NAVFAC
Naval Facilities Engineering Command
ENGINEERING AND EXPEDITIONARY WARFARE CENTER

Emerging Contaminants: Per- and Polyfluoroalkyl Substances (PFASs)

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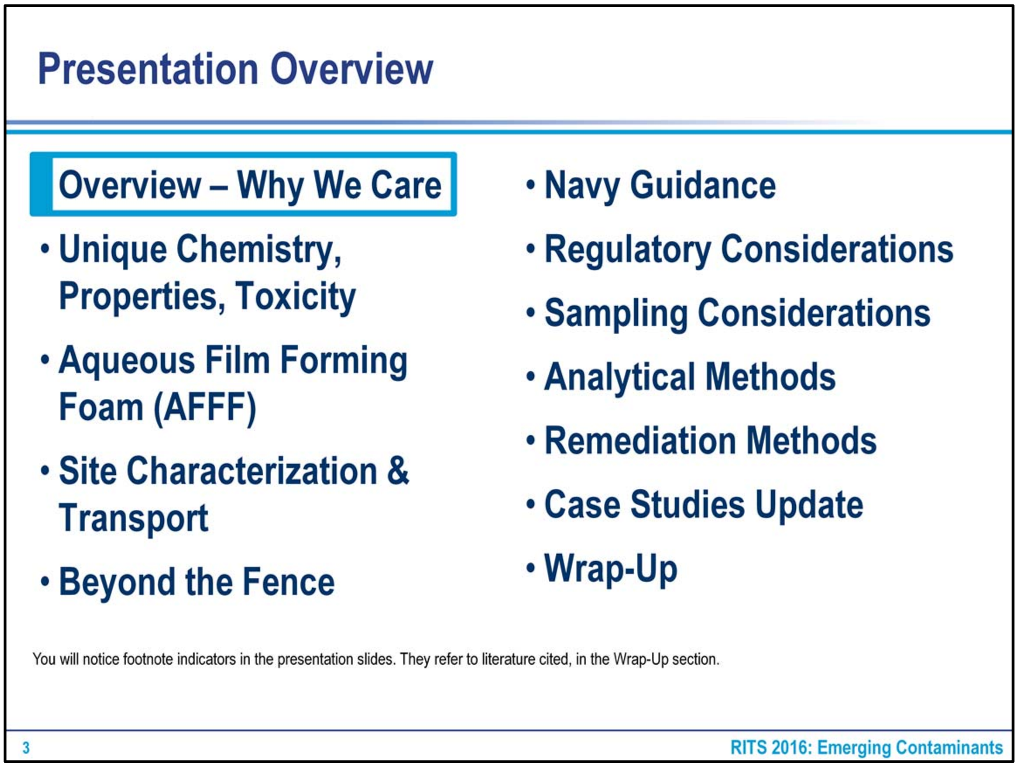
NAVFAC EXWC

Introductions

- **Jennifer A. Field**
  - Professor Oregon State University
  - Ph.D. in Geochemistry, Colorado School of Mines
  - 20+ yrs experience in PFAS analysis, fate, and transport
  - 26 peer-reviewed publications on PFASs
  - Associate Editor for Environmental Science & Technology
- **John Kornuc**
  - Biologist, Naval Facilities Engineering Command (NAVFAC) Engineering and Expeditionary Warfare Center (EXWC)
  - Ph.D. Biochemistry, UCLA; BS Microbiology, Ohio State
  - 30+ years experience in environmental – site investigations, remediation, laboratory establishment


Presentation Overview
Overview – Why We Care
• Unique Chemistry, Properties, Toxicity
• Aqueous Film Forming Foam (AFFF)
• Site Characterization & Transport
• Beyond the Fence
• Navy Guidance
• Regulatory Considerations
• Sampling Considerations
• Analytical Methods
• Remediation Methods
• Case Studies Update
• Wrap-Up
You will notice footnote indicators in the presentation slides. They refer to literature cited, in the Wrap-Up section.
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PFASs Overview – Why We Care

- A class of chemicals that are ubiquitous due to
  - Wide variety of uses
  - Persistence
  - High mobility
- They are a concern due to:
  - Known or suspected toxicity, especially for PFOS and PFOA
  - Bioaccumulation
  - Some have very long half lives, especially in humans
- DoD's use of Aqueous Film-Forming Foam (AFFF)
  - Some AFFF formulations contain high levels of PFOS
  - Resulted in elevated levels of these chemicals in the environment up to 106 higher than background
  - State representatives for Warminster area have recently called on Navy to perform a health effects (C8) study

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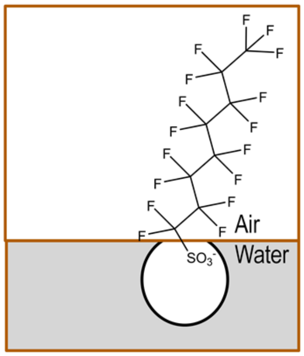
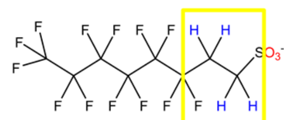
Unique Chemistry of PFASs ~~PFCs~~

- **C-F bond**: shortest & strongest bond in nature
  - Properties less predictable: hydrophobic and oleophobic[1]
- **Perfluorinated** – *all* carbons in chain bonded only to F (e.g., PFOS and PFOA)
  - Few engineered or environmental degradation processes degrade perfluorinated forms



PFOS (***per***fluorooctane sulfonate)

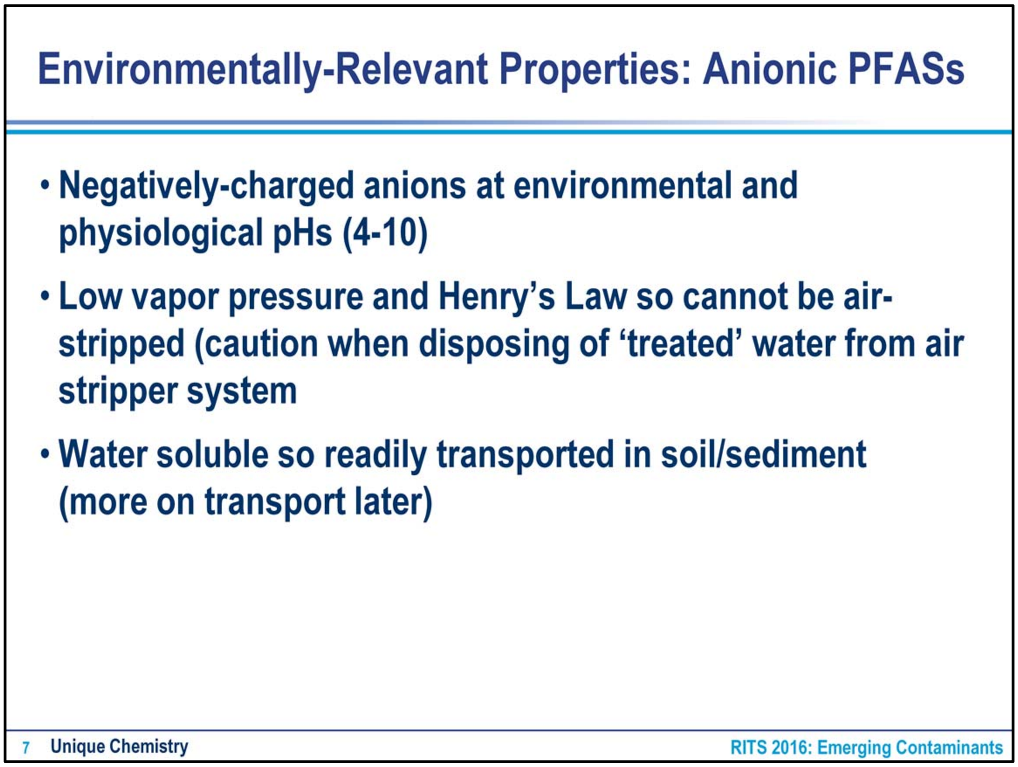
- **Polyfluorinated**
  - Not all carbons in chain bonded to F
  - CH_2 – linkages = 'weakness' in molecule, open to chemical and biological degradation
- **Per- and polyfluoroalkyl substances (PFASs)**[2]



6:2 FTSA (fluorotelomer sulfonate)

6 Unique Chemistry RITS 2016: Emerging Contaminants

Literature Cited
[1]Goss and Bronner, 2006, J Phys Chem
[2]Buck et al., 2011 Integr Environ Assess Manag



Chemical Abstracts (CAS) Numbers for both protonated (free acid) forms and salts (Na^+, K^+, NH_4^+) of PFOS and PFOA

Chemical properties (water solubility, vapor pressure, Henrys Law) depend on form

Properties in databases (TOXNET)[1] are specific to protonated form

Properties difficult to predict (e.g., EPISUITE)[2] since PFASs were not in the 'training sets' used to establish predictions

[1]TOXNET (http://toxnet.nlm.nih.gov/newtoxnet/hsdb.htm)
HSDB is a toxicology database that focuses on the toxicology of potentially hazardous chemicals. It provides information on human exposure, industrial hygiene, emergency handling procedures, environmental fate, regulatory requirements, nanomaterials, and related areas. The information in HSDB has been assessed by a Scientific Review Panel.

[2]EPISUITE (http://www2.epa.gov/tsca-screening-tools/epi-suitetm-estimation-program-interface) The Estimation Programs Interface (EPI) suite TM was developed by the US EPA's Office of Pollution Prevention and Toxics Syracuse Research Corporation.

Why are PFASs Emerging Now?

- PFASs are non-volatile and cannot be detected using traditional analytical instruments (gas chromatography mass spectrometry or GC/MS)
- Field reports of foaming groundwater and soil were major clues about PFAS occurrence but significance was not recognized
- PFAS are measured by liquid chromatography tandem mass spectrometry (LC-MS/MS), available <15 years ago

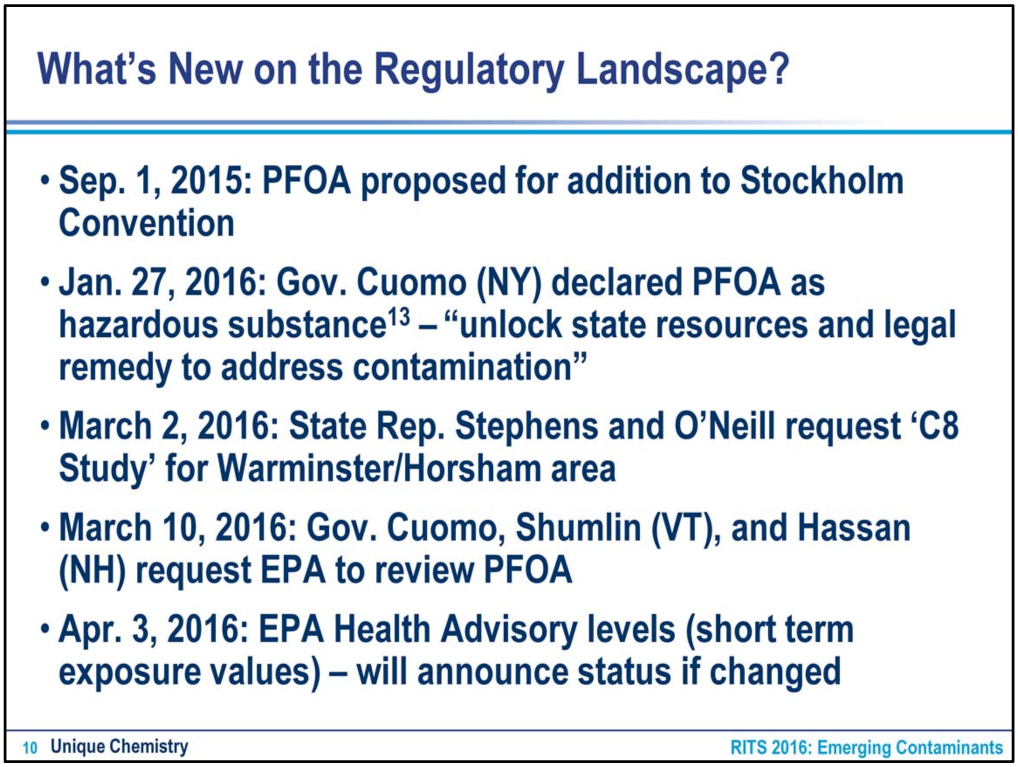
Toxicity

- **Carcinogenicity**
  - **Production workers**
    - PFOA – excess leukemia[3,4] and kidney[4] cancers
    - PFOS – increased prostate cancers[5]
  - **Exposed community studies – 70,000 Ohio & West Virginia residents (C8 Health Project)[6]**
    - Correlations between PFOA and kidney, testicular, prostate, ovarian cancer, & non-Hodgkin lymphoma
- **Immunotoxicity**
  - **Negative associations with antibody levels in children[7] and adults[8]**
- **Many PFASs detected in human blood (US, China, Germany – many classes, not just PFOS and PFOA)[9]**
- **Half lives in humans**
  - **PFOA 2.3 to 3.5 – 3.8 yrs[10,11] and PFOS 4.8 - 5.4 yrs[11]**
  - **PFHxS 7.3 – 8.5 yrs[11] (longest reported half life of any PFAS)**
  - **PFBS 25.8 days[12]**

9 Unique Chemistry RITS 2016: Emerging Contaminants

Literature Cited

[3]O'Berg et al., 1987, J Occup Med
[4]Deposition: Hearing before Leach et l vs. EI DuPont de Nemours Company. Civil Action No 01-C-608, Circuit Court of Wood County, West VA, June 25, 2004
[5]Alexander et al., 2003, Occup Environ Med; Lundin et al., 2009, Epidemiology
[6]Steenland and Woskie, 2012, Am J Epidemiol
[7]Grandjean et al., 2012, JAMA
[8]Granum et al., 2013, J Immunotox
[9]Yeung et al., 2016, Env Chem
[10]Bartell et al., 2010, Environ Health Perspect
[11]Olsen et al., 2007, Environ Health Perspect
[12]Olsen et al., 2009, Toxicol



[13]https://www.governor.ny.gov/news/governor-cuomo-announces-immediate-state-action-plan-address-contamination-hoosick-falls

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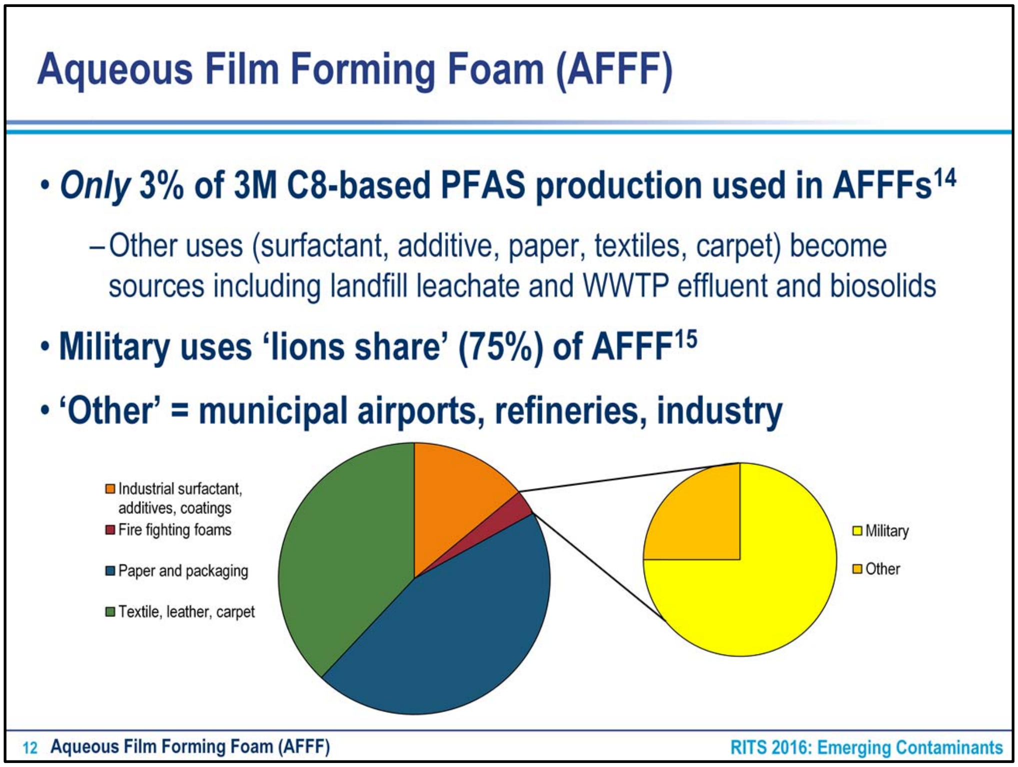


Literature Cited

[14]US EPA 2000a

[15]Moody et al., 2000, Environ Sci Technol

History of AFFF Use

- Aqueous film forming foam[16]
  - Complex, proprietary mixtures of fluorinated & hydrocarbon surfactants, water, corrosion inhibitors, solvent (e.g., butyl carbitol)
  - PFASs only a few% but still mg/L levels PFASs in AFFF product
  - Need 10^6 dilution to get below EPA PHAs for PFOS/PFOA

Courtesy U.S. Navy

- 6% (Navy) AFFFs on the Qualified Product List (QPL)[17]
  - 1970-1976 Light Water™ (3M) and Ansulite® (Ansul)
  - 1976 Aer-O-Water® (National Foam)
  - 1994 Tridol (Angus)
  - After 2002 Chemguard (Chemguard), FireAde® (Fire Service Plus)
- Bottom line: Multiple AFFFs used at most sites

13 Aqueous Film Forming Foam (AFFF) RITS 2016: Emerging Contaminants

[16]Kevin Matlock, Fire Emergency Services, Air Force, Tyndall AFB
[17]Information and photos courtesy of John Farley, Director, CBD/ex-USS SHADWELL Fire Test Operations, Naval Research Laboratory, Washington DC

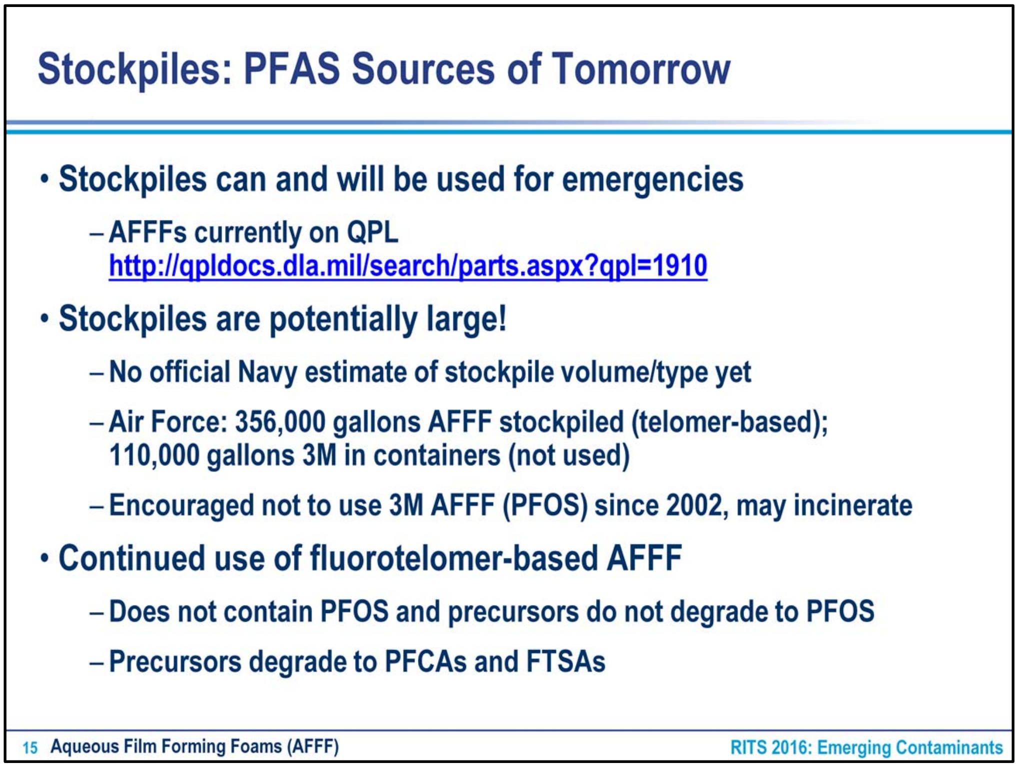
AFFF: Historical Equipment Testing & Training[18]

Test Type	Diluted AFFF (gal)	AFFF (L)	Event/yr	PFOS (kg)	PFOA (kg)	ΣPFAS (kg)	Σ20 yr (kg)
Capacity (2 trucks)[19]	3,000	341	1	3.2	0.032	4.7	**93**
Nozzle discharge[19]	10	1.1	1	0.01	0.0011	0.015	0.31
Training[20]	20	2.3	4	0.084	0.0084	0.12	**2.5**
Crash[21]	50,000	5,678				**41 kg**	

- **Navy has not conducted Capacity/Time and Distance tests with AFFF since at least 2003[22]**
- **Refractometer tests also conducted but frequency & volume variable[22]**
- **Navy stopped training with 'live' AFFFs late 1980s-1990s but AFFF training activity continues at a limited number of Navy sites, wastes collected for disposal[22]**

14 Aqueous Film Forming Foams (AFFF) RITS 2016: Emerging Contaminants

Literature Cited
[18]Kevin Matlock, Fire Emergency Services, AFCEC/CXF
[19]No fuel used, testing specified in National Fire Association (NFA) Standard 412, annual testing suspended by Air Force in 2015
[20]500-700 gallons fuel used & training varied by base, twice per year required, may have been quarterly depending on personnel training schedule
[21]B2 crash 20,000 gallons fuel & actual AFFF used not known (Ansul used as example)
[22]Carl Glover, Navy CNIC



Guidelines
- DoD information on AFFF[W]
- MN guidelines[X]
- German guidelines

Excerpts from guidelines
- Class B fires only (do not use on wood, paper, textiles)

Common sense
- Avoid off-label uses like cleaning
- Avoid all unnecessary discharges to water/soil/sediment
- Foam has high BOD, depletes oxygen from water
- Foam has the potential to remove oils from birds (hypothermia)

[W]http://www.denix.osd.mil/cmrmd/upload/Chemical-&-Material-Emerging-Risk-Alert-for-AFFF.pdf
[X]http://www.pca.state.mn.us/index.php/view-document.html?gid=17926

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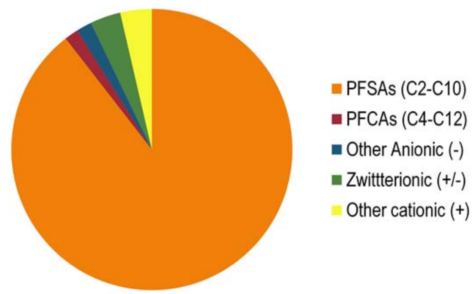
3M AFFF: Military Wide Use Began in 1970

- 89% PFSAs (e.g., PFOS) in 3M AFFF
- Only 1.6% of 3M AFFFs are PFCAs (e.g., PFOA)
- All contribute to total fluorine

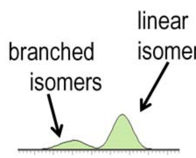


Transport

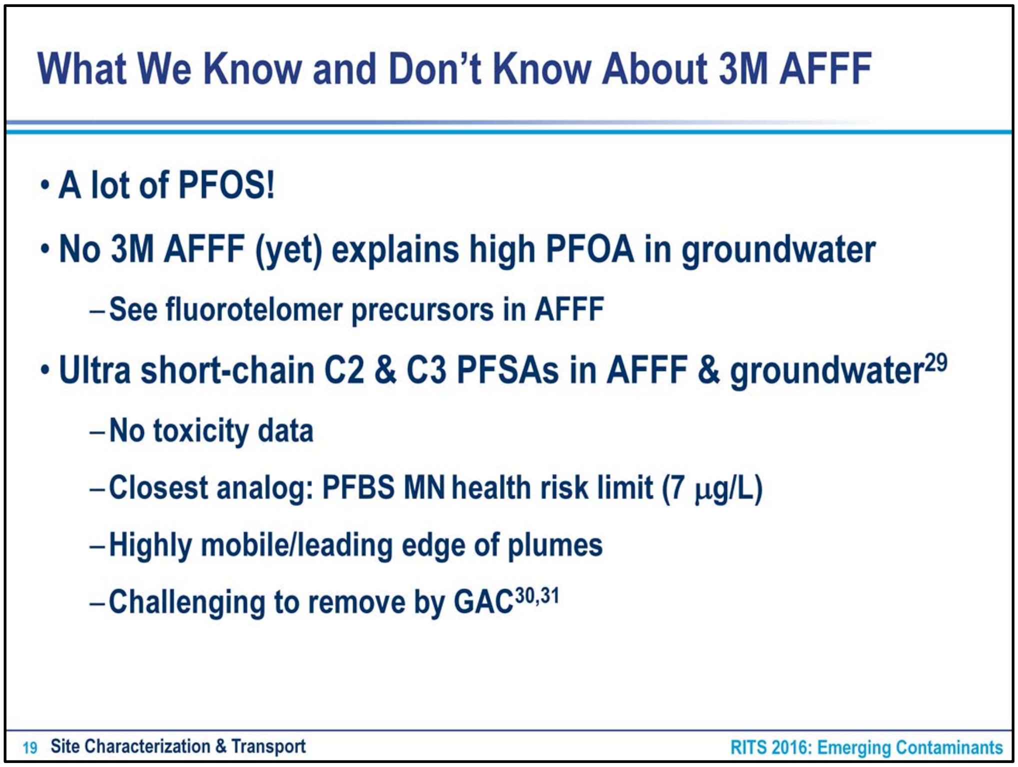
- Anions > zwitterions > cations
- Anions, shorter chain lengths generally migrate faster (less retardation)
- Weak acids/bases, transport will depend on pH and molecule’s charged state (ionic or neutral)

PFSAs and PFCAs in 3M AFFF

- **When produced 3M's electrofluorination (ECF) process[27]**
  - 'Crude' synthesis, many side products
  - Odd & even[23,24] chain lengths (C2-C14)[25,26]
  - **Since 2015 RITS, C2 & C3 sulfonates found in AFFF and groundwater**
  - Branched & linear isomers (30:70)[23,27,28]
    - **If exclude branched isomers, concentrations underestimated (biased low) by 25%**
- **PFOA also made by telomerization = only linear chain lengths**



Literature Cited
[23]Alexander et al., 2009, ES&T
[24]3M 1999, EPA docket No. OPPT-2002-0043-0006
[25]Barzen-Hensen et al., 2015, ES&T Letters
[26]Backe et al., 2013, ES&T
[27]Benskin, Rev Environ Contam Toxicol, 2010
[28]Prevedouros et al., 2006, ES&T



Literature Cited
[29]Barzen-Hanson et al., 2015, Environ Sci Technol
[30]Rahman et al., 2014, Water Res
[31]Appleman et al., 2014, Water Res

3M Degradation Pathways

- None for PFOS/PFOA
- N-EtFOSE[32] degradation products identified
  - Little if any data on N-EtFOSE in AFFF
  - Degradation products
    - Sulfonamide acetic acids (N-EtFOSAA and FOSAA)
    - Sulfonamide (FOSA)
    - PFOS and PFOA

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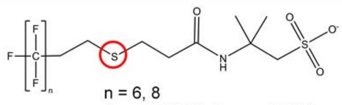
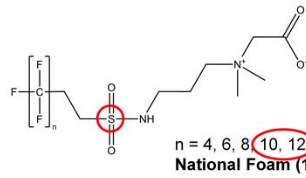
Literature Cited

[32]Rhoads et al., Environ Sci Technol, 2008

Fluorotelomer-Based AFFFs

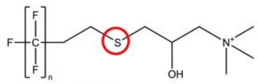


n = 6, 8
Ansul (1970), Angus (1994), Chemguard (2002)

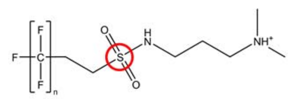


n = 4, 6, 8, 10, 12 **note: long chain lengths**
National Foam (1976), Fire Service Plus (2002)

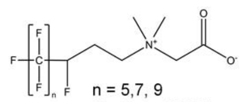
- Add to total mass of F
- None on UMCR3 & Method 537 lists
- Potential to degrade to 6:2 & 8:2 fluorotelomer sulfonates & PFCAs
- 6:2 & 8:2 fluorotelomer sulfonates not major components in AFFF



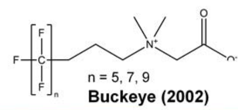
n = 6, 8
Angus (1994)



n = 6, 8
National Foam (1976), Fire Service Plus (2002)



n = 5,7, 9
Buckeye (2002)



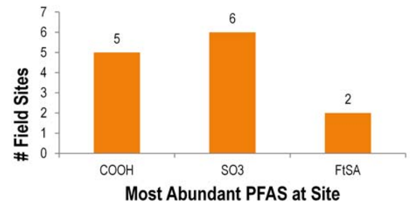
n = 5, 7, 9
Buckeye (2002)

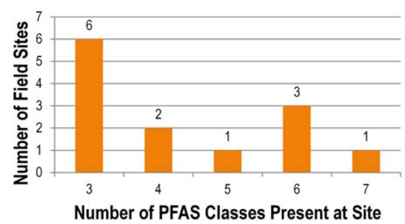
Transport

- Anions > zwitterions > cations
- Anions: shorter chain lengths generally migrate faster (less retardation)
- Weak acids/bases: transport will depend on pH and molecule's charged state (ionic or neutral)

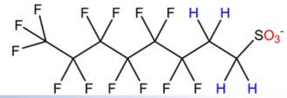
Occurrence of Most Abundant PFASs in Groundwater at Navy and Air Force Bases

- **13 Air Force & Navy bases**
- **PFSAs and PFCAs not always the most abundant**
- **All sites have PFSAs & PFCAs >>EPA PHAs**
- **No site has just PFSAs & PFCAs**
- **Highest concentrations in groundwater measured**
  - PFOS = 1,000 μg/L
  - PFOA = 6,600 μg/L
  - 6:2FTSA = 14,600 μg/L





More on FTSAs



6:2 FTSA (fluorotelomer sulfonate)

- **Most sites have μg/L to mg/L levels of FTSA**
- **Australia: human health screening criteria 5 μg/L[36]**

FTSA (μg/L)	Proposed Action	# DoD Sites
Not detected	None	1
<5	No further action	2
5 – 290	Monitor, confirm exposure pathways	6
<290	Remediate	1

- **Aquatic organisms**
  - D. magna 48-h EC50[37] (>112 mg/L) may be within same order of magnitude as PFOS (58 mg/L)[38] and PFOA (>100 mg/L)[39]
  - Algae most sensitive species (compare to Daphnia and fish)[37]

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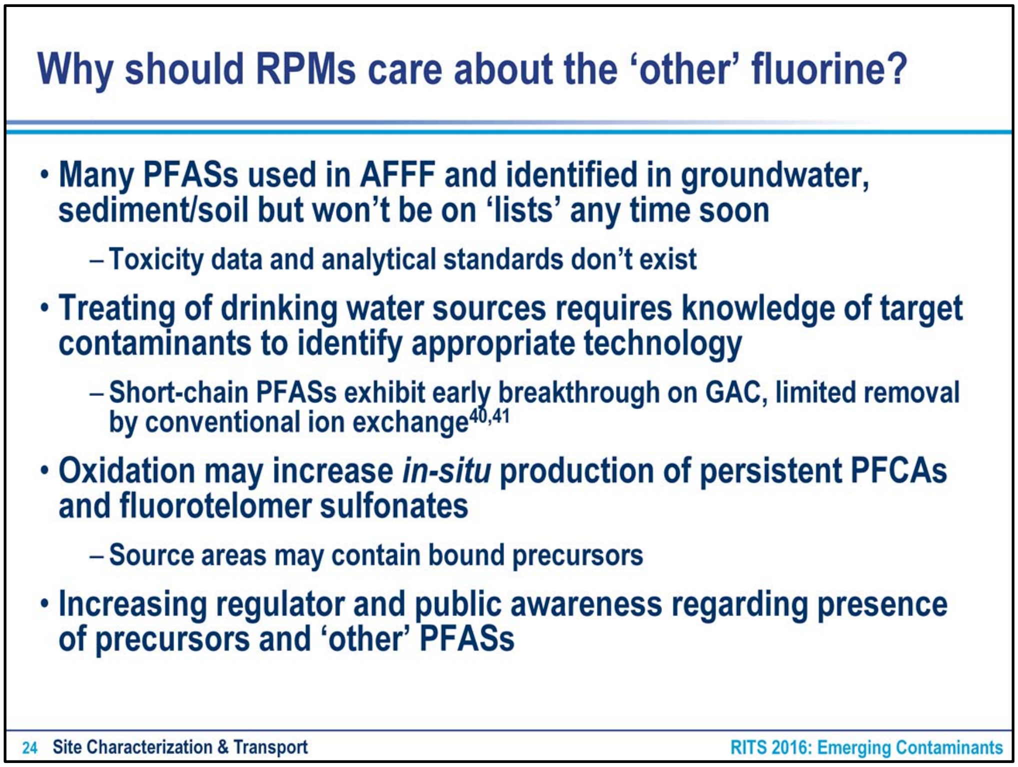
Literature Cited

[36]Jarman et al., A Human Health Screening Criteria, Abstract E017
[37]Hoke et al., Chemosphere, 2015
[38]Beach et al., Rev Environ Contam Toxicol, 2006
[39]Colombo et al., Ecotox Environ Safety, 2008



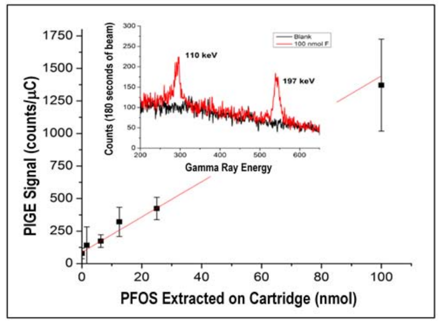
Literature Cited

[40] Rahman et al., 2014, Water Res

[41] Appleman et al., 2014, Water Res

Precursors and Total Fluorine: Alternative Methods

- **Total oxidizable precursor (TOP) assay[42]**
  - **Polyfluorinated chemicals react with hydroxyl radicals but *perfluorinated* do not (e.g., PFOS and PFOA)**
  - **Net increase in PFCAs after oxidation of sample = precursors**
- **Total fluorine by PIGE[43]**
  - **PFAS sorbed onto media to create 'target'**
  - **10 nA of 3.4 MeV protons for 180 s**
  - **Quantitative, high-throughput, inexpensive**



Literature Cited

[42]Houtz et al., ES&T, 2013

[43]Lunderberg et al., 2015, Fluoros, Golden, CO

Transport: General Concepts

- **Transport related to chemical structure**
  - **Anions > zwitterions > cations**
  - **Shorter chain lengths generally migrate faster (less retardation, lower Koc)**
    - Likely to impact surface waters
    - Challenging to remove by GAC
  - **For many precursors, transport will depend on pH and molecule's charged state**
- **Cationic & zwitterionic PFASs may be cation exchanged onto source-zone sediments**
- **pH impacts ionization and transport of ionizable substances**

Sorption of PFAAs – Chain length and head group

Analyte	Carbons in Tail	K_{oc}[44]	Rf
PFBA	3	76	5
PFPeA	4	23	1.4
PFHxA	5	20	1.1
PFHpA	6	43	3
PFOA	7	78	5
PFNA	8	229	14
PFDA	9	912	57
PFUnA	10	3,600	225
PFBS	4	62	4
PFHxS	6	112	7
PFOS	8	631	39

- **Affinity for sediment organic carbon (K_{oc} & K_d) ~ # carbons in tail**
- **Short-chain PFCAs = greater K_{oc} than expected**
  - **Sorption not explained by only f_{oc} of sediment**
- **Compare retardation factors (R_f) to groundwater velocity to predict arrival time at a groundwater well**

$$R_f = 1 + K_d \frac{\text{Bulk density}}{\text{Porosity}}$$

where $K_d = K_{oc} * f_{oc}$
and f_{oc} = fraction of organic carbon

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Literature Cited
[44] Guelfo and Higgins, 2013, *ES&T*

Solution Chemistry & Transport

- Decreasing pH (more acidic), increases retardation
- Increasing ionic strength increases retardation – may be relevant for sites near estuaries/ocean
- Remedial approaches that change pH or introduces polyvalent cations (i.e., ISCO) potentially impacts anionic PFAS transport
- Sorption generally increases in the presence NAPLs

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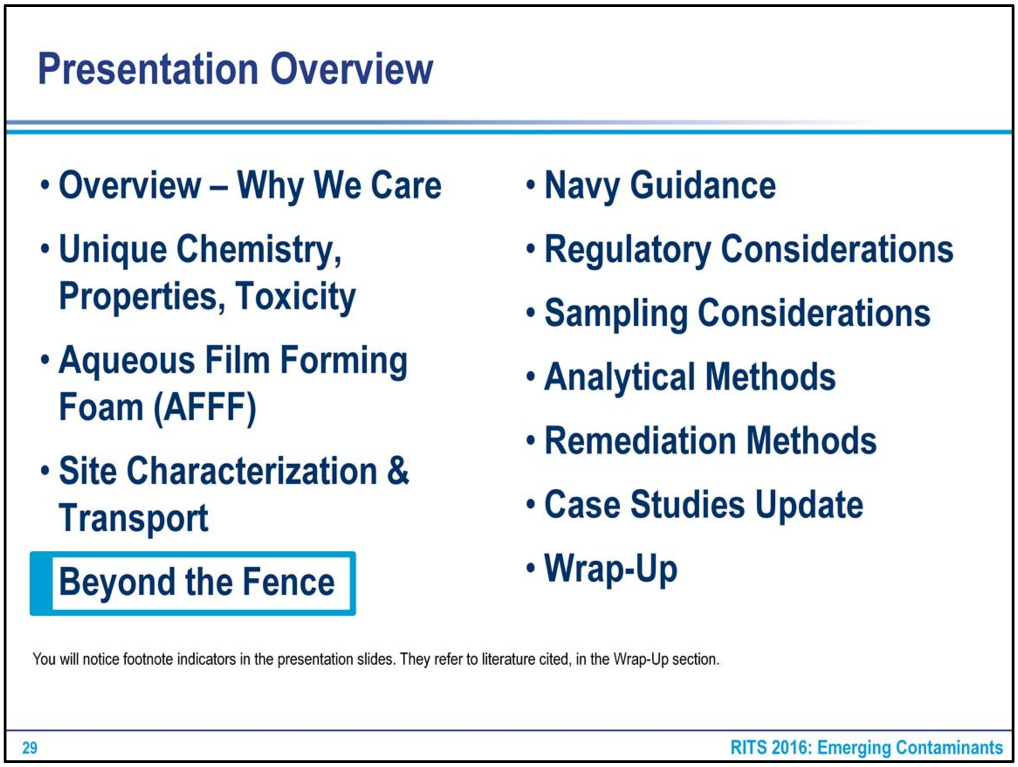
Literature Cited

[1] Guelfo and Higgins, 2013, *ES&T*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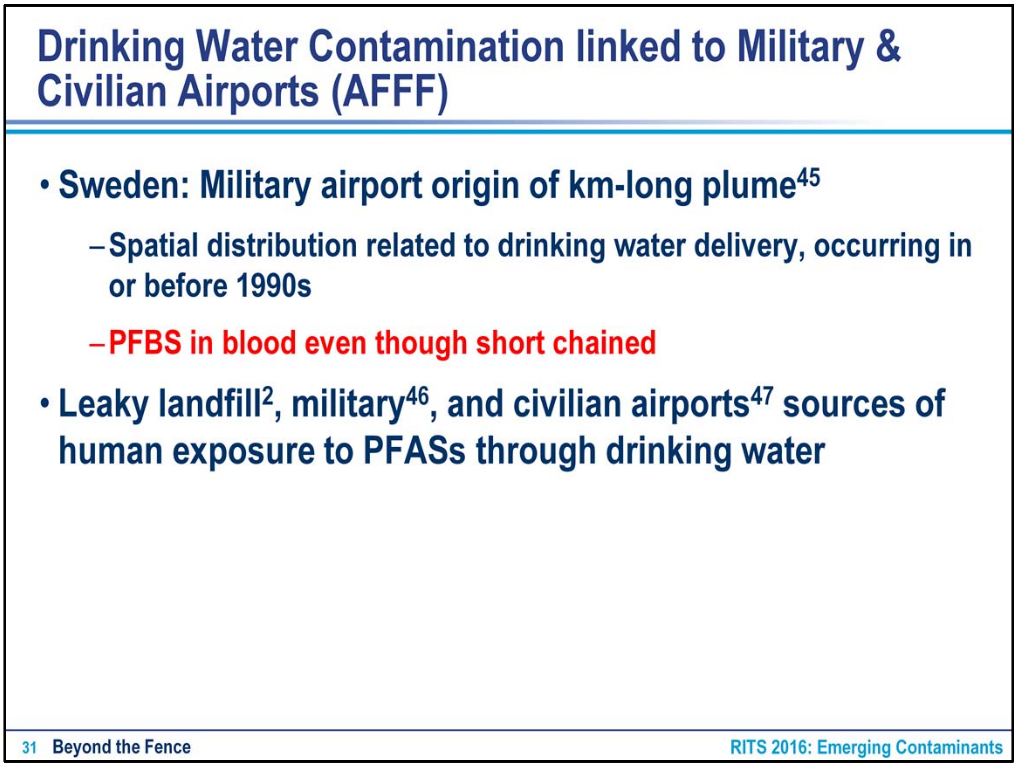
Beyond the Fence: Impacted Public Water Supplies

- EPA program ended December 2015
- Sample from public water systems serving >10,000 people
- 6 (3 PFSAs & 3 PFCAs) analyzed
- Positive hits (>MRL) for one or more PFASs (June 2015 UCMR3 database)



Literature Cited
[45]Gyllenhammar et al., 2015, Environ Res
[46]Eschauzier et al., Sci, 2013, Tot Environ
[47]Weiss et al., 2012, Intl J Hygiene Environ Health

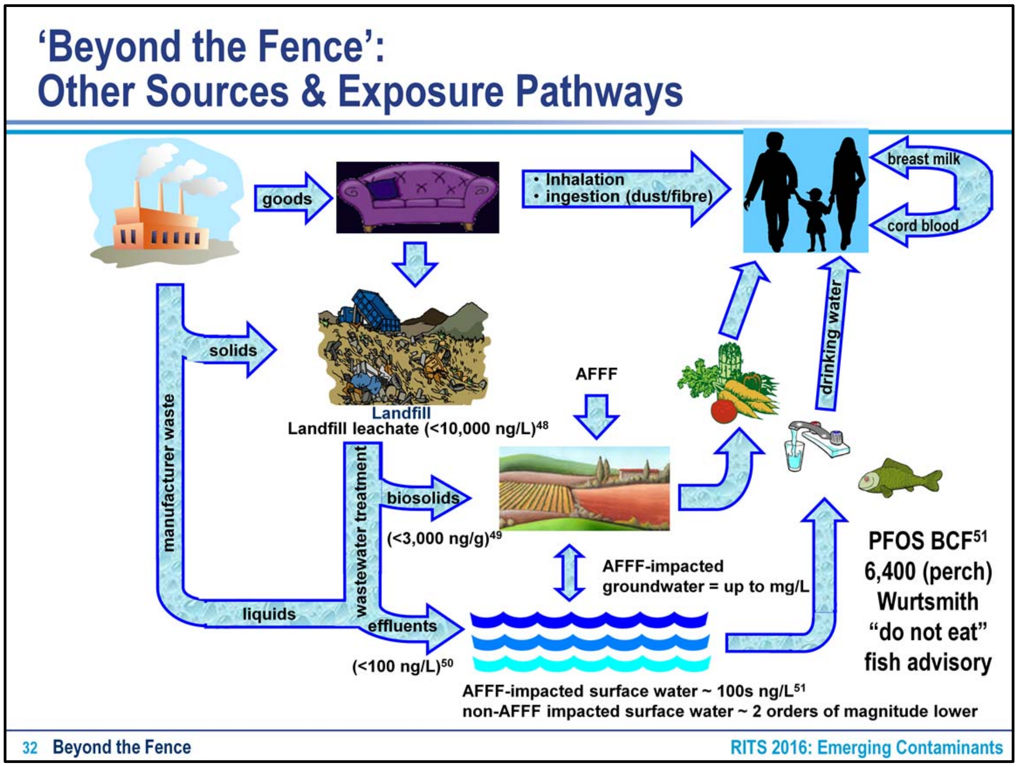


Figure adapted from Oliaei 2013, Environ Pollut Res
[48]Allred et al., 2014, J Chrom
[49]Schultz et al., 2006; Higgins ES&T, 2005
[50]Schultz et al., 2006, a&b ES&T
[51]Ahrens et al., 2015, Chemosphere

Beyond the Fence: Wastewater Treatment

- **Municipal and industrial wastewater treatment plant (WWTP) effluent**
  - **3rd highest source (<0.1 μg/L levels) after landfill leachates and AFFF-impacted sites[52-54]**
  - **No significant removal of PFOA & 6:2 fluorotelomer sulfonate[52]**
  - ***Net increase* in PFOS mass flow during WWTP[52]**
- **Impacted drinking water due to**
  - **Land application of WWTP biosolids[55] in US**
  - **Other organic solid waste in Germany[56]**

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Literature Cited

[52]Schultz et al., 2006, Environ Sci Technol
[53]Sinclair and Kannan, 2006, Environ Sci Technol
[54]Logananthan et al., 2007, Water Res
[55]Lindstrom et al., 2011, Environ Sci Technol
[56]Skutlarek et al., 2006, Environ Sci Pollut Res

Beyond the Fence: Landfills

- **Landfill Leachate**
  - 2nd most concentrated (tens of μg/L)[57-59] point source of many PFAS classes after AFFF-impacted groundwater
  - Most abundant short-chain PFCAs & fluorotelomer acids (unique signature to landfill leachate)[59]
- **Cautionary tale**
  - Pump and treat system installed (N) to treat VOCs in landfill leachate impacted groundwater[60]
    - 'Spray air stripper system' sprayed into water containing PFASs into air to strip out VOCs
    - PFASs penetrated soil profile

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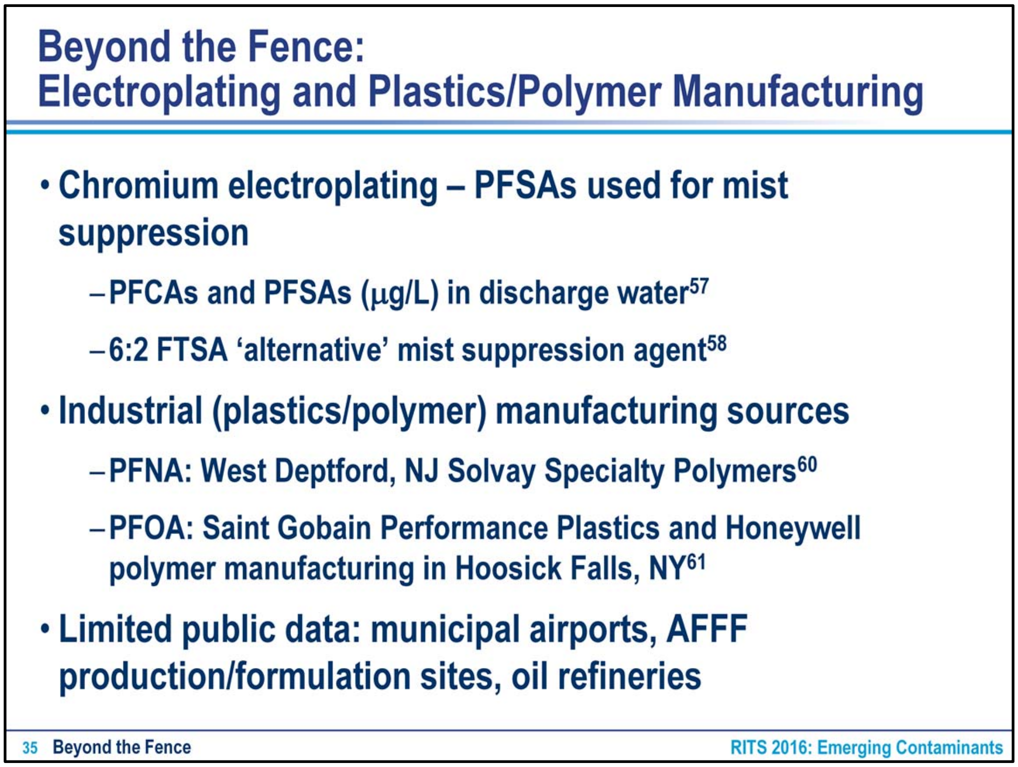
Literature Cited

[57] Allred et al., 2014, J Chrom A
[58] Allred et al., 2015, Envion Sci Technol
[59] Benskins et al., 2012, Environ Sci Technol
[60] EPA Region 5 PFOS Chromium Electroplater Study, 2009
[x] Yang et al., 2014, Env Sci Pollut Res
[y] Oliaei et al., 2013, Environ Sci Pollut Res



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[61]Yang et al., 2014, Env Sci Pollut Res
[y]Oliaei et al., 2013, Environ Sci Pollut Res

Mid-Talk Key Points and Take-Away Messages

- Hundreds of fire/crash testing (mixed waste) sites
- PFOS and PFOA are important but not the only major PFASs at AFFF-contaminated sites
- Full characterization of PFAS contamination needed
  - More accurate conceptual site models, identify remedial approaches that save time and cost
  - Optimized monitoring
  - Fingerprinting PFAS sources and source zones
  - Accurate predictions of transport & indicators of in-situ biotransformation
- Mobility in groundwater anions > zwitterions > cations and anion mobility depends on chain length, influenced by sediment, soil, and water geochemistry
- Groundwater contaminated by PFAS used as drinking water source is a potential exposure pathway for humans and wildlife
  - Attention to short-chain PFAS highly mobile, difficult to remove from water

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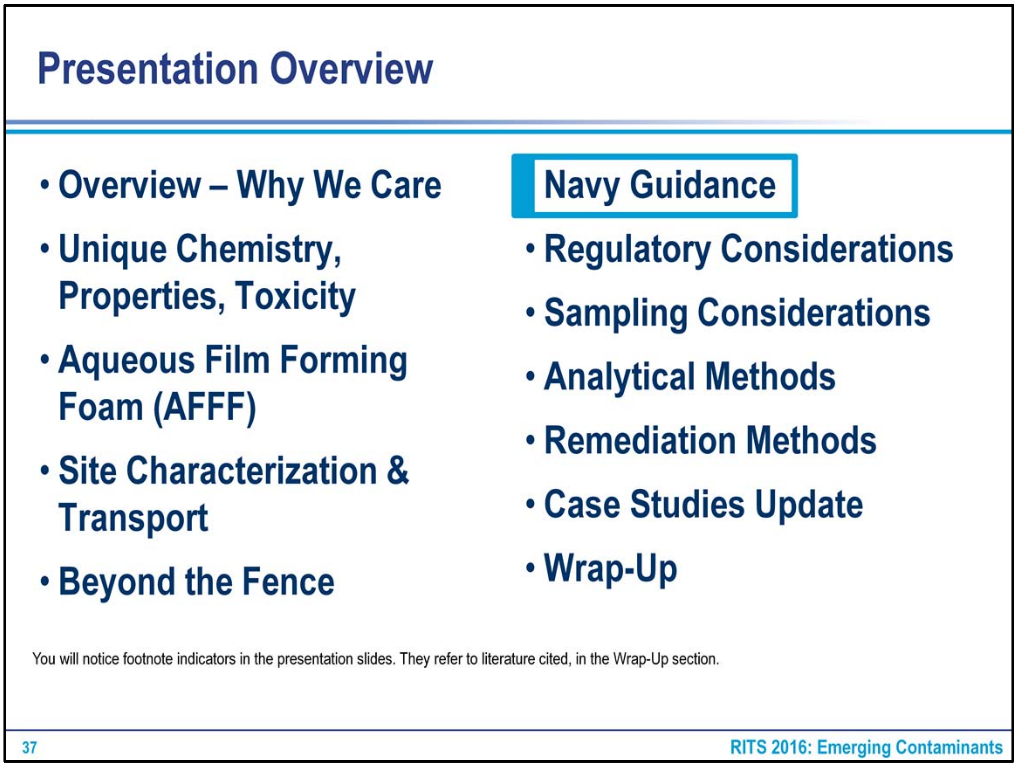
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DoD Instruction – ECs

Emerging Contaminants
Department of Defense
INSTRUCTION June 11, 2009

As identified by the DUSD(I&E), a contaminant that has:

- **Possible pathway to enter environment**
- **Potential unacceptable human health or environmental risk**
- **Developing regulatory standards, new detection capabilities, or pathways**

Department of Defense
INSTRUCTION

NUMBER 4715.18
June 11, 2009
Certified Current Through June 11, 2016

USD(AT&L)

SUBJECT: Emerging Contaminants (ECs)

References: See Enclosure 1

1. PURPOSE. This Instruction establishes policy and assigns responsibilities for the identification, assessment, and risk management of ECs that have the potential to impact the ~~Department of Defense~~ *DoD* in accordance with the authority in DoD Directive (DoDD) 5134.01 (Reference (a)) and the guidance in DoDD 4715.1E, DoD Instruction 5000.02, and Defense Acquisition University Risk Management Guide (References (b), (c), and (d)).

2. APPLICABILITY. This Instruction:

a. Applies to OSD, the Military Departments, the Office of the Chairman of the Joint Chiefs of Staff and the Joint Staff, the Combatant Commands, the Office of the Inspector General of the Department of Defense, the Defense Agencies, the DoD Field Activities, and all other organizational entities within the ~~Department of Defense~~ *DoD* (~~hereafter~~ referred to collectively *in this Instruction* as the "DoD Components").

b. Applies to the DoD activities and programs involving the development, production, use, storage, or release of chemicals and materials that can be considered ECs at DoD operations, activities, and installations in the United States.

c. Applies to the DoD managed response actions at formerly used defense sites.

d. Does not apply to:

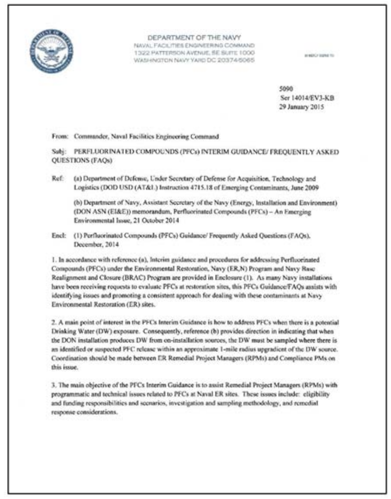
(1) Contractor-owned or contractor-operated facilities.

(2) Radiological data collected under the Naval Nuclear Propulsion Program or other DoD radiological programs.

(3) Chemical, biological, radiological, nuclear, and explosive incident training or response programs.

NAVFAC PFC Interim Guidance/FAQs

- **Finalized/Issued: January 29, 2015**
- **Objective: Assist RPMs with issues related to PFCs (PFASs) at ER sites to promote a consistent approach across Navy installations**
- **Issues Addressed:**
  - **Funding responsibilities: BRAC, ERN***
  - **Investigation and sampling methodology**
  - **Remediation considerations**
- **Focus on Drinking Water (DW)**
  - ***Past release as substantiated by the CSM**



DEPARTMENT OF THE NAVY
NAVAL FACILITIES ENGINEERING COMMAND
1322 PATTERSON AVENUE, SE SUITE 1000
WASHINGTON NAVY YARD DC 20374-5065

5090
Ser 14014/EV3-KB
29 January 2015

From: Commander, Naval Facilities Engineering Command

Subj: PERFLUORINATED COMPOUNDS (PFCs) INTERIM GUIDANCE/ FREQUENTLY ASKED QUESTIONS (FAQs)

Ref: (a) Department of Defense, Under Secretary of Defense for Acquisition, Technology and Logistics (DOD USD (AT&L) Instruction 4715.18 of Emerging Contaminants, June 2009

(b) Department of Navy, Assistant Secretary of the Navy (Energy, Installation and Environment) (DON ASN (EI&E)) memorandum, Perfluorinated Compounds (PFCs) – An Emerging Environmental Issue, 21 October 2014

Encl: (1) Perfluorinated Compounds (PFCs) Guidance/ Frequently Asked Questions (FAQs), December, 2014

1. In accordance with reference (a), Interim guidance and procedures for addressing Perfluorinated Compounds (PFCs) under the Environmental Restoration, Navy (ER,N) Program and Navy Base Realignment and Closure (BRAC) Program are provided in Enclosure (1). As many Navy installations have been receiving requests to evaluate PFCs at restoration sites, this PFCs Guidance/FAQs assists with identifying issues and promoting a consistent approach for dealing with these contaminants at Navy Environmental Restoration (ER) sites.

2. A main point of interest in the PFCs Interim Guidance is how to address PFCs when there is a potential Drinking Water (DW) exposure. Consequently, reference (b) provides direction in indicating that when the DON installation produces DW from on-installation sources, the DW must be sampled where there is an identified or suspected PFC release within an approximate 1-mile radius upgradient of the DW source. Coordination should be made between ER Remedial Project Managers (RPMs) and Compliance PMs on this issue.

3. The main objective of the PFCs Interim Guidance is to assist Remedial Project Managers (RPMs) with programmatic and technical issues related to PFCs at Naval ER sites. These issues include: eligibility and funding responsibilities and scenarios, investigation and sampling methodology, and remedial response considerations.

http://navfac.navy.mil/content/dam/navfac/Specialty%20Centers/Engineering%20and%20Expeditionary%20Warfare%20Center/Environmental/Restoration/er_pdfs/gpr/don-ev-guid-pfc-faq-20150129i.pdf

NAVFAC PFC Interim Guidance – Highlights

- If CSM indicates:
  - Past use of AFFF or other PFAS-containing material
    - And a potential route of exposure exists
  - Then investigate for presence of PFOS, PFOA, and PFBS
- If detections exceed PHAs in a drinking water source:
  - Immediately provide alternate drinking water, report and determine further action (plume control, TCRA, treatment, etc.)
- If detections exceeding screening levels:
  - Delineate and perform quantitative RA; if no chance for exposure and migration delay further action until state of science advances; if potential for exposure, at a minimum delineate and possibly take further action (LUCs, plume control, TCRA, remediation, etc.)
- Consult HQ, LANT, Risk Assessment Workgroup (RAW)

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What/Where to Sample

- **Investigation Considerations**
  - **CSM Substantiates Investigation; Generally 2 Categories in DON:**

Historical release and/or use of AFFF; Examples
Fire Training Areas (FTAs) Using AFFF
Crash or Fire Sites Where AFFF Was Used
Fuel Spills Treated With AFFF
Hangars, Runways, and Flight Line Areas
Storage Areas, Piping, and Equipment Cleanout Areas
Runoff Areas

Historical activities that may have released PFC; Examples
Mist Suppression in Plating Facilities
Oil-water Separators
Other Piping Systems

- **The CSM should be used to make decisions on whether an area should be investigated particularly with regard to potential exposure pathways, especially drinking water**
- **Media may include one or all media potentially impacted, depending on CSM**

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Which PFAS Compounds to Analyze?

LET'S REVIEW:

- **PFAS comprise a large group of compounds**
- **AFFF formulations differ in which compounds are present**
- **PFOS, PFOA, and PFBS are not transformed in the environment**
  - **3M produced AFFF containing high levels of PFOS until 2002**
    - Also contains a variety of other perfluorinated PFASs (including PFBS)
  - **The other manufacturers produce(d) AFFF with polyfluorinated PFASs**
    - No PFOS, PFOA, or PFBS
    - However, some compounds may degrade to PFOA and other PFCAs
  - **A variety of AFFF products were used over time at FTAs, so sites likely contain many PFASs, and transformation products**

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Regulatory Considerations

- **Only PFOS, PFOA and PFBS have EPA toxicity values…**
  - **PFOS and PFOA: Have Tier III toxicity values (Provisional Health Advisories [PHAs])**
    - These are not promulgated and not ARARS, but can be used for risk determination
  - **PFBS: Has a Tier II toxicity value (EPA Superfund Reference Dose [RfD])**
- **SO, per NAVFAC Interim Guidance (January 2015) only PFOS, PFOA (and PFBS) should be used to initially assess site**

Regulatory Values

- **The PHAs are currently under review and revisions (likely downward) are expected soon; at that time, the revised values will be applicable**
  - Current (as of April 3, 2016):
  - – PFOS: 0.2 μg/L (PHA)
  - – PFOA: 0.4 μg/L (PHA)
  - – PFBS: 7 μg/L (RfD)
- **Per NAVFAC Guidance:**
  1) If DW levels of PFOS, PFOA or PFBS are Greater Than (GT) Regulatory Values, provide alternative DW and take further action per Interim Guidance on PFCs
  2) If DW levels are GT 25% of Regulatory Value but Less Than (LT) Regulatory Value, continue sampling and monitoring
  3) If DW levels are LT 25% of Regulatory Value only monitor plume migration

Regulatory Values (cont.)

- States, in some cases have also set their own regulatory values
  - If an installation is located in that state, and the value is promulgated, the more stringent value will apply
  - If the value is not promulgated, the EPA PHA will be used
  - Example: New Jersey, PFOA and PFNA
- Check with LANT, RAW, or HQ before using values other than the EPA PHAs (for PFOS and PFOA) and the Superfund RfD (for PFBS)

Regulatory Values, States

Authority	Media	PFOS (μg/L)	PFOA (μg/L)	PFBS (μg/L)	PFBA (μg/L)
EPA	Drinking Water	0.2 (PHA)	0.4 (PHA)	7 (RfD)	
MI	Drinking Water	0.012	0.42		
MN	Drinking Water	0.3	0.3	7	7
NJ	Drinking Water		0.04 (not promulgated)		
			PFNA: 0.013 (μg/L) (promulgated MCL)		
NC	Groundwater		1		
IL	Provisional groundwater remediation objectives	0.2 (Class I and II)	0.4 (Class I) 2 (Class II)		
ME	Remedial Action Guidelines: groundwater residential	0.06	0.1		
OH	Amended US/DuPont consent agreement		0.4		

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Screening Levels

- **Human Health Risk Assessment**
  - **Screening Levels**
    - Developed between RPM and regulators
    - Ordinarily begin with EPA Regional Screening Level (RSL) tables; but these are not yet developed for PFOS and PFOA
    - EPA Provisional Health Advisories (PHAs are Tier III – least confident):

Media	PFC	Residential Exposure*	Industrial Exposure*
Groundwater (μg/L)	PFOA	4.0	NA
	PFOS	1.6	NA
Soil (mg/kg)	PFOA	12	165
	PFOS	4.9	66

*** Values calculated using RfD derived by EPA in their short term provisional HAL (2009) and the exposure assumptions used to calculate EPA RSLs in May 2014)**

Screening Levels (cont.)

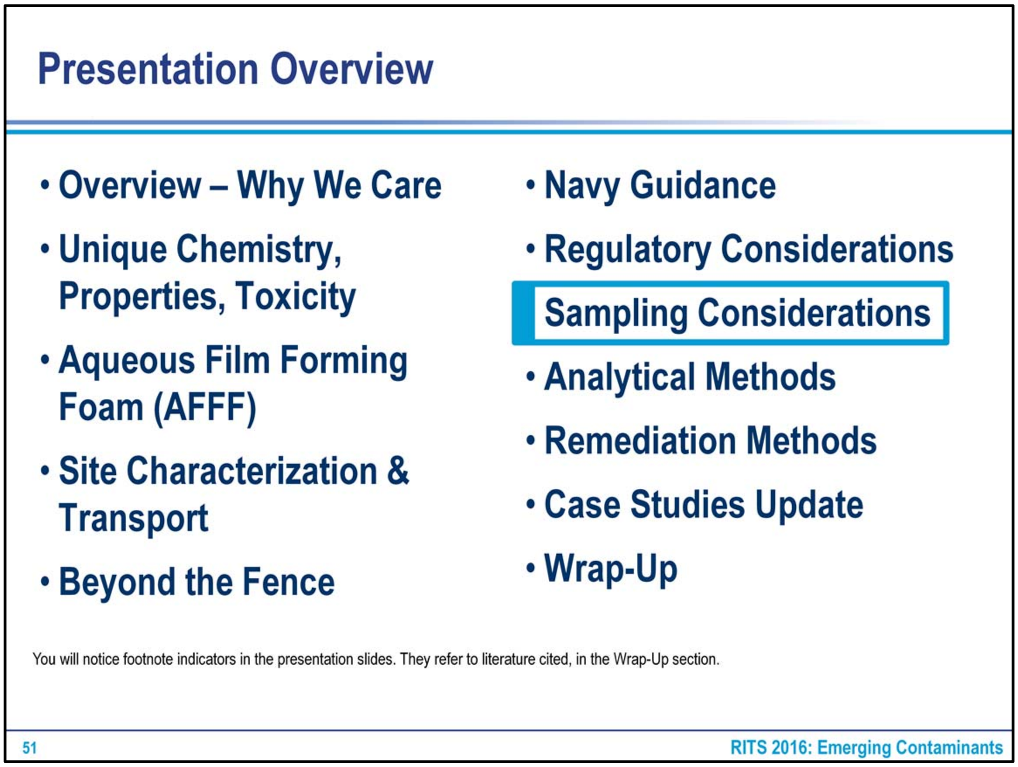
Other PFAS Screening Levels:

- **PFBS:**
  - 1,230 mg/kg residential soil
  - 16,500 mg/kg industrial soil
  - 383 μg/L residential groundwater
  - Calculated using EPA's Online RSL Calculator, December 2014
  - http://epa-prgs.ornl.gov/cgi-bin/chemicals/csl_search
- **6:2 FTSA (6:2 Fluorotelomer Sulfonate):**
  - 5 μg/L groundwater screening level in Australia (Jarman, 2014)
- **EPA Region 4 calculated residential soil screening values of 6 mg/kg for PFOS and 16 mg/kg for PFOA**

Ecological Risk

- Include ecological risk if CSM substantiates
- Screening Levels:
  - Ecological screening levels for PFAS do not exist at this time though some States have guidance for surface water (MN example below)
  - If regulators recommend values, they should be vetted by a Navy ecorisk assessor (10-50 μg/L are typical effects levels)
  - PFOS bioaccumulates in fish; PFOA does not
  - Vegetation: Studies of biosolids containing PFASs applied to land have shown uptake by plants to varying degrees
    - Screening levels or health advisory levels not yet established by EPA

Minnesota Criteria	PFOA Lake (μg/L)	PFOA River (μg/L)	PFOS Lake (μg/L)	PFOS River (μg/L)
Fish Consumption	1.6	2.7	0.012	0.006
DW plus Fish Consumption	0.61	0.72	0.012	0.006
Ecological Acute	15,000	15,000	85	85
Ecological Chronic	1,700	1,700	19	19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Sampling for PFAS

- Many common materials and sampling equipment contain PFAS
- Dealing with ultra-low detection levels

AVOID	OK
Tyvek®	Plastic containers (polypropylene, no lined caps)
Teflon™	Nitrile gloves (change often)
Waterproof clothing	HDPE tubing and bailers
New clothing	Alconox® or Liquinox® soaps
Blue Ice®	PFC-free laboratory certified water
Handling food packaging	
Non-stick or water/grease/stain-resistant	
Glass containers	

Sampling for PFAS (cont.)

- **PFAS Stratification**
  - PFAS accumulates on water surface
  - Do not collect water at the very surface
  - Bailers work well

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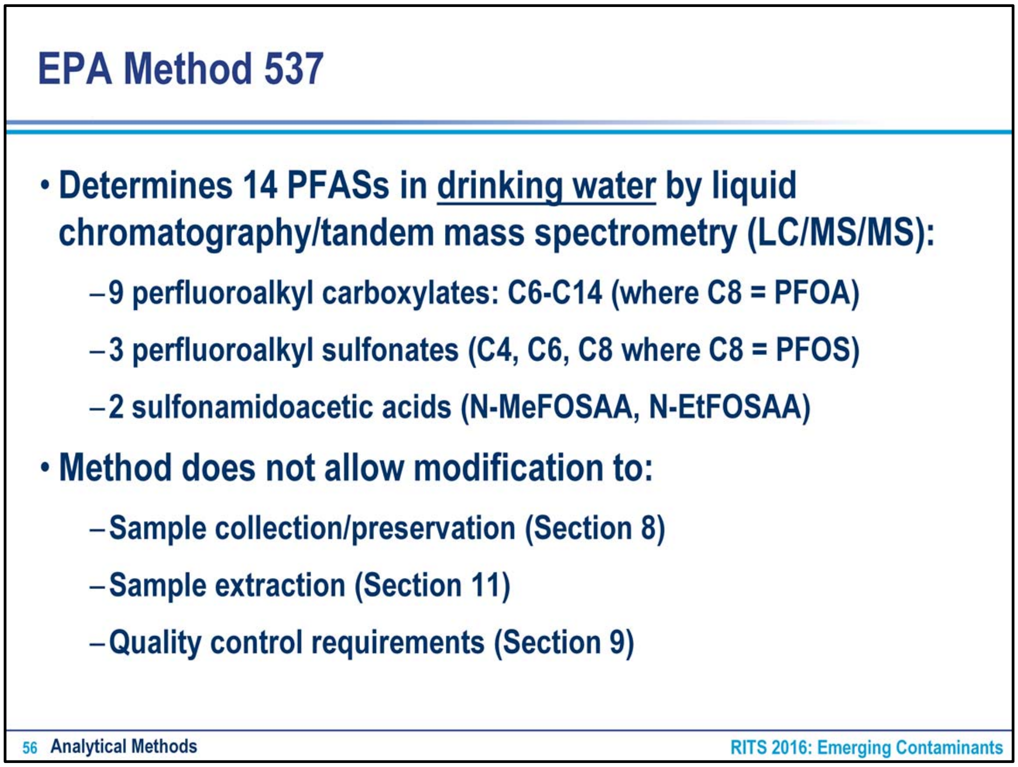
PFAS Analytical Methods

- Only PFOS, PFOA and PFBS have vetted toxicity values at this time, therefore, for initial investigations these would be the primary contaminants of concern
  - Drinking Water: EPA Method 537 Version 1.1; labs may include additional PFAS in addition to the standard list
  - Groundwater, Soil, Sediment (any media other than drinking water): Each lab has their own method (most are based on EPA 537) since a standard (HW) method does not exist; QA issues have been identified in some labs – check with Navy Chemist or EDQW
  - Must be ELAP-Certified for ER project, currently there are 9 labs that analyze PFAS using various analyte lists in various medias



EPA Method 537 is for drinking water samples only, for a defined list of analytes. This is a promulgated method that must be followed verbatim when analyzing drinking water.

This method clearly states certain sections of the method that are not allowed to be modified.

Modified 537 or In-House Methods

- Can modify the method in any way, including ways prohibited in the method
- No EPA guidance on hold times, thermal preservation requirements
- EPA published methods are sorely needed
- In the meantime, DoD ELAP addressing these issues through modification to DoD QSM requirements

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When a method is identified as a “Modified” method or in-house method, it is not required to meet all of the requirements of the referenced method, in this case, Method 537.

There is also no guidance published by the EPA for critical parts of these methods including hold times and thermal preservation requirements. As a result, each laboratory has come up with their own requirements.

As a result of this, methods for matrices other than drinking water greatly vary from laboratory to laboratory. These differences may or may not have a significant impact on your data. The bottom line is a validated published EPA method(s) [for matrices other than DW] is greatly needed to help projects achieve comparable results from laboratory to laboratory and ensure a minimum of precision and accuracy is achieved.

In the meantime, the Environmental Data Quality Workgroup (EDQW) is addressing the situation by including additional specific requirements for PFAS analysis by these methods in the DoD Quality Systems Manual (DoD QSM).

DoD-ELAP Labs for PFAS Analysis

- Current as of Jan. 27, 2016 (See DENIX website for current listings):
  - Accutest Laboratories SE (PFAAs in DW, GW, soil)
  - ALS Environmental Kelso (PFAAs in DW, GW, soil, tissue)
  - Eurofins Lancaster Laboratories (PFAAs and 8:2 FTS in DW, GW, soil)
  - Maxxam Analytics Intl. (PFAAs and FTS in DW, GW, soil)
  - TestAmerica Denver (PFAAs in GW, soil)
  - TestAmerica West Sacramento (PFAAs and FTS in GW, soil)
  - Vista Analytical (PFAAs and FTS in GW, soil, tissue)
  - Weck Laboratories (PFAAs 6 compounds)
  - Axys Analytical – BC Canada (PFAAs and FTS, in DW, GW, soil, tissue)

What About the Other PFASs?

- Over 200 PFASs have been identified in AFFF and groundwater
- 6:2 Fluorotelomer Sulfonate found at high levels in DoD GW at FTA
- Some compounds at levels greater than PFOS/PFOA (which can be in ppm range)

59 Analytical Methods

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Analyzing Other PFASs After the Initial Assessment

- Useful when:
  - Additional toxicity data or regulatory values become available
  - States require other PFASs (if promulgated)
  - For delineation (shorter compounds C4 and C2 move faster)
  - Treatment feasibility (e.g., GAC may not adsorb short chain compounds)
  - Biotic and abiotic transformation / mass balance
  - Tracing sources in mixed plumes
  - Source zones may contain cations and zwitterions not normally analyzed; these may be mobilized by being transformed by ISCO, for example
  - Fluorotelomer AFFF formulations are being delineated

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Treatments

Ineffective

- Riverbank Filtration
- Coagulation
- Sedimentation
- Granular Filtration
- Aeration
- Dissolved Air Flotation
- Microfiltration
- Ultrafiltration
- Ozone
- Aeration Packed Tower
- Chlorine
- Ultraviolet Photolysis
- Advanced Oxidation Process
- Chlorine Dioxide
- Chloramination

Partially Effective

- Anion Exchange
- Granular Activated Carbon

Effective

- Reverse Osmosis

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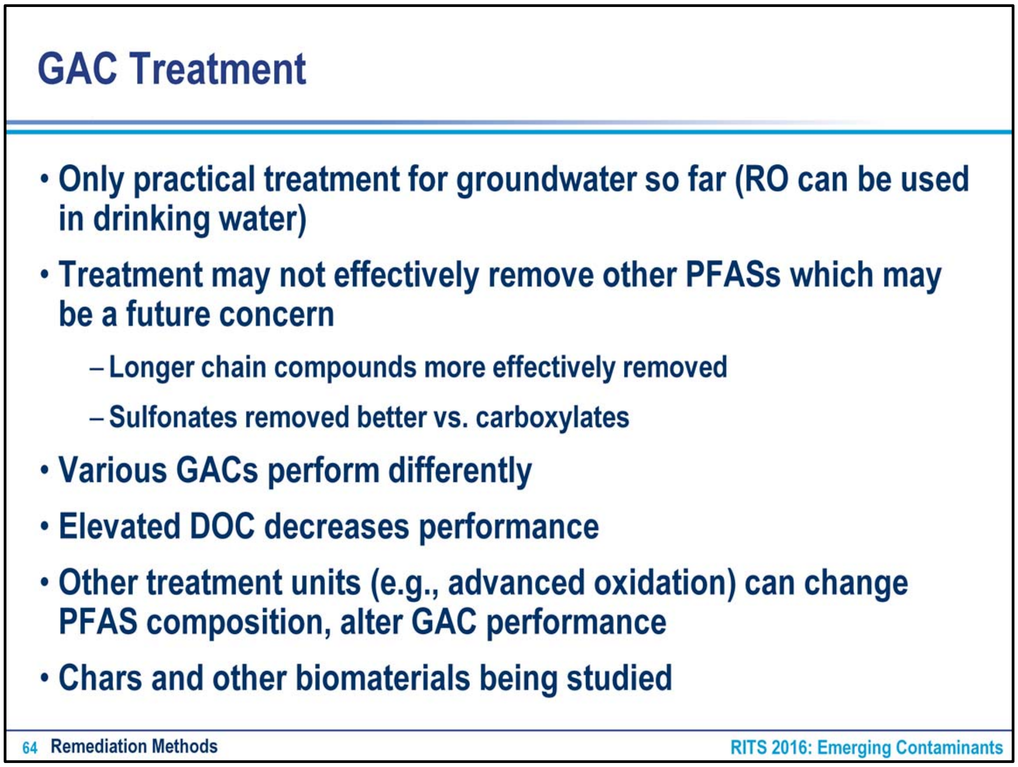
Treatment Options for PFAS by Media

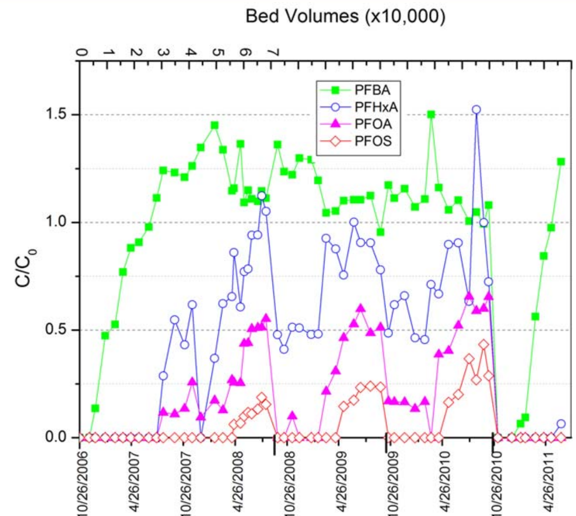
- Groundwater: GAC
- Drinking Water: GAC, RO, Nano Filtration, Anion Exchange
- Concentrates, Solids, etc.: High Temp Thermal Oxidation
  - New Technologies: Plasma-based, Sonochemical, Permanganate/Persulfate



Calgon’s “PFC” carbon, F600, at Warminster $$$ vs. Coconut Shell Carbon at Brunswick

GAC Treatment (cont.)

- Calgon® F600
  - Calgon recommends this carbon for PFAS
- 380 – 400 gpm
- ~13 min. EBCT
- Almost 2X cost of other carbons, benefit still being determined at Brunswick and Warminster
- F300 worked just as well in lab testing



GAC Treatment Currently in Use for PFAS

GAC treatment is currently being used at:

- NAS Brunswick, ME – two 5k lb GAC units (in series) sampled monthly coconut shell (lead) and F600 (lag)
- NAWC Warminster, PA – two 18k lb GAC units; started with reactivated bituminous carbon, changed out to F600
  - Sites are being monitored at influent, mid-point and effluent
  - Data being collected will allow for estimates of frequency of carbon changes and projections of cost
  - Some samples will be analyzed for full suite of 100+ PFAS

Oxidation in Field: Potential to Increase PFCAs and FTSAs

- Thermally-activated persulfate oxidized precursors to PFCAs, including PFOA[42]
- Fluorotelomer sulfonates (FTSAs) oxidized by UV/H_2O_2 to ≤ C7 PFCAs[61]
- Telomer-based AFFFs oxidized by $KMnO_4$ to 6:2 and 8:2 fluorotelomer sulfonates (FTSAs)[62]

KEY POINT Bottom line: Sites that undergo advanced oxidation as remedial strategies run the risk of increasing PFCA and FTSA concentrations.

[42]Houtz et al., ES&T, 2013;[61]Yang et al., 2014, Environ Sci Pollut Res, [62]Fang et al., 2015, Environ Toxicol Chem

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Case Study: NAWC Warminster, PA Summary

- FTA sampled found to contain PFAS exceeding PHAs in 2011-2012
- Found PFAS in public supply well (less than PHAs in 2013)
- Initiated Potential Sources Evaluation Report
- Warminster Municipal Authority (WMA) samples and posts UCMR3 data to EPA database 2014
- Navy develops RI SAP, completes Potential Source Evaluation report
- WMA Wells 10, 13 and 26 shut down due to PFAS levels
- The next month EPA issues SDWA Administrative Order to provide treatment of WMA wells and provide permanent safe DW for private wells at or above PHAs
- 200 attend NMCPHC supported public meeting, ATSDR and EPA drinking water and Federal Facilities RPM's participated
- Navy awards $3.9M ESCA grant for GAC treatment of 3 WMA wells, as well as covering other costs

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NAWC Warminster, PA Update

- Of 107 wells tested around Warminster, 13 at* or exceed PHA, 15 are between 25% of the PHA and the PHA
- 12 of the 13 wells exceeding the PHA at Warminster are now hooked up to PWS
- 15 wells were less than the PHA but exceeded 25% of PHA – will continue to be sampled/monitored
- Cost per hookup $15-20k, and about $200/foot of main installed
- Cost for treatment of on-site Navy PWS estimated to be $1M

*Since PHAs are published to 1 significant figure (e.g., 0.2 μg/L for PFOS), the DW rounding rule applies for laboratory results; i.e., any result equal to or greater than 0.15 will result in an exceedance because the result must be rounded up to 0.2)

NAWS Willow Grove, PA Update

- Of 272 wells sampled around Willow Grove 51 are at* or above PHA
- 52 wells require continued monitoring (i.e., levels are between 25% of PHA but less than the PHA
- Will require 30-40 hookups to PWS

*Since PHAs are published to 1 significant figure (e.g., 0.2 μg/L for PFOS), the DW rounding rule applies for laboratory results; i.e., any result equal to or greater than 0.15 will result in an exceedance because the result must be rounded up to 0.2)

71 Case Studies Update RITS 2016: Emerging Contaminants

Inter-Agency Partnering, Public Outreach Key

Lessons learned by BRAC PMO from handling of Warminster and other sites:

- Existing partnerships between Federal, State, and local government were enhanced to provide concerned citizens with coordinated information
- Engage the NMCPHC; they are a valuable resource
- Involve the PAO
- Community meetings have been well-attended and are useful; follow-on meetings tend to decline in attendance if objectives in communication are being met
- A proactive approach is needed, otherwise an Order could be issued; PHAs are being enforced as if an MCL

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- **Wrap-Up**

You will notice footnote indicators in the presentation slides. They refer to literature cited, in the Wrap-Up section.

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Conclusions

- Nearly 300 sites have been identified by the Navy as potential PFAS sites based on their use – of these, FTAs are by far of greatest concern
- PFASs should be included as a COPC if the CSM indicates (i.e., past use)
- PFAS plumes have unique properties that can cause them to behave differently than most other "conventional" contaminants such as VOCs
- Initially PFOS, PFOA and PFBS should be assessed, but:
  - The total mass of PFASs is likely much larger and comprised of numerous other compounds; this can:
    - Have human health and ecological risk implications
    - Impact site investigations and treatment of PFASs and commingled contaminants
- Treatment options are limited and largely restricted to GAC but new technologies are being developed, as are F&T information for improved CSMs

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Footnotes

1. Goss and Bronner, 2006, J Phys Chem
2. Buck et al., 2011, Integr Environ Assess Manag
3. O'Berg et al., 1987, J Occup Med
4. Deposition: Hearing before Leach et l vs. El DuPont de Nemours Company. Civil Action No 01-C-608, Circuit Court of Wood County, WV, June 25, 2004
5. Alexander et al., 2003, Occup Environ Med; Lundin et al., 2009, Epidemiology
6. Steenland and Woskie, 2012, Am J Epidemiol
7. Grandjean et al., 2012, JAMA
8. Granum et al., 2013, J Immunotox
9. Yeung et al., 2016, Env Chem
10. Bartell et al., 2010, Environ Health Perspec
11. Olsen et al., 2007, Environ Health Perspect
12. Olsen et al., 2009, Toxicol
13. https://www.governor.ny.gov/news/governor-cuomo-announces-immediate-state-action-plan-address-contamination-hoosick-falls
14. US EPA 2000a
15. Moody et al., 2000, Environ Sci Technol
16. Kevin Matlock, Fire Emergency Services, Air Force, Tyndall AFB
17. Information and photos courtesy of John Farley, Director, CBD/ex-USS SHADWELL Fire Test Operations, Naval Research Laboratory, Washington DC
18. Kevin Matlock, Fire Emergency Services, AFCEC/CXF
19. No fuel used, testing specified in National Fire Association (NFA) Standard 412, annual testing suspended by Air Force in 2015
20. 500-700 gallons fuel used & training varied by base, twice per year required, may have been quarterly depending on personnel training schedule
21. B2 crash 20,000 gallons fuel & actual AFFF used not known (Ansul used as example)
22. Carl Glover, Navy CNIC
23. Alexander et al., 2009, ES&T
24. 3M, 1999, EPA docket No. OPPT-2002-0043-0006
25. Barzen-Hensen et al., 2015, ES&T Letters
26. Backe et al., 2013, ES&T
27. Benskin, 2010, Rev Environ Contam Toxicol
28. Prevedouros et al., 2006, ES&T
29. Barzen-Hanson et al., 2015, Environ Sci Technol
30. Rahman et al., 2014, Water Res
31. Appleman et al., 2014, Water Res
32. Rhoads et al., 2008, Environ Sci Technol
33. Backe et al., 2012, Environ Sci Technol
34. Weiner et al., 2013, Environ Chem
35. Harding-Marjanovic et al., 2015, Environ Sci Technol
36. Jarman et al., A Human Health Screening Criteria, Abstract E017
37. Hoke et al., 2015, Chemosphere
38. Beach et al., 2006, Rev Environ Contam Toxicol
39. Colombo et al., 2008, Ecotox Environ Safety
40. Rahman et al., 2014, Water Res

Footnotes (cont.)

41. Appleman et al., 2014, Water Res
42. Houtz et al., 2013, ES&T
43. Lunderberg et al., 2015, Fluoros, Golden, CO
44. Guelfo and Higgins, 2013, ES&T
45. Gyllenhammar et al., 2015, Environ Res
46. Eschauzier et al., 2013, Sci, Tot Environ
47. Weiss et al., 2012, Intl J Hygiene Environ Health
48. Allred et al., 2014, J Chrom
49. Schultz et al., 2006; Higgins ES&T, 2005
50. Schultz et al., 2006, a&b ES&T
51. Ahrens et al., 2015, Chemosphere
52. Schultz et al., 2006, Environ Sci Technol
53. Sinclair and Kannan, 2006, Environ Sci Technol
54. Logananthan et al., 2007, Water Res
55. Lindstrom et al., 2011, Environ Sci Technol
56. Skutlarek et al., 2006, Environ Sci Pollut Res
57. Allred et al., 2014, J Chrom A
58. Allred et al., 2015, Envion Sci Technol
59. Benskins et al., 2012, Environ Sci Technol
60. EPA Region 5 PFOS Chromium Electroplater Study, 2009
61. Yang et al., 2014, Env Sci Pollut Res
62. Fang et al., 2015, Environ Toxicol Chem