crystalline or metamorphic rocks of low permeability and porosity. This is seen in the head differences encountered over short distances at the Quarry and confirmed by (for example) the apparent absence of any significant connection between I-7 and I-8 and the target area at the eastern end of the site.

In an ideal setting, the potential pathways of the steam could be investigated prior to steam injection by conducting advective tracer experiments between the proposed steam injection intervals and adjacent observation (withdrawal) wells. Experience with conducting these types of experiments at similar sites (e.g., Novakowski et al., 1999), has shown that the link between hydraulic response and tracer arrival is strong; however, the effort to conduct tracer experiments is significant in comparison to the completion of interconnectivity testing. Thus, interconnectivity testing is a less resource intensive approach that should provide information of similar quality to that provided by tracer experiments. In future investigations of SER in fractured bedrock, it may be worthwhile to determine if tracer experiments can add enough value to the characterization process such that the extra expense is warranted.

11.1.1.10. Deep Well Ground Water Sampling

The deep, angled wells (SM-1, 2, and 3, described in Chapter 4.1.5) represented a departure from the conventional monitoring well approach. The intention was that they would contribute to the overall characterization effort using logging and transmissivity profiling techniques, as had been used in the vertical wells within the target area, by collecting this data from a wider area and over a greater depth. By using angled borings, it was possible to target particular groups of planar structures, such as vertical fractures, for investigation by orienting the boring to intersect the fracture at a high angle. As each of these borings was completed with multi-level sampling devices, they also served the longer term purpose of acting as monitoring wells. By having an angled orientation, they were able to intersect potential fluid pathways over long horizontal distances, effectively acting as a monitoring screen in a way that could only be duplicated by many vertical wells. In addition, at sites of suitable geometry, deep angled monitoring wells allow the rock mass underlying the remediation target volume to be sampled during operations without passing through the zone

directly affected by the remediation technique itself. At sites where mobile DNAPL may be contained in horizontal fractures, drilling from outside the source area does not have the potential to allow downward movement of the pooled DNAPL. Angled drilling in hard bedrock is more commonly required in geotechnical and mining applications than in environmental applications, thus, local environmental drilling companies may not be familiar with the technique. However, it is not technically challenging and need not be more expensive than vertical drilling if drillers familiar with the technique are employed.

11.1.2. Steam Enhanced Remediation

This section lists a number of specific lessons that were learned during the course of the field implementation of SER.

- Operation of SER in structurally complex, fractured rock sites requires a much more intensive characterization exercise than is typically the case for un lithified soils. In addition to the focused fracture interconnectivity hydraulic testing conducted during this study, it is important to determine the extent of the zone that will be influenced by injection and extraction in the remediation volume and how this likely interacts with existing flow paths to influence potential down-gradient receptors.
- SER heating was unexpectedly slow at the Loring Quarry, as discussed in Chapter 11.2.2 below. It could not be concluded that SER would have been able to meet the temperature targets set at this site, even if a much longer operational period had been allowed. Heat conduction into the rock matrix, heat losses to outside of the target zone, and heat withdrawn with the extracted fluids all will severely limited the size of the steam zone. However, despite the limited size of the steam zone, the heat in the system was mostly at the fracture surfaces (where most of the contaminants were located), and significant increases in the contaminant removal rates were achieved. It is possible that adequate treatment might have been achieved even without achieving target temperatures throughout the target zone.
- Increased steam injection pressures relative to those typically used in unconsolidated materials could be used to achieve increased injection rates and thereby accelerate heating. As a general rule, injection pressures in unconsolidated materials are limited to approximately 11 kPa/meter (0.034 atm/foot). It was observed at this site that the pressure could be more than doubled without steam excursions or other problems. The greater strength and density of the strongly lithified rock present at the Quarry allowed for injection at pressures as high as 34 kPa/meter (0.10 atm/foot) of depth to the top of the injection interval.
- Theoretical considerations suggested that thermal expansion of the rock matrix during heating could lead to shrinkage of the fracture apertures, as the rock expands and pressure builds at the contact points (Ketcheson and Zwiers, 1997). The importance of this phenomenon was evaluated by measuring steam injection rates at constant pressures. At this site, no reduction in steam injection rate was observed, suggesting that no significant shrinkage of fracture aperture caused by thermal expansion had occurred.
- At this site, the surface vapor cap proved to be relatively ineffective at preventing air infiltration to the extraction wells. This was not due to a deficiency in the cap itself, but was likely caused by the properties of the fractured bedrock system being addressed. The presence of a vertical face adjacent to the wellfield coupled with an abundance of near-horizontal interconnected fractures in the upper 6 meters (20 feet) of the subsurface, where blasting and other quarry activities had created and opened abundant fractures, likely resulted in the relatively low well-field vacuums achieved (less than 10 kPa; 0.10 atm) at the design flow rates. At other SER sites, typical vacuums in the subsurface are 17 to 50 kPa (0.17 to 50 atm). This would be a much less significant problem at sites that had not been subjected to quarrying, mining or other excavation activities.
- The steam injection rate could not, in practice, have been substantially increased above the rates achieved without a corresponding increase in the liquid recovery rate, since the water balance showed the net extraction to have been modest (when compared to net extraction rates at unconsolidated media sites). Thus, faster heating at this site could not have been achieved solely by injecting more steam. The liquid extraction rate would also have to be increased, which would likely have involved the installation of more extraction wells.
- In-ground air stripping after steam injection appeared to be very effective, as discussed under Technology Objective-9 (TO-9). At this site, it was found that a period of steam injection followed by a period of air injection increased the COC removal rates significantly (see Chapter 10.2).
- As discussed under TO-3 (Chapter 10.3.2), the heating of the subsurface at this site was severely limited by thermal conduction. Steam entering the fractures quickly gave up its energy to the rock matrix, limiting the extent of the steam zone in fractures. At the same time, with the temperature gradients present at this site, conduction rates were very low, and the entire rock matrix could not be heated. The large heat losses along fractures away from the steam injection points led to rapid condensation, and very short travel distances for the steam.
- For those wells completed with both injection and extraction intervals (e.g., I-4 and I-5), it was observed that steam short-circuiting from the lower injection interval to the upper extraction interval led to extraction of a significant fraction of the injected steam. This could have occurred through leaks in the grout seals, or by migration of steam through fracture systems near the boreholes. Cement-bond logging to detect fractures or voids in the grout in the well annulus which might permit steam short-circuiting could be a useful technique for future applications. In any case, while short-circuiting through grout seal leaks leads to a loss of energy without benefit, short-circuiting through fractures in the formation is beneficial for both heat-up and COC removal.

- Permanently installed, nested steam and air injection wells in a single boring are a simple and convenient way to inject steam at targeted depths over a large vertical interval, contacting the majority of open, permeable fractures with steam at a pressure large enough to allow flow into the fractures. Grout seals may be used successfully to separate the injection intervals, allowing higher pressures to be applied in the deeper intervals. The multiple-layered injection and extraction wells used at this site performed well (with the exception of steam short circuiting noted above), allowing multiple uses of the same boreholes and conversion of extraction wells to injection wells during operation, which increased the heating rate significantly.
- Moveable, inflatable packers would offer a more flexible solution to the need for making adjustments to injection and extraction intervals, provided that bladder polymers of suitable temperature and chemical resistance could be used. Initial development work by inflatable packer manufacturers suggested that suitable materials could be produced; however, it proved impossible to reliably produce polymers of suitable performance during the course of the project. Thus, the project proceeded with fixed installations.
- The steam generation and effluent treatment systems were purposely oversized for the project, in order to provide spare capacity. As the observed flow rates were between 10 and 30 percent of the design rates, systems of 25-33 percent of the capacity of those used could be employed at similar sites with consequent cost reductions in construction and operation.
- Downward mobilization of DNAPL due to lowering of interfacial tensions is a significant concern of any flushing/displacement technology. However, the interfacial tension of the PCE-water system is not reduced substantially by heating (Heron et al., 1998b). The reduction is less than 15 percent during heating from 10 to 88°C (50 to 190°F), and thus does not lead to a significantly increased mobility of the DNAPL. Significant details of the downward mobilization issue are provided in Heron et al. (1998b). However, it is likely that the interfacial tension of the spent solvents at this site was significantly different from that of pure liquid PCE, and the effect of temperature on the interfacial tension of NAPLs in the subsurface has not commonly been measured. For this site, three deep monitoring wells were installed and sampled for the purpose of determining if contamination existed below the treatment area before or after treatment. Although these wells did not indicate that contaminant concentrations increased below the target treatment zone (see Chapter 10.3.1), this is a limited number of sampling points on which to evaluate downward movement. Also, a low permeability zone at approximately 33 meters (100 feet) bgs at this site may have aided in limiting downward movement of contaminants. We can only conclude that the monitoring points that we had did not indicate that downward movement had occurred.
- Monitoring during SER could include subsurface pressure monitoring, which may include the use of pressure transducers or water level monitoring in suitable wells. Subsurface pressure monitoring could be conducted in both active wells used in the application of SER and in dedicated monitoring wells within and surrounding the remediation volume. The location and number of monitoring points will be dependent on the complexity of the site and the conceptual model of ground water flow available at the time of installation. Subsurface pressure monitoring should begin during site characterization, as part of the establishment of ambient conditions in the subsurface, and continue during remediation operations and during the recovery phase. The network of pressure monitoring wells surrounding the remediation volume should cover an area sufficient to encompass the zone of potential hydraulic influence. At Loring Quarry, possibly a much larger area was affected by ground water extraction than the zone of heating, and this may have been detected by subsurface pressure monitoring.

Overall, the impression of the leading experts in SER application was that this site may be the most complex and difficult site ever attempted using SER, and that the technology was severely challenged by the hydrogeology and COC distribution at this site. It is believed that while several promising indications of remedial progress were seen, the impressive results achieved at other sites may not be practically achievable at a site of this complexity using SER alone.

11.2. Technology Application

11.2.1. General Challenges for SER Applications in Fractured Rock

This section discusses challenges and general difficulties relevant to the application of SER in fractured rock. Despite the impressive results obtained at sites with unconsolidated materials and at the two first SER applications at fractured rock sites in Prague (Dusilek et al., 2001) and at Edwards AFB (Earth Tech and SteamTech, 2003), fractured rock sites with more complex geology and hydrology have characteristics which make it difficult for the geologists and engineers to provide a robust design. These characteristics include:

1. It is extremely difficult, and arguably impractical, to fully characterize the spatial distribution and physical properties of all fractures in any real geological setting. The location, geometry, and morphology of individual fractures in areas not directly sampled are often largely unknown. Even with careful site characterization, the highly variable properties of the fractures make prediction of flow direction of injected fluids difficult.
2. The vertical extent of DNAPL penetration is extremely difficult to establish, and may never be fully understood. For the design and cost estimates to be realistic, a target treatment depth needs to be established. This is more challenging at rock sites due to the “hit- or miss” results of typical characterization efforts.

3. Typically, weathering or human activity increases fractures near the surface, but fractures become less abundant with increasing depth. This makes it more difficult to heat the bottom of a treatment volume with techniques based on fluid flow, which was true at both Loring Quarry and Edwards AFB Site 61 (Earth Tech and SteamTech, 2003).
4. Fractures larger than $1\text{-}3 \times 10^{-4}$ meters ($3\text{-}10 \times 10^{-4}$ feet) are not likely to retain DNAPL effectively (Schwille, 1977), but will be preferential paths for injected fluids. This research has shown that significant contaminant concentrations can be found in fractures that appear to be closed, and do not appear to be active in the ground water flow system. The smaller and potentially dead-end fractures that may contain DNAPL residuals are much less permeable to steam, air, and hot water, and therefore, the flow system is not favorable for displacement of NAPL from injection to extraction points.
5. Rock porosity and matrix diffusion may limit the rate at which contaminants can be removed by vaporization. A significant fraction of the contaminant mass may be situated in the rock matrix. For example, a study of PCE contamination at the Smithville fractured rock site estimated that two thirds of the mass was contained in the porous limestone matrix rock, and only one third of the mass was in the open fractures (MacFarlane et al., 1997). At the Quarry site, small contaminant concentrations were found in the rock matrix approximately 0.30 meters (1 foot) from the nearest fracture. This complicates any technology that relies on contaminant flow through fractures during remediation. For SER, when the fractures are filled with steam or hot condensate, temperature gradients will be inward towards the matrix block centers during heat-up, potentially discouraging diffusion out of the matrix. After heat-up, pressure cycling is hoped to enhance removal by creating boiling of the pore water in the matrix. However, the effects of heat transport from fractures on contaminants within the rock matrix have not been the subject of research studies, and the effects are largely unknown. The remedial efficiency for the COCs that exist within the matrix should be a topic of future investigations, as discussed in Chapter 12.
6. Small fracture apertures, clay lining of fractures, and infrequent occurrence of fractures may severely limit the achievable rate of steam injection, and thereby, the heating rate.
7. Hydraulic and pneumatic control is always important for SER. In fractured rock, such control is much more challenging to achieve than in unconsolidated materials, as well as very difficult to document.

While these are general challenges for the designers and implementers, it should be noted that many fractured rock sites lend themselves to SER applications without presenting all these difficulties. Properties that make sites more amenable to SER include:

1. A relatively permeable formation overlying a permeability barrier such as a tight, competent shale.
2. Crystalline rock of low porosity and negligible matrix diffusion with a large number of open fractures.
3. Formations with predictable fracture pattern and angles, such as the roof sequence joints in the Valley and Ridge province of the U.S. Appalachians (excluding areas of karst features; Perry, 1978; Engelder, 2004).
4. Formations with strongly developed bedding fracture systems (such as the paleozoic limestones of the Niagara region, e.g., Novakowski and Lapcevic, 1988).
5. Formations with a high degree of fracture connectivity but lacking karst features.
6. Sites with a thick vadose zone in weathered rock, residual soil, or unconsolidated porous deposits where contaminant capture is achievable (as Edwards AFB Site 61; Earth Tech and SteamTech, 2003).
7. Large sites where SER can be very economical per unit volume in the target treatment zone.

In conclusion, while rock sites are more challenging than most unconsolidated media sites, they represent a continuum from relatively easy to practically impossible for the application of SER. In the following sections, approaches for SER in fractured rock and potential amendments and alternatives are discussed.

11.2.2. Recommended Approach for SER Implementation at Fractured Rock Sites

Ideally, site characterization would be completed before work began on a remediation design. Many years of experience in unconsolidated porous media by different researchers has shown that steam remediation designs can use two basic operational strategies:

1. Where the true lateral extent of a contaminated aquifer is known, the treatment area can be surrounded by injection wells, and extraction can proceed from the interior, utilizing a conventional steam-drive approach to maximum effect.
2. Where the true lateral extent of a contaminated aquifer is not known (as at the Loring Quarry) or full remediation is beyond the scope of the project (as in a pilot test), the treatment area will likely consist of a cell within a larger impacted area. The treatment design must then use a perimeter of extraction wells in order to provide the best circumstances for maintaining hydraulic control of the site and preventing lateral spreading of contaminant, and to control recontamination of the treatment cell after the end of treatment.

At the Loring Quarry, insufficient characterization data were available at the time of the original design to allow an adequate understanding of the contaminant distribution and hydrogeology. However, due to budget and time constraints, the decision was made

that operational wells would be used for the detailed characterization effort that was needed. Unfortunately, the operation wells could not also provide characterization of the larger scale hydrogeology surrounding the site. This prevented an effective assessment of the location and extent of any migration of steam, hot water, or mobilized contaminant away from the site during the project and also precluded the possibility of assessing the impact of the hydrologic manipulations conducted during the test on the ambient ground water flow regime. In many, if not all, “real-world” sites, funding is likely to be limited; thus, embarking on a lengthy and expensive characterization of a site is likely to be impossible. With that in mind, it makes practical sense to make operational wells an integral part of the characterization effort. It is apparent that a phased approach to characterization and well installation is appropriate, thereby allowing the understanding of the site conditions to be incrementally increased and the remediation design to be adapted to site conditions. To this end, flexibility in design is important, and all wells should be constructed in such a way as to allow them to be used for injection, extraction, or monitoring with a minimum of modification, as may be dictated at a later stage in implementation by the findings of the characterization effort.

The following sequence of events describes the characterization effort needed in order to truly understand a fractured rock environment such as the Loring Quarry.

1. Desk study – Use all existing data to develop a conceptual model and preliminary remediation design, including provisional characterization and operational well locations. This should include all available site investigation and characterization work. An attempt should be made to incorporate the site into a broader hydrogeological conceptual model.
2. 2-Dimensional (2-D) electrical resistivity (ER) survey – This should consist of a minimum of two lines of a length that is not less than six times the depth of interest. The lines should form an intersecting grid pattern covering the proposed treatment cell and the surrounding area and provide cross-sections of resistivity data to a depth at least as deep as the proposed target body of rock. The survey can provide an indication of the presence and orientation of major resistivity anomalies, which may correspond to hydraulically significant features such as faults, fracture zones, and highly permeable lenses or beds. In so doing, this survey can contribute to the overall understanding of the site geology and provide a broad framework into which subsequent borehole characterization efforts can be placed.
3. Phase I drilling – Core drilling should be completed to a total depth equivalent to the base of the target bedrock zone (at 0.15 meter (0.5 foot) boring diameter) in two borings located in areas of different resistivity, based on the findings of the 2-D ER survey. It is recommended that one of these should be a centrally-located boring. The soil profile (at sites where there is overburden) should be logged, tested for NAPL using Sudan IV, and sampled where NAPL is present or at mid-screen depths for VOCs if NAPL is not present. Bedrock geology should also be cored at HQ size from auger refusal to the total depth. The recovered core should be logged and tested for NAPL presence using Sudan IV dye. If NAPL is detected or suspected in discrete fractures or geological features in core, a rock chip sample should be collected using MERC protocols. These borings should also be subjected to geophysical logging prior to completion.

The completion of all wells is dependent on the requirements of the site owner and regulatory agencies. If possible, borings in bedrock should remain open during all phases of characterization. At sites where a substantial thickness of overburden is present, a temporary casing may be required to stabilize the upper part of the boring. At some sites, it may be unacceptable to leave borings open for the extended period necessary to conduct all characterization activities, because of the potential for downward mobilization of DNAPLs and cross-contamination of dissolved-phase or LNAPL contamination. In such cases, a temporary impermeable textile liner such as the FLUTE system should be everted into the well to block fracture intersections within the wellbore. The liner can be removed when the well is ready for final completion. At sites where a temporary liner is unacceptable, or where there are concerns regarding its ability to prevent cross-contamination, the wells should be completed as multiple screened wells according to the requirements of the remediation design. If this approach is followed, the diversity of characterization data and degree of flexibility in final well completion are substantially reduced. Useful characterization data can, however, still be gathered.

4. Phase II drilling – The remaining 0.15 meter (0.5 foot) borings should be drilled to completion depth. Coring or sampling need not be carried out. The completed borings should be fitted with a temporary casing to bedrock to maintain the integrity of the upper boring. All wells should then be profiled using standard geophysical logging methods, which should include, at a minimum, caliper, fluid temperature and resistivity, and OTV/BIPS or similar. In some settings, natural gamma (TD), electric (SP/SPR/8-32-in normal resistivity), ATV, and heat pulse flow meter (HPFM) may also be beneficial. Upon completion of geophysical logging, the well should be installed with a temporary liner or, if deemed necessary, completed according to their final remediation design.
5. Phase III drilling – If employed, Vertical Electrode Array (VEA) borings for cross-borehole ERT sensors should be drilled to completion depth at 0.10 meter (0.33 foot) diameter. Unless these borings are intended for use in further characterization activities, the pre-fabricated VEA/temperature probes should be installed and grouted into place after completion of any characterization activities.

6. Phase IV drilling –Any vertical or angled monitoring wells should be drilled and installed at this time. New monitoring wells should be drilled at 0.15 meter (0.5 foot) diameter and logged for the full suite of geophysical profiling methods as described above. Upon completion of geophysical logging, the well should be installed with a temporary liner or, if deemed necessary, completely installed as described in the remediation design. Any wells that may lie within the treatment zone, where significant heating can be expected, must be completed with all steel components to prevent failure if contacted by steam during operations. Angled wells that are located and oriented in such a way as to be expected to remain relatively cool during remediation operations can be completed with PVC materials, including multi-level sampling systems.
7. Development of all new monitoring wells – Pre-existing wells within the treatment cell should also be developed if found to be impacted by drilling of adjacent new wells. All wells should be gauged at the completion of development and head distribution maps produced.
8. Ground water sampling and transmissivity profiling – In open wells, intervals isolated by straddle packer assemblies should be sampled for COCs using low-flow techniques. Upon completion of sampling, slug tests may be conducted in the same packer-isolated intervals to measure transmissivity. Where multiple-screen completion wells have been installed, the screened intervals could be sampled as conventional monitoring wells, and slug tests could be used to determine transmissivity adjacent to the screened intervals.
9. Interconnectivity testing – Where open wells are available, individual pairs of transmissive fractures can be tested using the pulse interference method described in Chapter 4.1.6. Short depth intervals, isolated by straddle packer assemblies, and identified on the basis of previous geological interpretation and transmissivity profiling, should be selected for testing. Whenever practical, observations of response to pulse interference testing in adjacent, open wells should also be attempted. This approach serves to identify interwell connections that may be analyzed in subsequent tests, thereby augmenting the hydrogeological interpretation of previously acquired characterization data. At sites where wells cannot remain open for extended periods, the pulse interference method can also be used to quantify the transmissivity of interwell connections between the fixed, screened depth intervals.
10. Additional hydraulic testing – If deemed appropriate, additional conventional aquifer tests can also be conducted. Such tests might include step-drawdown tests, constant rate drawdown tests, and additional slug tests or pumping tests in overburden. While these tests were not conducted at the Loring site and add considerable expense and difficulty to the overall characterization effort, they would address questions of hydraulic control and ground water migration paths over a larger area than can be addressed by pulse interference testing alone. Also, they may elucidate low transmissivity interconnections that are not readily detected by short term slug interference tests.
11. Final well installation – At sites where wells have been left open during hydraulic testing, final completion as multiple screen injection/extraction wells can begin after final remediation design modifications have been made in response to findings of the characterization effort.
12. Aquifer recovery – The aquifer should then be allowed to recover for a period of several months after completion of hydraulic testing. The length of time at any particular site will vary, dependent on the local hydrogeological conditions. After the aquifer or aquifers have recovered, the first round of background ground water samples can be collected from the treatment and surrounding monitoring wells. During the recovery period, characterization data can be analyzed and the design and work plan modified where necessary.
13. Start of operations – Remediation operations can now begin.

11.2.3. Amendments and Alternative Approaches

As described in the discussion of Technology Objective 1 (TO-1; Chapter 10.3.2), the application of SER at this site did not lead to the expected and needed heating of the target treatment zone, and the maximum temperatures achieved were significantly below the target temperature. The most likely reasons for this were discussed under TO-3 and TO-6, and included:

- The widely-spaced fractures and low transmissivity of the target intervals.
- Only a limited number of borehole intervals were well suited for steam injection. This led to a design where steam injection was conducted at the eastern end of the test area, preferentially in deep zones with limited concentrations of COC. The site geometry, geology, and COC distribution were limiting factors themselves.
- The observed steam injection rates were relatively low, and raising the injection pressures to the limit of the steam generator did not lead to substantially faster heating. The most effective method that served to accelerate the heating of the subsurface was to increase the number of steam injection points by converting some extraction wells to injection wells, as was done with wells I-7, I-8, and VEA-5, about half way through the operational phase.
- The operational data convincingly showed that the heat migration, including the component related to thermal conduction, was insufficient at the timescale permitted by the project funding and schedule.
- The operational data indicate that heat losses into the matrix lead to steam condensation after relatively short travel distances in the formation. These heat losses lead to condensation of significant quantities of steam, creating a warm water front that had

to be displaced for the steam to fill the fractures. The resulting heating rate for a site with sparse fracturing and low fracture apertures is very slow.

Two alternatives are suggested for improving the completeness of heating at a site comparable to the Loring Quarry:

1. Operate SER over much longer periods, using smaller steam injection and effluent treatment systems. The maximum steam injection rate achieved for the whole site was approximately 500 kg/hour (1,200 lbs/hour), while the steam generator had a capacity of 3,600 kg/hour (8,000 lbs/hour). Similarly, the water extraction rates were below 20 lpm (5 gpm), and the treatment system had a capacity greater than 75 lpm (20 gpm). By operating over a longer period, improved heat distribution would have been achieved, even with the low heat-up rates observed. By reducing the size of the above ground equipment, the system could be run more cost effectively. However, it should be noted that the data collected during this project failed to show that the target temperatures could be achieved using this approach. Other factors, such as increased overall heat losses when operating for longer periods and the increased sensitivity to cold water moving through the target area, must be evaluated before a conclusive recommendation could be made.
2. Heat the site using different methods such as Electrical Resistance Heating (ERH) or Thermal Conduction Heating (TCH). ERH is limited by the electrical resistivity of the rock. A site-specific analysis on the applicability of ERH would have to be made, including a determination of acceptable electrode separations. For sites with very resistive rock such as limestone, it is likely that the electrodes would have to be placed close together (less than 4.5 meters (15 feet) separation) in order to achieve sufficient current flow through the formation to reach target temperature. The application of TCH is dependent on the thermal conductivity of the rock. Since the thermal diffusivities of limestone and quartz minerals are similar, it may be assumed that TCH can be used to heat limestone. Typical TCH heater well temperatures are in the 700°C (1,300°F) range, which significantly increases the conductive heating rate over that observed during SER, where maximum temperatures were 100-130°C (212-266°F). Using TCH, inter-well temperatures above 100°C can be achieved within an operational period of less than one year using well separations between 3.5 and 6 meters (12 and 20 feet).

The second option is attractive from a different standpoint as well: It is possible to extract fluids from all the TCH and ERH heating boreholes, which increases the chance of capturing COCs during heating by contacting and extracting from all the fractures that are penetrated by the boreholes. This keeps fluids moving inward towards the heated zone during operation, and reduces or eliminates the risk of spreading COCs.

One potential disadvantage of ERH and TCH is that the energy demand is larger for heating, since the entire matrix would be heated. However, the energy necessary to heat limestone is on the order of 65-130 kWh per cubic meter (6,300-12,600 Btu/cubic foot), which equals between \$6.5 and \$13 per cubic meter (\$0.20 and \$0.40 per cubic foot) at typical power costs.

While SER could probably reach target temperatures with a modified approach and more limited scope, and no claims are made regarding the alternative heating approaches as they have not yet been tested in fractured limestone, our collected experience indicates that for sites as complex as the Loring Quarry, the ostensibly more predictable heating of energy intensive methods such as ERH or TCH have promise. The use of these technologies in fractured rock warrants research in the future.

11.2.4. Conceptual Comparison of SER and TCH/ERH Costs for a Range of Site Complexity

The choice of heating technology depends on the complexity and size of the site. Likewise, the cost of both the remediation and the associated characterization necessary to design, implement, and document the remedial results, depend on site complexity and size. The following generalizations are offered:

- For complex sites such as the Loring Quarry, the effort necessary to fully define the source zone to be targeted for remediation would be substantial. For this project, the cost of the characterization effort exceeded the cost of the SER implementation (however, it should be kept in mind that SER costs were reduced by using boreholes that had been used for characterization). Yet, there is general consensus among the project team that while our understanding of the site was greatly increased by the characterization efforts, the subsurface distribution of COCs and the location of ground water flowpaths were only partly constrained and ultimately remained undefined.
- Assuming that a perfect source removal action were to be completed, the amount of data needed to document that the cleanup objectives had been met would be as substantial and expensive to collect as the pre-removal characterization had been. For many complex sites the available funding may not be sufficient for the characterization effort necessary to fully document that the remediation objectives have been met.
- When a more predictable remediation method (i.e., one that is not sensitive to subsurface properties that can vary significantly within the treatment zone) is used, less characterization efforts are necessary. Since there would be greater confidence that heat-up would be achieved, fewer thermocouples and sampling locations would be necessary. This reduces the cost of monitoring and characterization during and after remediation using a predictable heating method when compared to SER.
- Simple sites require less characterization and are easier to remediate using SER than complex sites, since steam flow and heating are more predictable in simple sites. This leads to relatively low cost per unit volume (see for example the predicted costs for scale-up application of SER at Edwards AFB; Earth Tech and SteamTech, 2003).

- SER application costs are strongly dependent on site complexity. As the complexity increases more boreholes are needed, there are more critical steps during implementation, longer operation times may be needed, and significantly more monitoring and adjustments may be needed during operation.
- The heating approach and cost for sites treated using more predictable heating methods such as TCH or ERH are relatively insensitive to complexity, since the heater wells or electrodes are placed throughout the target zone, and the heating occurs primarily by thermal conduction or electrical conduction. Complexity does not affect thermal or electrical conduction as much as it affects permeability.

Figure 11.2.3-1 qualitatively indicates how the cost of any source removal technology is higher for complex sites than for simple ones. For very complex sites, the characterization cost can be prohibitive. For a range of sites, including the simple to moderately complex sites, the cost of treatment dominates over the characterization costs. SER costs are likely to be lower than TCH costs for very simple sites where an inexpensive SER system can be used. However, the costs of a more predictable heating method such as TCH or ERH become more and more favorable compared to SER costs as the complexity of the site increases.

While these are merely speculative interpretations based on our knowledge of these technologies, the indication is that for a complex site such as the Loring Quarry, more predictable heating methods such as ERH or TCH, that do not rely on fluid movement to deliver the heat, would likely be more cost-effective.

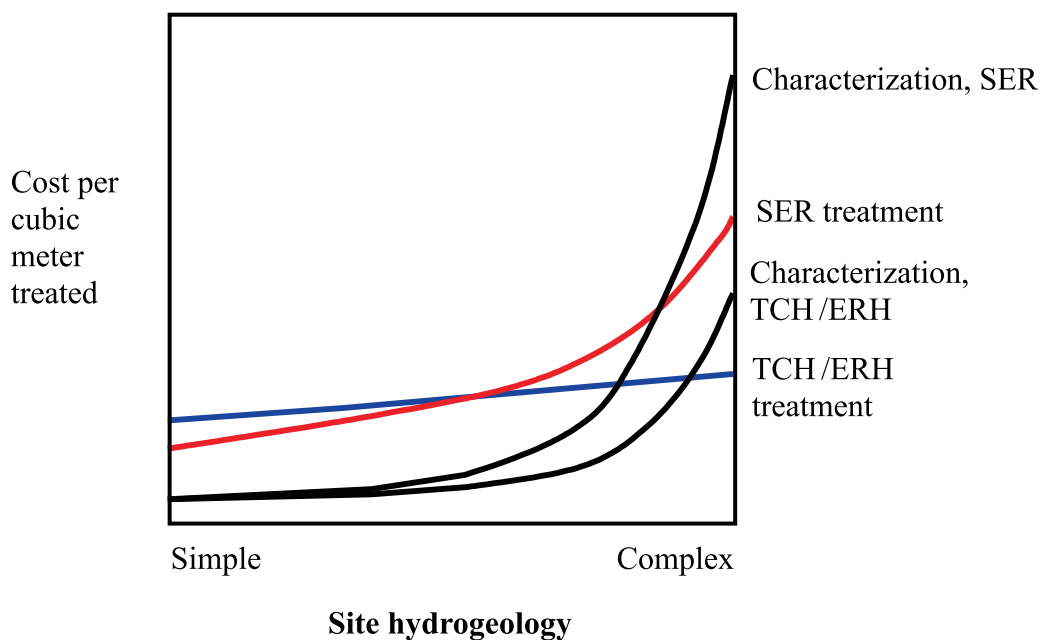


Figure 11.2.4-1. Sketch of comparative cost of site characterization and treatment costs for SER and TCH/ERH applications to sites with varying complexity.