Review & Comment on LNAPL Interim Options at the Kirtland Air Force Base Bulk Fuels Facility Site Albuquerque, NM

Independent Technical Review Panel

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Summary

An interagency Biogeochemical Workgroup that is providing technical assistance on site investigation and remediation at the Kirtland Air Force Base (KAFB) Bulk Fuels Facility (BFF) fuel spill prepared a spreadsheet titled “Options for Interim Measures to Treat the LNAPL and Dissolved, Adsorbed and Vapor Phase Contaminants in the LNAPL Area (revised 04/23/2015)” that was submitted to the New Mexico Environment Department. This spreadsheet lists 18 candidate technologies that might be used accomplish interim remediation of soil and groundwater contamination in the area where light non-aqueous phase liquid (LNAPL) has reached the groundwater. The NMED contracted with Thomson & Associates to establish an Independent Technical Review Panel (ITRP) to review the spreadsheet to confirm that the technologies are properly identified, and that their effectiveness, limitations, and other attributes that may affect their implementation in the LNAPL contaminated source area at the KAFB BFF are accurately summarized.

The Panel found that the soil and groundwater remediation methods identified in the spreadsheet appear to represent a complete list of possible technologies that could in principle be applied to remove and/or degrade contaminants in the LNAPL zone at the KAFB BFF site. Generally the spreadsheet describes the technologies accurately however, the Panel made numerous suggestions to improve the descriptions of the capabilities and limitations of each.

The Panel made three substantive suggestions to the material in the spreadsheet. First, most of the technologies have few or no references to support their description. It is recommended that references to current work with these technologies be cited, and the Panel provided numerous references for consideration. Second, the descriptions do not identify which contaminants are remediated by each technology nor whether the technology is applicable to contaminated groundwater, the vadose zone, or trapped LNAPL. Third, each technology is identified and described independent of its possible interactions with other technologies. The Panel believe it is important to identify potential synergies or incompatibilities between technologies because it is likely that more than one technology may be applicable.

In addition to its review of technologies listed in the spreadsheet, the Panel recognized that there are other factors that will determine whether a remediation method can be applied at the KAFB BFF site. These are: 1) the impact of the rising water table and trapped LNAPL on the contaminant source term, 2) the challenges associated with characterizing the LNAPL zone at this site., 3) the need for metrics to assess the performance of field scale pilot tests and remediation methods, 4) the geohydrologic complexity of the site, and especially the effects of heterogeneity on the ability to circulate fluids through the most contaminated strata, and 5) whether alternative well construction such as horizontal wells might be a better method of circulating fluids through the LNAPL source zone than conventional deep vertical wells with short screens.

Finally, the Panel believes that a spreadsheet format is not an appropriate method of summarizing these technologies because there is so much information about each. It is recommended that the information be presented in text format.

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Introduction

A draft document in the form of a spreadsheet was submitted to the NMED titled "Options for Interim Measures to Treat the LNAPL and Dissolved, Adsorbed and Vapor Phase Contaminants in the LNAPL Area (revised 04/23/2015)." This spreadsheet, prepared by the KAFB Biogeochemistry Workgroup, is a spreadsheet that lists candidate technologies that might be applicable to accomplish interim remediation of soil and ground water contaminants in the aea where light non-aqueous phase liquid (LNAPL) has reached ground water at the Kirtland Air Force Base (KAFB) Bulk Fuels Facility (BFF) contamination site. The spreadsheet identifies 18 technologies that might be utilized on an interim basis while a Corrective Measures Examination (CME) is being conducted to develop a final remediation strategy. It provides a brief description of each technology and provides a preliminary evaluation of its applicability to the KAFB BFF site. The technologies include:

Enhanced In-Situ Technologies

- Biostimulation options (Aerobic)
- Biostimulation options (Anaerobic)
- Bioaugmentation options
- Cometabolic options (Aerobic)
- In-situ Chemical Oxidation
- Other Abiotic Degradation Options (Addition of reactive reductants, sulfide, zero valent Fe)
- In-situ Biogeochemical Transformation (ISBGT)

Sparging Options

- Air Sparging with Soil Vapor Extraction
- Thermally Enhanced Sparging with SVE
- Source Area Biosparge
- Other Enhanced Sparging techniques
- In-Well Treatment

Vadose Zone Treatment Technologiesl

- Soil Vapor Extraction (SVE)
- Bioventing with/out SVE
- Enhanced SVE Techniques

Flushing Technologies

- Solvents
- Surfactant/Cosolvent - Surfactant Enhanced Aquifer Remediation (SEAR)
- Water

In addition, two technologies are listed in the spreadsheet but no description or attributes were provided; Dissolved phase 1,2-Dibromoethane - Anaerobic Groundwater, and Monitored Natural Attenuation. These were not considered by the Panel.

The NMED contracted with Thomson and Associates to establish an Independent Technical Review Panel (ITRP) to review the spreadsheet to confirm that the technologies are properly identified, and that their effectiveness, limitations, and other attributes that may affect their implementation in the LNAPL contaminated source area at the KAFB BFF are accurately summarized. Furthermore, the Panel was asked to suggest other technologies that might be applicable at this site if they were not mentioned by the Biogeochemistry Workgroup.

The objective of this report is to review the technologies described in the spreadsheet for completeness and accuracy. The task assigned to the Panel was not to review the technologies in detail nor to rank them according to their effectiveness in the LNAPL zone. Instead, the Panel's review was restricted to confirming the completeness and accuracy of the Workgroup's summary of each of the technologies. The Panel did not make a determination as to whether each technology could be successfully implemented to address contamination in the LNAPL, dissolved, sorbed, and vapor phases at the KAFB BFF site.

General Comments

The Panel found that the soil and groundwater remediation methods identified in the spreadsheet represent a complete list of possible technologies that could in principle be applied to remove and/or degrade contaminants in the LNAPL zone at the KAFB BFF site. Generally, the descriptions of the technologies and their abilities, limitations and other constraints are accurately presented. In order to evaluate these technologies for implementation as an interim or final remediation measure additional information on their capabilities is needed for many of them. Accordingly, the panel has provided citations to appropriate references for each of the technologies. Several general references that may be of assistance to the Workgroup are also listed at the end of this report.

The Panel found that a spreadsheet format is not the best way of presenting and summarizing the technologies under consideration. This is primarily because the information on each technology and its effectiveness, limitations, and constraints is descriptive rather than quantitative. This type of information is not well suited to summarizing in a spreadsheet. As the Biogeochemistry Workgroup proceeds in its evaluations it may be appropriate to include diagrams, biogeochemical reactions, and summary calculations that are difficult to include in a spreadsheet. In addition the spreadsheet has grown to the point that it is difficult to view on a computer screen and as a printed document. It is also difficult for reviewers of a spreadsheet to make corrections and comments. For these reasons the panel has converted each technology listed in the spreadsheet to a Word document and included these descriptions as an Appendix to this report. In the future the Workgroup may wish to convert this information to a database format.

Generally, the Panel agrees that the criteria listed in the spreadsheet are appropriate for describing the technologies, their capabilities and limitations. The Panel notes that some of the criteria had almost no entries including "Control releases to reduce or eliminate further releases of hazardous constituents" and "Comply with standards for waste management." The Panel found that these criteria are unclear and suspects that the lack of entries is an indication that Workgroup members experienced the same confusion.

The Panel found three notable areas in which the spreadsheet can be improved. First, most of the technologies have few or no references to support the descriptions, capabilities and limitations of the method. The Panel recognizes the very preliminary nature of the spreadsheet but feels strongly that including a few critical references to previous work is important because: 1) It documents the Workgroup's familiarity with each of the technologies and their attributes; 2) Citations to key references help reviewers such as members of the Independent Technical Review Panel understand what processes the Workgroup is referring to as many of the descriptions are quite vague; 3) Cited references provide ready access to information so that members of the Workgroup and other readers can understand and evaluate each technology, and 4) it appears to the Panel that some of the descriptions rely closely on published references that are not cited. The Panel has provided examples of references at the end of the description of each technology in Appendix 1.

The second observation is that some of the descriptions in the spreadsheet do not identify clearly which contaminants are remediated by the technology nor whether the technology is applicable to the vadose zone and/or the aquifer, and within that spatial domain whether it is appropriate to remediate the LNAPL, and/or dissolved, sorbed, and vapor phase contaminants. For example with regard to contaminants, the LNAPL is apparently a major target for remediation, but so too is dissolved EDB and other toxic compounds of interest (e.g., BTEX). The Panel recommends the addition of two categories (headings) that explicitly identify the contaminants that are the primary target for that technology and where in the contaminated domain that technology would find application. With regard to contaminant phase the Panel recommends that the technology description better clarify how a treatment of one phase, e.g., vapor extraction, also indirectly treats another phase, e.g., LNAPL, by mass transfer between phases. This coupling is only implicit in many of the descriptions. Finally, some treatment technologies have multiple paths to remediation, e.g., LNAPL that is indirectly treated by mass transfer between phases but also by mobilization of the LNAPL itself. While in many cases mobilization is a secondary process it is neglected in several relevant descriptions, despite the need to recognize and control the newly mobilized LNAPL.

The third observation is that each technology is identified and described solely based on its capabilities as a stand-alone technology. Given the nature of the contaminants, the size of the LNAPL zone and dissolved a vapor phase contaminant plume, as well as the hydrogeologic complexity of the site it is likely that multiple remediation technologies will eventually be utilized. The Panel believes that the description of each technology should therefore include mention of its compatibility with other technologies. For example, air sparging and SVE would be compatible with oxidation processes but not with anaerobic degradation processes. This information will be increasingly important as the Workgroup moves forward with technology evaluation and selection.

The following section provides summary comments of the Panel's review of each technology.

Summary Comments of the Reviews of Each Technology

1.1 Biostimulation options (Aerobic)

The spreadsheet provides a good summary of aerobic biostimulation technologies. The Panel agrees that it could be effective for the hydrocarbons and that EDB cometabolism would be possible, but that further investigation is needed. This would likely consist of microcosms or pilot studies if EDB elimination is required. It should be mentioned that biostimulation without sparging would cause much less stripping of EDB than would biosparging.

Although the Panel agrees with the statement that “aerobic biostimulation represents a mature technology that has been effectively applied at a large number of fuel hydrocarbon sites” the overview should include a caveat. The term, “aerobic biostimulation” typically includes bioventing and biosparging which are listed as technology 2.3. Here it is appropriately restricted to delivery of oxygen releasing compounds. Remediation of large NAPL source zones by delivery of chemically produced oxygen is much less common and references should be provided to successful use of this technology. The spreadsheet appropriately mentions mass transfer limitations and the high potential for biofouling.

Unless the problem has been documented and quantified at KAFB the Panel suggests deletion of the term “carcinogenic PAH” as it is not clear that these compounds have been detected in ground water.

The Panel is aware that some microcosm studies have been conducted. If these preliminary studies are relevant to aerobic biostimulation processes the findings should be mentioned, referenced, and briefly summarized.

1.2 Biostimulation options (Anaerobic)

Anaerobic biostimulation is described well in the spreadsheet. Throughout the description it might be helpful to more clearly distinguish between the fundamentally different processes of biostimulation for removal of fuel components and chlorinated solvents. For clarity, each section could be divided into two subsections and then an indication about how the two processed might interact. In some situations they might be mutually exclusive.

With respect to chlorinated solvents the technology is used primarily where electron donor concentrations are limited. There is little information on biostimulation of EDB reductive dehalogenation in the presence of fuel hydrocarbons. There is, however, quite a bit of information about natural attenuation of chlorinated solvents in the presence of fuel hydrocarbons in the older natural attenuation protocols. Appropriate references could be mentioned. Lactate stimulates EDB degradation in laboratory microcosms containing fuel hydrocarbons but field experience with this technology is limited.

Biostimulation of hydrocarbon biodegradation by sulfate or nitrate addition is well documented, but reductive dehalogenation of chlorinated solvents under such conditions should be discussed and explained. Because of the reduction potential of the various electron acceptors, sulfate would be less likely than nitrate to inhibit reductive dehalogenation.

EDB cometabolism under methanogenic conditions should be mentioned. Here and throughout the document estimation of natural attenuation at the site could be used as a benchmark in evaluation of the various technologies.

The Panel is aware that some microcosm studies have been conducted. If these preliminary studies are relevant to anaerobic biostimulation processes the findings should be mentioned, referenced, and briefly summarized.

1.3 Bioaugmentation options

The spreadsheet provides a clear description of bioaugmentation and indicates that it might be used for the destruction of EDB but would not be necessary or helpful for elimination of hydrocarbons. Most of the field experience has been with bioaugmentation in conjunction with biostimulation to treat chlorinated solvents. There seems to be little or no literature on the effectiveness of bioaugmentation to treat EDB mixed with hydrocarbon fuels. Thus, there would be more uncertainty surrounding this technology than technologies that are more established.

The Panel is aware that some microcosm studies have been conducted. If these preliminary studies are relevant to bioaugmentation processes the findings should be mentioned, referenced, and briefly summarized.

There is no commercially available culture designed to catalyze the reductive dehalogenation of EDB in the presence of fuel hydrocarbons. Most cultures use small organic acids as the electron donors and the addition of such electron donors would inhibit biodegradation of the fuel hydrocarbons. Testing of available cultures or development of new cultures would be necessary if this option is selected.

1.4 Cometabolic options (Aerobic)

This technology is a subset of Technology 1.1- Biostimulation-aerobic that has been discussed above. Essentially it involves aeration with addition of propane to stimulate growth of the appropriate bacteria and induction of monooxygenase enzymes. Small aliphatic compounds (methane-pentane) are the most effective primary substrates because they induce alkane monooxygenases. Addition of methane or propane has been demonstrated to be effective for conditions similar to those in the downgradient EDB plume where potential electron donors are depleted. Establishing appropriate conditions for propane dependent aerobic cometabolism in the LNAPL zone at the KAFB BFF site will be constrained by the high mass of fuel hydrocarbons that will compete for oxygen. The hydrocarbons in the LNAPL will include BTEX and some small aliphatic compounds that could serve as primary substrates if oxygen is provided. Such cometabolism will take place under conditions described in Technology 1.1 Biostimulation-aerobic. The extent of such cometabolism during biostimulation by addition of oxygen alone should be estimated and compared with results expected when propane is added. The results are likely to depend on the extent to which the small alkanes have been depleted from the weathered fuel contaminants that constitute the LNAPL.

References should be included for successful application of propane dependent cometabolism in the presence of fuel hydrocarbons. Results from recent microcosm studies might provide insight about the effectiveness of propane addition.

Problems with competition and inhibition are likely to be minimal due to the relatively low EDB concentrations compared to hydrocarbons from fuels.

The Panel is aware that some microcosm studies have been conducted. If these preliminary studies are relevant to cometabolic degradation processes the findings should be mentioned, referenced, and briefly summarized.

1.5 In-situ Chemical Oxidation (ISCO)

The spreadsheet provides a reasonable summary of the chemistry of in-situ chemical oxidation. However, the spreadsheet is unclear on which contaminants would be subject to remediation; dissolved EDB, entrained LNAPL, or dissolved hydrocarbons. There is no discussion of the delivery of the chemical oxidants to the LNAPL zone. Most sites at which ISCO has been used have shallow depth to ground water. The large depth to ground water and the highly heterogeneous conditions at the KAFB BFF site will be make implementation very challenging. Hence, the Panel recommends that in addition to laboratory testing of the technology, the spreadsheet recognize that field scale pilot testing would be required before the ISCO could be implemented.

Fenton's reagent has been shown to be capable of oxidizing EDB hence its effectiveness should be changed to "Uncertain" instead of "Not effective."

In-situ chemical oxidation of EDB does not appear to have been discussed by either ITRC or EPA. However, other studies have shown that EDB can be oxidized by Fenton's reagent.

NM has a ground water standard for iron of 1.0 mg/L and manganese of 0.2 mg/L. Therefore, if an iron or manganese based oxidant is used it will be necessary to assure that these standards are not violated.

1.6 Other Abiotic Degradation Options

As described in the spreadsheet, this technology is focused strictly on EDB degradation. It does not address hydrocarbon contaminants that are present in the LNAPL zone at the KAFB BFF. It is not clear that it would achieve any removal of any contaminants other than EDB. Although abiotic reduction of EDB has been demonstrated in a few laboratory studies, little information has been developed on the variables that affect process performance and how it might be applied to achieve remediation at a site such as the KAFB BFF site. It is not apparent that in-situ abiotic degradation of EDB has been used elsewhere. This uncertainty and the limited current knowledge regarding abiotic degradation of EDB lead the Panel to believe that the potential to attain cleanup standards/goals is low. Some of the reactive constituents identified here such as compounds used to stimulate microbial growth are probably more appropriately considered in section 1.7 In-situ Biogeochemical Transformations (ISBGT).

Although the technology is protective of human health, NM has a ground water standard for iron of 1.0 mg/L. Therefore, if an iron-based abiotic degradation process is used it will be necessary to assure that this standard is not violated.

1.7 In-situ Biogeochemical Transformation (ISBGT)

The spreadsheet provides a good summary of the in-situ biogeochemical transformation (ISBGT) technology for possible remediation of EDB at the KAFB BFF site. The summary might state that ISBGT will likely have no beneficial effect on phase separated hydrocarbons. The Panel generally agrees that the assessment of the technology and its constraints are properly captured in the spreadsheet.

However, regarding the "Schedule to Implement" criteria, the Panel understands that considerable microcosm testing using core and water samples from the KAFB BFF has been completed and has produced meaningful results. Nevertheless, it is likely that field scale pilot testing will be required to confirm process performance which, due to the slow nature of anaerobic processes and ground water flow, may take several years to complete. Therefore, the panel believes that full scale implementation of the ISBGT would likely not be feasible for 4 to 5 years or longer.

2.1 Air Sparging with Soil Vapor Extraction

The Panel agrees that air sparging has been widely used to remediate both hydrocarbons and halogenated compounds, and there is a large body of literature that describe its performance as well as its limitations. Although there is little reported experience with EDB, results of sparging to remove chlorinated compounds with similar solubility and Henry's law constants has been demonstrated, and this experience can be used to estimate EDB removal. Another factor that should be considered is how effective the technology will be at addressing weathered aviation gasoline and jet fuel (JP4 and JP8).

It is likely that air sparging/SVE technology can be implemented with current technology and understanding of the hydrogeology at the KAFB BFF site. However, the relatively shallow extent of the plume beneath the top of the water table may require use of a large number of sparge wells with short well screens.

The Panel agrees that air sparging/SVE is a mature remediation technology. Nevertheless, experience with air sparging has demonstrated challenges associated with preferential air flow pathways through the aquifer that limit contact with groundwater and reduce the radius of influence of the sparge wells and consequently the effectiveness of the technology. The Workgroup might consider use of horizontal wells instead of vertical wells as a means of improving the zone of influence of the sparging process.

Use of sparging/SVE technology will likely require a large amount of infrastructure at the surface including blowers, air distribution lines, and possibly vacuum blowers, collection lines, and off gas treatment if SVE and treatment is required. This should be mentioned in the spreadsheet.

The Panel agrees that hydrocarbon vapors may not be detected at the surface, however, it is not clear that the same conclusion can be made for EDB. Any technology that may volatilize EDB will be subject to considerable public scrutiny. In order to implement this technology it will be necessary to convince the public that this contaminant will not reach the surface at detectable concentrations. Because of these concerns it is likely that SVE and subsequent off gas treatment would be required to achieve public acceptance of this technology which will increase the cost and complexity of the sparging process.

2.2 Thermally Enhanced Sparging with SVE

The Panel agrees that thermally enhanced air sparging and SVE has been used to remediate both hydrocarbons and halogenated compounds and there is a modest body of literature that describe its performance as well as its limitations. Although there is little reported experience with EDB, results of thermally enhanced sparging to remove chlorinated compounds with similar solubility and Henry's law constants has been demonstrated and can be used to estimate EDB removal. Another factor that should be considered is how effective the technology will be at addressing weathered aviation gasoline and jet fuel (JP4 and JP8).

The Panel agrees that thermally enhanced air sparging/SVE is a relatively mature remediation technology. However, it is not clear that it has been demonstrated at sites as deep as the KAFB BFF site. Because of this large depth it is not clear that a fluid heated at the surface such as steam or hot air could due to heat losses during conveyance in long pipes to the contamination zone. The Workgroup should give further thought to the heating mechanism and heat transfer if the process were to be used at KAFB. The Workgroup might consider use of horizontal wells instead of vertical wells as a means of improving the zone of influence of the sparging process

It is likely that thermally enhanced air sparging/SVE technology can be implemented with current technology and understanding of the hydrogeology at the KAFB BFF site. However, the relatively shallow extent of the plume beneath the top of the water table may require use of a large number of sparge wells with short well screens. Thermally enhanced air sparging/SVE technology will likely require a considerable amount of infrastructure at the surface including blowers, steam or air heaters, air distribution lines, and possibly vacuum blowers, collection lines, and off gas treatment if SVE and treatment is required. Furthermore, heating the air or soil introduces additional complexity, cost, and energy requirements that must be considered in evaluating the technology.

The Panel agrees that hydrocarbon vapors may not be detected at the surface, however, it is not clear that the same conclusion can be made for EDB. Any technology that may volatilize EDB will be subject to considerable public scrutiny. In order to implement this technology it will be necessary to convince the public that this contaminant will not reach the surface at detectable concentrations. Because of these concerns it is likely that SVE and subsequent off gas treatment would be required to achieve public acceptance of this technology which will increase the cost and complexity of the sparging process.

2.3 Source Area Biosparge

The Panel agrees that biosparging has been used to remediate hydrocarbons at other sites and there is a considerable body of literature describing its application and limitations. The Panel notes that there is some uncertainty regarding the effectiveness of aerobic biodegradation of

EDB in that some studies claim it works well while others report that anaerobic degradation is faster and more complete. These concerns have been captured in the discussion of technologies 1.1, 1.2, and 1.3.

The distinction between air sparging and biosparging based on the air flow rate might be too subtle for many readers of the spreadsheet. Flow rates that are low enough to minimize stripping would be unlikely to provide sufficient oxygen for elimination of the LNAPL. Low flow rates have been used for biosparging to remove dissolved BTEX where the total mass of hydrocarbons is low. Even low flow rates would transport substantial amounts of nitrogen that would cause stripping. Sparging with pure oxygen would be the only way to minimize stripping while providing sufficient electron acceptor for elimination of the LNAPL.

The panel is not aware of constraints related to microbial acclimation and development of robust populations of aerobic hydrocarbon degraders. The plume is anoxic because of the action of aerobic hydrocarbon degraders that have consumed available dissolved oxygen.

The Panel understands that a small field scale pilot study of biosparging was attempted earlier at the KAFB BFF site. The results of this study should be included in future evaluation of this technology.

The Panel agrees that hydrocarbon vapors may not be detected at the surface, however, it is not clear that the same conclusion can be made for EDB. However, any technology that may volatilize EDB will be subject to considerable public scrutiny. In order to implement this technology it will be necessary to convince the public that this contaminant will not reach the surface at detectable concentrations. Because of these concerns it may be that SVE and subsequent off gas treatment would be required to achieve public acceptance of this technology.

A number of references have been provided that may be of assistance in evaluating this technology.

2.4 Other Enhanced Sparging techniques

No description of this technology is listed in the spreadsheet other than “Same as above (2.3) with exotic amendments to sparge gases.” The Panel has no way of knowing what is meant by this description. Addition of amendments to stimulate aerobic or anaerobic biodegradation are covered in technologies 1.1 through 1.4 and 1.7. Chemical amendments to achieve degradation are discussed in technologies 1.5 and 1.6. Use of solvents, surfactants, or other additives to enhance flushing are discussed in technologies 4.1 and 4.2. The Panel believes that the discussion in these sections would cover any likely additives to enhance sparging techniques hence finds that this technology is redundant and recommends that it be eliminated from the spreadsheet.

2.5 In-Well Treatment

The Panel finds this to be a well-written summary of the SERDP/ESTCP chapter by the same author (Alleman 2010). It is clear as indicated in the spreadsheet that implementation would be difficult and expensive. The assessment here accurately indicates that although the technology should remove contaminants that enter the well, because of potential fouling and because of the lack of availability of the submerged NAPL, it would have a small radius of influence on the bulk of the contamination.

Recent applications for successful treatment of NAPL or halogenated compounds associated with fuel contamination should be cited.

3.1 Soil Vapor Extraction (SVE)

This description should clearly state that SVE is primarily a technology that is applicable to the vadose zone and does not treat LNAPL that has been entrapped (drowned) below a rising water table, and that it is also not a very effective treatment for LNAPL floating on top of the water table. However, used in combination with other methods (for example those described in Section 2) it can be effective in remediating floating and drowned LNAPL.

The Panel agrees that the spreadsheet provides a reasonable summary of human health and environmental aspects, although it should also put more emphasis on the impact to conditions below the water table. For example, the description might include: "As the method does not effectively treat floating or drowned LNAPL it has little impact on remediating them or dissolved constituents in groundwater, except by preventing additional mass from reaching the water table."

Addressing short term effectiveness the Panel notes (and suggests editorial changes/additions) that sedimentary heterogeneity creates high permeability preferential flow paths and low permeability (especially stratified) barriers. Both lead to by-passing of contaminated zones and reduce the effectiveness of SVE. Contamination that is sequestered in low permeable soils may lead to a rebound effect upon termination of SVE and may decrease short-term SVE effectiveness.

The discussion in the "Comments" column appears to be a reasonable set of additional comments. One item missing is that SVE increases air flow and, if the injected air is not humidified, this promotes drying or dessication of the vadose zone. Excessive dessication will inhibit the growth of microbes, preventing coincidental biodegradation of hydrocarbons and possibly making it more difficult to subsequently transition to a biologically-oriented treatment, such as bioventing. Biosparging in conjunction with SVE would overcome potential problems with dessication.

3.2 Bioventing with/out SVE

It is important to recognize that, as with SVE, bioventing of the BFF LNAPL vadose zone does nothing to remediate floating or drowned LNAPL, or dissolved hydrocarbon components found in the groundwater. The primary benefit of bioventing to groundwater will be to reduce future hydrocarbon loading of the aquifer. There is another very important issue not mentioned in the description. Bioventing increases air flow through the vadose zone, although to a lesser degree than SVE. If the air entering the system is not humidified air flow will promote drying or dessication of the vadose zone. Excessive dessication will inhibit microbial growth and limit the biodegradation of hydrocarbons. It should be straightforward to humidify air injected through wells. If instead, the ground surface is the source of air, and air flow is induced by extraction wells, then it will be difficult or impossible to humidify the air entering the system from the surface. In this case, air induced to move laterally through the vadose zone from the surrounding area may have sufficient moisture. Moisture management will affect the design and operation of any bioventing scheme. The Biogeochemistry Workgroup mentions the effects of dessication (desiccation) of the vadose zone on bioremediation; the Panel suggests that it should be emphasized.

Vadose-zone sedimentary heterogeneity plays a very important role in the effectiveness of bioventing. If induced air does not contact portions of the vadose zone containing contaminants they will not be treated. Heterogeneity creates high permeability preferential flow paths and low permeability (especially stratified) barriers to air movement. Both of these lead to by-passing of contaminated zones reducing the effectiveness of bioventing. Bioventing also has difficulty accessing contamination that is sequestered in low permeability soils. Reactions occur in the higher permeability aerobic zone surrounding low permeability soils. The rate of treatment is then controlled by diffusion of hydrocarbon components within the low permeability soils to the surroundings. Depending on the mass of hydrocarbon sequestered, this limits short term effectiveness. The low permeability soils will also have a higher water content, further suppressing vapor phase diffusion.

The description should explicitly mention that bioventing does not treat LNAPL that has been entrapped (drowned) below the water table, and that it is also not a very effective treatment for LNAPL floating on top of the water table. In other words, operated by itself bioventing is a treatment for LNAPL, and dissolved, sorbed or vapor phase components, contained only within the vadose zone. However, used in combination with other methods (e.g., §2) it can be effective in remediating floating and drowned LNAPL.

This description emphasizes past work and infrastructure at KAFB in the BFF source area, and the extensive knowledge of the vadose zone and past SVE operations that has been gained through that work. This knowledge and existing infrastructure can both be leveraged in future remedial efforts. Although experience with SVE at the KAFB BFF site has included radius of influence testing, it is possible that some additional tests on soil vapor diffusion would be desirable. However, given the sedimentary heterogeneity in the vadose zone it is not clear that this would be useful. Both permeability and diffusion tests should examine a range of water contents.

3.3 Enhanced SVE Techniques

As with the other SVE technologies (3.1 and 3.2) it should be clear that this technology only achieves remediation of contaminants in the vadose zone above the top of the water table. Editorial suggestions are provided to emphasize that this a reasonable summary of effectiveness of enhanced SVE only as it applies to the vadose zone. It is not effective for the treatment of floating or drowned LNAPL or the dissolved contamination in the source area groundwater.

However, used in combination with other methods such as those described in Section 2 it can be effective in remediating floating and drowned LNAPL.

This description only addresses adding heat to SVE. They do not address many of the nuances and special conditions associated with steam injection. With heat and SVE the basic remediation mechanism is mass transfer of volatiles from LNAPL and water to the air phase, and removal from the vadose zone by producing the air. There are minor secondary NAPL mobilization effects due to temperature dependent fluid interfacial tensions, densities, and viscosities. With steam injection the phase behavior is much more complex as both water and NAPL are actually displaced. NAPL mobilization thus becomes more important. In other words, this technology includes displacement as well as enhanced mass transfer as a primary mechanism. The displacement mechanism is not discussed thoroughly in the spreadsheet.

The spreadsheet's evaluation of short-term effectiveness as "high" does not acknowledge the very important role of sedimentary heterogeneity which creates high permeability preferential flow paths and low permeability (especially stratified) barriers. Both lead to by-passing of contaminated zones and reduce the effectiveness of enhanced SVE. Contamination that is sequestered in low permeable soils may lead to a rebound effect upon the termination of SVE and decreases short-term SVE effectiveness. However, the use of heat in enhanced SVE should significantly increase the rate of diffusion within these fine-grained units and speed their remediation. This may be one of the principle benefits of enhanced SVE. Finally, the description contains an ambiguous statement that processes "benefiting from heat enhancement may take time to establish in the subsurface." It is followed by and appears to be setting up a description of heat transfer limitations. Language clarifying this limitation is suggested.

Assuming that dry heat is applied in enhanced SVE vadose-zone dessication becomes a more significant issue. If steam is used instead the description notes that moisture will be added to the vadose zone, changing water saturations and possibly increasing groundwater recharge. In the Panel Comments on bioventing above we note the need for a moisture management component to the remedial scheme. This discussion of enhanced SVE provides further evidence for the need to formally recognize and deal with moisture management of the vadose zone.

4.1 Solvents

The spreadsheet presents a good summary of solvent flooding which might be applied in the LNAPL zone at the KAFB BFF. The suggested 99% recovery needs some explanation. That is the kind of recovery one gets during a bench test of a homogeneous coarse sediments. Aquifer heterogeneity, depth to water table, and the size of the source area make this degree of recovery efficiency for LNAPL very unlikely.

The estimated time to accomplish remediation assumes that the conceptual site model accurately identifies the aquifer heterogeneity issue, and that it includes a good description of the spatial pattern of drowned LNAPL and dissolved contamination. Even in that case, however, there are issues not yet understood that could slow clean up. The rate of mass transfer from drowned LNAPL ganglia and pools depends on their size, shape, volume fraction and location, for which there is little characterization data. This NAPL geometry controls the interfacial area between water and NAPL phases, the efficiency of component diffusion toward the interface, and the flow rate of the water-solvent mixture adjacent to the interface, all influencing mass transfer. Larger pools and larger NAPL phase saturations have slower mass transfer rates no matter how much the solubility is increased by addition of a solvent. But larger NAPL pools and lower water saturations also create more tortuous and resistive water flow paths, making it more difficult to bring injected reactants into contact with dissolved components located next to NAPL-water interfaces, limiting dissolution and reducing mass transfer even more. Consequently, larger pools are more difficult to remediate, and will take longer. This factor emphasizes the need to understand the proportion of the LNAPL in the source area that is in larger pools, how large they are, and how they will respond to the solvent-based treatment technology?

One of the first activities is to identify the solvent or family of solvents to be used. Several candidate solvents could be included in the bench tests. The bench and pilot studies should include the geochemistry of solvent-sediment interaction, particularly the fine grained fraction. Design and operation would be assisted by coupling the flow and reactive transport computer model to an optimization scheme to find the best depths, locations and rates for injection/extraction. The design should recognize that the scheme should adapt to changing conditions as the water table continues to rise and as LNAPL mass is reduced.

The expectation that solvent extraction would require 150 to 500 wells concerns the Panel. While the size of the KAFB source area suggests a large number wells might be required, the significant depth to the water table (500 feet) suggests fewer. Perhaps with a high spatial-resolution description of aquifer heterogeneities, and a similar description of the spatial distribution of dissolved concentrations and LNAPL, a large number of wells could be used effectively to more quickly apply this approach. However, the uncertainty in this characterization, coupled with the difficulty in siting wells and their very high costs, suggest that a smaller number of wells might be feasible, perhaps a few tens of wells, despite the size of the source area. Using the conceptual site model and a validated groundwater flow and transport model, together with optimization techniques, an effective groundwater control (extraction and injection) scheme could be designed to best meet cost and human health/environmental constraints and/or goals with significantly fewer wells.

4.2 Surfactant/Cosolvent

The spreadsheet provides a good summary of surfactant flooding appropriate for the LNAPL zone at the KAFB BFF site, although it is missing an important but somewhat obvious point. Surfactant flooding remediates LNAPL mainly by increasing the solubility of LNAPL components. There is a secondary and important effect that can actually mobilize the LNAPL, in which the surfactant also reduces the interfacial tension between LNAPL and water, reducing capillary forces. The discussion in this section is focused on the solubility effect and not NAPL mobilization. The suggested 50-90% recovery of LNAPL needs some explanation, as well as the 99% recovery of more soluble components. That is the kind of recovery obtained in a laboratory bench test or small pilot project containing fairly homogeneous coarse sediments. Aquifer heterogeneity, the presence of fine-grained sediments, the significant depth to water table, and the size of the source area make recovery efficiencies for LNAPL and more soluble constituents unlikely at the KAFB BFF site. The Panel also suggests removing the broader reference to enhanced oil recovery (EOR) as irrelevant and distracting. Note that many of the listed remediation technologies in this spreadsheet have a similar petroleum recovery technologies (e.g., solvent flooding, stream flooding, and water flooding). (Aside: This spreadsheet should not be a review of EOR. In particular, a lot of EOR processes use (or must use) low salinity water, not brine, to achieve the desired chemistry. In fact "low salinity water flooding" (<5000 ppm) without added chemicals is a rapidly growing EOR method. Also, CO_2 flooding is only one EOR method; one that might work for KAFB's drowned LNAPLs if they were located 2000 feet below the water table in the CO_2 supercritical zone. The most common and productive EOR method has been alkaline flooding, according to Larry Lake of UT Austin).

The spreadsheet's assessment of remediation time assumes that the conceptual site model adequately addresses the aquifer heterogeneity issue, and that it includes a good description of the spatial pattern of drowned LNAPL and dissolved contamination. Even in that case, however, there are issues not yet understood that could slow clean up. The rate of mass transfer from drowned LNAPL ganglia and pools depends on their size, shape, volume fraction and location, for which there is little characterization data. This NAPL geometry determines the interfacial area between water and NAPL phases, the efficiency of component diffusion toward the interface, and the flow rate of the water-surfactant solution adjacent to the interface. These factors all influence mass transfer rates and the potential to mobilize NAPL through reduction of interfacial tensions (IFTs). Larger pools and larger NAPL phase saturations have slower mass transfer rates no matter how much the solubility is increased by addition of a solvent. But larger NAPL pools and lower water saturations also create more tortuous and resistive water flow paths, making it more difficult to bring injected reactants into contact with dissolved components located next to NAPL-water interfaces, limiting dissolution (and IFT reduction) and reducing mass transfer even more. Consequently, larger pools are more difficult to remediate, and will take longer. This factor emphasizes the need to understand the proportion of the LNAPL in the source area that is in larger pools, how large they are, and how they will respond to the solvent-based treatment technology?

In order to further evaluate this technology one of the first activities should be to identify the surfactant(s) to be used. Several candidate surfactants could be evaluated in the bench tests. The bench and pilot studies should include the geochemistry of surfactant-sediment interaction, particularly for the fine grained fraction. Design and operation would be assisted by coupling the flow and reactive transport computer model to an optimization scheme to find the best depths, locations and rates for injection/extraction. The design should recognize that the scheme could adapt to changing conditions as the water table continues to rise and as LNAPL mass is reduced.

The expectation that solvent extraction would require 150 to 500 wells concerns the Panel. While the size of the KAFB source area suggests a large number wells might be required, the significant depth to the water table (500 feet) suggests fewer. Perhaps with a high spatial-resolution description of aquifer heterogeneities, and a similar description of the spatial distribution of dissolved concentrations and LNAPL, a large number of wells could be used effectively to more quickly apply this approach. However, the uncertainty in this characterization, coupled with the difficulty in siting wells and their very high costs, suggest that a smaller number of wells might be feasible, perhaps a few tens of wells, despite the size of the source area. Using the conceptual site model and a validated groundwater flow and transport model, together with optimization techniques, an effective groundwater control (extraction and injection) scheme could be designed to best meet cost and human health/environmental constraints and/or goals with significantly fewer wells.

4.3 Water

The spreadsheet provides a succinct but somewhat vague description of the effect of groundwater flow passing through the KAFB BFF source zone, dissolving the more soluble components (including EDB) from the drowned LNAPL, transporting that dissolved phase contamination downgradient where it is presumably removed and treated ("recirculation," "extraction," etc). The description places emphasis on reducing the time to displace a pore volume within the source zone with the likely reasonable assumption that mass transfer is limited only by the groundwater flow rate. This section also talks about additives ("reinjection-with-substrate(s) added"), but few details are provided. Sections 4.1 and 4.2 focus specifically on two types of additives, solvents and surfactants. Both of those additives increase the solubility of LNAPL components, with a less important impact on LNAPL interfacial tension with water, increasing the propensity to mobilize some of the NAPL.

The description of the potential to attain cleanup standards/goals is a bit vague. Is the "dilute plume" the down gradient plume or is it the dissolved plume in the source area itself? Assuming the latter, then as long as the LNAPL remains so will the source area dissolved plume. It is claimed that the potential to meet this goal is better for the dissolved plume than for LNAPL, but this assumes that the more soluble components will be depleted from the LNAPL to the point where aquifer dissolved concentrations are significantly reduced even though LNAPL remains. Is there a mass balance calculation to support this assumption? Finally, the term "dilute" is itself vague and should probably be replaced by "dissolved." From an aqueous property point-of-view all constituents in groundwater at this site are dilute even though some of them may exceed groundwater standards. The term dilute may be misleading when the focus is on human health and the environment. Finally, the Panel presumes that the emphasis on a "high resolution CSM (conceptual site model)" refers, among other things, to a strong grasp of sedimentary architecture and heterogeneity, and to the spatial distribution of drowned LNAPL. In any event, for each section of this spreadsheet the term should be redefined with emphasis on aspects of the CSM of special concern to the remedy being assessed. This further emphasizes the point that subsurface heterogeneity is an issue for all of the proposed methods.

The Panel recognizes that pilot studies make sense but what is a "bench study" for the injection and extraction of water? Does this term refer to "additives"? Why is this approach "difficult" to implement? The depth? The limited information to form a high resolution CSM? The technology itself is not the limitation.

The expectation that solvent extraction would require 150 to 500 wells concerns the Panel. While the size of the KAFB source area suggests a large number wells might be required, the significant depth to the water table (500 feet) suggests fewer. Perhaps with a high spatial-resolution description of aquifer heterogeneities, and a similar description of the spatial distribution of dissolved concentrations and LNAPL, a large number of wells could be used effectively to more quickly apply this approach. However, the uncertainty in this characterization, coupled with the difficulty in siting wells and their very high costs, suggest that a smaller number of wells might be feasible, perhaps a few tens of wells, despite the size of the source area. Using the conceptual site model and a validated groundwater flow and transport model, together with optimization techniques, an effective groundwater control (extraction and injection) scheme could be designed to best meet cost and human health/environmental constraints and/or goals with significantly fewer wells.

The description of the technology suggests a need for a second set of wells "To flush the LNAPL." It is not clear what this means. The LNAPL is not expected to migrate as it cannot be mobilized by water alone, although an additive that reduces interfacial tensions could mobilize it (see for example Section 4.2). The groundwater will flow through the drowned LNAPL zone. No additional wells are needed to deal with the LNAPL unless additives are used to mobilize it. Finally, infrastructure requirements/constraints need to include all of the surface plumbing and treatment systems needed for this approach.

Additional Considerations

The Panel is aware of and fully recognizes the complexities associated with conducting remediation of contamination in the LNAPL zone at the KAFB BFF site. It is also apparent that these are recognized by the members of the Biogeochemistry Workgroup. In performing this review the Panel has identified three factors that introduce special complexity beyond that found at most other sites, including those of similar depth. The Panel believes that these factors should be specifically considered as the Biogeochemstry Workgroup continues its evaluation of remediation measures.

<u>Rising Water Table and Trapped LNAPL:</u> The rapidly rising water table at this site exacerbates the remediation difficulties in a couple of important ways that should be explicitly recognized. First, it greatly complicates quantification of the source term. The trapped free product (i.e. phase separated liquid) creates a 4 phase source zone LNAPL architecture consisting of trapped air, water, free product, and soil particles. This results in a very complicated partitioning problem that is dynamic and cannot be addressed by simple equilibrium partitioning calculations such as use of distribution coefficients usually represented as K_d. Potential dissolution and/or mobilization of contaminants such as dissolution of EDB and hydrocarbons from trapped LNAPL as remediation proceeds should be considered in evaluating and selecting technologies for interim and final remediation.

<u>Challenge of Characterizing the LNAPL Zone:</u> Further complexity is introduced by the sedimentary heterogeneity, the long period over which the leak occurred, and the fact that three different fuels were released, avgas, JP4 and JP8. Each migrates at a different rate and each weathers by different mechanisms and at different rates through the complex sedimentary architecture of both the vadose zone and aquifer. This "heterogeneity" of both sediments and contaminant distribution challenges characterization and remediation. For example, a successful remedial measure in one portion of the LNAPL zone may not work in another, while a successful treatment at one location may need to shift to another treatment technology as remediation proceeds.

The contamination heterogeneity suggests that technologies be divided into two groups: 1) those that are largely indifferent to the details of composition and 2) those that are a highly sensitive to those details. The former would be more “robust” in their application, although perhaps not as effective as a measure fine tuned to the specific subsurface biogeochemical environment at a location within the source area, if indeed that could be known.

The Panel is aware of the urgency with which remediation activities must implemented and is not recommending that further site characterization studies need be conducted before proceeding to interim measures. Rather, it is recommending that as remediation technologies are considered for application, the ability to modify them as new information is generated on subsurface complexity be included in the evaluation criteria, and that as remediation proceeds characterization activities be woven into observations of remedial progress.

<u>Need for Metrics to Assess Performance:</u> The spreadsheet prepared by the Workgroup provides a cursory summary of each of the treatment technologies which is appropriate for a preliminary scoping of possible remediation methods. The Panel suggests that an additional criteria be considered; identification of metrics that can be used to measure the performance of the process. The simplest method of measuring performance is to collect samples and measure the disappearance or appearance of specific constituents which might include regulated contaminants, indications of redox transformations such as reduced iron or sulfur compounds, or evidence of microbial growth. Indirect indicators of performance might also be feasible such as installing downhole sensors in selected wells to measure electrochemical parameters such as Eh, pH, or concentration of specific ions.

Metrics suggested below refer to total mass of hydrocarbons, the specific contaminants of concern, (e.g., NAPL, BTEX, EDB), and for flux/concentration some related indicator variables of reactions (such as alkalinity and various reactants) as appropriate:

- Groundwater flow rates through the source area (relevant for mass transfer processes) and how it is changing over time.
- Spatial patterns of dissolved phase constituents in the plume area and their changes over time.
- Mass removed and rate of removal from the source area.
- Dissolved phase mass flux leaving the source area in groundwater and how it is changing over time.
- Vapor phase mass flux between the aquifer and vadose zone, or that leaving the source area (to the surface or laterally within the vadose zone) and how it is changing with time.

Note that the last three bullets constitute the basic elements of a mass balance. The degree to which the mass balance doesn’t close is an indication of uncertainty and/or of a missing process.

In addition to identifying measures of process performance, it will be important to establish how these measures will be used to optimize remedial design and operation, and to quantify remediation performance. This information can then be used to modify remediation activities to improve performance and also can be incorporated in contaminant fate and transport models to assist in understanding and communicating the future behavior of the downgradient contaminant plume.

Geohydrologic Considerations: All of the technologies rely on the ability to circulate fluids including air, water, slurries, and solvents through the saturated and unsaturated soils at the KAFB BFF site. Little consideration has been given in the spreadsheet to possible factors which might limit this ability. Two examples have been brought to the attention of the Panel. First, approximately 10 years of conducting soil vapor extraction at the site has resulted in drying of the vadose zone. This has had the beneficial effect of removing a large amount of volatile hydrocarbons from the soil. In addition drying of the soil also creates a "dry barrier" to flow of water or other liquids as unsaturated hydraulic conductivities decrease by many orders of magnitude as a soil dries. However, drying the soil may also diminish microbial degradation because the organisms cannot grow in a very dry environment which may result in slower removal of less volatile but degradable constituents. The relative merits of continued SVE should be considered in light of these competing consequences.

A second consideration is the relatively shallow extent of the contaminants below the top of the water table; nearly the entire dissolved EDB plume is less than 40 ft below the top of the water table. Injection and extraction wells used in the remediation process must therefore have short screen lengths in order to limit their influence to the contaminated zone in the aquifer, while at the same time recognizing that the optimal depth for a screen may change as the water table continues to rise. The short screen length limits the pumping rates for these wells and therefore each well's radius of influence. Thus, a large number of wells with short screen lengths will be needed in order to circulate fluids through this zone. The Panel received information that the cost of monitoring wells at this site range from $200K to $500K. It is likely that injection/extraction wells will cost at least as much and will have additional costs associated with pumps and the infrastructure at the surface such as power supplies, blowers, piping and residuals treatment. The number and cost of injection/extraction wells for each remediation technology should be factor in evaluating remediation technologies.

Reducing contaminant concentrations in the dissolved phase through biological or chemical reaction may increase the dissolution of LNAPL components, for those constituents where the mass transfer rate depends on solution composition. But below the water table the mass transfer rate is also controlled by the shape, size, and volume fraction of LNAPL ganglia and entrained pools of hydrocarbons. This LNAPL geometry controls the interfacial area between water and LNAPL phases, the efficiency of component diffusion toward the interface, and the flow rate of water adjacent to the interface, all influencing mass transfer. Larger pools and larger LNAPL concentrations in soil have slower mass transfer rates no matter how effective the reaction. Furthermore, larger LNAPL pools and consequent lower water content also provide more tortuous and resistive water flow paths, making it more difficult to bring reactants into contact with dissolved constituents next to LNAPL-water interfaces, limiting reactions where they are important and further reducing mass transfer.

Injection & Extraction Methods: Virtually all of the remediation methods identified in the spreadsheet rely upon the ability to circulate fluids through the subsurface environment. Based on work reviewed by the Panel it appears that the Workgroup has only considered use of vertical injection and extraction wells to achieve this circulation. There are several notable problems with vertical wells at the KAFB BFF site. These include:

- The depth to groundwater means that all wells are deep and expensive. Specifically, most groundwater remediation wells require drilling through ~500 ft of uncontaminated vadose zone to place a short screen near the top of the water table.
- The contaminant plume is almost entirely within 50 ft of the top of the water table, hence each well will have a very short screen length which limits the flow rate of injection and extraction wells.
- Limited pumping rates result in limited radius of influence thus requiring installation of many wells. Furthermore, large drawdowns may be undesirable at this site in order to prevent downward contaminant migration.
- The strata is highly heterogeneous and stratified with thin clay stringers and gravel deposits that create preferential horizontal flow paths and limit vertical flow, thereby impacting the ability to achieve groundwater gradient control.
- Due to the length of the plume, many of the remediation wells will likely have to be constructed beyond the KAFB boundary which introduces problems associated with off-site surface impacts.

The Panel recommends that the Workgroup carefully consider the methods for circulating fluids to support the various remediation alternatives. In particular the Panel suggests that horizontal wells be considered at this site as this technology offers many important advantages over vertical wells with short screen lengths. The depth, plume length, and formation characteristics do not appear to offer any challenges to conventional horizontal well drilling methods. Some of the advantages of horizontal wells over vertical wells include:

- Far fewer wells would be required than for vertical wells with short screens. Each horizontal well would access a much larger portion of the contaminated area than would a vertical well, covering an area that would require many vertical wells, while drilling down through the vadose zone only once.
- All drilling activities can be done on KAFB property with little or no off site surface impacts, and all surface infrastructure can be located on Base property thereby minimizing impact on neighbors and enhancing security of equipment.
- Horizontal wells are a better method of introducing gases (air, propane, etc.) to a subsurface formation as gases percolate up through formation from the horizontal screen rather than through preferential channels immediately adjacent to a vertical well. Injected gases will still travel up through preferred channels from a horizontal well, however, these channels will be distributed along the length of the screen.
- By using well packers different regions of the contaminated zone can receive different fluids, so for example anaerobic degradation could be implemented in one zone and an aerobic technology could be used in another, all accessed from the same horizontal well.

One issue with horizontal well design may be the impact of the rising water table. This may be important if horizontal wells are intended to capture liquids as in a solvent or surfactant remediation scheme. In this case the wells should be located within the contaminated zone which is expected to rise over the course of site remediation. However, if the horizontal wells are installed to introduce gases such as air or propane for a sparging or biostimulation process the depth of a horizontal well is less critical as it simply needs to be beneath the contaminated zone.

Conclusions

The Independent Technical Review Panel found that the summary of technologies described by the multi-agency Biogeochemistry Workgroup to address contaminants in the LNAPL zone at the KAFB BFF site was generally accurate and complete. The Panel focused its attention on identification of technologies to address contaminants in the LNAPL zone at the KAFB BFF site. Based on its review, the Panel did not identify any remediation technologies that were overlooked by the Workgroup.

The amount of information and level of detail in the descriptions varied among the technologies which likely reflects both the different levels of maturity of the technologies and the makeup of the Workgroup. The presentation would be strengthened if it included recent key references related to the application of each technology in similar situations.

The spreadsheet format was found to be limiting due to the descriptive rather than quantitative nature of most of information in it. This limitation will increase as new information related to the site and to each technology is entered. Subsequent evaluations would be facilitated if the information could be transferred to a Word file.

There was concern that the description of most technologies did not identify whether they were applicable to dissolved EDB, dissolved hydrocarbons, submerged LNAPL, or vadose zone contaminants. The Workgroup's analysis should specifically identify which contaminants are amenable to remediation by each technology to address this oversight.

Finally, the Panel noted that each technology is identified and described solely based on its capabilities as a stand-alone technology. It is likely that multiple remediation technologies will eventually be utilized at the KAFB BFF site. The description of each technology should therefore include discussion of its compatibility with other technologies.

Five additional topics merit consideration in order evaluate candidate remediation technologies for interim application. These are:

- Rapidly rising water table which will trap vadose zone NAPL and complicate the quantitation of EDB, hydrocarbons, and other constituents.
- The challenge of characterizing the LNAPL zone to maximize the understanding of the geochemical and hydrogeological behavior of the contaminants and the source term.
- Identifying metrics to measure the effectiveness of selected remediation methods for field scale pilot testing, interim remediation activities, and for final remediation.
- Improved understanding of the geohydrological complexities at the site. Of particular concern is how heterogeneities in the subsurface environment will affect the performance of candidate remediation technologies.
- Virtually all of the remediation methods considered for the LNAPL zone require circulating fluids through the subsurface environment. The ability to inject and/or extract

fluids at this site is challenging. Horizontal wells may offer advantages over traditional vertical injection/extraction wells that have been used to date.

References

Interstate Technology & Regulatory Council (ITRC) (2014). Petroleum Vapor Intrusion Fundamentals of Screening, Investigation, and Management, prepared by the ITRC Petroleum Vapor Intrusion Team, Washington, D.C., 388 p.

Interstate Technology & Regulatory Council (ITRC) (2009). Evaluating Natural Source Zone Depletion at Sites with LNAPL, prepared by the ITRC LNAPLs Team, Washington, D.C., 76 p.

Interstate Technology & Regulatory Council (ITRC) (2009). Evaluating LNAPL Remedial Technologies for Achieving Project Goals, prepared by the ITRC LNAPLs Team, Washington, D.C., 157 p.

McCray, J.E., Tick, G.r., Jawitz, J.W., Gierke, J.S., Brusseau, M.L., Falta, R.W., Knox, R.C., Sabatini, D.A., Annable, M.D., Harwell, J.H., Wood, A.L. (2011). Remediation of NAPL Source Zones: Lessons learned from Field Studies at Hill and Dover AFB, Ground Water, 49(5), 727–744, U.S. Environmental Protection Agency Papers. Paper 89. http://digitalcommons.unl.edu/usepapapers/89

National Research Council (NRC) (2005). Contaminants in the Subsurface: Source Zone Assessment and Remediation, National Academies Press, Washington, D.C., 371 p. (http://www.nap.edu/catalog/11146.html)

Wilson, J.T., Banks, K., Earle, R.C., He, Y., Kuder, T., Adair, C. (2009). Natural Attenuation of the Lead Scavengers 1,2-Dibromoethane (EDB) and 1,2 Dichloroethate (1,2-DCA) at Motor Fuel Release Sites and Implication for Risk Management, EPA 600/R-08/107USEPA Office of Research and Development, National Risk Management Research Laboratory, Ada, OK, 74 p.

Appendix 1 – Technologies Considered for Implementation

In this appendix the descriptions of each technology and its attributes contained in the spreadsheet prepared by the Biogeochemistry Workgroup have been converted into MSWord format. This was done to aid in interpreting and understanding the material by the Panel as well as to facilitate adding comments and where appropriate, making editorial suggestions. Additions, comments and editorial suggestions offered by the Panel are denoted by text with a colored background.

Source Area Interim Treatment Technology Options

1.1 Biostimulation options (Aerobic) (Bruce Alleman, Adria Bodour, Paul Hatzinger, and Rob Steffan)

Panel comments and suggestions are denoted by text with a colored background.

Description of technology being evaluated - How will the technology be used?

For the purposes of this evaluation, aerobic biostimulation includes remediation approaches that entail the use of liquid or solid reagents to supply oxygen to anoxic/anaerobic groundwater to stimulate fuel hydrocarbon degradation activity of indigenous microorganisms. The technology can be implemented in an inject only, or in a recirculation configuration. Injection only mode relies on the injected volume, groundwater flow driven advection, and dispersion to distribute reagents. Recirculation systems can often afford more control of reagent distribution. Note: sparging technologies, which also are designed to stimulate aerobic biodegradation, are discussed below and are not included under the aerobic biostimulation remedies in this technology grouping. Aerobic cometabolism may be a natural outcome of aerobic biostimulation; however, aerobic cometabolism as a specific engineered approach is discussed below.

Protective of human health and environment (Yes/No/Uncertain) - Additional info may be needed to qualify answer, specify if LUCs are required

Yes.

Aerobic biodegradation of fuel hydrocarbons via ""direct"" metabolism is well understood. Cometabolism of EDB could be stimulated if suitable primary substrates are present. Biodegradation of EDB may be limited, however, presence of toluene or other primary substrate may promote cometabolism.

Potential to attain of cleanup standards/goals within reasonable timeframe (<50 years) (High/Medium/Low)

"High.

Attainment of cleanup standards is dependent on effective aquifer conditioning to aerobic conditions and the ability to effectively and efficiently maintain those conditions. Final determination depends on additional characterization of LNAPL present in the subsurface (e.g., shutdown testing and coring in source area)."

Control releases to reduce or eliminate further releases of hazardous constituents

The technology would minimize volatilization of EDB compared to sparging.

Comply with standards for waste management (Yes/No)

Long term reliability and effectiveness (High/Medium/Low) - Include technology maturity

High.
Aerobic biostimulation represents a mature technology that has been effectively applied at a large number of fuel hydrocarbon sites. Key is that there are primary substrates available for EDB. This is highly effective for fuel and uncertain for EDB.

Panel Comment: The statement that there are primary substrates available to support microbial EDB biodegradation requires explanation. Examples of such substrates present in the LNAPL zone at KAFB should be included.

Reduction of toxicity, mobility, mass, or volume (Yes/No/Uncertain) - Phase specific and should specify what is being reduced

Yes.
The lighter and hence more mobile fraction of the fuel hydrocarbons and the carcinogenic PAHs represent the majority of the toxicity associated with the BFF fuels and are aerobically biodegradable. As the lighter fractions are degraded, the residual hydrocarbon becomes composed of the fuel constituents with lower aqueous solubility due to their higher molecular weight. Aerobic biodegradation will reduce contaminant mass and subsequently, the volume of the residual LNAPL and the associated dissolved-phase plume. Reduction of toxicity and contaminant properties of EDB is uncertain.

Short-Term Effectiveness (High/Medium/Low/Not effective) - Phase specific, requires specification

Medium.
The effectiveness of aerobic biostimulation could be mass transfer limited as biodegradable fuel hydrocarbons must diffuse from the LNAPL to the aqueous phase. Aquifer lithology and hydraulic properties are limiting factors in short-term effectiveness. Short-term effectiveness for EDB is uncertain.

Implementability (Difficult/ Moderate/Easy/Not applicable)

Moderate.
Implementing this technology option requires the ability to effectively deliver and distribute remedial reagents (i.e., an oxygen source and, if necessary, nutrients) throughout the aquifer volume targeted for treatment. Converting an anaerobic environment in and adjacent to the LNAPL zone to aerobic conditions is frequently (almost always) plagued by problems associated with changes in geochemistry and reactive-phase mineralogy. Introduction of an oxygen source frequently results in biofouling of injection well screens and the packing and formation around the screened interval. The challenges can be controlled to an extent and wells can usually be rehabilitated, but fouling issues at the BFF may prove to be prohibitive, given the depth and the number of injection wells that might be required. Strategically targeted volumes of aquifer could be the more suitable application for aerobic biostimulation.

Cost - Capital & O&M (High/Medium/Low) - 1 (>$500M), 2 ($350 - $500M), 3 ($200 - $350M), 4 ($50 - $200M), and 5 (<$50M)

Medium.
The cost for implementing this technology will be driven by the number of injection wells required to effectively distribute remedial reagents throughout the targeted aquifer volume. The number of wells, as well as the need for recirculation, would dictate the requirements for pumps and above-ground equipment and infrastructure. Chemical costs could be substantial. Cost of treatment of water generated during aquifer testing in the source area could be substantial depending on volume of water generated.

Schedule to Implement (Long/Medium/Short/Not applicable) - Long (>10 yrs.), Medium (5-10 yrs.), and Short (<5 yrs.)

Short???
Aerobic biostimulation is straight forward and should not require any laboratory microcosm testing. Aquifer test data would be needed for designing and placing injection wells and extraction wells, if recirculation is required. Logistics and permitting of aquifer testing and treatment/disposal of wastewater generated during testing could impact schedule. Additional impact to schedule with the timeline of submittal and approval of Remediation Action Plan for the treatment of Hazardous Waste.

Infrastructure Requirements and Constraints (List of infrastructure required)

Injection Only Requirements:
A set of injection wells drilled into the targeted aquifer volume (i.e., contaminant distribution and aquifer properties) would dictate the number and placement of injection wells. Above ground infrastructure would include a building to house equipment; reagent chemicals; sampling and PPE supplies; electrical and potable water service; chemical metering pumps, chemical storage and mixing tanks; a chemical staging area; and, system and building security systems

With Recirculation:
All of the above plus: extraction wells; well pumps; water conveyance piping and associated equipment; extracted and reinjected water-quality monitoring systems; and, a leak detection system.

Waste Management (List waste streams to be managed)

Waste management during installation

- Drill cuttings and waste fluids pending installation of additional injection wells
- Waste chemical containers
- Used PPE
- Wastewater generated during aquifer testing

Waste management during operations:

- Waste chemical containers
- Used PPE
- Waste associated with rehab of fouled recirculation wells"

Permit Requirements (Low/Med/High) (e.g., OSE, NMED, EPA, AEHD, rights of entry agreements) Medium?

- May require a UIC permit
- Recirculation may require additional permits for reinjection of amended water with residual contamination remaining in solution. See B4
- Groundwater discharge permit
- Remediation Action Plan
- OSE permits (drilling of well and use for remediation.)"

Potential Stakeholder Objections

Comments (include references as applicable)

Aerobic biodegradation of the fuel hydrocarbons is likely occurring on the periphery of the LNAPL source area and in the capillary fringe where contaminants encounter groundwater with sufficient dissolved oxygen concentrations (> 1 mg/L). While this is promising from a plume control standpoint, those areas would not benefit from additional oxygenation. Other areas where the aquifer is experiencing nitrate reducing conditions may be candidates, as these areas would benefit from the added oxygen and the injection wells may not suffer the same level of changing geochemical-mineralogical condition fouling potential that the highly reduced portions of the aquifer might experience. Upgradient portions of the plume undergoing nitrate reduction would be better than downgradient portions that can carry elevated dissolved iron, total carbonate alkalinity, and other potential fouling chemicals.

Bibliography

References should be included for guidance documents and recent documented successful applications with emphasis on large NAPL source zones. Below are some general links.

http://clu-in.org/techfocus/default.focus/sec/Bioremediation/cat/Overview/
http://www.epa.gov/oust/pubs/tum_ch12.pdf

Danko, A. S., Leitão, P. O., Verce, M. F., & Freedman, D. L. (2012). Efficacy of pentane, toluene, and benzene to support aerobic cometabolism of ethylene dibromide. New biotechnology, 30(1), 39-43.

McKeever, R., Sheppard, D., Nüsslein, K., Baek, K. H., Rieber, K., Ergas, S. J., ... & Park, C. (2012). Biodegradation of ethylene dibromide (1, 2-Dibromoethane [EDB]) in microcosms simulating in-situ and biostimulated conditions. J. of hazardous materials, 209, 92-98.

Source Area Interim Treatment Technology Options

1.2 Biostimulation options (Anaerobic) (Bruce Alleman, Adria Bodour, Paul Hatzinger, and Rob Steffan)

Panel comments and suggestions are denoted by text with a colored background.

Description of technology being evaluated - How will the technology be used?

Anaerobic biostimulation entails the delivery and distribution of remedial reagents into the portion of aquifer targeted for treatment. For fuel constituents, inorganic reagents such as nitrate or sulfate can be added to serve as an alternative electron acceptor to oxygen, and essential nutrients and buffer, if needed, also can be injected. For EDB, fermentable substrates, which could include any of a number organic compounds, as well as hydrogen gas, can be added to condition the aquifer redox and to serve as an electron donor source to promote reductive debromination. Essential nutrients and buffers, if needed, also can be used to condition the aquifer (both redox and pH adjustment/buffering are sometimes required). When indigenous microorganisms capable of carrying out the required degradation pathway(s) are not present in sufficient numbers, bioaugmentation may be employed to introduce microbial cultures with the requisite degradation capabilities. Bioaugmentation is not considered under this treatment technology option but is discussed separately below.

Anaerobic biostimulation can be implemented in an injectant(s) only, or in a recirculation configuration. Injection only mode relies the injected volume, groundwater flow driven advection, and dispersion to distribute reagents. Recirculation systems can often afford more control of reagent distribution."

Protective of human health and environment (Yes/No/Uncertain) - Additional info may be needed to qualify answer, specify if LUCs are required

Yes.

While anaerobic biodegradation is known to occur, degradation rates are usually lower than the rates achieved under aerobic conditions. The approach, however, can still be protective as the lighter fraction of the fuels (i.e., BTEX compounds) represent the largest contributor to human health and environmental risks and the degradation rates for those compounds are the highest among the fuel hydrocarbon constituents. Anaerobic biotic reductive debromination of EDB also is well understood and under optimal conditions can result in the complete debromination of EDB to form ethene and bromide.

Panel Comment: In addition, the description should note that EDB can be cometabolized under methanogenic conditions.

Potential to attain of cleanup standards/goals within reasonable timeframe (<50 years) (High/Medium/Low)

Medium.

While degradation rates under anaerobic biostimulation should easily achieve the cleanup goals within 50 years, these technologies require effective delivery and distribution of the reagents, achieving and sustaining suitable subsurface conditions, and effective contact between the microorganism, the electron acceptors/donors, and the contaminant. The rates of dissolution of targeted fuel constituents, as well as EDB, will strongly influence the rate at which the cleanup goal will be attained.

Control releases to reduce or eliminate further releases of hazardous constituents

Comply with standards for waste management (Yes/No)

Long term reliability and effectiveness (High/Medium/Low) - Include technology maturity

High.

Engineered anaerobic biostimulation has matured substantially over the past several decades and different approaches of the technology have been employed at many sites. Most of the attention has focused on chlorinated solvents, but case histories with other chlorinated organics have been and are continuing to be reported. The advances made through numerous laboratory and field demonstration/pilot studies have developed the technology into one of the most frequently applied approaches for chlorinated organics and has sprung an entire industry of companies offering products and services for effective implementation. Anaerobic biostimulation for petroleum hydrocarbons has been studied for many years; however, field implementations of the technology are limited owing to the effectiveness of the aerobic approaches. That said, anaerobic fuel hydrocarbon degradation does occur at spill sites and engineered approaches have proven effective.

Reduction of toxicity, mobility, mass, or volume (Yes/No/Uncertain) - Phase specific and should specify what is being reduced

Conditional Yes.

Under optimal conditions, anaerobic biostimulation should reduce the toxicity, mobility, mass, and volume of contaminant. A potential concern is the possibility of incomplete reductive debromination of EDB to form ethylene bromide. A similar concern accompanies reductive dechlorination of the chlorinated solvents, which can result in vinyl chloride production. Substantial work has been done to minimize this potential and to address the challenge, if and when it arises. Overall, engineered solutions are available to ensure complete debromination is achieved (see the Bioaugmentation options below).

Short-Term Effectiveness (High/Medium/Low/Not effective) - Phase specific, requires specification

Medium.

The effectiveness of anaerobic biostimulation is a function of the reagent delivery effectiveness, the ability to control and sustain conducive aquifer conditions, and the overall short-term effectiveness could be mass transfer limited as anaerobically biodegradable fuel hydrocarbons and EDB must diffuse from the LNAPL to the aqueous phase.

Implementability (Difficult/ Moderate/Easy/Not applicable)

Moderate.

This technology option requires the ability to effectively deliver and distribute remedial reagents (i.e., substrates/electron donor(s) and nutrients and buffers, if necessary) throughout the aquifer volume targeted for treatment. Implementing the technology in already anaerobic zones in the aquifer would be easiest. Implementing the technology in aerobic portions of the site could be more challenging as the redox would need to be lowered, which could require substantial effort depending on the geochemistry, the mineralogy and the groundwater flow dynamics, and the microbial population may not be present in sufficient numbers.

Introduction of substrates (and nutrients, if needed) frequently result in biofouling of injection well screens and the packing and formation around the screened interval. The challenges can be controlled to an extent and wells can usually be rehabilitated, but fouling issues at the BFF may prove to be prohibitive given the depth and the number of injection wells that might be required. The loss of an injection well to fouling would represent a substantial cost impact. Strategically targeted portions of the aquifer that are already anaerobic, but that may be substrate/electron donor limited, would benefit from engineered anaerobic biostimulation and such areas could be the more suitable for implementation of this technology.

Cost - Capital & O&M (High/Medium/Low) - 1 (>$500M), 2 ($350 - $500M), 3 ($200 - $350M), 4 ($50 - $200M), and 5 (<$50M)

Medium. ($50M to $350M)

The cost for implementing this technology will be driven by the number of injection wells required to effectively distribute remedial reagents throughout the targeted aquifer volume. The number of wells, as well as the need for recirculation, would dictate the requirements for pumps and above-ground equipment and infrastructure. Chemical costs could be substantial.

Schedule to Implement (Long/Medium/Short/Not applicable) - Long (>10 yrs.), Medium (5-10 yrs.), and Short (<5 yrs.)

Short. (<5 yrs)

Anaerobic biostimulation is straight forward but frequently requires laboratory microcosm and or field treatability testing. Laboratory microcosm studies are underway that could provide a proof-of-concept for anaerobic biostimulation in the BFF source area. Aquifer performance test data would be needed for designing and placing injection wells and extraction wells, if recirculation is required.

Panel Comment: Additional microcosm studies will be required to identify potential limitations and possible bottlenecks to EDB removal and to rigorously establish degradation mechanisms, end products, and mass balances.

Infrastructure Requirements and Constraints (List of infrastructure required)

Injection Only Requirements:

A set of injection wells drilled into the targeted aquifer volume (i.e., contaminant distribution and aquifer properties would dictate the number and placement of injection wells). Above ground infrastructure would include a building to house equipment; reagent chemicals; Sampling and PPE supplies; electrical and potable water service; chemical metering pumps, chemical storage and mixing tanks; a chemical staging area; and, system and building security systems.

With Recirculation:

All of the above plus: extraction wells; well pumps; water conveyance piping and associated equipment; extracted and reinjected water-quality monitoring systems; and, a leak detection system.

Waste Management (List waste streams to be managed)

- Drill cuttings and waste fluids pending installation of additional injection wells
- Waste chemical containers
- Used PPE

Permit Requirements (Low/Med/High) (e.g., OSE, NMED, EPA, AEHD, rights of entry agreements)

- May require an UIC permit.
- Recirculation may require additional permits to allow for reinjection of amended water with contaminants remaining in solution. See response in O4.

Potential Stakeholder Objections

Comments (include references as applicable)

Bibliography

Suggested references are primarily laboratory work. Consider including guidelines, protocols and reviews about field work from EPA, SERDP and others.

Baek, K., McKeever, R., Rieber, K., Sheppard, D., Park, C., Ergas, S. J., & Nüsslein, K. (2012). Molecular approach to evaluate biostimulation of 1, 2-dibromoethane in contaminated groundwater. Bioresource technology, 123, 207-213.

Henderson, J. K., Freedman, D. L., Falta, R. W., Kuder, T., & Wilson, J. T. (2007). Anaerobic biodegradation of ethylene dibromide and 1, 2-dichloroethane in the presence of fuel hydrocarbons. Environ. Sci. & Tech., 42(3), 864-870.

Stroo, H. F., & Ward, C. H. (Eds.). (2010). In-situ remediation of chlorinated solvent plumes. Springer Science & Business Media.

Yu, R., Peethambaram, H. S., Falta, R. W., Verce, M. F., Henderson, J. K., Bagwell, C. E., & Freedman, D. L. (2013). Kinetics of 1, 2-dichloroethane and 1, 2-dibromoethane biodegradation in anaerobic enrichment cultures. Applied and environmental microbiology, 79(4), 1359-1367.

Source Area Interim Treatment Technology Options

1.3 Bioaugmentation options (Bruce Alleman, Adria Bodour, Paul Hatzinger, and Rob Steffan)
Panel comments and suggestions are denoted by text with a colored background.

Description of technology being evaluated - How will the technology be used?

Bioaugmentation entails the addition of exogenous microorganism to sites where naturally occurring microbial populations are not present or are present at such low numbers and limited distribution that the remedial timeframe would benefit from the ""kick start"" of degradation capacity. Laboratory enrichment of indigenous microbial populations has been used as a form of bioaugmentation; however, the vast majority of the implementations have involved the injection of commercially available cultures that have been developed and are maintained by a select number of product vendors.

Bioaugmentation most frequently entails biostimulation such as the Treatment Technology Options described above. Bioaugmentation also can be coupled with the sparging options discussed below. In the case of the BFF, bioaugmentation might be possible without biostimulation, if there is sufficient substrate/electron donor available from the residual fuel and the geochemical conditions in the source area aquifer are conducive to survival and activity of the added microbial culture(s).

Protective of human health and environment (Yes/No/Uncertain) - Additional info may be needed to qualify answer, specify if LUCs are required

Yes.
This technology option is protective of human health and the environment and is similar to the biostimulation technologies described above, with bioaugmentation providing an added level of protectiveness. Bioaugmentation would be specific to EDB reduction under anaerobic conditions.

Potential to attain of cleanup standards/goals within reasonable timeframe (<50 years) (High/Medium/Low)

Medium.
While stimulated degradation rates and the bioaugmentation bonus should easily achieve the cleanup goals within 50 years, these technologies require effective delivery and distribution of the reagents, achieving and sustaining suitable subsurface conditions, and effective contact between the microorganisms, the electron acceptors/donors, and the contaminant. The rates of dissolution of targeted fuel constituents, as well as EDB, will strongly influence the rate at which the cleanup goal will be attained.

Control releases to reduce or eliminate further releases of hazardous constituents

Comply with standards for waste management (Yes/No)

Long term reliability and effectiveness (High/Medium/Low) - Include technology maturity

Medium.

Bioaugmentation has been employed at many organic-contaminated sites. The majority being chlorinated solvent sites; however, cultures have been and are continuing to be developed to treat a wider range of the more recalcitrant contaminant compounds. Bioaugmentation can be employed at startup of biostimulation, or may be required throughout the life cycle of the project, if the added culture cannot survive and if indigenous populations do not develop to microbial densities that effectively degrade the targeted contaminants. The need to continually add cultures due to lost activity from the previous bioaugmentation injection, can add cost and in the long term could reduce the long-term reliability. It is unknown whether bioaugmentation at the BFF source area would require frequent or repetitive inoculations. Effective bioaugmentation would need to select targeted areas that would benefit from this technology.

Reduction of toxicity, mobility, mass, or volume (Yes/No/Uncertain) - Phase specific and should specify what is being reduced

Yes.

Bioaugmentation when necessary is designed to enhance the degradation rates/extents of the targeted contaminant(s). Effective bioaugmentation should result in substantial increases in contaminant biodegradation, which at the BFF would reduce toxicity by minimizing the potential for incomplete reductive debromination of EDB.

Short-Term Effectiveness (High/Medium/Low/Not effective) - Phase specific, requires specification

High.

Bioaugmentation is designed to introduce a robust population of contaminant degrading microorganisms and/or to reduce the acclimation period of low populations of indigenous microorganisms. EDB is known to be reductively debrominated to ethene and bromide ion and bioaugmentation can help ensure that the biotic pathway is complete in groundwater in contact with LNAPL.

Implementability (Difficult/ Moderate/Easy/Not applicable)

Difficult.

Effectively injecting and distributing bioaugmentation cultures would require a substantial number of injections wells and possibly the ability to recirculate groundwater. The current BFF well network is most likely insufficient for bioaugmentation. Spot treatments may be possible around available wells, but the ability to monitor the plume with those wells would be diminished and the value of doing spot treatment is questionable. Targeted treatment that optimizes the number of injection wells may be a feasible approach if the extent of coverage is kept to the minimum necessary for maximum benefit.

Cost - Capital & O&M (High/Medium/Low) - 1 (>$500M), 2 ($350 - $500M), 3 ($200 - $350M), 4 ($50 - $200M), and 5 (<$50M)

Medium.

The cost for implementing bioaugmentation under an anaerobic biostimulation scenario would be slightly higher that the costs for anaerobic biostimulation alone; however, additional injection wells may be required to effectively distribute the culture. If bioaugmentation could take place in the anaerobic portion of the aquifer where there is substantial electron donor and geochemical conditions that are conducive to the survival and activity of the added culture, the cost of implementation could be less. Regardless, the number of wells would be the primary cost driver.

Schedule to Implement (Long/Medium/Short/Not applicable) - Long (>10 yrs.), Medium (5-10 yrs.), and Short (<5 yrs.)

Short. (<5 yrs)

Bioaugmentation has developed to the point where the technology can easily be incorporated into biostimulation work plans. Optimal bioaugmentation could benefit from some laboratory microcosm and or field treatability testing, which could add 6 months to one year to the schedule. Laboratory microcosm studies are underway at the BFF that should provide a proof-of-concept for bioaugmentation and help to design an approach for field-scale implementation. As with the biostimulation options, aquifer test data would be needed for designing and placing injection wells and extraction wells if recirculation is required.

Infrastructure Requirements and Constraints (List of infrastructure required)

Bioaugmentation with Biostimulation in an Injection Only Mode Requirements:

A set of injection wells drilled into the targeted aquifer volume (i.e., contaminant distribution and aquifer properties would dictate the number and placement of injection wells). Above ground infrastructure would include a building to house equipment; reagent chemicals; sampling and PPE supplies; electrical and potable water service; chemical metering pumps, chemical storage and mixing tanks; a chemical staging area; and, system and building security systems.

Bioaugmentation with Biostimulation with Recirculation:

All of the above plus: extraction wells; well pumps; water conveyance piping and associated equipment; extracted and reinjected water-quality monitoring systems; and, a leak detection system.

Bioaugmentation into existing groundwater wells

No additional permanent infrastructure would be required."

Waste Management (List waste streams to be managed)

- Drill cuttings and waste fluids pending installation of additional injection wells
- Waste chemical containers
- Used PPE

Permit Requirements (Low/Med/High) (e.g., OSE, NMED, EPA, AEHD, rights of entry agreements)

- May require UIC permits for the substrates and the culture.
- Recirculation may require additional permits to allow for reinjection of amended water with contaminants remaining in solution. See response in P4."

Potential Stakeholder Objections

Comments (include references as applicable)

Panel Comment: The spreadsheet should provide references on the effectiveness of bioaugmentation to treat EDB mixed with hydrocarbon fuels.

Bibliography

General references:
Stroo, H. F., Leeson, A., & Ward, C. H. (2012). Bioaugmentation for groundwater remediation (Vol. 5). Springer Science & Business Media.

http://clu-in.org/techfocus/default.focus/sec/Bioremediation/cat/Overview/

Source Area Interim Treatment Technology Options

1.4 Cometabolic options (Aerobic) (Bruce Alleman, Adria Bodour, Paul Hatzinger, and Rob Steffan)

Panel comments and suggestions are denoted by text with a colored background.

Description of technology being evaluated - How will the technology be used?

Cometabolism of a contaminant describes the fortuitous degradation of the contaminant by an enzymatic system expressed and activated independent of the contaminant. This fortuitous degradation typically occurs with an energetic cost to organisms expressing the enzyme. Aerobic cometabolism requires oxygen and a suitable primary substrate to increase cometabolic activity. Suitable substrates may already be present (e.g., toluene for toluene monooxygenase), but otherwise need to be supplied (e.g., propane or ethane biosparging). Sufficient dissolved oxygen levels need to be maintained. Possible inhibition of desired enzymes by primary substrates may require pulsed additions of substrate. If microorganisms capable of expressing the desired enzyme are not present, bioaugmentation may supply a sufficient population

Protective of human health and environment (Yes/No/Uncertain) - Additional info may be needed to qualify answer, specify if LUCs are required

Yes.

Proper design of an cometabolic system should be protective of human health and the environment. Compounds may be volatilized during sparging and this must be assessed during design. Toxic intermediates, if produced, are not anticipated to be long-lived or more mobile than original compounds of concern.

Potential to attain of cleanup standards/goals within reasonable timeframe (<50 years) (High/Medium/Low)

Medium.

Kinetics of aerobic cometabolism are rapid under proper circumstances. As with other bioremediation technologies, cometabolism requires effective delivery and distribution of the reagents, achieving and sustaining suitable subsurface conditions, and effective contact between the microorganism, the electron acceptors/donors, and the contaminant. Some risks are inhibition of desired activity by various substrates. Microorganisms not expressing the desired enzymes may outcompete those with desired enzymes and desired enzymes may be inhibited by primary substrate itself. Problems with competition and inhibition are likely to be minimal due to the relatively low EDB concentrations compared to hydrocarbons from fuels.

Control releases to reduce or eliminate further releases of hazardous constituents

Yes

Comply with standards for waste management (Yes/No)

Long term reliability and effectiveness (High/Medium/Low) - Include technology maturity

Medium.

Cometabolism has been used at several sites and can effectively treat contaminants of concern to very low concentrations (<ppb) because the contaminant does not serve any benefit to degrading organisms. Challenges in operation are similar to other biostimulation and biosparging efforts. Sustained delivery of primary substrate and oxygen have challenged full-scale implementation of this technology. The effectiveness of the fuel hydrocarbon cocontaminants as primary substrates will need to be assessed. Small aliphatic compounds (methane-pentane) are the most effective primary substrates because they induce alkane monooxygenase enzymes.

Perhaps include the results of recent microcosm studies?

Reduction of toxicity, mobility, mass, or volume (Yes/No/Uncertain) - Phase specific and should specify what is being reduced

Yes.

If proper conditions are maintained, cometabolic degradation of EDB may be quite rapid and result in less toxic and shorter lived products.

Short-Term Effectiveness (High/Medium/Low/Not effective) - Phase specific, requires specification

High.

This is specific for the dissolved phase. If suitable microorganisms can be enhanced by appropriate substrates, degradation of contaminants may be rapid. Distribution of these conditions throughout zones of contamination is challenging. There may be a significant sink for dissolved oxygen that does not enhance cometabolism of the contaminant. As with other aqueous phase treatment options, degradation in the aqueous phase near LNAPL will enhance repartitioning of contaminants from LNAPL phases into the aqueous phase, enhancing reductions of contaminant mass within the LNAPL.

Implementability (Difficult/ Moderate/Easy/Not applicable)

Moderate to Difficult

This technology option depends on microbial ecology and presence of substrates. If suitable organisms and substrates capable of facilitating cometabolism of contaminants are already present, sparging with air/oxygen may be the only need to stimulate co-metabolism. If organisms/substrate are not present, addition of these and distribution of these may add significant complexity. Nutrient limitations may also hinder effective stimulation of co-metabolism.

Cost - Capital & O&M (High/Medium/Low) - 1 (>$500M), 2 ($350 - $500M), 3 ($200 - $350M), 4 ($50 - $200M), and 5 (<$50M)

Medium (Uncertain) ($50M to $500M)

This can range from costs of simple sparging/biosparging to one where various amendments and microorganisms need to be provided and distributed.

Schedule to Implement (Long/Medium/Short/Not applicable) - Long (>10 yrs.), Medium (5-10 yrs.), and Short (<5 yrs.)

Short?

Schedule for implementation should be fairly similar to other in-situ bioremediation options.

Infrastructure Requirements and Constraints (List of infrastructure required)

Injection only requirements:

Infrastructure necessary for providing gases (e.g., oxygen, air) to the aquifer are necessary. Flammable gases (e.g., propane) may be suitable primary substrate and may be need to be provided to a significant number of wells. Requirements to inject cultures and amendments are similar to other bioremediation technologies with the exception that flammability of propane/air mixtures must be managed.

Waste Management (List waste streams to be managed)

Drill cuttings and waste fluids pending P7installation of additional injection wells. Waste chemical containers.

Permit Requirements (Low/Med/High) (e.g., OSE, NMED, EPA, AEHD, rights of entry agreements)

May require an UIC permit.

Potential Stakeholder Objections

Comments (include references as applicable)

Bibliography

Danko, A. S., Leitão, P. O., Verce, M. F., & Freedman, D. L. (2012). Efficacy of pentane, toluene, and benzene to support aerobic cometabolism of ethylene dibromide. New biotechnology, 30(1), 39-43.

Hatzinger, P. B., Streger, S. H., & Begley, J. F. (2015). Enhancing aerobic biodegradation of 1, 2-dibromoethane in groundwater using ethane or propane and inorganic nutrients. Journal of contaminant hydrology, 172, 61-70.

McKeever, R., Sheppard, D., Nüsslein, K., Baek, K. H., Rieber, K., Ergas, S. J., ... & Park, C. (2012). Biodegradation of ethylene dibromide (1, 2-Dibromoethane [EDB]) in microcosms simulating in-situ and biostimulated conditions. Journal of hazardous materials, 209, 92-98.

Source Area Interim Treatment Technology Options

1.5 In-situ Chemical Oxidation (ISCO) (Javier Santillan, Patrick Longmire, and Jonathan Myers)

Panel comments and suggestions are denoted by text with a colored background.

Description of technology being evaluated - How will the technology be used?

Injection of inorganic oxidants, including permanganate, Fenton's reagent, activated persulfate, ozone, calcium peroxide, peroxone, percarbonate, and hydrogen peroxide, to chemically oxidize dissolved organic contaminants is a viable treatment technology of hydrocarbon fuels. Effective reagent distribution to assure effective and long-term encounter with organic contaminants is essential for establishing and maintaining contaminant attenuation and abiotic oxidation. Secondary geochemical reactions most likely will take place, including reprecipitation of ferric (oxy)hydroxide and manganese dioxide accompanied by changes (decrease) in pH and redox potential (increase). Oxidants such as persulfate have the potential to create acidic pH conditions in groundwater containing relatively low concentrations of total carbonate alkalinity. Injection wells and monitoring are required for implementing this treatment option, in addition to suitable hydrological conditions with favorable permeability to deliver oxidants to the contaminants. This treatment technology would be applied to anaerobic groundwater in contact with LNAPL to oxidized hydrocarbon fuel components to carbon dioxide gas and water.

Panel Comment: This is a reasonable summary of the chemistry of in-situ chemical oxidation. However, there is no discussion of the delivery of the chemical oxidants to the LNAPL zone. Most sites at which ISCO has been used have shallow ground water. The large depth to ground water and the high degree of heterogeneity at the KAFB BFF site will be make implementation very challenging.

Protective of human health and environment (Yes/No/Uncertain) - Additional info may be needed to qualify answer, specify if LUCs are required

Yes

In-situ chemical oxidation of dissolved hydrocarbon fuel constituents is protective of human health and environment, whether adsorbed on soil particles or dissolved in groundwater. However, according to ITRC, only activated persulfate may have an impact on attenuation (oxidation) of EDB. Injecting and effectively distributing activated persulfate through the vadose zone (500 ft thick) is unlikely at KAFB. Therefore, activated persulfate is not applicable for EDB at KAFB. Oxidative dissolution of trace $FeCO_3$, $MnCO_3$, and FeS may release natural soluble trace elements to groundwater. Acid-base chemical reactions and metal mobility need to be critically evaluated prior to field implementation. Several coreholes will have to be drilled near the LNAPL zone and samples will be required to quantify reactive phase mineralogy, suitability and effectiveness of this technology, chemical composition of LNAPL including distribution and effective solubilities of hydrocarbon components and EDB, and hydraulic properties of sediments.

Panel Comment: In-situ chemical oxidation of EDB does not appear to be discussed by either ITRC (2005) or EPA (Huling and Pivetz, 2005). However, studies cited by Pignatello et al. (2007) have shown that EDB can be oxidized by Fenton's reagent. In addition, NM has a ground water standard for iron of 1.0 mg/L and manganese of 0.2 mg/L. Therefore, if an iron or manganese based oxidant is used it will be necessary to assure that these standards are not violated.

Potential to attain of cleanup standards/goals within reasonable timeframe (<50 years) (High/Medium/Low)

High.
Cleanup standards and reasonable timeframes are achievable for hydrocarbon fuel components using this technology option.

Low to Negligible
Reaching effective cleanup goals for EDB in a reasonable timeframe are unlikely, as this aquifer system (groundwater and redox-sensitive minerals) becomes strongly oxidized. Oxidative dissolution of reduced minerals may release soluble trace elements to groundwater.

Control releases to reduce or eliminate further releases of hazardous constituents

Comply with standards for waste management (Yes/No)

Long term reliability and effectiveness (High/Medium/Low) - Include technology maturity

Medium, but Variable
Short-term reliability and effectiveness is initially high for hydrocarbon fuel components, but rebound over the long-term is possible, which is influenced by residual anaerobic conditions containing non-accessible hydrocarbons. This technology option has a medium to high maturity, but it is not practical to address EDB degradation under the strongly aerobic conditions induced by the oxidants, including persulfate. Secondary oxidation reactions may enhance dissolution of mineral phases initially stable under reducing conditions, resulting in the release trace elements to groundwater. Site-specific degradation (oxidation) reaction rates for key contaminants including benzene and EDB are needed prior to field implementation. Hydraulic properties of regional aquifer must be known in detail. Total carbonate alkalinity present in contaminated groundwater may impact effectiveness of persulfate by reacting with radicals and forming ligands with cationic metals. These reactions limit the long-term oxidizing capacity of persulfate. Oxidative precipitation of ferric (oxy)hydroxide and manganese dioxide may result is clogging of injection points, which will impact delivery of the oxidant(s). Laboratory testing of this technology option is required prior to potential field implementation.

Panel Comment: In addition to laboratory testing of the technology, it is likely that field scale pilot testing would be required as well.

Reduction of toxicity, mobility, mass, or volume (Yes/No/Uncertain) - Phase specific and should specify what is being reduced

Yes

This technology option has the ability to enhance reduction of hydrocarbon fuel contaminant mass through robust oxidation processes and volume in the dissolved and sediment adsorbed phase, but probably will have no (uncertain) impact on EDB removal.

Short-Term Effectiveness (High/Medium/Low/Not effective) - Phase specific, requires specification

High

This technology option has a strong potential for attenuating hydrocarbons present in dissolved phase, and is less effective for attenuating or oxidizing hydrocarbon components that are either adsorbed or trapped onto surfaces of fine-grained sediment not in contact with the oxidant(s).

Not Effective.

This technology option is not practical or effective for EDB, which biodegrades under anaerobic conditions characterized, in part, by sulfate reduction.

Implementability (Difficult/ Moderate/Easy/Not applicable)

Difficult

The thick vadose zone at KAFB will control the ability to effectively deliver and mix reagents at 500 ft bgs.

Cost - Capital & O&M (High/Medium/Low) - 1 (>$500M), 2 ($350 - $500M), 3 ($200 - $350M), 4 ($50 - $200M), and 5 (<$50M)

1. to 4. ($50M to >$500M).

This treatment option is medium to high in terms of cost and operation and maintenance of injection wells, depending on injection well grid selected based on well spacing requirement to assure proper reagent distribution.

Schedule to Implement (Long/Medium/Short/Not applicable) - Long (>10 yrs.), Medium (5-10 yrs.), and Short (<5 yrs.)

Long (>10 yrs).

This technology option requires multiple injection and monitoring wells. Numerous injections of oxidants may need to be repeated to control rebound (due to slow contaminant release from fine-grained sediment into groundwater).

Infrastructure Requirements and Constraints (List of infrastructure required)

Substantial.

Multiple deep (500 ft bgs) injection and monitoring points (minimum approximately 200, maximum approximately 740) are required for this technology option.

Waste Management (List waste streams to be managed)
In-situ treatment, little waste generated. The need to safely store oxidants on site will be required.

Permit Requirements (Low/Med/High) (e.g., OSE, NMED, EPA, AEHD, rights of entry agreements)
NMED reagent injection permit is required. Rights of entry for multiple injection points and monitoring wells.

Potential Stakeholder Objections

Comments (include references as applicable)
More boreholes need to be drilled in and near the LNAPL zone to collect the soil core and LNAPL samples that are required to characterize types and distribution of reactive minerals, distribution and chemical composition of LNAPL, including EDB, and suitability of this technology option. Laboratory testing of this technology option is required prior to potential field implementation. Clu-in Quote "EDB is expected to behave similarly to 1,2-dichloroethane; therefore, in-situ oxidation by hydrogen peroxide, Fenton's reagent, sodium/potassium permanganate, and iron activated persulfate generally is ineffective (Huling and Pivetz 2006). Heat- or alkaline-activated (pH>10.5) persulfate, however, should be effective (ITRC 2005)." Excellent reference: Siegrist et al., In-situ Chemical Oxidation for Groundwater Remediation, 2011. (SERDP, ESTCP)

Bibliography

Huling, Scott G. ; Pivetz, Bruce E., (2006). In-Situ Chemical Oxidation, Engineering Issue, USEPA, 61 p. (http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA507297)

Interstate Technology & Regulatory Council (ITRC) (2005). Technical and Regulatory Guidance for In-situ Chemical Oxidation of Contaminated Soil and Groundwater, 2nd ed, ISCO-2, 172 p. (http://www.itrcweb.org)

Pignatello, J.J. , Oliveros E., MacKay, A., (2007). Advanced Oxidation Processes for Organic Contaminant Destruction Based on the Fenton Reaction and Related Chemistry, Crit. Revs. In Environ. Sci. and Technol., 36, 1-84, (http://www.tandfonline.com/doi/pdf/10.1080/10643380500326564).

Siegrist, R.L., Crimi, M., Simpkin, T.J. (editors) (2011). In-situ Chemical Oxidation for Groundwater Remediation, Springer, (SERDP & ESTCP), New York, NY, 678 p.

Source Area Interim Treatment Technology Options

1.7 In-situ Biogeochemical Transformation (ISBGT)
(Bruce Alleman)
Panel comments and suggestions are denoted by text with a colored background.

Description of technology being evaluated - How will the technology be used?

Engineered ISBGT is an anaerobic approach that exploits the activity of indigenous microbial populations to produce reactive minerals, primarily iron sulfide (FeS) and pyrite (FeS2), that catalyze the degradation of select contaminants. While other reactive minerals can be biologically formed, engineered ISBGT is primarily focus on biologically mediated iron sulfide production. Engineering the process starts with through analysis of the geochemistry and subsurface mineralogy to determine if the aquifer is lacking a bioavailable iron or sulfate source, and to assess potential substrate/electron donor limitations. When iron is limited, iron salts, minerals (e.g., hematite or magnetite), or organo-iron compounds (e.g., ferrous lactate) can be added. The salts and organo-iron compounds are more easily injected but tend to be short lived, while the mineral forms can be difficult to inject but provide a more sustained source of iron. Magnetite itself is reactive and can provide an added degree of treatment. If sulfate is limited, sulfate salts (e.g., sodium sulfate, calcium sulfate, potassium sulfate, ferrous sulfate, or magnesium sulfate [Epsom salt]) or gypsum could be added as a sulfate supplement. If the site is substrate/electron donor limited, any of the common formulations used to stimulate anaerobic reductive dehalogenation would be suitable. The objective is to support the metabolic activity of iron reducing and sulfate reducing bacteria to provide the ferrous iron and free sulfide that complex to form the reactive iron sulfide. At fuel sites with LNAPL, the residual hydrocarbons can serve as a suitable substrate/electron donor reservoir. The challenges with adding iron and sulfate sources are achieving effective distribution so that the reduced iron and sulfide can interact and to achieve the proper dosages to ensure that excess sulfide does not become toxic to the microorganisms. The degradation of halogenated contaminants is abiotic through the ß-elimination pathway, and while not specifically targeted, biotic reductive dehalogenation via hydrogenolysis. Select fuel constituents may undergo anaerobic cometabolism. It should be noted that to date, the more successful engineered application of ISBGT have involved excavation-based approaches (e.g., biowalls and in-situ bioreactors) where the necessary supplements were added during construction. Approaches attempting to inject soluble supplements have proven challenging due to well/formation clogging and ineffective distribution.

Protective of human health and environment (Yes/No/Uncertain) - Additional info may be needed to qualify answer, specify if LUCs are required

Yes.
The technology option is viable and protective of human health and the environment depending effective distribution of supplements and the formation of the reactive mineral species. Forming

the reactive mineral forms and retaining their reactivity will be subject to aquifer geochemistry (alkalinity and other passivating compound concentrations).

Potential to attain cleanup standards/goals within reasonable timeframe (<50 years) (High/Medium/Low)

Medium to Low.
Biogeochemical transformation of EDB under sulfate-reducing conditions is potentially achievable in certain redox zones
Low.
This technology option is not applicable to degrading fuel hydrocarbons.

Control releases to reduce or eliminate further releases of hazardous constituents

Uncertain.
As with any technology that entails reagent injection, displacement may be an issue. Use of hydrophobic substrates such as vegetable-oil based preparations could sequester select contaminants, which could in turn reduce further release.

Comply with standards for waste management (Yes/No)

Yes

Long term reliability and effectiveness (High/Medium/Low) - Include technology maturity

Medium.
The long-term effects of mineral production on the aquifer permeability are unknown. Control of reagents and microbial communities deep in the subsurface can be challenging.

Reduction of toxicity, mobility, mass, or volume (Yes/No/Uncertain) - Phase specific and should specify what is being reduced

Yes.
The abiotic transformation of EDB would reduce its toxicity and mass. The effect on the fuel constituents is less certain, but degrading the lower molecular weight aliphatics should reduce toxicity, mass and mobility.

Short-Term Effectiveness (High/Medium/Low/Not effective) - Phase specific, requires specification

Medium and Low.
Medium for EDB pending delivery and contact. Low for fuel hydrocarbons as anaerobic kinetics tend to be slower than aerobic kinetics.

Implementability (Difficult/ Moderate/Easy/Not applicable)

Difficult.
Effective distribution may require establishing iron-reducing and sulfate-reducing zones, which could prove difficult at 500+ feet bgs. Fouling issues could cause well screen clogging and formation permeability losses that are very difficult to rectify. ISBGT requiring only the addition of one supplement class (iron, sulfate, or substrate/electron donor) may be more easy to implement.

Cost - Capital & O&M (High/Medium/Low) - 1 (>$500M), 2 ($350 - $500M), 3 ($200 - $350M), 4 ($50 - $200M), and 5 (<$50M)

5 (<$50M).
The number of wells required, chemical costs and labor will be the main drivers.

Schedule to Implement (Long/Medium/Short/Not applicable) - Long (>10 yrs.), Medium (5-10 yrs.), and Short (<5 yrs.)

Low.
Site characterization (cores for mineralogy, groundwater for geochemistry and LNAPL distribution/characterization) and laboratory microcosm testing may be required.

Infrastructure Requirements and Constraints (List of infrastructure required)

Substantial.
Injection and monitoring wells, pumps, mixing tanks, electrical service, potable water supply, conveyance lines equipment housing.

Waste Management (List waste streams to be managed)

Chemical containers, sampling purge water, used PPE

Permit Requirements (Low/Med/High) (e.g., OSE, NMED, EPA, AEHD, rights of entry agreements)

UIC (NMED) and rights of entry.

Potential Stakeholder Objections

Comments (include references as applicable)

Bibliography

Kennedy, L.G., J.W. Everett, E. Becvar, and D. DeFeo. 1996. Field-scale demonstration of induced biogeochemical reductive dechlorination at Dover Air Force Base, Dover,S2 Delaware. Journal of Contaminant Hydrology 88, 119–136.

He, Y.T., Wilson, J.T. Wilkin, R.T. (2008). Transformation of reactive iron minerals in a permeable reactive barrier (biowall) used to treat TCE in groundwater. Environ. Sci. Technol., 42(17), 6690–6696.

NAVFAC. 2014. In-situ Biogeochemical Transformation Processes for Treating Contaminated Groundwater. Fact Sheet. 6 pgs. (http://www.clu-in.org/download/techfocus/bio/bio-insitubiogeochem-FS.pdf.)

Whiting, K., P.J. Evans, C. Lebrón, B. Henry, J.T. Wilson, and E. Becvar. 2014. Factors Controlling In-situ Biogeochemical Transformation of Trichloroethene: Field Survey. Groundwater Monitoring & Remediation. 34(3), 79–94."

Source Area Interim Treatment Technology Options

2.1 Air Sparging with Soil Vapor Extraction (Steve Reuter, Stuart Shealy)
Panel comments and suggestions are denoted by text with a colored background.

Description of technology being evaluated - How will the technology be used?

This technology consists of injecting air below the water table, below LNAPL zone to strip both free phase and dissolved contaminants. Air sparge off gas would be collected by soil vapor extraction (SVE) for treatment at ground surface. Effectiveness on EDB removal is not precisely known and case histories with application to KAFB have not been identified.

Protective of human health and environment (Yes/No/Uncertain) - Additional info may be needed to qualify answer, specify if LUCs are required

Yes
Air sparging is protective of human health and the environment for LNAPL but is uncertain or not documented for EDB. Air sparge off gasses can be collected by a properly designed SVE system that is a technology that is well understood. Given the excessive depth of the contaminants in groundwater and the propensity for hydrocarbon vapors to biodegrade, SVE capture of the air sparge off gasses may not be necessary.

Panel Comments: The Panel agrees that hydrocarbon vapors may not be detected at the surface, however, it is not clear that the same conclusion can be made for EDB. Furthermore, because of public concerns about EDB it is likely that SVE and subsequent off gas treatment would be required for public acceptance.

Potential to attain of cleanup standards/goals within reasonable timeframe (<50 years) (High/Medium/Low)

Medium to Low
Medium for dissolved phase and LNAPL at regional water table; probable for submersed LNAPL and adsorbed phase. This technology option is low for EDB, based on the compound's relatively low Henry's law constant.

Control releases to reduce or eliminate further releases of hazardous constituents

Panel Comments: The Workgroup should consider whether sparging in the LNAPL zone in the absence of vapor recovery would lead to actual or publicly perceived migration of contaminants to the surface.

Comply with standards for waste management (Yes/No)

Long term reliability and effectiveness (High/Medium/Low) - Include technology maturity

High/Mature

Air sparging is a mature technology that continues to be applied to treat primarily dissolved-phase hydrocarbon plumes. The effectiveness/reliability of the technology probably will not be compromised at a site with the depth and lateral extent of the BFF. Challenges associated with fouling and limited ability to effectively contact the contaminant as will be needed at the BFF and could substantially reduce the reliability of sparging. A more directed application in areas of the dissolved plume that would benefit from in-situ stripping and that is not highly reduced may be more suitable of sparging. This technology option requires the need to identify limitations with thick vadose zone with heterogeneous sediments. References are needed.

Reduction of toxicity, mobility, mass, or volume (Yes/No/Uncertain) - Phase specific and should specify what is being reduced

Yes

Reduction of toxicity and contaminant properties and distribution in the subsurface is feasible for dissolved and LNAPL at regional water table using this technology option. This technology has potential application to submersed LNAPL and adsorbed phase.

Short-Term Effectiveness (High/Medium/Low/Not effective) - Phase specific, requires specification

Medium to High

Short-term effectiveness is technically feasible for dissolved phase and LNAPL at the regional water table; but is uncertain or to low for submersed LNAPL and adsorbed phase.

Implementability (Difficult/ Moderate/Easy/Not applicable)

Moderate

This technology option is moderate for dissolved and LNAPL at regional water table; moderate for submersed LNAPL and adsorbed phase with KAFB property; but is considered to be difficult off Base. A robust site conceptual model is required to bound uncertainties associated implementing this technology.

Cost - Capital & O&M (High/Medium/Low) - 1 (>$500M), 2 ($350 - $500M), 3 ($200 - $350M), 4 ($50 - $200M), and 5 (<$50M)

Medium

Cost will depend on the number of injection wells. The cost for implementing this technology will be driven by the number of injection wells required to effectively volumes of air as a stripping agent throughout the targeted aquifer volume. The number of wells would dictate the requirements for pumps and above-ground equipment and infrastructure. Partitioned implementation might prove desirable.

Schedule to Implement (Long/Medium/Short/Not applicable) - Long (>10 yrs.), Medium (5-10 yrs.), and Short (<5 yrs.)

Short

This technology could be applied with existing wells augmented with additional air sparge points to evaluate technology as an interim measure. Infrastructure to process off-gasses already exists and could be expanded reasonably well for field implementation. Documentation of successful application of this technology is needed to determine its applicability to KAFB.

Infrastructure Requirements and Constraints (List of infrastructure required)

Treatment Compound Conveyance Lines, well head and vault construction.

Panel Comments: The sparging/SVE technology will likely require a considerable amount of infrastructure at the surface including blowers, air distribution lines, and possibly vacuum blowers, collection lines, and off gas treatment if SVE and treatment is required.

Waste Management (List waste streams to be managed)

Minimal/vapor treatment to meet air permits.

Permit Requirements (Low/Med/High) (e.g., OSE, NMED, EPA, AEHD, rights of entry agreements)

Air Permits AEHD/NMED.

Potential Stakeholder Objections

Comments (include references as applicable)

Provide references. Air sparging should have significant applicability for the dissolved phase in the oxygenated portion of the aquifer, as well as the LNAPL portion of the contaminant plume. Subsurface heterogeneity has the potential to increase the effective radius of the air sparge, although it will increase the difficulty in determining effectiveness. Air sparging will remediate both through mechanical stripping of contaminant as well as enhancing conditions for in-situ aerobic degradation of contaminants. Application of this technology in portions of the hydrocarbon plume that are currently anerobic will need to be compared to other enhanced anerobic technologies. Substantial infrastructure requirements may be mitigated by taking advantage of the significant overlying vadose zone that potentially may allow for biodegradation of the air sparge off-gasses and negates the need for associated soil vapor extraction. In addition, potential mobilization of EDB by air sparging will need to be quantified during field implementation, which may be desirable or detrimental.

Bibliography

Bass, D.H., Hastings, N.A., Brown, R.A., (2000). Performance of air sparging systems: a review of case studies, J. Haz. Materials, 72(2-3), 101-119

EPA. 1997. Analysis of Selected Enhancements for Soil Vapor Extraction. EPA-542-R-97-007. www.clu-in.org/download/remed/sveenhmt.pdf

Hinchee, R.E. editor (1994). Air Sparging for Site Remediation, CRC Press, Inc., Boca Raton, FL, 142 p.

Ground Water Remediation Technologies Analysis Center. 1996. Air Sparging Technology Overview Report. http://clu-in.org/download/toolkit/sparge_o.pdf

McCray, J.E., Tick, G.r., Jawitz, J.W., Gierke, J.S., Brusseau, M.L., Falta, R.W., Knox, R.C., Sabatini, D.A., Annable, M.D., Harwell, J.H., Wood, A.L. (2011). Remediation of NAPL Source Zones: Lessons learned from Field Studies at Hill and Dover AFB, Ground Water, 49(5), 727-744.

USACE. 2002. Engineering and Design: Soil Vapor Extraction and Bioventing. EM 1110-1-4001. http://140.194.76.129/publications/eng-manuals/em1110-1-4001/toc.htm
USACE. 2008. Engineering and Design: In-situ Air Sparging. EM 1110-1-4005.

Source Area Interim Treatment Technology Options

2.2 Thermally Enhanced Sparging with SVE (Steve Reuter, Stuart Shealy)

Panel comments and suggestions are denoted by text with a colored background.

Description of technology being evaluated - How will the technology be used?

Subsurface heating (hot air injection, steam injection Electro-thermal desorption) is performed to increase volatility and increase mobility of free phase hydrocarbon contamination. A capture system for volatilized hydrocarbons and a well-defined site conceptual model are needed to further develop this potential technology option. The potential for precipitation of calcium carbonate needs to be quantified as pore water in the vadose zone is heated and carbon dioxide gas is driven off.

Protective of human health and environment (Yes/No/Uncertain) - Additional info may be needed to qualify answer, specify if LUCs are required

Yes.

Air sparge off gasses can be collected by a properly designed SVE system that is a technology that is well understood. Given the excessive depth of the contaminants in groundwater and the propensity for hydrocarbon vapors to biodegrade, SVE capture of the air sparge off gasses may not be necessary.

Panel Comments: The Panel agrees that hydrocarbon vapors may not be detected at the surface, however, it is not clear that the same conclusion can be made for EDB. Furthermore, because of public concerns about EDB it is likely that SVE and subsequent off gas treatment would be required for public acceptance.

Potential to attain of cleanup standards/goals within reasonable timeframe (<50 years) (High/Medium/Low)

Yes

Potential to attain cleanup standards is feasible for dissolved phase and LNAPL at regional water table; probable for submersed LNAPL and adsorbed phase. This technology option requires a bounding statement for energy requirements.

Control releases to reduce or eliminate further releases of hazardous constituents

Panel Comments: The Workgroup should consider whether thermally enhanced air sparging in the LNAPL zone in the absence of vapor recovery would lead to actual or publicly perceived migration of contaminants to the surface.

Comply with standards for waste management (Yes/No)

Long term reliability and effectiveness (High/Medium/Low) - Include technology maturity

High/Adolescent

Enhanced air sparging may be desirable to address the lower volatility of the contaminants at the BFF. Suitability of enhancement can be evaluated during interim measure application Significant cost increase can be anticipated. Documentation is required to determine if this technology is applicable to KAFB.

Reduction of toxicity, mobility, mass, or volume (Yes/No/Uncertain) - Phase specific and should specify what is being reduced

Yes

Reduction of toxicity and contaminant mass and properties are achievable for dissolved and LNAPL at regional water table; probable for submersed LNAPL and adsorbed phase. This technology option requires proper technology design to achieve reduction in toxicity and contaminant properties.

Short-Term Effectiveness (High/Medium/Low/Not effective) - Phase specific, requires specification

Medium to High

Short-term effectiveness for dissolved and LNAPL at regional water table is feasible; uncertain-low for submersed LNAPL and adsorbed phase. References of this technology are required to determine applicability of thermally enhanced sparging to KAFB.

Implementability (Difficult/ Moderate/Easy/Not applicable)

Moderate

Implementation of this technology is moderately feasible for dissolved and LNAPL at regional water table; but is difficult for submersed LNAPL and adsorbed phase beneath KAFB. This technology option is difficult off KAFB property. A detailed concept on how this technology would be implemented is required prior to any bench, pilot, and field-scale implementation.

Panel Comments: The Panel agrees with this assessment of the implementability of thermally enhanced air sparging/SVE technology, however, the relatively shallow extent of the plume beneath the top of the water table may require use of a large number of sparge wells with short well screens. Further, evaluation of this technology must include identification of the heating method because the great depth to ground water at the KAFB BFF site may not allow use of steam.

Cost - Capital & O&M (High/Medium/Low) - 1 (>$500M), 2 ($350 - $500M), 3 ($200 - $350M), 4 ($50 - $200M), and 5 (<$50M)

1. (>$500M)

Any enhancement to the air sparge strategy or SVE strategy will have a profound increase on costs.

Schedule to Implement (Long/Medium/Short/Not applicable) - Long (>10 yrs.), Medium (5-10 yrs.), and Short (<5 yrs.)

Low

This technology could be applied with existing wells to evaluate technology as an interim measure. Infrastructure to process off-gases already exists and could be expanded reasonably and may not be necessary. References are needed to further determine the likelihood of successfully implementing this technology prior to starting laboratory and field studies.

Infrastructure Requirements and Constraints (List of infrastructure required)

Treatment Compound Conveyance Lines, well head and vault construction. Substantial infrastructure will be required.

Waste Management (List waste streams to be managed)

Minimal/vapor treatment to meet air permits. Waste products could be substantial when LNAPL is removed from the subsurface.

Permit Requirements (Low/Med/High) (e.g., OSE, NMED, EPA, AEHD, rights of entry agreements)

Air Permits AEHD/NMED.

Potential Stakeholder Objections

Comments (include references as applicable)

Same as above (2.0 – Air sparging). Additional significant costs will be associated with any enhancements to the air sparge strategy, which may limit the technical feasibility of this technology.

Bibliography

EPA (2015). Thermal Treatment: In-situ, USEPA web site listing thermally enhanced technologies to remediate contaminated groundwater. Accessed June 2015, https://clu-in.org/techfocus/default.focus/sec/Thermal_Treatment%3A_In_Situ/cat/Application/

Heron, G., Baker, R.S., Bierschenk, J.M., LaChance, J.C. (2006). Heat it All the Way - Mechanisms and Results Achieved using In-Situ Thermal Remediation, Remediation of Chlorinated and Recalcitrant Compounds: Proceedings of the Fifth International Conference, Battelle, Columbus, OH (http://www.researchgate.net/profile/Gorm_Heron/publication/228497895_Heat_it_All_the_Way-Mechanisms_and_Results_Achieved_using_In-Situ_Thermal_Remediation/links/0f3175304b162c81d4000000.pdf)

Kingston, J.L.T., Dahlen, P.R., Johnson, P.C. (2012). Assessment of Groundwater Quality Improvements and Mass Discharge Reductions at Five In-situ Electrical Resistance Heating Remediation Sites, Ground Water Monitoring & Remediation, 32(3) 41-51.

Park, G., Shin, H.-S., Ko, S.-O. (2007). A Laboratory and Pilot Study of Thermally Enhanced soil Vapor Extraction Method for the removal of Semi-Volatile Organic Contaminants, J. of Environ. Sci. and Health, Parth A: Toxic/Haz. Subs. And Environ. Engr., 40(4), 881-897.

Source Area Interim Treatment Technology Options

2.5 In-Well Treatment (Bruce Alleman)

Panel comments and suggestions are denoted by text with a colored background.

Description of technology being evaluated - How will the technology be used?

In-well treatment utilizes the space within a well casing as the "reactor" where groundwater enters one portion of the well, typically the lower portion, and then leaves the well to return to the formation through the other portion, treatment is applied to facilitate contaminant removal. Groundwater movement is achieved using mechanical pumps or air-lift pumping and the extraction and injection occurring in the same well without pumping the water above grade creates a groundwater circulation cell that has both horizontal and vertical flow components. Treatment occurs via phase transfer or through contaminant destruction. Phase-transfer technologies include air stripping and activated carbon adsorption. Destruction technologies include physical/chemical such as chemical oxidation or zero-valent iron (ZVI) and/or biological processes. Air lift systems utilize air to lower the density of the water in the well relative to the water in the formation, which causes the water to rise. The injected air also serves to "strip" contaminant from the water phase into the air phase with the air either collected from the well head for aboveground treatment, or injected into the vadose zone for enhanced biodegradation. Mechanical pumping also is applied with air stripping when higher air to water ratios are required to effect treatment, or when treatment units that impart head loss are utilized in the well. Air-lift configurations operate almost exclusively in an "up flow" mode. For the bulk fuel facility, the most suitable configuration would be one that uses in-well air stripping. While the efficiency of in-well air stripping cannot match that of ex-situ air stripping, the oxygenation of groundwater moving through the well could support aerobic biodegradation in the formation.

Protective of human health and environment (Yes/No/Uncertain) - Additional info may be needed to qualify answer, specify if LUCs are required

Uncertain.

Limited waste stream highly desirable. While properly designed, constructed and operated in-well treatment systems can be very effective for treating the fuel constituents, the effectiveness against EDB is uncertain. EDB is not easily stripped and because the in-well air-stripping efficiency is not optimal, EDB treatment would most likely rely on aerobic cometabolism, which would require the presence of a primary substrate. Fortunately, select fuel hydrocarbons are suitable primary substrates and if necessary, other gas-phase substrates can be easily supplemented.

Potential to attain of cleanup standards/goals within reasonable timeframe (<50 years) (High/Medium/Low)

Medium to Low

This technology is feasible for the dissolved phase and LNAPL at regional water table, submersed LNAPL and adsorbed phase. EDB cleanup goals should be attainable within 50 years through both air stripping and biodegradation. If EDB remains above the MCL after the BTEX has been degraded, the well can be reconfigured to include ZVI, which is known to destroy EDB.

Control releases to reduce or eliminate further releases of hazardous constituents

Operation of in-well treatment at a site with LNAPL showed that the LNAPL was initially smeared within the circulation cell. While subsequent in-well and in-formation treatment could address the smeared contamination, the potential for enhanced release of EDB and BTEX exists. A single well pilot test would be required to assess that potential at the BFF.

Comply with standards for waste management (Yes/No)

Yes

In-well treatment configurations do not pump groundwater above grade. The effluent vapor-phase should be treated in the vadose zone. If necessary, the vapor can be collected from the well head for aboveground treatment. Configurations that utilize phase transfer media may require disposal of hazardous waste; however, such configurations are not appropriate for application at the BFF.

Long term reliability and effectiveness (High/Medium/Low) - Include technology maturity

Medium

Operation of an air-stripping in-well treatment system in an anaerobic aquifer can result in excess fouling of the well components (air diffuser and well screens) and the formation. Dissolved iron entering the well will be oxidized and can precipitate from solution. Aerating groundwater containing elevated levels or readily degradable substrate (i.e., jet fuel constituents) could result in excessive biomass buildup in the well screen openings and the well casing. The high fouling potential would challenge the remediation practitioner in keeping these systems operating. The depth of the wells at the BFF would make it difficult and expensive to rehabilitate the wells. Sustainable technology and elimination of waste water containment, transport, treatment and disposal suggest significant long term effectiveness of this technology. Demonstration of significant ROI and potential fouling of well screens and pump may be limiting factors.

Panel Comments: This description and other comments on the technology suggest a sufficiently large amount of uncertainty about its capabilities that it probably does not justify a "Medium" assessment of its reliability, effectiveness, and maturity, especially when considered for application at a site as deep and complex as the LNAPL zone at the KAFB BFF facility.

Reduction of toxicity, mobility, mass, or volume (Yes/No/Uncertain) - Phase specific and should specify what is being reduced

Yes

While there may be an initial increase in dissolved concentrations, mobility and even toxicity due to the smearing effect, the subsequent treatment could counter those results. The challenge would be to ensure capture and treatment before the contaminants leave the circulation cell. The reductions for EDB would be dependent on aerobic cometabolic biodegradation as well as air stripping, so capture by the well(s) would be paramount.

Short-Term Effectiveness (High/Medium/Low/Not effective) - Phase specific, requires specification

Low

In-well treatment relies on mass transfer of contaminants from the aquifer to the well and is limited by site hydrogeology as well as the limitations of the well designs. Treatment inside the well is not expected to be as efficient as could be achieved in properly designed ex-situ systems, and delivery of oxygenated water will result in a "treatment front" that is usually slow to move along the periphery of the circulation cell. The bottom line is that these systems are not designed for short-term effectiveness.

Implementability (Difficult/ Moderate/Easy/Not applicable)

Difficult

The potential for fouling in the BFF source area is high and the depth of the wells would make routine well rehabilitation and maintenance difficult and expensive. Monitoring well efficiency in terms of pumping rates, air to water ratios, stripping efficiency, and circulation cell hydraulics would be challenging at the required depths. Short-circuiting potential becomes greater with depth and as fouling occurs.

Cost - Capital & O&M (High/Medium/Low) - 1 (>$500M), 2 ($350 - $500M), 3 ($200 - $350M), 4 ($50 - $200M), and 5 (<$50M)

1. (>$500M)

Some in-well configurations require large diameter wells (e.g., up to 26 inches) which would be very expensive. The expected radius of influence is a function of the aquifer properties, the stratigraphy, and the length and spacing of well screens. The number of required wells will drive the capital cost. Depending on demonstrated ROI and ultimate design of implementation, costs could be manageable. Savings associated with reduced wastewater management may make this a viable technology.

Schedule to Implement (Long/Medium/Short/Not applicable) - Long (>10 yrs.), Medium (5-10 yrs.), and Short (<5 yrs.)

Short

This technology could be evaluated as an interim measure using existing wells; however, to obtain accurate and representative data would likely require installation of one or more treatment wells that are designed to operate as recirculating wells. Infrastructure to process off-gasses if needed could be managed with mobile units of marginal additional infrastructure.

Infrastructure Requirements and Constraints (List of infrastructure required)

Treatment Compound, air compressor(s), air conveyance lines, well head and vault construction, in-well components (air distributor or other reactor equipment).

Waste Management (List waste streams to be managed)

Minimal

Off gas could require treatment prior to atmospheric discharge. Vadose zone treatment would eliminate that need as well as support bioventing of residual contaminant above the water table.

Permit Requirements (Low/Med/High) (e.g., OSE, NMED, EPA, AEHD, rights of entry agreements)

Air Permits AEHD/NMED if system off gas is extracted.

Potential Stakeholder Objections

Stakeholders may be uncomfortable with the smearing potential and the lack of control of the pumping rates and the treatment efficiency.

Comments (include references as applicable)

In well air-stripping is a modified pump and treat strategy that has merit due to the potential limited waste stream. Simplified permitting and negating the need to contain, treat, transport and dispose of large quantities of groundwater increase the potential viability of this approach. Uncertainties regarding radius of influence and ultimately the level of effort in terms of the number of necessary wells may limit its applicability as a large scale interim action. The strategy has some merit in limited application for protection of identified receptors.

Bibliography

Alleman, B.C. 1996. In-Well Air Stripping/Bioventing at Tyndall Air Force Base, Florida. Report Prepared for Environs Directorate, Tyndall AFB, FL. No. EQ-TR-1995-0039. (www.dtic.mil/dtic/tr/full text/u2/a317134.pdf)

Alleman B.C. 1998. Groundwater Circulation Well Assessment and Guidance. Report No. AFRL-ML-TY-TR-1998-4606. April 1998, 268 pp. (http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA583026)

Alleman, B.C. 2010. In-well Treatment for Chlorinated Solvent Remediation. In In-situ Remediation of Chlorinated Solvent Plumes. H.F. Stroo and C.H. Ward Eds. Springer Science + Business Media, New York, NY 10013. Chapter 18. pp. 591 - 630.

Source Area Interim Treatment Technology Options

3.1 Soil Vapor Extraction (SVE) (Steve Reuter, Rick Shean, Billy Gallegos, Stuart Shealy)
Panel comments and suggestions are denoted by text with a colored background.

Description of technology being evaluated - How will the technology be used?

A vacuum is applied to unsaturated soils and sediments in the vadose zone to induce hydrocarbon volatilization and vapor flow toward vadose-zone extraction wells where it is recovered and removed to the surface for treatment or venting. There are a variety of design options that could impact cost, schedule, and short term effectiveness. Aviation gas and jet fuel (as fluids) are suitable for application of SVE and SVE is commonly used for the EDB remediation. While aviation gas and jet fuel have constituents that are more volatile than EDB, the technology summary provided is inclusive of toxic compounds in fuel (including EDB) unless specifically indicated otherwise.

Panel Comment: Minor editorial suggestions are offered to emphasize that SVE is primarily applied in the vadose zone. This description should explicitly mention that SVE does not treat LNAPL that has been entrapped (drowned) below the water table, and that it is also not a very effective treatment for LNAPL floating on top of the water table. In other words, operated by itself SVE is a treatment for LNAPL, and dissolved, sorbed or vapor phase components, contained only within the vadose zone. However, used in combination with other methods (e.g., §2) it can be effective in remediating floating and drowned LNAPL.

Protective of human health and environment (Yes/No/Uncertain) - Additional info may be needed to qualify answer, specify if LUCs are required

Yes

SVE technology is well understood and waste stream management is demonstrably reliable and safe. Application of SVE would diminish and eventually mitigate the potential for additional contaminant mass from reaching groundwater where human health impacts are greater. There may be an increased risk of human exposure to recovered vapors; however engineering controls and treatment are proven to abate this risk. Additionally, hydrocarbons like EDB readily photo decay in the presence of UV radiation.

Potential to attain of cleanup standards/goals within reasonable timeframe (<50 years) (High/Medium/Low)

High

The potential for achieving cleanup standards is feasible, if this technology is properly designed and focused on appropriate zones. Treatment goals should be readily attained provided that SVE is properly designed, focused on appropriate zones, adequate pore volume exchanges are achieved, and operation /optimization plans are implemented properly. Treatment time is dependent on how aggressively it is applied and is likely to require longer term application to treat zones that are diffusion-controlled. Technology optimization (e.g. cycling or well replacement to modify screened zones) may extend the implementation schedule at discrete hot spots, even if most of the system has been turned off.

Control releases to reduce or eliminate further releases of hazardous constituents

Comply with standards for waste management (Yes/No)

Yes

Control and treatment of extracted vapors will be necessary through the early portion of the treatment period.

Long term reliability and effectiveness (High/Medium/Low) - Include technology maturity

High

Soil vapor extraction is a mature and proven technology for treating all forms of fuels. The technology has been applied at thousands of sites ranging from corner gas stations to large-volume crude spills. SVE is often considered the presumptive remedy for hydrocarbon fuel present in a vadose zone. SVE has been proven effective at treating petroleum hydrocarbon contamination, and is has been applied and refined at fuel spill sites for more than 30 years.

Reduction of toxicity, mobility, mass, or volume (Yes/No/Uncertain) - Phase specific and should specify what is being reduced

Yes

This technology option has the ability to reduce contaminant mass/volume as soil vapor through advection and diffusion processes. This includes adsorbed contaminants, vapor-phase contaminants, and LNAPL. Application of SVE at this site has demonstrated the ability for this technology to recover volatile contaminant mass from the vadose zone.

Panel Comment: The panel suggests this description be re-written as follows.

Yes

This technology option has the ability to reduce vadose zone contaminant mass/volume through soil-vapor advection and diffusion processes. This includes reduction of sorbed, dissolved and vapor-phase contaminants, and LNAPL, in the vadose zone. Past application of SVE to the vadose zone at this site has demonstrated the ability for this technology to recover significant volatile contaminant mass from the vadose zone.

Short-Term Effectiveness (High/Medium/Low/Not effective) - Phase specific, requires specification

Variable

Advection in highly permeable soils is very effective for enhancing the effectiveness of SVE. Diffusion from low permeable soils is more likely to impact SVE operations.

Panel Comment: The panel suggested this description be re-written as follows.

Variable
Advection in permeable soils induced by extraction wells is very effective for enhancing the effectiveness of SVE. However, sedimentary heterogeneity creates high permeability preferential flow paths and low permeability (especially stratified) barriers. Both lead to by-passing of contaminated zones and reduce the effectiveness of SVE. Contamination that is sequestered in low permeable soils leads to a rebound effect upon the termination of SVE and decreases short-term SVE effectiveness.

Implementability (Difficult/ Moderate/Easy/Not applicable)

Easy to Moderate
The thickness of the vadose zone at KAFB is a major control on the implementability of this technology option only because of the excessive depths. Infrastructure installation and operation are comparatively easy to implement. Because of the excessive vadose zone thickness and heterogeneities, the identification and treatment of the appropriate zones adds a level of complexity.

Panel Comment: The panel suggests this description be re-written as follows.

Easy to Moderate
The thickness of the vadose zone at KAFB is a major control on the implementation of this technology option only because of the significant depths. Otherwise, infrastructure installation and operation are comparatively easy to implement. Because of the significant vadose zone thickness and sedimentary heterogeneities, the identification and treatment of the appropriate zones adds complexity

Cost - Capital & O&M (High/Medium/Low) - 1 (>$500M), 2 ($350 - $500M), 3 ($200 - $350M), 4 ($50 - $200M), and 5 (<$50M)

2 to 4. ($50M to $500M)
Demonstration of significant radius of influence coupled with effective implementation and operation could make this option economically desirable. Costs can be highly variable, based on the number of wells and how aggressive the technology is applied (i.e. targeted pore volume exchange rates). For technology comparisons, it is assumed that none of the existing infrastructure is used; however, consideration of this technology must include the benefit of the ability to exploit existing infrastructure, as well as the extensive knowledge gained by past SVE operations.

Panel Comments: A minor editorial suggestion is offered. It is important to emphasize past work at KAFB in the source area, and the extensive knowledge of the vadose zone and SVE operations that has been gained through that work. This knowledge and existing infrastructure can both be leveraged in future remedial efforts.

Schedule to Implement (Long/Medium/Short/Not applicable) - Long (>10 yrs.), Medium (5-10 yrs.), and Short (<5 yrs.)

Medium to Long

This technology option is highly dependent on how aggressively it is applied. It is likely to require long-term application with optimization applied during operation lifetime. Pilot testing, design, and infrastructure procurement are relatively straight forward and permitting requirements are not onerous. Access agreements could delay drilling. SVE infrastructure already exists on site which will likely be incorporated into the final strategy.

Infrastructure Requirements and Constraints (List of infrastructure required)

Extraction wells, wellheads, conveyance piping, moisture knockout, filters, silencers, blower(s), blower motor(s), compound / building, manifold, PLC, vapor treatment (oxidizer, GAC, etc.), instrumentation, liquid storage tank, 3-Phase power.

Waste Management (List waste streams to be managed)

Contaminated vapors, condensate, waste oil, grease, PPE, particulate filters. Drilling derived waste (soil cuttings, solid waste, and spent PPE).

Permit Requirements (Low/Med/High) (e.g., OSE, NMED, EPA, AEHD, rights of entry agreements)

OSE well permits, Air Quality permit, building permits, compliance with KAFB security protocols.

Potential Stakeholder Objections

Comments (include references as applicable)

SVE is a well understood technology and applicable strategy for remediating subsurface vadose zone hydrocarbon contamination. In porous media, SVE is the preemptive remedy and, as such, is an appropriate interim strategy. Efforts at SVE to date have been highly successful with significant demonstrated radii of influence and substantial contaminant reduction in zones of the hydrocarbon plume were the technology has been applied. Vapor treatment technologies are likely to change throughout the course of the remediation time period, as treatment transitions to largely diffusion controlled processes in the subsurface.

Panel Comment: The panel suggests this description be re-written as follows.

SVE is a well understood technology and applicable strategy for remediating subsurface vadose zone hydrocarbon contamination. In porous media, SVE is the preemptive remedy and, as such, is an appropriate interim strategy. Efforts at SVE to date have been highly successful with significant demonstrated radii of influence and substantial contaminant reduction in the KAFB source area vadose zone where the technology has been applied. Vapor treatment technologies are likely to change throughout the course of the remediation time period, as system performance transitions to largely diffusion controlled processes in the subsurface.

Panel Comment: This appears to be a reasonable set of additional comments. One item missing is that SVE increases air flow and, if the injected air is not humidified, this promotes vadose zone dessication. Excessive dessication will inhibit the growth of microbes, preventing coincidental biodegradation of hydrocarbons and possibly making it more difficult to subsequently transition to a biologically-oriented treatment, such as bioventing.

Bibliography

AFCEE (n.d.) Soil Vapor Extraction. www.afcee.af.mil/resources/technologytransfer/programsandinitiatives/sourcezonetreatment/background/soilvaporextract/index.asp

EPA (1994). How To Evaluate Alternative Cleanup Technologies for Underground Storage Tank Sites, A Guide for Corrective Action Plan Reviewers. EPA 510-B-94-003. www.epa.gov/oust/pubs/tums.htm

EPA (1997). Analysis of Selected Enhancements for Soil Vapor Extraction. EPA-542-R-97-007. www.clu-in.org/download/remed/sveenhmt.

EPA (n.d.). Technology Focus: Soil Vapor Extraction. www.clu-in.org/techfocus/default.focus/sec/Soil_Vapor_Extraction/cat/Overview

ITRC (2009), Evaluating LNAPL Remedial Technologies for Achieving Project Goals. LNAPL-2
http://www.itrcweb.org/GuidanceDocuments/LNAPL-2.pdf

Johnson, P. C., C. C. Stanley, M. W. Kemblowski, D. L. Byers, and J. D. Colthart (1990). A Practical Approach to the Design, Operation, and Monitoring of In-situ Soil Venting Systems, Ground Water Monitoring Review 10(2): 159–78.

Johnson, P. C., M. W. Kemblowski, and J. D. Colthart (1990). Quantitative Analysis for the Cleanup of Hydrocarbon-Contaminated Soils by In-situ Soil Venting, Ground Water Journal 3(28): 413–29.

USACE 2002. Engineering and Design: Soil Vapor Extraction and Bioventing. EM 1110-1-4001. http://140.194.76.129/publications/eng-manuals/em1110-1-4001/toc.htm

Source Area Interim Treatment Technology Options

3.2 Bioventing with/out SVE (Bruce Alleman, Adria, Steve Reuter, Rick Shean, Billy Gallegos, Stuart Shealy)

Panel comments and suggestions are denoted by text with a colored background.

Description of technology being evaluated - How will the technology be used?

This is a vadose-zone bioremediation technology that utilizes ambient air to provide oxygen to indigenous vadose zone microorganisms that degrade fuel hydrocarbons under the established aerobic conditions. The technology can be operated in either injection or extraction mode depending on site specific conditions. In-situ bioremediation of vadose zone soils/sediments is achieved through the introduction of oxygen via vacuum or air injection.

Panel Comment: The description should explicitly mention that bioventing does not treat LNAPL that has been entrapped (drowned) below the water table, and that it is also not a very effective treatment for LNAPL floating on top of the water table. In other words, operated by itself bioventing is a treatment for LNAPL, and dissolved, sorbed or vapor phase components, contained only within the vadose zone. However, used in combination with other methods it can be effective in remediating floating and drowned LNAPL.

Protective of human health and environment (Yes/No/Uncertain) - Additional info may be needed to qualify answer, specify if LUCs are required

Yes.

Bioventing was developed in the early 1990s and has since been applied at a large number of fuel spill sites. Similar to SVE, bioventing relies on the ability to move vapors in the subsurface. Bacteria capable of degrading petroleum hydrocarbons are ubiquitous in the subsurface. Application of bioventing would diminish and eventually mitigate the potential for additional petroleum hydrocarbons contaminants from reaching groundwater where human health impacts are greater. During bioventing, there is the potential to biodegrade EDB via cometabolic processes if a suitable primary substrate is available. Additional testing and analyses are required to demonstrate that the BFF fuel hydrocarbons are/can support cometabolic degradation of EDB.

Panel Comment: This is a reasonable summary of human health and environmental aspects, although it should also put more emphasis on the impact to conditions below the water table. For example, one could add: “As the method does not effectively treat floating or drowned LNAPL it has little impact on remediating them or the groundwater plume of dissolved constituents, except by reducing additional mass from reaching the water table.

Potential to attain of cleanup standards/goals within reasonable timeframe (<50 years) (High/Medium/Low)

Yes.

Bioventing was developed in the early 1990s and has since been applied at a large number of fuel spill sites. Similar to SVE, bioventing relies on the ability to move vapors in the subsurface. Bacteria capable of degrading petroleum hydrocarbons are ubiquitous in the subsurface. Application of bioventing would diminish and eventually mitigate the potential for additional petroleum hydrocarbons contaminants from reaching groundwater where human health impacts are greater. During bioventing, there is the potential to biodegrade EDB via cometabolic processes if a suitable primary substrate is available. Additional testing and analyses are required to demonstrate that the BFF fuel hydrocarbons are/can support cometabolic degradation of EDB.

Panel Comment: This is a reasonable discussion of bioventing cleanup conditions in the vadose zone, including the discussion of EDB. However, the method is not appropriate for the floating or drowned LNAPL, or the dissolved plume in the source area (BFF). For those contaminated areas the potential of bioventing to achieve aquifer cleanup standards/goals is low unless coupled to other remediation methods.

Control releases to reduce or eliminate further releases of hazardous constituents

Comply with standards for waste management (Yes/No)

Panel Comment: The answer to this question should be "Yes," although if extraction wells are used to induce air movement the extracted vapors should be controlled and treated as needed. Although bioventing does not depend on volatilization of hydrocarbons it will nevertheless occur and extraction wells will produce some hydrocarbon vapors, likely including EDB.

Long term reliability and effectiveness (High/Medium/Low) - Include technology maturity

High.
Bioventing is a mature and proven technology for treating all forms of fuels. The technology has been applied at thousands of sites ranging from corner gas stations to large-volume crude spills. There is uncertainty that bioventing would efficiently treat or fully degrade EDB in the vadose zone.

Reduction of toxicity, mobility, mass, or volume (Yes/No/Uncertain) - Phase specific and should specify what is being reduced

Yes.
Aerobic metabolism ultimately oxidizes fuel hydrocarbons to carbon dioxide and water. Some of the fuel is used by the microorganisms to increase biomass. Over time as the fuel hydrocarbons are depleted, the biomass will breakdown through endogenous decay. There is a reduction in contaminant mass and volume in unsaturated zone. If residual and mobile LNAPL persists in the vadose zone, the rate of biodegradation may not prevent some LNAPL from

reaching groundwater. Should bioventing successfully biodegrade EDB, then mass reduction and toxicity is expected.

Panel Comment: The panel suggests this description be re-written as follows.

Yes.
Aerobic metabolism ultimately oxidizes fuel hydrocarbons to carbon dioxide and water. Some of the fuel is used by the microorganisms to increase biomass. Over time as the fuel hydrocarbons are depleted, the biomass will breakdown through endogenous decay. There is a reduction in contaminant mass and volume in vadose zone. This includes reduction of sorbed, dissolved and vapor-phase contaminants, and LNAPL, in the vadose zone. If residual and mobile LNAPL persists in the vadose zone, the rate of biodegradation may not prevent some LNAPL from reaching groundwater. Should bioventing successfully biodegrade EDB, then reduction of mass-and toxicity due to that compound is expected.

Short-Term Effectiveness (High/Medium/Low/Not effective) - Phase specific, requires specification

Medium.
Implementing bioventing in an aerobic vadose zone will require a short time to acclimated the bacteria to the aerobic conditions, and then to build up a robust population. Experience shows that this acclimation/growth period is completed within 6 months to one year depending on subsurface conditions. As startup, the effective distance that oxygen is delivered from the venting wells can be limited if there are high levels of microbial activity. As venting continues and the more easily degradable fraction of the fuel hydrocarbons is depleted, the effective distance for oxygen delivery will increase. Kinetics of rates of biodegradation are important in bioventing. Effectiveness will be based on the ability of bioventing to fully degrade EDB to targeted clean up levels.

Implementability (Difficult/ Moderate/Easy/Not applicable)

Moderate to Easy
The network of current SVE extraction and soil-vapor monitoring wells can be incorporated into an effective bioventing design. Additional vent wells may be required to ensure effective oxygenation. Inexpensive blowers can easily be plumbed to multiple wells or to single wells where logistics dictate or it makes engineering sense. The thick vadose zone at KAFB is an important factor in designing both extraction and injection wells. Excessive depth of vadose zone and need for for both injection and extraction wells complicate implementing of this treatment technology. Successful application would require delivering oxygen to targeted zones, which may require custom well design and strategies.

Panel Comment: The panel suggests this description be re-written as follows.

Moderate to Easy
The network of current SVE extraction and soil-vapor monitoring wells can be incorporated into an effective bioventing design. Additional vent wells may be required to ensure effective oxygenation. Inexpensive blowers can easily be plumbed to multiple wells or to single wells

where depending on land use constraints at the surface and construction costs. The thick vadose zone at KAFB is an important factor in designing both extraction and injection wells. The significant depth to groundwater at KAFB and need for both injection and extraction wells complicate implementation of this treatment technology. Successful application requires delivering oxygen to targeted zones, which may require custom well design and strategies.

Cost - Capital & O&M (High/Medium/Low) - 1 (>$500M), 2 ($350 - $500M), 3 ($200 - $350M), 4 ($50 - $200M), and 5 (<$50M)

Medium to High.
Bioventing eliminates the need for off-gas treatment, utilizes smaller less expensive equipment that SVE, and given the existing and usable infrastructure the costs for implementation should be much lower that the $10M cutoff. Costs could be wide ranging, based on the number of wells. Vapor treatment costs are eliminated or much reduced compared to SVE. Additional site characterization and laboratory analyses are needed to evaluate the potential for effective EDB treatment using bioventing.

Panel Comment: A minor editorial suggestion is offered. This description emphasizes past work and infrastructure at KAFB in the BFF source area, and the extensive knowledge of the vadose zone and past SVE operations that has been gained through that work. This knowledge and existing infrastructure can both be leveraged in future remedial efforts.

Schedule to Implement (Long/Medium/Short/Not applicable) - Long (>10 yrs.), Medium (5-10 yrs.), and Short (<5 yrs.)

Low.
Effective bioventing implementation would require some short-term soil-gas permeability testing to effectively design an optimal system. It is anticipated that a bioventing system would require approximately one year to design, construct, and put into operation, depending on the various permitting and approval steps required along the way. Bioventing is highly dependent on how aggressively it is applied. This remediation technology is likely to require long term application for complete treatment of contaminated soil/sediment in the vadose zone. The schedule may be dependent on project goals. Soil Vapor Extraction infrastructure already exists on site, which could be incorporated into the final strategy. Questions about aerobic biodegradation of EDB need to be addressed through laboratory microcosm testing using sediments collected from targeted treatment zones. This will requiring drilling and sampling tasks independent of well installations. Soil vapor extraction infrastructure already exists on site, which could be incorporated into the final strategy.

Infrastructure Requirements and Constraints (List of infrastructure required)

- Vent wells; soil-gas monitoring points; blowers (regenerative blowers work well) and associated equipment; conveyance piping, filters, silencers, equipment building, manifold, electrical service including 3-Phase power, heat exchanger.

Waste Management (List waste streams to be managed)

- Drill cuttings and waste fluids pending installation of additional vent wells or soil-gas monitoring points
- Used PPE
- Contaminated vapors, condensate, waste oil, grease, PPE, particulate filters, GAC."

Permit Requirements (Low/Med/High) (e.g., OSE, NMED, EPA, AEHD, rights of entry agreements)

May require an UIC permit. Other permits include OSE well permits, Air Quality permit, building permits, etc.

Potential Stakeholder Objections

Comments (include references as applicable)

Bioventing without air sparging has promise as an interim measure due to the reduction in infrastrucure costs associated with the reduction in equipment necessary to operate the SVE portion of the strategy.

Bibliography

Hinchee, R.E. (1993), Bioventing of Petroleum Hydrocarbons, in Handbook of Bioremediation, CRC Press, Boca Raton, FL.

Leeson, A. Hinchee, R. (1995a). Principles and Practices of Bioventing, Volume I: Bioventing Principles. EPA/540/R95/534a.

Leeson, A. Hinchee, R. (1995b). Principles and Practices of Bioventing, Volume II: Bioventing Design. EPA/540/R95/534b.

Hinchee, R.E. Alleman, B.C. (1997). Bioventing. In Subsurface Restoration. Ann Arbor Press. Chelsea, MI 48118. Chapter 22. pp. 357 - 371..

Foor, D.C., Zwick, T.C., Hinchee, R.E., Hoeppel, R.E., Kyburg, C., Bowling, L. (1995). Passive Bioventing Driven by Natural Air Exchange. In-situ Aeration: Air Sparging, Bioventing and Related Remediation Processes. Battelle Press.

Zimmerman, C.T., Sass, B.M., Zwick, T.C., Alleman, B.C., Payne, C.A., Hoeppel, R.E., Bowling, L., (1997). Principles of Passive Aeration for Biodegradation of JP-5 Jet Fuel. Bioventing Applications and Extensions. Battelle Press.

Natural Pressure-Driven Passive Bioventing, Naval Facilities Engineering Service Center September 2000.

Rossabi, J., Riha, B.D., Vanpelt, R.S., Kmetz, T., Pemberton, B., (1998). Passive Soil Vapor Extraction for Interim Remediation at the Savannah River Site, Physical, Chemical, and

Thermal Technologies, Remediation of Chlorinated and Recalcitrant Compounds. Battelle Press.

Source Area Interim Treatment Technology Options

3.3 Enhanced SVE Techniques (Steve Reuter, Rick Shean, Billy Gallegos, Stuart Shealy)

Panel comments and suggestions are denoted by text with a colored background.

Description of technology being evaluated - How will the technology be used?

Same as 3.1 with addition of heated air or other amendments to enhance volatilization and recovery of contaminants or enhance aerobic biodegradation. The addition of heat raises the vapor pressure of the contaminants, which enhances volatilization and recovery. This technology enhances the recovery of comparatively less volatile compounds, like EDB, and removal of contaminants from fine-grained soils. Inductive and radio-frequency heating are alternatives to thermal enhancement that likely have limited application due to the ~~excessive~~ significant depth/thickness of the vadose zone at KAFB.

Panel Comment: A minor editorial suggestion is offered.

Protective of human health and environment (Yes/No/Uncertain) - Additional info may be needed to qualify answer, specify if LUCs are required

Yes

If properly designed, this technology option would be highly protective of human health and the environment. It would remove the source of hydrocarbon contamination in the subsurface. Enhanced SVE would remove toxic compounds from the vadose zone. Viscosity changes to residual LNAPL could result in its mobilization, if vapor extraction is inadequate. There may be an increased risk of human exposure to recovered vapors; however vapor treatment and engineering controls are proven to abate this risk.

Panel Comment: The Panel suggests this description be re-written as follows.

Yes

If properly designed, this technology option would be highly protective of human health and the environment. It would remove hydrocarbon contamination located in the vadose zone, including sorbed, dissolved, vapor phase, and LNAPL contamination. However, if vapor extraction is inadequate the reduction of LNAPL viscosity associated with higher temperatures could mobilize some residual product. There may be an increased risk of human exposure to recovered vapors; however vapor treatment and engineering controls could be implemented to abate this risk.

Panel Comment: This summary of human health and environmental aspects has been edited for clarity and completeness, above. In addition, the summary should put more emphasis on conditions below the water table. For example, one could add: “As the method does not effectively treat floating or drowned LNAPL it has little impact on remediating them or the groundwater plume of dissolved constituents, except by reducing additional mass from reaching the water table, provided that the enhanced SVE system is operated so as to not mobilize vadose zone LNAPL and allow it to migrate downward to the water table.

Potential to attain of cleanup standards/goals within reasonable timeframe (<50 years) (High/Medium/Low)

High.

Treatment goals should be readily attained in less time than traditional SVE. Optimizing success depends on proper system design, focus on appropriate zones, achieving adequate pore volume exchanges, and implementation of operation/optimization plans. Treatment time is dependent on how aggressively the technology is applied.

Panel Comment: This is a reasonable summary of potential cleanup conditions in the vadose zone, but the method is not appropriate for the floating or drowned LNAPL, or the dissolved plume in the source area (BFF). For those groundwater contaminated areas the potential of enhanced SVE to achieve aquifer cleanup standards/goals is low unless coupled to other remediation methods (e.g., §2). In another comment, this statement and some earlier ones use terms like "Treatment time is dependent on how aggressively the technology is applied." It is not clear what this means. What is an "aggressive application"? Does it refer to air flow rate, thermal energy input, or something else? In any event, there is likely to be an optimal treatment flow rate and temperature, such that increasing either of them above a certain threshold offers no benefit, or even has a detrimental effect. The term "aggressive application" needs to be defined and explained, or perhaps discarded.

Control releases to reduce or eliminate further releases of hazardous constituents

Comply with standards for waste management (Yes/No)

Panel Comment: The Panel suggests that this response be written as follows (similar to that in Section 3.1).

Yes

Control and treatment of extracted vapors will be necessary through at least the early portion of the treatment period.

Long term reliability and effectiveness (High/Medium/Low) - Include technology maturity

High.

Soil Vapor Extraction is a mature and proven technology for treating all forms of fuel. Enhancing the technology with heat or exotic gas amendments has demonstrably significantly reduced remediation times. Heating enhancements of SVE have been proven effective at treating petroleum hydrocarbon contamination. Potential concerns may include the condensation of steam in the soil pores, which would reduce permeability. Additionally, steam injection would introduce moisture to the system, resulting in the potential for the transfer of contaminants from near-groundwater soils to groundwater.

Panel Comment: The Panel suggests this description be re-written as follows.

High.
Soil Vapor Extraction is a mature and proven technology for treating all forms of fuel. Enhancing the technology with heat or exotic gas amendments has demonstrated significantly reduced remediation times. Heating enhancements of SVE have been proven effective at treating petroleum hydrocarbon contamination. Potential concerns may include the condensation of steam in the soil pores, which would increase water saturation and reduce air permeability. Additionally, steam injection would introduce moisture to the system, resulting in the potential for enhanced groundwater recharge and the transfer of dissolved contaminants from the vadose zone to groundwater.

Reduction of toxicity, mobility, mass, or volume (Yes/No/Uncertain) - Phase specific and should specify what is being reduced

Uncertain.
This technology option reduces contaminant mass/volume as soil vapor through advection and diffusion processes. This technology is also effective for adsorbed contaminants and LNAPL. Mobility is typically increased through heat addition. Increased vapor mobility is an intended benefit of this technology and SVE needs to be designed to capture liberated contaminants.

Panel Comment: The Panel suggests this description be re-written as follows:

Uncertain.
This technology option has the ability to reduce vadose zone contaminant mass/volume through soil-vapor advection and diffusion processes. This includes reduction of sorbed, dissolved and vapor-phase contaminants, and LNAPL in the vadose zone. LNAPL mobility as a separate liquid phase is typically increased through heat addition, however, care must be taken to ensure that the enhanced SVE system is designed to minimize the vertical migration of mobilized LNAPL.

Short-Term Effectiveness (High/Medium/Low/Not effective) - Phase specific, requires specification

High
If properly designed and implemented, this technology could prove to be highly effective in the short term. Increased volatility and mobility of the COCs in the subsurface would enhance contaminant recovery. Controlling enhanced mobility of the contaminants would be a primary design concern. Short term effectiveness of SVE will be high, but fully benefiting from heat enhancement may take time to establish in the subsurface. The heat capacity of the soil/sediment will dictate how long it takes to promulgate heat away from extraction wells. The excessive thickness of the vadose zone at KAFB may complicate application of this technology across the entire volume of vadose zone contamination.

Panel Comment: The Panel suggests this description be re-written as follows:

High
If properly designed and implemented, this technology could prove to be highly effective in the short term. Increased volatility and mobility of the COCs in the subsurface would enhance contaminant recovery. Controlling mobility of the LNAPL would be an important design criteria. Short term effectiveness of SVE will be high, but fully benefiting from heat enhancement may take time to establish due to heat transfer limitations. The heat capacity of the soil/sediment, and the latent heat of water, will dictate how long it takes to promulgate heat away from extraction wells. The significant thickness of the vadose zone at KAFB may complicate application of this technology across the entire volume of BFF source area.

Panel Comments: The Panel noted that the statement does not acknowledge the very important role of sedimentary heterogeneity which creates high permeability preferential flow paths and low permeability (especially stratified) barriers. Both lead to by-passing of contaminated zones and reduce the effectiveness of enhanced SVE. Contaminants that are sequestered in low permeable soils may lead to a rebound effect upon the termination of SVE and decrease short-term SVE effectiveness. However, the use of heat in enhanced SVE should significantly increase the rate of diffusion within these fine-grained units and speed their remediation. This may be one of the principle benefits of enhanced SVE. Finally, the description contains an ambiguous statement that "benefiting from heat enhancement may take time to establish in the subsurface." It is followed by and appears to be setting up a description of heat transfer limitations. The suggested modification to the description are intended to clarify this.

Implementability (Difficult/ Moderate/Easy/Not applicable)

Easy to Moderate.
The thick vadose zone at KAFB is a significant factor in implementing this technology at KAFB. Heat loss in the vadose zone may be significant. Treating the entire contamination volume of vadose zone with heat enhancement may not be feasible or necessary. The implementation strategy may limit concentrating enhanced SVE at discrete zones of highly contaminated soil or for specific compound treatment (i.e. EDB).

Panel Comment: The Panel suggest this description be re-written as follows.

Easy to Moderate.
The thick vadose zone presents a significant challenge in implementing this technology at KAFB. Applying heat only to the very deep LNAPL zone without losing heat to uncontaminated soils will be difficult. This may be important since heating the entire volume of vadose soils with heat enhancement may not be feasible or desirable. The implementation strategy may limit the application of enhanced SVE to discrete zones of highly contaminated soil or to address specific contaminants (i.e. EDB).

Cost - Capital & O&M (High/Medium/Low) - 1 (>$500M), 2 ($350 - $500M), 3 ($200 - $350M), 4 ($50 - $200M), and 5 (<$50M)

High.
Utilities, steel pipe and casing required for heat enhancement. Any enhancement to the air sparge strategy or SVE strategy will have a profound increase on costs. Significant cost differences from SVE include increased utility infrastructure and operating costs, steel pipe and well casing, protection of existing subsurface infrastructure, and heating equipment.

Panel Comment: First, applying heat only to the LNAPL zone as discussed in the previous paragraph has a significant cost aspect. Cost may limit the application of "enhanced SVE to discrete zones of highly contaminated soil or for specific compound treatment (i.e. EDB)." This should be repeated here. Second, it is important to emphasize past work at KAFB in the source area, and the extensive knowledge of the vadose zone and SVE operations that has been gained through that work. This knowledge and existing infrastructure can both be leveraged in future remedial efforts.

Schedule to Implement (Long/Medium/Short/Not applicable) - Long (>10 yrs.), Medium (5-10 yrs.), and Short (<5 yrs.)

Medium.
This technology option is highly dependent on how aggressively it is applied. It is likely to require long term-application with optimization applied during operation. Pilot testing, design, and infrastructure procurement are straight forward and permitting requirements are not onerous. Access agreements could delay drilling. SVE infrastructure already exists on site, which will likely be incorporated into the final strategy. However, all injection infrastructure would need to be installed with materials compatible with high heat. Additional vadose zone characterization may be needed in advance of the design to optimize heat application.

Panel Comment: This description is somewhat vague. "This technology option is highly dependent on how aggressively it is applied." What is highly dependent? Cost? Time? Infrastructure? After the first two sentences the description becomes tractable and adequate. If anything it could put greater emphasis on the challenges of working with "high heat."

Infrastructure Requirements and Constraints (List of infrastructure required)

Extraction wells, injection wells, wellheads, conveyance piping, moisture knockout, filters, silencers, blower(s), blower motor(s), compound / building, manifold, PLC, vapor treatment (oxidizer, GAC, etc.), instrumentation, liquid storage tank, 3-Phase power.

Waste Management (List waste streams to be managed)

Contaminated vapors, condensate, waste oil, grease, PPE, particulate filters

Panel Comment: The equivalent waste management consideration listed in Section 3.1 for SVE includes additional items, missing here. The list here should be no shorter.

Permit Requirements (Low/Med/High) (e.g., OSE, NMED, EPA, AEHD, rights of entry agreements)

OSE well permits, air quality permit, building permits, etc.

Potential Stakeholder Objections

Comments (include references as applicable)

Same as SVE above. Significant project cost savings may be realized with shortened project timelines associated with a properly designed enhanced SVE strategy. Some enhancements have been demonstrated to significantly reduce necessary operational time for remediation systems. In addition, enhanced SVE techniques may be desirable to address increasing the mobility and volatility of the contaminants of concern.

Panel Comments: Why is it “In addition” to say that enhance SVE increases mobility and volatility. That is why project timelines and operational times are shortened (lines 1 and 3). The last sentence is redundant and unnecessary. In the Panel Comments on the equivalent section on SVE extraction we noted the issue of dessication of the vadose zone. Assuming that dry heat is applied in enhanced SVE that becomes an even more significant issue. If steam is used instead the spreadsheet notes that moisture will be added to the vadose zone, changing water saturations and possibly increasing groundwater recharge. In the Panel Comments on the equivalent section on bioventing we note the need for a moisture management component to the remedial scheme. This discussion of enhanced SVE provides further evidence for the need to formally recognize and deal with moisture management of the vadose zone.

Bibliography

AFCEE (n.d.) Soil Vapor Extraction. www.afcee.af.mil/resources/technologytransfer/programsandinitiatives/sourcezonetreatment/background/soilvaporextract/index.asp

EPA (1994). How To Evaluate Alternative Cleanup Technologies for Underground Storage Tank Sites, A Guide for Corrective Action Plan Reviewers. EPA 510-B-94-003. www.epa.gov/oust/pubs/tums.htm

EPA (1995). In-situ Remediation Technology Status Report: Thermal Enhancements. EPA/542-K-94-009. www.clu-in.org/download/remed/thermal.pdf

EPA (1997). Analysis of Selected Enhancements for Soil Vapor Extraction. EPA-542-R-97-007. www.clu-in.org/download/remed/sveenhmt.

EPA (1998). Steam Injection for Soil and Aquifer Remediation. EPA/540/S-97/505. www.epa.gov/tio/tsp/download/steaminj.pdf

EPA (1995). In-situ Remediation Technology Status Report: Thermal Enhancements. EPA/542-K-94-009. www.clu-in.org/download/remed/thermal.pdf

EPA (n.d.) “Technology Focus: In-situ Thermal Heating.” www.clu-in.org/techfocus/default.focus/sec/Thermal_Treatment:_In_Situ/cat/Overview

FRTR (n.d._ “Remedial Technology Screening and Reference Guide, Version 4.0, In-situ Thermal Treatment.” www.frtr.gov/matrix2/section4/4-9.html

ITRC, (2009), Evaluating LNAPL Remedial Technologies for Achieving Project Goals. LNAPL-2 http://www.itrcweb.org/GuidanceDocuments/LNAPL-2.pdf

Johnson, P. C., C. C. Stanley, M. W. Kemblowski, D. L. Byers, and J. D. Colthart (1990). A Practical Approach to the Design, Operation, and Monitoring of In-situ Soil Venting Systems, Ground Water Monitoring Review 10(2): 159–78.

Johnson, P. C., M. W. Kemblowski, and J. D. Colthart (1990). Quantitative Analysis for the Cleanup of Hydrocarbon-Contaminated Soils by In-situ Soil Venting, Ground Water Journal 3(28): 413–29.

USACE (2002). Engineering and Design: Soil Vapor Extraction and Bioventing. EM 1110-1-4001. http://140.194.76.129/publications/eng-manuals/em1110-1-4001/toc.htm

USACE (200. Engineering and Design: In-situ Thermal Remediation. EM-1110-1-4015. http://140.194.76.129/publications/eng-manuals/em1110-1-4015/entire.pdf

Source Area Interim Treatment Technology Options

4.1 Solvents (Javier Santillan, Bruce Alleman, Adria Bodour)

Panel comments and suggestions are denoted by text with a colored background.

Description of technology being evaluated - How will the technology be used?

This technology is based on mature technologies as described by ITRC, and is applicable to the LNAPL source area at BFF. Expectations indicate that over 99% of the light hydrocarbons and EDB would be recovered. ITRC indicates a DNAPL recovery of 75%. There could be differences when extracting an LNAPL. The solvent selected should be non-hazardous and biodegradable over short periods of time to assure NMED acceptance. The hydrophobic-lipophilic balance of the flushing solution would be designed for KAFB-BFF conditions. High definition of site lithology and hydrogeology is essential for system design. It is essential to have an effective recovery (extraction) system to capture all products during LNAPL mobilization.

Panel Comments: This is a good summary of solvent flooding that may be appropriate for application at the KAFB BFF site. However, the suggested 99% recovery needs some explanation. That is the kind of recovery one gets during a bench test of homogeneous coarse sediments. Aquifer heterogeneity, depth to water table, and the size of the source area make this level of recovery for LNAPL very unlikely.

Protective of human health and environment (Yes/No/Uncertain) - Additional info may be needed to qualify answer, specify if LUCs are required

Yes.

If properly designed, it would be highly protective of human health and the environment. It would remove the source of contamination. Implementation will be complex, and handling the solvent mixture may not be a simple issue. Handling and disposal of recovered contaminants and waste within the exclusion zone must be kept secure.

Panel Comment: This is a reasonable summary of human health and environmental aspects. It should be noted that to prevent the solvent/contaminant mixture from migrating offsite it is essential to maintain excellent control of groundwater flow in and surrounding the source area.

Potential to attain of cleanup standards/goals within reasonable timeframe (<50 years) (High/Medium/Low)

High.

A properly designed system, based on an accurate CSM would have high probability of meeting cleanup goals in < 50 yrs.

Panel Comments: This assessment of time assumes that the CSM adequately addresses the aquifer heterogeneity issue, and that it includes a good description of the spatial pattern of drowned LNAPL and dissolved contamination. Even in that case, however, there are issues not yet understood that could slow clean up. The rate of mass transfer from drowned LNAPL ganglia and pools depends on their size, shape, volume fraction and location, for which there is little characterization data. This NAPL geometry controls the interfacial area between water and NAPL phases, the efficiency of component diffusion toward the interface, and the flow rate of the water-solvent mixture adjacent to the interface, all influencing mass transfer. Larger pools and larger NAPL phase saturations have slower mass transfer rates regardless of how much the solubility is increased by addition of a solvent. But larger NAPL pools and lower water saturations also create more tortuous and resistive water flow paths, making it more difficult to bring injected reactants into contact with dissolved components located next to NAPL-water interfaces, limiting dissolution and reducing mass transfer even more. Consequently, larger pools are more difficult to remediate, and will take longer. The description should recognize that further characterizing the LNAPL source will help determine the potential effectiveness of solvent-based treatment technologies.

Control releases to reduce or eliminate further releases of hazardous constituents

Comply with standards for waste management (Yes/No)

Panel Comment: The characterization of this technology should be written as follows:

Yes
Control of solvents, and treatment and control of extracted water will be necessary.

Long term reliability and effectiveness (High/Medium/Low) - Include technology maturity

High.
There are several remediation technologies being applied here, but all of them are mature, and well documented. Reliability should be high, if properly designed and operated.

Panel Comment: For reliability and effectiveness to be high you need sufficient characterization information on sedimentary heterogeneity and LNAPL spatial distribution (high resolution CSM), and complete control of groundwater flow, in the KAFB source area.

Reduction of toxicity, mobility, mass, or volume (Yes/No/Uncertain) - Phase specific and should specify what is being reduced

Yes.
If properly designed and operated, toxicity will be reduced and contaminant mass removed from the known LNAPL area.

Short-Term Effectiveness (High/Medium/Low/Not effective) - Phase specific, requires specification

High.
If properly designed and operated, effectiveness will be high for the dissolved phase.

Panel Comment: The Panel suggests that this description be re-written as follows and that its characterization be changed from "high" to "uncertain."

Uncertain.
This technology option is uncertain without a high resolution CSM.

High, Uncertain
If properly designed and operated, effectiveness will be high for the dissolved phase and medium for the LNAPL. Uncertainty is due to the quality of the CSM and its delineation of aquifer heterogeneity and LNAPL distribution.

Implementability (Difficult/ Moderate/Easy/Not applicable)

Difficult.
Prior to system design, a high definition (HD) CSM and a hydrogeological computer model would have to be developed. Bench and pilot studies would need to be conducted to evaluate solvent mixture; injection, and extraction points, and management of effluent.

Panel Comments: One of the first activities is to identify the solvent to be used, or the family of potential solvents. Several candidate solvents could be included in the bench tests. The bench and pilot studies should include the geochemistry of solvent-sediment interaction, particularly the fine grained fraction. Design and operation would be assisted by coupling the flow and reactive transport computer model to an optimization scheme to find the best depths, locations and rates for injection/extraction. The design should recognize that the scheme should adapt to changing conditions as the water table continues to rise and as LNAPL mass is reduced.

Cost - Capital & O&M (High/Medium/Low) - 1 (>$500M), 2 ($350 - $500M), 3 ($200 - $350M), 4 ($50 - $200M), and 5 (<$50M)

1 to 3. ($200M to >$500M)
Cost would be medium to high depending on the number of wells required to implement this technology.

Panel Comment: The Panel suggest that the description be re-written as follows.

1 to 3. ($200M to >$500M)
Cost would be medium to high depending on the number of wells required to implement this technology, the mass of solvent needed for implementation and its unit cost. In addition, volume and quality of extracted water requiring treatment and its subsequent disposal options will influence the cost of the technology.

Schedule to Implement (Long/Medium/Short/Not applicable) - Long (>10 yrs.), Medium (5-10 yrs.), and Short (<5 yrs.)

Long (>10 yrs)
This technology option requires multiple extraction, injection, and monitoring points. Bench and pilot studies are required to select the solvent mixture. Extraction and injection points may need to be relocated and repeated to increase effectiveness of the cleanup action.

Infrastructure Requirements and Constraints (List of infrastructure required)

Substantial.
Multiple extraction, injection, and monitoring points are required to flush the LNAPL, it would require 150 to 500 wells.

Panel Summary: As described in the spreadsheet, this technology will require a lot of wells. While the size of the KAFB source area suggests a large number wells be used, the significant depth to the water table (500 feet) suggests that fewer may be feasible. Perhaps with a high spatial-resolution description of aquifer heterogeneities, and a similar description of the spatial distribution of dissolved concentrations and LNAPL, a large number of wells could be used effectively to more quickly apply this approach. However, the uncertainty in this characterization, coupled together with the cost of wells at this depth, suggest that a much smaller number of wells would be more reasonably deployed, perhaps a few tens of wells, despite the size of the source area. Using the CSM and groundwater model for flow and transport, together with optimization techniques, an effective groundwater control (extraction and injection) scheme can be designed to best meet cost and human health/environmental constraints and/or goals with significantly fewer than 150-500 wells.

Waste Management (List waste streams to be managed)

Substantial.
Wastewater will have to be handled and treated. Solvent recycling or attenuation adds another layer of complexity.

Permit Requirements (Low/Med/High) (e.g., OSE, NMED, EPA, AEHD, rights of entry agreements)

Reinjection and/or wastewater disposal permits will have to be procured from NMED. Rights of entry for multiple extraction, injection, and monitoring wells.

Potential Stakeholder Objections

Comments (include references as applicable)

ITRC (2003). Technical and Regulatory Guidance for Surfactant/Cosolvent Flushing of DNAPL Source Zones, ITRC.

EPA (n.d.). In-situ Flushing Overview http://www.clu-in.org/techfocus/default.focus/sec/In_Situ_Flushing/cat/Overview/[1/13/2015 2:18:07 PM]

McCray et al., Remediation of LNAPL Source Zones: Lessons Learned from Field Studies at Hill and Dover AFB,   Vol. 49, No.5–GROUNDWATER–September-October 2011 (pages 727–744)"

Bibliography

AFCEE (n.d.) "Cosolvent or Surfactant-Enhanced Remediation." www.afcee.af.mil/resources/technologytransfer/programsandinitiatives/

Ground-Water Remediation Technologies Analysis Center (1997). In-situ Flushing Technology Overview Report. TO-97-02. http://clu-in.org/download/remed/flush_o.pdf

ITRC (2003). Technical and Regulatory Guidance for Surfactant/Cosolvent Flushing of DNAPL Source Zones. DNAPL-3. http://www.itrcweb.org/Guidance/GetDocument?documentID=20

ITRC, (2009). Evaluating LNAPL Remedial Technologies for Achieving Project Goals. LNAPL-2 http://www.itrcweb.org/GuidanceDocuments/LNAPL-2.pdf

McCray et al.. (2011). Remediation of LNAPL Source Zones: Lessons Learned from Field Studies at Hill and Dover AFB, <u>Groundwater</u>, 49(5), 727-744.

Source Area Interim Treatment Technology Options

4.2 Surfactant/Cosolvent

Surfactant Enhanced Aquifer Remediation (SEAR) (Javier Santillan, Bruce Alleman, Adria Bodour)

Panel comments and suggestions are denoted by text with a colored background.

Description of technology being evaluated - How will the technology be used?

This technology is based on a mature enhanced oil recovery (EOR) technology developed by the petroleum industry which has also been tested and used for aquifer remediation, and would primarily be applicable to the LNAPL source area for the purpose of removing at least 99.9% of the light hydrocarbons and EDB and 50 to 90% of the remaining fuel components (based on a Hill AFB Study). The surfactant should be non-hazardous and biodegradable. The hydrophobic-lipophilic balance of the flushing solution would be designed for KAFB-BFF conditions. High definition of site lithology and hydrogeology is essential for system design. It is essential to have an effective recovery (extraction) system to capture all products during mobilization of LNAPL.

Panel Comments: The description has been slightly edited as indicated above. This is a good summary of surfactant flooding appropriate for KAFB, although it is missing an important but somewhat obvious point. Surfactant flooding remediates LNAPL mainly by increasing the solubility of LNAPL components. There is a secondary and important effect that can actually mobilize the LNAPL, in which the surfactant also reduces the interfacial tension between LNAPL and water, reducing capillary forces. This description is focused on the solubility effect and not NAPL mobilization. The suggested 50-90% recovery of LNAPL needs some explanation, as well as the 99% recovery of more soluble components. That is the kind of recovery one gets during a bench test, or small pilot project, for fairly homogeneous coarse sediments. Aquifer heterogeneity, the presence of fine-grained sediments, the significant depth to water table, and the size of the source area make recovery efficiencies such as these, for LNAPL and the more soluble components, very unlikely at the KAFB source area. We also suggest removing the broader reference to EOR as irrelevant and distracting. Note that many of the considered remediation technologies in this spreadsheet have a similar applications in petroleum recovery (e.g., solvent flooding, stream flooding, and water flooding). (Aside: This spreadsheet should not be a review of EOR. Besides, a lot of EOR processes use (or must use) low salinity water, not brine, to achieve the desired chemistry. In fact "low salinity water flooding" (<5000 ppm) without added chemicals is a rapidly growing EOR method. Also, CO_2 flooding is only one EOR method – one that might work well for drowned LNAPLs at KAFB if they were located 2000 feet below the water table in the CO_2 supercritical zone.).

Protective of human health and environment (Yes/No/Uncertain) - Additional info may be needed to qualify answer, specify if LUCs are required

Yes.

If properly designed, it would be highly protective of human health and the environment. It would remove the source of contamination. Implementation will be complex, and handling of the surfactant and cosolvent may not be a simple issue. Handling and disposal of recovered contaminants within the exclusion zone must be kept secure.

Panel Comments: This is a reasonable summary of human health and environmental aspects. However, the quote "would remove the source of contamination" is unrealistic. The method could substantially reduce the mass of more soluble components, like BTEX and EDB, but it would be less effective in dealing with the heavier, less soluble hydrocarbons in the LNAPL.

It should be noted that to prevent the surfactant/contaminant mixture/solution from migrating offsite it is essential to maintain excellent control of groundwater flow in and surrounding the source area.

Potential to attain of cleanup standards/goals within reasonable timeframe (<50 years) (High/Medium/Low)

High

A properly designed system, based on an accurate CSM would have a high probability of meeting cleanup goals in < 50 yrs.

Panel Comments: This assessment of time assumes that the CSM adequately addresses the aquifer heterogeneity issue, and that it includes a good description of the spatial pattern of drowned LNAPL and dissolved contamination. Even in that case, however, there are issues not yet understood that could slow clean up. The rate of mass transfer from drowned LNAPL ganglia and pools depends on their size, shape, volume fraction and location, for which there is little characterization data. This NAPL geometry controls the interfacial area between water and NAPL phases, the efficiency of component diffusion toward the interface, and the flow rate of the water-surfactant solution adjacent to the interface, all influencing mass transfer and the potential to mobilize NAPL through reduction of interfacial tensions (IFTs). Larger pools and larger NAPL phase saturations have slower mass transfer rates no matter how much the solubility is increased by addition of a solvent. But larger NAPL pools and lower water saturations also create more tortuous and resistive water flow paths, making it more difficult to bring injected reactants into contact with dissolved components located next to NAPL-water interfaces, limiting dissolution (and IFT reduction) and reducing mass transfer even more. Consequently, larger pools are more difficult to remediate, and will take longer. What proportion of the LNAPL at the KAFB source area is in larger pools, how large are they, and how will they respond to the solvent-based treatment technology?

Control releases to reduce or eliminate further releases of hazardous constituents

Comply with standards for waste management (Yes/No)

Panel Comment: The Panel suggests that the response be written as:

Yes

Control of surfactants, and treatment and control of extracted water will be necessary.

Long term reliability and effectiveness (High/Medium/Low) - Include technology maturity

High.
There are several remediation technologies being applied here, but all of them are mature, and well documented. Reliability should be high, if properly designed and operated.

Panel Comment: For reliability and effectiveness to be high you need sufficient characterization information on sedimentary heterogeneity and LNAPL spatial distribution (high resolution CSM), and complete control of groundwater flow, in the KAFB source area.

Reduction of toxicity, mobility, mass, or volume (Yes/No/Uncertain) - Phase specific and should specify what is being reduced

Yes.
If properly designed and operated, toxicity will be reduced and contaminant mass removed from the known LNAPL area.

Short-Term Effectiveness (High/Medium/Low/Not effective) - Phase specific, requires specification

High, Uncertain
If properly designed and operated, effectiveness will be high in eliminating the source of BTEX and EDB.

Panel Comments: The Panel believes that the short-term effectiveness is better characterized as “uncertain” rather than “high.” It is not clear what is meant by the “source of BTEX and EDB.” Does this mean removing these soluble components from the LNAPL by mass transfer to the dissolved phase? In any event while this method is effective for the dissolved phase, it is uncertain for the LNAPL itself. This is due in part to the volume of NAPL present, the limited solubility of heavier components, and the possible presence of large NAPL pools with poor mass transfer characteristics. This estimate is uncertain is due to the quality of the conceptual site model and its delineation of aquifer heterogeneity and LNAPL distribution

Implementability (Difficult/ Moderate/Easy/Not applicable)

Difficult.
Prior to system design, a high definition (HD) CSM and a hydrogeological computer model would have to be developed. Bench and pilot studies would need to be conducted to evaluate surfactant mixture; injection, and extraction points, and management of effluent.

Panel Comments: One of the first activities is to identify the surfactant to be used, or the family of potential solvents. Several candidate surfactants could be included in the bench tests. The bench and pilot studies should include the geochemistry of surfactant-sediment interaction, particularly for the fine grained fraction. Design and operation would be assisted by coupling the flow and reactive transport computer model to an optimization scheme to find the best depths, locations and rates for injection/extraction. The design should recognize that the scheme could adapt to changing conditions as the water table continues to rise and as LNAPL mass is reduced.

Cost - Capital & O&M (High/Medium/Low) - 1 (>$500M), 2 ($350 - $500M), 3 ($200 - $350M), 4 ($50 - $200M), and 5 (<$50M)

1. to 3. ($200 M to >$500M)

Cost would be medium to high depending on the number of wells required to implement this technology, the mass of surfactant needed for implementation, and the volume and concentration of extracted water requiring treatment.

Panel comment: The Panel suggests additional clarification to the description as shown above. The likelihood of medium cost is low. The price of surfactant is likely to drive the cost up, although no particular surfactant has yet been suggested.

Schedule to Implement (Long/Medium/Short/Not applicable) - Long (>10 yrs.), Medium (5-10 yrs.), and Short (<5 yrs.)

Long

This technology option requires multiple extraction, injection, and monitoring points. Bench and pilot studies are required to select the surfactant mixture. Extraction and injection points may need to be relocated and repeated to increase effectiveness of the cleanup action.

Infrastructure Requirements and Constraints (List of infrastructure required)

Substantial

Multiple extraction, injection, and monitoring points to flush the LNAPL are required, and it would require 150 to 500 wells.

Panel comments: As described in the spreadsheet, this technology will require a lot of wells. While the size of the KAFB source area suggests a large number wells be used, the significant depth to the water table (500 feet) suggests fewer. Perhaps with a high spatial-resolution description of aquifer heterogeneities, and a similar description of the spatial distribution of dissolved concentrations and LNAPL, a large number of wells could be used effectively to more quickly apply this approach. However, the uncertainty in this characterization, coupled with the cost of wells at this depth, suggest that a much smaller number of wells would be more reasonably deployed, perhaps a few tens of wells, despite the size of the source area. Using the CSM and groundwater model for flow and transport, together with optimization techniques, an effective groundwater control (extraction and injection) scheme can be designed to best meet cost and human health/environmental constraints and/or goals with fewer than 150-500 wells.

Waste Management (List waste streams to be managed)

Substantial.

Wastewater will have to be handled and treated. Surfactants and cosolvent recycling or attenuation adds another layer of complexity.

Panel Comment: There will also be wastes from the drilling operation.

Permit Requirements (Low/Med/High) (e.g., OSE, NMED, EPA, AEHD, rights of entry agreements)

Reinjection and/or wastewater disposal permits will have to be procured from NMED. Rights of entry for multiple extraction, injection, and monitoring wells.

Panel Comment: See edits above.

Potential Stakeholder Objections

Comments (include references as applicable)

Technical and Regulatory Guidance for Surfactant/Cosolvent Flushing of DNAPL Source Zones, ITRC, April 2003

EPA In-situ Flushing Overview http://www.clu-in.org/techfocus/default.focus/sec/In_Situ_Flushing/cat/Overview/[1/13/2015 2:18:07 PM]

"New surfactant classes for enhanced oil recovery and their tertiary oil recovery potential", Iglauer et al. Journal of Petroleum Science and Engineering 71 (2010) 23-29 "

Bibliography

AFCEE (n.d.) Cosolvent or Surfactant-Enhanced Remediation. www.afcee.af.mil/resources/technologytransfer/programsandinitiatives/sourcezonetreatment/background/cosolvent-surfac/index.asp

EPA (1991). In-situ Soil Flushing. EPA 540-2-91-021.

EPA (1995). Surfactant Injection for Ground Water Remediation: State Regulators' Perspectives and Experiences. EPA 542-R-95-011. www.epa.gov/tio/download/remed/surfact.pdf

Ground-Water Remediation Technologies Analysis Center (1997). In-situ Flushing Technology Overview Report. TO-97-02.
http://clu-in.org/download/remed/flush_o.pdf

ITRC (2003). Technical and Regulatory Guidance for Surfactant/Cosolvent Flushing of DNAPL Source Zones. DNAPL-3. http://www.itrcweb.org/GuidanceDocuments/DNAPLs-3.pdf

ITRC (2009). Evaluating LNAPL Remedial Technologies for Achieving Project Goals. LNAPL-2 http://www.itrcweb.org/GuidanceDocuments/LNAPL-2.pdf

NAVFAC (2003). Surfactant-Enhanced Aquifer Remediation (SEAR) Implementation Manual. NFESC TR-2219-ENV. www.clu-in.org/download/techdrct/td-tr-2219-sear.pdf

NAVFAC (2006). Surfactant-Enhanced Aquifer Remediation (SEAR) Design Manual. TR-2206-ENV. http://74.125.93.132/search?q=cache:CcfUkrCwimAJ:www.clu-in.org/download/contaminantfocus/dnapl/Treatment_Technologies/SEAR_Design.pdf+Surfactant-Enhanced+Aquifer+Remediation+(SEAR)+Design+Manual&cd=1&hl=en&ct=clnk&gl=us

Source Area Interim Treatment Technology Options

4.3 Water (Javier Santillan, Bruce Alleman, Adria Bodour)

Panel comments and suggestions are denoted by text with a colored background.

Description of technology being evaluated - How will the technology be used?

This technology would be primarily applicable to the EDB dissolved plume in the KAFB source area. Water flushing the LNAPL in the source area would only solubilize light hydrocarbons and EDB with limited efficiency. Water: recirculation, extraction/reinjection, extraction/treatment/reinjection, extraction/treatment/reinjection-with-substrate(s) added are all different versions of water flushing technologies. Each is applicable to dissolved phase under specific favorable conditions. The primary purpose is to reduce the time required to move a pore volume through the contaminated zone; thus, accelerating cleanup. Time reduction is attained by adjusting the recirculation volume, based on the site's hydraulic properties. Extraction-reinjection fields are directly proportional to soil particle size: shorter for tight soils and larger for sandy soils. High definition of site lithology and hydrogeology is essential for system design.

Panel Comments: Minor editorial suggestions are offered. This is a succinct but somewhat vague description of the value of groundwater flow passing through the KAFP BFF source zone, dissolving the more soluble components (including EDB) out of the drowned LNAPL, carrying that dissolved phase contamination downgradient where it is presumably removed and treated ("recirculation," "extraction," etc). The description places emphasis on reducing the time to displace a pore volume within the source zone with the likely reasonable assumption that mass transfer is limited only by the groundwater flow rate. This section also talks about additives ("reinjection-with-substrate(s) added"), but below there is little attention paid to this option. Sections 4.1 and 4.2 focus specifically on two types of additives, solvents and surfacts. Both of those additives increase solubility of LNAPL components, with a less important impact on LNAPL interfacial tension with water, increasing the propensity to mobilize some of the NAPL.

Protective of human health and environment (Yes/No/Uncertain) - Additional info may be needed to qualify answer, specify if LUCs are required

Yes.

This technology option is protective of human health and the environment for both hydrocarbons present in fuel and EDB in dissolved phase. Longer chain hydrocarbons present in the LNAPL will not be significantly attenuated. EDB is the primary risk driver at the site, and it will be removed. However, contaminants will be brought to the surface where contact with receptors can occur. Handling and disposal of recovered contaminants within the exclusion zone must be kept secure. Limited effectiveness on the LNAPL.

Panel Comment: This is a reasonable summary of human health and environmental aspects as long as the groundwater flow is controlled, and with the caveat that it is not clear that this technology would remove all EDB ("it will be removed") due to its presence in LNAPL and due to aquifer heterogeneity.

Potential to attain of cleanup standards/goals within reasonable timeframe (<50 years) (High/Medium/Low)

Variable.
A recirculation system designed based on a high definition CSM will have a high probability to meet cleanup goals within a reasonable time in the dilute downgradient plume, if source zone is attenuated and controlled. In the absence of a high resolution CSM, potential to meet goals is medium for the dilute plume and low for the LNAPL.

Panel Comments: This description is a bit vague. Is the "dilute plume" the downgradient dissolved plume (thus the suggested edit above), or is it the dissolved plume in the source area itself? Assuming the latter, then as long as the LNAPL remains so will the source area dissolved plume. It is claimed that the potential to meet this goal is better for the dissolved plume than for LNAPL, but this assumes that the more soluble components will be depleted from the LNAPL to the point where aquifer dissolved concentrations are significantly reduced even though LNAPL remains. Is there a mass balance calculation to support this assumption? Finally, the term "dilute" is itself vague and should probably be replaced by "dissolved." In solution all concentrations in this aquifer are very dilute. Concentrations are low enough that water density, viscosity, and other properties are not affected. However, concentrations can be many times greater than groundwater or drinking water standards. The term dilute may be misleading when the focus is on human health and the environment. Finally, we presume that the emphasis on a "high resolution CSM" refers, among other things, to a strong grasp of sedimentary architecture and heterogeneity, and to the spatial distribution of drowned LNAPL. In any event, for each section of this spreadsheet the term should be redefined with emphasis on aspects of the CSM of special concern to the remedy being assessed. It turns out that aquifer (or vadose zone) heterogeneity is an issue for all of the proposed methods.

Control releases to reduce or eliminate further releases of hazardous constituents

Comply with standards for waste management (Yes/No)

Panel Comment: The Panel suggests that the response be written as.

Yes
Control and treatment of extracted water will be necessary.

Long term reliability and effectiveness (High/Medium/Low) - Include technology maturity

Medium to Low
Recirculation is based on mature pump and treat (P&T) technologies. The design and its implementation is the primary difference with traditional P&T. Addition of substrates is also a mature technology commonly implemented as ISEB. However, injecting and extracting from the

appropriate aquifers locations at 500' bgs may prove to be difficult. Therefore, the reliability is medium to low. A high definition CSM would improve reliability of this technology.

Panel Comment: The Panel suggests that this description be re-written as follows.

Medium to Low
Recirculation, extraction and injection is based on mature pump and treat (P&T) technologies. The KAFB site's need for a unique design and implementation is the primary distinction from traditional P&T. Addition of substrates to support biodegradation is also a mature technology often implemented as *in-situ* enhanced bioremediation (ISEB). However, identifying appropriate aquifer units for injection and extraction at depths of 500 ft may prove to be difficult. Therefore, the reliability is medium to low. A high definition CSM would improve confidence in this technology.

Reduction of toxicity, mobility, mass, or volume (Yes/No/Uncertain) - Phase specific and should specify what is being reduced

Yes, Potentially Uncertain.
If properly designed and operated, toxicity will be reduced and contaminant mass removed from the dissolved plume. However, without a high resolution CSM and attenuation of the source zone, reduction in toxicity of the entire site is uncertain.

Panel Summary: What is "attenuation of the source zone?" From the context it appears to be referring to NAPL. This statement should be changed to indicate that in the source-area aquifer the system will remove dissolved mass, control dissolved concentrations and their migration, eventually reduce concentrations of more soluble components, and control mobility of the LNAPL. It will have minor effect on LNAPL mass.

Short-Term Effectiveness (High/Medium/Low/Not effective) - Phase specific, requires specification

High, Potentially Uncertain.
If properly designed and operated, effectiveness will be high for the dissolved phase within the source area groundwater, but without a high resolution CSM effectiveness would still be uncertain.

Panel Comments: Minor editorial suggestions are offered. The phrase "a high resolution CSM effectiveness" is unclear. Elsewhere the spreadsheet refers to "CSM resolution" and "CSM definition." The Workgroup should be encouraged to use consistent terminology.

Implementability (Difficult/ Moderate/Easy/Not applicable)

Difficult
Prior to system design, a high definition (HD) CSM and a hydrogeological computer model would have to be developed. Bench and pilot studies would need to be conducted to evaluate injection, extraction, and substrate requirements.

Panel Comments: See previous comments regarding CSM. Pilot studies make sense but what is a "bench study" for the injection and extraction of water? Does this term refer to "additives"? Why is this approach "difficult" to implement? The depth? The limited information to form a high resolution CSM? The technology itself is not the limitation.

Cost - Capital & O&M (High/Medium/Low) - 1 (>$500M), 2 ($350 - $500M), 3 ($200 - $350M), 4 ($50 - $200M), and 5 (<$50M)

1 to 3. ($200M to >$500M)
Cost would be medium to high, depending on the number of wells required to implement this technology.

Schedule to Implement (Long/Medium/Short/Not applicable) - Long (>10 yrs.), Medium (5-10 yrs.), and Short (<5 yrs.)

Long (>10 yrs)
This technology option requires multiple extraction, injection, and monitoring points. Extraction and injection points may need to be relocated and repeated to optimize flushing.

Panel Comment: The system can be designed in stages, not only to expand the spatial coverage but to also take advantage of increasing knowledge developed as the system evolves. In other words, the system can be designed to not only help remediate the site but to gather characterization information.

Infrastructure Requirements and Constraints (List of infrastructure required)

Substantial.
Multiple extraction, injection, and monitoring points to address the ~~dilute~~ dissolved plume (minimum ~50 Maximum ~ 100). To flush the LNAPL, it would require an additional 150 to 500 wells.

Panel Comments: A minor editorial suggestion is offered. As described in the spreadsheet, this technology will require a lot of wells. With a high spatial-resolution description of aquifer heterogeneities, and a similar description of the spatial distribution of dissolved concentrations and LNAPL, such a large number of wells could be used to more quickly apply this approach. However, the uncertainty in this characterization, coupled together with the cost of wells at this depth, suggest that a much smaller number of wells might be more reasonably deployed, perhaps 20-25, despite the size of the source area. Using the site CSM and groundwater model (see implementability above) for flow and transport, together with optimization techniques, an effective groundwater control (extraction and injection) scheme can be designed to best meet cost and human health/environmental constraints and/or goals with fewer wells. This description also asks for a second set of wells "To flush the LNAPL"? What does this mean? The LNAPL is not migrating, for all practical purposes. It cannot be mobilized by water alone, although an additive that reduces interfacial tensions could mobilize it (see, e.g., Section 4.2). The groundwater will flow through the drowned LNAPL zone. No additional wells are needed to deal with the LNAPL unless additives are used to mobilize it. Finally, infrastructure requirements/constraints need to include all the surface plumbing and treatment systems needed for this approach.

Waste Management (List waste streams to be managed)

Substantial
Wastewater will have to be handled and treated.

Permit Requirements (Low/Med/High) (e.g., OSE, NMED, EPA, AEHD, rights of entry agreements)

Reinjection and/or wastewater disposal permits will have to be procured from NMED. Rights of entry for multiple extraction, injection, and monitoring wells.

Panel Comment: A minor editorial suggestion is offered.

Potential Stakeholder Objections

Comments (include references as applicable)

Fred Payne, ""Detail Structure in Large, Dilute Plumes"" June 20 2012 (http://www.frtr.gov/pdf/meetings/jun12/presentations/payne-presentation.pdf)

Krishna R. Reddy, "Physical and Chemical Groundwater Remediation Technologies" NATO Science for Peace and Security Series C: Environmental Security 2008, pp. 257-274.

Bibliography

ITRC (2009). Evaluating LNAPL Remedial Technologies for Achieving Project Goals. LNAPL-2 http://www.itrcweb.org/GuidanceDocuments/LNAPL-2.pdf