Introduction

- Historically, petroleum recovery systems have been long undertakings (operation for +10 years)
- Heavy reliance on pump and treat (P&T) / soil vapor extraction (SVE)
- Polishing technologies added haphazardly at the end to overcome remediation plateaus
- Does not adequately address the different phases of petroleum contamination (ITRC, 2010)
Introduction (cont.)

- Site characterization and conceptual model development is not an ongoing process to address:
  - Residual hot spots
  - Variable capture zones between recovery wells
  - Challenging zones in the formation
- Rebound of residual liquid phase hydrocarbons (LPH) and dissolved phase constituent levels often occurs, but historically was not explicitly addressed in the Corrective Action Plan

Four Phases of Petroleum Contamination

![Diagram showing four phases of petroleum contamination](ITRC 2010)
A Holistic View of Petroleum Recovery
System Optimization

Four Phases of Petroleum Contamination (cont.)

- **Mobile LPH** – LPH is mobile either as a migrating plume or locally mobile within a footprint. LPH moves readily with hydraulic control.

- **Residual LPH** – LPH plume is non-mobile or adsorbed to formation. May still have LPH levels from a few inches to a reoccurring sheen in wells.

- **High Groundwater Concentrations** – Dissolved levels >1,000 ppb near source (mobile or residual LPH), causing down gradient impacts.

- **Low Groundwater Concentrations** – Dissolved levels >100 ppb, down gradient receptors may drive the cleanup to lower endpoints.

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**Four Phases of Petroleum Contamination (cont.)**

- Migrating LPH is mobile due to high saturation of LPH in subsurface and a driving force (i.e. ongoing release).
- Typically ceases to migrate with 1 to 3 years of release ending.
Four Phases of Petroleum Contamination (cont.)

Mobile LNAPL

- Mobile LPH is typically mobile only within a stable footprint
- Footprint stable because LPH saturation is too low at edges of plume and driving force not present (i.e. release controlled)
- Major source of high dissolved phase plumes

Residual LNAPL Saturation

- Residual phase LPH is completely entrained in the subsurface
- Can result in occasional LPH in wells and sheens with water table drops, particularly in core of plume
- Major source of high and low dissolved phase plumes
Cautions to the Historical Approaches to Recovery System Design

• Preliminary Site Conceptual Model based upon:
  – Emergency recovery well installation
    • Location and screened intervals may not be ideal
  – Source zone wells converted to recovery wells
    • Few wells remain to monitor system performance
  – Limited gauging and sampling data
    • Don’t have the full picture
  – PID readings from well logs
    • Not ideal

Cautions to the Historical Approaches to Recovery System Design (cont.)

• Short term pilot test using existing monitoring wells as observation wells to save $
  – Installing appropriately designed and spaced observation wells will provide better data
• Generic slotted screens, gravel pack, and screened intervals
  – More efficient recovery wells using PVC wrapped wire screens with formation specific slots and gravel pack
Appropriate Technologies for The Four Phases of Product

- **Mobile LPH** – Hydraulic Recovery / Control
  - Single / multi-well enhanced fluid recovery (EFR) with vacuum trucks
  - Emergency / portable systems
  - P&T
    - Expensive/high maintenance
    - Period of mobile LPH recovery is relatively short (months)
    - Move to appropriate technology for next phase, when point of diminishing returns is reached

Appropriate Technologies for The Four Phases of Product (cont.)

- **Mobile LPH** – Vapor Recovery
  - SVE
  - EFR
  - Emergency / portable vapor recovery units
  - P&T used to lower water levels and expose smear zone to remove residual LPH with SVE
Appropriate Technologies for The Four Phases of Product (cont.)

• Traditional P&T / SVE
  – Can treat all phases, but may be other more effective solutions
  – Hydraulic control
  – Vapor control
  – Dissolved capture
  – Dewater smear zone

• Residual LPH
  – P&T dewatering of smear zone with SVE
  – Sparge wells with SVE
  – Surfactant soak with hydraulic recovery
  – Chemical oxidation
    • Best for low amounts of LPH
    • Existing SVE can be used to capture vapors
  – Steam, heat, radio frequency
    • Used in conjunction with SVE
  – Co-solvents
    • Good for heavy oils
  – Move to appropriate technology for the next phase, when the point of diminishing returns is reached
Appropriate Technologies for The Four Phases of Product (cont.)

• Residual / High Dissolved Phase
  – SVE / Sparge

[Diagram showing Unsaturated Zone, Capillary Transition Zone, NAPL Source, Dissolved Plume, and Hydraulic Pumping]

• Residual / High Dissolved Phase

[Diagram showing Oxidizers, Heat, Surfactants, and Solvents]
Appropriate Technologies for The Four Phases of Product (cont.)

- **High Dissolved Phase Concentrations**
  - SVE / Sparge
  - Chemical oxidation (chemox)
  - Oxygen addition technologies – ORC, oxygen / ozone diffusers
  - Nutrient / microbial treatments
  - Combined – chemox / ORC (Regenox™)
  - If low dissolved phase level cleanup is required, move to next technology when point of diminishing returns is reached

- **Low Dissolved Phase Concentrations**
  - Sparge - in favorable formations
  - ORC, oxygen addition methods
  - Nutrient / microbial amendments
  - Regenox (chemox with time release ORC)
Hydraulic Control

• Full time pumping vs. pulsed vs. treatment pumping
• Hydraulic control is part of the treatment train for the four different phases
  – Pulsed pumping allows time for adsorbed material to move into the dissolved phase, less $ (mobile, residual phases)
  – Surfactants / chemox – cause residual LPH to move out of adsorbed phase and move down gradient as high dissolved levels – need short term treatment pumping to capture

Hydraulic Control (cont.)

• P&T system can be used to expose the smear zone for treatments of dissolved phase constituents and later recovery
  – Formation capture zones, groundwater velocity will determine time interval of pulsing
  – Surfactant solution or other treatments – design to prevent fouling of the water treatment system
Hydraulic Control (cont.)

- Long term capture zones may differ from initial pilot test design
- May not need to run all of the recovery wells as the plume shrinks in size
- Dead zones – where capture is inefficient due to formation characteristics
- Hot spots – source strength is variable, some areas easier to clean up
  - Source material at the bottom of smear zone may be inaccessible

Vapor Control

- Separate monitoring of mass recovery of hydraulic vs. vapor influent provides clues for which aspect of the system needs a change in strategy
- SVE often run beyond the point of diminishing returns in hopes of decreasing dissolved phase concentrations
  - May be ineffective in addressing deeper smear zone contamination
Improving the Site Conceptual Model (SCM) – Initial Steps

- Instrument multi-well EFRs to get initial pilot test data to augment / design later formal pilot test
- Conduct bail-down tests to determine LPH hydraulic conductivity and LPH recharge rates for different wells within the plume
- Instrument surrounding wells during system operation to determine equilibrium capture zones
- Pulse system and test individual wells for capture, water and LPH hydraulic conductivity, LPH recharge rates

Improving the SCM – Treatment Train Strategy (cont.)

- Define the horizontal and vertical extent of smear zone, dead zones and hot spots with targeted direct push investigations at different decision points
  - Laser Induced Fluorescence (LIF) – residual LPH
  - Membrane Interface Probe (MIP) – residual LPH and high dissolved
  - Electrical Conductivity – fine tune knowledge of lithology
  - Hydraulic profiler – fine tune understanding of preferential zones of water flow, injection rates, etc.
Targeted Assessment - Direct Push Tools

Analysis of Targeted Assessment - 3-D Rendering
Fine Tuning the Well Network

- Based upon improvements to the SCM from additional targeted delineation
  - Add additional recovery well locations
  - Fine tune the next round of injections – amounts and intervals (surfactants, chemox, ORC, etc.)
  - Add monitoring well locations to improve understanding of the remaining extent of plume
  - Abandon locations that are no longer providing useful data to attain a representative and cost effective monitoring well network
  - Design monitoring well network for post-remediation monitoring, to address rebound, and achieve case closure

Well Maintenance and Redevelopment

- Wells are developed after installation to remove fines and ensure an efficient well
- Over time wells become silted in and well screens get clogged with fines and microbial growth – redevelop with mechanical surging, pH, and temperature treatments
- Recovery wells that once removed LPH need regular redevelopment due to higher microbial growth rates and surfactant redevelopment after LPH is absent
- Post remediation monitoring should be done with a clean well network
- Surface seals get compromised and need maintenance – monitoring well data should not reflect the effects of surface runoff
Rebound of LPH and Dissolved Phase Concentrations

- Site specific and can lengthen project and 
- Rebound depends upon:
  - Formation complexity
  - Appropriate technology for each phase of petroleum contamination
  - Strength of SCM
  - Mass of petroleum remaining after each treatment
  - Approach to dead zones and hot spots
  - Well maintenance
  - Representativeness of monitoring well network

Improved Time Frames for Different Phases of Cleanup

- Mobile LPH (migrating) – 6 months to 1 year
- Mobile LPH (locally mobile, but not migrating) – 6 months to 2 years
- Residual – 6 months to 2 years
- Dissolved – depends upon risk scenario and cleanup goals – 1 to 2 years
- Post-remediation monitoring 1 to 2 years
- Average time to closure with Holistic Approach – 6 ¼ years instead of +10 years
Cost Offsets

- Shorter time of remediation offsets costs for:
  - SCM updates
  - Targeted direct push investigations
  - Monitoring well network improvements
  - Well maintenance
  - Additional work plans/bench and pilot testing for different technologies, reporting to regulators

Costs of Remediation Plateaus / Failure to Close Case

- If closure not achieved, Responsible Party (RP) often switches consultants
  - Loss of project memory
  - Down time during consultant switch
  - Loss of property value/revenue
  - RP is concerned about throwing good money after bad - which limits options for the next consultant
    - May lead to overselling a technology, e.g. chemox with too much residual LPH present
Regulatory Perspective

- Pressure from EPA and upper management to close cases for the last 5 years
  - “Low hanging fruit” has already been picked
  - Remaining cases are in difficult formations/complex source issues (dead zones, hot spots, etc.)
  - Economic downturn
  - Major oil companies getting out of retail
  - Will need to work more cost effectively in the future

Conclusions

- The remedial treatment train should recognize the limitations of different technologies for different phases of petroleum contamination
- Hydraulic control is expensive, use judiciously
- Don’t run SVE too long
- Collect the right pilot test and operational data to understand what your system is capturing and missing
- Continual evolution of the SCM
- Gather targeted source data using the latest direct push tools to focus remediation efforts and improve monitoring well network
- Maintain the monitoring well network