Onsite PFAS Remedial Alternatives Analysis Matrix

Former North Pole Refinery, North Pole, Alaska

Prepared for
Williams Alaska Petroleum, Inc.

Prepared by

Integral Consulting Inc.
1701 Pearl Street
Suite 200
Boulder, CO 80302

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Table 1. Technology Screening Matrix for On-Refinery PFAS Remediation

Type	Technology	Screening			Screening Result
		Effectiveness	Implementability	Relative Cost	
Institutional Controls & Monitoring	Government Controls Property Controls Enforcement Permits Information Tools Site Management Plans	*Potentially Effective* • Can be effective when used in combination with other technologies to restrict access, reduce exposure, and aid in long-term maintenance and monitoring. • Ineffective as a standalone remedy.	*Few Challenges to Implement* • Legal and regulatory requirements may present challenges to implementing, maintaining, and/or enforcing institutional controls.	*Low*	*Retained* Only in conjunction with other technologies.
	Monitored Natural Attenuation	*Potentially Effective* • Recalcitrance of COCs reduces effectiveness to low concentration scenarios (i.e., diffusion, dispersion, and dilution only). • Given COC concentrations, ineffective as a standalone remedy.	*Moderate Challenges to Implement* • Requires additional technologies (and associated implementation issues). • Readily available resources and expertise. • Long-term stewardship required.	*Low*	*Retained* Only in conjunction with other technologies.
Containment / Stabilization	Engineered Capping	*Effective* • Effective at isolating and preventing direct contact exposure. • Can be constructed as a low permeability cap to isolate unsaturated soils reducing migration to groundwater.	*Few Challenges to Implement* • No significant impediments to implementation. • Short construction window. • Readily available resources and expertise. • Design considerations and approval from Marathon required. • Potential impacts to existing site stormwater management.	*Low*	*Retained*
	In Situ Stabilization & Solidification	*Effective* • Effective at eliminating or reducing the mobility of COCs. • Many case studies for PFAS demonstrating a proven and well understood remedy. Site-specific considerations may present some limitations: 1) Contaminants not removed or destroyed, thus long-term stewardship required. 2) Heterogeneous distribution of soil types and contamination may lead to incomplete/uneven treatment. 3) Likelihood of residual sources post-treatment would prevent restoration of groundwater quality in reasonable time frame.	*Moderate Challenges to Implement* • Requires use of heavy construction equipment. • Typical soil overages of 5%-15% requires either raising existing site grade or disposal of PFAS-impacted soils. • Above- and below-ground obstructions would need to be removed prior to treatment. • Design considerations and approval from Marathon required • Future land use restrictions.	*Moderate to High*	*Retained*
	Injectable Colloidal Activated Carbon	*Highly Effective* • Effective at containing COCs in groundwater through sorption and preventing downgradient migration in groundwater. • Many case studies for PFAS demonstrating a proven and well understood remedy. • Additional technologies would likely be necessary to limit the source of COCs to groundwater.	*Few Challenges to Implement* • Minimal disturbance during implementation. • Groundwater remedy only. Cannot be implemented in unsaturated soil source areas. • Design considerations and approval from Marathon required (drilling required).	*Moderate to High*	*Retained*
	Barrier Wall	*Potentially Effective* • May eliminate or reduce migration of contaminated groundwater. • Often implemented with other technologies as part of an effective containment remedy.	*Moderate Challenges to Implement* • Short construction window. • Reasonably available resources and expertise. • Changes to site groundwater flow difficult to manage. • Future land use restrictions. • Disruptive to existing Marathon operations during construction.	*Low to Moderate*	*Screened* Low effectiveness and undesirable effects to site hydraulics.

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Removal & Disposal	Soil Excavation	*Effective* • Highly effective at eliminating potential exposure to soils and removing source mass. • Unlikely to completely eliminate COC sources to groundwater without further delineation. • Inefficient when targeted low level contamination.	*Significant Challenges to Implement* • Potential shoring and groundwater dewatering for deep excavation. • Dewatering requires extensive treatment of water prior to discharge, adding considerable complexity. • Additional delineation is required to eliminate source. • Significant risk and disruption to existing site operations (heavy truck traffic, heavy machinery, dust nuisance, etc.). • Above- and below-ground obstructions would need to be removed.	*High* Excavated soils require transportation and off-site disposal, which is expensive.	*Retained*
Removal & Disposal	Offsite Disposal / Incineration	*Effective* • Offsite incineration and disposal is an effective approach for end-treatment of excavated soils.	*Moderate Challenges to Implement* • New RCRA rules may require disposal as hazardous material. Further evaluation required. • Disposal requirements may require challenging logistics to find a facility that will accept soils. • Requires extensive truck traffic that represents a hazard to workers and the community.	*High* Very expensive to incinerate soil mass at PFAS-required temperatures.	*Retained*
Groundwater Pump and Treat	*Ex Situ* Groundwater Pump and Treat – Sorptive Removal	*Effective* • Can be performed with either granular activated carbon or anion exchange resins. • Effective at removing COCs from groundwater. • Widely implemented for both drinking water and groundwater remediation systems for PFAS treatment. • Groundwater chemistry may limit ability to treat site COCs without pretreatment.	*Moderate Challenges to Implement* • Additional delineation required to best place extraction wells. • Discharge permitting required. • Disposal of spent sorbent required. • Construction required for treatment building as well as extraction system piping network and freeze protection for year round operation.	*Moderate to High* While capital costs may be moderate, long-term O&M and treatment may extend for >30 years, increasing costs.	*Retained*
Groundwater Pump and Treat	*Ex Situ* Groundwater Pump and Treat – Foam Fractionation	*Moderate Effectiveness* • Field case studies demonstrate potential effectiveness at removing COCs from groundwater at higher concentrations. • Capable of small to moderate treatment volumes only.	*Significant Challenges to Implement* • Disposal or additional treatment of foam waste stream required. • Unlikely to have treatment capacity for the volume of water requiring treatment. • Additional delineation required to best place extraction wells. • Construction required for treatment building as well as extraction system piping network.	*High*	*Screened* Ineffective at concentrations present at site.
Groundwater Pump and Treat	*Ex Situ* Groundwater Pump and Treat – Reverse Osmosis	*Effective* • Effective at removing COCs from groundwater. • Groundwater chemistry may limit ability to treat site COCs without pretreatment.	*Significant Challenges to Implement* • Complex operations and maintenance. • Disposal or additional treatment of concentrate required. • Significant pretreatment may be required. • Additional delineation required to best place extraction wells. • Construction required for treatment building as well as extraction system piping network.	*High*	*Screened* Inefficient at concentrations present at site.

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Destructive Technologies	Thermal Conductive Heating (*in situ* or *ex situ*)	*Effective* • Effective at treating site COCs. • Limited case studies for *in situ* treatment. • Proven case studies for *ex situ* treatment. • Requires extensive vapor recovery and treatment.	*Significant Challenges to Implement* • Requires considerable infrastructure. • Requires appropriate safeguards to prevent worker exposure to high voltages. • Extensive excavation required for *ex situ* treatment • Any metal objects (e.g., piping) or debris in the subsurface can constitute a safety hazard. • *In situ* limited if high water table is present.	*High*	*Retained*
	Advanced Oxidation & High-Energy Destruction Techniques: Ozonation, Sonolysis, Electrochemical Oxidation, Photolysis, Supercritical Water Oxidation etc.	*Low to Moderate Effectiveness* • Experimental PFAS destruction technologies. • Inability to treat low level concentrations to desired remedial goals. • Extensive pretreatment and preconditioning of media required.	*Significant Challenges to Implement* • Significant pretreatment required to concentrate media for effective treatment. • Highly complex technologies to implement, few resources and expertise available. • Requires management of chemical reagents and/or waste streams.	*High* Extremely high operating costs.	*Screened* Experimental technology and ineffective at concentrations present at site.
	Ball Milling	*Potentially Moderate Effectiveness* • Early research demonstrates PFAS removal/destruction. • Effectiveness unproven for full-scale implementation.	*Moderate to Significant Challenges to Implement* • Contaminant mass / concentrations too low to implement. • Full-scale not proven for PFAS.	*High*	*Screened* Unproven technology at full-scale.
	Ex Situ Smoldering Combustion (i.e., STAR systems)	*Moderate to High Effectiveness* • Early research demonstrates PFAS removal/destruction. • Effectiveness unproven for full-scale implementation at low level concentrations.	*Moderate to Significant Challenges to Implement* • Full-scale not proven for PFAS. • Requires carbon mass (typically granular activated carbon addition) to sustain combustion at low level concentrations.	*High*	*Screened* Unproven technology at full-scale.
	In situ Chemical Oxidation & Reduction	*Not Effective* • Unproven to remove or treat PFAS.	*NA*	*NA*	*Screened* Unproven for PFAS treatment.
	Bioremediation Bioaugmentation Bio-oxidation Biosparging	*Not Effective* • Unproven to remove or treat PFAS.	*NA*	*NA*	*Screened* Unproven for PFAS treatment.

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Separation	Soil Washing	*Low to Moderate Effectiveness* • Limited case studies for PFAS treatment. • Likely not effective at site concentrations. • Unproven at full scale.	*Significant Challenges to Implement* • Impractical due to the large area and extensive disturbance required. • Wash water management or handling of hazardous chemicals, that would require specialized treatment systems and expertise. • Significant potential for odor generation.	*Moderate*	*Screened* Unproven technology at full-scale.
Separation	Thermal Desorption via Resistive Heating Steam Heating	*Not Effective* • Unproven to remove or treat PFAS.	*NA*	*NA*	*Screened* Unproven for PFAS treatment.
Separation	Soil Vapor Extraction Air Sparging	*Not Effective* • Unproven to remove or treat PFAS.	*NA*	*NA*	*Screened* Unproven for PFAS treatment.
Phytoremediation	Phytoextraction Phytodegradation Phytosequestration	*Not Effective* • Unproven to remove or treat PFAS.	*NA*	*NA*	*Screened* Unproven for PFAS treatment.

Note:

Shaded = Technologies screened from consideration in development of remedial alternatives

COC = chemical of concern
NA = not applicable
PFAS = per- and polyfluoroalkyl substances
RCRA = Resource Conservation and Recovery Act

Table 2. Remedial Alternative Matrix for On-Refinery PFAS Remediation

			Media		**Alternative Considerations**					
	Alternative	**Treatment Mechanism**	**Soils:** *Migration to Groundwater Soil Cleanup Levels*	**Groundwater:** *Groundwater Cleanup Levels*	**Implementability**	**Short-term Remedy**	**Long-term Remedy**	**Cost**	**Retain for 2024 IRA**	**Additional Comments**
1	**Institutional Controls**	Indirect/administrative methods e.g.: No-dig areas, Deed/land-use restrictions, Critical water management area	○ Does not mitigate COC mass in soils	○ Does not mitigate COC mass in groundwater	● • Few resources needed to implement • Coordination with existing facility, operations, and applicable agencies	◑ • Can be established within a short timeframe • Prevents new exposure pathways	◑ • Prevents future exposure pathways when COC mass remains in the subsurface • Long-term stewardship potentially required, depending on control implemented	Minimal	**No**	Must be combined with other alternatives to meet remedial goals
2	**Monitored Natural Attenuation**	Diffusion, dispersion, and dilution in groundwater if COCs are sufficiently low in concentration	○ Does not mitigate COC mass in soils	◑ COC concentration decreases over time	● • Few resources needed to implement • Potential expansion of monitoring well network required • Requires additional technology to mitigate soil migration to groundwater pathway	○ • Unable to achieve remedial goals at present COC concentrations	◑ • COCs remain in place, but concentrations decrease over time • Long-term monitoring required • ICs necessary to manage site access, land use, and prevent future exposure pathways (i.e. new private wells, etc.)	$ to $$ Cost dependent on duration of monitoring, potentially very long	**No**	Must be combined with other alternatives to meet remedial goals
3	**Engineered Capping**	Low-permeability cap reduces surface water infiltration through the soil column Eliminates transport mechanism from soil to groundwater	● Eliminates COC pathway to groundwater	◑ Reduces source-loading on groundwater over time	● • Relatively low requirement to excavate on active refinery, depending on selected cap material • Soil disturbances minimalized • Can incorporate existing foundations and site features to reduce time and materials needed • Large area required to ensure cutoff of infiltration	◑ • Large area required will necessitate longer construction period • Low complexity of civil requirements and no pilot testing required • Additional site characterization, design and development needed to implement	● • Cuts off infiltration long-term • COCs remain in place • Long-term O&M required to maintain cap integrity • ICs necessary to manage site access, land use, and prevent disturbance of cap	$ Requires long-term O&M costs	**No**	May require additional technologies necessary to remedy groundwater
4	**Targeted Excavation and Offsite Disposal**	Removes COC mass from site Disposal or destruction of soils at landfill or incinerator	● Removes COC source material	◑ Reduces source-loading on groundwater over time	◑ • Effective for targeted "hot spot" areas, but inefficient for low-level impacts • Significant disruption to facility operations and subsurface features • Marathon "no dig" areas restrict access • Poor delineation may lead to future recontamination of excavation areas if nearby mass is not removed • Offsite disposal facilities not yet identified; selection and transportation logistics may be challenging	● • Targeted "hot spots" can be implemented within a short time frame • Low complexity of civil requirements and no pilot testing required • Additional site characterization required for larger excavation footprints • Immediate COC reduction • Potential excavation areas poorly delineated	◑ • Time required to complete additional remedial investigation activities for additional impacted soils • No long-term O&M • Persistent low-level COC concentrations may remain • Some areas may be difficult to access to remove source material	$$ to $$$ Relatively high costs associated with transportation and disposal Lower costs if only utilized in targeted "hot spots"	**Yes** **Hot spot excavation**	May require additional technologies necessary to mitigate impacted groundwater Excavated soils may use UV exposure to simultaneously treat sulfolane
5	**Injectable Colloidal Activated Carbon**	Forms a permeable sorptive barrier in groundwater to stabilize PFAS and limit migration	○ Does not mitigate COC mass in soils	● Contains and prevents COC migration in groundwater	● • Reduced impact to existing operations • Subsurface injections require facility input and approval • Requires pre-design pilot studies to assess subsurface conditions, radius of impact, effectiveness, etc. • Typically most effective as a downgradient groundwater control	● • Relative low complexity allows for quick implementation and additional treatments, if required • Immediate reduction in COC concentration downgradient of sorptive barrier • Requires pilot-scale testing	◑ • Requires long-term groundwater monitoring • Does not remedy soil or source area • Potential for PFAS desorption long-term is poorly understood	$ to $$ Low complexity Continued groundwater monitoring required	**Yes** **Pilot field study**	Additional technologies necessary to mitigate COC source soils
6	**Stabilization and Solidification Technologies**	Amendments are added to the soil via mixing to stabilize PFAS and prevent mobilization	● Stabilizes COCs in soils, typically assessed through leachate criteria	◑ Reduces source-loading on groundwater over time	◑ • Requires pre-design pilot studies to assess subsurface conditions, radius of impact, effectiveness, etc. • May cause groundwater mounding (solidification); hydraulic controls may be needed • Highly disruptive to site operations and significant soil disturbance • Expanding soil volume requires soil management	○ • Extensive disturbance, complexity of design, and required additional remedial investigation activities will make short-term implementation challenging • Short duration (months) required to stabilize COCs in subsurface	● • Stabilized material will remain in place • Long-term reductions in groundwater concentrations expected • Long-term monitoring necessary to evaluate potential leaching of COCs	$$ to $$$ May include cost for excavation and disposal of expanded soil volume Long-term monitoring required	**No**	Additional technologies may be necessary to mitigate downgradient groundwater Solidification *in situ* may reduce the effectiveness of future treatments and thus limit future remedial efforts

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			Media		Alternative Considerations					
	Alternative	**Treatment Mechanism**	**Soils:** *Migration to Groundwater Soil Cleanup Levels*	**Groundwater:** *Groundwater Cleanup Levels*	**Implementability**	**Short-term Remedy**	**Long-term Remedy**	**Cost**	**Retain for 2024 IRA**	**Additional Comments**
7	**Targeted Thermal Treatment (thermal conductive heating)**	Reduction of source contamination via thermal desorption and extraction	● Complete removal / degradation of COCs in soils	◑ Reduces source-loading on groundwater over time	◑ • Requires complex infrastructure to power, heat, extract and treat vapor • *Ex situ* treatment requires excavation • Requires pre-design pilot studies to assess subsurface conditions, operating conditions, effectiveness, etc. • Incompatible with existing subsurface features onsite (i.e. melting pipes, etc.) • Disruptive to site operations and significant soil disturbance • *In situ* treatment not possible below water table • Heat treatment must be conducted away from permafrost locations	○ • Long time frame needed to design, construct, and implement • Relatively fast results following construction (weeks to months) • Specialized equipment and personnel required to construct and operate	● • Complete removal of soil COC mass will reduce groundwater concentrations over time • No residual COCs remain in place to be monitored	$$$ High costs associated with infrastructure and energy requirements	**No**	Additional technologies necessary to control COC sources at and below the water table Thermal treatment may additionally treat sulfolane contamination Significant safety considerations for implementation (high temperatures, electrical, etc.)
8	**Groundwater Pump and Treat**	Provides hydraulic control through groundwater extraction and limits COC migration	○ Does not mitigate COC mass in soils	◑ Removes and treats groundwater COCs Can be difficult to reduce groundwater below standards at ppt concentrations	● • Requires ongoing operation • Potential to repurpose existing pump and treat system; however, expansion of extraction network and piping likely • Additional above-ground piping and process units require year-round freeze protection • Ongoing disposal of waste streams required • Regular operations required during winter months	○ • Short-term hydraulic control of groundwater plume attainable • Little impact to groundwater COC concentration in the short-term • Existing infrastructure may potentially speed up pilot and treatability testing and/or construction	◑ • Long-term O&M required • Inefficient mass removal requiring extensive operation period • Long-term hydraulic control expected	$$ High costs associated with long-term operations.	**No**	Additional technologies necessary to control COC in sources to groundwater.

Notes:

Treatment mechanism = Treatment, recycling, or destruction process and extent for eliminating source material, residual COCs, and preventing migration of COCs.
Implementability = Technical and administrative feasibility, and availability of services and materials.
Short-Term Remedy = Management of short-term impacts (risks to community, workers, environment) and time to achieve protection.
Long-Term Remedy = Magnitude of residual risk remaining after remediation. Adequacy of controls to prevent migration, risk of exposure, and maintain institutional controls.
Cost = Includes consideration of capital cost (direct and indirect) and long-term operation and maintenance costs.

Construction window likely limited to April through October to avoid freezing temperatures and winter conditions.

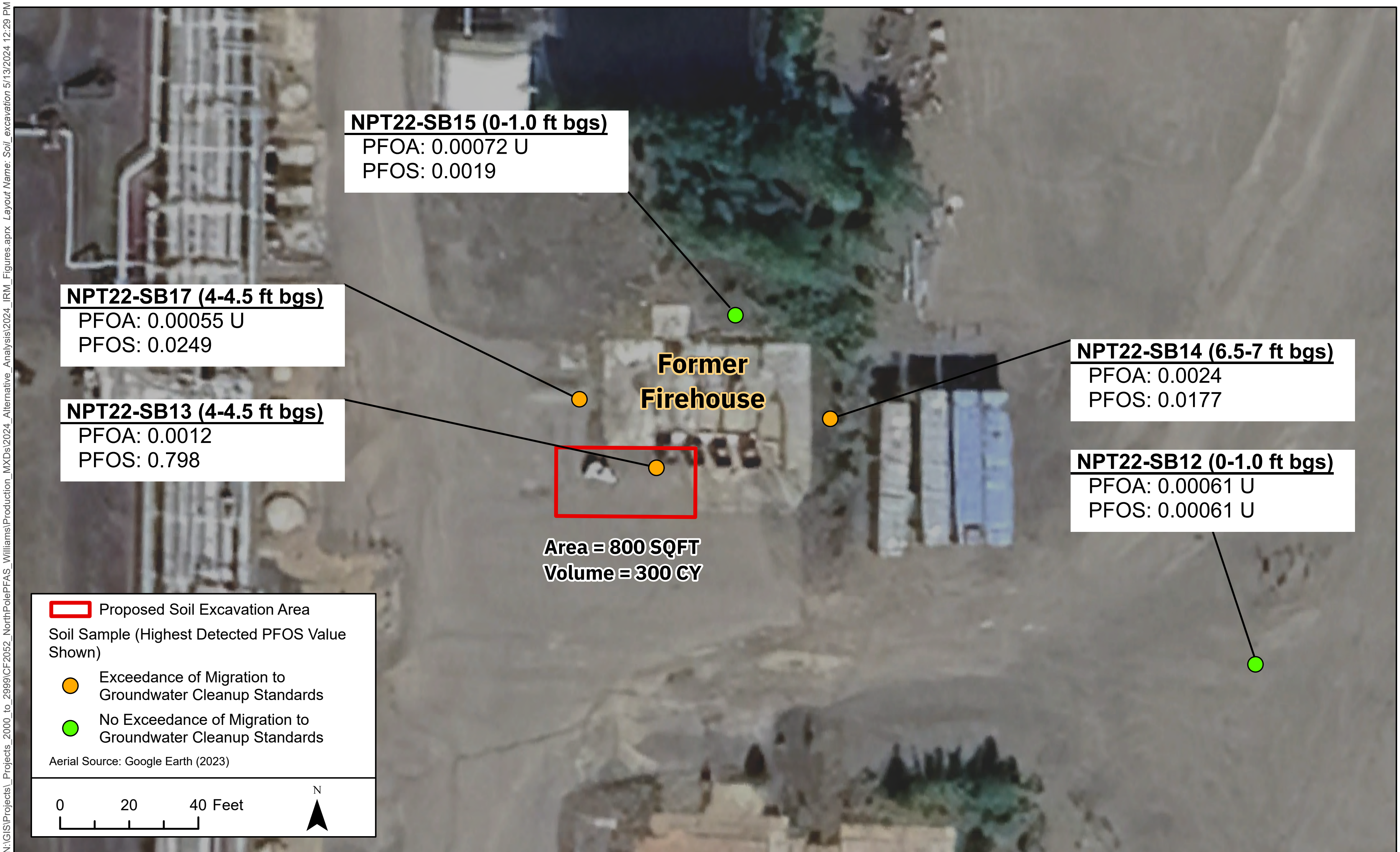
COC = contaminant of concern
IC = institutional control
O&M = operation and maintenance
PFAS = per- and polyfluoroalkyl substances

Criterion Rating Definitions:
Least favorable = ○
Favorable = ◑
Most favorable = ●

Low relative cost = $
Average relative cost = $$
High relative cost = $$$

References:

ITRC. 2024. PFAS Treatment Technologies. https://pfas-1.itrcweb.org/12-treatment-technologies/#12_4
Regenesis. 2024. PlumeStop. https://regenesis.com/en/pfastreatment/
TerraTherm. 2024. Frequently Asked Questions About High Temperature Thermal Conductive Heating for PFAS. https://terratherm.com/blog/high-temperature-thermal-faqs/



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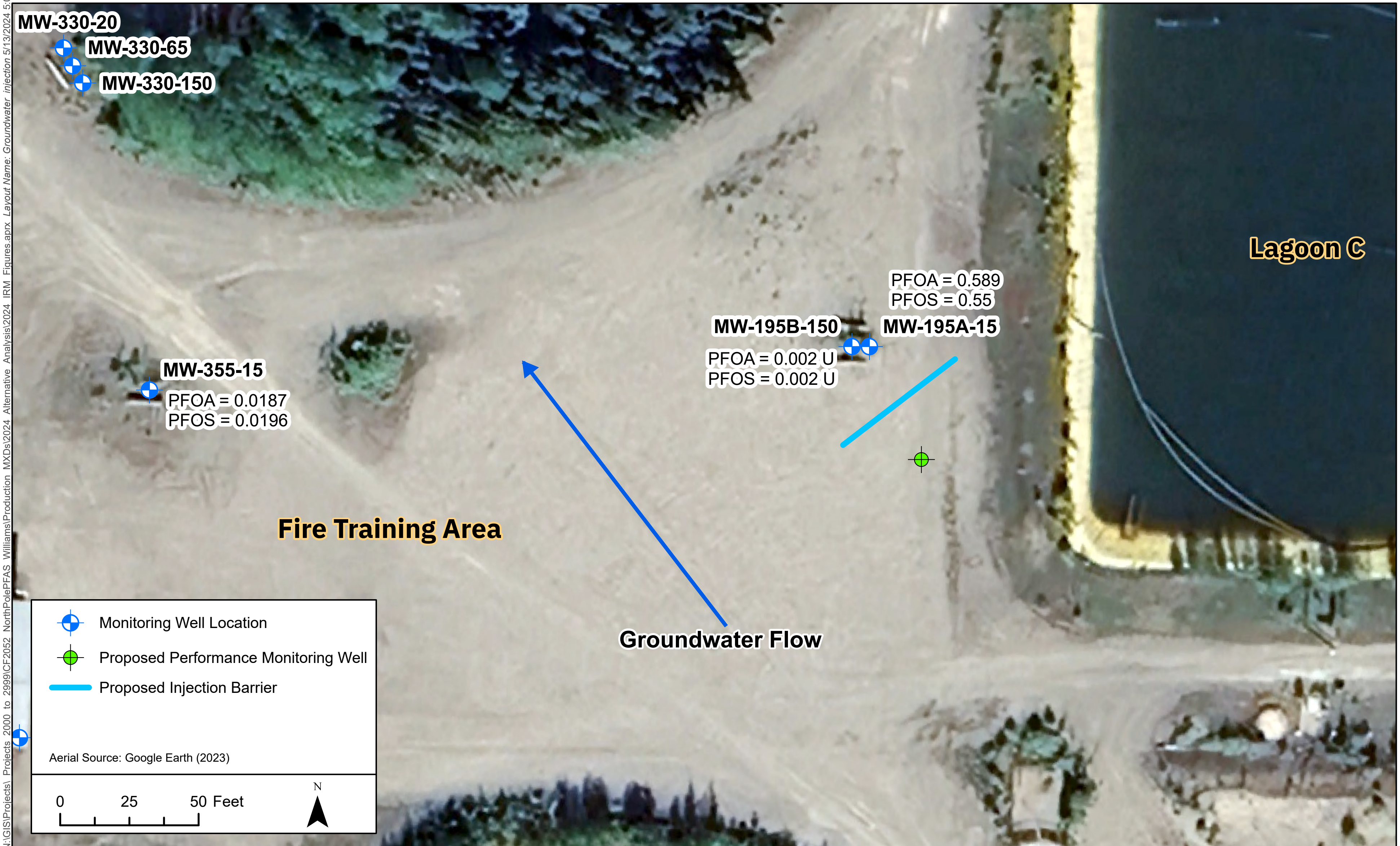
Notes.
1. Analytical results in mg/kg.
2. Excavation volume calculated as in-place volume.
3. U = Data Qualifier. The material was analyzed for, but not detected.

Figure 1.
Proposed Soil Excavation Area
2024 Interim Removal Action for On-Refinery PFAS



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Notes.
1. Analytical results are from December 2020 and shown in ug/L.
2. Groundwater flow direction based on December 2020 monitoring results.
3. U = Data Qualifier. The material was analyzed for, but not detected.

Figure 2.
Proposed Colloidal Carbon Injection Area
2024 Interim Removal Action for On-Refinery PFAS