



ITRC PFAS Roundtable Webinar Session 3

Treatment Technologies and Aqueous Film Forming Foam (AFFF)

This question and answer digest was prepared based on the Roundtable Session 3 event from April 6, 2021, including some additional questions that were submitted but not answered live on the roundtable. The information presented here is not a transcript of the session, but a summary of the information. Included in the answers below, the ITRC Technical and Regulatory Guidance Document, <https://pfas-1.itrcweb.org>, is abbreviated “Tech Reg.” The user is encouraged to reference the Tech Reg document for more details.

The Roundtable was hosted through EPA Clu-In and promoted with the following information:

This Roundtable Session offers a unique opportunity to interact directly with PFAS experts from around the country on two topics: *Treatment Technologies* and *Aqueous Film Forming Foam (AFFF)*. Participants were requested to submit questions in advance with registration for the event to be addressed during this Question and Answer discussion with expert panelists. The session was intended to be tailored to the specific needs of its participants, with the expectation that the participant have a basic understanding of these topics prior to attending the Roundtable Session.

Per- and polyfluoroalkyl substances (PFAS) constitute a large family of fluorinated chemicals, exceeding several thousand in commercial use or the environment that vary widely in their chemical and physical properties. The persistence and mobility of some PFAS, combined with decades of widespread use in industrial processes, certain types of firefighting foams, and consumer products, have resulted in their being present in most environmental media at trace levels across the globe. PFAS have relatively recently come to the attention of investigators and the public in large part due to the fact that until the early 2000s analytical methods to detect low levels of PFAS in the environment were available only in a few select research institutions. It was not until the early 2010s that these methods to detect a limited number of PFAS became widely available and had detection limits in water low enough to be commensurate with levels of potential human health effects. Toxicological studies have raised concerns regarding the bioaccumulative nature and potential health concerns of some PFAS. As a result, our understanding of PFAS and the risks they may pose is rapidly evolving.

This Roundtable Session is based on the following ITRC-produced resources:

- **A series of fact sheets** at synthesize key information for the following core subjects: (1) Naming Conventions and Physical and Chemical Properties, (2) Regulations, Guidance, and Advisories, (3) History and Use, (4) Environmental Fate and Transport, (5) Site Characterization Considerations, Sampling Precautions, and Laboratory Analytical Methods, and (6) Aqueous Film-Forming Foam (AFFF). The fact sheets were first published between 2017 and 2018, and updated in 2020.
- **A web-based technical and regulatory guidance document** published by the ITRC PFAS Team in April 2020, with updates published in September 2020, May 2021, and December 2021. The document presents the breadth and depth not given by the fact sheets, stakeholder points of view, technical challenges and uncertainties, risk communication strategies, and provides links to pertinent scientific literature. ITRC published a risk communication toolkit in June 2020. In 2022 and 2023, ITRC will continue its work, with plans to update the technical and regulatory guidance document with new information and regulatory approaches that become available to address the evolving understanding of these contaminants.
- **Online training materials** that convey the information presented in the technical and regulatory guidance document. Ten video training modules and brief introductory videos on the topics are posted on ITRC's YouTube channel. Additionally, the Team has provided in-person training workshops to approximately 2,500 attendees since 2018. The Team plans to continue to provide online and in person training resources. More information will be available on the ITRC Training page.

The target audience for this guidance and Roundtable Session is:

- State and federal environmental staff working on PFAS-contaminated sites
- Other project managers and decision makers
- Stakeholders who are involved in community engagement

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As a participant in this Roundtable Session you should learn more about:

- Aqueous Film-Forming Foams
- Treatment technologies and methods for PFAS-containing liquid and solid media

Participants are highly encouraged to review the Guidance Document (<https://pfas-1.itrcweb.org> - specifically Sections 3 and 10), and review the associated ITRC video training modules prior to attending the Roundtable Session:

- [ITRC Video Training Modules](#)

1 Roundtable Webinar Series Session 3 Panelists



Michelle Crimi, Ph.D. is a Professor jointly appointed in Civil & Environmental Engineering and Engineering & Management at Clarkson University. Her research focuses on developing in situ treatment technologies for groundwater contamination, determining the impact of groundwater technologies on aquifer quality, and integrating treatment technologies for optimized risk reduction. Her projects are often conducted in partnerships with industry and consulting organizations and have a strong technology transfer focus with the objective of moving technologies from the laboratory to full scale adoption by developing guidance, tools, protocols, and workshops to support field application. She has been PI or co-PI on several research projects focused on treating emerging contaminants, funded primarily by the U.S. Department of Defense's Strategic Environmental Research and Development Program (SERDP) and the Environmental Security Technology Certification Program (ESTCP). She earned her B.S. in Industrial Hygiene and Environmental Toxicology from Clarkson University, her M.S. in Environmental Health from Colorado State University, and her Ph.D. in Environmental Science and Engineering from the Colorado School of Mines. She spent the 2014-2015 academic year as a Fulbright Scholar at the University of KwaZulu-Natal in Durban, South Africa.



Bill DiGuseppi is a 30+ year experienced Principal Hydrogeologist with Jacobs in their Denver office. Bill is an expert in the history, occurrence and remediation of 1,4-dioxane and PFAS, and leads Jacobs Emerging Contaminants Community of Practice. Bill has been actively engaged with the ITRC PFAS Team as a co-leader of the Treatment Technologies writing subgroup (2017-2019) and an instructor on several PFAS topics since 2018. He has been invited as session keynote and luncheon speaker for international conferences in the US, Europe, and Australia. His enthusiastic support of ITRC earned him the 2018 Industry Member of the Year award. Bill is the Vice Chair for Emerging Issues for the SAME National Environmental Community of Interest (COI) and is a regular speaker for SAME national and Denver Metro Post events. Bill is also an adjunct faculty member in the Civil and Environmental Engineering Department at the Colorado School of Mines.



Jennifer Field has a Ph.D. in geochemistry from the Colorado School of Mines. Dr. Field is a professor in Environmental and Molecular Toxicology at Oregon State University. Dr. Field's current research focuses on the development and application of quantitative analytical methods for organic micropollutants and their transformation products in natural and engineered systems with a focus on per- and polyfluoroalkyl substances (PFAS). Early in her career, she focused on field-based research to investigate the fate and transport of surfactants in groundwater and wastewater treatment systems. She is considered a pioneer in the area of PFAS occurrence and behavior and has focused on groundwater contaminated by fire-fighting foams and PFAS in municipal wastewater treatment systems and in municipal landfill. Current work focuses on the development of PFAS fingerprinting sources, characterizing PFAS in landfill gas, and PFAS on specialized textiles and other materials. She serves as an Executive Editor for Environmental Science and Technology.



Cliff Shierk is a principal engineer with the solid waste permitting group at the Minnesota Pollution Control Agency. He has 15 years of experience in the field of environmental engineering and has worked extensively with landfills, remediation systems, and large environmental cleanup projects. He began his career as a design engineer on a large “lift-and-line” landfill project involving PFAS-laden waste and has been addressing PFAS in landfill leachate and groundwater ever since. Cliff is a registered professional engineer in Minnesota and holds degrees from the University of Illinois at Chicago (M.S.) and the University of Minnesota-Twin Cities (B.C.E.). He has served as a co-leader of the ITRC PFAS Treatment Technologies writing subgroup since 2018.



Richard Spiese has a B.S. from The Pennsylvania State University in Geological Sciences. Richard has been with the Vermont Department of Environmental Conservation, Waste Management Division since 1987. His job duties include overseeing the cleanup of hazardous waste sites in the Sites Management Section, responding to spills on the Waste Management Division’s Spill Team, and responding to hazardous materials emergencies as part of the Public Safety Division’s Vermont Hazardous Materials Response Team. In February 2016, he began investigation of PFAS contamination in Bennington Vermont, which continues today. Richard has been part of the EPA Region I Regional Response Team as the governor’s designee since 1992 and on the State Emergency Response Commission since 1994. He has been on the ASTSWMO Leaking Underground Storage Tank (LUST) Task Force 1994 to 2008, and was the co-chair from 1996-2010. He rejoined this Task Force in 2014 and just recently stepped down from this position. Richard joined the Interstate Technology & Regulatory Council Board of Advisors in 2016 as the State At-Large Member. In 2017, he was asked to become the Team Leader Liaison on the Board, which he accepted. At the 2018 Annual Meeting he was elected co-chair of ITRC for 3 years. He currently serves as a co-leader of the ITRC PFAS Aqueous Film-Forming Foam (AFFF) writing subgroup.



Shalene Thomas is Vice President, Global Emerging Contaminant Program Manager, and PFAS Work Group lead for Wood. She has more than 23 years of experience in environmental consulting that includes 13 years of experience supporting per- and polyfluoroalkyl substances (PFAS) evaluations. She has supported State, Federal, and industrial clients with PFAS services ranging from strategic liability management and litigation support to investigation, risk assessment, and remediation. She has served as PFAS/AFFF keynote speaker and panel member and supported PFAS projects across the U.S. as well as in Europe, Australia, and Canada. She currently serves as a co-leader of the ITRC PFAS AFFF writing subgroup, serves as Technical Panel member for the Fire Protection Research Foundation (FPRF) “Firefighting Foams: Fire Service Roadmap” as well as member of the PFAS Subcommittee for the FPRF Fire Fighter Cancer Cohort Study (FFCCS). Shalene received a B.S. in Biology from Western University and an M.S. from Duquesne University in Environmental Science and Management.



Kate Emma A. Schlosser, P.E. serves as the supervisor of the Emerging Contaminants Section of the NH Department of Environmental Services (NHDES) Hazardous Waste Remediation Bureau, and currently focuses her work on investigation and response actions for per- and polyfluoroalkyl substances (PFAS) contaminated sites. Prior to joining the NHDES in 2016, Kate Emma worked in private consulting for 15 years, where her experience included environmental site assessment, remedial actions, and brownfields redevelopment for the public and private sectors. Kate Emma received a B.S. in Civil Engineering with a concentration in Environmental Engineering from the University of Vermont, and is a registered professional engineer in New Hampshire. Kate Emma is currently a co-leader of the ITRC PFAS Team.

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1. Are PFAS still used in firefighting foams, and if so, which types of foams contain PFAS?

[Thomas] Some, but not all Class B foams contain PFAS. Class B firefighting foams are commercial surfactant solutions that are designed and used to combat Class B flammable fuel fires. All Class B foams are not the same. Although not usually categorized this way from a fire protection viewpoint, they can be divided into two broad categories from a PFAS perspective: fluorinated foams that contain PFAS and fluorine-free foams (F3) that do not contain PFAS. Figure 3-2 of the Tech Reg illustrates the types of foam classes that are part of the Class B family of foams. Most major manufacturers make both F3 and fluorinated foams so brand alone does not dictate if a foam is fluorinated or not. ITRC's effort has focused to date on AFFF as these are the primary foams that contain fluorosurfactants.

2. Do all AFFF Contain PFAS?

[Spiese] Yes, all AFFFs contain PFAS, however the mixture of PFAS in the concentrate varies by manufacturing process, and manufacturer formulation. AFFF products are synthesized by combining hydrocarbon foaming agents with fluorinated surfactants to achieve a product that has been used at military installations, civilian airports, petroleum refineries, bulk storage facilities, chemical manufacturing plants, and fire departments. The product is considered a 3% concentrate intended to be mixed with 97% water or a 6% concentrate intended to be mixed with 94% water to fight fires. As illustrated in Figure 3-3 of the Tech Reg, a general 3% concentrate contains more than 60% or more of water/diluent, more than 20% solvents, a small percentage of additives and modifiers, and approximately 15-18% surfactants, of which less than 2% are fluorosurfactants. These fluorosurfactants contain PFAS.

3. Given that the PFAS mixture will vary by manufacturer formulation, can you provide information about what PFAS were used (are used) in fire-fighting foams? For example, are PFOA and PFOS ingredients in foam?

[Field] Yes, PFAS are still being used in firefighting foams. For composition we have to consider both historical and current AFFF formulations. There are foams that were requalified in 2015 under different criteria. For the historical formulations, there are literature sources cited in the Tech Reg that provide quantitative (Backe, Day, and Field 2013), or qualitative compositions (D'Agostino and Mabury 2017; Xiao et al. 2017), and a new paper on the requalified Mil-Spec AFFF currently listed on the QPL (Ruyle et al. 2021). New Mil-Spec contains PFAS at similar levels to older AFFFs, Mil-Spec, AR-AFFF and non- Mil-Spec contain PFAS. We know less about the non-Mil-Spec AFFF today. For both the DOD and the FAA, military specification 24385 is required per performance specifications. Current Mil-Spec requires fluorinated surfactants, but maximum of 800 ppm of PFOS or PFOA.

[Schlosser] Section 3 of the Tech Reg includes the information about AFFF and links to the references just mentioned.

4. What proven technologies are currently available for water? Is pump and treat the only proven groundwater remedy at this time?

[Shierk] The Tech Reg contains descriptions of proven groundwater treatment technologies and the rest of this roundtable will cover many of these approaches. The two most widely implemented technologies for water treatment are granular activated carbon (GAC) and ion exchange resins (IX), and these are commonly utilized in drinking water systems, which you could argue are essentially pump and treat systems. Reverse Osmosis (RO) is also an effective treatment method for water.

While there are no destructive groundwater remedies that have been demonstrated at full-scale, in situ sequestration with injected colloidal activated carbon is a field demonstrated alternative to pump and treat for limiting groundwater migration. But in terms of "treatment" - specifically other traditional remediation techniques like excavation and disposal don't technically "treat" the source - these are currently the only field-scale options being used.

[Schlosser] See also the treatment technologies tables, Table 12-1 Liquids and Table 12-2 Solids, that are provided as separate downloadable files linked in Section 12 of the Tech Reg that have more information about technologies.

5. Are there effective on-site treatment technologies that are currently available for soil, or are the remedial approaches limited to excavation and off-site disposal?

[DiGuseppi] Field demonstrated approaches for soil include excavation and offsite landfilling or incineration, and soil stabilization, which can be conducted fully on site. Soil washing has been performed successfully at limited field

locations, and mostly overseas. Thermal desorption shows promise for implementation on site but has only been implemented at the bench and small field pilot sites. Two field-scale pilot tests for thermal treatment are pending for later this year. A question came into the Q&A about incineration, USEPA has been working on sampling and analytical methods for off-gas related to incineration, to understand that better. We have more information later in this session.

6. What innovative or new technologies are being developed, and how far along are these approaches?

[Crimi] Some new and innovative technologies for treating groundwater include use of advanced sorptive media with very high sorption capacity or those that can target particular types or compounds of PFAS; as well as some aggressive treatment approaches that rely on thermal destruction or free radical-based processes are advancing. Although, it is important to note that not all free radical approaches are effective at degrading PFAS. Many of these technologies coming down the pipeline are introduced in the Tech Reg, with references provided for further detail.

7. Please describe the two primary manufacturing processes for PFAS in AFFF and comment whether AFFF manufactured by different processes have different mixtures of branched and linear isomers.

[Field] The fluorosurfactants in AFFF formulations can be produced using the electrochemical fluorination (ECF) process or fluorotelomerization (FT) processes. The ECF process is a complex process, that starts with a branched and linear feedstock and transformed it into a fluorinated branched and linear mixture. Right out of the process, the branched are about 75% and the linear are about 25% and the ratio is characteristic of ECF chemistry. Both ECF-derived and telomer-derived AFFF contain diverse mixtures of PFAS. However, the ECF process results in a PFAS mixture dominated by perfluoroalkyl sulfonates (PFSA), while the fluorotelomerization process generates linear polyfluorinated compounds. ECF-based AFFF formulations were voluntarily phased out of production in the United States in approximately 2002.

8. Are the ECF-based AFFF formulations that were phased out of production roughly 20 years ago called “Legacy AFFF”?

AFFF via ECF ceased manufacturing approximately 20 years ago. However, AFFF based on fluorotelomer-based PFAS remained on the MilSpec. The version of the Mil-Spec was issued in 2015 with limits on the levels of PFOS and PFOA.

The Tech Reg refers to two kinds of AFFF as “Legacy AFFF”: (1) Legacy PFOS-based AFFF was manufactured in the US from the late 1960s until 2002 exclusively by 3M and sold under the brand name “Light Water” and (2) legacy fluorotelomer-based AFFFs were manufactured in the US from the 1970s until 2016 and encompass all other brands of AFFF except for 3M Light Water or their licensed products.

9. Please further describe the telomer based foams, and comment on how these telomer formulations varied over the past few decades of AFFF use.

[Thomas] The telomerization process, produced mainly linear isomers with an even number of carbon chains as the major products. These have been manufactured since the 1970s. There are some legacy fluorotelomer products as well as modern fluorotelomer products. The nomenclature includes n:2 fluorotelomers, where n represents the perfluorinated carbon chain length and 2 represents the non-fluorinated ethane attached to the functional group, such as alcohols, carboxylates, sulfonates, etc. Fluorotelomers are predominantly produced in 4:2-, 6:2-, 8:2-, and 10:2-carbon chain lengths although 12:2 is seen in some Mil-Spec AFFF.

Modern fluorotelomer AFFF was developed in response to the USEPA 2010/2015 voluntary PFOA Stewardship Program (USEPA 2018). Most foam manufacturers now produce short-chain (C6) fluorotelomer-based fluorosurfactants. These modern fluorotelomer AFFFs, or “C6 foams,” do not contain or break down in the environment to PFOS or PFOA and are currently considered to be less toxic and have reduced bioaccumulative potential compared to long-chain (C8) or legacy foams. But under particular environmental conditions, breakdown products of C6 foams can include PFHxA, PFPeA, and 5:3 FTCA (Kempisty, Xing, and Racz 2018). Modern fluorotelomer AFFF may contain trace levels of PFOA and PFOA precursors as unintended manufacturing impurities or byproducts.

[Schlosser] Section 2 of the Tech Reg includes more information about PFAS nomenclature.

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10. For those PFAS reported on a target analysis (say 15-30 different PFAS, depending on the method), are there typical PFAS that would also be found in AFFF formulations? If so, what are those PFAS?

[Field] Of the target PFAS in commercial analytical methods, PFASs are active ingredients in AFFFs based on ECF chemistry (e.g., PFOS). In the AFFF concentrate, there are gram per liter quantities of the sulfonates, but carboxylates (e.g., PFOA) are one one-hundredth of the PFSA concentrations. For the FT AFFF, commercial labs, will detect ng/L to ug/L concentrations, but correspond to minor components. The commercial analytical methods are not really set-up to detect the active ingredient, higher concentration PFAS in FT-based AFFF.

11. Are there other PFAS that we should be looking for in the environment that are not typically analyzed for but might be precursors to the commonly regulated PFAS like PFOA and PFOS?

[Field] PFAS including the C6 sulfonamide (PFHxSA, short chain cousin to PFOSA) is found in surface waters (D'Agostino and Mabury 2017; and Schwichtenberg et al. 2020) and groundwater (Adamson et al. 2020 and Nickerson et al. 2021) and 5:3 FTCA is associated with landfill leachates. Both PFHxSA and 5:3 FTCA are shorter than C8 so they are not precursors of PFOS or PFOA.

12. As we just heard, the modern FT foams might contain 6-carbon-based fluorotelomers, which could break down to PFHxA, PFPeA, and PFBA, each of which are regulated in various states. Are states tracking each application of these 'new' foams? How is that tracked?

[Spiese] States are only getting started on these tracking efforts. The Tech Reg Section 3, and as illustrated in Figure 3-1 and section 3.8.1, outlines best management practices for tracking from procurement, to use, and disposal. State Emergency Management groups and many municipal and local fire departments (FDs) are re-evaluating how best to track the use of foam. This has not yet been standardized across foam users/industries.

13. How much PFAS are in foam? Do more recent Safety Data Sheets show PFAS percentages in AFFF products?

[Thomas] SDSs do not generally define anything specific as it relates to fluorine content. Total PFAS content in foam varies as well as the specific compounds in the foams. The current Mil-Spec requires no more than 800 ppb of PFOA or PFOS be present in Mil-Spec 24385 foam concentrates. The Green Screen Certified Firefighting Foams identifies that there is no intentionally added PFAS and no more than 100 ppm of total organic fluorine be present as a result of unintentionally added impurities. The Green Screen require the entire PFAS chemical class, verified with analytical testing, have a finding less than 1 ppm or 0.0001 weight percent total organic fluorine of intentionally added PFAS. Figure 3-3 of the Tech Reg illustrates the typical composition of 3% concentrate. When the concentrate is used it is diluted with 97% water.

14. What is the preferred method (both feasible and cost effective) for home water treatment technologies.... IX resin, or GAC, or RO? Or maybe these technologies in series? And are there documents that describe the life cycle costs of in-home treatment compared to connecting to public supplied water?

[Shierk] All three mentioned technologies are suitable and available. Relatively inexpensive multi-stage filters are available with carbon and ion exchange, which would likely eliminate any PFAS in the water, if maintained properly. The choice of which technology to use may depend more on the background water quality than the PFAS concentrations, as there may be other constituents like iron that could affect the efficiency of the treatment technology.

Details on life cycle costs are not readily available because there are many variables that can affect the maintenance and the efficiency of the chosen technology. Site-specific assessment would need to be made.

15. What treatment technologies have been implemented for public drinking water supplies? Have standard specifications been developed for these approaches? Can you speak to the effectiveness and the associated cost?

[Shierk] The primary technologies applied to PFAS in drinking water are GAC and IX. RO is used, but it is often a secondary treatment technology. Adsorption systems have NSF and AWWA standards, although not specific for PFAS. Equipment is standard for drinking water. In general, site-specific testing, such as rapid small-scale column tests for GAC, must be performed before designing any drinking water treatment systems for PFAS. Operating expenses are hard to predict and are driven by background water quality, PFAS concentrations, and what the treatment objectives are for the water.

16. Is pump and treat primarily used as remedial action or just for containment and control?

[DiGuseppi] Just like for other soluble contaminants, pump and treat is most effective when used for hydraulic containment and control. In general, because of matrix diffusion, pump and treat is not effective for aquifer cleanup.

17. If pump and treat was used as a containment strategy, what depth should the extraction wells favor - shallow or deeper? Does the target depth vary based on the type of release (for example, a release at a historic industrial site versus a release at a fire training area) and/or the type of PFAS present?

[DiGuseppi] That's an interesting question and the answer of course is site-specific, but most of the PFAS that we are concerned about today (for example, PFOS and PFOA) don't commonly exhibit NAPL (e.g., sinking) behavior and behave as soluble compounds in groundwater. Therefore, sampling the "first water" is a sufficient initial characterization approach. However, for nature and extent assessment in a remedial investigation, deeper samples may be required to bound the impacts vertically.

Of course, if the groundwater is diving downward, the soluble PFAS would also migrate downward in the aquifer, so the pump and treat system would need to be designed accordingly.

Related to the circumstances of release, there is some evidence that the release scenario can affect PFAS occurrence in vadose zone soils, but there is little evidence that the release mechanism has an impact on the resulting vertical occurrence in an aquifer because of the mobility of PFOS or PFOA in groundwater. Information about fate and transport processes in the environment is in Section 5 of the Tech Reg.

18. Are capping and barrier walls being used for containing source material to reduce contact with ground water, or reduce GW migration?

[DiGuseppi] I'm not aware of specific applications of barrier wells for PFAS source or plume control, but that sort of containment would be a reasonable option, depending on the site-specific objectives.

19. Many of the treatment techniques used to remediate groundwater seem to be by pump and treat using GAC or IX, which was formerly the standard practice for other groundwater contaminants. However, other in-situ practices have since been implemented for other contaminants, and these other in-situ technologies are generally more efficient and cost effective than pump and treat. Have in-situ treatments been developed and applied for treatment (and destruction) of PFAS in groundwater?

[Crimi] In situ sequestration has been field demonstrated by a commercial vendor at around a half dozen full scale sites and it appears to be effective. This is a sorption approach, not destruction. Destructive in situ technologies have been tested on the bench scale, but to our knowledge no successful full-scale in situ field project has been conducted. There is a demonstration funded by ESTCP coming up this year that will be testing a new in situ sonolysis based treatment approach.

20. Are there any in-situ technologies effective for soil treatment? How effective are these treatment methodologies?

[DiGuseppi] In situ soil mixing using stabilizing or sequestering agents, such as activated carbon and zeolite clays, have been demonstrated in the field. These technologies sorb PFAS, making them immobile. In situ thermal desorption will be tested this year under an ESTCP field demonstration project. We are not aware of any other in situ technologies documented as being effective for PFAS in soils. The Tech Reg has references to the technologies that we are aware of at this time.

21. Are there any case studies or implementation examples we can look at for these techniques?

[DiGuseppi] The Tech Reg has case studies for implementation of well-documented, common technologies.

22. How effective are the groundwater treatment technologies if the PFAS are a co-contaminant, like with a solvent plume?

[Crimi] It is a site-specific answer. Sorption with GAC can be effective for CVOCs, BTEX, and other organic compounds. Ion exchange resins for PFAS are specialized products, although IX in general can be effective for some metals. RO can be effective for co-contaminants in some cases but clearly not all. Some of these co-contaminants can interfere with PFAS sorption, but it is up to the engineering design professionals to take those co-contaminants

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into account when selecting the remedial technologies, as is already the case with other co-contaminants (like CVOCs and 1,4-dioxane). Site-specific treatability testing is highly recommended.

23. Are there any known issues with co-contaminants if the preferred remedy is in-situ colloidal carbon + polymer injection (barriers) in subsurface?

Co-contaminants can compete with PFAS in any sorptive treatment process, but the extent will depend on site-specific factors like concentrations of contaminants and co-contaminants, contaminant ratios, and groundwater geochemistry.

24. One common co-contaminant is petroleum - could you review how petroleum in particular could affect sorptive technologies or other in situ remedial techniques?

[Shierk] Petroleum-based co-contaminants could take up sorption sites, depending on the sorptive media processes. They could also interfere with destructive treatment kinetics and effectiveness. It depends on many things, including PFAS and co-contaminant concentrations, site-specific properties, and characteristics of the treatment approach. Again, site-specific treatability testing is highly recommended.

25. Has there been any experimentation with pretreated GAC that would enhance short-chain PFAS adsorption without significantly impacting loading capacity?

[Crimi] There are some proprietary products that combine carbon with polymers and other materials for targeted treatment of short-chain PFAS. The Tech Reg describes some of these products and provides references for them. There is a lot of research going on in this area.

26. How are rapid small-scale column tests (RSSCTs) results validated for GAC?

RSSCT are becoming more standard for sorptive media. These are treatability tests to evaluate site-specific competition and compound-specific breakthrough. RSSCT results should be validated with an on-site pilot study to make sure RSSCT results are valid for the larger system as well.

27. Available information suggests that PFAS can break through GAC quicker than VOCs, and thus compliance schedules typically used for VOC treatment wouldn't be applicable. Are there established compliance sampling frequencies for GAC for PFAS treatment?

[Shierk] There are no standard frequencies that have been developed for GAC for PFAS treatment. Sampling schedules are typically dictated by the various permits needed for this type of remediation, cleanup criteria, and other operational requirements. Presumably the regulatory oversight entity will take into consideration the projected breakthrough for PFAS when defining monitoring schedules and issuing permits, as these compliance schedules are likely determined on a case-by-case basis. And of course, site-specific treatability testing is required to understand projected breakthrough times.

28. How much fluorine-containing foam is being stored [in tanks] at DOD sites and other locations?

[Spiese] Currently, much of the AFFF stored at DOD facilities is stored in tanks, for example at hangars or for fire-fighting apparatus, but also may be stored in drums or 5-gallon pails. Likewise, most FAA airports, (these are the Part 139 airports and airport fire response departments), are required by the FAA to be Mil-Spec compliant, they would have similar storage arrangements. It's been estimated that DOD stored about half of the AFFF in the country (Darwin 2011), these foams would have included both legacy and modern AFFF foams. There has been a transition from legacy C8 foams to modern C6 foams in many locations, but some locations and industries have not transitioned. Users are awaiting a certified Mil-Spec foam that is fluorine-free which is not yet available, and FAA still requires Mil-Spec foam, which is fluorinated. Across sectors and users, training and testing activities have been modified such that fluorinated surfactants are no longer being used which has minimized fluorinated foam use and discharge to the environment.

29. Do we have any information and/or data on PFAS concentrations and compositions for fluoroprotein type foams - both currently and historically?

[Field] Figure 3-2 of the Tech Reg illustrates that there are both fluorinated Class B protein foams and non-fluorinated Class B protein foams. In terms of detailed concentration and composition, that is unknown. We at Oregon State have a few of these foams and are currently studying them, but right now we have very limited information.

30. How frequently are AFFF (or Class B foams) used? Is there still a lot of use?

[Thomas] Class B foams are broadly used across different industries and those are defined in Section 3 of the Tech Reg. Current AFFF use is limited, in the last year or two now, to emergency response for fires. As a result of some states having implemented bans for training, through regulatory and legislative changes, AFFF is generally no longer being used for training. Mandatory AFFF use, as required by Mil-Spec 24385, occurs currently for both the DOD and certain airports per FAA. Not for training, but for emergency.

31. Can you please describe an actual fire training event? For example, how long do they typically last? How often do they typically occur?

[Spiese] To our understanding, at DOD facilities or FAA facilities, when training personnel train to extinguish a fire, fuel is often put into a pit or container and then lit on fire. The AFFF was applied to the fire to encapsulate it and put it out. This was a short event since they put out fires quickly (a few minutes). In the past, in the 1960s – 80s timeframe, these events might happen weekly at DOD sites. More recently, the training events have been conducted less frequently. Larger amounts of AFFF were used and released to the environment when testing equipment, for example, where an entire truck of foam was emptied and the truck was re-filled.

32. Have all of the airports in the U.S. done an initial investigation of AFFF inventory, releases, and presence onsite? And are airports taking steps to limit future risk from AFFF releases?

[Thomas] Airports do have a heightened awareness around AFFF. Currently sampling activities in general are being driven at the state level and only some states have dictated sampling at airports (for example, MI, CA). Many US airports are employing best management practices to limit future risk from AFFF releases. For example, best management practices have been published by the FAA, for the part 139 airports, as a FAA Cert Alert (No. 19-01) that Mil-Spec foam is required but that equipment testing may be conducted using one of three pre-approved closed-loop systems (EcoLogic, NoFoam, Oshkosh Eco EFP) to minimize environmental impact and releases to environment during mandatory equipment testing, as well as development of SOPs for storage, handling and disposal. Some states have even purchased the pre-approved equipment for circulation across airports, not just the part 139 airports, during required testing events.

33. Do you know if local fire departments (FDs) track AFFF use and purchase?

[Spiese] This will be different for different FDs; we don't have specific information in Tech Reg on this except in the BMPs Table 3-1, published May 2021, where we encourage tracking use and purchase. Experienced FDs are careful to track due to possible cross-contamination of AFFFs and reactions that occur by mixing non-Mil-Spec AFFFs. Many smaller FDs purchased AFFF through mutual aid associations and that makes record keeping more challenging. Figure 3-1 illustrates the life cycle considerations for AFFF; these are described in Section 3. The BMPs Table 3-3 is in Section 3.8.1, and emphasizes the importance of tracking purchases, storage, use, and disposal of fire-fighting foams.

34. Was (or is) the use of AFFF at training facilities by local or volunteer fire departments very common or limited to special training?

Volunteer and local fire department do have on-going fire training requirements and frequency of training vary by local, regional, state jurisdictions. Some training using AFFF would have occurred. Many municipal fire departments have centralized training locations for fire response and might not train at their municipal locations; however, there likely was (or is) some training at municipal locations, but this would be on a case-by-case basis.

35. Do AFFF releases cause air deposition of PFAS? If so, how significant are those impacts relative to impacts from industrial facilities?

[Field] There are no data available that I know of about air deposition from AFFF use. There are limited data on volatile PFAS in AFFF. Two recent papers, Favreau et al. (2017) looked at volatile fluorotelomer alcohols and sulfonamido ethanols in AFFF, which are unreacted intermediates, and Roth et al. (2020) looked at aerosols containing PFAS above AFFF. We don't have information about air deposition of PFAS from AFFF use, so we can't put that into context with industrial downwind deposition, which has been much more widely studied.

36. What is being done to investigate spills of AFFF that weren't previously required to be reported as a spill?

[Spiese] Some states have passed legislation that requires reporting of AFFF when spilled/disposed. Examples are NY and WA state. NH has an advisory to report in a 2017 memo to FDs. States are also testing public water supplies

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for PFAS, and so indirectly are identifying PFAS releases. The ITRC PFAS team is currently working on expanding the regulatory table as part of activities in Section 8.2 to present all types of regulatory activity pertaining to PFAS. This is anticipated to be published by the end of the year.

37. For each of the technologies, can you please describe how each technology actually destroys (or transfers) PFAS?

[Crimi] Many technologies do not destroy PFAS, but merely transfer them to another medium, such as from the aqueous phase to a solid phase. PFAS destruction approaches typically involve heat/pressure, and aggressive free radicals, especially aqueous electrons. There are many references provided in the Tech Reg that point to detailed mechanisms. These can also be found in recently published review papers focusing on treatment mechanisms (Wanninayake 2021; Miklos et al. 2018; Marino et al. 2016).

38. What approaches are used to manage remedial wastes, and are there any publications that describe requirements or recommendations for waste determination and disposal?

[Shierk] Management of remedial wastes is something that needs to be considered when evaluating different PFAS treatment technologies. The US EPA published a document in December 2020 titled "Interim Guidance on Destroying and Disposing of Certain PFAS and PFAS-Containing Materials That Are Not Consumer Products." The document was released for public comment and the public comment period ended in February, so there may be revisions coming that remove the "Interim" title. This document outlines proven technologies for addressing PFAS waste, including thermal treatment, landfilling, and underground injection. It also addresses gaps in the current knowledge for PFAS destruction and disposal and identifies needed and ongoing research.

As for regulations governing waste determination and disposal, PFAS are not currently designated as hazardous substances under any Federal environmental regulatory program. Some states have regulated these compounds and have published guidance outlining their rules. We recommend contacting your local regulators when deciding how to manage and dispose of PFAS remedial wastes.

In addition, there was a question that came in on the chat about reactivation of granular activated carbon (GAC). GAC can be thermally reactivated as well as reactivated by solvents. If regenerated or reactivated GAC is being considered for use, we again recommend contacting your local regulators to determine whether reactivated GAC can be used in the specific application.

39. Thermal treatment was discussed in that EPA document and incineration of PFAS has been an emerging issue. Is incineration used for treatment of PFAS-impacted media? And if so, is there a resource that has published minimum combustion temperatures to reach complete destruction of PFAS?

[Shierk] Incineration is still being used as a treatment option, but incineration remains a hot topic for PFAS destruction. In addition to the "Interim Guidance" document, the USEPA also published a technical brief in July of 2019 that specifically discusses the use of incineration to manage PFAS waste streams. This document is only a couple pages long and provides a summary of the state of the science.

Both documents provide information on the combustion temperatures that have been identified in research settings to destroy PFAS, but also identify gaps in the research and acknowledge that the ability to completely destroy PFAS through incineration is not well understood. This is an active area of research, and we expect that the science behind incineration for PFAS-impacted wastes will advance in the coming years.

40. How are spent resins managed?

[DiGuseppi] Some specialty ion exchange resins can be regenerated, and systems are being built and installed to do that regeneration on site. Single use resins are generally landfilled or incinerated, or in some cases, burned in lower temperature thermal desorption kilns because they are typically polystyrene media with BTU value that can be captured. It's critical to work with your regulators to be sure that these solutions are acceptable within that state's regulatory program. Disposal options may change in the future if PFAS are designated as hazardous substances at the state or federal level.

41. What is the current status of using incineration to destroy PFAS given that only a small number of PFAS analytes can be detected through air testing?

[DiGuseppi] USEPA is working on developing an analytical method to measure PFAS in off-gas through incineration/thermal systems. This is an active research area. For now, well documented proof of complete

destruction of target PFAS is lacking. In Alaska, a thermal desorption facility, a rotary kiln with thermal destruction of the off-gas, is permitted based on total fluorine emissions, not emissions of specific compounds.

42. Is there an approved disposal method for virgin or spent AFFF?

[Thomas] The USEPA interim guidance document that Cliff mentioned earlier includes AFFF. Currently, there is not an "approved" disposal method for AFFF that is broadly accepted by federal and state regulatory authorities. Disposal of AFFF products represents a significant challenge for any owner of firefighting foam concentrates. The disposal of AFFF concentrates through all the currently available disposal options carries inherent risk and potential future liability that the practitioner should be aware of such that the best disposal option can be selected, and future potential liability can be considered. The ITRC PFAS team is currently working on an AFFF disposal table that will be released later this year, presenting currently available options including stabilization and burial, deep well injection, and incineration, that are discussed in the USEPA interim guidance, as well as advantages and disadvantages associated with each method and experimental disposal technologies under development when the table was prepared. The disposal options that are currently available for materials impacted with dilute AFFF wastes are presented in Section 12 of the Tech Reg.

43. Section 3.7.2 refers to disposal of flush water with dilute concentrations of PFAS. Are there any concentrations or indicators of a waste threshold for disposal of liquids or solids? The commenter says, "Any activity we have seems to generate significant amounts of rinse water and ever-increasing amounts of decontamination water."

[Thomas] There are currently no widely accepted criteria for waste thresholds for disposal of liquids or solids. In case studies, these values have generally followed published values, whether guidance or promulgated rule, for various media, such as 70 ppt for groundwater and drinking water or in some cases lower available state values. We are also working on a table summarizing case studies for transition to fluorine-free foams and documenting the information that was used for those case studies.

44. While incineration is studied, are there other technologies that destroy PFAS and not just absorb them?

[Shierk] The Tech Reg describes several technologies that destroy PFAS. Most have not yet been tested in the field, but are limited application or developing technologies as we describe in the Tech Reg. A few examples are electrochemical, non-thermal plasma, and sonolytic treatment for liquids.

45. Can PFAS degrade in the natural environment? Have degradation rates been measured in laboratory settings?

[DiGuseppi] We have to keep in mind that PFAS are a broad family of compounds with many different properties. There is some evidence of biologically mediated breakdown of some precursors, through enzymatic and oxidation processes. There is not documented evidence of complete natural destruction of specific target compounds, such as PFOS. However, 20 years ago, we considered MTBE and 1,4-dioxane to be non-biodegradable, but increasing evidence has demonstrated that biodegradation of these compounds can occur and may in fact be common. So, hope springs eternal that we will find some similar biological solution for PFAS.

46. Is bioremediation of PFAS a tested technology? Are there any microbes that can help with cleanup?

[DiGuseppi] Some oxidative reactions related to bacterial enzymes have been shown to destroy some PFAS, but not the most recalcitrant target compounds like PFOS. Additionally, fungal enzymes are able to degrade some precursors to produce carboxylic acids. But these biological approaches have only been tested at the beaker scale and have shown mixed results. For right now, bioremediation of PFAS is not a tested technology.

47. Is phytoremediation effective for PFAS?

[DiGuseppi] There is considerable research happening now on uptake of PFAS into plants, to address the question of whether exposure to agricultural products is a human-health exposure issue. The evidence does support that some plants do pull PFAS from soil and shallow groundwater into the plant material or fruiting bodies. However, to my knowledge, there are no documented studies of PFAS phytoremediation as a remedial action.

48. Is exposure to UV effective for treatment, and if so, how much?

[Crimi] There is little evidence of effectiveness of UV alone in destruction of PFAS, especially PFSAAs. Some destruction of PFCAs has been documented in bench-scale testing. More often we see UV combined with another agent, such as UV/ozone and UV/peroxide methods, these seem to be effective on PFCAs but less so on PFSAAs.

Addressing a question from the chat, does boiling water work to break the carbon-fluorine bond. The answer is no; it really takes aggressive approaches to breakdown PFAS, such as supercritical water oxidation (SCWO) where the water is pressurized to allow it to reach 350 degrees C.

49. For AFFF release sites, is it possible to tie a release of AFFF and the associated AFFF impacts found in soil and groundwater to a particular AFFF manufacturer, formulation, and timeframe of manufacture?

[Field] The good news is that there are a number of research groups that have been funded to try to develop information to address these kinds of questions. Right now, it is premature to make a definitive connection between environmental concentrations and specific products. The presence of PFOS in the environment indicates the use of AFFF based on ECF chemistry (that at present we largely connected to 3M AFFF). The telomer sulfonates are more challenging. Telomer sulfonates being measured in environmental samples can arise from a number of different fluorotelomer-based AFFFs. It will be much more difficult to sort out among the different manufacturers. The telomer sulfonates occur as minor impurities and major intermediate in precursor degradation so right now we can't trace the telomer sulfonates back to a particular formulation, timeframe, or manufacture. We see few FT precursors in groundwater, but one indication of FT AFFF use may be the presence of only linear PFCAs.

[Thomas] This is an active area of research. The challenges include: AFFF were stockpiled (not necessarily used in the year purchased), being listed on the USDOD QPL did not indicate large-scale purchase by bases or facilities, and variation by year for a given manufacturer is not yet well documented. Not all foams are the same which makes this forensics evaluation of formulation, timeframe, manufacturer very difficult. We are adding some information in Section 3 on this with the new information at the end of this year.

[Field] Some questions from the chat, about whether the AFFF manufacturers are paying for this research information about their formulations. From the perspective of Oregon State, the answer is no. AFFF composition reverse engineering has been funded by US DOD research programs (e.g., SERDP-ESTCP). Further, AFFF SDS sheets do not include detailed composition information because that is considered confidential business information.

50. Is there an expected or typical degradation pathway observed at AFFF release sites for polyfluorinated precursors to transform to perfluoroalkyl acids like PFOA and PFOS?

[Field] There is information in the literature on the biodegradation of FT precursors (Weiner et al. 2013 and Harding-Marjanovic et al. 2015) to form fluorotelomer sulfonates (many FT precursors are likely to have fluorotelomer sulfonates as intermediates). Fluorotelomer sulfonates can further biodegrade under aerobic conditions but to date there is no evidence that they degrade under anaerobic conditions (Zhang et al. 2013), which is why they may be preserved under anoxic groundwater conditions.

51. Do the longer chain PFAS in AFFF typically break down to shorter chain PFAS once released in the environment? What mixtures of PFAS would we typically see at a AFFF release site where some degree of weathering has occurred compared to the original composition in AFFF?

[Field] Another question from earlier, about biotransformation, fluorotelomer sulfonates FTS can be biotransformed into shorter chain PFCAs and unsaturated intermediates (Weiner et al. 2013 and Harding-Marjanovic et al. 2015). Long chain FT AFFF are likely breaking down but there is less field evidence for the biotransformation of ECF PFAS, which is due in part to the complexity of the ECF-based AFFFs. Elevated level of C6 PFCA (e.g., PFHxA), which are observed at AFFF release sites, may be an indicator of ECF PFAS biotransformation (Houtz et al. 2013). Attention needs to be paid to the branched and linear composition of PFCAs at AFFF-impacted sites (Houtz et al. 2013).

52. How safe is it to assume that groundwater containing fluorotelomers and precursor compounds are "more recent" releases, in that fluorotelomer-based foams were the predominant form of AFFF since the 2000s?

[Spiese] It is not a safe assumption that groundwater containing fluorotelomers and precursor compounds are more recent releases because legacy fluorotelomer foams have been around since the 1970s. They may not have been the predominant foams, but they were around. Environmental forensics for AFFF is difficult and we should use multiple lines of evidence to understand the sources at any specific site. However, the phase-out of the longer chain PFAS by global manufacturers has shown quantifiable increase more recently in shorter-chain concentrations and decreased

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concentrations of longer chains at some of the areas investigated. This may indicate more "recent" releases, but again multiple lines of evidence should be used to understand the sources at any particular site.

53. What do the presence of precursors NETFOSAA and NMEFOSAA indicate about the potential source material? Does it indicate that AFFF is the source material? Does it indicate the PFAS are from a fluorotelomer source?

[Field] These are biological oxidation products of sulfonamidoethanols (Woudneh et al. 2019) and are found in WWTP biosolids. They are derived from ECF chemistry and include branched and linear isomers and they are not considered FT chemistry. Based on the current evidence we have, it is not clear that this is unequivocal evidence of AFFF since these chemicals may have other sources (e.g., wastewater treatment plant biosolids).

54. If one needs to evaluate if the impacts are from different AFFF releases or sources, what is the approach that should be used? Should ratios of certain PFAS be compared or should the evaluation include a determination of the presence/absence of certain PFAS?

[Spiese] Ratios are a great place to start as well as tracking the ratio of branched/linear isomers (keep in mind that partitioning and transport alter ratios). At some of the sites I have worked on, one of the first things we have looked at is comparing the concentration ratios in a water supply well sample to the concentration ratios of potential source area samples. Other PFAS to look for to understand sources are compounds such as fluorotelomer acids (for example, 5:3 FTCA may be an indicator of landfills) and ether compounds as the analytical chemistry methods become more available and we can measure the ether compounds.

55. Can you discuss how we can forensically identify AFFF impacts from other PFAS sources?

[Field] There are many challenges. One aspect is the limited list of target compounds that can be analyzed by commercial laboratories. The EPA and contract labs are doing a great job to expand those lists. The chemistry of AFFF is complex consisting of anionic, cationic, zwitterionic, and neutral species; in addition, different formulations of AFFF from the same manufacturer also vary in their chemistries. PFAS forensic analysis of environmental samples is challenging as many of the PFAS-contaminated sites consist of co-mingled sources. Forensic analysis of such complex, AFFF-impacted co-mingled sources would require consideration of many factors and multiple lines of evidence to better understand the identification and delineation of sources. Current topics in PFAS forensics include: (1) PFAS isomer profiles and chain length ratios, which may differ from source due to transport; (2) identifying unique source-specific markers, which require a detailed understanding of known sources to identify a source related to a sample; and (3) development of high-resolution mass spectrometry (HRMS) tools to help identify and characterize a broad suite of PFAS in sources (e.g., specific PFAS markers). In addition to HRMS analysis, application of statistical analysis tools shows great promise in identifying sources of PFAS contamination. The ITRC PFAS team is working to add an AFFF forensics section to Section 3 of the Tech Reg which will be available later this year. See also Charbonnet et al. 2021.

56. What is the typical timeline from release of AFFF to contamination of soil and groundwater?

[Spiese] The timeline of AFFF releases to contamination of soil and groundwater can depend on site-specific factors however, discharges of AFFF, occurring during firefighting operations, system testing, equipment malfunctions, or incidental releases, can impact soil immediately and groundwater very quickly upon release. In addition to foam, a large amount of water is often applied when attempting to suppress a fire. Due to the highly miscible nature of AFFF, impact can be very quick. The main objective of the initial mitigation efforts should be to reduce the footprint of contamination by limiting the spread of foam and fire water. This is often done through various preplanning, containment, and recovery tactics while making sure that the release has been abated and response personnel are safe. More information can be found in the Tech Reg Section 3.5.

57. Where should site characterization efforts be focused to address AFFF releases?

[Thomas] Site characterizations should focus on fire training areas as well as equipment testing areas primarily. A thorough evaluation of any documented crash sites and/or emergency activities where AFFF was applied, such as accidental spills or releases should be thoroughly vetted. From the Tech Reg document, other considerations include:

- low-volume releases of foam concentrate during storage, transfer, or operational requirements that mandate periodic equipment calibration
- moderate-volume discharge of foam solution for apparatus testing and episodic discharge of AFFF-containing fire suppression systems within large aircraft hangars and buildings

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- occasional, high-volume, broadcast discharge of foam solution for firefighting and fire suppression/prevention for emergency response, as well as repeated spray nozzle testing

58. Are there areas to consider beyond crash or training sites that might not be typically expected? For example, as runways are expanded, could source areas now be located under runways? Also, what about airplanes that are scrapped that might be sprayed down pre-emptively, and wouldn't be at your typical crash site?

[Thomas] Many aviation facilities also had spray nozzle test areas, fire stations, and inadvertent AFFF releases from hangars and other storage areas. Additionally, there could be accidental leaks from foam distribution piping between storage and pumping locations, and from storage tanks and railcars. Depending on the development history of the facility, PFAS-impacted soil could be under runways or buildings. Once the foam is applied, if not properly contained, it can migrate overland in drainage swales or along runway blacktop. It is not clear whether the residual PFAS from AFFF application on an airplane during an emergency response could be sufficient to raise a concern at the "end of life" location (scrap heap, landfill, etc.)

59. How much cleaning is required during foam transition? Is there research on how to clean piping and tanks that have contained AFFF after AFFF is removed such that new replacement foam is not contaminated with PFAS?

For example, one registrant stated: Our aviation facilities have AFFF fire protection systems. The AFFF has migrated through the piping back flow preventers into the broader water distribution network. We have triple-rinsed the piping and have sampled for PFOS and PFOA several times and cannot obtain levels less than the 70ppt standard. We are looking for technologies to clean the piping and valves, and even considering piping replacement. We have this same situation with fire truck storage tanks.

[Thomas] There is currently very little published about how much cleaning is acceptable during foam transition. There is however research currently being conducted by the US DOD via SERDP-ESTCP to evaluate appropriate methodologies for clean-up of piping, tanks during transition. These include the use of precipitation/coagulation/flocculation processes, desalination nanofiltration, and plasma technology to name a few. Some of these are showing promise but many factors play into the decontamination of a system. Additionally, the NFPA Research Foundation just kicked off a project to develop best management practices and guidance for transition from AFFF to F3 foams. See <https://www.nfpa.org/News-and-Research/Resources/Fire-Protection-Research-Foundation/Current-projects/Firefighting-Foams-Fire-Service-Roadmap> for more information.

60. Is treatment typically focused only on long-chain PFAAs, or are short-chain PFAAs included in treatment goals even if these aren't regulated (yet)?

[Crimi] In the lab where we are developing and advancing treatment approaches, we are indeed looking at shorter-chain compounds and a broad suite of PFAS more generally.

[DiGuseppi] In general, most field systems have compliance with regulations as a primary remedial objective. Those regulations are seldom focused on short-chain PFAS. That may change in the future, and as additional compounds are regulated, system designers and operators will need to look at more than just a few PFAS. Of course, some facility owners are interested in going beyond the regulations and treating all detectable PFAS, but we are currently limited by the analytical suites available.

61. What are the effects that precursors have on treatment effectiveness and the effects that treatment has on precursors?

[Crimi] Most treatment decisions focus on PFOS and PFOA as the commonly regulated PFAS, but it's important to understand what's going on with precursors before, during, and after treatment. Precursors can compete with sorption sites, for example, and will also impact the efficiency of destructive treatment processes. Our target PFOS and PFOA compounds can, in fact, form as intermediates during destructive treatment, so understanding those precursor transformations is important.

62. How do you track or measure those effects?

[Crimi] It's a tricky endeavor because we only have analytical standards for a small handful of the hundreds of precursors that can be present, but by measuring total fluorine, fluoride, and by conducting the TOP Assay, we can understand (at least semi-quantitatively) the initial precursor load and effects of treatment on precursors. We can also then have a site-specific understanding of treatment effectiveness and efficiency. So, we are using multiple lines of evidence to understand treatment effectiveness and efficiency.

63. Are there demonstrated effective technologies to remove PFAS from wastewater and biosolids (apart from thermal destruction)? Does the remedial technology matter based on the source (like AFFF releases or industrial releases)?

[Shierk] There are many researchers working on this, but we are unaware of treatment approaches that are currently commercially available for treating PFAS in wastewater and biosolids. The efficiency of viable approaches will likely depend on the PFAS source (AFFF vs industrial sources), but the ultimate effectiveness of the treatment technology probably does not depend on the source.

64. Some water systems are reporting that GAC is less effective with the new very low target PFAS state drinking water standards, such that older treatment systems are needing to be upgraded to technologies such as resin. Can you speak about this 1st generation, 2nd generation treatment evolution?

[Shierk] Currently there is no strong evidence that GAC is less effective on achieving lower PFAS concentrations. We recommend conducting a site-specific evaluation of the treatment system to determine if the system can achieve lower concentrations, some modifications may be needed, but changing the whole treatment technology may not be required.

65. Given the high cost of PFAS removal and off-site disposal, is soil stabilization effective for PFAS?

[DiGiuseppi] Soil stabilization with a number of tailored amendments has been shown to be effective at reducing or eliminating PFAS leaching from soils. This can be implemented in situ with large diameter augers or with a standard excavator with shallow soils. The overall concept seems capable of mitigating PFAS-leaching from soils.

66. Can soil characteristics and partitioning impact the effectiveness of soil stabilization?

[DiGiuseppi] Absolutely. Depending on the mechanism used for stabilizing, the soil chemistry can make a big difference, such as sorption with carbon versus ion exchange with clays, the soil types could have a significant impact, primarily through competitive adsorption. Also, some soil stabilization technologies suggest the presence of oxides to be the dominant factor in retaining anions, their role in natural soils is really not clear.

PFAS partitioning between soil, soil moisture, and soil vapor is poorly understood right now, but substantial research is being performed now to generate a better understanding of PFAS interactions with soil. Section 5 of the Tech Reg document includes information about these processes.

67. Will clay-rich soils influence the selection of treatment strategies? Are there technologies that are more effective (or less effective) in certain types of soil?

[DiGiuseppi] Yes, soil grain size can also be an important thing to look at. For instance, soil washing is sensitive to grain size, such that more clays would slow down the process, or require multiple passes through the washing system, increasing the treatment cost. Thermal desorption, on the other hand, is relatively immune to grain size issues. Stabilization utilizes mechanisms similar to those that clay rich or organic rich soils would exhibit. So, in some cases the presence of clays or organic matter in soils may actually enhance the sequestration processes.

68. Are you aware of case studies that discuss PFAS remediation in wetland environments?

[Shierk] We have touched on this a little bit regarding biological breakdown and phytoremediation, and there are some encouraging studies around these topics. For wetlands specifically, I am not aware of this being done at a field scale. I have seen one study where a bacterial strain from a wetland was cultured in a lab and showed promising results for defluorinating PFAS, but to my knowledge this has not been applied in the field. There are also several lab-scale studies under SERDP that have looked into passive stormwater treatment with combinations of sorption, bioswales, and engineered wetlands. Assessment of this technical approach is advancing rapidly, and more information should be available in the coming years.

69. Are there data available on the potential diffusion rates of PFAS through HDPE geomembranes? If so, do different PFAS diffuse at different rates?

[DiGiuseppi] Some vendor information about reactivity between PFAS and geomembranes has been identified, as well as academic research in this subject just in the past year. One study found diffusion of PFOS and PFOA through geomembranes to be 1000 times slower than for benzene (Di Battista et al. 2020). It is advised to discuss this issue with geomembrane suppliers and perform necessary testing before implementing geomembranes for containment of PFAS wastes.

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The following questions were not answered during the live session as there were more questions asked than could be answered in the time allotted.

70. Do the transport/diffusion rates of PFAS through geomembranes change when intermixed with hydrocarbon or chlorinated solvent VOCs?

The panelists are not aware of any exhaustive studies into geomembrane behavior in the presence of co-contaminants. The industry is just now assessing geomembrane diffusion, so these detailed studies are still ahead of us.

71. What technologies exist to address migration of PFAS from soil to groundwater?

Soil stabilization is probably the most directly applicable technology since it reduces or eliminates leaching of PFAS from soil into water. Any other technology that would remove PFAS from the soil, like soil washing or thermal desorption, would also address migration to groundwater through source removal.

72. Are there documents that describe the effectiveness and the environmental and economic costs of GAC, IX, and RO (including regeneration)? What is the suggested approach for comparison of these technologies that are still in developmental phases? Energy use per mass PFAS?

The panel is not aware of any comprehensive compilation of cost and effectiveness data for these technologies, beyond the case studies that are presented in the Tech Reg. It should be noted that site-specific testing and engineering assessment is almost always needed to be able to predict behavior and longevity of treatment systems. For instance, one project (Hwang and Grieco 2021) found that the GAC effectiveness was 3x greater (for example, 3x longer life), if total organic carbon in the water was reduced from 1.5 mg/L to 0.5 mg/L. Section 12 of the Tech Reg has a new figure on water treatment trains that provides more information about pretreatment steps. This figure will be published by the end of the year.

73. Is there a fluorine-free foam (F3) that is approved for use by the DOD? Has DOD announced a timeline for a new Mil-Spec that requires fluorine free foam?

There is not currently a F3 that is approved for use by the DOD. There are several SERDP-ESTCP research projects currently in progress to evaluate and define adequate AFFF alternatives. The NDAA of 2020 outlines specific requirements for the timeline for AFFF to F3 transition including completion of new Mil-Spec by January 2025 for F3 to be used at all DOD installations and institution of complete ban on fluorinated foams on military installations by September 2029. It should be noted that other countries (for instance Australia, Canada) have accepted F3 foams and transitioned most of their foam applications to these new products.

74. What methods are available to determine if a foam is fluorine-free?

For foams required for use by DOD and FAA, they are listed on the Qualified Product database-Mil-Spec (<https://qpldocs.dla.mil/search/parts.aspx?qpl=1910>). Several foams will be highlighted in our Foam Characteristics table when the Tech Reg is updated. The table will include If an AFFF product is/was fluorinated; If an AFFF product is/was considered a modern or legacy foam and if it is/was manufactured using fluorotelomerization or electrochemical fluorination; When an AFFF product is/was approved for use and for what specific use/application and to what specific performance standard(s); Any other pertinent and available information on the product (compatibility, composition information, equipment requirements, etc.). Additionally, the Draft DOD AFFF01 method for quantifying PFOA and PFOS in AFFF concentrates has been released, <https://denix.osd.mil/edqw/>.

3 References and Acronyms

The references cited in this digest, and further references can be found at <https://pfas-1.itrcweb.org/references/>.

The acronyms used in this digest and the Guidance Document can be found at <https://pfas-1.itrcweb.org/acronyms/>.