

Detecting and Quantifying Low Levels of Fluoropolymer Polymerization Aids – A Guidance Document

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1.0 Purpose

This document will focus on the determination of low levels of Fluoropolymer Polymerization Aids (FPAs) in various matrices. This document is not meant to be all-inclusive, but rather to emphasize the state of knowledge and the difficulty of ensuring reliable sampling and data acquisition on these materials. Since the FPAs cover a wide range of chemical structures, a successful method for one compound does not necessarily ensure the method will be as useful for another. Also, this document will direct the reader to a subset of the appropriate literature that will be useful in establishing analytical protocols. Table 1 will provide the reader with the terminology and definitions used in the field.

2.0 Introduction

Fluoropolymer Polymerization Aids (FPAs) are used in diverse industrial applications as surfactants, dispersants, etc. The most common use of FPAs is as surfactants. Fluorosurfactants are similar in structure to conventional surfactants in that they have a hydrophilic part and a hydrophobic part. The difference lies in that the hydrophobic part of the fluorosurfactant molecule contains fluorinated carbons. The extent of the fluorination and the position of the fluorine atoms in the surfactant molecule affect the characteristics of the fluorosurfactant. Consequently, the surfactants may be termed either partially or fully fluorinated (aka perfluorinated). The hydrophobes of partially fluorinated surfactants contain both fluorine and hydrogen atoms. Unlike the hydrophobes of hydrocarbon surfactants, the partially fluorinated hydrophobe consists of two mutually phobic parts which are not compatible. Consequently, partially fluorinated surfactants exhibit anomalies in macroscopic characteristics, such as critical micelle concentration (cmc), and in microscopic phenomena as well. However, partially fluorinated surfactants have several advantages over fully perfluorinated surfactants. The hydrocarbon segment provides solubility in more commonly used solvents, lowers the melting point of the surfactant, reduces volatility, and decreases the acid strength of fluorinated acids.¹

Perfluorinated surfactants are remarkably stable, having exceptional thermal and chemical stability, which enables them to be used in applications that would be too severe for conventional hydrocarbon-based surfactants. The very strong C-F bond in a carbon chain (note: the F attached to C=O is not stable) is stable to acids, alkali, oxidation, and reduction, even at relatively high temperatures. It is this very stability that is the root cause of the difficulties in the determination of low levels of FPAs using conventional analytical techniques.

Fluorosurfactants as a class of compounds cover a range of chemical structures. Like all surfactants, fluorosurfactants are either ionic or nonionic. Ionic surfactants can, unlike nonionic surfactants, dissociate into ions in an aqueous medium. The hydrophilic part can belong to a negative or positive ion.

Fluorosurfactants can be classified into four types: 1) anionic, where the hydrophilic part is an anion; 2) cationic, where the hydrophilic part is a cation; 3) amphoteric, which have at least one anionic and one cationic group, and 4) nonionic.

Like their hydrocarbon counterparts, ionic fluorosurfactants dissociate in water and form a surface-active ion with an oppositely charged counterion. It is the surface-active ions of anionic fluorosurfactants that bear the negative charge. It is the anionic fluorosurfactants that are the most important class of fluorinated surfactants. They are classified based on the structure of

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Table 1. General Terminology and Definitions

Fluorinated Chemical	A general, non-specific term used synonymously with "fluorochemical."
Fluorinated Organic Polymer	A general term used to describe a polymer which has a hydrocarbon backbone (polyamide, polyester, polyurethane, etc.) to which is appended a fluorinated carbon chain, also known as a fluorinated alkyl chain; an example would be a polymer such as $-\text{[CH}_2\text{CH(C(O)OCH}_2\text{CH}_2\text{(CF}_2\text{)}_8\text{F)]}_n-$
Fluorinated Organic Surfactant	A term to describe a surface active, low molecular weight (<1000), substance which contains fluorinated carbons; the term fluorosurfactant is non-specific but often used synonymously; an example is $\text{F(CF}_2\text{)}_6\text{CH}_2\text{CH}_2\text{SO}_3\text{NH}_4^+$
Fluorochemical	A general, non-specific term used to describe broadly all chemicals containing the element fluorine; specifically, the term is used most commonly to describe small (1-8 carbon length) fluorinated molecules that are most often used for refrigeration, as fire suppression agents and as specialty solvents.
Fluoropolymer	A general term used to describe a polymer which has fluorine attached to the majority of carbon atoms which comprise the polymer chain backbone [common fluoropolymers are: polytetrafluoroethylene (PTFE), polyvinylidene fluoride (PVDF), fluorinated ethylene-propylene (FEP), etc.]; these are typically high molecular weight polymers used in high performance applications where chemical resistance and thermal stability are essential.
Fluoropolymer Polymerization Aid	A general term used to describe a subset of perfluoroalkylated substances; members of a class of commercially available perfluoroalkyl carboxylate surfactants, dispersants, etc.
Fluorosurfactant	A non-specific, general term used to describe a surface active, low molecular weight (<1000), substance where carbons bear fluorine in place of hydrogen. Examples would include $\text{CF}_3\text{(CF}_2\text{)}_7\text{SO}_3\text{K}^+$, $\text{H(CF}_2\text{)}_7\text{COO}^-\text{NH}_4^+$, $\text{F(CF}_2\text{CF}_2\text{)}_3\text{CH}_2\text{CH}_2\text{SO}_3\text{NH}_4^+$, $\text{CH}_3\text{CH}_2\text{CF}_2\text{CF}_2\text{CH}_2\text{COONH}_4^+$, etc.
Perfluoro- / Perfluorinated	Describes specifically a substance where all hydrogen atoms attached to carbon atoms are replaced with fluorine atoms - CF_n - where $n = 1 - 4$.
Perfluorinated Surfactant	A term used to describe a surface active, low molecular weight (<1000), substance where all carbons bear fluorine in place of hydrogen; the term fluorosurfactant is less specific but used synonymously; an example is $\text{F(CF}_2\text{)}_6\text{SO}_3\text{NH}_4^+$
Perfluoroalkylated Substance	A general term describing a substance that bears a perfluorocarbon unit, also known as a perfluoroalkyl functional group, $\text{F(CF}_2\text{)}_n\text{-R}$, where n is an integer and R is not a halogen, or hydrogen. Examples include $\text{F(CF}_2\text{)}_6\text{CH}_2\text{CH}_2\text{OH}$, $\text{F(CF}_2\text{)}_6\text{SO}_2\text{N(CH}_3\text{)CH}_2\text{CH}_2\text{OH}$, and $p\text{-F(CF}_2\text{)}_6\text{-C}_6\text{H}_4\text{OH}$

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their hydrophile, which can be divided into four main categories: a) carboxylates ($R_f\text{COO}^-M^+$), b) sulfonates ($R_f\text{SO}_3^-M^+$), c) sulfates ($R_f\text{OSO}_3^-M^+$), and d) phosphates ($R_f\text{OP}(\text{O})\text{O}_2^-M_2^+$), where R_f is a fluorine-containing hydrophobe and M^+ an inorganic or an organic cation. The predominate form used and for which there is the most analytical data are the perfluorinated carboxylic acids (PFOAs) and their salts.

In cationic fluorinated surfactants, the fluorinated hydrophobe is attached directly or indirectly to a protonated amino group, a quaternary ammonium group, or a heterocyclic base.¹ Cationic surfactants dissociate in water, forming a surface-active positively charged ion and a negatively charged counterion. Like anionic surfactants, cationic surfactants are usually affected by the pH of the medium and the electrolytes. There is a general belief that cationic surfactants adsorb on negatively charged surfaces.¹

Amphoteric fluorinated surfactants are bifunctional compounds having at least one cationic group, one anionic group, and are electronically neutral around their isoelectric points. Amphoteric fluorinated surfactants can function both as anionic and as cationic surfactants depending on the pH of the medium.² They are compatible with other types of surfactants and are believed to adsorb on either positively or negatively charged surfaces.¹ Amphoteric fluorinated surfactants are used in foam stabilizers, emulsifiers for manufacturing fluoropolymers, wetting agents, repellants for paper and textiles, fire-extinguishing agents, spreading agents on hydrocarbon surfaces, cleaning agents for degreasing metal surfaces, and personal care products.

Nonionic fluorinated surfactants are soluble in an acid or an alkaline medium. They do not dissociate into ions in water. Consequently, nonionic fluorinated surfactants are less sensitive to pH and electrolyte changes. They are not preferentially adsorbed on charged surfaces.¹

Appendix A covers some of the structure types of these molecules. Appendix B discusses general physical and chemical properties.

3.0 Safe Handling Information for Fluoropolymer Polymerization Aids

Read safety information prior to use, including MSDSs, and the Society of the Plastics Industry, Inc. (SPI) "Guide to Safe Handling of Fluoropolymers Dispersions," available either online (<http://www.fluoropolymers.org/news/APFOsafehandlingguide.pdf>) or directly from SPI.³ Any information, whether in an MSDS or in this guide, may change as results of further studies become available. Consult your supplier or SPI for the most up-to-date information.

A general treatment of physical and other properties of FPAs may be found in *Fluorinated Surfactants*.¹ The majority of the toxicology data and health studies on FPAs have been conducted on ammonium perfluorooctanoate (APFO). APFO is a perfluorinated chemical; it is extremely stable, degrades slowly, and therefore persists in the environment. APFO can be absorbed by the body and may be detected in the blood stream following ingestion, inhalation or skin contact. APFO has been classified by the American Conference of Governmental Industrial Hygienists (ACGIH) as an animal carcinogen, but available evidence does not suggest that the agent is likely to cause cancer in humans except under uncommon or unlikely routes or levels of exposure.⁴

Use of engineering controls, good hygienic practices and personal protection equipment (PPE) are critical in reducing exposure to FPAs. Avoid contact when handling materials containing FPAs. FPAs may be released when dispersions are heated or dried. Although solids,

some FPAs have high vapor pressures. It is important to clean up spills before they dry and allow the FPA to sublime.

Handle all chemicals with caution, including fluorosurfactants. It is the responsibility of the individuals handling neat materials, standards, and samples to determine the most appropriate precautions to follow based on available information.

4.0 Analytical Technologies

The logical approach to determining which analytical method to use for a particular application is to define the need, determine which analytical technologies might be able to solve the problem, determine if these resources are available in a timely fashion, and if so, proceed. Often the process is not as simple as it might seem, especially if the analyte of interest is difficult.

A useful tool to define the need is "Fitness for Purpose." Fitness for Purpose is the property of data produced by measurement that enables the user of the data to make technically correct decisions for a stated purpose.⁵ Fitness for Purpose refers to the magnitude of the uncertainty associated with the measurement in relation to the needs of the application area. For many applications of perfluorinated fluoropolymer polymerization aids, it might be sufficient to simply determine the total fluoride after combustion with a fluorine ion-selective electrode. For measurements required in an industrial, regulated environment, it would be necessary to have more exacting quantitative and qualitative tools with defensible quality assurance as an integral part of each step.

The following checklist might also be a useful tool in selecting the analytical method.

- What is the purpose of the measurement?
- What concentration of analyte is expected?
- How will the material be identified?
- What quality assurance procedures are required?
- How will sampling and transport be accomplished?
- What are the sources of potential cross contamination?
- What is the method specificity?
- Should screening be used to expedite the measurement process?
- What is the linearity and range of the measurement?
- What is the detection limit (both method and instrument)?
- What is the stability of the sample in the containers and conditions from sampling to analysis?
- What type of error analysis is appropriate? What criteria are needed to reject data? (R^2 , blank less than the method detection limit (MDL), nonzero blanks)
- Validation
- Time, money, resources
- Have you carefully considered the next steps ("What if" planning) after the data are obtained?

In evaluating the overall Fitness for Purpose, consideration should be given to the resources needed to improve the accuracy, precision, and qualitative nature of the analysis. Generally, the more precise, accurate, and certain, the higher the cost and greater the time needed.

The most common fluoropolymer polymerization aid is ammonium perfluorooctanoate, APFO. Since it is the most common material in use, it is also the most studied and reported upon. In water, APFO dissociates into its anion, perfluorooctanoate, and its cation, ammonium. For analytical measurements, the concentrations are usually expressed as the original ammonium salt (APFO) or its parent, perfluorooctanoic acid (PFOA). The following sections will highlight various aspects involved in the sampling, sample preparation, analysis, and data reduction for PFOA.

5.0 Analysis of PFOA in Water

5.1 Sampling and Preservation

Care must be used in sampling to avoid later problems in analysis, especially when determining perfluorooctanoic acid (PFOA) and its salts at part per billion (ppb) levels or less. It is important that multiple blanks and standards are run. If blanks show measurable quantities of PFOA, results should be considered suspect. To avoid contamination from sampling equipment and containers, fluoropolymers should be avoided, since PFOA is often used in fluoropolymer manufacture. Field blanks can help to identify problems in this area. It is important to ensure the sampling equipment being used is not subject to adsorption, absorption, or volatilization losses, and does not compromise the sample.

Sample history should be well documented and contain details of sample collection and transport. It is important to verify hold times for analyses of this type. If not analyzed promptly, samples should be stored at temperatures at or near zero degrees Celsius.

5.2 Preparation

Different types of water have different sample preparation issues associated with them. If the PFOA salts dissolve more readily than the free acid, it may be necessary to adjust solution conditions through the addition of appropriate bases, such as ammonium hydroxide (see Appendix B). Since PFOA and its salts are surfactants, they tend to spread and coat sample containers and apparatus. Thus unnecessary changing of the test sample container should be avoided, and spike recovery analyses should be performed to assess the degree to which the analyte may be lost due to this phenomenon. Filtration of the sample may be necessary to remove undissolved solids. This should be done only if necessary, since analyte may be lost due to absorption onto the filter. Polypropylene filter media may be preferred for certain perfluorinated surfactants, since absorption is generally less than for other materials.⁶

In the case of very dilute samples it may be necessary to preconcentrate the sample. This can be accomplished using preconditioned cartridges such as C18⁷, Porapak[®] Q, or Tenax[®]. Recovery of spiked blanks and samples should be assessed to determine the efficiency of analyte recovery from such cartridges.

Additional sample preparation may be necessary depending on the analytical method chosen for the determination.

5.3 Types of Water

"Clean" water, such as drinking water, usually should not require filtration. Since the concentration of PFOA is likely to be very low, however, it is especially important to avoid contamination during sampling and handling. Preconcentration and pH adjustment may be necessary. Interference from inorganic fluoride may cause problems with a non-specific analytical method, such as total fluorine content.

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Groundwater and river water may or may not require filtration, depending on the source. Most of the comments pertaining to "clean" water also apply. There may be additional problems created by the presence of biological organisms and other interfering compounds, especially in river water.

Process water, such as that found in fluoropolymer manufacturing facilities or in plants that use fluoropolymers in their manufacturing processes, may contain relatively high concentrations of PFOA or its salts. It is important that the time and place of sampling is carefully noted, since concentrations of PFOA may fluctuate substantially with time. Filtration may be necessary to remove undissolved solids, but it will probably be necessary to analyze any solids removed, since they may contain sizeable quantities of PFOA as a result of sorption. Interference from other components in the process stream should be considered when choosing an analytical technique.

Each type of water mentioned above should be considered as unique, and has its own set of sampling and analytical problems. Seasonal variations might be significant. Again, it is important to verify hold times for analyses of this type.

5.4 Analytical Methods

There are many methods that may be applied to the analysis of PFOA and its salts. Factors to be considered when choosing a method include cost and availability of equipment, analytical skill level required for analysts, time requirements for sample preparation and analysis, and any trade-offs required between sensitivity, accuracy, and precision of measurement. These considerations are summarized in Appendix C.

Total fluorine content is non-specific to PFOA, but may be adequate for relatively high concentrations in samples where it is known that there are no other sources of fluorine besides PFOA. The organic fluorine must be converted to soluble fluoride ion for many of the more common techniques, and this will require some type of combustion. It should be noted that perfluorinated compounds, such as PFOA, are difficult to combust completely.⁷ Analysis of standards and spiked samples are important to ensure that combustion is complete.

Gas chromatography with flame ionization (FID), electron capture (ECD), or mass spectroscopic (MSD) detection can be used to determine PFOA. These methods have been reported for the determination of PFOA in blood plasma and urine^{6,9,10}, and may be adapted to water analysis. Since the acid form cannot be chromatographed, it is necessary to first convert the carboxylic acid to an ester. Various procedures can be used for the esterification, and it is important to ensure that the esterification is complete by using spiked samples. These techniques are semi-specific, since the retention times of known standards can serve to identify the materials being analyzed. The lower limit of detection for these techniques is of the order of one to five parts per million by weight. They have the advantage of using relatively inexpensive and widely available equipment.

Nuclear magnetic resonance (¹⁹F-NMR) has been reported⁸ to be applicable to PFOA analysis in water with a detection limit of 10 µg/L. It is also semi-specific, but perfluorinated surfactants other than PFOA can interfere with the determination. The presence of branched surfactants can lead to erroneous quantitation; care must be taken to account for the amount of branching. Pre-concentration of samples may be necessary, but derivatization is not. The equipment is expensive and may be available only in larger laboratories.

High performance liquid chromatography (HPLC) has been reported to be applicable to the analysis perfluorocarboxylic acids in biological samples¹¹, and may be adaptable for water analysis. Since PFOA and its salts lack chromophores, it is also necessary to derivatize the sample before analysis when using fluorescence detection. As with gas chromatography, it is semi-specific in that retention time of standards can be used to identify the analyte. HPLC

equipment is only moderately expensive and is reported to be more sensitive than gas chromatography.¹¹

Liquid chromatography/tandem mass spectrometry (LC/MS/MS) has been used to determine PFOA in river water⁸ and human serum.¹² It is compound specific and does not require derivatization of the sample prior to analysis. It is superior to LC/MS in that it provides an additional dimension, which helps to avoid false positives. A detection limit of 1 pg was reported for water⁸ and 10 ng/mL for serum.¹² It is likely to be the most generally applicable technique, especially for trace levels, but the equipment is expensive and likely to be available only in larger laboratories.

5.5 Analytical Method Validation

Before generating analytical data on unknown samples with any of the methods mentioned above, it is important to ensure that the method is validated. This is especially important if a method developed for one type of medium, e.g. human serum, is to be adapted to another medium, e.g. water. Lab spiking should be performed to address matrix effects. Blanks are very important for low-level quantitation and minimizing sampling artifacts. Good guidelines for method validation can be found in reference 13.

6.0 Analysis of Ammonium Perfluorooctanoate (APFO) in Air

Applications of air sampling and analyses methods to the measurement of APFO should include method validation criteria consistent with appropriate regulatory guidance. Due to the potential biphasic nature of APFO and other airborne fluorochemicals consideration of sampling media is critical. Method development should include "zero" air measurements as well as adsorption and desorption efficiencies, and holding time measurements. Preferably the method should be able to discriminate between analyte on particles versus analyte in the vapor phase. There should be "real" blanks, including field blanks taken to the field and exposed to all conditions except for having the air pumped through them. Demonstration of lab capability via analysis of spiked samples and replicates and all associated quality control requirements should be documented. This documentation should include instrumental calibrations and written Standard Operating Procedures (SOPs) or written lab procedures for each step from materials preparation, sampling, analysis, documentation, reporting and deliverables, and data retention. Third party validation or review is desired. Established quality criteria including method performance should be documented (Limit of Quantitation - LOQ, uncertainties, accuracy, precision, specificity, calibration criteria, blank criteria, matrix or lab control spike criteria, replicates, retention-time window criteria, tuning criteria).

Reports of analyses of semivolatile or non-volatile fluorochemicals in air have been limited.^(14,15) A recent analytical air method exists for the analysis of APFO in workplace atmospheres. This method involves LC/MS/MS analysis of acetone extracts from OSHA Versatile Sampler (OVS) tubes (Occupational Safety and Health Administration, OSHA).¹⁴ This method applies to the analysis of "clean" ambient workplace air. Application of the method to environmental manufacturing emissions sampling or other air matrices would require source specific validation. OVS tubes were used to simultaneously trap fluorochemical particulates and vapors from workplace air. Analytical methods were developed for air samples collected on OVS tubes to quantitatively analyze for both total fluorine, using oxygen bomb combustion/ion selective electrode, and for nineteen analyte specific organofluorochemicals using LC/MS, GC/MS, and IC (ion chromatography).¹⁴ A method validation study was conducted according to

the National Institute of Occupational Safety and Health (NIOSH) with minor revisions of the experimental design due to specifics of this particular sampling application.¹⁶ Method performance for APFO analysis was sufficient in terms of analytical recovery, sampler capacity, storage stability, determination of limits of detection, and precision and bias of the samples. The method combines OVS tube sampling with LC/MS analysis and is applicable for quantitation of 0.06 – 6 µg APFO in an OVS tube sample. This method range corresponds to quantitation of APFO in ambient air in the concentration range of 0.001 - 0.1 mg/m³ with a 60-liter air sample.

7.0 Determination of Ammonium Perfluorooctanoate (APFO) in Biological Matrices

Analyte specific detection of APFO in biological matrices at trace levels (parts per billion by weight) can be accomplished using two primary analytical detection techniques.^(8, 17, and refs within)

The first technique combines chemical derivatization techniques coupled with gas chromatography/mass spectrometry detection. The second technique combines biological matrix extraction with liquid chromatography/mass spectrometry detection.

Biological matrices are highly variable and impact analytical method performance with unpredictable results. Significant differences in method performance criteria can be observed for the same analytical method when it is applied to biological matrix variations of tissue type (e.g., liver versus sera), tissue fractions/components (e.g., whole blood versus serum), and species variation (e.g., rabbit versus rat). Food and Drug Administration (FDA) bioanalytical method validation guidance has been recently published to ensure analytical method performance criteria are defined and are consistent with regulatory method guidelines for data reporting.¹³

Some recent publications on the determination of APFO in biological matrices show low spike recovery. Low (i.e., <70%) spike recovery percentages may not be appropriate for reporting to regulatory agencies.

Analytical method validation plans for “partial” validation of a method that already has successfully met all requirements of a full validation will differ based on the specific method change that requires validation. Examples of specific method changes requiring “partial validation” are given as a list in the FDA guidance document.

1. Transfers between laboratories or between analysts
2. Change in analytical methodology (e.g., detection system)
3. Change in anticoagulant in harvesting biological fluid
4. Change in matrix within species (e.g., human plasma to human urine)
5. Change in sample processing procedures
6. Change in species within matrix (e.g., rat plasma to mouse plasma)
7. Change in relevant concentration range
8. Change in instruments and/or software platforms
9. Limited sample volume (e.g., pediatric study)
10. Rare matrices (e.g., limited number of individual samples-endangered species)
11. Selectivity in the presence of concomitant medications
12. Selectivity in the presence of specific metabolites

8.0 Solids

The determination of perfluorinated carboxylic acids or their salts in solids can be accomplished directly or indirectly. An indirect method such as the combustion of the material with a Wickbold⁷ torch for total organic fluoride, followed by determination with fluoride ion-selective electrode measurement, is used to see if a fluorinated compound is present in the solid. Of course the indirect method cannot definitively confirm the presence of any specific fluorinated material. A direct method would probably employ either thermal desorption, derivatization, gas chromatography mass spectrometry (GC/MS) or solvent extraction followed by liquid chromatography tandem mass spectrometry (LC/MS/MS). The mass spectrometric methods are specific and definitive since they provide both qualitative and quantitative data. The mass spectrum and retention time are the minimum data needed to identify the presence of a material in a solid.

Often with a complex matrix, such as a solid, it is necessary to also characterize the solid since the extraction efficiency of the analyte from its matrix will depend on the composition of the solid and also perhaps how long the solid has been exposed to the analyte of interest. It might also be necessary to perform an aging and sequestration study to determine the effect of aging and other components of the matrix. The EPA document "Preparation of Soil Sampling Protocols: Sampling Techniques and Strategies"¹⁸ notes that most of the variance involved in soil analysis comes from the sampling and not from the laboratory analysis. With solids from a manufacturing process, however, more information on the composition of the solid would be known so that defining the analytical task should be somewhat less complex. If the solid's matrix contains other fluorinated species, a determination of the concentration and source (decomposition or reaction with the analyte of interest) might also have to be performed to ascertain the "real" concentration.

9.0 Additional Analytical Considerations

Fluoropolymer polymerization aids are unique in their physicochemical properties; therefore special care must be taken in sample preparation and analysis. Common predictive models may lead to significantly erroneous results for physicochemical properties: Since these compounds "look" like hydrocarbons, the temptation is to assume similar characteristics for measures of volatility, solubility, etc. This temptation must be resisted and thought given to each step in the method with a full slate of quality assurance (QA) components incorporated into the process from sampling through analysis and data acceptance and reduction.

Method validation studies need to be conducted to ensure the method is sufficient in terms of analytical recovery, sampler capacity, storage stability, determination of limits of detection, and precision and bias of the samples.¹⁶ Before any data are reported, it is important that the work be reviewed for quality and rigor. A good resource is "Guidance for Industry, Bioanalytical Method Validation."¹³ This document is especially useful when GC or LC methods are employed, and is especially helpful for a single laboratory initiated validation.

Table 2 contains some suggested QA components that will add to the defensibility of the data.

Table 2. Definitions of Quality Assurance (QA) Criteria

QA Criteria	Definition
Blank	A sample subjected to the usual analytical or measurement process to establish a zero or baseline value.
Calibration	A comparison of a measurement standard, instrument, or item with a standard or instrument of higher accuracy to detect and quantify inaccuracies and to report or eliminate those inaccuracies by adjustments.
Check Standard	A standard prepared independently of the calibration standards and analyzed exactly like the samples.
Duplicate Samples	Two samples taken from, and representative of, the same population and carried through all steps of sampling and analytical procedures in an identical manner.
Field Blank	A blank used to provide information about contaminants that may be introduced during sample collection, storage, and transport.
Laboratory Control Spike	Determines the desorption efficiency of the target analytes from the sampling media. Samples are prepared by spiking blank sampling media, preferably from the same lot of media used in sample collection, with quantities of target analytes commensurate with the range determined in samples.
Laboratory Split Samples	Two or more representative portions taken from the same sample and analyzed by different laboratories to estimate interlaboratory precision or variability and the data comparability.
Matrix Spike	A sample prepared by adding a known mass of a target analyte to a specified amount of matrix sample for which an independent estimate of the target analyte concentration is available.
Method Blank	A blank prepared to represent the sample matrix as closely as possible and analyzed exactly like the calibration standards, samples, and quality control (QC) samples. Results of method blanks provide an estimate of within batch variability of the blank response and an indication of the bias introduced by the analytical procedure.
Split Samples	Two or more representative portions taken from one sample in the field and or in the laboratory and analyzed by different analysts or laboratories.
Surrogate Spike or Analyte	A pure substance with properties that mimic the analyte of interest.
Validation	Confirmation by examination and provision of objective evidence that the particular requirements for a specific intended use have been fulfilled.
Variance (statistical)	A measure of the dispersion of a sample or population distribution.

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APPENDIX A: Examples of Fluoropolymer Polymerization Aids

Chemical Name	Synonym	CAS #	Formula
Heptafluorobutanoic acid	C4 acid	375-22-4	C3F7COOH
Nonafluoropentanoic acid	C5 acid	2706-90-3	C4F9COOH
Ammonium nonafluoropentanoate	C5 NH4 salt	68259-11-0	C4F9COONH4
Undecafluorohexanoic acid	C6 acid	307-24-4	C5F11COOH
Sodium undecafluorohexanoate	C6 Na salt	2923-26-4	C5F11COONa
Ammonium undecafluorohexanoate	C6 NH4 salt	21615-47-4	C5F11COONH4
Tridecafluoroheptanoic acid	C7 acid	375-85-9	C6F13COOH
Potassium tridecafluoroheptanoate	C7 K salt	21049-36-5	C6F13COOK
Ammonium tridecafluoroheptanoate	C7 NH4 salt	6130-43-4	C6F13COONH4
Pentadecafluorooctanoic acid	C8 acid	335-67-1	C7F15COOH
Potassium pentadecafluorooctanoate	C8 K salt	2395-00-8	C7F15COOK
Sodium pentadecafluorooctanoate	C8 Na salt	335-95-5	C7F15COONa
Ammonium pentadecafluorooctanoate	C8 NH4 salt	3825-26-1	C7F15COONH4
Heptadecafluorononanoic acid	C9 acid	375-95-1	C8F17COOH
Sodium heptadecafluorononanoate	C9 Na salt	21049-39-8	C8F17COONa
Ammonium heptadecafluorononanoate	C9 NH4 salt	4149-60-4	C8F17COONH4
Nonadecafluorodecanoic acid	C10 acid	335-76-2	C9F19COOH
Potassium nonadecafluorodecanoate	C10 K salt	51604-85-4	C9F19COOK
Sodium nonadecafluorodecanoate	C10 Na salt	3830-45-3	C9F19COONa
Ammonium nonadecafluorodecanoate	C10 NH4 salt	3108-42-7	C9F19COONH4
Heneicosafleuroundecanoic acid	C11 acid	2058-94-8	C10F21COOH
Potassium heneicosafleuroundecanoate	C11 K salt	30377-53-8	C10F21COOK
Sodium heneicosafleuroundecanoate	C11 Na salt	60871-96-7	C10F21COONa
Ammonium heneicosafleuroundecanoate	C11 NH4 salt	4234-23-5	C10F21COONH4
Tricosafluorododecanoic acid	C12 acid	307-55-1	C11F23COOH
Potassium tricosafluorododecanoate	C12 K salt	6060-71-5	C11F23COOK
Sodium tricosafluorododecanoate	C12 Na salt	307-67-5	C11F23COONa
Ammonium tricosafluorododecanoate	C12 NH4 salt	3793-74-6	C11F23COONH4

Appendix B: General Physical and Chemical Properties

a. Thermal Stability

Perfluorinated surfactants are remarkably stable; enabling them to withstand conditions which would be too severe for hydrocarbon surfactants.^{1,16} The C-F bond is one of the strongest known, thus providing the fluorosurfactant stability even at high temperature in the presence of acids, alkali, oxidation and reduction. It has been found that perfluoroalkanecarboxylic acids and perfluoroalkanesulfonic acids are the most stable fluorinated surfactants, while their salts decompose more readily with the cation and R_f chain length apparently of profound influence.^{1,17,18}

b. Chemical Stability

Perfluorinated alkanic and alkanesulfonic acids have excellent chemical stability towards acids, oxidants and alkali.^{1,18,19} Perfluorinated alkanecarboxylic acids are strong acids, similar in strength to mineral acids.²⁰

c. Melting Points

The perfluorinated carbon chains of surfactant molecules, as compared to their hydrocarbon analogs, are stiff and inflexible due to the rigidity of the C-F bond.¹ It is believed that this contributes to their higher melting points, a high Krafft point with reduced solubility in solvents. The R_f chain length and branching of the terminal units have been found to have a marked effect on the melting point.²¹ The size of the cation also has an effect on the melting point. The melting points of perfluorooctanoates with inorganic cations do not increase linearly with increasing size of ionic radii.¹⁷ This phenomenon is believed to be due to the reduced stability of the salt with increasing size of the ionic radii.

d. Solubility

The unusual properties of the fluorine atom and the C-F bond also affect the solubilities of the fluorinated surfactants. Perfluoroalkanes are more hydrophobic than their hydrocarbon analogs as shown by their solubility data.^{22,23} The R_f chain and the hydrophile have an effect on the solubility of the fluorinated surfactant.¹ The solubility of perfluoroalkanoic acids decreases with increasing chain length. At 25 °C, C1 to C6 perfluorinated alkanic acids are miscible in water in all proportions whereas the C8 and C10 perfluorinated alkanic acids are only slightly soluble.²⁴ The same is true for the solubility of alkali metal salts of perfluorinated alkanic acids in water – i.e. it decreases with increasing chain length.

Table 3: Physical and Chemical Properties

	CAS #	Molecular Formula	Molecular Weight	Boiling Point	Melting Point
Perfluorobutanoic acid (a)	375-22-4	C ₄ HF ₇ O ₂	214.04	120 °C	-19.5 °C (b)
Perfluorovaleric acid (a)	2706-90-3	C ₅ HF ₉ O ₂	264.05	127 °C (c)	N/A
Undecafluorohexanoic acid (a)	307-24-4	C ₆ HF ₁₁ O ₂	314.06	157 °C at 742 mm (d)	12 - 14 °C (f)
Perfluoroheptanoic acid	375-85-9	C ₇ HF ₁₃ O ₂	364.06	175-177 °C	54 °C in CCl ₄ (c)
Pentadecafluorooctanoic acid (g)	335-67-1	C ₈ HF ₁₅ O ₂	414.07	189 °C at 736 mm	55 - 56 °C
Ammonium Pentadecafluorooctanoate (a)	3825-26-1	C ₈ HF ₁₅ O ₂ ·H ₃ N	431.10	N/A	157-165 °C (h)
Perfluorononan-1-oic acid (a)	375-95-1	C ₉ HF ₁₇ O ₂	464.08	N/A	71-77 °C
Perfluoro-N-decanoic acid (a,g)	335-76-2	C ₁₀ HF ₁₉ O ₂	514.09	218 °C at 740 mm	83 - 85 °C
Perfluoroundecanoic acid (a,g)	2058-94-8	C ₁₁ HF ₂₁ O ₂	564.09	160 °C at 60 mm	96 - 101 °C
Perfluorododecanoic acid (a,g)	307-55-1	C ₁₂ HF ₂₃ O ₂	614.10	245 °C at 740 mm	107 - 109 °C

^a Beilstein Institut zur Foerderung der Chemischen Wissenschaften. Copyright 1988-2001

^b Henne; Fox; J. Amer. Chem. Soc., 73, 2323 (1953).

^c Benefice-Malouet, S, Blancou, H., Itier, J., Commeyras, A; Synthesis, 647-648 (1991).

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^g Data from MSDS sheets

^h D. Lines and H. Sutcliffe, J. Fluorine Chem., 25, 505-512 (1984).

N/A – not available

	CAS #	Density	Refractive Index	Vapor Pressure	Water Solubility
Perfluorobutanoic acid (a)	375-22-4	1.764 g/cm ³ (d)	1.297	10 mm Hg at 20°C	N/A
Perfluorovaleric acid (a)	2706-90-3	1.713 g/cm ³ (d)	1.294 at R.T. at 589 nm (e)	N/A	N/A
Undecafluorohexanoic acid (a)	307-24-4	1.762 g/cm ³ (d)	1.298 at R.T. at 589 nm	N/A	N/A
Perfluoroheptanoic acid	375-85-9	1.792 g/cm ³ (d)	1.3119 at 27°C at 589 nm	N/A	N/A
Pentadecafluorooctanoic acid (g)	335-67-1	N/A	N/A	0.1 kPa (0.75 mm Hg)	3.4 - 9.5 g/L
Ammonium Pentadecafluorooctanoate (a)	3825-26-1	N/A	N/A	N/A	N/A
Perfluorononan-1-oic acid (a)	375-95-1	N/A	N/A	N/A	N/A
Perfluoro-N-decanoic acid (a,g)	335-76-2	N/A	N/A	N/A	N/A
Perfluoroundecanoic acid (a,g)	2058-94-8	N/A	N/A	N/A	N/A
Perfluorododecanoic acid (a,g)	307-55-1	N/A	N/A	N/A	N/A

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APPENDIX C: Comparison of Available Analytical Techniques for Fluoropolymers¹

<u>Technique</u>	<u>Sensitivity</u>	<u>Strengths</u>	<u>Weaknesses</u>	<u>Cost of Instrumentation</u>	<u>Timing After Sample Preparation and Instrument Calibration</u>
Total Fluorine	Low ppm	Non-matrix specific Versatile	Non-specific Operator dependent	< \$20,000 USD	One sample per hour
¹⁹ F NMR*	Low ppm	Specificity	Field strength dependent	> \$100,000 USD	One sample every 8 hours
GC/FID	Low ppm	Readily available	Non-specific Multi-step (derivatization)	\$20,000 – 50,000 USD	Data acquisition less than 1 hour
GC/MS*	Low ppm	Specificity	Multi-step (derivatization)	\$50,000 – 100,000 USD	Data acquisition less than 1 hour
GC/ECD	Low ppm	Sensitivity	Multi-step (derivatization) Narrow range of linearity Radiation (⁶³ Ni source)	\$20,000 – 50,000 USD	Data acquisition less than 1 hour
LC	Low ppm	Sensitivity	Detector dependent	\$20,000 – 50,000 USD	Data acquisition less than 1 hour
LC/MS*	ppb	Specificity Minimal sample preparation	Possible matrix interference	\$50,000 – 100,000 USD	30 minutes per sample
LC/MS/MS*	Sub-ppb	Specificity Minimal sample preparation	Possible matrix interference	> \$100,000 USD	30 minutes per sample

¹ Analytical techniques should be validated for each individual fluoropolymer being analyzed for.

* Technique which requires greater or significantly greater operator skill than others listed here.