Preventing Columbia/Potomac Aquifer Cross Contamination in the Decommissioning of an In-Ground Frozen Earth Propane Storage Facility, Delaware City Refinery, Delaware

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In-Ground Frozen Earth Propane Storage

Proprietary design developed by Phillips Petroleum Co.

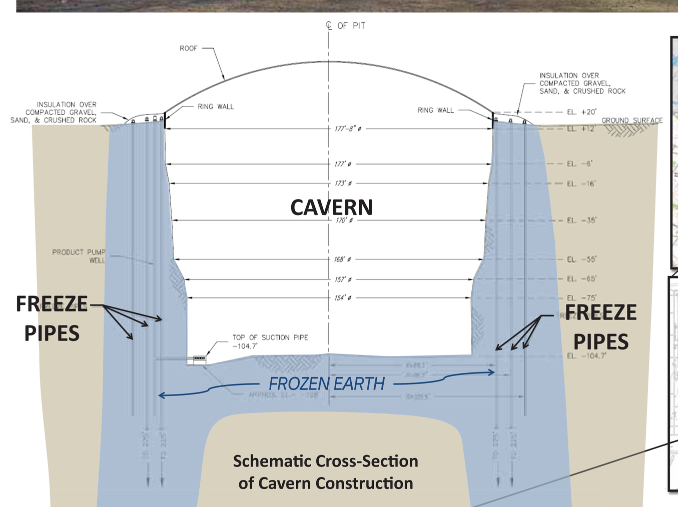
One of two covered subterranean propane storage caverns in US; commissioned in 1966

Stored propane/propylene (C3) at -45°F, atmospheric conditions (0.3 psi)

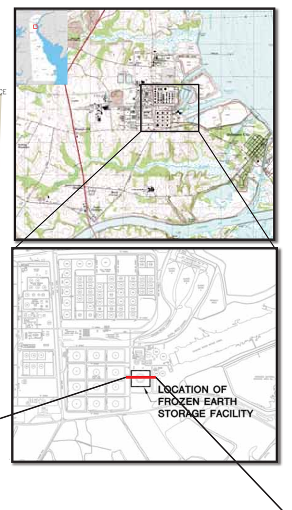
165 feet in diameter and 128 feet deep, with capacity of about 495,000 barrels

Cavern wall integrity accomplished by circulation of liquid propane through three concentric rings of 250 vertical "freeze" pipes.

Fugitive emissions from cavern triggered Conciliation Order (CO) from DNREC in 2008. CO required the FES be closed in a safe and environmentally sound method.

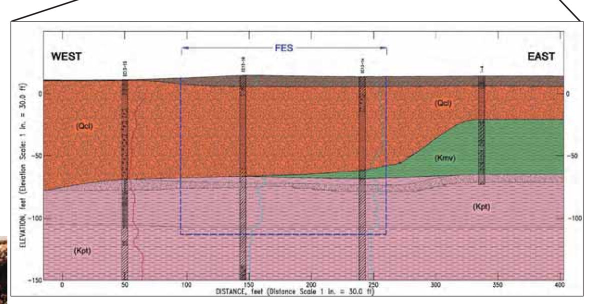


Schematic Cross-Section of Cavern Construction



Geologic Setting

Investigative programs conducted throughout the refinery provided extensive knowledge of subsurface conditions underlying the FES facility.



Cavern was excavated through Columbia, the remnant thickness of the Merchantville, and about 45 feet of upper Potomac sand and interlaminated sand and silt beds.

Columbia Formation (Qcl): Pleistocene-age fluvial fine- to coarse-grained, poorly-sorted quartz sand with silt and gravel.

Merchantville Formation (Kmv): Late Cretaceous-age (Early Campanian) shallow marine silt to clayey silt with intervals of fine-grained sandy silty clay, silty clay and fine-grained sand; locally a confining layer.

Potomac Formation (Kpt) – Early (Aptian, Albian) and Late (Cenomanian) Cretaceous-age succession of non-marine (anastomosing river systems and wet floodplains) silts, clays, and sands; Upper and lower sandy, aquifer-prone intervals provide much of the drinking water for this region of Delaware.

Hydrogeology

Southward groundwater flow

Columbia Fm and Potomac Fm aquifers are hydraulically connected to the west of FES.

Groundwater of the unconfined Columbia Fm aquifer and upper sands of Potomac Fm aquifer has been impacted by historical refinery operations, primarily petroleum hydrocarbons (benzene, naphthalene) and additive contaminants (methyl-tert-butyl-ether [MTBE]).

Decommissioning Concerns

Cavern would represent a significant "open channel" connection between the Columbia and Potomac Fms once the FES returns to ambient ground temperatures.

250 freeze pipes penetrate deep (225 feet) into Potomac Fm and could create conduit for impacted groundwater.

Confirming the decommissioning does not degrade water quality.

PROJECT OBJECTIVES

1. **Re-establish a low permeability horizon that will separate the Columbia Fm from the Potomac Fm**
2. **Properly abandon vertical freeze pipes to seal off potential conduit between Columbia and Potomac Fms**
3. **Implement groundwater monitoring to develop baseline groundwater conditions and monitor groundwater quality before, during, and after decommissioning activities**

BACKFILLING THE CAVERN

Re-establishing Aquifer ***Isolation***

Grout Specifications

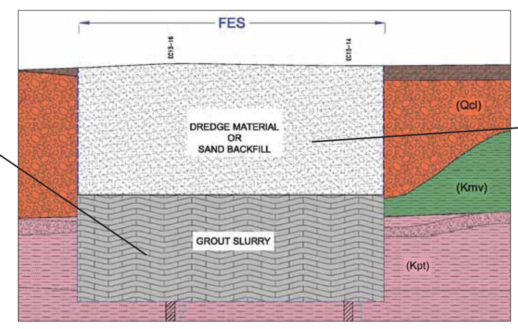
Hydraulic Conductivity less than 1 x 10^{-3} cm/sec

Unconfined Compressive Strength >25 psi

60 feet thick, from cavern bottom to 68 ft bgs

Material and leachate certified clean: below Delaware Uniform Risk-Based Remediation Standard (DURS) for Protection of Human Health

Total of 42,000 CY



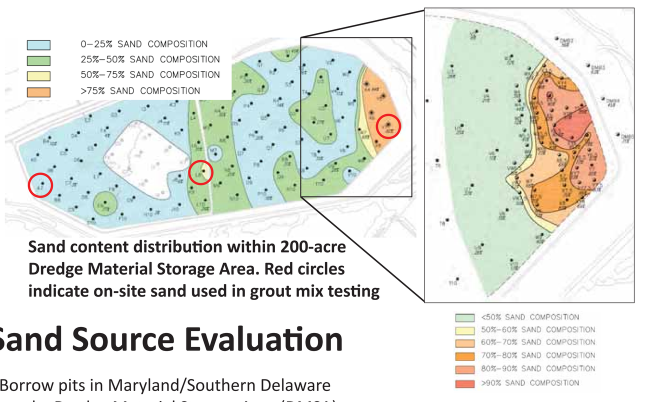
Multi-Layer Grout Slurry Plug and Sand Backfill Method selected as most protective and cost-effective backfill method

Sand Backfill Specifications

Particle size >75% Sand

Material and leachate certified clean: below Delaware Uniform Risk-Based Remediation Standard (DURS) for Protection of Human Health

Total of 60,000 CY



Sand content distribution within 200-acre Dredge Material Storage Area. Red circles indicate on-site sand used in grout mix testing

Grout Testing

Three mixtures of varying amounts of sand/gravel, cement, bentonite, water

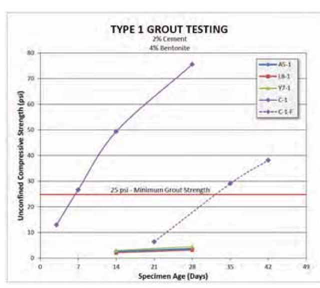
Sand included three DMSA sands (A7, L8, Y7) and one off-site sand (C)

Brackish water from refinery-supplied fire water system (from Delaware River) used in mixes

Samples frozen for 14 days at 0°F/-17°C, thawed and tested

Compressive Strength (D2166), Permeability (D5084), environmental analytical testing

Testing Results



On-site sand mixes did not meet specifications, requiring use of off-site sand mixes

Frozen samples exhibited lower strengths and increased hydraulic conductivity, but met specifications

Analytical results for VOCs, SVOCs, Pesticides, PCBs, and Metals below DURS

Brackish water suitable for use in mixes

Type 1 mix with Off-site sand selected for grout

Sample Identification	Grout Mix Type	Compressive Strength (psi) 7 days	14 days	28 days	Permeability (cm/sec) 28 days
DMSA 3 Sample A5					
A5-1	Type 1	too weak	2.6	3.7	too weak
A5-2	Type 2	too weak	2.6	3.5	2.5E-07
A5-3	Type 3	1.9	7.8	18.9	7.1E-07
DMSA 3 Sample L8					
L8-1	Type 1	too weak	2.1	3.2	too weak
L8-2	Type 2	too weak	1.7	2.4	too weak
L8-3	Type 3	2.6	4.3	12.5	1.0E-06
DMSA 3 Sample Y7					
Y7-1	Type 1	too weak	3.0	4.5	too weak
Y7-2	Type 2	too weak	2.6	4.5	too weak
Y7-3	Type 3	2.4	3.9	11.6	5.2E-06
Off-Site Sand Material Fill					
C-1	Type 1	26.7	49.4	75.6	6.9E-07
C-2	Type 2	101	158	178	2.0E-07
C-3	Type 3	231	263	445	1.9E-07
C-1-Frozen	Type 1	6.4	29.1	38.2	7.70E-04
C-3-Frozen	Type 3	57	79	118	5.40E-04

Grout Mix Type 1 - 2% cement, 4% bentonite (plus slag, water)
Grout Mix Type 2 - 3% cement, 3.5% bentonite (plus slag, water)
Grout Mix Type 3 - 5.6% cement, 2.5% bentonite (plus slag, water)
Samples C-1-F and C-3-F were frozen for 14 days between 0 and -5 degrees Fahrenheit immediately after casting

On-site computer-controlled grout plant assembled to provide 1,000 CY of grout per day

Sand Source Evaluation

Off-site source: Borrow pits in Maryland/Southern Delaware
On-site source: nearby Dredge Material Storage Area (DMSA)

- Detailed investigation of DMSA determined 80,000 CY was sand
- Some naturally occurring arsenic; VOCs, SVOCs, Pesticides, PCBs, and Metals below DURS

On-site DMSA dredge sand selected; approved by DNREC for use as backfill

Beneficial Re-use of On-Site Dredge Sand

Eliminated potential safety issues and road degradation caused by 8,300 roundtrips of trucks hauling on Delaware roads

Estimated 40,000 gallons of diesel fuel conserved

Saved approximately $150,000 compared with purchase of off-site sand

Excavation of sand from DMSA

Stockpile of 70,000 CY of sand excavated from DMSA; located 1,500 ft from FES Cavern

Grout Emplacement

Grout emplaced via pumping into crane-supported tremie pipe.

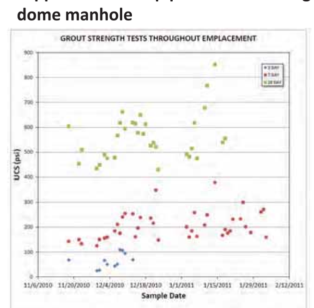
On-site batch plant provided 42,000 CY, emplaced in 50 days

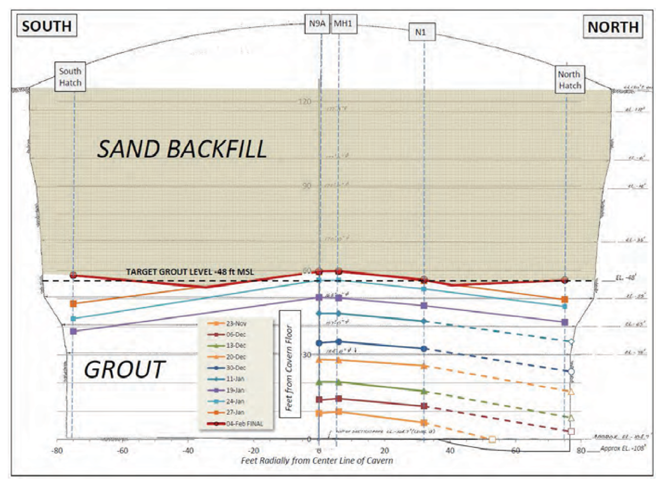
Measured depths to grout daily

Grout strengths and hydraulic conductivity consistent throughout emplacement

Strengths and hydraulic conductivity met specifications

Delivery of grout into cavern via crane-supported tremie pipe inserted through dome manhole





Chronologic progression of grout emplacement and final as-built grout elevations

Sand Emplacement

70,000 CY excavated during dry summer months and stockpiled close to cavern

Field QC confirmed material >75% fine to medium sand; 78% of tests were > 90% sand

Emplaced sand via direct loading through hatches cut in dome

60,000 CY sand emplaced over ~65 days

Direct loading of sand into cavern

Field testing grout strength

Final grout plug surface at 68 feet below ground surface

Sand backfill piles within cavern

Sand pile on south side of cavern (left); Columbia Fm bedding visible on cavern walls (right)

ABANDONING THE FREEZE PIPES

Protecting the Potomac Formation Aquifer

Freeze Pipe Abandonment

253 vertical pipes in three concentric rings

150 to 225 feet deep

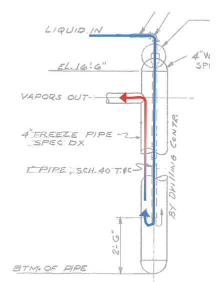
Buried under earthen berm

1-inch diameter inner pipe within 4.5-inch diameter outer pipe

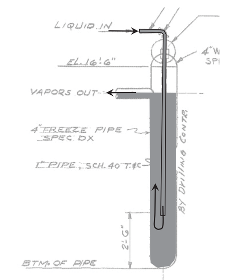
Liquid propane supplied within 1-inch pipe and propane vapor returns through the annular space of the 4.5-inch pipe

Utilized existing 1-inch pipe as a tremie pipe to fill pipe from bottom up

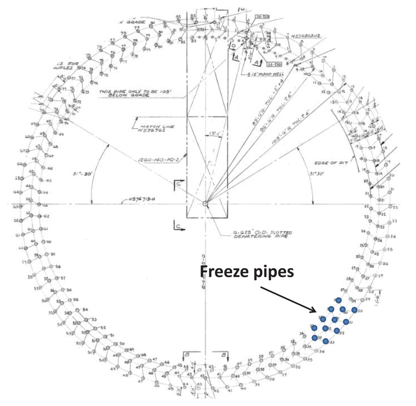
Portland cement grout placed in one-continuous operation until grout overflowed at surface



Freeze pipe diagram showing circulation of propane during refrigeration



Used same circulation design to abandon freeze pipes with grout



Layout of three concentric rings of freeze pipes around cavern

"Delaware Regulations Governing the Construction and Use of Wells" Section 9.0 – Well Abandonment

Objective to seal each pipe "to limit its potential as a pathway for vertical migration of fluids between different aquifers."

- Concrete, Portland cement grout, sodium-based bentonite clay grout, or combinations of these materials will be used to abandon the pipes.
- Portland cement grout and sodium-based bentonite clay grout shall meet the weight and composition requirements of Section 4.07(J)(1) and (2) of the Well Regulations.
- All pipes will be filled with the appropriate sealing materials starting from the bottom of the pipe upward using the tremie grouting technique to ensure proper displacement of water or air in the pipe.
- When Portland cement grout or concrete is used as a sealing material, it shall be placed in one continuous operation.
- The pipes will be filled until the sealing material overflowing the pipe is of the same consistency and density as the sealing material being pumped into the pipe.

1. Array of freeze pipes after removal of earthen berm

2. Cutting of 4.5-inch pipe and lifting to expose 1-inch inner pipe

3. Array of freeze pipes awaiting abandonment

4. Portland cement delivered by truck to drill rig

5. Grout hose connected to 1-inch inner pipe

6. Portland cement returning to surface through 2-inch vapor return port during pumping

7. Array of abandoned freeze pipes

8. Cutting abandoned pipes with shear attachment

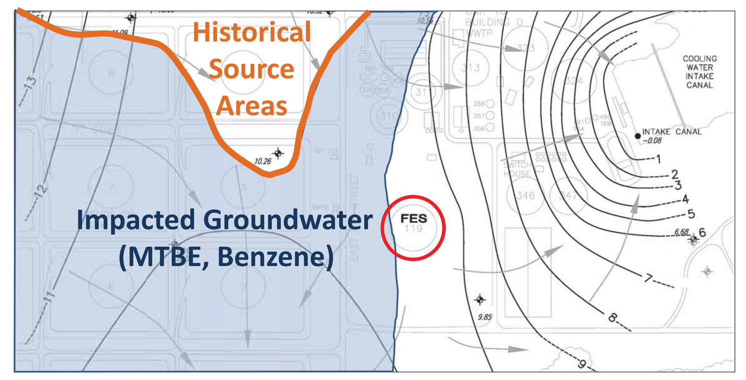
GROUNDWATER MONITORING

Documenting the Decommissioning

Monitoring Objectives

Document groundwater quality of the Columbia and Potomac formations in the vicinity of the FES before, during, and after the FES closure activities to determine if:

- Historical petroleum hydrocarbon impacts are present in the vicinity of the FES
- Decommissioning activities significantly alter groundwater quality
- Groundwater near the FES is impacted with propane



Hydrogeologic Conditions

Groundwater flows southwest towards the FES, and continues to the south-southwest

Frozen soil and groundwater causing groundwater to flow around the FES cavern

Downward vertical hydraulic gradient – 0.012 ft/ft

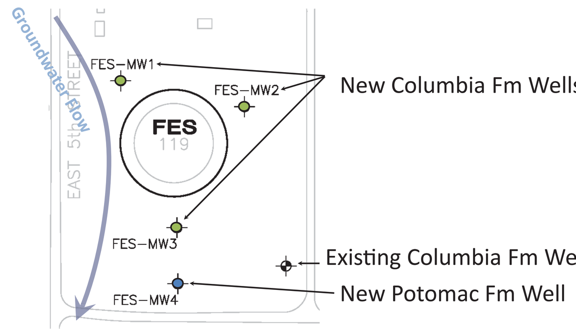
Groundwater Investigation

Installed three new Columbia Fm wells

Installed one new Potomac Fm well

Sampling events:

- Prior to Decommissioning (Dec 2009)
- During Decommissioning (Nov 2010)
- After Decommissioning (Dec 2011)



Drilling MW3 into Columbia Fm aquifer using Roto-sonic drilling methods

Installing 6-inch isolation casing at MW4 (Potomac well)

MWH geologist logging soils from MW1

Groundwater Results

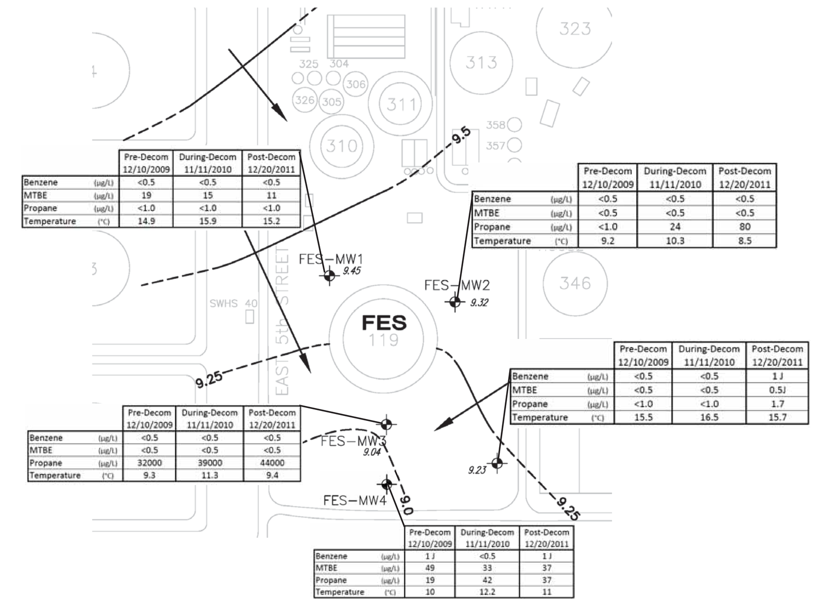
Benzene and MTBE concentrations are consistent with nearby wells related to the pre-existing plume

Benzene and MTBE did not change significantly during or after the decommissioning

Propane is present in groundwater at relatively low concentrations, except immediately downgradient (MW3)

Although main source of propane has been removed, the continued presence of propane in groundwater is attributed to:

- Thawing of the frozen soil around the cavern releasing small amounts of entrapped propane
- Depressed groundwater temperatures around the cavern hindering the volatilization of propane



FES-MW1

	Pre-Decom 12/10/2009	During-Decom 11/11/2010	Post-Decom 12/20/2011
Benzene (µg/L)	<0.5	<0.5	<0.5
MTBE (µg/L)	19	15	11
Propane (µg/L)	<1.0	<1.0	<1.0
Temperature (°C)	14.9	15.9	15.2

FES-MW2

	Pre-Decom 12/10/2009	During-Decom 11/11/2010	Post-Decom 12/20/2011
Benzene (µg/L)	<0.5	<0.5	<0.5
MTBE (µg/L)	<0.5	<0.5	<0.5
Propane (µg/L)	<1.0	24	80
Temperature (°C)	9.2	10.3	8.5

FES-MW3

	Pre-Decom 12/10/2009	During-Decom 11/11/2010	Post-Decom 12/20/2011
Benzene (µg/L)	<0.5	<0.5	<0.5
MTBE (µg/L)	<0.5	<0.5	<0.5
Propane (µg/L)	32000	39000	44000
Temperature (°C)	9.3	11.3	9.4

Existing Columbia Fm Well

	Pre-Decom 12/10/2009	During-Decom 11/11/2010	Post-Decom 12/20/2011
Benzene (µg/L)	<0.5	<0.5	1 J
MTBE (µg/L)	<0.5	<0.5	0.5J
Propane (µg/L)	<1.0	<1.0	1.7
Temperature (°C)	15.5	16.5	15.7

FES-MW4

	Pre-Decom 12/10/2009	During-Decom 11/11/2010	Post-Decom 12/20/2011
Benzene (µg/L)	1 J	<0.5	1 J
MTBE (µg/L)	49	33	37
Propane (µg/L)	19	42	37
Temperature (°C)	10	12.2	11

OBJECTIVES ACCOMPLISHED

Sealing off the Potomac and Merchantville Fms provided protection from potential future litigation regarding the historically impacted groundwater

Abandoning the freeze pipes prevented potential future conduit for impacted groundwater to deeper portions of the Potomac Fm aquifer

Groundwater monitoring demonstrated that the decommissioning did not adversely affect groundwater

Post-closure condition of former FES cavern after final backfilling and grading