



MONASH University

School of Chemistry

**Fundamental Properties of Fluorinated
Surfactants and their Practical Implications**

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A thesis submitted for the degree of *Doctor of Philosophy* at Monash University

March 2021

*There is a theory which states that if ever anyone discovers exactly what the Universe is for and why it is here, it will instantly disappear and be replaced by something even more bizarre and inexplicable.
There is another theory which states that this has already happened.*

- Douglas Adams

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Abstract

Perfluorinated surfactants have been an important component in coatings formulations, fire-fighting foams and industrial fluoropolymer synthesis for many years. Their chemical inertness and unique physical properties provides superior performance in these applications. However, these properties also result in low biodegradability in the environment and potential for bioaccumulation. The persistence in the environment of perfluorinated surfactants is now a topic of increasing concern due to evidence of a variety of negative health outcomes arising from prolonged exposure.

In this thesis, fundamental properties of representative perfluorinated alkyl substances (PFAS) are investigated using salts of perfluorooctanoate (PFO), one of the more common perfluorinated surfactants, and examining its interactions with hydrocarbon ions and lipids in solution. Two main properties are considered: surface activity and aggregation behaviour in solution. Practical implications of both aspects are subsequently investigated, focussing on improving potential remediation methods through changes in surface activity and furthering understanding of how PFO interacts with model biological liposomes.

Changes in aggregation behaviour and surface activity of PFO with a variety of organic ammonium counterions were analysed (Chapter 3). Pendant drop tensiometry was used to measure equilibrium surface tension while aggregation in solution was analysed using small angle neutron scattering. Changes in degree of substitution and carbon chain length of counterion substituents provided a matrix of differing geometries and overall hydrophobicity in counterions. Increasing counterion hydrophobicity resulted in lower cmc values and favoured formation of lamellar phases in solution, even at relatively low concentrations. This behaviour was rationalised as a greater binding of the counterion to the surfactant headgroup as counterion hydrophobicity increased.

Using organic amine molecules to increase the surface activity of PFO was investigated further (Chapter 4) as a method to improve remediation of PFO-contaminated water in a proof-of-concept foam flotation experiment. Primary amines of different chain lengths were added to

dilute PFO solutions and the changes in equilibrium surface tension, dynamic surface tension and foaming potential were measured. These changes were then compared to measured amounts of PFO in extracted foams from a lab-scale foam separation apparatus. Inclusion of organic amines improved the yield of PFO in extracted foams, and was correlated to their hydrophobicity, but only until the amine molecules had some surfactant qualities themselves. Addition of a surface active amine molecule (*n*-octylamine) produced an anti-foam effect with a detrimental decrease in performance.

Properties of phosphatidylcholine liposomes in the presence of dilute PFO were analysed using small and ultra-small angle neutron scattering (Chapter 5). PFO was found to readily partition into hydrocarbon lipid phases. Structural changes in liposomal bilayers were analysed at low PFO concentrations while phase changes and the presence of coexistent liposome/micelle compositions were observed at higher concentrations. Lipid molecules were varied in their degree of saturation and head group chemistry, and lipids with a degree of unsaturation in the chains showed a gradual decrease in bilayer thickness as PFO was incorporated.

First author publications during enrolment

1. **M. J. Pottage**, T. L. Greaves, C. J. Garvey, R. F. Tabor, The effects of alkylammonium counterions on the aggregation of fluorinated surfactants and surfactant ionic liquids. *Journal of Colloid and Interface Science*, 2016, **475**, 72–81.
2. **M. J. Pottage**, S. Blundell, R. F. Tabor, Increasing surface activity and foaming of dilute perfluorooctanoate solutions by addition of organic amines. *Langmuir*, 2021, *submitted*.

Other publications during enrolment

1. T. M. McCoy, A. Valiakhmetova, **M. J. Pottage**, C. J. Garvey, L. de Campo, C. Rehm, D. A. Kuryashov, R. F. Tabor, Structural evolution of wormlike micellar fluids formed by erucyl amidopropyl betaine with oil, salts, and surfactants. *Langmuir*, 2016, **32**, 12423–12433
2. Y. Hu, J. B. Marlow, R. Ramanathan, W. Zou, H. G. Tiew, **M. J. Pottage**, V. Bansal, R. F. Tabor, B. L. Wilkinson, Synthesis and Properties of Photoswitchable Carbohydrate Fluorosurfactants. *Australian Journal of Chemistry*, 2016, **68**, 1880–1884.
3. M. K. Adam, Y. Hu, J. S. Poisson, **M. J. Pottage**, R. N. Ben, B. L. Wilkinson, Photoswitchable carbohydrate-based fluorosurfactants as tuneable ice recrystallization inhibitors. *Carbohydrate Research*, 2017, **439**, 1–8.
4. J. B. Marlow, **M. J. Pottage**, T. M. McCoy, L. de Campo, A. Sokolova, T. D. M. Bell, R. F. Tabor, Structural and rheological changes of lamellar liquid crystals as a result of compositional changes and added silica nanoparticles. *Physical Chemistry Chemical Physics*, 2018, **20** 16592–16603.
5. J. E. Moore, T. M. McCoy, J. B. Marlow, **M. J. Pottage**, S. T. Mudie, G. R. Pearson, B. L. Wilkinson, R. F. Tabor, Rich liquid crystal phase behavior of novel alkyl-tri (ethylene glycol)-glucoside carbohydrate surfactants. *Journal of Colloid and Interface Science*, 2019, **540**, 410–419.
6. L. W. Giles, S. P. Meaney, R. Prathapan, **M. J. Pottage**, G. P. Knowles, A. L. Chaffee, S. R. Batten, R. F. Tabor, Surfactant-controlled crystal growth of metal–organic frameworks and their nanoparticle pyrolysis products. *Materialia*, 2020, **13**, 100849.

Declaration: Thesis including published works

I hereby declare that this thesis contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

This thesis includes **one** original paper published in peer reviewed journals and **one** submitted publication. The core theme of this thesis is fundamental properties of perfluorinated surfactants. The ideas, development and writing up of all the papers in the thesis were the principal responsibility of myself, the student, working within the School of Chemistry under the supervision of A/Prof. Rico Tabor.

The inclusion of co-authors reflects the fact that the work came from active collaboration between researchers and acknowledges input into team-based research.

In the case of Chapters 3 and 4 my contribution to the work involved the following:

Experimental design and execution, materials formulation and synthesis, data analysis and presentation, and manuscript drafting. Further details specific to each chapter are provided in the Table below.

Thesis chapter	Publication Title	Status	Nature and % of student contribution	Co-author name(s), nature and % of co-author contribution	Co-author(s) Monash student (Y/N)
3	The effects of alkylammonium counterions on the aggregation of fluorinated surfactants and surfactant ionic liquids	Published	78%, experimental design, synthesis and sample formulation, data analysis, manuscript drafting	a) T. L. Greaves, 5%, assistance with material characterisation. b) C. J. Garvey, 5%, assistance with neutron scattering. c) R. F. Tabor, 12%, concept design, assistance with neutron scattering measurements, manuscript editing.	a) N b) N c) N
4	Increasing surface activity and foaming of dilute perfluorooctanoate solutions by addition of organic amines.	Submitted	80%, experimental design and execution, data analysis, manuscript drafting	a) S. Blundell, 10%, assistance with HPLC/MS measurements. b) R. F. Tabor, 10%, concept design, manuscript editing.	a) N b) N

I have renumbered sections of submitted or published papers in order to generate a consistent presentation within the thesis.

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I hereby certify that the above declaration correctly reflects the nature and extent of the student's and co-authors' contributions to this work. In instances where I am not the responsible author I have consulted with the responsible author to agree on the respective contributions of the authors.

Main Supervisor name: Rico F. Tabor

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Date: 30th June 2021

Acknowledgements

First and foremost, I would like to thank my supervisor Rico Tabor. This has been a long journey and without his tireless support and unending patience over the years this work would not have been possible. Through the ups and downs Rico's optimism and enthusiasm were constant and his insights and encouragement always found ways to keep me going. The amount I've learned through his knowledge and expertise goes beyond the work in this thesis and I'm grateful I have had the opportunity to work in the Soft Materials and Colloids (SMaC) group.

I would like to acknowledge support of the Bragg Institute at the Australian Nuclear Science and Technology Organisation (ANSTO), whose facilities were used for neutron scattering experiments. Thanks to Chris Garvey, Anna Sokolova and Liliana de Campo at ANSTO for their technical expertise and insightful conversations. Thanks also to Tam Greaves and Scott Blundell for their assistance in my published and submitted works included here, your contributions are greatly appreciated.

To my fellow SMaC members past and present, thanks for all the support along the way and countless helpful discussions. Special mention to group members who contributed to the success of our neutron scattering trips to ANSTO, especially Tom McCoy and Mark Vidallon for their time spent helping on the beamline during key experiments.

This research was supported by an Australian Government Research Training Program (RTP) Scholarship and I acknowledge the financial support of 3M Corporation Australia provided through the Monash GRIP Program. Thanks to the School of Chemistry and all the staff and fellow students who supported me through my candidature.

Finally, I would like to acknowledge the support and encouragement from my family over all the years that brought me here, especially my parents Angela and David, my brother Thomas and my grandfather Ellis. Thanks for keeping me on track and encouraging me through all stages of my learning. Most importantly, special thanks to my amazing partner Louise, for always believing in me. Your selfless support from beginning to end made this possible.

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List of commonly used abbreviations

DPPC	1,2-dipalmitoyl- <i>sn</i> -glycero-3-phosphocholine
NaPFO	Sodium perfluorooctanoate
PFAS	Per- & poly- fluorinated substances
PFO	Perfluorooctanoate
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctane sulfonate
POPC	1-palmitoyl-2-oleoyl- <i>sn</i> -glycero-3-phosphocholine
POPS	1-palmitoyl-2-oleoyl- <i>sn</i> -glycero-3-phospho-L-serine (sodium salt)
SANS	Small angle neutron scattering
USANS	Ultra small angle neutron scattering

Chapter 1

Introduction

1.1 Introduction

1.1.1 Surfactants

Structure and chemistry

Surfactants (surface-active agents) are amphiphilic molecules made up of both hydrophilic and hydrophobic segments, consisting of a hydrophobic chain (tail) bonded to a hydrophilic head group. These contrasting portions give the molecules an affinity for both polar and non-polar materials, but mean they will not be entirely solvated by either highly polar or non-polar liquids. The “surface-active” part of their name refers to their tendency to accumulate at interfaces for this reason; in water the hydrophobic tail avoids interactions with water by locating at or within a more favourable environment such as air, oils, solids or aggregating with other surfactant molecules. This gives surfactants properties that are widely exploited in a variety of areas: they reduce the surface tension of water, which is useful for foaming and wetting of liquids on solids. They can stabilise oil/water interfaces to produce emulsions or solid/water interfaces to disperse particulates. At high concentrations the aggregates that form in solution can be useful as rheology (flow) modifiers for aqueous dispersions.

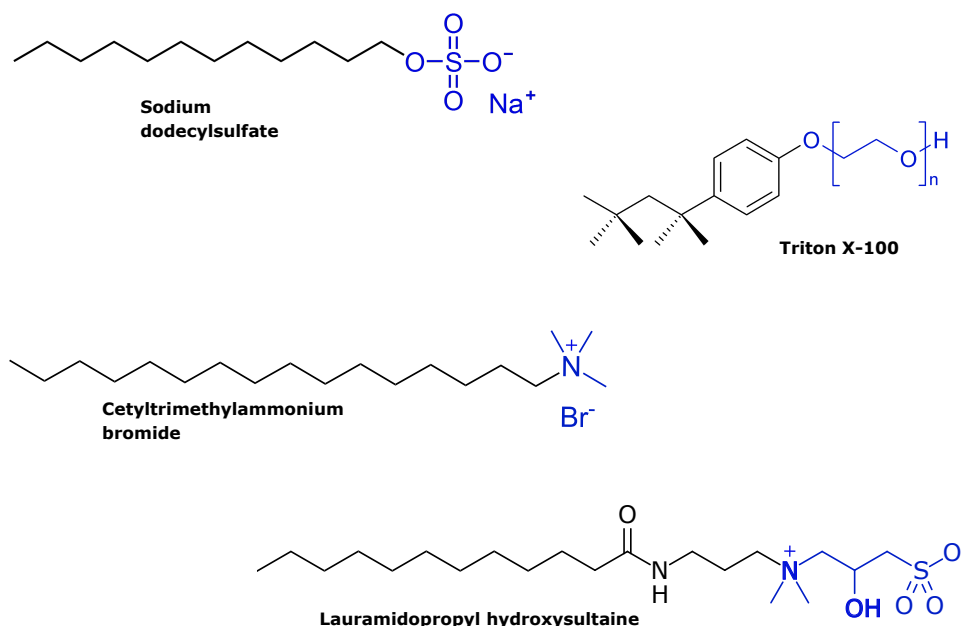


Figure 1.1 Examples of some common surfactants used in consumer products from each head group class. The hydrophilic head groups are highlighted in blue.

Structurally, surfactants are incredibly diverse with many different functionalities represented.¹ Because the tail groups are (generally) very similar, surfactants are more commonly classed based on their head groups, which can be either ionic (cationic or anionic), non-ionic or zwitterionic. Ionic surfactants tend to be more hydrophilic so have better water solubility, but can be less effective in the presence of other dissolved salts, while non-ionic surfactants are more resilient to a variety of aqueous conditions but are generally less hydrophilic. While chemically similar, differences in tail length and branching can provide even more variations to surfactant molecular properties. Variations in structure and chemistry can be used to tailor surface activity for different applications. Larger hydrophobic regions are favoured for emulsification of oils (as found in lecithins or sorbitan monooleate) while smaller ionic surfactants such as sodium dodecylsulfate are commonly encountered as detergents and foaming agents in many consumer products. Although the most commonly encountered surfactants utilise hydrocarbon-based tail groups, there are two important exceptions: the silicone and fluorocarbon surfactants. Silicones incorporate siloxane groups into their hydrophobic chain; fluorocarbons are organic molecules where hydrogen atoms have been totally or partially replaced with fluorine atoms. These are more specialized surfactants, being harder and more

costly to produce but with greater tolerance to aggressive physical or chemical conditions. Fluorosurfactants are the main focus of this thesis and are discussed in more detail in subsequent sections.

Surface activity and adsorption

The most prominent property of surfactants is their ability to reduce the interfacial tension between immiscible phases. Interfacial tension (or surface tension) is the force holding an interface together and arises from the unequal interactions experienced by molecules at the interface and can be equally thought of as a surface Gibbs free energy.^a The tendency for surfactants to adsorb at interfaces is a thermodynamic effect driven by the unfavourable interactions of part of the molecule with the solvent or substrate.² In water, the hydrophobic tails will organise themselves to minimise the unfavourable interactions with the solvent once the molecular solubility is exhausted. Initially the most favourable interface is the liquid/air interface and the molecules will adsorb there with their hydrophobic portion in air and their hydrophilic region remaining solubilised in the aqueous phase. These more hydrophobic molecules disrupt intermolecular bonds between water molecules at the interface which results in reduction of surface tension of the liquid. Surface tension will decrease until the surface is saturated with surfactant molecules.

This process creates an interface that is enriched in surfactant; the concentration of surfactant in the layer at the interface is above that in the bulk solution. This is called the surface excess concentration and is calculated from the Gibbs adsorption isotherm using the equation:

$$\Gamma = -\frac{1}{nRT} \left(\frac{\partial \gamma}{\partial \ln C} \right) \quad (1.1)$$

^aSurface tension can be defined using force or energy, with units of force per unit length (N/m) or energy per unit area (J/m²) respectively. The two expressions are equivalent but force units tend to be used to describe fluid interfaces, whereas energy units are more common in describing solid surfaces.

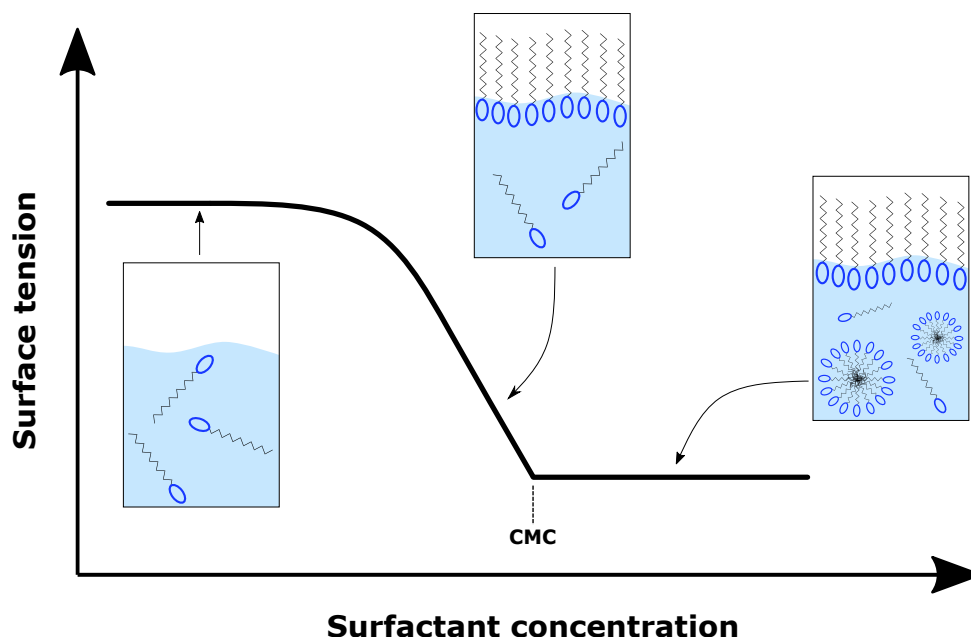


Figure 1.2 A representative plot of surface tension vs. concentration of a surfactant in water. Inset are schematic illustrations showing the change in solution behaviour of surfactant molecules as concentration increases. Taking the natural logarithm of concentration on the x axis allows for the slope approaching the cmc to be used to calculate the surface excess concentration using the Gibbs adsorption isotherm.

where Γ is the surface excess concentration, R is the gas constant, T is temperature, γ is the liquid surface tension and $\left(\frac{\partial \gamma}{\partial \ln C}\right)$ is the slope of the γ vs. $\ln C$ plot just prior to the critical micelle concentration. The factor n depends on the type of surfactant: for non-ionic surfactants $n = 1$ and for ionic surfactants $n = 2$. The critical micelle concentration represents the point at which the air/water interface has been saturated. After this point, additional surfactant molecules will aggregate with each other into micelles. These aggregates keep the hydrophobic portions interacting with each other while the hydrophilic head groups remain solvated (discussed in more detail below). After this point, surface tension remains unchanged as concentration increases, and additional surfactant molecules are incorporated into micelles. From analysing a plot of surface tension as a function of concentration for a given surfactant, the key parameters of critical micelle concentration and surface excess concentration can be determined.³

Aggregation in solution and soft matter phases

The large hydrophobic regions of surfactant molecules provide a strong thermodynamic drive to de-mix from an aqueous phase. From a thermodynamic perspective the solvation of large hydrophobic regions is unfavourable and at a certain concentration it becomes energetically favoured to form micelles. Micelles are molecular aggregates where surfactant molecules are organised such that their hydrophobic regions are minimising contact with water while their hydrophilic head group remains solvated (Figure 1.2). Although such supramolecular aggregates are entropically unfavoured at low concentrations, at higher concentrations there is a net increase in entropy arising from the release of water molecules solvating the surfactant tails on micelle formation.³ The point this energy balance is reached and surfactants begin to form micelles is the critical micelle concentration.

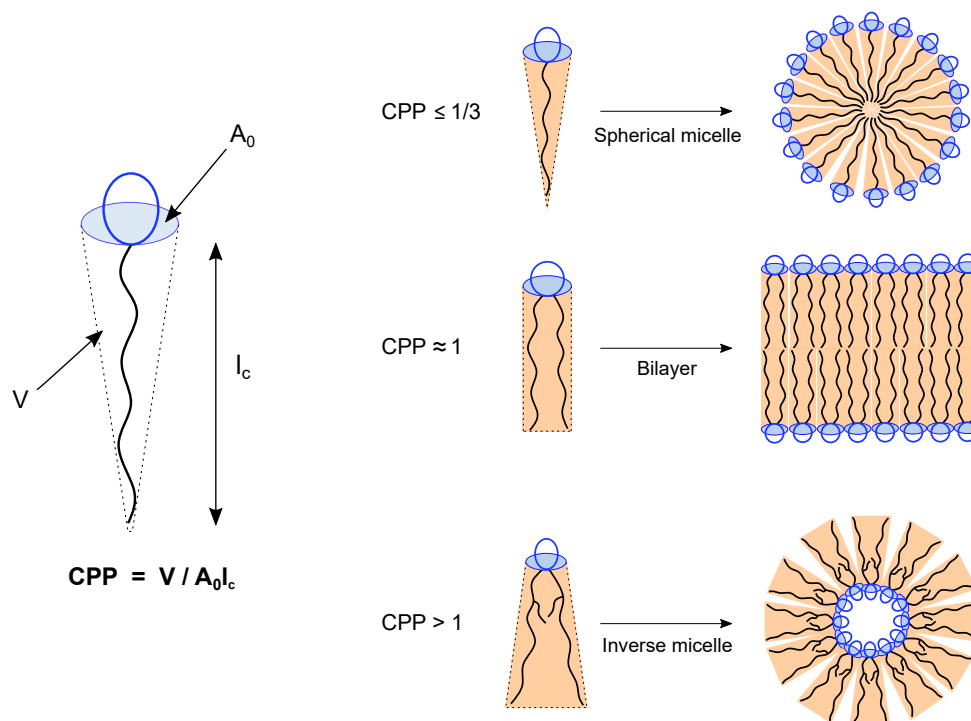


Figure 1.3 A visual representation of the critical packing parameter and its relationship to the geometry of surfactant aggregates. The CPP results in a favoured curvature of the packed structures ranging from spherical micelles through to inverse structures. When the ratio is 1 (a cylindrical molecule) bilayers are preferred (zero curvature).

Micelles (usually represented in spherical form) are the simplest type of surfactant assembly, but a variety of geometries and packing can be produced under different conditions. Together, these are referred to as *soft matter phases*: the aggregates resemble solid particles or surfaces but are only held together through the hydrophobic interactions of the surfactant tails. They are dynamic, self-assembled structures that can readily break and re-form. The type of aggregates observed in a system is determined by a number of factors (such as concentration, temperature and amount of dissolved salts) but shape of the surfactant molecules provides favoured packing arrangement. This is represented using the critical packing parameter⁴, CPP:

$$CPP = \frac{v}{a_0 l_c} \quad (1.2)$$

where v is the surfactant tail volume, l_c is the length of the tail and a_0 is the area per molecule at the surface of aggregates (this is dependent on the nature of the head group). This relationship describes a favoured degree of curvature in the aggregates formed (Figure 1.3); a larger head group size relative to tail volume favours high curvature structures such as spheroidal micelles, while bulkier chains or smaller head groups favour lower curvature interfaces such as bilayer structures. The packing parameter concept is not an accurate analytical tool due to the complexity of surfactant aggregation, but can be a useful guide for predicting and comparing surfactant behaviour in concentrated solutions.

1.1.2 Fluorinated surfactants

Properties and uses

Fluorinated surfactants (fluorosurfactants) are synthetic surfactants where hydrogen atoms in the hydrophobic carbon chain are replaced with fluorine atoms. The larger size and high electronegativity of the fluorine atom produces unique properties in the resulting compounds. The strength and low polarisability of the carbon-fluorine bond makes fluorocarbons extremely

stable but with very weak intermolecular forces.⁵ Fluorocarbons (e.g. perfluorohexane^b) tend to be much denser but more volatile than their hydrocarbon counterparts, while the strength of the carbon-fluorine bond renders them largely inert chemically and results in greater thermal stability. The low polarisability means they are not particularly susceptible to dispersion forces like hydrocarbon molecules, and therefore have the unusual property of being both hydrophobic and lipophobic.⁶ The fluoropolymer polytetrafluoroethylene (PTFE) is a widely known example of this behaviour and is now a common feature of non-stick appliances.

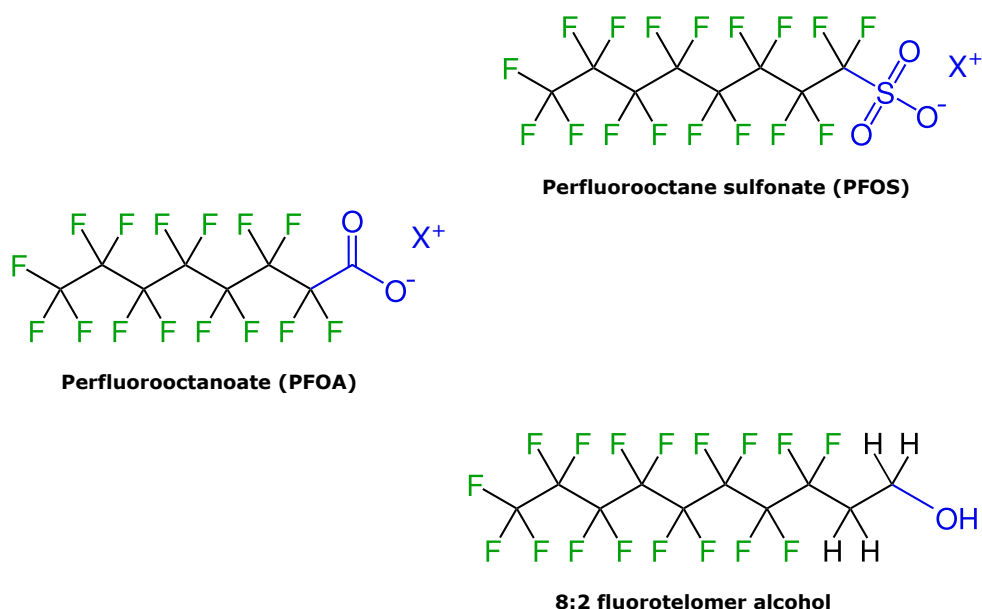


Figure 1.4 Examples of commonly (or historically important) fluorinated surfactants. For PFOS and PFOA, X^+ is most commonly NH_4^+ , Na^+ or K^+ . Fluorotelomer alcohols are the simplest form of fluoroelomers, there are a wide variety of reported ‘spacer’ hydrocarbon chains and head group combinations for specific applications.

Fluorinated surfactants are dispersible in water but retain these properties in their hydrophobic region. Because of the greater hydrophobicity of the fluorocarbon tail they are the most surface active of the surfactant classes. They lower aqueous surface tension more than any other type of surfactant with equivalent tail length and correspondingly are superior wetting agents.¹ Being surfactants they readily adsorb at interfaces and surfaces and are a prominent component of stain-repellent and water-proofing coatings. As coatings, they can create very low energy surfaces repelling both water and oils, and formulation into liquid

^bThe prefix *per*– is used to denote a compound where all hydrogens in the carbon chain have been replaced with fluorine.

sprays makes them more widely applicable than PTFE coatings. Between the two types of compounds, their use in coatings is arguably the application that is most commonly encountered. They are also used as additives in other functional coatings such as paints or lubricants to aid wetting, ensuring a consistent and even film formation on a wide variety of surfaces.

Fluorosurfactants are also utilised in the production of PTFE through emulsion polymerisation as they solubilise fluorocarbon monomers more effectively than other surfactants and stabilise the resulting polymer particles, which are insoluble in practically all solvents.⁷ Fluorosurfactants were also included as a key ingredient in aqueous film forming foam (AFFF) and film-forming fluoroprotein foams (FFFP) used in firefighting, particularly for fires involving large amounts of hydrocarbon fuels.^{8,9} The mixture of hydrocarbon and fluorocarbon surfactants in these foams allows for the formation of an aqueous film over the hydrocarbon fuel, which is only possible due to the exceptionally low surface tension provided by aqueous fluorosurfactants. Such foams were widely distributed and used in areas where large fuel based fires were possible, such as airfields or fuel production sites. Other smaller industrial uses are in specialty cleaning fluids (e.g. in electronics), enhanced oil recovery and electroplating.⁹

Many industries are moving away from the use of fluorinated surfactants, especially longer chain (C8 - C10) perfluorinated surfactants and many of these applications are either less widespread or undergoing a compositional shift in their ingredients. Production of the two most common perfluorosurfactants historically, perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) and their derivatives, has been phased out in the western world due to health concerns. Shorter chain surfactants or more functionalised molecules such as perfluoro-polyethers (PFPEs) are often seen as having a lower environmental impact, although this is still under investigation. The inclusion of perfluorinated surfactants is generally considered with more caution for dispersive applications than it was in the past and therefore many industries are adapting accordingly.

Problems and remediation

Many fluorinated surfactants are now considered chemicals of concern internationally, along with a variety of similar compounds under the umbrella of per- and poly- fluorinated substances (PFAS).¹⁰ This classification is used to cover the large range of chemicals used in various applications that include fluorinated organic carbon chains. Perfluorocarbons without additional functionality (e.g. perfluorohexane or PTFE) are biologically inert and insoluble in aqueous systems and so present relatively low risks to health. Because of this the recognition of potential effects of fluorinated surfactants was slow, and they were used relatively indiscriminantly for decades. There is now growing evidence of a variety of negative health outcomes from exposure to fluorinated surfactants and other functionalised derivatives.^{11–13} Because of their water-solubility, surfactants are the most problematic of these chemicals, due to the combination of being used in more dispersive applications and their mobility in the environment when released.^{14,15}

The relative inertness of fluorosurfactants, while useful for many applications, is the main reason these materials are now considered problematic. Although not acutely toxic, their inertness means they are practically non-biodegradable and persist in the environment leading to potentially prolonged exposure. As persistent organic pollutants they are prone to bioaccumulation and have relatively long half-lives in biological systems, but the magnitude of these effects is not consistent across the class. Longer and less functionalised perfluorocarboxylic acids and sulfonates are the chemicals of most concern, partly due to being those produced and used in the largest volumes. PFOS (in 2009) and PFOA (in 2019) are now included in the Stockholm Convention on Persistent Organic Pollutants, although exemptions for some uses remain.¹⁶ Other compounds are still in use however, as are many fluorotelomers (molecules where a hydrocarbon ‘spacer’ group has been added between the head group and fluorinated tail). Because the properties of fluorosurfactants are indispensable in many applications, most industries are adapting to fluorinated compounds with a lower environmental impact, although the safety and potential impacts of many compounds is still not conclusively known.

The need for remediation and treatment of contaminated materials is now greater than ever. Even though there are now tighter regulations governing the use and containment of waste material, the use of fluorinated surfactants is continuing. Furthermore, due to their persistence in the environment there are now many sites where historical contamination is still an issue, such as around chemical production sites or areas with large-scale use of fluorinated firefighting foams.¹⁷ Contamination in water sources is particularly problematic as soluble compounds inevitably end up in wildlife and people,¹⁴ either through direct or indirect contact. Remediation of such sites is difficult and where it is attempted currently relies on adsorption-based processes to remove PFAS from water sources. Use of activated charcoal is a common option,^{18,19} but ion-exchange resins provide greater efficiency and can also be utilised.²⁰ Whatever substrate is used, treatment of large volumes through filtration is a costly and time-consuming process. Understanding the surface chemistry and unique properties of fluorinated surfactants is essential both for improving the efficiency of existing remediation processes and developing new ones, and most research on the topic historically has not been focussed in such a way.

1.1.3 Project aims and scope

This project aims to further understanding of the physical chemistry of perfluorinated surfactants, specifically focusing on effects of hydrophobic ions on the surface activity and aggregation of aqueous fluorinated surfactants and the interactions of fluorinated surfactants with other hydrocarbon surfactants and lipids. These are investigated using a fundamental approach with direct measurements of surface activity through a variety of methods combined with modelling of surfactant aggregation using Small Angle Neutron Scattering (SANS) to cover multiple aspects of the surfactant properties. Perfluorooctanoate is largely used throughout for these studies due to its prevalence and simple structure. Initial studies analysing surfactant interactions with hydrophobic organic ammonium ions are then broadened to determine how these interactions can be used to increase efficiency of remediation processes

by increasing surface activity of the fluorinated surfactants. Interactions with hydrocarbon surfactants and changes in aggregation are interpreted from a similar perspective and then extended to determine the effects of fluorinated surfactants on model cell membranes composed of representative lipid bilayers.

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Chapter 2

Literature Review: Interactions of fluorinated surfactants with ions and hydrocarbons – Effects on surface activity and aggregation

2.1 Introduction

The effects of different ions on the properties of dissolved substances has been a subject of research for well over 100 years and shows up in many diverse fields. While increasing ionic strength of solutions will generally result in changes to solution behaviour, ion-specific effects refer to differences in outcomes for similar ionic strength solutions with different ionic species. The classic example is the work Hofmeister^{1,2} which produced a now well-known series on ion-specific effects in protein coagulation. More recently, much work has gone into providing greater theoretical understanding of the ion-specific effects observed in various fields, although the complicated nature of the interactions responsible has made it a difficult task, and empirical studies still provide useful insights to specific classes and interactions. It is now acknowledged that the effects of ions are largely a product of differences in solvation between ions which affects how they interact with various substrates^{3,4} and interfaces^{5,6}.

Surfactants (especially ionic surfactants) are an interesting case as there are many as-

pects of their behaviour that can be influenced by changing salt concentrations. Solubility and hence surface activity are affected like other organic species, but other important properties such as foaming⁷, aggregation and emulsification are subject to variation at different ionic strengths. Having both hydrophilic and hydrophobic regions adds another dimension as larger, more hydrophobic ions can interact with either. This can be seen in larger simple ions such as Cs^+ or I^- that are less strongly hydrated and often considered to have a hydrophobic character⁷, and extended to more classically hydrophobic charged organic species such as protonated or quaternary ammonium species.⁸ Fluorinated surfactants have an additional complication as the hydrophobic tail also has lipophobic properties.⁹ This creates an interesting balance when combined with hydrocarbon species in solution between the mutual negative interactions with water and negative interactions with each other.

Fully cataloguing the variety and complexity of such systems could produce many reviews from the available literature. This review will focus on the interactions of fluorinated surfactants with dissolved ions, both inorganic and organic. The main focus will be on changes to surface activity and aggregation, and particular attention is paid to the commonly used fluorinated surfactant perfluorooctanoate which is a prominent feature of this thesis. A small section is included highlighting implications for the remediation of fluorinated surfactant species, although this is not comprehensive. The aim is to contextualise the current state of the literature with some insight into how these effects impact the behaviour of ionic fluorosurfactants in the environment and remediation processes. Currently, remediation of fluorosurfactant contaminated water relies heavily on the surface activity of species present through adsorption processes, and finding ways to enhance adsorption would increase the effectiveness of these remediation methods.

2.1.1 Anionic Fluorinated surfactants

Fluorinated surfactants are found in many applications due their superior surface activity and chemical stability compared to hydrocarbon counterparts, as well as their lipophobicity

and affinity for other fluorocarbon oils and polymers.⁹ Anionic perfluorinated alkyl sulfonates and carboxylates are the simplest and oldest of the fluorinated surfactants and historically the most widely used.^{10,11} These surfactants range from C4 to C10 carbon chains, with the most common examples being the C8 surfactants perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS) and their salts. Their simple structure and synthesis¹² also makes them the most chemically stable and simplest to produce. Over time, many different surface active fluorinated compounds were developed^{10,13,14} but PFOA and PFOS remained prominent until health and environmental concerns in the late 2000s led to a reduction in usage. Even with the phasing out of production in many areas, their lack of biodegradation¹⁵ (and potential renewal through breakdown of fluorotelomers¹³) means they are likely going to be chemicals of concern for some time with a lot of attention now on their effects on the environment and remediation.

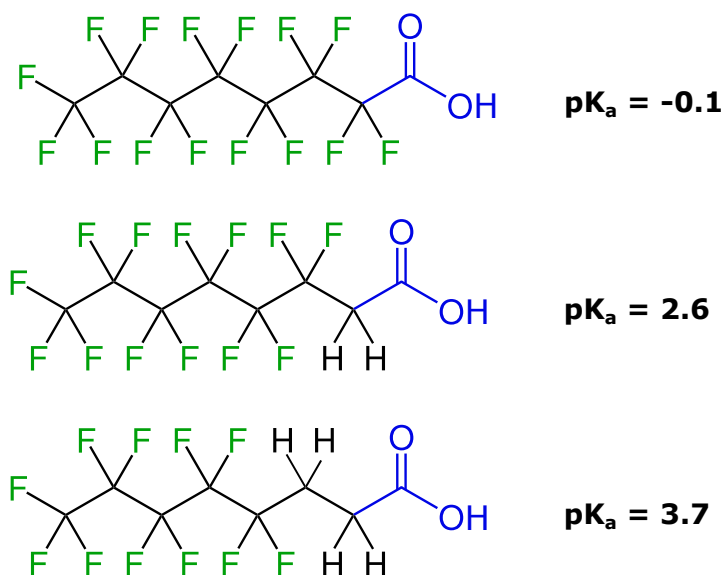


Figure 2.1 Ideal pK_a values of perfluorinated carboxylic acids such as PFOA (top) are much lower than typical carboxylic acid groups due to the electronegativity of fluorine atoms. pK_a values are taken from Goss¹⁶ and calculated theoretically. In more concentrated solutions this is not realistic, as protons are poorly dissociated from PFOA micelles. The presence of hydrogen atoms between the carboxylic acid group and fluorine atoms reduces this effect.

These anionic fluorosurfactants have the characteristic surface activity of fluorosurfactants, being able to reduce the surface tension of water to below 20 mN/m due to the weak intermolecular forces of the fluorocarbon tail.^{17,18} As fluorines are highly electronegative

and electron withdrawing, they are much more acidic molecules than comparable hydrocarbons.^{16,19} The carboxylic acids are particularly notable, with pK_a values either below or close to zero for normally weak carboxylic acids.¹⁶ This isn't seen even in ionic fluorotelomer surfactants, with addition of hydrocarbon spacer groups between the head group and fluorocarbon tail reducing this effect. PFOA has a calculated pK_a of -0.1, adding a $-CH_2$ adjacent the acid group increases this to 2.6 and $-C_2H_4-$ to 3.7 (Figure 2.1).¹⁶ However, there is a marked difference in dissociation before and after the cmc for PFOA²⁰ and in the micellar form, dissociation is low and higher values have been quoted.^{16,21} This effect is less prominent in the sulfonic acid surfactants since these are already quite strong acids relative to carboxylic acids. Being ionic, these fluorosurfactants still retain many properties in common with other ionic surfactants. Electrostatic interactions still play a large roll in their functionality²² and they have similar interactions with other simple hydrotropes such as urea^{23,24}.

Above the cmc, aggregation behaviour is different from hydrocarbon surfactants. The fluorine atoms have a much larger size than hydrogen atoms which creates a much bulkier tail group. Furthermore, because of the increased hydrophobicity in fluorosurfactants, their tail groups are considerably shorter than typical hydrocarbon surfactants. This produces much shorter and 'blockier' tail groups which, combined with relatively small head groups, increases the critical packing parameter and hence makes lower curvature aggregates more favourable.^{17,25} Simple anionic fluorosurfactants such as PFOA and PFOS are exemplary in this respect, as they lack hydrocarbon spacer groups that are present in fluorotelomer surfactants. In practice the behaviour is not as dramatic as theory would imply, and spherical micelles (which are high curvature structures) are common for PFOA²⁶⁻²⁸ and PFOS salts²⁹ in dilute solutions. However, the phase diagrams of these salts often have a prominent lamellar phase at lower concentrations than is seen in comparable hydrocarbon surfactants (where they often do not show one at all). For example, in ammonium perfluorooctanoate the transition to a lamellar phase occurs between 40-45 %wt,^{27,30} whereas sodium dodecyl sulfate doesn't form a lamellar phase in solution at all under ambient conditions, only being seen

at 75 %wt and 50°C,³¹ and in its hydrated crystal structure. As with surface activity however these properties are affected by electrostatic interactions. In both cases specific (and non-specific) ion effects play an important role in their behaviour.

2.2 Specific ion effects in fluorinated surfactants

2.2.1 Physical properties and surface activity

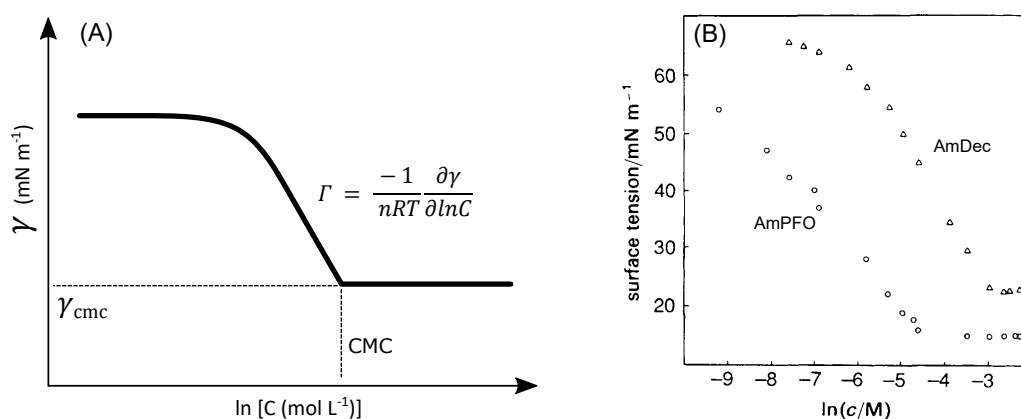


Figure 2.2 (a) The surface excess concentration can be determined from a plot of surface tension (γ) vs. the natural log of surfactant concentration using the Gibbs adsorption isotherm. (b) experimental data for ammonium perfluorooctanoate (circles) and ammonium decanoate (triangles) in 0.1 M NH₄Cl/NH₄OH buffer, taken from Simister *et al.*³².

Ion specific effects in ionic surfactants can be observed in many properties and measured in a number of ways. Increasing the ionic strength of a solution will have an effect on the behaviour of ionic surfactants regardless of the specific ions present; the presence of electrolytes provides a greater degree of bulk screening as well as a larger quantity of counter charges to interact with the ionic head group. This reduces the effective charge on the head group which can reduce solubility and increase surface activity and fluorinated surfactants are prone to this like other ionic surfactant classes.³³ For example, the cmc of ammonium perfluorooctanoate is reduced to 11 mM in a 0.1 M NH₄Cl/NH₄OH buffer,³² compared to 25 - 30 mM when measured in pure water (Table 2.1). ‘Specific ion effects’ refers to differences in behaviour in the presence of different ions at comparable conditions and should be differentiated from these

general electrostatic interactions. This requires a comparative approach to be meaningful, and usually a commonly encountered and well-dissociated form of the surfactant is used as a benchmark.

Table 2.1 Table showing the parameters of the fluorosurfactant perfluorooctanoate and perfluorooctane sulfonate with simple monovalent counterions. Values are at 25 °C unless otherwise noted.

Counterion	cmc (mM)	γ_{cmc} (mN.m ⁻¹)	Γ_{cmc} (mol.m ⁻²)	Krafft temp. (°C)
PFOA				
H ⁺	9 ³⁴ , 10.5 ³⁵ , 9.6 ²⁰	15.2 ³⁶		20 ³⁴
NH ₄ ⁺	33 ³⁴ , 26 ³⁷ , 28.0 ³⁸ 27.2 ⁴⁰ , 26.5, 24.5 ²³	20.5 ³⁹ 18 ²³	3.46 × 10 ⁻⁶ ³⁹ 2.6 × 10 ⁻⁶ ²³	2.5 ³⁴
Li ⁺	31.1 ⁴¹ , 31 ⁴² , 31.7 ⁴³ 34.1 ²⁰ , 33.4 ⁴⁵ , 30-31 ⁴⁶		4.5 × 10 ⁻⁶ ⁴⁴	<0 ³⁴
Na ⁺	36 ³⁴ , 31 ⁴⁷ , 30.6 ²⁰ 25.00 ⁴⁸ , 36 ⁴⁶ 31.3 ⁴⁹ , 30 ⁵⁰ 30.6 ⁴⁵ (30°C)	24.6 ³⁶ 22.6 ⁴⁸ 25 ⁵⁰	5.4 × 10 ⁻⁶ ⁴⁴ 4.07 ⁴⁸ × 10 ⁻⁶	8 ³⁴ 8.8 ⁴⁹
K ⁺	27 ³⁴ , 28.4 ⁴⁵ 27 ⁴⁷ (35°C)	20.6 ³⁶	8.8 × 10 ⁻⁶ ⁴⁴	25.6 ³⁴
Rb ⁺	28 ³⁴		8.6 × 10 ⁻⁶ ⁴⁴	20.2 ³⁴
Cs ⁺	24 ⁵¹ 23.4 (20°C) ⁵²	18 (20°C) ⁵²	8.4 × 10 ⁻⁶ ⁴⁴ 3.6 × 10 ⁻⁶ (20°C) ⁵²	<0 ³⁴ 6.9 ²⁸
PFOS				
H ⁺				<0
NH ₄ ⁺	5.5 ³⁶	27.8 ³⁶		41 ³⁶
Li ⁺	6.3 ³⁶	29.8 ³⁶		<0 ³⁶
Na ⁺	8.5 ³⁶	40.5 ³⁶		75 ³⁶
K ⁺	8.0 ³⁶	34.5 ³⁶		80 ³⁶

The most prominent and ‘obvious’ measure is the solubility of ionic surfactants with different counterions in the absence of any other influences. Commercially, the choice of what counterion a surfactant is produced with is usually a trade off between ease of preparation, cost and performance.⁵³ Usually one counterion is predominantly paired with a given surfactant, for example sodium with dodecyl sulfate and alkylbenzene sulfonate surfactants. Fluorinated surfactants have a little more variability being specialty surfactants: perfluorooctanoate

is often encountered as either the sodium or ammonium salt commercially.

The property that has the greatest effect on the practical applications of a surfactant is the Krafft temperature. The Krafft temperature is defined as the temperature where a surfactant's solubility equals the critical micelle concentration.²² Below the Krafft temperature, the solubility of the surfactant is too low for micelles to form which severely limits its usefulness in most applications. Table 2.1 shows surfactant properties of PFOA and PFOS with common hydrophilic ions (alkali metals and ammonium) and it is readily apparent that Krafft temperature is the property most affected by changing surfactant counterion. For PFO, the value ranges from below 0 °C for Li^+ up to 25 °C for K^+ , with an interesting trend in the alkali metal counterions around a maximum value: $\text{Li}^+ < \text{Na}^+ < \text{K}^+ > \text{Rb}^+ > \text{Cs}^+$. Li^+ is the smallest, and most strongly hydrated ion of the series, with Cs^+ being less hydrated, which results in Li^+ having the largest *hydrated* ionic radius and Cs^+ having the smallest.^{54,55} Unfortunately there is no data for PFOS with the heavier counterions Rb^+ and Cs^+ but it is likely an effect of the thermodynamics of hydration of the cations and a similar trend would be continued for PFOS. Although a full analysis of this aspect is beyond the scope of this review, a higher Krafft temperature represents a more stable crystalline form and less favourable dissolution. The effects of divalent metals such as Mg^{2+} or Ca^{2+} in hard water on surfactants is well known due to the formation of soap scum, and this phenomenon occurs via the same mechanism: the resulting salts have a higher Krafft temperature and hence low solubility at ambient conditions.⁵⁶

Cmc values and surface tension at cmc are less affected by a change in counterion. Interfacial behaviour and thermodynamic drive towards micellisation are largely due to the properties of the surfactant ion itself⁵⁷ once dissociated. The Krafft temperature is a good representation of this behaviour; below the Krafft temperature the surfactant remains mostly insoluble, rather than experiencing any reduction in cmc. Because PFOS is more hydrophobic than PFOA (having an extra $-\text{CF}_2-$ group) cmcs are lower and Krafft temperatures generally higher than PFOA derivatives, but much like PFOA, Krafft temperature is quite varied while

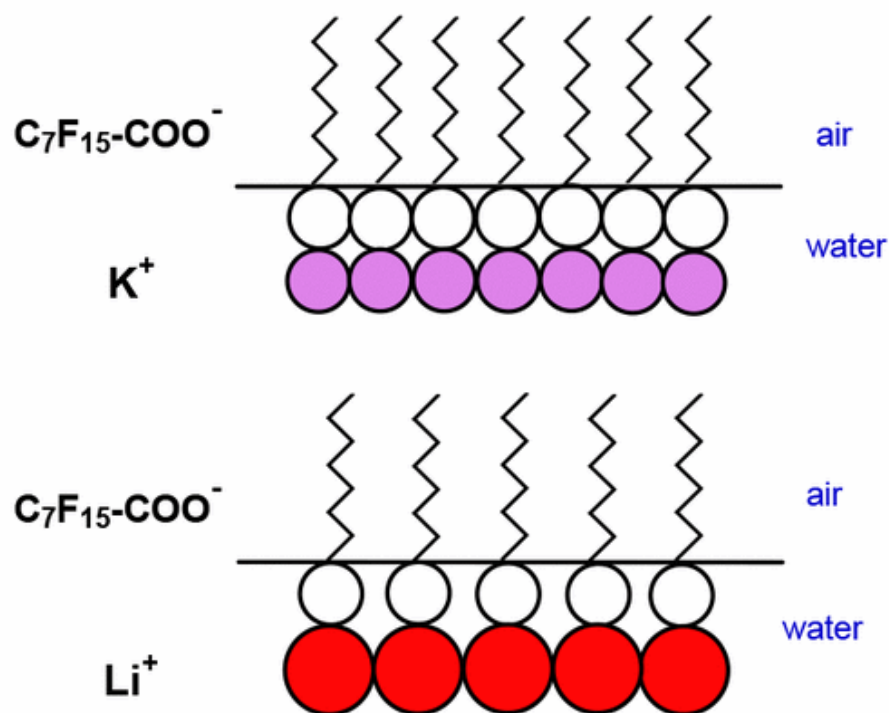


Figure 2.3 Possible ion effects on surfactant packing at the interface as proposed by Lunkenheimer *et al.*⁴⁴ The larger hydrated ionic radius of Li^+ makes packing of molecules at the interface slightly less efficient as fewer counterions can be fit across the aqueous layer with the surfactant head group. The trend of values in Table 1 increasing and decreasing around the potassium salt is therefore possibly due to an equivalence in head group and counterion size for PFO.

cmc remains reasonably consistent. Data for the heavier alkali metals caesium and rubidium is also less prevalent as they are rarely encountered in a practical setting, and not elements that feature prominently in the environment which might limit the value of any correlations. It is worth noting that measured cmc values can be influenced by the measurement technique used. The values compiled here range from early works to recent reports, therefore some variations would be expected. The effects of impurities on measurements, especially surface tension measurements, has been noted in fluorinated surfactants due to the electrofluorination process producing significant amounts of branched isomers as byproducts.⁵⁸

It has been noted that the binding strength of counterions decreases with hydrated radius from Cs^+ to Li^+ , a trend which is seen in both PFO⁵⁹ and in alkylsulfate hydrocarbon surfactants.^{60,61} Similarly, other work with hydrocarbon surfactants has supported the view

that counterions that interact less strongly with water are better at promoting micellisation⁶² likely due to less dissociation of head group and counterion. Where surface excess concentration has been studied, there is a clear inverse relationship between hydrated ionic radius of the cation and surface excess concentration of surfactant at the air/water interface, with less variation for heavier alkali metal counterions with PFO.⁴⁴ PFO with K^+ , Rb^+ and Cs^+ produces surface excess concentrations between $8 - 9 \times 10^{-6} \text{ mol}\cdot\text{m}^{-2}$ ($r_{hyd} = 230 - 240 \text{ pm}$), which drops down to $5.4 \times 10^{-6} \text{ mol}\cdot\text{m}^{-2}$ for Na^+ ($r_{hyd} = 275 \text{ pm}$) and further to $4.5 \times 10^{-6} \text{ mol}\cdot\text{m}^{-2}$ for Li^+ ($r_{hyd} = 340 \text{ pm}$). It is worth noting that the maximum value is for the potassium salt as in other properties, although the difference between K^+ , Rb^+ and Cs^+ is small. It is proposed⁴⁴ that the maximum adsorption is related to the size of the counterion, as an equivalence in cross-sectional area between the surfactant and hydrated counterion promotes more efficient packing of surfactant molecules at the interface (as shown in Figure 2.3). Although not discussed in that work, this could be a reasonable hypothesis for the variation in Krafft temperature as well, since this would also imply more efficient packing in a crystal structure which would produce a higher entropic barrier to dissolution due to the stronger cation-anion interactions.

2.2.2 Aggregation and phase behaviour in solution

The aggregation of fluorinated surfactants is known to favour lower curvature interfaces compared to their hydrocarbon counterparts due to their bulkier hydrophobic tail.^{17,63} Although the lamellar phase is prominent in the phase diagrams of most PFOA salts, it is not as dominant as the critical packing parameter might imply. At commonly encountered concentrations, soluble PFOA salts tend to form spheroidal micelles and lamellar phases are encountered only at higher concentrations.^{26,64} Being ionic, dissociation produces a charged head groups which have a mutual electrostatic repulsion due to the like charges. The result is that *relative* head group size is larger than the physical size in solution, and this repulsion drives the curvature observed in dilute micelles for species such as LiPFO and AmPFO. Nevertheless, the lamellar

phase is still more notable in the phase diagrams of some of these species than in comparable hydrocarbon surfactants (Figure 2.4). The lamellar phase is present in LiPFO (at 65%wt)²⁶, AmPFO (at 40-45%wt)^{27,30,64,65} and CsPFO (at 40%wt).^{28,55,66-68} In RbPFO, only a nematic phase (a loosely ordered transition region between isotropic micellar and lamellar) is observed at standard conditions although reports are conflicting, possibly indicating a narrow stability window.^{69,70} Only an isotropic micellar region is present otherwise. Neither lamellar nor nematic regions are reported for either NaPFO or KPFO, which is interesting considering the trends observed in Table 2.1.

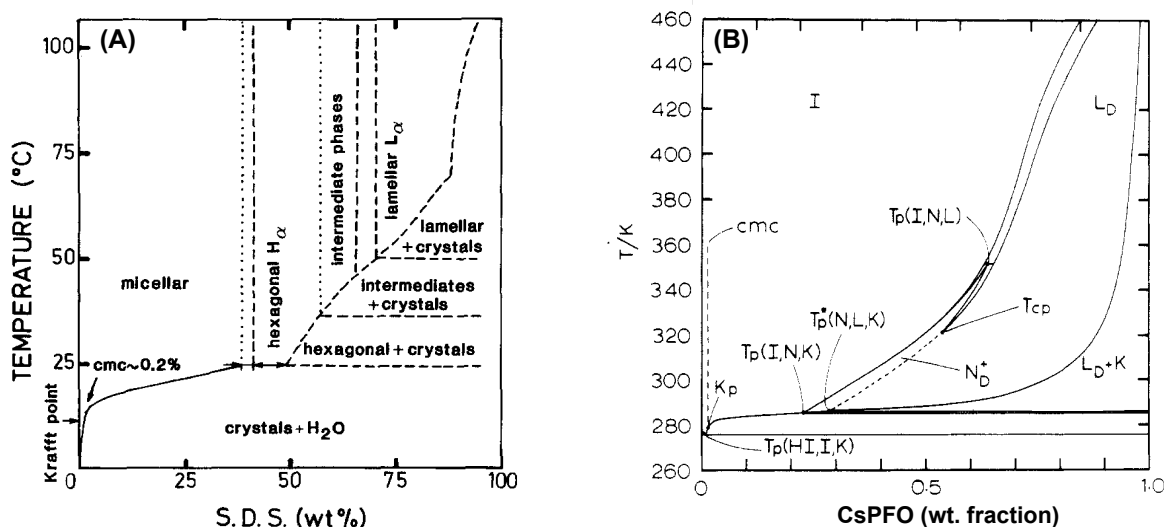


Figure 2.4 (a) The phase diagram for sodium dodecyl sulfate in water, taken from Kekicheff *et al.*³¹. The lamellar phase isn't encountered at standard conditions. Compared this to CsPFO (b) where the lamellar phase forms after the isotropic micellar region with a transitional nematic phase. Data taken from Boden *et al.*²⁸ with some labels adjusted for clarity. In this plot I: isotropic micellar phase, L_D: lamellar phase, N_D discotic nematic phase, K_p indicates the Krafft point and T_p indicates various triple points at phase boundaries.

Although data is not extensive on this topic, it seems greater hydrated ionic radius promotes higher curvature interfaces in PFO micelles, when other factors are equal. LiPFO is the only species that shows a phase other than micellar or nematic/lamellar with a prominent hexagonal micellar region in its phase diagram²⁶ and higher onset of the lamellar phase than in the other PFO species. This concurs with a SANS investigation on aggregate structure⁵⁷, with LiPFO producing higher curvature prolate spheroids in dilute solution which transition

through spherical for AmPFO and NaPFO and slightly oblate spheroids for RbPFO at comparable concentrations. Although data is limited, it is possible that a similar mechanism to the effects seen at interfaces is occurring in aggregation, with the higher ionic radius less effective at shielding head group charge and hence a slightly higher curvature is favoured. However, the fact that a lamellar phase forms for LiPFO but not NaPFO or KPFO would be in contradiction to this theory. More data on the complete phase diagrams of these species is needed in order to be more conclusive. Adding additional electrolytes to solution can reduce this effect by providing additional shielding, even when the counterions are the same. In AmPFO, rod-like micelles are formed in an $\text{NH}_4\text{Cl}:\text{NH}_4\text{OH}$ buffer,⁷¹ compared to the more spherical form found in pure H_2O solutions.⁵⁷

2.3 Hydrocarbon ions as surfactant counterions

Hydrocarbon-based ions as counterions are less commonly encountered in practical settings, but have been widely investigated in both fluorinated and hydrocarbon surfactants. For anionic surfactants they are typically organic ammonium derivatives, ranging from simple primary alkylammonium through to quaternary ions.⁸ These can result in a large range of hydrophobicity, from highly hydrophilic NH_4^+ through to quite hydrophobic quaternary species such as tetrabutylammonium ($(n\text{-Bu})_4\text{N}^+$). Physically, substituting more common, smaller and more hydrophilic counterions for these more diffuse and hydrophobic ones tends to lower the melting point⁷² of the surfactant, and can produce ionic liquids in some systems.^{73–78} Krafft temperature is correspondingly lower and often goes unreported in these systems. The surfactant properties of PFO with various substituted ammonium counterions are shown in Table 2.2. Compared to the common hydrophilic ions, there is substantially more variation in properties for surfactants in general as the counterion hydrophobicity increases. As noted in the previous section, physical differences between the common mono-valent alkali counterions are relatively small. For substituted ammonium derivatives there is much greater variety, with variations in both degree of substitution and length of carbon chain.

Table 2.2 Physicochemical parameters of the fluorosurfactants perfluorooctanoate (PFOA) and perfluorooctane sulfonate (PFOS) with organic ammonium counterions. Data is taken at standard lab conditions unless otherwise noted. Counterion association β is the fraction of ions not dissociated into the bulk solution and interacting with the surfactant head group at the micellar surface.* indicates values noted by authors as inaccurate due to low solubility.

Counterion	cmc (mM)	γ_{cmc} (mN·m ⁻¹)	Γ_{cmc} (mol·m ⁻²)	Counterion association (β)
PFOA				
NH ₄ ⁺	33 ³⁴ , 26 ³⁷ , 27.2 ⁴⁰ 28.0 ³⁸ , 26.5/24.5 ²³	20.5 ³⁹ 18 ²³	3.46×10 ⁻⁶ ³⁹ 2.6×10 ⁻⁶ ²³	0.60 ³⁷
(Me) ₂ NH ₂ ⁺	13.6 ⁷⁹	14.9 ⁷⁹	2.7×10 ⁻⁶ ⁷⁹	
(Et) ₂ NH ₂ ⁺	7.9 ⁷⁹	15.5 ⁷⁹	3.3×10 ⁻⁶ ⁷⁹	
(<i>n</i> -Pr) ₂ NH ₂ ⁺	6.6 ⁷⁹	23.3 ⁷⁹	2.5×10 ⁻⁶ ⁷⁹	
(<i>n</i> -But) ₂ NH ₂ ⁺	1.3 ^{79*}	29.3 ^{79*}	2.0×10 ⁻⁶ ⁷⁹	
(Me) ₄ N ⁺	7.2 ³⁵ , 12 ³⁷ 12.0 ³⁸ , 12.8 ⁴⁰ 15 ⁴⁷ (35°C)			0.75 ³⁷ 0.72 ³⁸
(Et) ₄ N ⁺	7 ³⁷ , 7.5 ⁴⁰ 8.9 ³⁸ , 7.19 ²⁰			0.79 ³⁷ 0.76 ³⁸
(<i>n</i> -Pr) ₄ N ⁺	4 ³⁷ , 4.7 ⁴⁰ 3.9 ³⁸			0.82 ³⁷ 0.81 ³⁸
(<i>n</i> -Bu) ₄ N ⁺	2 ³⁷ , 2.8 ⁴⁰ 2.1 ³⁸			0.90 ³⁷ 0.90 ³⁸
PFOS				
(Me) ₂ NH ₂ ⁺	2.8 ⁷⁹	16.4 ⁷⁹	2.6×10 ⁻⁶ ⁷⁹	
(Et) ₂ NH ₂ ⁺	1.4 ⁷⁹	15.2 ⁷⁹	3.0×10 ⁻⁶ ⁷⁹	
(<i>n</i> -Pr) ₂ NH ₂ ⁺	0.76 ⁷⁹	23.2 ⁷⁹	2.1×10 ⁻⁶ ⁷⁹	
(Me) ₄ N ⁺	1.2 ⁸⁰			
(Et) ₄ N ⁺	1.0 ⁸⁰ 0.98 ⁸¹	21.7 ⁸¹	5.51×10 ⁻⁶ ⁸¹	

The variation in counterion properties makes direct comparisons to data in the previous section difficult, but there are some interesting similarities. Looking at the surface excess concentration, the diethylammonium salts of both PFOA and PFOS are a local maximum in the set of secondary ammonium ions (at 3.3×10⁻⁶ and 3.0×10⁻⁶ mol·m⁻² respectively),⁷⁹ with lower values for the dimethylammonium and dipropylammonium salts. This might indicate an ‘ideal’ counterion size for efficient packing at the interface similar to the alkali metals discussed in the previous section. It also appears that smaller ions produce lower surface tension values.⁷⁹ The surface tension at cmc is also notably higher for dipropylammonium salts, which would indicate less surfactant at the interface. In each set of amines (secondary and quaternary) there is a clear trend of decreasing cmc as the length of the substituted car-

bon chains (and hence overall hydrophobicity) increases. The difference is more significant than the variation seen between the alkali metals, for example 13.6 mM for dimethylammonium PFO down to 6.6 mM for dipropylammonium PFO. This contrasts to the data seen for metal counterions, where cmc is largely unaffected by change a in counterion. A possible explanation lies in the much higher degree of counterion association. A higher prevalence of surfactant-counterion pairs in solution may produce less hydrophilic head group compared to the dissociated form prevalent for the more hydrophilic ions in the previous section, where effects on the cmc are small. The overall increase in hydrophobicity is therefore making the surfactant more surface active but with a lower overall solubility in monomeric form, and dibutylammonium PFO was noted as problematic for surface tension measurements due to poor solubility.⁷⁹ It is likely producing reasonable data on larger species would be difficult, although addition of data on the primary and tertiary ammonium ions would aid this interpretation.

2.3.1 Aggregation in solution

Many studies have explored changes in self-assembly behaviour of ionic surfactants as hydrophobicity of the counterion is increased. The change in aggregation usually involves a reduction in curvature of the aggregates⁸ although the exact structures and behaviour can vary. Quaternary ammonium counterions (R_4N^+) have been found to increase the radius and aspect ratio of PFO micelles measured with dielectric spectroscopy.⁸² As R went from methyl to butyl, aggregates went from spherical through oblate spheroids and finally rod-like for tetrabutylammonium PFO. In ethylammonium PFO, most of the phase diagram is comprised of the lamellar phase with varying degrees of swelling of the water layers depending surfactant concentration;⁷⁶ an isotropic micellar phase is only fleetingly observed immediately after the cmc.

Similar behaviours are observed with PFOS: for PFOS with $(Me)_4N^+$, shorter rod-like micelles are formed⁸³. With tetraethylammonium hydroxide^{35,81,84} the curvature decreases fur-

ther and a highly viscoelastic solution, indicative of entangled worm-like micelles, is formed. Electrical conductivity also shows the increased binding of the counterion to the micellar surfaces in these studies.

In perfluorononanoate, phase diagrams of tetramethylammonium, dimethyl and diethylammonium salts are dominated by the lamellar phase⁷², and perfluorodecanoate has been shown to transition from spherical micelles, rod-like micelles, vesicles and finally to bilayers as counterion substitution changed from $(\text{Me})_4\text{N}^+$ to $(n\text{-Bu})_4\text{N}^+$.⁸⁵ As a point of comparison, changes in the hydrocarbon surfactant dodecylsulfate are far less extreme: with tetraalkylonium the micelles are found to shrink but do not exhibit such drastic phase changes.⁸⁶ However, similar changes in cmc and counterion binding are observed, as cmc decreases for SDS as the counterion hydrophobicity increases from $(\text{Me})_4\text{N}^+$ through to $(n\text{-Bu})_4\text{N}^+$.⁸⁷ It has been noted that effects of changing the counterion to tetraethylammonium (compared to sodium) are greater for PFO than for dodecyl sulfate⁸⁸, with the cmc lowered by a factor of 4 in the former and a factor of 2 in the latter.

These phenomena are generally discussed as an effect of the greater binding of the counterion to the surfactant head group^{35,82}. Fluorinated surfactants such as PFO would be expected to favour low curvature interfaces based on their geometry; from the critical packing parameter theory²² the combination of a small carboxylic acid head group and bulky fluorocarbon tail would favour low curvature interfaces such as bilayers. However, for highly dissociated counterions in the previous section, the lamellar phase is not often seen except at high concentrations. This is because the highly dissociated head groups share a strong electrostatic repulsion due to like charges; as the more hydrated counterions are less effective at screening the charge, the increased repulsion between head groups increases the *effective* head group size of the surfactant and therefore produces the spherical micelles observed in species such as AmPFO or NaPFO. The closer binding of counterions as hydrophobicity increases provides greater screening of the head group charge and reduces the *effective* head group size, and therefore drives the fluorosurfactants to a more favoured geometry for their relatively bulky

tail groups.

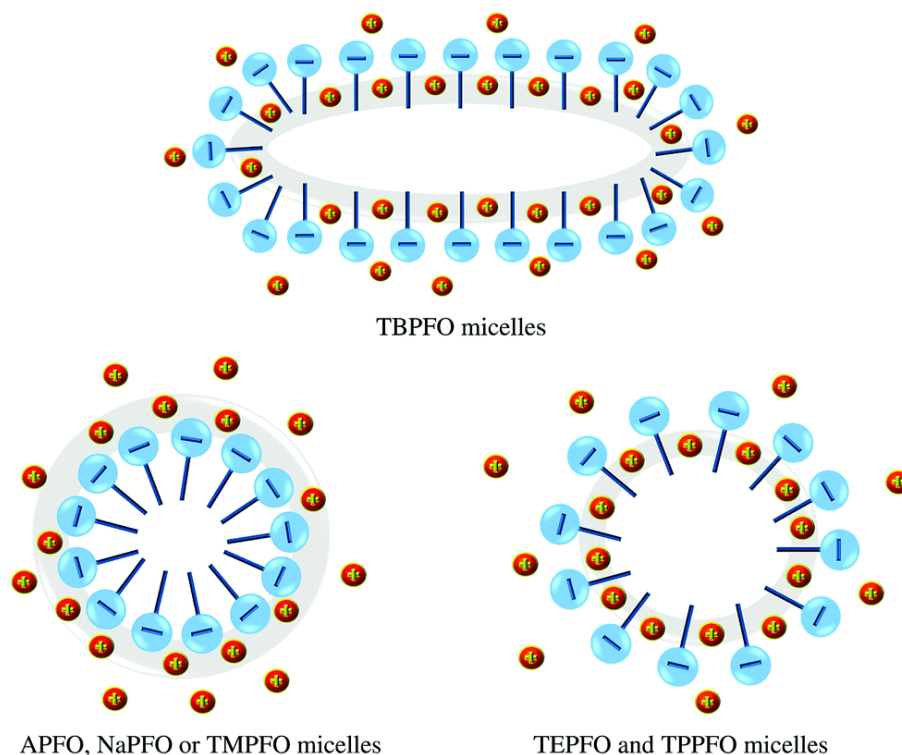


Figure 2.5 Schematic drawing of the change in micelle geometry as counterion hydrophobicity is varied taken from Zhang *et al.*⁸² In general, greater hydrophobicity in the counterion favours lower curvature interfaces. Note the misleading void in the micellar core; this would not be present in real micelles.

In ethylammonium PFO, the lamellar phase is found even at low concentrations⁵⁷ whereas the ammonium, lithium, sodium and rubidium salts are spheroidal. The lamellar phase is also readily seen in $(\text{Me})_4\text{N}^+$ PFO⁸⁹. A similar effect is seen using non-ionic co-surfactants. PFO was found to form incredibly ordered lamellar phases with addition of a C8 fluorotelomer alcohol⁹⁰ due to the separation of head group charges by the alcohol co-surfactant. These phase changes are more pronounced in ionic fluorinated surfactants such as PFO and PFOS due to the more tenuous relationship between head group charge and the preferred packing in aggregates. Since the bulkier chain so strongly favours low-curvature packing, even small changes in counterion binding can produce large changes in the geometry of aggregates typically only observed by adding co-surfactants.⁹⁰

For these systems it is not conclusive whether counterions are residing within the micelle

or remain bound to the surface. Fluorescence spectroscopy of micelles of tetraalkylammonium PFOs have shown some anomolous results inconsistent with other counterion systems⁹¹ (such as sodium or ammonium), which the authors mention could be due to counterions residing within the micelle. The degree of penetration of counterions into the micelle (shown schematically in Figure 2.5) due to hydrophobic interactions is currently unknown as most studies use techniques that are not capable of determining this. It is likely that there is an increase in the amount of counterions within the micelle; micelles are not hard surfaces (hence the term *soft matter*) and there is continuous dynamic exchange of both monomers and even water in soft matter systems.²² Realistically, the most likely scenario is a shift of the equilibrium location of the counterions closer to the micelle surface as hydrophobicity increases, with a greater proportion then diffusing into the micelle core than for small, hydrophilic counterions. Tetraalkylammonium counterions have also been found to have a lower binding affinity than the total hydrophobicity would suggest⁹², likely due to steric hindrance shielding the charge on the central nitrogen atom. However, a study using NMR on tetraalkylammonium PFOs indicated closer contact between the counterions and surfactant head groups as alkyl chain length increased,⁴⁰ and this would imply that some penetration of alkyl chains between surfactant head groups is likely.

Interactions between these species are also independent of other species in solution, and surfactant properties appear as for the closest binding component. For example, tetraethylammonium binds preferentially to PFOS in a solution of LiPFOS with a high binding coefficient (0.80)⁹³. This can also decrease binding of PFO to other substrates depending on the conditions; a study investigating the binding of PFO to β -lactoglobulin found binding of PFO to the protein decreased as counterion hydrophobicity increased from tetramethylammonium to tetrapropylammonium, but increased for tetrabutylammonium PFO.³⁸ This could support the hypothesis of the quaternary amines having a lower binding affinity than expected, although the authors in that work propose a synergistic binding effect.

Interestingly, unusual clouding behaviour has been reported for anionic surfactants with

quaternary ammonium counterions, with defined cloud points producing a two-phase system at elevated temperatures ($> 40\text{-}50^\circ\text{C}$). This has been reported for both fluorinated (PFO)^{37,94–96} and hydrocarbon (alkylsulfonate) surfactants⁹⁷ with tetralkylammonium counterions. Cloud points are generally considered a feature of non-ionic surfactants where they occur due to the dehydration of ethylene oxide groups often incorporated into the hydrophilic group, and are not seen in typical ionic surfactants. For tetralkylammonium PFO surfactants a ‘pseudo-nonionic’ is likely produced due to the poorly hydrated counterion, which could be similarly dehydrated and condenses with the surfactant ion as temperature increases. Electrical conductivity measurements have supported this,³⁷ with the degree of association of the counterion in tetrabutylammonium PFO shown to increase as temperature increases, whereas typically this decreases in ionic surfactants. It is also notable that the measured cmc continuously decreases as temperature increases until the cloud point is reached, which is another feature of non-ionic surfactants not typically seen in ionic species.

2.4 Surface chemistry in the environment and remediation methods

2.4.1 Environmental relevance

For most of the practical applications of fluorinated surfactants, the changes in properties noted here are either insignificant or unwanted. Changes in phase behaviour need to be treated carefully as more complex structures such as worm-like micelles can affect the rheology (flow) of resulting solutions.^{98,99} For example, in applications such as emulsion polymerisation or firefighting foams, changing phase behaviour from an isotropic micellar phase to more complex structures could be detrimental to performance due to lower diffusion and increased viscosity. Changes in surface activity could be useful, but the scale of variation in more approachable simple alkali counterions is not significant at a practical level, and

changes in Krafft temperature probably the most significant feature. However, as PFOA and PFOS are being phased out of many applications along with other perfluoroalkyl substances (PFAS), more attention is being paid to monitoring contaminated areas.^{100–102} The effects of ions and dissolved substances are becoming even more relevant due to potential impacts on environmental mobility and remediation methods.

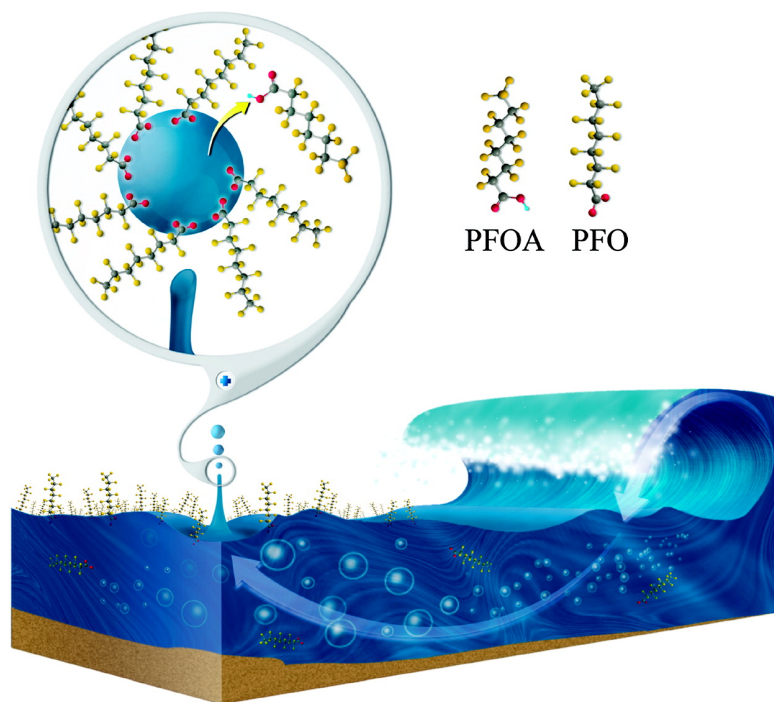


Figure 2.6 Accumulation of PFAS species at the air/water interface can lead to enriched aerosols being released through wave action. This effect is greater in oceans where high salt concentrations increase the surface activity of ionic species such as PFOA and PFOS. Figure taken from McMurdo *et al.*¹⁰³

Surface activity and partitioning of PFOA and PFOS is a key parameter in determining the transport and ultimate fate of these materials in the environment.^{104–106} Although mobility in the environment is mechanistically complicated and affected by many factors, in aqueous systems, dissolved ions such as Na^+ , K^+ , Mg^{2+} and Ca^{2+} are ubiquitous and their interactions with PFOA/PFOS are an important consideration. In the environment, surface activity of PFOA/PFOS leads to adsorption at both water/air interfaces and water/soil interfaces,¹⁰⁷ and although environmental concentrations are generally below that where these molecules are measurably surface active (such as through surface tension measurements), enrichment

at air/water interfaces still occurs^{107,108}, with PFOS being somewhat more active than PFOA. Enrichment at the air/water interface has implications beyond the local area; the enrichment and subsequent bursting of surface bubbles resulting in ejection of an aerosol droplet has been found to be an important component of PFAS transport.^{103,108} The quantity of dissolved ions has a large effect on this process, and in lab experiments the enrichment of PFO in aerosols was found to be highly dependent on the water source used. Enrichment factors of 5.6 for pure water, 8.1 for lake water and 55.7 for sea water have been determined¹⁰³ with the much saltier seawater proving far more effective at releasing PFOA in aerosols (Figure 2.6). Both PFOS and PFOA have been measured in air samples^{109,110} even though they are not considered particularly volatile, and this aerosolisation and subsequent long-range transport is a viable mechanism for the detection of PFAS compounds in remote locations.¹⁰⁰

In groundwater, adsorption at both water/air interfaces and water/soil interfaces can occur. Partitioning has been measured for PFOA and PFOS,¹⁰⁴ and both have been found to remain predominantly dissolved rather than adsorbed to sediment. In water-unsaturated sand, PFOA was noted to prefer the air/water interface with 50-75% adsorbed there.¹⁰⁷ The amount of retention to solids is further complicated by the composition of the soil as well as the solution. PFOA has a lower mobility in limestone sediments than in sand,¹¹¹ and the effect of Na^+ and Ca^{2+} on mobility was more significant, with noticeably higher retention in limestone-based columns. An examination of adsorption to different soil types indicates there is both an electrostatic and hydrophobic component to adsorption to soils.¹¹² Red soils with a positive surface charge show a higher adsorption of PFOA, while sandy, desert soil with a negative surface charge shows less adsorption. However, an increase in ionic strength produces an increase in adsorption in the negatively charged soils but reduces it in positively charged soils.¹¹²

Experiments with sand columns show similar results, with PFOA adsorption increased by increasing the ionic strength, and Ca^{2+} producing greater retention of PFOA than Na^+ . Adding a cationic surfactant (CTAB) to PFOS solutions dramatically increased their adsorp-

tion to natural sediments while an anionic surfactant (sodium dodecyl benzene sulfonate) produced mixed, concentration dependent results.¹¹³ This indicates that screening head group charges in PFOS/PFOA would increase the hydrophobic interactions which would enhance any adsorption to substrates without favourable electrostatic interactions, while *reducing* screening can enhance adsorption in substrates with favourable electrostatic interactions. This interaction would only be relevant to ionic PFAS species such as PFOA and PFOS; non-ionic species would be expected to adsorb mostly through hydrophobic interactions. A more comprehensive study¹⁰⁵ has highlighted this, with adsorption properties of different soil types showing differences for anionic, zwitterionic and non-ionic PFAS species. Furthermore, changing solution properties such as pH will affect both PFAS compounds *and* soil substrates, so for chemically diverse substrates such as complex soils, the outcome could be more complicated than some of the lab-based measurements imply.

2.4.2 Remediation of PFOA/PFOS contamination

Current large scale remediation methods for PFAS are reliant mostly on adsorption processes, so understanding physicochemical interactions of PFAS molecules is also useful for improving and developing remediation methods for contaminated water sources. Currently, hydrophobic, carbonaceous adsorbent materials (such as activated charcoal or carbon nanomaterials) are the most commonly reported^{114–118}. Being generally hydrophobic substrates, hydrophobic interactions are the dominant force in adsorption^{119,120} although performance can vary depending on the exact material and any surface modifications.^{114,115} Using a material such as alumina¹²¹ can shift this balance such that electrostatic interactions are more relevant; in alumina an increase in ionic strength decreases adsorption of PFOA and PFOS. In this study PFOS adsorption was less affected by Ca^{2+} than PFOA.

Ion-exchange resins can be a more effective adsorbent than activated carbon,^{122,123} and are useful on a small scale, but costly and difficult to implement on a large scale. Coexisting ions in solution can understandably also effect this process and reduce effectiveness,¹²⁴ but this is

dependent on both the system and species analysed. There is a lot of potential for enhancing these processes through careful choice of additives to increase adsorption onto cheaper hydrophobic substrates. As seen in previous sections, additives that reduce the effective head group charge could be useful for driving PFOA and PFOS to the liquid/solid interface and increasing the efficiency of the remediation process.

Another prominent remediation method where surface activity is crucial is foam flotation/separation. Foam flotation is widely utilised in a number of fields for separation of hydrophobic materials, and is an emerging prospect for PFAS remediation.^{125–129} It has the advantage of being easily scalable and cheap to operate as there is no need for replacement of adsorbent substrates. However, environmental concentrations are typically well below the cmc, therefore there is negligible foaming from PFOA or PFOS species and their interfacial adsorption is relatively low. Foaming can come from other sources such as other forms of dissolved organic carbon¹³⁰, but this can't be relied upon in all water sources. Efforts to get around this have been attempted, such as capture of aerosols in conjunction with foam removal¹³¹ and uptake into surface duckweed during aeration.¹³² These are arguably not feasible on a large scale. The use of surfactants will aid foam flotation by allowing foam formation,¹²⁷ but increasing the surface activity of PFOS and PFOA with additives would go further to improving the efficiency of the process. This has been shown with high valence metal ions Fe(III), La(III) and Al(III), which have been shown¹²⁵ to improve the yield of both PFOA and PFOS extraction in foam separation. These species are highly pH dependent however and require quite low pH (2.3) for maximum effectiveness, showing only minimal effect at neutral conditions. In foaming processes there is only the air/water interface to consider, which simplifies interactions considerably. Although there are many factors that affect the degree of foaming of a solution, potentially any species that is increasing the surface activity of PFOS and PFOA could be included in the process to enhance the adsorption at the air/water interface and increase the efficiency of the process.

In either case, a thorough understanding of the solution composition and how each com-

ponent will affect a given process is important for success. It has been shown here that adsorption of PFOA and PFOS can be either increased or decreased by ionic species, but other dissolved species are usually present in real world samples. Humic acid, ethanol and hydrocarbon surfactants have been found to also affect the interfacial adsorption of PFOA¹³³ and likely other ions and dissolved organic species that haven't been mentioned here as well. A process that works for a given wastewater stream may not work for another, and a holistic understanding of the underlying interactions at play would enable increased efficiency through relatively minor changes to solution composition.

2.5 Conclusion

The behaviour of ionic fluorinated surfactants is affected in many ways by interactions with different dissolved ions. For alkali metal cations this is most apparent in changes to Krafft temperature and energy of crystallisation, and interestingly the ionic radius of the counterion has a significant role. For PFOA, Krafft temperatures and other parameters trend around a maximum value: $\text{Li}^+ < \text{Na}^+ < \text{K}^+ > \text{Rb}^+ > \text{Cs}^+$. When the counterion is changed to a more hydrophobic organic ammonium ion, surface activity is increased and the cmc trends downward as overall hydrophobicity of the counterions is increased. More complex phase behaviour is observed above the cmc with a strong preference for lower curvature interfaces, especially lamellar phases. This is rationalised as a decrease in dissociation between the surfactant head group and counterion, which more effectively screens the surfactant head group charge, and hence lowers the curvature of aggregates formed. The effects of dissolved ions on the surface activity of PFOA and PFOS, which are known persistent organic pollutants, are now relevant not just as an academic or commercial pursuit but have wide ranging implications for determining the fate of these molecules in the environment, as well as the implementation of efficient remediation methods. Current remediation methods rely on separation *via* interfacial adsorption which can be inefficient due to the low environmental concentrations that are typically encountered. Increasing surface activity through changes in solution

chemistry can be a useful way of increasing removal efficiency in low-cost, scalable methods such as foam flotation.

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Chapter 3

The effects of alkylammonium counterions on the aggregation of fluorinated surfactants and surfactant ionic liquids

3.1 Introduction

This chapter aims to further understanding of interactions between fluorinated surfactants and hydrophobic ions. As was seen in Chapter 2.3, there are a variety of studies covering this topic in the literature, but they are all rather limited in scope and there are gaps preventing any correlations from being conclusive. This is particularly true for organic ammonium ions where there is potential for varying both degree of substitution (and hence geometry) as well as the chain length of substituent alkyl groups.

There are examples in the literature covering some organic ions with PFOA, such as the secondary ammonium salts of PFOA and PFOS¹ and quarternary ammonium salts²⁻⁴. Other PFOA species only appear sporadically, such as the ethylammonium salt^{5,6} and cholinium salts.^{7,8} This leaves primary and tertiary amines unstudied, and although some conclusions can be drawn from the literature about overall hydrophobicity, a systematic understanding of this, along with the effects of counterion geometry, is missing.

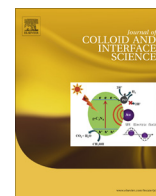
It had been suggested that overall hydrophobicity is the main determiner in counterion binding in dodecyl sulfate,⁹ however it is unclear if the same is true for fluorinated surfactants which have shown different, stronger interactions with hydrophobic ions compared to hydrocarbon surfactants.¹⁰ To this end, a study of both surface activity and solution aggregation of perfluorooctanoate with a suite of organic ammonium counterions was undertaken. The sample matrix covers counterions comprising primary, secondary and tertiary amines with substitutions covering 1–3 carbons in length, providing a comprehensive overview of how hydrophobicity and geometry of the counterion affects surfactant properties.

The effect of temperature on aggregation is also explored. The unsubstituted ammonium salt is included for comparison as a typical hydrophilic counterion that is commonly encountered with perfluorooctanoate. This work has been published and is included here as it appears in the *Journal of Colloid and Interface Science*, Volume 475 (2016), pages 72 - 81. The Supporting Information for this publication can be found in Appendix 1.

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The effects of alkylammonium counterions on the aggregation of fluorinated surfactants and surfactant ionic liquids



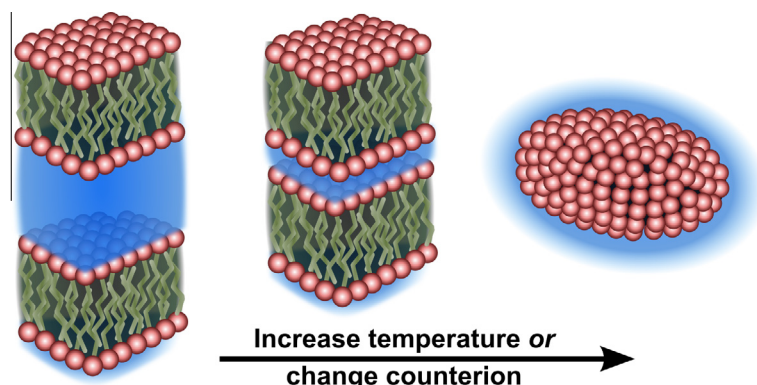
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GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:

Received 3 April 2016

Revised 25 April 2016

Accepted 25 April 2016

Available online 26 April 2016

Keywords:

Fluorosurfactant

Aggregation

SANS

Surfactant ionic liquid

ABSTRACT

The effects of organic counterions with varying carbon number on surfactant aggregation have been analysed by coupling perfluorooctanoate surfactant anions with various alkylammonium counterions. Both the degree of substitution (primary to tertiary) and alkyl chain length (0–3 carbons) of the counterions were varied to provide a comprehensive matrix of geometries and lipophilicities. Surface activity was measured using pendant drop tensiometry, while temperature-controlled small-angle neutron scattering was used to probe changes in aggregation morphology. It was found that the use of such alkylammonium counterions resulted in a strong preference for bilayer formation even at low surfactant concentration (<2 wt%), when compared to simple inorganic counterions such as sodium which favour near-spherical micelles. At increased temperatures, some counterions led to unique phase behaviour wherein a transition between two structurally different lamellar phases is seen, rationalised as a transition into a microscopic phase separation wherein a surfactant-rich lamellar phase coexists with a dilute micellar phase. The results indicate that aggregation is controlled by a delicate balance of counterion size, hydrophilicity and diffuseness of charge, providing new methods for the subtle control of surfactant solutions.

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1. Introduction

Since Hofmeister's early observations of salt-specific effects in protein precipitation over a hundred years ago [1], the issues of

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ion specific effects and electrolyte composition are now understood to be central in a variety of fields. In surfactant science, while the effects of electrolytes are often discussed, the nature of the surfactant counterion in ionic surfactants is not always scrutinised in the same detail, as the main properties of interest in surfactants are generally assumed to be dictated by the nature of the surfactant ion itself [2]. However, changing the counterion can produce significant and useful changes in the behaviour of a given surfactant, with properties such as solubility, critical micelle concentration (cmc) and post-cmc aggregation behaviour being affected due to changes in the interactions between the surfactant and counterion [3,4]. Adding electrolytes that compete with the surfactant counterion can produce similarly pronounced effects on processes such as photochemical quenching within micelles [5]. For fluorosurfactants, James and Eastoe recently reviewed the physical and chemical effects of a range of counterions [6].

Surfactant counterions may be simple inorganic species (e.g. sodium, potassium) or more exotic organic ions (e.g. ethylsulfonate, tetramethylammonium). Larger, more hydrophobic counterions generally lower the solubility and cmc of ionic surfactants [4] when compared to smaller, hydrophilic counterions such as alkali metals or halides, also decreasing micelle ionisation degree. Bonilha et al. determined that alkylammonium counterions were able to outcompete sodium, binding strongly to dodecylsulfate micelles [7]. Brown et al. more recently showed that alkylammonium ions could induce different aggregation structures and subtly control phase behaviour for a range of hydrocarbon surfactants and surfactant ionic liquids [8]. Hydrophobic ions have generally found fewer applications and are less common in the literature than their inorganic counterparts. However, changing counterion size or hydrophobicity can be a useful tool for tuning the properties of a particular surfactant. It has been reported recently that protic ionic liquids formed from perfluorinated acids (such as perfluorooctanoate) and hydrocarbon counterions form discrete polar, hydrocarbon and fluorocarbon regions, making them potentially versatile surfactants for dissolving both hydrocarbon and fluorocarbon oils in aqueous solution [9,10].

The physical effects of changing the counterion in ionic surfactant systems can result from increasing the steric bulk of a counterion to influence micelle aggregation, or from the interaction of the mutually hydrophobic areas of the surfactant and counterion. Indeed, hydrophobicity in the counterion adds additional complexity to surfactant-counterion interactions, with the generally considered purely electrostatic interactions of small counterions replaced by a more thermodynamically complex balance between electrostatic and hydrophobic forces [11]. This is especially relevant for fluorocarbon surfactants, which can display both lipophobic and hydrophobic characteristics [12].

The concept of hydrophobicity intrinsically originates from the orientation of water molecules around chemical species [13], and is therefore conceptually related to the more commonly discussed hydration of ions. The term 'hydrophobic' often appears in the literature when referring to organic ions, but is frequently used in a generic and loosely defined sense. This can be a useful general term when comparing such ions to small, highly hydrophilic ions (e.g. alkali metals), however the specific effects of organic ions are more complex, and can perhaps be better addressed by exploring their solubility and interfacial activity [3]. For a counterion, size, geometry and diffuseness of charge are all important factors in determining how an ion interacts in solution; the combination of these related properties dictate how strongly the counterion is hydrated by water molecules.

The combination of fluorocarbon surfactant ions with hydrocarbon counterions is only sparsely covered in the surfactant literature. While for perfluorooctanoate, the tetraalkylammonium salts have been known for some time [14–16], counterions with lower

substitution have been rarely reported, in common with other surfactant ions. The surface activity of dialkylammonium perfluorooctanoates has been reported along with the trialkylammonium perfluorooctanesulfonates [17]. Each showed a noticeable drop in the surface tension at the critical micelle concentration (cmc), which correlates also with a lowering of the cmc. While aggregation in solution is a less studied property, it has been noted in perfluorodecanoates that using substituted ammonium counterions favours the formation of lower curvature interfaces [18]. We also made similar observations in our previous study [19], with the phase behaviour of ethylammonium perfluorooctanoate dominated by the lamellar phase.

At the other end of the spectrum, recent reports have demonstrated that the incorporation of highly hydrated counterions favours an increase in interfacial curvature; the use of strongly hydrated and hydrolysable counterions such as carbonates and phosphates promoted formation of spherical micelles at unusually high surfactant concentrations [20], and unusually high salt concentrations [21].

Previously we have demonstrated how changing the size and shape of simple counterions can effect the solution aggregation of perfluorooctanoate surfactants [19]. Herein we build on the previous study with a systematic investigation of the perfluorooctanoate surfactant anion combined with short chain alkylammonium cations. Traditional pendant drop tensiometry is utilised to determine changes in surface activity and interfacial adsorption, whereas small-angle neutron scattering is used to directly determine surfactant aggregation in bulk aqueous solutions. Combining these techniques allows a comprehensive overview of the changes in the properties of a particular surfactant as the properties of its counterion are changed. We address the concept that diffuseness of charge and how strongly the counterion is hydrated are more relevant properties than simply 'hydrophobicity' when exploring counterion characteristics. By analysing a matrix of different cations with varying chain lengths (from 1 to 3 carbons) and degrees of substitution (primary to tertiary amines), we probe the subtle counterplay between these two properties and how they can control the behaviour of surfactants in solution.

2. Materials and methods

2.1. Materials

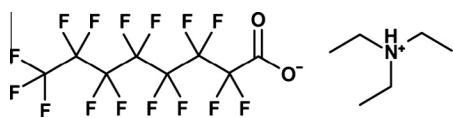
The organic amines methylamine (40% in H₂O), ethylamine, *n*-propylamine, isopropyl amine, dimethylamine (40% in H₂O), diethylamine, dipropylamine, trimethylamine (40% in EtOH), triethylamine, tripropylamine (reagent grade from Sigma Aldrich), and perfluorooctanoic acid (Fluorochem, 99%) were all used as received. The perfluorooctanoate derivatives were prepared via stoichiometric neutralisation of perfluorooctanoic acid with the appropriate amine in ultrapure water. Approximately 40 mL of the resulting liquids were placed in a vacuum oven at 70 °C for 14–16 h to obtain the dried surfactants. For convenience, we abbreviate the names of the surfactants as detailed in Table 1. Ultrapure water was obtained from a Millipore Direct-Q 5, with a minimal resistivity of 18.2 MΩ cm, and for neutron scattering experiments, D₂O was obtained from Sigma Aldrich (99.98 atom% D) and used as received.

2.2. Small-angle scattering

SANS measurements were made on the Quokka beamline at ANSTO, Lucas Heights, Australia. Samples were prepared in 2 mm path-length quartz cells using D₂O, and temperature control was achieved using a recirculating water bath with characteristic preci-

Table 1

List of the counterions of perfluorooctanoate studied and their abbreviations. The chemical structure of one surfactant – triethylammonium perfluorooctanoate – is shown as an example.



Counterion	No. of carbons	Abbreviation
Ammonium	0	AmPFO
Methylammonium	1	MaPFO
Ethylammonium	2	EaPFO
<i>n</i> -Propylammonium	3	nPaPFO
Isopropylammonium	3	iPaPFO
Dimethylammonium	2	dMaPFO
Diethylammonium	4	dEaPFO
Di- <i>n</i> -propylammonium	6	dPaPFO
Trimethylammonium	3	tMaPFO
Triethylammonium	6	tEaPFO
Tri- <i>n</i> -propylammonium	9	tPaPFO

sion of ± 0.05 °C. The temperature was monitored using a thermocouple placed in one of the sample holders to ensure accuracy at the sample position. Data were reduced from the raw counts on a two dimensional detector to a radially averaged absolute intensity versus the scattering vector q , under the assumption of isotropic scattering, where q is defined:

$$q = \frac{4\pi}{\lambda} \sin \frac{\theta}{2} \quad (1)$$

wherein λ is the wavelength of the incident neutron beam and θ is the scattering angle. Thus the q range is defined by the instrument configurations and the size of the detector. On Quokka, an incident wavelength of $\lambda = 5$ Å ($\Delta\lambda/\lambda = 10$) was used with two sample-detector distances of 2 and 14 m, giving a q -range of 0.005–0.400 Å^{−1}. To reduce the raw data, the response of each detector pixel was normalised to the response of a flat isotropic scatterer, and then the scattering from an empty SANS cell was subtracted. The radial average of the intensity expressed as a function of q could then be obtained using the instrument configuration and detector characteristics. The absolute intensity scale was provided by normalising to the sample thickness (2 mm) and comparing the intensity to that of an empty beam measurement.

SANS spectra with lamellar characteristics were modelled using the paracrystalline stack model proposed by Nallet, Laversanne and Roux [22]. Spectra of micellar solutions were modelled using either a form factor for scattering from homogeneous ellipsoids [23] or one for rod-like micelles [24], combined with a Hansen-Hayter-Penfold-Ginzoa mean spherical approximation structure factor for charged interactions via a screened Coulomb potential [25,26]. A detailed description of these fitting methods can be found in previous work [27,19] and in the Supplementary Material.

2.3. Surface tension analysis

Surface tension was analysed using the pendant drop method on a custom designed pendant drop tensiometer [28]. Image analysis was performed using the OpenDrop software package (Version 1.1, www.opencolloids.com), which fits the drop profile iteratively using the Young-Laplace equation to determine the surface tension γ .

The main surfactant physicochemical quantities, namely critical micelle concentration (cmc), surface tension at cmc (γ_{cmc}), surfactant surface excess at the cmc (Γ_{cmc}) and the area per molecule at cmc (A_{cmc}) were obtained from the plot of γ vs $\ln C$, with Γ and

the associated A_{cmc} determined assuming adherence to the Gibbs adsorption isotherm for ionic surfactants:

$$\Gamma = -\frac{1}{2RT} \left(\frac{\partial \gamma}{\partial \ln C} \right) \quad (2)$$

where $\left(\frac{\partial \gamma}{\partial \ln C} \right)$ is the slope of the γ vs $\ln C$ plot immediately prior to the cmc. Linear fits to surface tension data in the immediate pre-micellar region were used to obtain surface excess and area per molecule values. We chose this approach over a polynomial fit as the change in surface tension with concentration was effectively linear in the region used, and no greater fidelity could be achieved by applying a polynomial. For surfactants where non-micellar aggregates form at even low concentrations, it is perhaps more accurate to describe the break in surface tension decrease as a critical aggregation concentration (cac) rather than a critical micelle concentration (cmc). However, as it is challenging to characterize the precise geometry of aggregates formed at such low concentrations, for the sake of simplicity we describe all cases as a cmc.

2.4. Differential scanning calorimetry

Differential scanning calorimetry (DSC) was performed with a Perkin Elmer Pyris system under a nitrogen atmosphere. The samples were run in an aluminum pan in a sealed furnace at a heating rate of 2.5 °C/min, starting at −30 °C.

2.5. Water content

Water contents of the neat surfactants were determined using a Mettler Toledo DL39 Karl Fischer titrator.

2.6. Polarising light microscopy

Polarising light microscopy (PLM) images were obtained using a CMOS camera (Flea3, Point Grey, Richmond, BC, Canada) coupled to a Kozo XJP-300 polarising light microscope. Temperature control was achieved using a resistor heated slide mount, and the sample temperature at the time of imaging was recorded using a calibrated thermocouple.

3. Results and discussion

3.1. Physical properties and surface activity

The physical properties and surface activity of the amines and resulting perfluorooctanoate surfactants are detailed in Table 2. In line with previous literature reports [9], the majority of the alkylammonium perfluorooctanoate derivatives had low melting points; with the exception of the ammonium and methylammonium salts, all were <100 °C, thus they can be defined as ionic liquids. As mixtures of quaternary ammonium salts and carboxylic acids are known to form deep eutectic solvents, it is possible that the decrease in melting points to give room temperature ionic liquids for certain combinations here is related to this phenomenon [33]. As expected, the melting points generally decreased with both increasing the alkyl chain size and the degree of substitution, with the tri-substituted ammonium counterions giving the lowest melting points (<0 °C). The exception was dPaPFO, which curiously showed an increased melting point compared to dEaPFO and dMaPFO. Such water dependant properties in ionic liquids (ILs) have been well documented in the literature [34,35], and indeed the melting point of EaPFO determined in this study, 68.6 °C, differs significantly from the 58 °C reported previously [9], consistent with water contents of 2.04% and 0.61% respectively. Therefore melting point values should be considered indicative but not

Table 2

Physical properties of mono-, di- and tri-substituted alkylammonium perfluorooctanoates: amine solubility parameter ($\log P$), water content, melting point (MP), critical micelle concentration (cmc), surface tension at cmc (γ_{cmc}), surfactant surface excess at the cmc (Γ_{cmc}) and the area per molecule at cmc (A_{cmc}).

Surfactant	$\log P^a$	Water (%)	MP ($^{\circ}\text{C}$)	cmc (mM)	γ_{cmc} (mN m $^{-1}$)	Γ_{cmc} (mol m $^{-2}$)	A_{cmc} ($\text{\AA}^2$)
AmPFO		0.14	157–165 [29]	31.2	19.0	3.47×10^{-6}	48
				33 [30]	20.5 [31]		
MaPFO	−0.57	1.01	121.7	21	14.3	2.7×10^{-6}	62
EaPFO	−0.13	2.04	68.6	19	14.9	2.4×10^{-6}	68
			58 [9]				
nPaPFO	0.48	2.30	63	11	15.2	2.6×10^{-6}	64
iPaPFO	0.26	1.33	92.3	12	15.4	2.5×10^{-6}	65
dMaPFO	−0.38	0.34	48	13.6 [17]	14.9 [17]	2.7×10^{-6} [17]	61 [17]
dEaPFO	0.58	0.46	28	7.9 [17]	15.5 [17]	3.3×10^{-6} [17]	50 [17]
dPaPFO	1.67	0.85	91.5	6.6 [17]	23.3 [17]	2.5×10^{-6} [17]	66 [17]
tMaPFO	0.16	1.51	<0	10.5	15.1	3.19×10^{-6}	52
tEaPFO	1.45	1.11	<0	7.86	16.3	2.98×10^{-6}	56
tPaPFO	2.79	0.52	<0	7.47	17.3	2.60×10^{-6}	64

^a $\log P$ values are for the conjugate base of the counterions (i.e. the non-protonated amines). Values taken from Sangster [32].

absolute for each species studied; the results are included to illustrate the effects of the more diffuse charge as the ‘bulkiness’ of ammonium species increases.

The surface activity of PFO species showed only slight variations (Fig. 1), in line with the expectation that surface adsorption is driven primarily by the surfactant ion itself. However, the properties of AmPFO showed a significant difference with respect to the salts of substituted amines. AmPFO showed a significantly greater cmc (likely indicating higher solubility), higher surface tension at cmc, higher surface excess concentration and correspondingly lower area per molecule than even the next most hydrophilic species, MaPFO. This reflects the strongly hydrophilic nature of the ammonium counterion. For the species with alkylated (and thus more hydrophobic) counterions, there was less variation between the different compounds. The surfactants could be grouped (with the exception of iPaPFO) depending on the degree substitution of the alkyl ammonium counterions, with slight but noticeable trends observed for each degree of substitution depending on the number of carbons in the alkyl chain(s). Increasing the number of carbons per chain lowered the cmc and raised γ_{cmc} . While these trends correlate with the expected counterion ‘hydrophobicity’ (as ascertained from the amines’ $\log P$ values), the changes in counterion geometry should not be discounted, indicating that caution should be exercised when comparing values between the different sets of counterions. Interestingly, the surface excess and area per molecule did not fit well to these substitution trends, with only the tertiary ammonium counterions giving a corresponding decrease in surface excess concentration as hydrophobicity increased.

A common conceptualisation of the reduction of the surface tension of water by surfactants is in viewing the surfactant molecules as a pseudo-liquid film between the air/water interface, thereby creating a surface approximating that of the parent molecule of the surfactant tail [2]. This often-used paradigm explains the difference between classes of surfactants, such as the difference between fluorocarbon and hydrocarbon surfactants. Bulk perfluorinated compounds such as perfluorooctane have low surface tensions due to their weak intermolecular forces [36], and therefore perfluorinated surfactants show the greatest reduction of surface tension in aqueous solution by providing a low energy fluorocarbon ‘film’ at the air/water interface. Although this is an idealised model, it can be useful for making broad predictions of the relative surface activity of different classes of surfactants (see Fig. 1).

If we consider the surfactant molecules as a surface film at the liquid/air interface, then it would be expected that lower values of γ_{cmc} would correlate with a lower A_{cmc} , since a smaller A_{cmc} implies

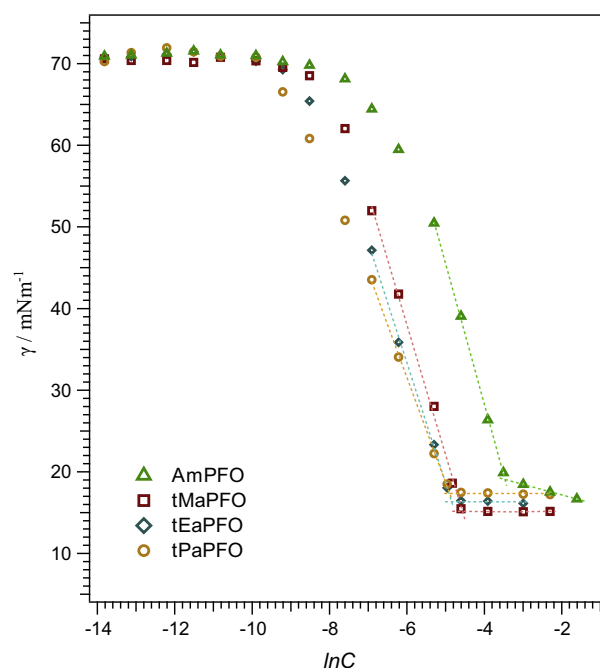


Fig. 1. Surface tension analysis of tertiary ammonium perfluorooctanoates compared to the ammonium salt. Plots for all species analysed can be found in the Supplementary Material.

a more closely packed and ‘complete’ surface film that approaches the surface tension of the parent molecule of the surfactant chain, in this case perfluorooctane. However, overall the values for the Γ_{cmc} and A_{cmc} do not support this conjectured relationship to γ_{cmc} , and indeed seem to show the inverse, with AmPFO having the lowest calculated area per molecule but the second highest γ_{cmc} . The species with substituted ammonium counterions showed lower surface tensions at the cmc, with the exception of the dPaPFO (which was also the least soluble), but greater area per molecule. The slope of the γ vs $\ln C$ experimental data was able to be fit quite accurately, and even though the parameters would naturally have a slightly greater uncertainty since they are derived rather than directly measured by this method, experimental errors are unlikely to result in such differences. Rather, when considering the aggregation behaviour explored in the following sections, it is apparent that the discrepancy likely arises from the assumptions made in using the Gibbs adsorption isotherm. The Gibbs equation for ionic

surfactants assumes complete dissociation (resulting in the factor of 1/2 compared to the formula for non-ionic surfactants). However as the SANS analysis below shows, when the PFO species with hydrophobic counterions formed micelles, they showed a very low degree of counterion dissociation α . For example, for tEaPFO at 2 wt%, α measured by SANS fitting was <0.1 , and for MaPFO at 10 wt% (and 48 °C) α was fitted as 0.05. Such low degrees of dissociation therefore indicate caution when using a standard Gibbsian analysis, which clearly provides a limiting case analysis of these data.

3.2. Surfactant aggregation in solution

The aggregation behaviour of the perfluorooctanoate anion, like other perfluorinated surfactants, strongly favours low-curvature phases [19,27], in particular lamellar phases. For perfluorooctanoate salts of simple, 'hard' counterions such as alkali metals and ammonium, the lamellar phase is seen at higher surfactant concentrations and spherical or ellipsoidal micelles are present in dilute solutions [19], with the notable exception of the sodium salt which does not display a lamellar phase [37]. With the more hydrophobic alkylammonium counterions studied here, the formation of the lamellar phase becomes even more favoured, with lamellar phases, albeit somewhat diffuse and disordered, appearing at remarkably low concentrations. For example, in the AmPFO/water system, only ellipsoidal micelles are seen at a surfactant loadings of 10 wt%, and the onset of the lamellar phase occurs at 40 wt% [38]. However, when the counterion is changed to even the least alkylated of alkylammonium cations, methylammonium, the phase behaviour is dominated by the lamellar phase from surfactant mass fractions as low as 2 wt% (Fig. 2b). This behaviour was seen in all the mono-substituted ammonium PFOs studied. For the dilute solutions (2 wt% and 5 wt%) the lamellar phases appeared quite disordered, with a strong q^{-2} dependence but little or no

evidence of the characteristic Bragg peak observed. The q^{-2} slope is generally indicative of surface scatter from bilayer structures [39], and the presence of 'Maltese cross' patterns in the PLM analysis confirmed the presence of a lamellar phase (Fig. 2).

The exact geometry of such weakly structured bilayer phases is difficult to determine unequivocally. It is clear that only minimal long-range orientational order can exist, as evidenced by the weak or absent Bragg peak. Similarly diffuse and smeared peaks are seen for surfactant sponge (L_3) phases [40,41] and also for incomplete or perforated lamellar systems [42]. It is plausible that for phases where the Bragg peak appears to be absent that it is simply at lower q values than we explored in these experiments. However, this would indicate very large characteristic spacings (>100 nm) which may be challenging to rationalise for a conventional lamellar phase. In any case, the PLM indicates that bilayer is definitely present, although further identification would likely require a cryo-microscopy study.

A more likely and consistent explanation is that such systems contain extended bilayer 'fragments', not unlike so-called 'bicelles' often seen for lipid systems, and more rarely for surfactant systems [43]. These fragments of bilayer would only experience minimal local correlation in dilute systems, with a more pronounced structure peak appearing at high concentrations where some degree of stacking would be required by the volume constraints of the system. Thus a simple description where the surfactant is self-assembled into bilayer structures, but these are only weakly locally correlated is most consistent with the data [22].

SANS spectra of 10 wt% solutions of all of the alkylammonium PFO surfactants studied are shown in Fig. 3a, with the exceptions of dPaPFO (which was insoluble at this loading), and tEaPFO, which formed a phase-separated microemulsion with excess water. At this concentration, all the species appear to exhibit a more well-defined lamellar phase, showing the distinctive Bragg peak and some with second or higher order peaks. From model fitting of

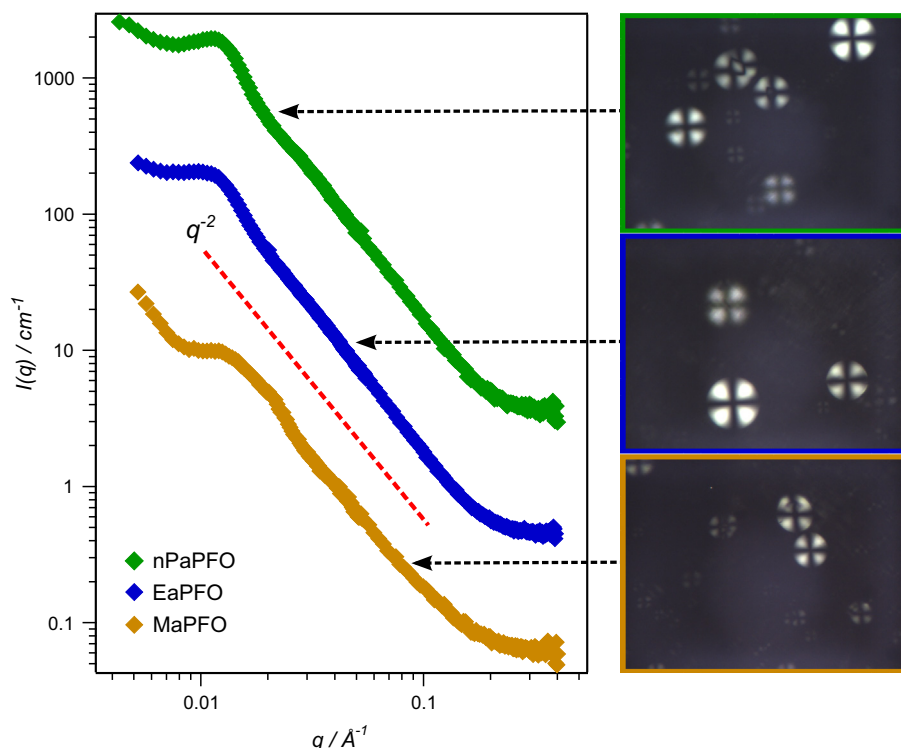


Fig. 2. SANS data and corresponding PLM images of 5% solutions of *n*-alkylammonium PFO surfactants, confirming weakly ordered bilayer structures. Images were obtained on a microscope slide without a cover slip, and therefore lamellar domains are not all in the focal plane; placing a cover slip onto the samples resulted in no birefringent 'Maltese cross' domains being observed.

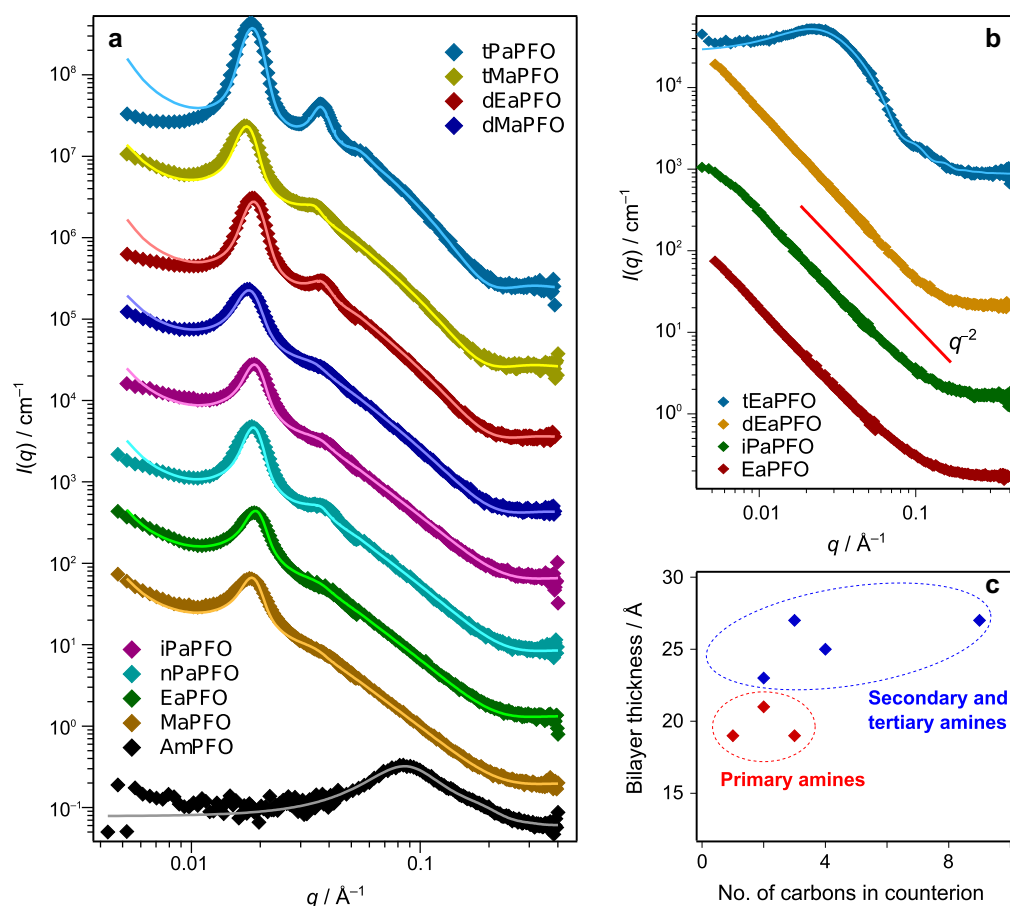


Fig. 3. (a) SANS spectra of 10% solutions of each PFO species, except for dPaPFO, which was insoluble, and tEaPFO, which phase separated. (b) SANS spectra of 2% solutions of selected PFOs. The diffuse surface scatter shown by the lower three plots was displayed by all the PFOs analysed at this concentration, with the exception of tEaPFO (shown top) and AmPFO. (c) A plot showing the effects of increasing the carbon number of the counterions on the bilayer thickness, δ .

these SANS profiles (see Section 2 for details), the main differences between the phases formed using different counterions here (see Table 3) manifest in the rigidity of the bilayers (as described by the Caillé parameter) and the thickness of the bilayers (δ). There was a noticeable decrease in the Caillé value (corresponding to more rigid bilayers) as the counterion alkyl character increased, with tPaPFO showing the lowest value (0.2) and therefore the most sharply defined peaks in the SANS spectrum. This was mirrored by an increase in the bilayer thickness, from 19 Å for the relatively diffuse lamellae formed by MaPFO, iPaPFO and dMaPFO, up to 27 Å for tMaPFO and tPaPFO. The fact that the data are well fit by a single contrast step between the bilayer and solvent indicates that there is not sufficient enrichment of the ammonium ions at the bilayer surfaces to require a two-step model. This implies that the ions are somewhat distributed throughout the system.

It is apparent from the SANS data (Fig. 3) that the degree of substitution of the ammonium counterion – and hence the steric bulk of the ion and diffuseness of the charge – is of greater importance than the absolute hydrophobicity. To provide an approximate basis for comparing the hydrophobicity of these ions, the octanol-water partition coefficients ($\log P$) of the unprotonated amines are shown in Table 2. Although these values are for the unprotonated species, and therefore not absolute values for the protonated ions, as the pK_a values for each species are similar, it is expected that the values provide a reasonable guide to the relative hydrophobicity of the counterions. Here we can see that, for example, dimethylamine is slightly more hydrophilic than ethylamine, yet as a counterion for perfluorooctanoate, its aggregation properties (e.g. δ and Caillé) bear more similarities to the other secondary and tertiary amines,

even those of much greater absolute hydrophobicity. Indeed, there is little apparent trend between the $\log P$ values and aggregation properties. Although not an ideal measure, in this context the amines' $\log P$ values serve to highlight the important distinction between hydrophobicity inferred purely from absolute solubility when compared to how strongly the molecule is hydrated in aqueous solution.

The effects of counterion hydration have been demonstrated recently with alkyltrimethylammonium surfactants [21], where strongly hydrated counterions were found to specifically favour the formation of spherical micelles. Using the strongly hydrated, hydrolysable counterions phosphate, oxalate and carbonate with these surfactants not only promoted the formation of spherical micelles, but these structures were maintained even in the presence of added electrolyte. Another study from the same authors [20] found these counterions enabled the formation of the rare hexagonally close-packed spheres (HCPS, $P6_3/mmc$) phase in these surfactants. This behaviour was rationalised by the large hydration shell of the counterion. This lowers the ability of the counterion to screen the charge of the surfactant headgroup, and hence results in spherical micelles being favoured. In the case of the perfluorooctanoate derivatives studied here, we have observed the inverse of this scenario, whereby changing to a less hydrated counterion has increased charge screening and allowed the formation of bilayer structures at much lower concentrations than observed for the more common alkali metal counterions. However, this is logical given packing parameter arguments for the respective surfactants, and accounting for the much bulkier fluorinated chains of the perfluorooctanoate derivatives (see Table 3).

Table 3

SANS fitting parameters for perfluorooctanoate (PFO) surfactants at 25 °C: bilayer spacing d , Caillé parameter η_{cp} and bilayer thickness δ .

Sample	wt% surf.	Geometry	d (Å)	η_{cp}	δ (Å)
AmPFO	0.10	Obl. ellips. ^a			
MaPFO	0.05	Disord. L_z	483 ^b		
	0.10	L_z	338	0.60	19
EaPFO	0.05	Disord. L_z	628 ^b		
	0.10	L_z	326	0.60	20.5
nPaPFO	0.05	Disord. L_z	628 ^b		
	0.10	L_z	335	0.43	19
iPaPFO	0.10	L_z	330	0.54	19
dMaPFO	0.10	L_z	346	0.50	23
dEaPFO	0.10	L_z	334	0.33	25
tMaPFO	0.10	L_z	358	0.40	27
tEaPFO	0.02	Ellips. ^c			
tPaPFO	0.10	L_z	339	0.20	27

^a Fitting parameters (oblate ellipse model used): ellipse radii $R_a = 9.7$ Å, $R_b = 16.3$ Å, aggregation number $N_{agg} = 37$ and degree of dissociation $\alpha = 0.95$.

^b Approximated assuming $d = 2\pi/q_b$, where q_b is the position of the first scattering maximum.

^c Fitting parameters (core-shell oblate ellipse model used): $R_a = 27/32.4$ Å, $R_b = 55.7/61.7$ Å, $N_{agg} = 1023$, $\alpha < 0.05$.

3.3. Effects of temperature on surfactant aggregation

Having established that counterion selection already provides some control over surfactant phase behaviour, and that this can be rationalised in terms of counterion hydration and diffuseness of charge, further exploration of the surfactant phase behaviour with temperature was performed. These experiments provided particularly interesting and unexpected features, as shown in Fig. 4. Taking as an example methylammonium perfluorooctanoate (MaPFO, Fig. 4a), at 25 °C the characteristic disordered lamellar phase described above is seen. On an increase to 35 °C, this phase is replaced by another apparently lamellar structure, this time significantly more ordered/crystalline, as evidenced by the much lower Caillé parameter required to fit the scattering curve (Table 4). On further heating to 48 °C this phase in turn evolves into a micellar phase (where the weak form factor scattering is somewhat overwhelmed by the intense structure peak as seen previously for similar micellar systems [27]). Finally at 60 °C, the same micellar phase exists, although the scattering indicates a decrease in aggregation number and increased dissociation, concomitant with increased overall surfactant solubility.

It would appear that all of the surfactants studied show this same progression of phases (to our knowledge as yet unreported in the surfactant literature) with temperature, although it is clear that not all phases are evidenced for all surfactants, indicating that the transition temperatures vary with both concentration and temperature when the counterion is changed, in line with expectation from the sections above. It can be seen that both transitions (disordered lamellar $\rightarrow$ ordered lamellar and ordered lamellar $\rightarrow$ micellar) occur at higher temperatures for ethylammonium PFO (Fig. 4b). For the trimethylammonium and diethylammonium surfactants (Fig. 4d and f) only the first transition from disordered to ordered lamellar is seen. Interestingly, at a lower concentration of 5 wt%, the diethylammonium analogue shows the same transition (disordered lamellar to ordered lamellar).

The lamellar to micellar transition is well known, and can be induced by temperature, pressure or salt addition for certain surfactants [44]. In this case, the transition can be explained in terms of two well-understood solubility effects: (1) as temperature increases, the surfactant becomes more soluble and thus the effective thermodynamic drive for formation of a higher order (lamellar) mesophase is lower; and (2) higher temperatures entropically favour counterion dissociation, resulting in greater

effective headgroup charge within the layer, the mutual repulsion of which causes curvature and micelle formation [45].

However, the explanation for the formation of a more ordered lamellar phase is more challenging. Transitions between different lamellar structures and crystalline states thereof are well known in the structurally diverse world of lipid membrane physics [46], although not routinely reported for simple surfactants such as those explored here. A key piece of information in interpreting the change seen here is in the comparison of diethylammonium perfluorooctanoate phases at 5 and 10 wt% (Fig. 4e and f respectively). As would be expected for monophasic lamellar system, the position of the main Bragg peak (albeit a rather diffuse one in the case of the 5 wt%) scales with concentration for the disordered lamellar structure seen at low temperature in each case. That is to say, for the more concentrated sample, the Bragg peak appears at higher q values (a reciprocal length scale) thus indicating smaller inter-membrane spacing, a logical conclusion from a simple volumetric space-filling argument (see Table 4).

However, tellingly, the primary Bragg peak for the high temperature ordered lamellar phase of both dEaPFO concentrations appears to indicate the same inter-membrane spacing. This is clearly not possible if the sample is a pure lamellar phase based on the disparity in available membrane volume fractions between the two samples. The most consistent explanation for these data is that the system is micro-phase separating into an ordered lamellar phase that coexists with a micellar phase, in a kinetically trapped state that may remain optically isotropic in appearance. The micellar phase is essentially 'invisible' in the scattering curve as its scattered intensity is so small compared to the lamellar signal [27], but its high viscosity inhibits macroscopic phase separation.

It is important to note that at the time of analysis macroscopic phase separation was only observed in tPaPFO, which showed distinct precipitation (seen in the SANS spectra as characteristic surface scatter – see Supplementary Material). Further subsequent analysis between crossed polarising filters (example pictures are shown in Supplementary Material) showed a distinct phase separation for MaPFO, although this was not observed for the larger counterions EaPFO or dEaPFO, at either 5% or 10%, despite some minor changes in birefringence. As noted in the above sections, samples of tEaPFO at 5% and above showed a macroscopic phase separation at room temperature, and hence were not analysed by SANS. In light of these results, it is likely that similar phase transitions are occurring for tEaPFO, but at temperatures below room temperature.

To our knowledge SANS data showing this behaviour has not been described previously, however we have seen related kinetic effects for perfluorooctanoate surfactants with simple inorganic counterions in the presence of a semi-fluorinated co-surfactant [27]; this is the first example for a single component (surfactant + counterion) system. Excitingly, this may indicate that the organic counterions explored here are behaving as *de facto* co-surfactants, in line with previous neutron reflectometry measurements that showed penetration of alkylammonium counterions into the surfactant headgroup layer for dodecylsulfate surfactants. Similar behaviour has also been hinted at but not quantified in some reports for fluorosurfactants also. For example, the behaviour of tPaPFO has been observed by adding tripropylammonium bromide to NaPFO solutions, which were found to show clouding above 40 °C [47]. This concurs with the SANS data obtained in this study (see Supplementary Material), that showed the tPaPFO/water system to precipitate above 40 °C. Furthermore, systems with tetraalkylammonium counterions have shown temperature related clouding effects, such as in the tetrabutylammonium perfluorooctanoate/water system [48] and the hydrocarbon dodecyl and tetradecylsulfates [49]. In the case of the former, given the initial homogenous phase was of rod-like micelles, it is unlikely that a

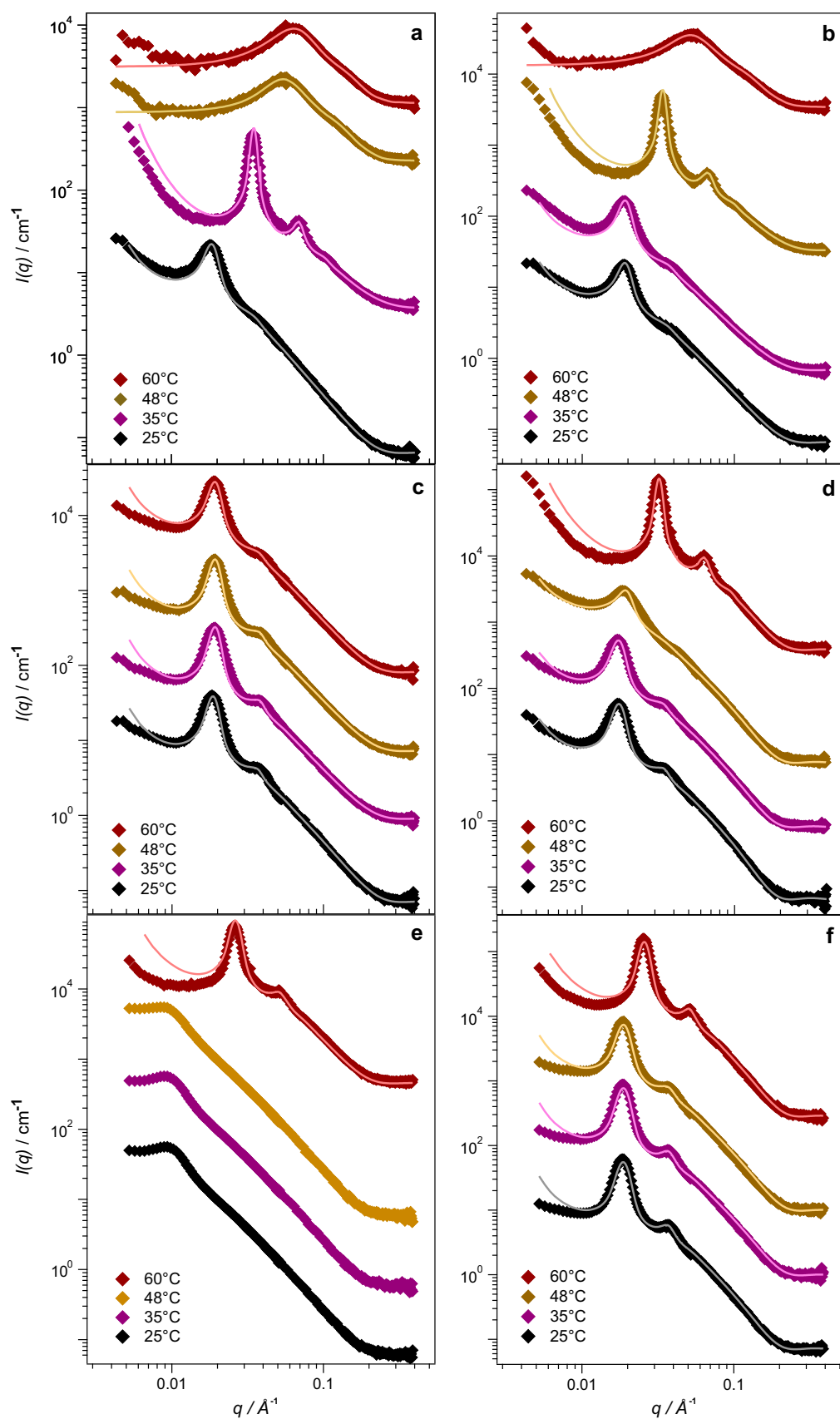


Fig. 4. Temperature controlled SANS analysis of 10% solutions of (a) MaPFO, (b) EaPFO, (c) nPaPFO, (d) tMaPFO, (f) dEaPFO and (e) 5% solution of dEaPFO. Full set of SANS data can be found in the Supplementary Material.

Table 4
SANS fitting parameters for 10% PFO surfactant solutions.

Sample	Φ	T (°C)	d (Å)	η_{cp}	δ (Å)	
MaPFO	0.10	25	338	0.60	19	
		35	180	0.26	14	
EaPFO	0.10	25	326	0.60	20.5	
		35	325	0.55	18.5	
		48	185	0.26	17	
nPaPFO	0.10	25	335	0.43	19	
		35	325	0.40	18.5	
		48	325	0.43	18.5	
		60	325	0.45	19	
tMaPFO	0.10	25	358	0.40	27	
		35	360	0.45	26	
		48	320	0.80	25	
		60	196	0.24	22	
			L (Å)	R (Å)	N_{agg}	α
MaPFO	0.10	48	195	11.7	245	0.06
		60	92	11.5	111	0.24
EaPFO	0.10	60	206	12.1	275	0.05

similar two-phase system is occurring. Indeed, both sets of authors speculate on the formation of a micellar network, where micelles are ‘bridged’ together by the bulky counterions, with obvious mechanistic similarities to the explanation offered here, but with different initial homogenous phases.

It is possible that the origins of the temperature effects observed for these ionic surfactants are similar to the known clouding behaviour of nonionic surfactants caused by dehydration of the head group [12]. The poorly hydrophilic alkylammonium counterions would likely also be susceptible to the same entropically driven dehydration, therefore increasing the attraction between the counterion and surfactant. Such charge condensation could also give rise to counterion penetration into the surfactant aggregates much like a cosurfactant, causing changes in phase curvature, an effect that is not without precedent [50]. While there is usually a strong distinction between ionic and nonionic surfactants in the literature, the characteristics of surfactants with poorly hydrated counterions, such as those described here, seem to indicate that they occupy a middle ground between the two, corroborated by their weak dissociation in certain cases.

4. Conclusion

We have explored the effects of increasingly bulky and ‘hydrophobic’ alkylammonium cations on the phase behaviour of perfluorooctanoate surfactant anions. As counterion substitution degree increases, a general trend to lower melting point materials is seen, and indeed the tri-*n*-alkylammonium analogues are all room temperature ionic liquids, adding to the known catalogue of fluorinated protic ionic liquids [10]. It is seen that in line with expectation [3], simple behaviour such as micellisation and air-water interfacial adsorption are enhanced by the addition of a hydrophobic counterion, although these effects are generally rather modest, indicating that adsorption and micellisation are driven primarily by the extreme hydrophobicity of the perfluorooctyl tail-group.

However, at higher concentrations, these surfactants are found to form single component lamellar mesophases in water, the properties of which can be subtly controlled by the choice of organic counterion (as well as *via* the conventional levers of temperature and concentration). This remarkable control is unprecedented for such molecules [14–16,19]. Membrane spacing and overall lamellar phase order, as evidenced by the Caillé parameter that describes

membrane flexibility, are significantly affected by the level of substitution of the alkylammonium counterion, demonstrating a decisive role for counterion steric bulk and charge density.

Interestingly, many of the systems studied showed a transition from disordered lamellar phases to micellar systems *via* a unique ordered lamellar-micellar coexistence region. The thermodynamic origin of this coexistence region is yet to be fully uncovered, but the temperature window within which it is seen is also highly counterion-dependent. These kinetically trapped systems may provide unique opportunities for templating [27], and the control offered by counterion choice means that they can be tailored to specific reaction conditions.

Moreover, this work indicates the strong role of counterion dissociation and condensation in such surface and aggregation studies, encouraging caution with analysis using assumptions of ideal Gibbsian dissociative behaviour. It also shows that measures of ‘hydrophobicity’ are generally insufficient in predicting and explaining the properties of surfactant counterions, and a more holistic understanding of size, diffuseness of charge and hydration is warranted.

Acknowledgements

M.J.P. acknowledges support from 3M Corporation and the Victorian Government. We acknowledge the support of the Bragg Institute, Australian Nuclear Science and Technology Organisation, in providing the neutron research facilities used in this work. We are indebted to Dr. Liliana de Campo for insightful discussions concerning the SANS data.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.jcis.2016.04.039>.

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Chapter 4

Increasing surface activity of perfluorooctanoate ions for enhancing their remediation by foam flotation

4.1 Introduction

The large scale production and use of fluorinated surfactants such as PFOA and derivatives has left a legacy of contaminated sites around the world. Most commonly these are around production facilities from release of untreated wastewater and areas where the use of aqueous film-forming foams (AFFF) was common, such as airfields. The chemical stability of these molecules means biodegradation in the environment is negligible and remediation methods are needed to remove these contaminants for destruction. Surface activity is a key part of these remediation processes, which currently rely on adsorption of surfactants to either solid/liquid interfaces (filtration) or air/liquid interfaces (foam separation).

Currently, filtration with carbon-based substrates is commonly utilised for PFOA remediation¹⁻⁴. This is due to a combination of being useful for both ionic and non-ionic PFAS species, and cost considerations. For ionic species such as PFOA and PFOS, ion-exchange substrates can provide more efficient removal (in terms of amount adsorbed)² but are more costly to

maintain than activated carbon substrates.

Being inherently surface active, foam separation is an attractive method for concentrating PFAS for destruction from contaminated water at large scales. As has been noted previously in this thesis, the major limitation is that typical environmental limits being set by regulatory bodies are far lower than the onset of measurable surface activity. In the US, the guidelines for acceptable concentrations of PFOA range from 0.1 - 1 $\mu\text{g/L}$ in groundwater,⁵ however for dissociated PFO the onset of surface activity based on lab measurements is on the order of 0.1 mM (40 $\mu\text{g/L}$) (Figure 4.2a). PFOS is somewhat more surface active than PFOA due to the larger hydrophobic region but the difference is not enough to make a meaningful difference for those limits.

Following on from work in the previous chapter, this chapter looks further into the surface activity of perfluorooctanoate with organic amine molecules. Surface activity is a key part of all remediation methods for perfluorooctanoate contamination, and the relevance of enhancing surface activity is shown by analysing the effect on a simple foam separation process. Foam flotation is a widely used separation process that is of interest in PFAS remediation due to its low cost and scalability. Currently, its applicability in this area is limited due to its low effectiveness in dilute solutions usually encountered in environmental contamination. The inclusion of suitable additives that could enhance the process at lower surfactant concentrations would make this method more widely applicable and could be easily implemented in existing designs.

4.2 Hypothesis and preliminary data

4.2.1 Foam separation remediation

Foam separation (or foam fractionation) is a useful separation process for removing and concentrating surface active materials from aqueous environments. It is superficially similar to

froth flotation used for separation of particulate matter in the mining industry, but more applicable to dissolved species⁶. It is an attractive separation method due to its cost effectiveness and ease of scalability. Since air can be used as the carrier gas the running costs are low compared to filtration methods, and the simplicity of the setup means designs can be easily produced for a wide range of volumes.

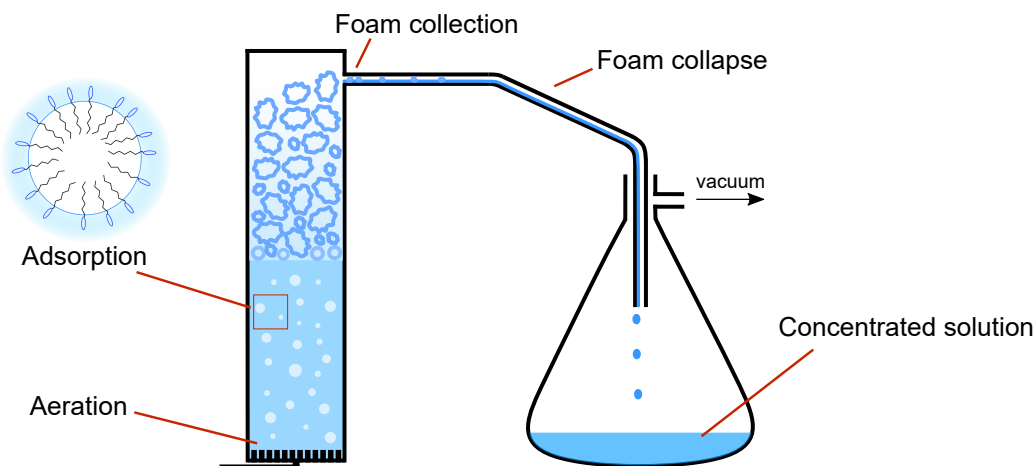


Figure 4.1 Schematic diagram of a simple lab-based foam separation process, similar to that used in this study. Aeration creates rising bubbles, and surfactant molecules adsorb to the air/water interface and are carried to the surface. Foam formed at the surface is then enriched in surfactant and is easily removed.

The process relies on the hydrophobic interactions of materials with water and the resulting drive to the air/water interface. Since air is a more favourable environment for hydrophobic species, they will adsorb to the air/water interface to reduce their interactions with water.⁶ For particles, the process can be more accurately pictured as bubbles adsorbing to the particle surface, depending on the relative size of the bubbles and particles. A continuous supply of air bubbles is introduced at the bottom of the vessel, which produce a large amount of air/water interface for adsorption. These naturally rise due to buoyancy through the solution where adsorption occurs, carrying material to the surface. At the surface, foam formed is therefore enriched with the surface active component and can be removed into a concentrated solution/slurry. A schematic for a simple lab-based setup for this process is shown in Figure 4.1.

Key considerations for a successful separation are stability of the bubbles and resulting

foams and the interactions between the material and bubbles. Additional surfactants can be included to control foam formation and stability.⁷ For dissolved surfactants such as PFO, surface activity is concentration dependent, therefore the amount adsorbed at the interface can be variable. PFO is a good foaming agent and in theory this would mean additional surfactants would not be necessary for the process. In practice, the high molecular solubility and low concentrations in relevant contaminated waters mean foaming is not guaranteed in a given wastewater stream, although coarse foams can be extracted from most solutions with sufficient gas flow. Additional surfactants can be included to produce stable foams and hence greater interfacial area for low concentration PFOA solutions^{8,9}. While this creates more area for adsorption, which is beneficial for the process, it does not solve the fundamental issue of low surface activity, and reaching lower concentrations in the treated water is still difficult. Additives that increase the surface activity of PFO could provide a greater benefit to removal efficiency and achieving lower concentrations in the treated product. Considering the low (and potentially still lowering) acceptable environmental release limits set for PFOA, it is likely reaching those with this process alone would be unrealistic, however being such a cost effective process means it can be implemented as a ‘first pass’ treatment step to reduce the burden on costly filtration processes required for complete removal. Lower amounts after the first step means more uptime on filtration substrates and less expenses replacing or regenerating them.

4.2.2 Surface activity of NaPFO and interactions with surfactants

As interactions of PFO with other surfactants are potentially an important factor, some preliminary measurements were performed to gain insight into whether PFO interacts in a synergistic manner with common hydrocarbon surfactants. This was achieved by investigating surface tension as a function of concentration for NaPFO and two common hydrocarbon surfactants, sodium bis(2-ethylhexyl)sulfosuccinate (Aerosol-OT, or AOT) and Triton X-100, and comparing this to that observed in a mixture of the two (at a 1:1 molar ratio). These sur-

factants were chosen as they are representative anionic (AOT) and non-ionic (Triton X-100) surfactants. These results are shown in Figure 4.2. Considering the NaPFO data alone, the high solubility of PFO is readily apparent and much higher than the hydrocarbon surfactants used. There is no measurable surface activity in the stock NaPFO solution below 0.1 mM and this point at the onset of surface activity was used for a large part of this study to determine any increases in surface activity. This allows the maximum possible range of surface tension reduction to be measurable in the presence of any additives.

Considering mixed systems, surface activity shows very similar results to the hydrocarbon surfactants alone. The slope of these data is related to the surface excess concentration through the Gibbs adsorption isotherm:

$$\Gamma = -\frac{1}{nRT} \left(\frac{\partial \gamma}{\partial \ln C} \right) \quad (4.1)$$

where Γ is the surface excess concentration, R is the gas constant, T is temperature, γ is the liquid surface tension and $\left(\frac{\partial \gamma}{\partial \ln C} \right)$ is the slope of the γ vs. $\ln C$ plot just prior to the critical micelle concentration. In our systems, background electrolyte is low, so for ionic surfactants such as NaPFO, $n=2$. The equation is more complicated in a mixture of multiple surface active components, but can be the slope can still be viewed qualitatively as a measure of the surface excess concentration. Both NaPFO/AOT and NaPFO/TX-100 systems have almost identical gradients as the equivalent pure hydrocarbon system and are significantly lower in magnitude than NaPFO alone. Surface excess is a measure of molecular packing at the water/air interface; greater surface excess concentration indicates more molecules at the interface. How the molecules pack at the interface is dependent on the geometry of the molecules, therefore these data indicate that the interface is predominantly saturated with the more surface active hydrocarbon surfactants. Furthermore, the measured cmcs are remarkably similar. Considering these findings, this implies that the presence of hydrocarbon surfactants is not increasing the surface activity of NaPFO and would not have a significant impact on the yield of a foam

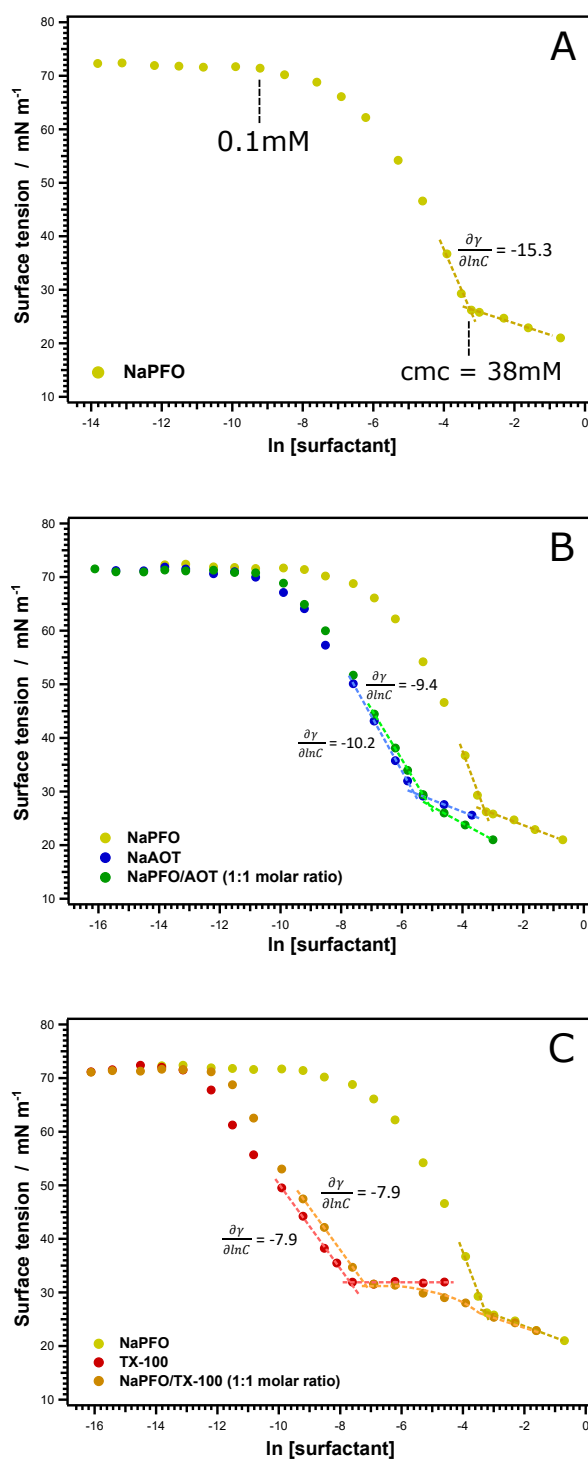


Figure 4.2 Surface tension as a function of concentration for NaPFO (a) and NaPFO mixed with the anionic surfactant NaAOT (b) and Triton X-100 (c). These mixtures were both at a 1:1 mole ratio and the combined surfactant concentration is graphed. Both mixtures show profiles closely matching the hydrocarbon surfactant indicating little in the way of synergistic interactions. The Triton/NaPFO system shows two cmcs indicating largely independent surface activity and little if any increase in NaPFO at the interface at low concentrations.

separation process. The NaPFO/TX-100 system also faintly shows a second cmc for NaPFO, which provides further evidence of largely independent interfacial activity in the mixture.

4.2.3 Surface activity of NaPFO with added organic ammonium species

From the work in Chapter 3, it was found that PFO with organic ammonium counterions showed a significant decrease in both cmc and surface tension at the cmc compared to the unsubstituted and hydrophilic ammonium counterion (Figure 1a). This, combined with other literature reports highlighted in Chapter 2, are good indications that these small molecules could be used as additives in PFO solutions to help drive the fluorosurfactant to the interface. The increased binding of these molecules to the surfactant headgroup that is likely responsible for this behaviour should be largely unaffected by other hydrophilic ions in solution. Preliminary measurements with *n*-butylamine and *n*-octylamine confirmed this hypothesis. Addition of these to a 0.1 mM NaPFO solution produced a significant reduction in surface tension, with the more hydrophobic *n*-octylamine showing the greatest effect (Figure 4.3b).

Cationic surfactants were deliberately excluded from the surfactants investigated in the previous section as they have known positive interactions with anionic surfactants due to electrostatic interactions of the head groups.^{11–13} This results in cmcs of the mixture often (but not always) lower than either individual component and with correspondingly lower solubility. A recent study has explored the use of cationic surfactants in PFOA remediation in detail, and this wasn't explored specifically in this project. The surface activity of cationic/anionic surfactant mixtures is complex (as seen in the behaviour of NaPFO/octylamine in Figure 4.3b) and could form a study in and of itself.

It was hypothesised that smaller amine molecules could provide a significant improvement without the extra considerations required when mixing surfactants. Instead, similar to work in the previous Chapter, a systematic approach was taken, with the choice of molecules added

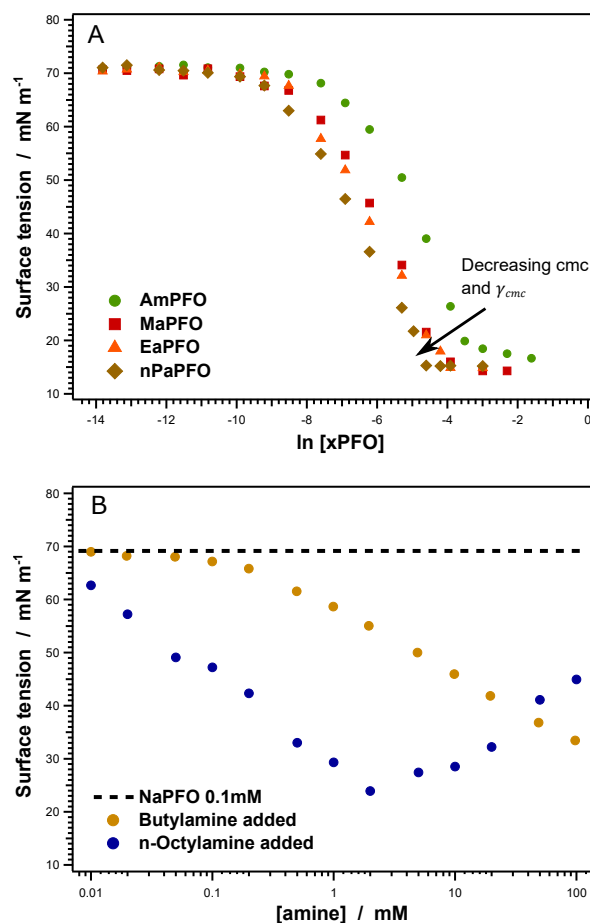


Figure 4.3 Equilibrium surface tension measurements showing the effects organic ammonium species have on surface activity of PFO. (a) Surface tension data of PFO with primary amine counterions adapted from the Supplementary Material of Pottage *et al.*¹⁰ (presented in Chapter 3). As hydrophobicity of the counterion increases, the cmc and surface tension at cmc decrease. (b) Preliminary tests of 0.1 mM NaPFO solutions with added butylamine and octylamine at pH 5. Increasing amount of amine lowered the surface tension of the NaPFO solutions, with the more hydrophobic and surface active octylamine showing the greatest reduction.

covering a range of hydrophobicity up to *n*-octylamine, which is weakly surface active by itself. This includes and expands upon on data presented in Figure 4.3b. Terminally di-substituted amines were also included at similar chain lengths to determine what effect increasing the amount of charge on the added molecules had on surface activity. The aim was to show how these or similar additives could increase the yield of foam separation remediation for PFOA, with both equilibrium and dynamic surface tension measurements used to analyse the fundamental surface chemistry combined with a simple foam separation setup to quantify the yield of PFOA in the presence of these different additives. The full study has been submitted for

publication in the journal Langmuir and is presented in the following section in its submitted form. Supplementary Material is included in Appendix II.

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Increased surface activity and foaming of dilute perfluorooctanoate solutions by addition of organic amines

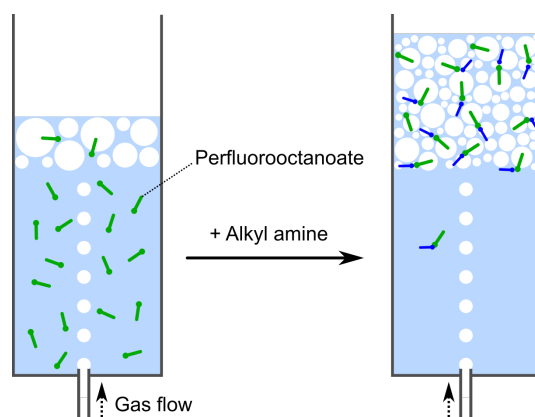
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Abstract



Foam fractionation for removal of low concentrations of surface active materials is an important method in environmental and municipal water decontamination. Persistent fluorinated organic pollutants (fluorosurfactants in the class per- and poly-fluorinated alkyl substances or PFAS) may benefit particularly from this technology. However, comparatively low surface activity and inefficient removal of the prototypical and environmentally deleterious perfluorooctanoate ion inhibits successful uptake

of foam-based removal methods. Here, surface activity of dilute (0.1 mM) sodium perfluorooctanoate solutions was analysed as a function of addition of mono- and di-substituted organic amines in order to determine their effect on surface activity for enhancing foam flotation-based remediation. Amine chain lengths were varied from 2 to 8 carbons, giving a wide range of hydrophobicity, with pH maintained at pH 5 to ensure effective charge-based interactions with perfluorooctanoate anions. For both mono- and diamines, increasing alkyl chain length (and thereby hydrophobicity) was found to increase surface activity of dilute NaPFO solutions, with a greater effect seen for the mono-substituted amines. Equilibrium surface tension measurements were compared to simple foam column tests and foam extraction measurements, to determine the viability of such compounds as additives for increasing the efficiency of PFAS remediation. Generally, the addition of organic amines resulted in an increase in PFOA concentration in the extracted foam and a greater decrease in bulk solution concentration, with a greater effect as hydrophobicity increased. The greatest effect was seen for butyl amine, which resulted in a 200% increase in PFOA concentration in separated foam. Mono-substituted amines showed a clear maximum in effectiveness with alkyl chain length; the more hydrophobic molecules n-hexylamine and n-octylamine had either less reliable or no foaming potential, which reduced the amount of PFO removed.

Introduction

Problems arising from the use and environmental persistence of per- and polyfluorinated alkyl substances (PFAS) are now widely accepted. While specific human health effects are still being investigated in many jurisdictions, there is now evidence for a variety of negative health outcomes resulting from persistent exposure to some PFAS species,¹ and large-scale use is generally being (or has been) phased out. However, due to the chemical stability and environmental persistence of these materials, the legacy of their past use is a contin-

uing problem. PFASs, such as perfluorooctanoic acid (PFOA) and perfluorooctylsulfonate (PFOS), saw widespread use over many years in manufacturing of fluorinated materials (e.g. PTFE and fabric-protecting stain repellants)² and as a major component in some firefighting foams.³⁻⁵ The size of contaminated areas and amount of contaminated material to be dealt with means efficient and scalable remediation processes are essential for any successful removal efforts.

Due to their amphiphilic nature, PFAS contamination can be found in both soil and water systems, and show significant mobility within environmental matrices due to their ability to adsorb readily at air–water and solid–water interfaces.^{6,7} The relatively high solubilities in water of some PFASs makes water contamination a greater problem than many persistent organic pollutants, and is the main pathway to bioaccumulation and negative affects in human and animal populations. This is particularly true for surfactant PFAS molecules such as PFOA and PFOS. Indeed, the complex solubility, assembly and partitioning of surfactant fluorinated alkanes in hydrocarbon (lipid) and aqueous systems is only recently being uncovered.⁸ Due to PFAS ubiquity in aqueous matrices, many methods have been proposed for remediation of PFAS-contaminated water. Most commonly reported procedures are based around sorption processes^{9,10} and ion-exchange. Activated charcoal is the most attractive substrate for such processes due its low cost and availability but is relatively inefficient for perfluorooctanoic acid,⁹ although more advanced substrates have been reported recently such as polymer/carbon composites,¹¹ amine-functionalised materials,¹² mineral/carbon composites,¹³ graphene composites¹⁴ and other nanomaterials.¹⁵ Ion-exchange can provide more efficient removal,^{16,17} however is more expensive to implement and vulnerable to rapid fouling from other components present in aqueous streams. The main drawback to these methods is the need for constant replacement of the adsorbent materials, which regardless of the efficiency of chosen adsorbent is still an ongoing cost and time consideration.

Foam flotation, a widely used separation method in a variety of fields, is an attractive alternative for surfactant remediation, relying on the surface activity of species to aid in

their removal. In wastewater, this process is used to separate particulates and hydrophobic materials from aqueous systems. For surfactants such as PFASs, being inherently surface active,⁶ this is an attractive alternative for low-cost, efficient remediation that is easily scalable. While not practical to meet most concentration limits by itself, it has the potential to be a useful ‘first pass’ method to concentrate PFASs from bulk solutions and relieve the burden on adsorbent processes and energy-intensive destruction methods. Foam flotation has been demonstrated as a means of PFAS remediation in several studies.^{18–21} While in theory a promising method for PFAS remediation, the high solubility and lability of key PFAS species at interfaces makes their recovery using this method inefficient for dilute solutions, as the concentration required for measurable surface activity and foaming of such surfactants is relatively high. A prominent example is perfluorooctanoate which has a critical micelle concentration (cmc) in the range 27–36 mM depending on counterion/solution conditions,²² which is many orders of magnitude above the concentration limits being advised by regulatory bodies (e.g. in US states²³). At the concentrations typically dealt with in wastewater and remediation situations, surface activity of perfluorooctanoate is negligible, making foam flotation extremely inefficient. Aeration with other recovery methods besides foam have been reported, such as aerosol capture^{24,25} and uptake by surface duckweed.²⁶ Hyphenated approaches are also possible, such as combining aeration with ion-exchange adsorption to improve adsorption²⁷ or combining foam extraction with aerosol capture.²⁵ While these have reported reduction of fluorinated surfactant levels, the scalability of these more elaborate techniques is less certain.

In order to make foam flotation more viable as a large-scale remediation method for fluorinated surfactants, it is necessary to find ways to increase the surface activity of these materials to make foaming more efficient and reach lower PFAS concentrations, which will help to reduce or remove the burden on adsorption processes. Addition of some metal ions to the system, for example, has been shown to increase PFAS recovery using this method.¹⁸ This study found high-valency metal ions (Fe(III), La(III)) most effective at increasing removal

by foam flotation, but this was highly pH dependent. The most efficient removal was at pH 2–3 which is not ideal for large scale water treatment, while no increase was observed above pH 6.

The present work aims to develop further understanding of how additives affect surface activity of PFASs, with a focus on potential for large-scale foam flotation under milder conditions. In previous work,²⁸ we investigated the behaviour of perfluorooctanoate with a variety of alkylammonium counter ions. Surface activity was found to increase as hydrophobicity of the counterion increased. Here, we explore the use of some common organic amines to increase surface activity of perfluorooctanoate solutions. For charge-based interactions to occur in these systems, the only requirement is that the pH is below the pK_a of amine functional groups, which reduces sensitivity to pH effects compared to high-valence metals. Changes in equilibrium surface tension and foaming behaviour are used to compare surface activity variation as a function of chain length and functionality of the amines used. Practical implications of this behaviour are explored using simple foam separation experiments to show how a similar approach could improve efficiency of foam separation based remediation processes.

Materials and Methods

Materials

Ultrapure water was obtained from a Millipore Direct-Q 5 with minimal resistivity of 18.2 M Ω ·cm. Sodium perfluorooctanoate (NaPFO) was prepared via stoichiometric neutralisation of perfluorooctanoic acid (FluoroChem, 99%) with NaOH (Merck, reagent grade) in ultrapure water. Excess water was evaporated and the resulting product was dried under vacuum at 70 °C. Organic amines ethylamine (70% in H₂O), n-butylamine (99.5%), n-hexylamine (99%), n-octylamine (99%), ethylene diamine (99.5%), 1,4-butanediolamine (99%) and hexamethylenediamine (98%) were all used as received from Sigma Aldrich. HCl (reagent grade, Univar) and NaOH (99%, Merck) were used for pH adjustment. Stock solutions of amines

were prepared with stoichiometric HCl to aid solubility of the more hydrophobic compounds and reduce the quantity of liquid needed for later pH adjustment.

Surface tension analysis

For equilibrium surface tension measurements, pendant drop tensiometry was used on a custom built apparatus.²⁹ Image analysis was performed using the OpenDrop software package (Version 1.1, www.opencolloids.com) which iteratively fits drop profiles using the Young–Laplace equation to determine surface tension. Drops were suspended inside a cuvette with a saturated atmosphere to keep evaporation minimal, and measurements were typically run for 50 seconds, which was sufficient for equilibration. Each sample was run in triplicate. Most measurements were made at pH 5, and adjustments for each sample were made immediately prior to measurements, with HCl or NaOH. The slight change in volume was taken into account in final concentrations recorded.

Foaming experiments

Foaming experiments were performed using a simple glass foam column with nitrogen as the carrier gas. All samples, except amine controls, used 50 mL of 0.1 mM NaPFO solution, which produced a consistent unsparged liquid height of 72 mm in the column. The gas flow rate was constant at 210 mL·min⁻¹ for 30 s to reach equilibrium foam height, then height was measured. This flow rate was chosen so as to produce a small layer of foam in the control sample so both increases and reductions would be noticeable.

Foam extraction

Foam separation was achieved using a 1 L twin-necked round bottom flask equipped with a still head to send foam to a receiving vessel (see Supporting Information). A polyethylene tube with a fritted end was inserted, and nitrogen was used to produce foam, with a weak

vacuum from an aspirator aiding the removal of the foam layer. Because of differences in foaming potential between samples, gas flow was not consistent between samples (ranging from 4.2 to 6 L·min⁻¹; instead the flow was adjusted such as to give a slow constant flow of foam to the reciever and a constant volume of foam was extracted (250 mL). Aliquots were taken from the bulk solution at 2 minutes, 5 minutes, and then subsequently at 5 minute intervals until extraction was complete, and the extracted foam was analysed on completion.

Perfluorooctanoate quantification

Analysis was carried out at the Monash Analytical Platform, Australia (School of Chemistry, Monash University). LC/MS data were generated using a Agilent 1200 series LC (Santa Clara, CA, USA) equipped with a Waters Micromass ZQ MS system (Milford, MA, USA) with an ESI source. An Agilent SB-C18-bonded silica 1.8 μ M (2.1 $\times$ 50 mm) column was used for the LC/MS study.

The mobile phase consisted of MeCN and H₂O, both containing 0.1% v/v formic acid, and delivered using a binary gradient over 10 min followed by re-equilibration to the starting conditions. The flow rate was 0.4 mL min⁻¹, and the injection volume was 5 μ L. LC/MS analysis was conducted in negative mode electrospray ionisation and elution of the analyte monitored in SIM mode. Concentrations were determined by comparison to a set of calibration standards prepared in blank solvent. The limit of quantitation was 0.01 mM.

Results and Discussion

Equilibrium surface activity of dilute NaPFO with alkyl amine additives

The effects of additives on dilute PFO surface tension were analysed using 0.1 mM NaPFO solution. This concentration was chosen as it is on the cusp of the downturn in surface tension

as a function of concentration (Fig. 1a), thereby providing greatest sensitivity for observing changes in surface tension. Solutions were adjusted to pH 5 to ensure protonation of amine groups while still being relatively ‘mild’ and feasible from a water treatment perspective. Both monoamines and diamines should be fully protonated at pH 5.³⁰ The surface activity of NaPFO was practically identical at pH 5 when compared to the unadjusted sample (pH $\approx$ 7, Fig. 1a), with an identical cmc value and only a slight change in slope in the pre-cmc region.

Amines investigated were either straight chain mono-substituted alkyl amines, or alkyl diamines substituted at their terminal carbons. The difference in substitution (and hence charged sites) means there is a large difference between the hydrophobicity of these two classes. As chain length increases, the mono-substituted amines develop some surface activity, although over the concentration range used, this was only prominent for n-octylamine (see Supporting Information). This transition is less noticeable for the di-substituted amines. Simple cations sodium and calcium (as chlorides) were included to compare the effects observed for the amines with those seen from a simple increase in ionic strength. Ionic surfactants such as NaPFO are well known to show an increase in surface activity as ionic strength increases, and this has been specifically reported for PFAS species³¹ with attention to salts found in natural groundwater systems. For the purposes of enhancing foaming potential of groundwater, effects greater in magnitude than those seen for these simple salts would be expected.

As can be seen in Fig. 1, all additives caused a reduction in the equilibrium surface tension of dilute NaPFO. Increasing amine chain length resulted in greater reductions in surface tension for both monoamines and diamines, however was more prominent for monoamines. For example, 0.1 mM NaPFO solutions with 1 mM ethylamine added showed only a very slight reduction in surface tension (4 mN m^{-1}) relative to pure 0.1 mM NaPFO, while 1 mM added octylamine reduced surface tension by 48 mN m^{-1} . Di-valent samples were much less varied, with surface tension decreases at 1 mM additive concentration ranging from

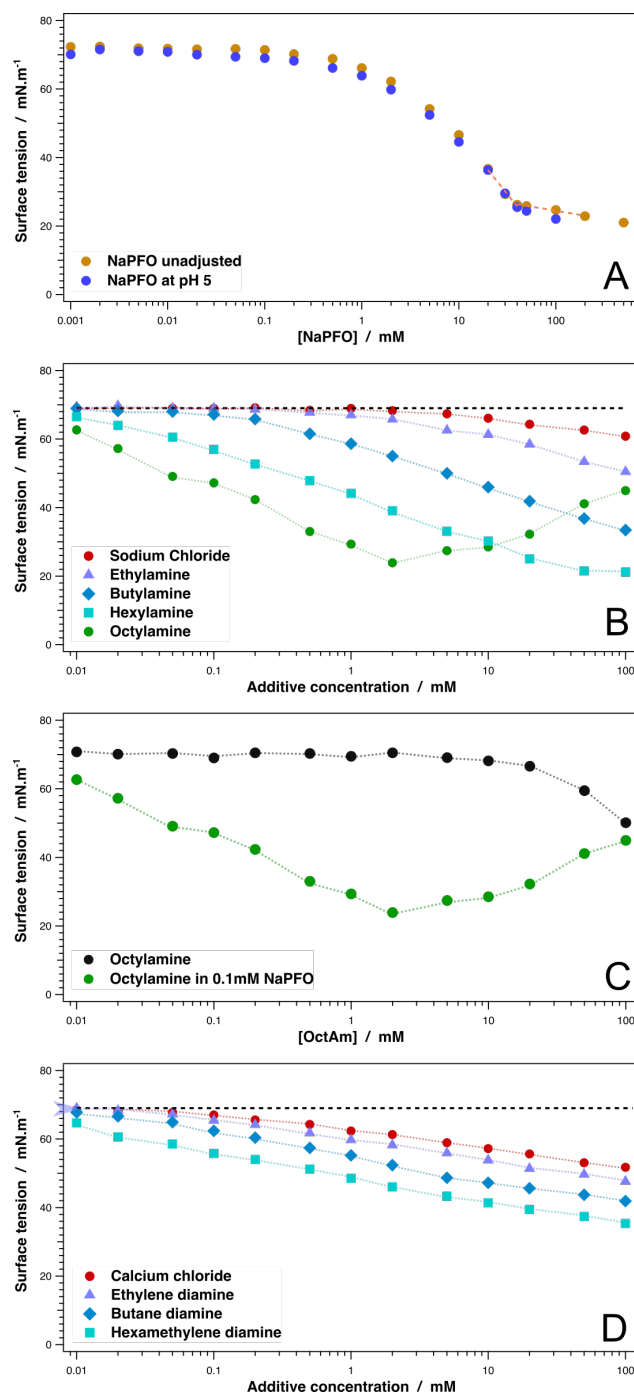


Figure 1: A) Equilibrium surface tension of NaPFO ($\text{pH} \approx 7$) and adjusted to $\text{pH} = 5 \pm 0.1$. NaPFO solutions (0.1 mM) were then analysed with B) monoamine additives and D) diamine additives at $\text{pH} = 5 \pm 0.1$. Dashed line represents the reference value for 0.1 mM NaPFO at pH 5, and dotted lines are drawn as a guide to the eye throughout. The NaPFO/octylamine system is complex, as octylamine is itself surface active (C); in large excess the measured surface activity indicates the interface is dominated by octylamine rather than PFO.

8–28 mN.m⁻¹ compared to 0.1 mM NaPFO. This reflects a more gradual change in overall hydrophobicity for diamine molecules as chain length increases compared to their monoamine counterparts.

It is noteworthy that these data do indicate considerable synergism between NaPFO and additives. Measurements conducted at 0.1 mM NaPFO concentration (where NaPFO itself is essentially non-surface active, surface tension = 69 mN m⁻¹) show large decreases in surface tension with added alkylamines of all types. Even though the amines are also essentially non-surface active in the concentration regimes where the greatest synergism is seen, at such concentration ratios, remarkable increases in surface activity of the PFO–amine complex are observed. This aligns with previous studies where it was seen that alkylammonium counterions decreases the cmc of perfluorooctanoate.²⁸

For n-alkyl amines, interactions with NaPFO become more complicated as the amine begins to become surface active itself. This can be seen in Fig 1c, where a 0.1 mM NaPFO solution with added n-octylamine shows a well defined minimum of surface tension at 2 mM n-octylamine concentration, beyond which surface tension increases again. Octylamine was the only molecule that showed significant surface activity across the additive concentration range explored here. In this case, the mixture of surface active species results in competition at the interface, and as n-octylamine becomes the dominant component it therefore dominates the interface. This is possibly a kinetic effect, although whether these values would reach the same minimum was not determined due to the lengthy time required (> 300 s, and thereby of little relevance to the highly dynamic conditions encountered in foaming).

In general, increasing hydrophobicity of a counterion results in a greater affinity for the ionic head group of the surfactant, and causes an increase in surface activity of the surfactant. This has been widely reported in both fluorinated^{28,32,33} and hydrocarbon surfactants.^{34,35} Most importantly this is largely independent of other ions in the system. As can be seen here, adding a more strongly associating counterion (e.g. alkylamine) to a fully dissociated surfactant system (i.e. alkali metal counterion) can change behaviour of the surfactant.

The main motivation for including two sets of molecules was to investigate whether multiple charged sites on the counterion would increase surface activity of interacting surfactant/counterion complexes when compared to the simple monovalent case. There is a noticeable difference between surface activity of PFO in the presence of Na^+ compared to Ca^{2+} , which indicates stronger binding of Ca^{2+} to the carboxylic acid group of PFO and potentially interaction of the counterion with two surfactant ions. For organic amine counterions, differences between monoamine and diamine samples are not as obvious. Not only is there less change as chain length increases for diamine samples, there is also a more gradual increase in surface activity as concentration of added diamine increases. And yet, for the two shortest alkyl chains (ethyl- and butyl-) there is a greater effect on surface tension at lower amine concentrations (up to 1 mM) when diamines are used, as even though change as a function of concentration is lower for diamines, the onset of increased surface activity is also at significantly lower concentration.

From these data it would appear that charged-based interactions between perfluorooctanoate and organic amines are strengthened by increasing the counterion charge, with the tradeoff of lowering the upper limit of effect on surface activity. In a practical setting, this would present an intriguing optimisation problem, especially in wastewater where any additives may have different upper limits on their usable concentrations, as well as interacting differently with other components that may be present.

It is also worth noting that it has been reported that the change in interfacial adsorption (measured as the adsorption coefficient K_i) for PFO is small when the systems are dilute (1–10 mg L⁻¹ PFO)³⁶ and the present work seems to support this. However, for a large scale remediation operation, even a small increase in surface activity would be advantageous.

Additive affects on foaming

To investigate whether the observed reduction in surface tension when adding organic amines to sodium perfluorooctanoate solutions could be useful for enhancing foaming capacity of

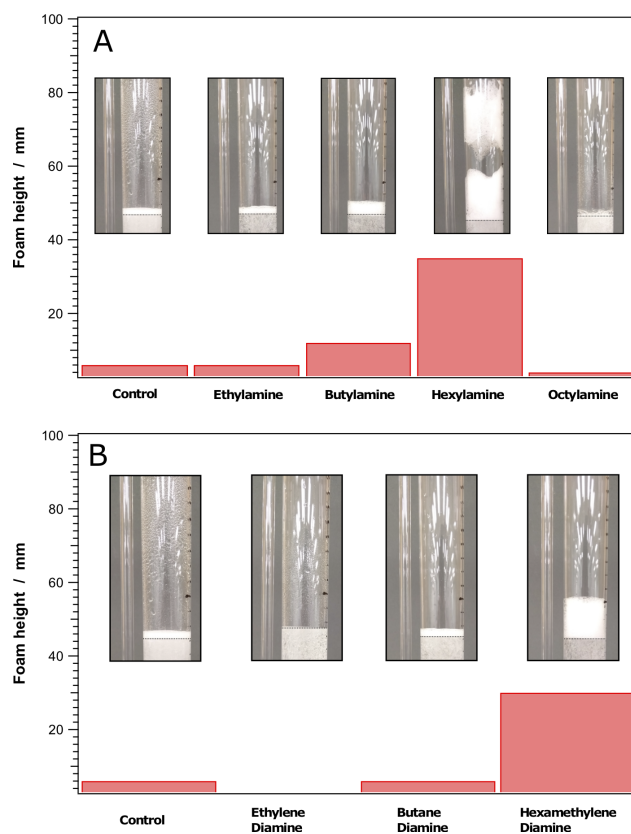


Figure 2: Foaming test results at room temperature for A) monoamines and B) diamines with 0.1mM NaPFO and 1mM of added amine. The dashed line indicates the foam/liquid interface and the black column markers indicate 10 mm intervals. The NaPFO/ hexylamine showed significant fluctuation in foam height, the image shown is indicative of the average equilibrium foam height.

dilute PFO, measurements were performed using a simple foam column setup. Based on data in Fig. 1, 1 mM additive loadings in 0.1 mM NaPFO solutions were analysed. As systems were quite dilute, observed foam volumes were comparatively small, making direct quantification of foam height possible. Conditions were deliberately kept so as to avoid exaggerating foaming of these systems, such as by increasing the gas flow rate. The flow rate used here was determined as that required for a small but measurable amount of foaming in the control sample (0.1 mM NaPFO with no additive), in order to best indicate significant increases while allowing decreases to also be measured.

Images of equilibrium foam heights are shown in Fig. 2. Despite the modest foaming observed, there is still a general trend of increasing foam height as length of the carbon chains increases for both monoamine and diamine systems. This generally correlates with equilibrium surface tension data, with n-octylamine and ethylene diamine being outliers and reducing foaming potential. Both of these samples showed no measurable foaming, which was an unexpected result. Octylamine’s behaviour was particularly unanticipated as its deviation from the trend seen for the other organic amines was quite dramatic. Measured foam heights are summarised along with other measured parameters in Table 1

We further investigated the short time adsorption dynamics of these systems using bubble pressure tensiometry to obtain dynamic surface tension data at short time-scales (Fig. 3). Broadly, these data follow the same trends as seen in equilibrium surface tension data, with greater decreases in surface tension at medium and longer times ($t > 1$ s) seen for increasing amine alkyl chain length. Interestingly however, at very short times ($t < 0.25$ s) the octylamine + NaPFO system did appear to show the least decrease in surface tension (see Supporting Information) before transitioning to be the most surface active combination after around 0.4 s. This may arise because octylamine would form the largest species (ion pair) with perfluorooctanoate, resulting in the slowest diffusion to the interface. It is also possible that stronger association between octylamine and perfluorooctanoate result in a very strongly bound ion pair with behaviour like a nonionic and highly hydrophobic species

(i.e. an antifoam).

Dynamic surface tension data in Fig. 3 is computed to apparent diffusion coefficients in the Supplementary Information (Fig. S3) and shows some evidence of a two-rate adsorption process at the interface for alkylamines with chain lengths from butylamine and above. This may indicate competition for the interface between alkylamine molecules and perfluorooctanoate–amine ion pairs. The exact nature of the adsorption process is not clear, and unravelling the role of each species (perfluorooctanoate ions, free alkylamine molecules, and perfluorooctanoate–amine ion pairs) would be a complex task beyond the scope of the present work. Nonetheless, these dynamic data do give valuable insight into short time adsorption behaviour of these systems relevant to foaming studies.

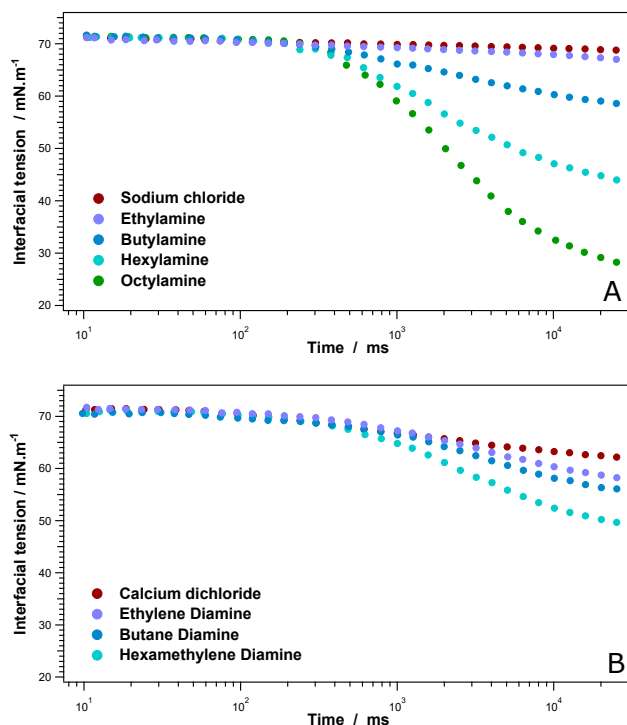


Figure 3: Dynamic surface tension for 0.1 mM NaPFO solutions with A) monovalent additives and B) divalent additives (1 mM) at pH=5 as measured by bubble pressure tensiometry. Data at very short times is presented separately on expanded axes in the Supporting Information.

Although there are strong correlations between (dynamic) surface tension and foaming potential for surfactant systems, other factors are also important, meaning that surface

tension alone is a poor predictor of foaming.³⁷ Foam drainage rate and film rupture are controlled by a complex suite of physicochemical phenomena including air–water surface charge, solution viscosity, steric effects and water structuring.³⁸ For ionic surfactants such as PFO, effective head group charge can be altered through addition of salts to screen electrostatic repulsions between neighbouring surfactant ions, and between surfactant ions and the air–water interface, which bears a negative surface charge at pH>4.³⁹ Moreover, different counterions may have different binding strengths to the surfactant head group, so can provide additional variation in behaviour. Providing more or less effective charge to the head group is often exploited for changing the aggregation of surfactants in solution, inducing changes in micelle structure.⁴⁰ Head group molecular architecture is extremely important in determining foamability,³⁷ but changing *effective* head group chemistry through binding counterions is often overlooked when considering foaming.

Results for NaPFO + octylamine in particular highlight the problems that can arise from using oppositely charged surfactants. Aside from the fact that the overwhelming majority of cationic surfactants are quaternary ammonium based with issues around toxicity, strong electrostatic interactions make them problematic even though they exhibit the greatest increase in surface activity. The apparent anti-foaming effect of the NaPFO + octylammonium complexes are obviously detrimental for foam recovery, making this pairing impractical for use in PFO recovery tests below, even though *at equilibrium*, this combination is the most surface active sample in the above measured data. This crucially highlights the important differences between dynamic and equilibrium surface tension studies, and further reinforces that surface tension alone is not a strong predictor of foaming capacity.

Even though its anti-foaming properties make the NaPFO + octylamine pairing impractical for the tests presented here, it might still be a useful addition for other remediation methods that rely on surface activity but not specifically foaming. The adsorption capacity of PFAS molecules on activated charcoal has been found to be proportional to their hydrophobicity,⁴¹ and similar behaviour is also reported for ion exchange resins,⁴² with the larger

molecules being preferentially adsorbed. These systems rely on equilibrium partitioning to a surface rather than fast dynamics, and so may benefit from the added hydrophobicity that octylamine confers as a counterion. Not only are there common adsorption processes as noted, but other aeration methods that utilise aerosol capture rather than foaming have been reported^{24,25} and a molecule like octylamine could be a useful addition in those situations to increase surface activity of PFO.

Perfluorooctanoate removal using foam extraction

A simple foam extraction setup (see Supporting Information) was created in order to determine what measurable effect these compounds would have on removal of PFO from bulk solutions under the conditions explored above. This lab scale proof-of-principle experiment was used to determine PFO concentration in extractable foams as a function of additives. While surface tension data indicates an enrichment of surface active species at the air–water interface that should translate to a greater surface excess (and hence greater concentration of PFO in the foam layer), differences in the nature of foams produced complicate what this simple correlation, indicating dynamic effects. In the simple setup used here, we attempted to account for this by changing gas flow between samples to keep the flow of foam constant while sampling the foam as a function of time, and then sampling the extracted liquid after a set *volume* was extracted (this was possible due to the foams being only metastable and rapidly draining).

This differs somewhat from other reported studies that often keep gas flow constant, but our approach more directly determines the increase in PFO concentration in the foam layer, which is the basis on which we compare systems. For this reason, changes over time are only indicative; although effort was put into keeping the rate of foam extraction approximately constant, this was secondary to ensuring a consistent volume of liquid had been extracted at the end of the experiment. It is worth noting that the nature of the foams was not consistent, and solutions with weaker foaming generally had a somewhat coarser and wetter foam. This

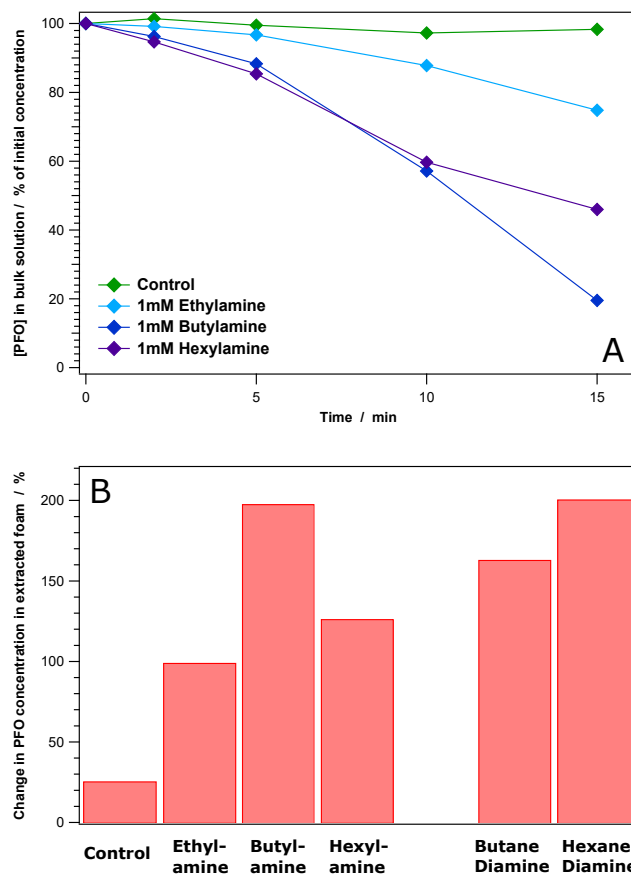


Figure 4: a) Measurements of PFO concentration in bulk solution over time during foam extraction. The final extracted volume was 250 mL for each sample. b) Enrichment of PFO concentration in the extracted 250 mL foam compared to starting PFO concentration in the bulk liquid phase.

affects surface area within the foam, which would be anticipated to be strongly correlated to enrichment in the extracted volume, potentially above effects contributed by increases in surface excess concentration.

Considering the foaming results above, ethylene diamine and octylamine were not analysed in this extraction test due to lack of foaming in these systems. Results for remaining additives show a strong correlation between PFO concentration in the extracted foam and equilibrium surface tension measured above (Fig 1). This was somewhat expected, since while surface tension by itself does not necessarily predict foam formation, a decrease in surface tension would imply an increase in concentration of PFO at the air–water interface for these systems, as the amines by themselves showed negligible surface activity at this concentration (see Supporting Information) as did NaPFO.

Measured concentrations of PFO in extracted foams indicated significant enrichment (Fig. 4; butylamine for example only decreased surface tension of 0.12 mM NaPFO to 58 mN/m when added at 1 mM, but this translated to a 200% increase in PFO concentration in extracted foam relative to the initial bulk concentration, thereby reducing the bulk concentration down to 0.026 mM, a reduction of 80% relative to the initial concentration with only 25% of the volume extracted. Hexane diamine produced equally good results, and interestingly butanediamine also performed strongly, somewhat in line with surface tension measurements, but better than the foam height tests would predict.

The outlier from these measurements of foam enrichment is the sample with hexylamine, which did not correlate with previous measurements, and performed somewhat worse than the butylamine sample. This was qualitatively apparent during the experiment from visual inspection, with foam quality dropping off substantially as the extracted volume increased, which is reflected in the analysis in Fig 4a. While the same volume was ultimately extracted, the foam was noticeably ‘wetter’ as the experiment progressed. This may be due to differences in foaming apparatus; pores of the aspirator in extraction experiments were larger than the fritted disc used in the foam column. Considering hexylamine also showed some surface

activity by itself (albeit only above 100 mM), this case possibly represents the border between the anti-foam effect seen for octylamine and the increase in surface activity seen for smaller alkylamines. This may mean that for hexylamine, performance might be more conditional on specifics of bubble size and quantity, dynamics, and other fluid factors.

Table 1: Summary of foaming tests and foam separation for PFO removal: equilibrium surface tension ($\gamma_{eq.}$), equilibrium foam height (h_{foam}), initial bulk PFO concentration ($[PFO]_{bulk}^{init}$), final bulk PFO concentration ($[PFO]_{bulk}^{end}$), and PFO concentration in extracted foam ($[PFO]_{foam}^{end}$). The enrichment % is calculated as the increase in PFO concentration in the extracted foam compared to the starting bulk liquid sample. The control sample was 0.12 mM NaPFO, and all measurements were made at pH=5. Concentrations are in mM. The starting volume for the extraction experiments was 1.1 L and 250 mL of foam was extracted. PFO concentrations of PFO were measured in both the extracted foam and remaining bulk solution.

Additive (1mM)	$\gamma_{eq.}$ mN m ⁻¹	h_{foam} mm	$[PFO]_{bulk}^{init}$ mM	$[PFO]_{bulk}^{end}$ mM	$[PFO]_{foam}^{end}$ mM	Enrichment %
Control ^a	69.0	6	0.119 (0.007)	0.117 (0.007)	0.141 (0.017)	18.8 (8.1)
Ethylamine	67.0	6	0.123	0.092	0.245	99
Butylamine	58.7	12	0.133	0.026	0.396	198
Hexylamine ^a	44.1	35	0.122 (0.013)	0.055 (0.01)	0.279 (0.07)	126 (31)
Octylamine ^b	29.3	0	-	-	-	-
Ethylene diamine ^b	59.8	0	-	-	-	-
Butane diamine	55.2	7	0.141	0.044	0.371	163
Hexamethylene diamine	48.5	30	0.140	0.027	0.421	201

^a Extraction values are mean values ($n = 5$) with standard deviation in parentheses.

^b No extraction was performed on these samples due to insufficient foaming.

It is somewhat difficult to quantitatively compare these results to other reports of PFO extraction due to differences in experimental methods and conditions. Most lab-based reports use higher PFOA concentrations to magnify foaming issues, from 450 mg L⁻¹ (1 mM)²⁰ to 11.5 mM.¹⁸ Removal of around 80% of PFO in the present work, such as for the PFO/butylamine system, is comparable to other reported values, such as 85%²¹ (over 2hr with a co-surfactant), 91%²⁰ and 96%.¹⁹ Where PFOS is utilised instead of (or in addition to) PFOA, it performs better in similar experiments due to its higher surface activity,^{18,21} although for actual wastewater samples, reported results were comparable.¹⁹ Experiments here were not designed to offer a deployment-ready method, but rather to illustrate interactions between organic (amine) cations and anionic PFASs. Foam separation has the advantage of being able to be implemented sequentially, with multiple passes being able to compound any increases.²⁵

The work of Lee¹⁸ offers the closest comparison to this study, as it also uses additives to enhance the surface activity to improve removal efficiency, in their case with metal ions. Higher valence metal ions such Fe^{3+} complex readily carboxylic acid groups, and this has a large affect on surface tension. This effect is also seen in the surface tension results here, with Ca^{2+} providing a significant increase in surface activity of PFO. Under optimum conditions (pH=2.2), removal in Lee’s study was very high > 99%), however the effectiveness reduced dramatically above pH=5 (and was negligible above pH=6) due to formation of hydroxide complexes that inactivated the metal ions.¹⁸ Sensitivity to pH is a big limitation in a wastewater context, where significantly adjusting pH is generally neither economical nor practical. The organic amines used here are much more versatile in that respect, their main limitation being that solutions must be below the $\text{p}K_a$ of the amines for charged-based interactions to occur.

Comparison between use of metal ions and amines is useful to illustrate the potential versatility of foam based remediation. As the majority of proposed large-scale remediation methods for PFASs rely on surface activity, either through interactions of surfactants with solid or liquid interfaces, understanding factors that affect this is key to developing an efficient process. Common approaches often used in surface science to promote surface activity in surfactants, such as large excesses of salt or extreme pH, are generally infeasible for large scale wastewater treatment. Similarly, any additives used to enhance processes must be effective at relatively low loadings. Most organic amines could not be used indiscriminantly without some secondary processing to prevent discharge, and metals such as iron may also be tightly regulated. However, neither the organic molecules investigated here nor metal ions are a comprehensive list, and there is still a large amount of optimisation that could be done, or other classes of molecules that could be investigated. Realistically, a combination of different additives could offer the most robust approach, especially considering variability in chemical composition of contaminated wastewaters.

Conclusions

For dilute perfluorooctanoate solutions, surface activity can be enhanced substantially by adding organic amines due to greater binding of these ions to surfactant head groups. Using common short to medium chain length alkylamines (protonated at pH=5), this effect was utilised successfully to increase the yield of PFO recovery from a simple foam extraction experiment. Generally, increasing hydrophobicity of the additive increased the measured surface activity, but the quantity of charged sites on the additive is also a factor. Alkyl-diamines showed a weaker change in surface activity as chain length increased, but most had measurable effects at lower concentrations compared to their equivalent monoamine counterparts. In extraction tests, PFO concentration in foams ranged between 100% and 200% of the initial bulk concentration, with n-butyl amine being the best performing additive. The corresponding bulk solutions were reduced to 20% of their initial PFO with 75% of the volume remaining after the foam extraction. While this demonstrates how counterion interactions can be utilised for PFO remediation, there is still a large amount of optimisation required for implementation. These are only a small selection of potential molecules and ions that could be useful for enhancing such procedures, but form an important proof of concept. Both organic and inorganic species could be useful in this application, and having a variety of options would likely be a necessity considering the variety of sources and fates for PFO contaminated wastewater. Furthermore, it is possible that applications could extend beyond that of foam extraction and have an impact on other remediation methods that rely on surface activity.

Acknowledgements

M.P. acknowledges 3M Australia for financial support. This work was supported in part by the grant of an ARC Future Fellowship (FT160100191). The authors gratefully acknowledge the Monash Analytical Platform for providing facilities for HPLC–MS measurements.

Associated Content

Supporting information includes supplementary surface tension data, diffusion analysis from dynamic surface tension, and further foaming data.

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Chapter 5

Effects of perfluorooctanoate on the structure of lipid liposomes

5.1 Introduction

Perfluorinated surfactants are chemicals of concern for their potential impacts on health. Due to their long term stability they are generally considered persistent organic pollutants and, although not considered acutely toxic, long term exposure has been linked to various negative health outcomes.¹⁻³ Exactly how these molecules interact with biological systems is a topic of significant interest due to their amphiphilic nature. Other persistent organic pollutants such as polychlorinated biphenyls (PCBs) or dioxins are known to build up in fatty tissues due to their hydrophobicity,^{4,5} however this effect is not as clear in amphiphilic fluorosurfactants which have been found to interact strongly with proteins^{6,7}. Due to their combination of both hydrophobicity and lipophobicity, how these molecules interact with biological (hydrocarbon) amphiphiles such as lipids is not clear. Lipids form the structural barrier around cells, and how molecules interact and move through them is an important aspect of their overall effect on bodily systems.

Phospholipids are a unique subsection of hydrocarbon amphiphiles. Their general struc-

ture consists of fatty acid chains bonded through a glycerol molecule to a phosphate-based head group. They are relatively insoluble in water in their pure form, but widely used as food-safe emulsifiers, usually as impure fatty extracts called lecithins.^{8–10} The natural extracts are variable in their composition, in research they are more often encountered in pure forms. The most common varieties are phosphocholine lipids with either myristic, palmitic, stearic or oleic tail groups^a. In solution their phase behaviour strongly favours bilayer structures due to their geometry,¹¹ and cell walls are based around these bilayer structures. They can also be deposited onto substrates as films, either as monolayers or bilayers.^{12,13} Due to their easier preparation this has been the focus of the majority of work on the interactions of perfluorinated surfactants and lipid molecules which is outlined below.

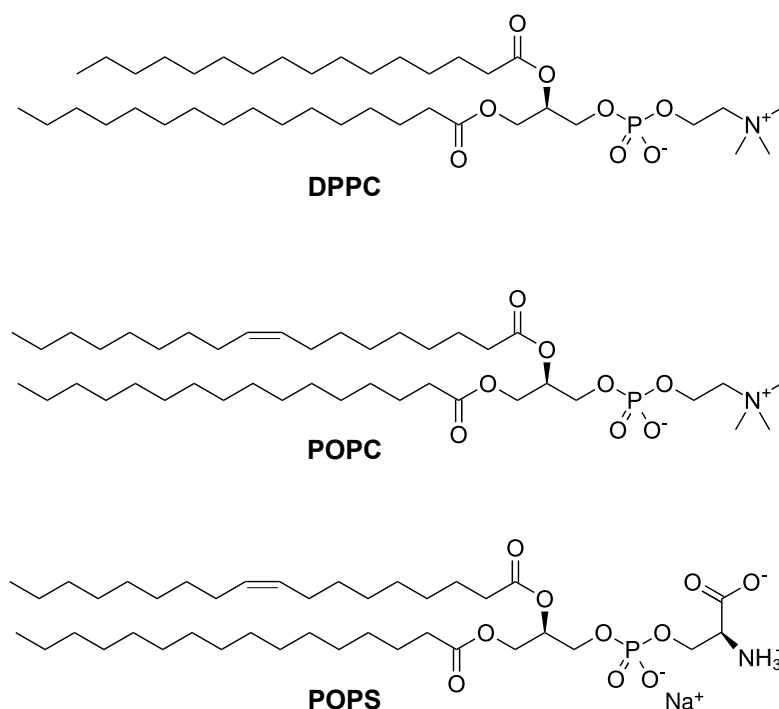


Figure 5.1 Chemical structure of the lipid molecules comprising the liposomes used in this study. Introduction of POPS into the liposome structure provides a negative surface charge, compared the neutral (zwitterionic) form when DPPC or POPC are used alone.

A prominent property of lipids is the crystallinity in their hydrocarbon chains when condensed in bilayers. The chain-melting transition temperature (t_m) represents the temperature

^aThe technical naming of these chemicals is long and acronyms are generally used for clarity. Acronyms highlight the tail groups and head groups present, for example DPPC refers to 1,2-dipalmitoyl-*sn*-glycero-3-phosphocholine and POPC refers to 1-palmitoyl-2-oleoyl-*sn*-glycero-3-phosphocholine.

where the hydrocarbon chains go from a more crystalline gel phase to a more fluid liquid-crystalline phase¹⁴. The temperature this occurs is dependent on the type of chains incorporated into the tail group, with saturated chains giving a higher chain melting temperature than unsaturated. In the presence of perfluorooctane sulfonate (PFOS), transition temperatures decrease for DPPC bilayers^{15–17} when measured with differential scanning calorimetry, and consistently decrease as PFOS concentration increases¹⁶. Combined with fluorescence anisotropy measurements, an apparent partition coefficient for PFOS in DPPC bilayers of 5.7×10^4 has been calculated¹⁶, indicating PFOS readily enters and disrupts lipid bilayers. Perfluorooctanoic acid (PFOA) has a lower estimated partition coefficient than PFOS¹⁸ and both are higher than for potassium octanoate,¹⁵ indicating the increased hydrophobicity of the fluorocarbon chains is the dominant driving force for interactions, outweighing the concurrent lipophobicity of fluorocarbons.

Interestingly, the chain length of lipids seem less important for partitioning. Studies using lipids with different chain lengths (di-myristoyl-, di-palmitoyl- and di-stearoyl- chains; DMPC, DPPC and DSPC respectively) with both PFOS¹⁹ and PFOA²⁰ have shown relatively consistent partition coefficients, for example ranging from 4.4×10^4 to 8.8×10^4 for PFOS¹⁹. The effect on transition temperature does decrease as lipid chain length increases,^{18,19} indicating a greater disruption to lipid-lipid interactions when the fluorocarbon chain is a more comparable length to the lipid molecules. Neutron reflectometry has found interactions with DMPC bilayers to be dependent on the chain length of the fluorosurfactant²¹ with longer PFAS chains having stronger interactions. Furthermore, head group chemistry was also found to have an effect, with interactions following the order $\text{SO}_2\text{NH}_2 > \text{SO}_3^- > \text{COO}^-$. This provides further support for hydrophobicity being the dominant interaction as the increase in hydrophobicity as a function of carbon chain length is much greater in fluorosurfactants than in the hydrocarbon lipids.

The penetration and residence of PFOA and PFOS has been demonstrated in lipid bilayers with other methods, such as infrared reflection/absorption²², voltammetry²³ and compu-

tational studies,²⁴ and the significantly higher partitioning coefficient of PFOS compared to PFOA has been shown in more detail with synthetic lipids²⁵. This is rationalised by the greater hydrophobicity of PFOS (having an extra -CF₂- group in its chain). As well as affecting transition temperatures, there is a corresponding effect on fluidity of the membranes as fluorosurfactants are incorporated. Surface pressure measurements at the air/water interface (using a Langmuir-Blodgett trough) have correlated the decrease in phase transition temperature of DMPC in the presence of PFOA with a more fluid monolayer at the air/water interface²⁶, with the gel-liquid transition temperature decreased above 5 %mol of PFOA. Similar behaviour is seen with PFOS and the lipids DPPC and DMPE²⁷.

Some studies have shown different behaviour between long and short lipid chains and fluorinated surfactants at the air/water interface. Longer chain hydrocarbon amphiphiles such as dodecanol and palmitic acid have been found to expel perfluoroheptanoic acid from the air/water interface compared to shorter amphiphiles such as *n*-octanol²⁸ where a mixed interfacial layer forms. This has also been shown in lipid molecules of different chain lengths²⁹: di-lauroyl phosphatidic acid (C12) with perfluorodecanoic acid forms a mixed monolayer at the air/water interface at both low and high surface pressures, whereas the longer di-stearoyl phosphatidic acid (C18) forms segregated domains at low surface pressure and expels the fluoro surfactant from the interface at high surface pressures.

However, behaviour at the air/water interface may not directly translate to behaviour in solution or biological contexts, as differences in solubility play a role in their adsorption at the air/water interface.³⁰ In soft matter phases or bilayers adsorbed to substrates this dynamic may be somewhat less fickle, although these results are consistent with the effects on transition temperatures noted previously. Investigating interactions with lipid soft matter phases (typically lamellar or liposome structures^b) is arguably a more informative approach for predicting behaviours in biological contexts.

^bLiposomes are spherical structures with a bilayer shell and solvent core. They are somewhat unstable thermodynamically and often require an extrusion procedure to produce homogenous dispersions. They are also referred to as vesicles, although in some contexts these terms are differentiated.

Interactions of PFAS with lipid liposomes has not had the same attention in the literature, possibly due to a greater instrumental barrier for probing subtle differences in liposome properties in bulk solution. Dynamic light scattering (DLS) can show large scale changes to liposome structure through changes in measured size and scattering intensity in DLS measurements have indicated partial solubilisation of lipid liposomes by PFOA at molar ratios greater than 1, indicated by a reduction in liposome scattering intensity and solution turbidity²⁰. However, incorporation of perfluorohexane sulfonate (PFHxS) into liposomes comprising different lipid molecules was found not to change their overall size at dilute concentrations even somewhat above an equimolar ratio³¹. Different chain length lipids were used in this study and zeta potential measurements indicated an increase in the amount of the anionic fluorosurfactant in the liposomes as the chain length of lipid increased, even though size changes weren't observed in any liposomes. In cells, PFOS was found to increase membrane fluidity and permeability,³² while the shorter PFHxS and perfluorobutane sulfonate (PFBS) didn't show any effects over the same concentration range. Although data is more limited in this area, this implies while mixing is favourable for both long and short fluorosurfactants with lipids, the more common C8 varieties PFOS and PFOA have a much greater effect on large scale lipid structures than shorter fluorinated surfactants.

The present work aims to provide greater detail on changes in liposome structure in the presence of sodium perfluorooctanoate (NaPFO). Liposome structure is directly measured using small angle neutron scattering (SANS) and ultra small angle neutron scattering (USANS) which allow both small changes in liposome structure to be modelled and the presence and nature of phase changes to be observed. Both a fully saturated lipid (DPPC) and an unsaturated lipid (POPC) are used due to their significantly different chain melting temperatures (hence crystallinity), which combined with a large array of liposome:PFO ratios provides a comprehensive analysis of changes in phase behaviour of biologically relevant lipids in the presence of perfluorinated surfactants in bulk solution.

5.2 Experimental

5.2.1 Materials and Preparation

Sodium perfluorooctanoate (NaPFO) was prepared from perfluorooctanoic acid (FluoroChem, 99%) through stoichiometric neutralisation with NaOH (Merck, 99%) in ultrapure H₂O (minimum resistivity 18.2 MΩ). The solvent was evaporated and the resulting solid dried under vacuum at 70 °C. The lipids 1-palmitoyl-2-oleoyl-*sn*-glycero-3-phosphocholine (POPC), and 1-palmitoyl-2-oleoyl-*sn*-glycero-3-phospho-L-serine (sodium salt) (POPS), and 1,2-dipalmitoyl-*sn*-glycero-3-phosphocholine (DPPC) were sourced from Avanti Polar Lipids as chloroform solutions (> 99% purity). Phosphate buffered saline solution (PBS) was prepared from tablets (SigmaAldrich) in D₂O (dPBS).

Liposome preparation

Lipid chloroform solutions were evaporated under nitrogen in glass scintillation vials and the resulting lipids dispersed in PBS with sonication to produce stock lipid solutions. Liposomes were prepared from these stock solutions using a commercial heating block extrusion setup (Avanti Polar Lipids). Solutions were subjected to 31 passes through a 50 nm pore size membrane. The extrusion was performed at ambient lab temperature for POPC and POPS dispersions and at 50 °C for DPPC dispersions. The liposome dispersions were then subsequently mixed with appropriate amounts of stock NaPFO solution to achieve desired mixing ratios and diluted with dPBS to either 2 mg/mL or 10 mg/mL for neutron scattering measurements. The final solution volume was 1 mL for SANS samples and 3 mL for USANS samples. Where lipid mixtures were used, the mixing was performed after the extrusion step. SANS analysis showed no difference between samples mixed before or after extrusion. Samples were prepared as close as possible to the time of measurement and stock solutions were refrigerated between measurements.

5.2.2 SANS and USANS analysis

SANS measurements were performed on the BILBY time-of-flight instrument at the ANSTO, Lucas Heights, Australia³³. Samples analysed in 1 mm path length demountable cells and all samples used a D₂O solution of phosphate buffered saline. Raw data were reduced from the 2 dimensional detector output and radially averaged to produce 1 dimensional plots of intensity as a function of the scattering vector q , where q is defined as:

$$q = \frac{4\pi}{\lambda} \sin \frac{\theta}{2} \quad (5.1)$$

with λ being the incident neutron wavelength and θ the scattering angle. The detector response is normalised using a flat scattering background comparison and all samples had a blank PBS/D₂O background subtracted. Neutron wavelength was 3 - 17 Å with a sample detector distance of 18 m producing an effective q -range of 0.015 - 0.6 Å⁻¹.

USANS measurements were taken on the KOOKABURRA beamline at ANSTO³⁴. This instrument uses a Bonse-Hart setup with parallel arrays of reflective silicon crystals monochromating and analysing the neutron beam. A neutron wavelength of 5 Å was used providing a q -range of 0.00005 Å⁻¹ - 0.01 Å⁻¹. The intensity after desmearing is normalised to match the SANS data for combined fitting, giving the combined USANS/SANS data an effective q range of 0.00005 Å⁻¹ - 0.57 Å⁻¹.

Data modelling

Data modelling was performed using the open source SasView software package specifically developed for modelling small angle scattering (<https://www.sasview.org/>). Liposomes are modelled using the vesicle model, which is essentially a core-shell sphere model with the special condition that the core is made up of solvent, and only the shell volume contributes to scattering. In this work, the more complex multi-layer vesicle model is used, which allows for

the contribution from multi-layer structures to be modelled. This adds variable parameters for solvent thickness (between layers) and number of bilayer shells present. Both models are derived from the work Guinier and Fournet³⁵. For multi-lamellar liposomes the 1D scattering pattern is given by the form factor:

$$P(q) = scale \cdot \frac{\Phi}{V(R_N)} F^2(q) + background \quad (5.2)$$

where

$$F(q) = (\rho_{shell} - \rho_{solvent}) \sum_{i=1}^N \left[3V(r_i) \frac{\sin(qr_i) - qr_i \cos(qr_i)}{(qr_i)^3} - 3V(R_i) \frac{\sin(qR_i) - qR_i \cos(qR_i)}{(qR_i)^3} \right] \quad (5.3)$$

with r_i being the solvent radius before shell i :

$$r_i = r_c + (i - 1)(t_s + t_w) \quad (5.4)$$

and R_i being the outer shell radius for shell i :

$$R_i = r_i + t_s \quad (5.5)$$

and Φ is the particle volume fraction, $V(r)$ is volume of a sphere of radius r , r_c is the solvent core radius, t_s is the shell thickness, t_w is the solvent layer thickness between shells and ρ_{shell} and ρ_{solv} are the scattering length density of the shell material and solvent respectively. Liposome bilayers were given a constant scattering length density of $0.3 \times 10^{-6} \text{\AA}^{-2}$, although incorporation of fluorocarbon would influence this where it occurs. This is discussed in more detail in subsequent sections.

Where liposomes are not homogenous and there are contributions from differently layered structures, a lognormal polydispersity function is used, centered around a given n shells value. The polydispersity function is built in to the software and is easy to incorporate, although it is limited in its accuracy under some circumstances. The main limitation is in the way the software ‘bins’ the resulting distribution into integer values (since number of shells can physically only take integer values) rather than using a continuous function. This can make it difficult to determine the exact contributions and obtain an accurate fit to the data in some cases, although in most cases is sufficient. Using an array of explicitly defined contributions from different number of shells in a given sample is possible, but more time-consuming to implement. Considering the contribution from multi-layer structures appeared small, the polydispersity function was used for simplicity and efficiency.

5.3 Results

5.3.1 Liposome modelling and stability

Two lipid concentrations were used in this study: a relatively low 2 mg/mL and a higher 10 mg/mL dispersion. The SANS/USANS data of the stock lipid dispersions are shown in Figure 5.2. Due to the consistent pore size in the extrusion process the overall diameter, indicated by the where the scattering intensity begins ‘flattening off’ at low q ($<0.01 \text{ \AA}^{-1}$), is consistent without any additives present and superficially there are no major differences in the scattering profiles. Fitting parameters are shown in Table 5.1 and show differences in the fine structure of liposomes produced from the different lipid compositions. Both DPPC and POPC produced comparable structural properties, with bilayer thicknesses at both low and high concentrations of 39 - 41 $\text{\AA}$, and in multilamellar structures the solvent layer thickness is 18 - 19 $\text{\AA}$. The presence of multilamellar structures was greater for POPC liposomes, where average number of shells (n) is 1.25 and 1.3 at low and high lipid concentrations, compared to 1.05 and 1.1 for DPPC liposomes with comparable polydispersity for both. Interestingly, when mixed with

POPS, both POPC and DPPC produced more comparable degrees of multilamellarity, with $n = 1.25$. These composite liposomes also showed decreased bilayer thickness and increase in solvent thickness, likely a result of the net negative charge present on the bilayer surface with the introduction of the anionic POPS.

Both DPPC and POPC have been widely studied, although differences in both preparation and methodology mean a range of structural parameters have been reported for their liposomes. The comparable chain lengths between DPPC and POPC mean no large differences in bilayer thickness were expected, and this is reflected in the similar modelled values (39 - 41 Å). This compares reasonably well to other reported values; for DPPC values of 37 Å³⁶, 42.8 Å³⁷ and 45 Å³⁸ have been reported. A similar range is seen for POPC, ranging from 37 Å³⁸ to 47 Å³⁹. This variability reflects both differences in preparation and analysis methods.

For POPS, a bilayer thickness of 40.3 Å⁴⁰ has been reported in 100 nm liposomes and 39 Å in mixed liposomes with POPC (70:30 POPC:POPS ratio). The degree of multilamellarity is highly dependent on the preparation method and therefore a comparison to other literature reports is not particularly meaningful, however where multilamellarity is reported, the solvent thickness between blayers is comparable, such as 18.9 Å³⁹ and 23 Å³⁸ for POPC and 21 Å³⁷ for DPPC. It has been noted^{41,42} that modelling this parameter accurately can be challenging in some cases due to changes in scattering length density due to solvent penetration into the head group region. SANS models have been proposed, such as that used by Schmiedel *et al.*³⁹, that use multiple contrast steps in the shell to more accurately model this hydrated head group region. This dramatically increases the number of variables and is computationally intense, therefore difficult to implement efficiently with the large data set considered in this Chapter to achieve unambiguous fits.

The quantity of multilamellar structures present can be modelled due to the presence of structure peak corresponding to the interlamellar spacing, appearing as minor bump before

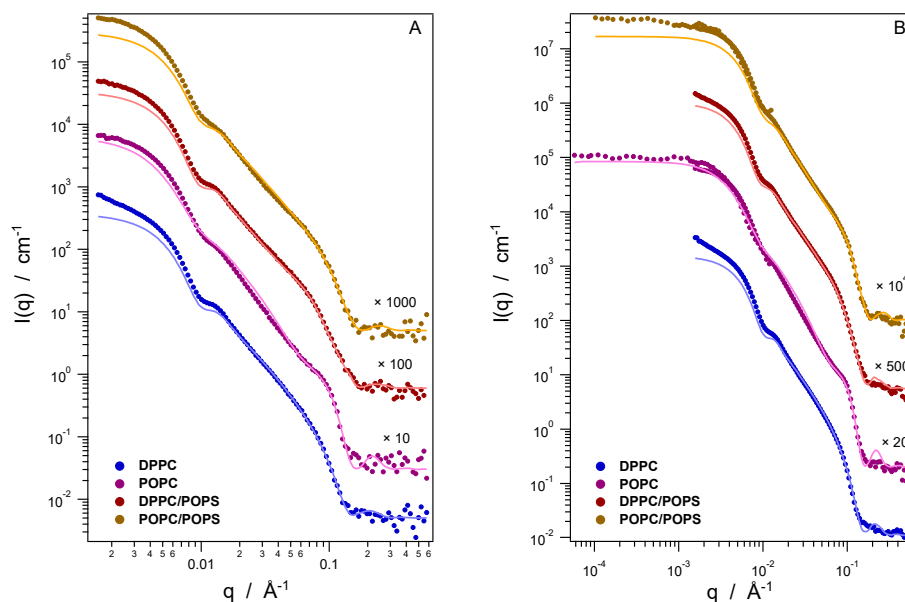


Figure 5.2 SANS/USANS measurements of stock liposome dispersions using a consistent extrusion method using (a) 2 mg/mL and (b) 10 mg/mL lipids. The anionic POPS lipid was incorporated to produce negatively charged liposomes by mixing with either DPPC or POPC at a 1:1 mass ratio. Symbols represent experimental data and overlaid solid lines represent model fits. Data are offset for clarity by flat multipliers noted. This will be employed in subsequent data sets but factors are omitted for clarity and are included here as examples.

the steep decay in intensity at $q \approx 0.1 \text{ \AA}^{-1}$. This is more prevalent for POPC and POPS liposomes in this study, indicated by the higher n value compared to DPPC liposomes. The extrusion process used here produced predominantly unilamellar vesicles with only a small contribution from multilamellar structures, and well-defined structure peaks from multilamellar liposomes aren't observed. Furthermore, model fitting showed a close relationship to the experimental data above $q \approx 0.01 \text{ \AA}^{-1}$, which corresponds to the size range of the main parameters of interest: bilayer thickness, solvent thickness and degree of lamellarity. Considering the comparative nature of this study, there is a good degree of confidence in fitting these parameters without the use of more advanced models incorporating solvent penetration and exact contributions from different number of shells.

There is a low quality of fit with the liposome model in the low q region (< 0.01) that is seen in many of the samples. This has an effect on the fitting of overall liposome size, since at this scale the scattering arises predominantly from the spherical form factor component of

the liposome. This could be indicative of the presence of large scale structures separate to the liposomes, most likely fragments of lipid bilayer that passed through the membrane without forming stable liposomes. One study which also noted these described them as ribbon-like bilayer structures⁴³. The continual slope in the DPPC scattering data particularly (both 2 mg/mL and 10 mg/mL) indicates some larger pseudo- two dimensional aggregates present, as these produce surface scattering with a larger gradient in intensity as q decreases. It was noted in later measurements with the introduction of NaPFO that the intensity in this region does drop off, indicating possible dissolution of excess lipid fragments by the co-surfactant.

Table 5.1 SANS fitting parameters for stock liposome dispersions shown in Figure 5.2. Polydispersity values are given in parentheses where applied.

Sample	Vol. fraction	Radius (Å)	Shell thickness (Å)	Solv. thickness (Å)	n Shells
2 mg/mL					
DPPC	0.002	290 (0.33)	41 (0.1)	18 (0.1)	1.05 (0.3)
POPC	0.002	250 (0.35)	39	19	1.25 (0.2)
DPPC/POPS	0.002	300 (0.35)	36 (0.1)	55 (0.1)	1.25 (0.2)
POPC/POPS	0.0021	260 (0.3)	35	35	1.05 (0.2)
10 mg/mL					
DPPC	0.01	260 (0.4)	40	19	1.1 (0.2)
POPC	0.011	250 (0.4)	39	18	1.3 (0.2)
DPPC/POPS	0.011	300 (0.25)	37 (0.1)	50	1.25 (0.1)
POPC/POPS	0.011	260 (0.3)	33	35	1.3 (0.2)

The main effect of the excess (non-liposomal) fragments is producing some uncertainty in the liposome radius in model fits, seen in fitting data for liposome stock solutions here (Table 5.1) and in subsequent data sets, with modelled radii ranging from 240 Å - 300 Å. This is particularly notable in SANS measurements where due to the narrower q -range, the full scattering profile of the spherical form factor isn't visualised. USANS measurements, such as for POPS and POPS/POPC liposomes at 10 mg/mL, more clearly show the intensity rounding off to a flat value at low q , which is a characteristic of scattering produced from spherical structures.³⁵ This allows for a more accurate fit of the overall liposome size, and in these data sets the modelled liposome radius is both closer to expected (250 Å - 260 Å for the 50 nm diameter pore size used in extrusion) and less variable than modelling using the narrower

SANS q -range.

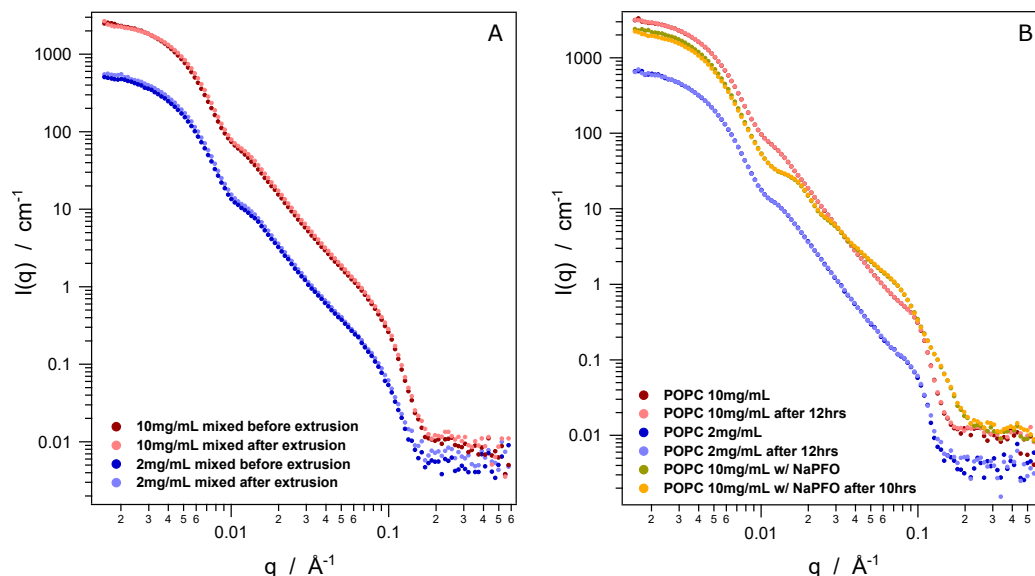


Figure 5.3 SANS data analysing differences in mixing and the stability of extruded liposomes. (a) POPC/POPS mixed liposomes showing both 2 mg/mL and 10 mg/mL dispersions mixed before extrusion and after extrusion. No difference is observed and mixing after extrusion was used as the protocol for the study. (b) low and high concentrations of liposomes and analysed at different time intervals. Negligible change was observed over the time frame of analysis, however some differences between samples are still possible due to the nature of the extrusion process.

In terms of the overall aims and quality of data this not particularly significant; the known pore size of the membrane provides a rough limit on liposome size and provides consistency across the different lipid compositions. Differences here due to interactions with NaPFO would likely be smaller than the variation introduced by excess material present. Issues fitting the low q region are a notable feature of liposome studies using SANS, and other studies using SANS to analyse liposomes have omitted this low q data due to the lack of useful information gathered and difficulty in accurate fitting^{38,39}. The parameters of greater interest, such as changes in shell thickness and the degree of lamellarity in the liposomes, occur at a much smaller length scale and feature in the ‘main’ slope region at $q > 0.01$. The full q -ranges available are included here for completeness, as micelles or mixed phases require the full q range for analysis where they are present.

Checks were made to probe the validity of measurements given the conditions of USANS/SANS measurements. The most important is stability over time, due to the time required

to complete a set of SANS/USANS measurements. Liposomes are known to be somewhat unstable^{44,45} and can break down over time. For SANS measurements, the combination of sample analysis time and potential wait time for subsequent samples in the multi-sample changer meant that samples could potentially be analysed hours after their extrusion time. To check that this would not be an issue in the present study, stock liposome dispersions were analysed again after 10-10 hrs to observe any changes (Figure 5.3b). Time affects not only liposomes but is also a factor in interactions with NaPFO, therefore a sample of lipids with NaPFO added (both at the highest concentration used, 10 mg/mL) was also analysed. Neither the lipids nor lipids with NaPFO showed any deviation in their SANS data over this time frame (which was the worst case scenario based on our experimental procedures), with data points exactly overlapping except for a slight reduction in the low q region in the POPC/NaPFO sample. This gives a high degree of confidence that the measurements were not compromised by any inconsistent changes over time between samples.

5.3.2 Liposomes in the presence of NaPFO

DPPC liposomes

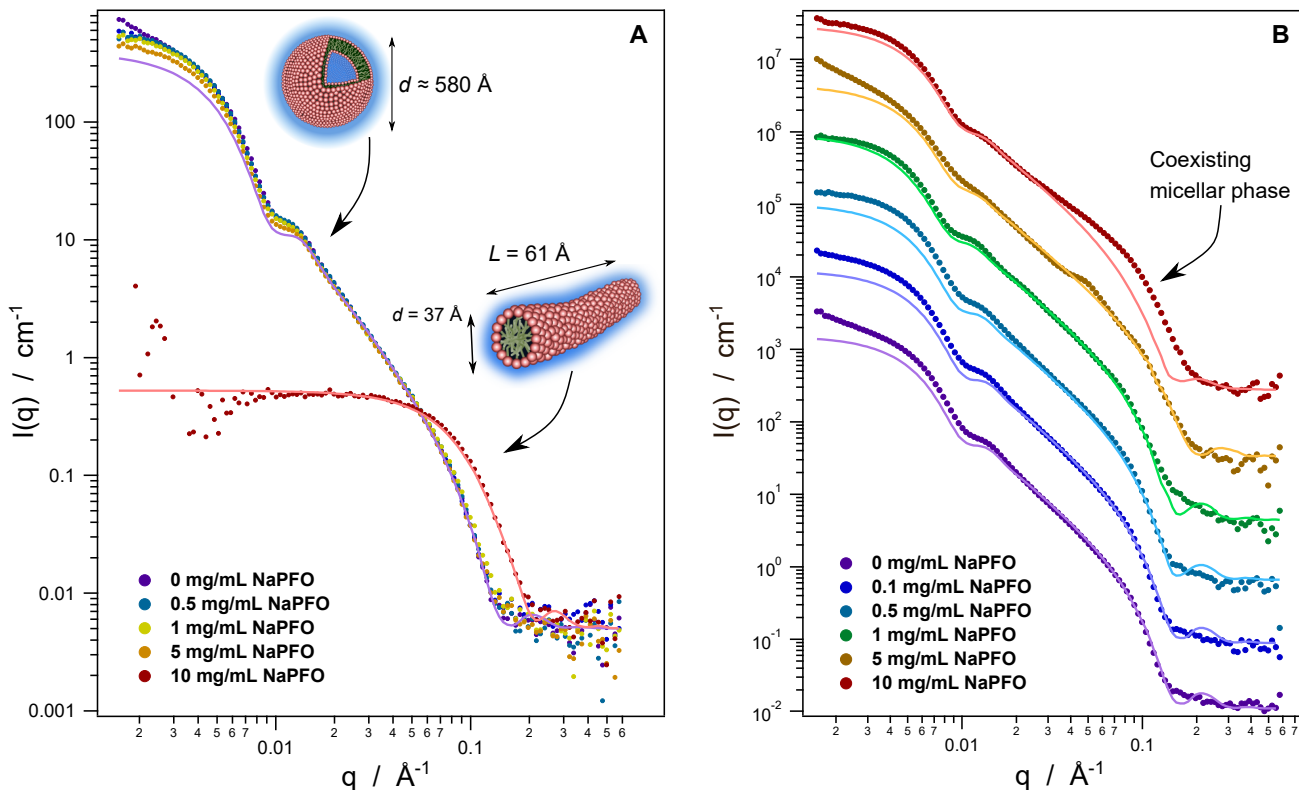


Figure 5.4 SANS data for DPPC liposomes with NaPFO at (a) 2 mg/mL DPPC and (b) 10 mg/mL DPPC with NaPFO concentrations as noted in the legend. Overlaid solid lines indicate model fitting (Table 5.2). For low concentration liposomes there is negligible change and until an abrupt phase change to mixed cylindrical micelles at 10 mg/mL NaPFO, while at the higher liposome concentration a more gradual change to is seen and a coexistence of micelles and liposomes is observed with 10 mg/mL NaPFO. Data sets in (b) are offset for clarity, while those in (a) are stacked to highlight their similarity.

DPPC liposomes showed the highest degree of homogeneity out of the liposomes studied, and this was true in the presence of added NaPFO as well. At 2 mg/mL there was no measurable change in liposome structure up to 5 mg/mL of added NaPFO. The only noticeable change in the scattering profile was a slight reduction in intensity in the low q region, likely indicating dissolution of bilayer fragments (responsible for poor model agreement in that region) by the added co-surfactant (Figure 5.4a). At 10 mg/mL of added NaPFO, an abrupt phase change to short, cylindrical (or rod-like) micelles is observed, with no evidence of any

liposome structures remaining. At this point, there is a much higher proportion of NaPFO than DPPC, so there is potential for a mixed system to form. However, the 37 Å micelle radius is consistent with the length of DPPC molecules and compares well to the bilayer thickness measured for the liposomes (Table 5.2). PFO is shorter and produces much smaller, spherical micelles ($R \approx 15$ Å).⁴⁶ Therefore this is likely a completely mixed micellar phase, with the cylindrical geometry of intermediate curvature between the normally spherical NaPFO and bilayer lipid structures. It is worth noting that the cmc of NaPFO is 31 mM⁴⁷ (14 mg/mL), significantly higher than the concentrations used here. Therefore there is unlikely to be any purely NaPFO micelles present.

Table 5.2 SANS fitting parameters for DPPC liposomes shown in Figure 5.4. For 10 mg/mL DPPC and 10 mg/mL NaPFO, the presence of a coexistent micellar phase means some liposome fitting parameters can't be determined and are indicated in parentheses. These were used in the overlaid model fit to highlight the contribution from the coexistent micellar phase.

NaPFO added (mg/mL)	Vol. fraction	Radius (Å)	Shell thickness (Å)	Solv. thickness (Å)	<i>n</i> Shells
DPPC 10 mg/mL					
0	0.01	260 (0.4)	40	19	1.1 (0.2)
0.1	0.01	260 (0.4)	40	19	1.1 (0.2)
0.5	0.01	275 (0.45)	40	25	1.2 (0.2)
1	0.012	300 (0.45)	40	27	1.1 (0.25)
5	0.014	260 (0.6)	31	20	1.1 (0.1)
10	0.007	250 (0.5)	(40)	(20)	(1.1 (0.2))
DPPC 2 mg/mL					
0 - 5	0.002	290 (0.33)	41 (0.1)	18 (0.1)	1.05 (0.3)
	Vol. fraction	SLD (Å ⁻²)	Radius (Å)	Length (Å)	Charge (<i>e</i> / micelle)
10	0.0075	3.0×10^{-6}	18.5	61	0

At 10 mg/mL DPPC, a more gradual change is seen as NaPFO is added. At low amounts of NaPFO, the shell thickness remains a constant 40 Å but the solvent thickness in multi-layer structures gradually increases, from 19 Å up to 27 Å at 1 mg/mL NaPFO. This likely indicates the PFO ion being incorporated into the lipid bilayer, with the additional charge increasing repulsion between layers, comparable to that observed in mixed liposomes with POPS. There is also a slight increase in measured volume fraction of liposomes with 1 mg/mL NaPFO, which supports this explanation. With more than 5 mg/mL of added NaPFO the sys-

tem begins transitioning to a mixed aggregate system, with the sample of 10 mg/mL DPPC plus 5 mg/mL NaPFO representing an intermediate that fits poorly to the liposome model. Therefore there is not a high degree of confidence in the fitted parameters, however the increase in polydispersity is readily apparent and the small feature in the slope at $q = 0.05 \text{ \AA}^{-1}$ doesn't correspond to any parameter in the liposome model, indicating a complex system and breakdown of liposome structure.

At equal amounts of DPPC and NaPFO (10 mg/mL), contribution from a coexistent micellar phase is seen as a decrease in liposome volume fraction and an increase in intensity in the higher q region ($q \approx 0.1 \text{ \AA}^{-1}$). This is distinct to a feature in that region that would imply multilamellarity, which produces a relatively sharp structure peak. Comparison can be made to more advanced mixed phases are seen in anionic liposomes detailed in a later sections. There are insufficient micellar features resolved to determine structural parameters in this spectrum, but likely short cylindrical micelles are present, similar to those observed with 2 mg/mL DPPC.

Due to the difference in neutron scattering length density (SLD) between the fluorinated and hydrocarbon chains, it is likely that the increase in volume fraction is slightly larger than measured. PFO has a neutron SLD of $4.0 \times 10^{-6} \text{ \AA}^{-2}$ compared to $0.3 \times 10^{-6} \text{ \AA}^{-2}$ for hydrocarbon lipids. This means the hydrocarbons have much greater contrast to D_2O (SLD = $6.4 \times 10^{-6} \text{ \AA}^{-2}$) and therefore the same molecular volume would produce a greater scattering intensity. To accurately determine these contributions and provide a more detailed picture for mixed systems, contrast matching could be used so only one component is analysed. This can be achieved by either deuterating the lipid chains (a costly and time-consuming process) or by matching the solvent SLD to that of fluorinated chain through addition of H_2O . Neither of these were carried out in this study, but could be utilised in future work specifically on these mixed phases for better understanding of the exact partitioning ratio.

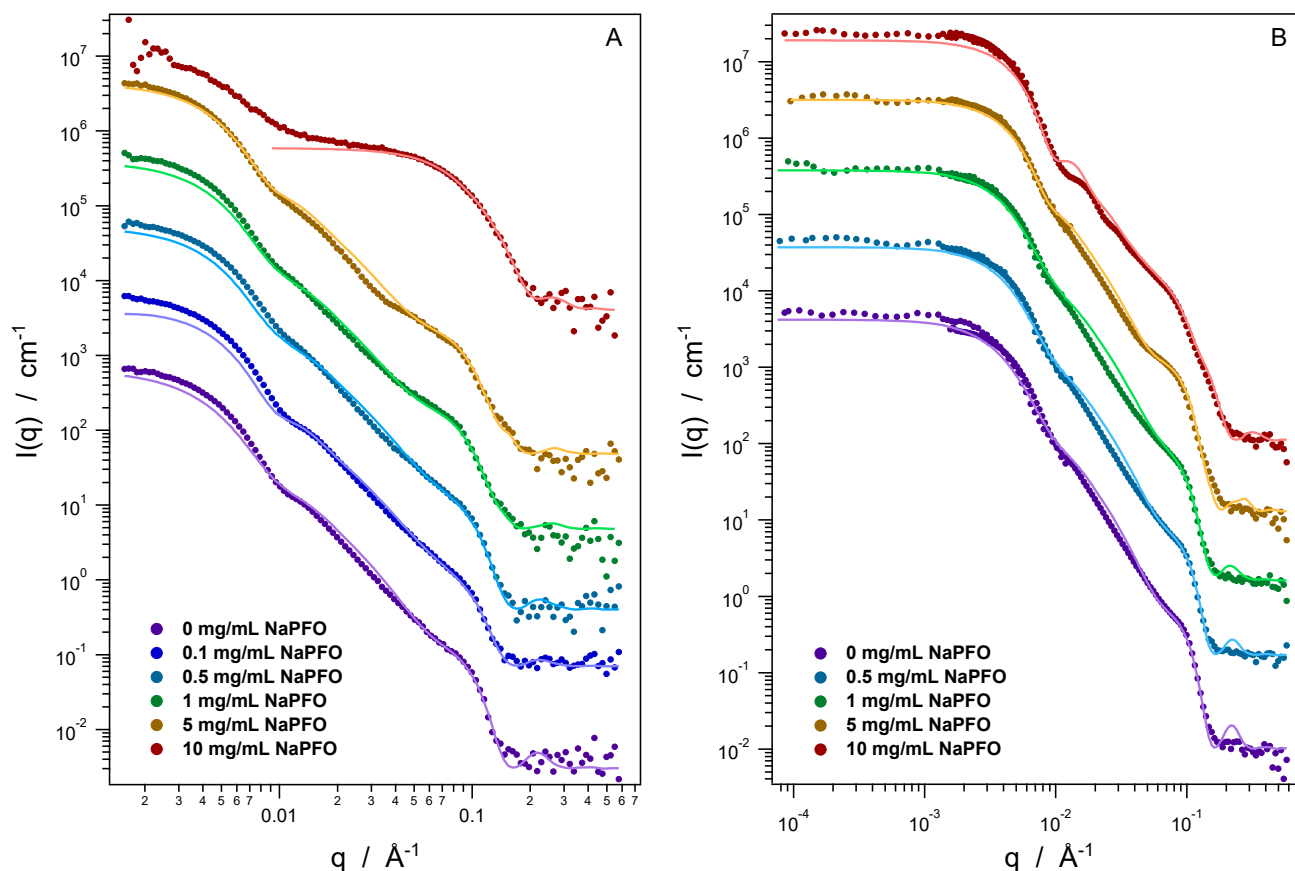


Figure 5.5 SANS data for POPC liposomes with NaPFO at (a) 2 mg/mL POPC and (b) 10 mg/mL POPC with NaPFO concentrations noted in the legend. Overlaid solid lines indicate model fitting (Table 5.3). For low concentration liposomes there is a gradual change in liposome structure as the amount of NaPFO increases and a broader transition region to a micellar phase, indicating some coexistence of fluorocarbon-rich and hydrocarbon-rich regions.

POPC liposomes

POPC liposomes were somewhat more challenging to model than DPPC liposomes due to greater polydispersity in radius and greater amounts of multilamellar structures. In some cases the measured liposome radius was less than expected at 240 Å, and these correspond to samples with the highest polydispersity in radius (Table 5.3). This is a result of the greater scattering intensity produced by larger structures compared to smaller ones; greater amounts of larger structures necessitate the average value be below the minimum expected based on the preparation method. Unlike DPPC liposomes, a small amount polydispersity is present in the solvent thickness parameter, possibly simply a reflection of the greater degree of mul-

tilamellarity but this also may indicate the more fluid nature of POPC bilayers at ambient temperature due to the presence of the unsaturated oleyl chain.

Unlike DPPC, at 2 mg/mL there is a gradual change in liposome structure with increasing amounts of NaPFO before the transition to micelles (Figure 5.5). Liposome volume fraction gradually increases, and bilayer thickness decreases from 39 Å with no added NaPFO to 32 Å with 5 mg/mL NaPFO. At this point, the quality of fit is reduced as the liposome structure shows signs of transitioning to a micellar phase. This phase transition is more gradual than for DPPC liposomes at the same concentration; with 10 mg/mL added NaPFO there is also some scatter at low q indicative of residual liposome or lamellar fragments still being present. This indicates some amount of coexistence of fluorocarbon-rich and hydrocarbon-rich regions, which is further indicated by the higher curvature in the micelles present. The ellipsoidal micelles, while still highly elongated, are narrower with $R_{eq} = 20$ Å which is more indicative of the shorter PFO molecules than lipids. Although the unstaurated oleyl chain in POPC makes the molecule less crystalline and possibly more accomodating to the shorter PFO molecule, it is likely these micelles are more enriched in PFO rather than the ideal mixing seen with DPPC.

At 10 mg/mL POPC, the trends are consistent with that observed previously, with decreasing bilayer thickness and increasing solvent thickness. In this case, with 10 mg/mL added NaPFO an interesting phase forms that is superficially similar to *less* polydisperse liposomes compared to the previous samples but with a much greater solvent thickness (50 Å). However, the secondary harmonic peak of the spherical form factor does not align in a meaningful way to the experimental data, and instead the overtones are at a different q vlaue to that expected with a liposome model(Figure 5.5b). One explanation may be a coexistent, fluorocarbon-rich lamellar phase, as this would provide an additional structure peak with such overtones. The interlamellar distance d can be estimated using the relationship:

$$d = \frac{2\pi}{q} \quad (5.6)$$

The bump at $q = 0.015$ would correspond to $d \approx 420$ Å. PFO has been found to form lamellar phases at low concentrations^{46,48} and this is also seen in Chapter 3. In these cases, the high water content produces large d spacings compared to more commonly reported lamellar phases. However, this is only hypothetical at present as there are insufficient data to be conclusive, and it is possible that other deformations in liposome structure and lamellarity could produce such a result. As with the previous data set, the use of contrast matching to remove the fluorocarbon component would be useful in determining the existence of a coexistent phase.

Table 5.3 SANS fitting parameters for POPC liposomes shown in Figure 5.5.

NaPFO added (mg/mL)	Vol. fraction	Radius (Å)	Shell thickness (Å)	Solv. thickness (Å)	n Shells
POPC 10 mg/mL					
0	0.011	250 (0.4)	39	18 (0.1)	1.3 (0.2)
0.5	0.012	240 (0.45)	38	19 (0.1)	1.3 (0.2)
1	0.013	240 (0.45)	38	21 (0.1)	1.25 (0.2)
5	0.014	240 (0.45)	34	31 (0.1)	1.2 (0.25)
10	0.018	290 (0.2)	27	50 (0.15)	1.1 (0.2)
POPC 2 mg/mL					
0	0.002	250 (0.35)	39	19	1.25 (0.2)
0.1	0.0021	250 (0.35)	37	21	1.2 (0.18)
0.5	0.0022	250 (0.37)	37	22 (0.1)	1.2 (0.2)
1	0.0024	250 (0.37)	34	36 (0.1)	1.2 (0.2)
5	0.003	250 (0.4)	32	38	1.2 (0.2)
	Vol. fraction	SLD (Å ⁻²)	R_{polar} (Å)	$R_{eq.}$ (Å)	Charge (e / micelle)
10	0.008	3.0×10^{-6}	45	20	40

Anionic liposomes

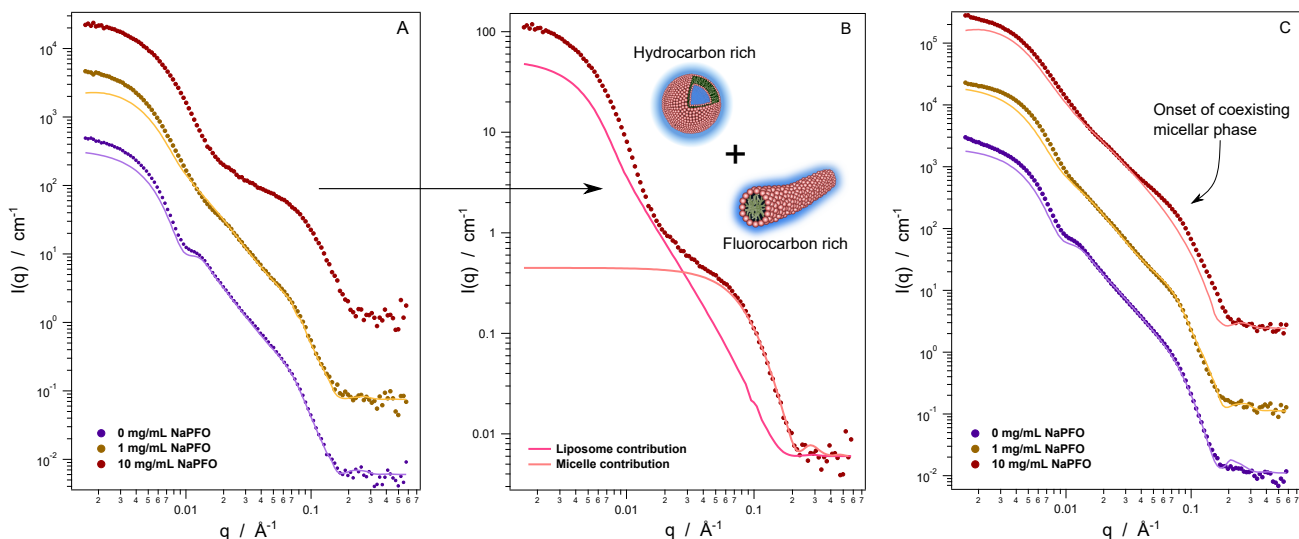


Figure 5.6 SANS data for mixed DPPC/POPS liposomes with NaPFO at (a) 2 mg/mL and (c) 10 mg/mL total lipid concentration with NaPFO concentrations noted in the legend. Overlaid solid lines indicate model fitting (Table 5.4). The coexistence of hydrocarbon-rich liposomes and fluorocarbon-rich micelles is seen with 2 mg/mL DPPC and 10 mg/mL NaPFO (where molar ratio of NaPFO/DPPC = 8.5) and the individual contributions to the scattering profile are highlighted in (b).

Introduction of anionic POPS to liposomes resulted in much thicker solvent layers in multilamellar liposomes and a slight reduction in bilayer thickness compared to the stock DPPC or POPC liposomes (Table 5.1). Like charges on the bilayer surfaces can produce a greater repulsive force on the bilayers, acting to increase the solvent layer thickness, as seen with the introduction of NaPFO to stock DPPC and POPC liposomes (Table 5.2 and Table 5.3 respectively). The magnitude differed from DPPC to POPC-based liposomes: DPPC/POPS liposomes showed very large solvent layers at 50 - 55 Å, while POPC/POPS liposomes showed a more modest 35 Å solvent thickness.

This notable difference is unexpected, as the two mixtures have the same head groups. If there was a change in the level of hydration of the head group region due to the more hydrophilic charged head group, it should be consistent in both sets of data. A greater amount of solvent in the head group region would lessen the scattering contribution of the head group and result in a apparently greater solvent layer and lesser bilayer thickness. This is unlikely

to be occurring here due to the large difference between the DPPC/POPS and POPC/POPS liposomes, and because the change in solvent thickness is far greater than the reduction in bilayer thickness. From the data available, the charge-repulsion hypothesis more accurately reflects the data and concurs with effects observed in the presence of added NaPFO.

Table 5.4 SANS fitting parameters for DPPC/POPS liposomes shown in Figure 5.6.

NaPFO added (mg/mL)	Vol. fraction	Radius (Å)	Bilayer thickness (Å)	Solv. thickness (Å)	<i>n</i> Shells
DPPC 10 mg/mL					
0	0.011	300 (0.25)	37 (0.1)	50	1.25 (0.1)
1	0.012	250 (0.4)	33 (0.1)	55	1.2 (0.15)
10	0.009	200 (0.5)	33 (0.1)	40	1.1 (0.1)
DPPC 2 mg/mL					
0	0.002	300 (0.35)	36 (0.1)	55 (0.1)	1.25 (0.2)
1	0.002	250 (0.8)	34 (0.1)	55 (0.1)	1.25 (0.2)
	Vol. fraction	SLD (Å ⁻²)	Radius (Å)	Length (Å)	Charge (<i>e</i> / micelle)
10	0.0025	3.0×10^{-6}	18	60	5

Incorporating anionic lipids into DPPC and POPC liposomes was found to produce a significant change in their interactions with NaPFO. Since PFO is an anionic surfactant, it was hypothesised that with interactions anionic lipids would be less favourable, and this is reflected in data for both DPPC/POPS and POPC/POPS liposomes. In the DPPC/POPS system, a coexistence of hydrocarbon-rich liposomes and fluorocarbon-rich micelles is observed with 2 mg/mL liposomes (Figure 5.6). Although there is insufficient data to accurately resolve the features of either phase, the contributions from liposome and micellar components are highlighted with approximate model fits in Figure 5.6b. This compares to the mixed micelles formed for pure DPPC liposomes, which is evidence for a less favourable interaction between NaPFO and anionic liposomes.

Although the data set is smaller here, there is a noticeable change at intermediate NaPFO concentrations, which is also different to the pure DPPC data set. Although the interactions seem less favourable, it is possible that incorporation of NaPFO into the liposomes is more disruptive to their structure due to the repulsion between head group charges. The presence of an unsaturated chain in POPS is also likely playing a role here, allowing for more flexibility

in the bilayers to adjust to the presence of additional PFO. Interestingly, with 10 mg/mL lipid and 10 mg/mL NaPFO, the micellar contribution also appears lower than for seen in pure DPPC, although the polydispersity is much higher and may be masking this to some extent.

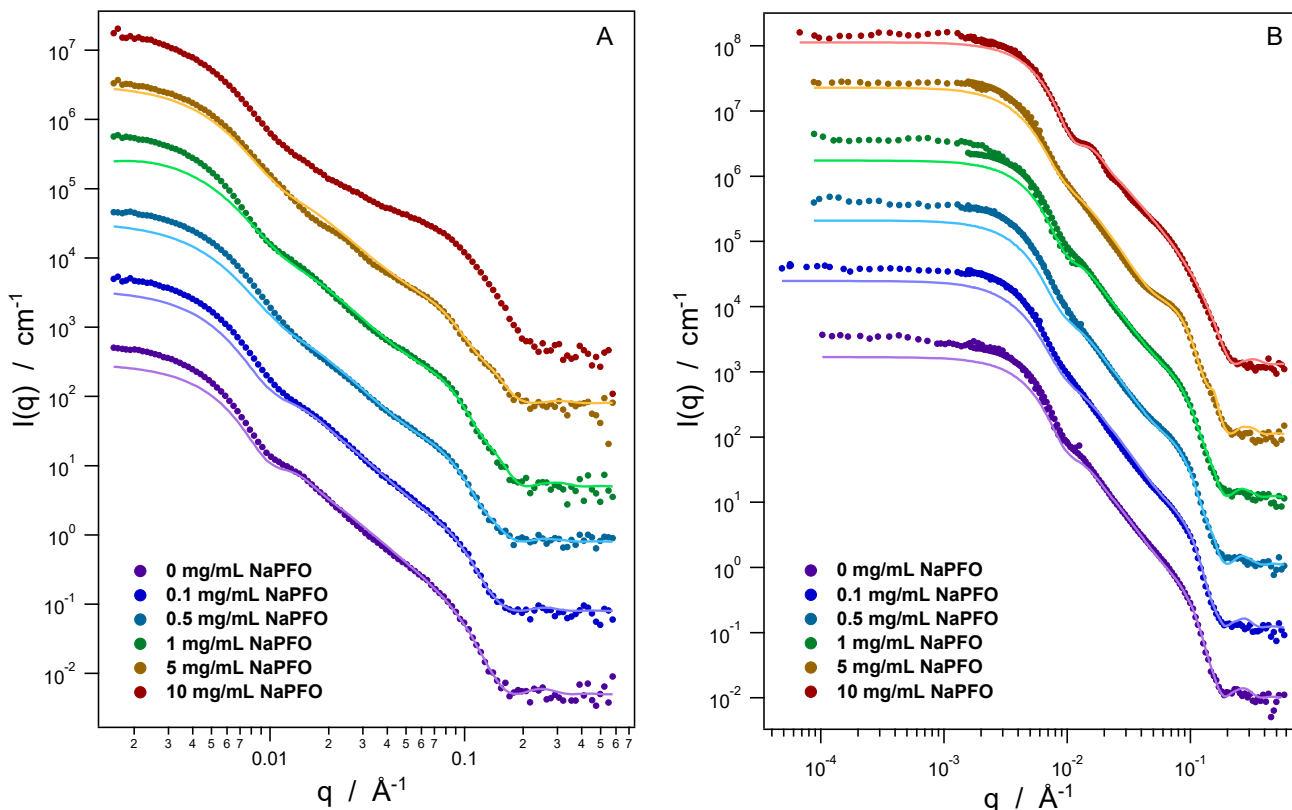


Figure 5.7 SANS data for mixed POPC/POPS liposomes with NaPFO at (a) 2 mg/mL and (b) 10 mg/mL total lipid concentration with NaPFO concentrations noted in the legend. Overlaid solid lines indicate model fitting (Table 5.5). For 2 mg/mL lipid with 10 mg/mL NaPFO, there are coexistent liposome and micellar phases, but insufficient features of either can be resolved for fitting.

In POPC/POPS liposomes there is a similar trend continuing, although the larger data set allows for a more detailed comparison than DPPC/POPS liposomes. Table 5.5 shows that the now familiar trends in increasing thickness of the solvent layers and decreasing bilayer thickness continue. Considering the bilayer thickness is starting at a lower value for POPC/POPS liposomes (at 33 - 35 Å) this results in relatively thin bilayers for lipids: at the maximum amounts of added NaPFO, bilayer thickness is reduced to 28 Å and 27 Å for 2 mg/mL and 10 mg/mL lipid dispersions respectively.

As with DPPC/POPS, there is clear liposome/micellar coexistence with 2 mg/mL POPC/POPS

liposomes and 10 mg/mL NaPFO (Figure 5.7a). Even an approximate fit wasn't possible for this sample, although qualitatively it is very similar to that seen for DPPC/POPS liposomes. Interestingly, in this data set the degree of multilamellarity appears much lower, with $n = 1.00 - 1.05$, which possibly reduces the accuracy of the measured solvent thickness (since only small amounts would be present). As NaPFO is added, the measured liposome radius also becomes highly inaccurate due to the increase in polydispersity, although as has been mentioned previously, this is an issue for all samples where only SANS data is available and is not a parameter that is of interest in this study.

Table 5.5 SANS fitting parameters for POPC/POPS liposomes shown in Figure 5.7.

NaPFO added (mg/mL)	Vol. fraction	Radius (Å)	Bilayer thickness (Å)	Solv. thickness (Å)	n Shells
POPC 10 mg/mL					
0	0.011	260 (0.3)	33	35	1.3 (0.2)
0.1	0.012	260 (0.35)	33	32	1.3 (0.2)
0.5	0.012	270 (0.35)	32	41 (0.1)	1.3 (0.2)
1	0.012	260 (0.35)	32	42 (0.1)	1.25 (0.2)
5	0.0135	250 (0.4)	30	44 (0.1)	1.2 (0.25)
10	0.015	250 (0.23)	27	-	1.0
POPC 2 mg/mL					
0	0.0021	260 (0.3)	35	35	1.05 (0.2)
0.1	0.0022	250 (0.3)	34	35	1.05 (0.2)
0.5	0.0023	200 (0.4)	32	44	1.0 (0.22)
1	0.0027	200 (0.4)	30	48	1.0 (0.22)
5	0.003	210 (0.38)	28	55	1.0 (0.21)

At 10 mg/mL POPC/POPS liposomes (Figure 5.7b), the effect of POPS seems less than at the lower lipid concentration, and the data set is quite similar to pure POPC liposomes with NaPFO. A notable difference is at 10 mg/mL of added NaPFO. This results in more homogenous liposomes; polydispersity in radius disappears and there is no longer any contribution from multilamellar structures. This is an unexpected result, since the overall trend when NaPFO mixes with liposomes is towards less homogenous liposomes. The increased volume fraction and good quality of fit imply that this is a mixed liposome, with NaPFO incorporated resulting in homogenous, unilamellar liposomes that form spontaneously. Although in mixed fluorinated/hydrocarbon systems PFO has been known to spontaneously form liposomes⁴⁹⁻⁵¹

these are typically with contrasting head group charges (cationic or zwitterionic hydrocarbon surfactants). This phase forming with an anionic lipid is highly unusual, and in the context of this study highlights a high degree of partitioning of NaPFO into lipids under these conditions.

5.4 Discussion

The comprehensive data sets above highlight several key features of lipid/NaPFO interactions, with both composition of the hydrocarbon chains and nature of the head group influencing the phase behaviour of liposomes in the presence of NaPFO. With fully saturated chains (DPPC), the bilayer thickness stays constant as the amount of NaPFO is increased. Although the extrusion process was carried out above the gel-transition temperature for DPPC (41°C)⁵², at room temperature these bilayers would likely return to their more crystalline phase. In this system, the liposome structure seems relatively stable in the presence of added NaPFO until either a mixed micellar phase forms if lipid volume fraction is low or a coexistent, fluorocarbon-rich micellar phase forms at higher lipid volume fractions. This reflects the greater stability and rigidity of fully saturated lipids below their gel-transition temperature;^{53,54} the more crystalline state may be accommodating additional molecules, but the relative inflexibility of saturated lipid chains in the gel phase prevents large changes in bilayer structure.

In contrast, liposome bilayers with an unsaturated chain in their structure (POPC and POPS) are more variable as the amount of NaPFO added increases. With the exception of the highest NaPFO:lipid ratio where fitting quality was poor, there is a linear decrease in bilayer thickness as the relative amount of NaPFO increases (Figure 5.8). Both POPC and POPC/POPS liposomes showed a similar trend, albeit from different starting values, indicating this is a property of the hydrocarbon chains and not influenced by lipid head group. This presumably reflects the greater flexibility of lipids with some degree of unsaturation in their hydrocarbon chains. Although most prominently associated with decreasing the gel-transition temperature (e.g. -2°C and 14°C for POPC and POPS respectively),⁵² it appears this also allows for their bilayer structure to adjust when incorporating other surfactant molecules such as NaPFO.

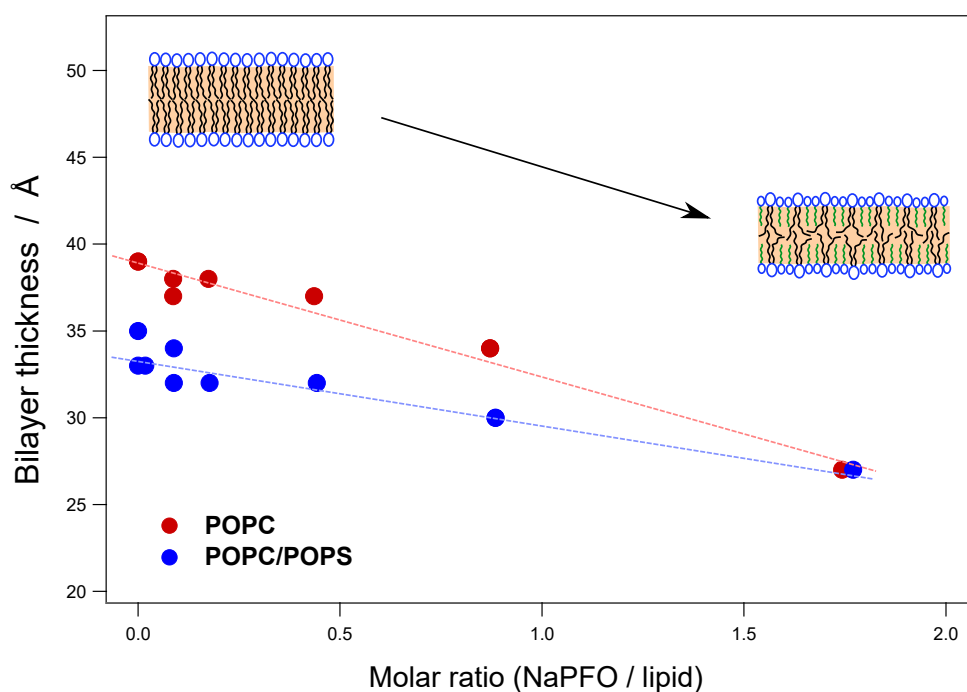


Figure 5.8 Liposome bilayer thickness as a function of NaPFO/lipid molar ratio for POPC and POPC/POPS liposomes. Increasing NaPFO concentrations relative to lipids produced thinner bilayers. Outlying points at NaPFO/lipid = 4.4 represent 2 mg/mL lipid and 5 mg/mL NaPFO were omitted, for both POPC and POPC/POPS liposomes these were likely inaccurate fits due to their non-standard scattering profile, and instead may indicate a coexistence region.

Incorporation of molecules into liposome structures is an active area of research but is focussed typically on more biologically relevant molecules such as cholesterol^{55,56} or drug molecules. These are unlikely to provide a meaningful comparison to surfactant molecules due to a lack of amphiphilicity. Anionic bile salts such as sodium cholate are somewhat more comparable due to their surfactant properties. In SANS measurements of multilamellar DMPC liposomes, the solvent thickness was also found to increase as anionic cholate is incorporated⁵⁷. In DPPC unilamellar liposomes mixed with deoxycholate (DC)⁵⁸, a gradual change in curvature is observed as the fraction of DC increases, transitioning smoothly from liposomes to spherical micelles with cylindrical and ellipsoidal intermediates. Bile salts such as cholates are significantly larger molecules, and the presence of multiple saturated carbon rings gives them their own molecular curvature that easily disrupts the bilayers. However, mixing still appears favourable, and the aggregate structures produced are a combination of those expected from both components.^{58,59}

The solubilisation of lipids and liposomes by surfactants is a well-known phenomenon^{60–62} and coexistent phases with hydrocarbon surfactants have been reported but seem uncommon.^{62–64} However, structural effects at low surfactant concentrations such as the present study have had little attention. It has been noted in SDS/lipid mixtures that solubilisation occurs over a concentration range rather than abruptly,^{64–66} and intermediate and coexistent aggregates are possible in this region.⁶⁴ Models have been proposed^{60,61} indicating the surfactant/lipid ratio where solubilisation occurs is related to the cmc of the surfactant. The relatively high concentrations of NaPFO present in this study before solubilisation occurs into mixed micelles reflects this. Samples in this study with a NaPFO/lipid ratio of 4.4:1 still showed liposome structures, albeit possibly with coexistence occurring, which is significantly higher than seen in SDS liposome mixtures⁶⁶ where complete solubilisation into micelles occurs at a SDS/lipid ratio of 3:1. This would not be unexpected when considering such dissolution models, as NaPFO has a significantly higher cmc than SDS (31 mM⁴⁷ and 8 mM⁶⁷ respectively). The incorporation of PFO into liposomes at concentrations much lower than the cmc indicates partitioning is quite favourable.

It has been noted that lipid chain *length* doesn't have a significant effect on the partition coefficient PFOA/PFOS in lipid bilayers^{19,20}. DPPC, POPC and POPS all have roughly the same chain lengths and were deliberately chosen to exclude chain length as a variable. However, the differences in *structural* changes between saturated and unsaturated lipid bilayers in the presence of PFAS has been overlooked in the literature so far. Analysis of partition coefficients is only part of the story for these interactions, and it has been established that for PFOA this is relatively consistent across lipid molecules due to similar amounts of hydrophobicity^{19,20}. The established decrease in transition temperatures for lipid bilayers in the presence of PFOA/PFOS^{15–17} has been correlated to more fluid layers at interfaces^{26,27} but the relationship to large structures hasn't been established. This work highlights how the lipid chain composition can be an important variable in how lipid bilayers respond to PFOA, and contradicts a computational study which found bilayer thickness to increase with the addition

of PFAS molecules²⁴.

Differences in NaPFO/lipid interactions when POPS is introduced are arguably less relevant from a biological perspective, as phosphatidylserine (PS) head groups make up a relatively low percentage of lipids in biological cells ($\approx 2 - 7\%$ of total lipids depending on the cell type)⁶⁸. In this work POPS was used to add a known repulsive interaction to determine what effect this has, if any, in counteracting the mutual hydrophobic interactions between surfactant tail groups. This produced interesting results: with a lower lipid volume fraction (2 mg/mL) less favourable NaPFO/lipid interactions were seen, indicated by the presence of coexistent liposome/micellar phases for both DPPC and POPC. However, with a higher lipid concentration (10 mg/mL) this effect wasn't observed and liposomes formed appear less affected by added NaPFO relative to pure DPPC or POPC liposomes. Changes in bilayer thickness indicate the presence of NaPFO in the liposome structure, and the trend is consistent as for the lower concentration of lipid (Figure 5.8).

Exactly why this behaviour differs is difficult to determine from the available data. There is the possibility of discrete fluorocarbon-rich and hydrocarbon-rich regions *within* the bilayer, with negative charges remaining spread out evenly. This seems unlikely, given that such a structure would have different preferred bilayer thicknesses and, even in a unilamellar vesicle such as seen with POPC/POPS, would likely produce a 'rippled' bilayer. This would result in a higher polydispersity in bilayer thickness. A more likely scenario may be that there is simply less NaPFO being incorporated, and more remains in solution outside the bilayers than for neutral liposomes. As noted previously, the cmc of NaPFO is relatively high at 31 mM⁴⁷, or ≈ 15 mg/mL. Measurements of blank 10 mg/mL NaPFO in dPBS showed no measurable micellar scattering, so it is assumed to be still below the cmc for NaPFO in these conditions, so there is potential for a large amount of PFO to remain dissolved in solution. It is telling that the interactions observed, especially formation of coexistent phases, are so noticeable at such low NaPFO concentrations.

5.5 Conclusion

The effect of NaPFO on lipid liposome structure was found to be dependent on both lipid chain composition and head group composition. NaPFO was found to be incorporated into liposome bilayers at the lowest concentrations measured (0.5 mg/mL), well below the cmc of NaPFO. This results in changes to bilayer thickness and at high concentrations (10 mg/mL NaPFO) complete phase changes are seen with examples of coexistent fluorocarbon-rich and hydrocarbon-rich phases.

With a fully saturated lipid (DPPC), bilayer thickness was relatively constant until either dissolution of liposomes occurred or excess NaPFO formed a fluorocarbon-rich coexistent micellar phase. When liposomes contain some degree of unsaturation in their chains such as POPC or POPS lipids, bilayer structure is more variable and a more gradual, linear decrease in bilayer thickness is observed as the amount of NaPFO added increases. Where multilamellarity is present, there is a corresponding increase in solvent layer thickness upon addition of NaPFO, for both DPPC and POPC liposomes. The inclusion of an anionic lipid (POPS) in the liposome structure promoted the formation of coexistent phases at lower lipid concentrations (2 mg/mL) but not at higher lipid volume fractions (10 mg/mL).

For both saturated and unsaturated lipids, phase transitions occurred at only the highest NaPFO:lipid molar ratio which was significantly greater than 1:1. When liposome concentration was lower (2 mg/mL), liposomes were still observed at a mole fraction of $\approx 4:1$ (NaPFO/lipid), indicating a high degree of partitioning and mixing of the two compounds. Although in some cases this ratio produced significant structural deformations, increases in measured volume fraction indicated the incorporation of significant amounts of fluorinated surfactant. Considering the low concentrations of NaPFO relative to its cmc, this indicates relatively favourable lipid/PFO interactions and a strong preference for partitioning into lipid bilayers.

Variable outcomes depending on both head group composition and tail group composition point to a complex narrative when considering the interactions of PFAS in biological systems. Biological lipids in cell structures are chemically diverse and those used here are only a fraction of potential bilayer compositions. There is potentially further information that could be gleaned from this data set that time did not allow, but further investigations could also expand on the variety of lipids and head group combinations. Information such as the study presented here is useful when considering toxicity of PFAS molecules, such as target organs where certain varieties of lipid molecules exist in greater proportion. A holistic understanding of the interactions between these two classes of chemicals is essential when considering the residence and accumulation of PFAS chemicals in biological systems and the resulting health outcomes.

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Chapter 6

Conclusions and Future Work

6.1 Conclusions

Perfluorooctanoate (PFO), once an important but understated industrial chemical, is becoming infamous as a chemical of environmental concern along with other perfluorinated alkyl substances (PFAS). Understanding fundamental interactions of fluorinated surfactants, such as PFOA, is critical to both determining efficient remediation methods and guiding investigations into effects in biological systems. This work aimed to further this understanding, focussing on the interactions of PFO with hydrocarbon ions and biological hydrocarbon amphiphiles.

Interactions of surfactants with hydrocarbon ions is not a prominent area of research, and investigations of fluorinated surfactants with hydrocarbon ions has a somewhat sporadic occurrence in current literature. A systematic approach was taken to fill in some of these gaps with respect to hydrophobicity and geometry in hydrocarbon ions, taking into account both surface activity and aggregation. These two aspects are then focussed on in a more practical setting in subsequent chapters: in Chapter 4 effects on surface activity are investigated to increase efficiency in a foam flotation remediation experiment and in Chapter 5 changes in aggregation behaviour of model lipid membranes in the presence of NaPFO is investigated.

In both cases the results are interpreted with respect to the underlying balance between hydrophobic, lipophobic and ionic forces governing the fluorosurfactant-hydrocarbon interactions in aqueous solutions.

This initial fundamental study in Chapter 3 used a large matrix of organic ammonium ions as counterions for PFO, incorporating primary, secondary and tertiary amines with 1 - 3 carbon chains. This provided a large range of variation in both geometry and hydrophobicity. Combined with evidence from the literature described previously, it is apparent that increasing hydrophobicity in the counterion promotes counterion and head group interactions. In dilute solution, increased binding of counterions to the head group will affect surface activity, resulting in decreased cmc values as counterion hydrophobicity increases. In concentrated solution, increased charge screening will affect the head group interactions, resulting in large changes in surfactant aggregation in PFO due to changing effective head group size. In PFO, a lamellar phase is readily formed even at low concentrations (down to 2%wt), even with only a relatively moderately hydrophobic counterion such as methylamine.

Changes in counterion geometry most prominently affect how the molecules pack in solids and films. Increasing the degree of substitution in counterions reduced the melting points (and likely Krafft temperatures, although these were not measured) considerably, with tertiary ammonium PFO species having melting points less than 0° C. Comparison to log*P* values indicate this is largely independent of hydrophobicity, for example the melting point of *n*-propylammonium PFO (63° C) is substantially higher than that of trimethylammonium PFO, despite its higher log*P* value. Consideration of other reports noted in Chapter 2 supports this view and variations at the air/water interface, such as minimum surface tension and surface excess concentration, could also be a reflection of changes in order of the interacting ions. Cmc values were strongly correlated to overall hydrophobicity while these two parameters were more variable with respect to overall hydrophobicity.

In Chapter 4, this concept was expanded to show how these interactions could be utilised

practically. Although use of PFO is decreasing, attention on remediation methods is increasing due to its status as a persistent organic pollutant. Current remediation methods for contaminated water rely on surface activity, for example in adsorption to solid substrates such as activated charcoal. Foam flotation is potentially more economical and scalable than adsorption methods but suffers from low efficiency in dilute solutions.

As organic ammonium counterions with PFO were found to increase surface activity, decreasing measured cmc values depending on the hydrophobicity of the counterion, this was hypothesised to provide a meaningful benefit to PFO concentrations in separated foams from dilute, weakly surface active solutions. Using dilute NaPFO solutions (0.1 mM) where measurable surface activity is low, organic ammonium species were found to provide a substantial increase in PFO removal as well as foaming potential. For example, an excess of hexylammonium provided a 100% increase in concentration of PFO in the extracted foam relative to the initial concentration with 25% of the volume extracted. Interestingly, removal and foaming potential correlated to hydrophobicity only until the added ammonium species had surface active properties itself. With *n*-octylamine added, reduction in measured surface tension was greatest but showed no foaming and no separation could be performed.

This highlights both how increasing the surface activity of PFO *via* simple adjustments to solution composition can provide large increases in removal efficiency, but also the complex nature of the fundamental interactions responsible. The unexpected results for *n*-octylamine indicate care needs to be taken when considering the optimal choice of any additive to use. Surface tension is only a part of the overall mechanics of foaming and the combination of PFO with a sufficiently hydrophobic ion seems to have an anti-foam effect, possibly due to ion pairs in solution behaving more like a hydrophobic, non-ionic surfactant.

Overall, the effect of solution chemistry in general is critical for any remediation method and the effects of either hydrophobic material or other dissolved ions need to be considered. Chapter 3 looked at PFO with organic counterions in isolation and supported stronger head

group and counterion interactions as the main driving force in observed results. Not only was this supported further in Chapter 4 but it also indicated that these interactions are largely independent of other ions present, and in a given solution the strongest binding ion will likely determine the surface activity along with other measurable properties. A holistic understanding of the interactions of PFAS with various dissolved materials allows for both development of more efficient remediation methods relying on surface activity, and also easier and more effective implementation of established methods to contamination sites with different water chemistry.

How PFO and other fluorinated surfactants interact with hydrocarbon surfactants has a long history in the literature due to the lipophobicity and potential de-mixing of fluorocarbon-rich aggregates. With the phase-out of PFO from many applications, interactions with biological surfactants such as lipids are now arguably of most interest to the wider scientific community. Continuing the theme on solution aggregation and soft matter phases, in Chapter 5 changes in liposome structure in the presence of NaPFO were analysed using neutron scattering. PFO molecules were found to readily diffuse into the lipid bilayers of model liposomes even well below their cmc. Complete phase changes were only observed at high NaPFO:lipid molar ratios ($> 2:1$). There was evidence of coexistent fluorocarbon-rich micelles and hydrocarbon-rich liposomes in some cases, but the majority of compositions indicated favourable mixing between the two amphiphiles.

The nature of the lipid chains has an influence on resulting structural changes. For POPC and POPS lipid molecules which have a degree of unsaturation in their carbon chain, bilayer thickness consistently decreases as the amount of added NaPFO increases. Fully saturated DPPC liposomes didn't show this effect, indicating the more crystalline chains are more resilient to structural deformations. Both cases showed phase changes and the presence of coexistent fluorocarbon-rich phases under approximately the same conditions. This supports previous reports analysing partition coefficients, with reported partition coefficients of PFOA into various lipid phases being relatively consistent. The influence of phospholipid head group

was not clear: at low concentrations (2 mg/mL lipid) the incorporation of anionic POPS appeared to promote the formation of mixed phases, but at high concentrations (10 mg/mL) seemed to have the opposite effect. Considerations of liposome structure had little precedence in the current literature, and since there are many different types of lipids that make up biological cells, and some lipids are more common in some cells than others, this study is only a beginning of understanding fully these interactions. Differences in structural deformations for certain lipids when partitioning into cell bilayers have major implications for how biological effects are interpreted, particularly when considering target organs in PFAS toxicity.

A common theme throughout this work is the balance between hydrophobic and lipophobic forces when perfluorinated surfactants interact with hydrocarbons in solution. Perfluorinated compounds are widely utilised for their oil-repellent properties but, for dissolved aqueous species where hydrophobicity is common to both, the results are still difficult to predict for a given system despite significant research over many years. In general, the results in this work don't indicate the level of antipathy theorised between the two classes of materials. For both hydrocarbon ions and hydrocarbon amphiphiles, interactions with PFO appear generally favourable in aqueous solution, indicating their mutual hydrophobicity is greater than the lipophobic force that would drive them to de-mix. This was found to be a double-edged sword: on one side this can be utilised to increase surface activity of PFO and hence efficiency in separation processes, but on the other means favourable residence and permeation through lipid bilayers, such as those comprising biological cell walls. While more work is still needed in both areas, furthering understanding on these fundamental properties will hopefully contribute to more efficient remediation methods and reduce impact of PFAS molecules on health and the environment in the future.

6.2 Future work

The interactions between PFAS molecules, including PFO, and lipids has been gaining increased attention in recent years. However, measuring structural changes in model lipo-

somes is still a developing area. Neutron scattering is a powerful analytical method for these experiments, however data in this work was analysed from a more qualitative perspective and improvements could be made even within the existing analysis to provide a more complete picture. The multi-layer vesicle model used was found to have some limitations for extreme deformations in liposome structure and accurately determining the amount of multi-lamellarity. These could be improved with a more manual fitting approach, such as using accurately defined shell arrays. Such approaches weren't applied here due to time limitations and the large amount of data but could be continually worked on in the future without additional experiments.

Further experiments using contrast-matching would provide much more detail on the nature of coexisting hydrocarbon-rich and fluorocarbon-rich phases. By using a 35:65 H₂O:D₂O ratio ($SLD = 3.9 \times 10^{-6} \text{ \AA}^{-2}$), the scattering from the PFO tail is removed due to the matching contrast, and only hydrocarbon scattering is observed. If further SANS measurements were available then concentrations where coexistence was apparent could be studied in more detail. The presence of coexistence implies the hydrocarbon phase is saturated with PFO, so these cases would provide more information on liposome structure under these extreme conditions.

Chapters 3 and 4 highlighted both the complexity of interactions between NaPFO and dissolved hydrophobic ions but also the potential for utilising this to increase surface activity and hence efficiency in PFAS remediation, in this case foam flotation. The aim of this work was to provide a comprehensive overview using different structures and hydrophobicities in the added ions. The application stage of this work in Chapter 4 is still only a proof-of-concept, and further work would be needed to move it forward. The solution chemistry could likely be further optimised through changes to pH and ionic strength, within a reasonable range for a 'mild' process suitable for discharge into the environment. The effects on adsorption to solid substrates could also be explored, especially when considering more hydrophobic additives such as *n*-octylamine. The anti-foam properties of this compound with PFO wasn't conducive

to foam separation, but the high surface activity measured may produce greater efficiency in adsorption to solid substrates where foaming is not a necessary.

Most importantly, additives chosen could be explored further with a focus on minimising toxicity and any environmental burden from the overall process. Experiments here were focussed on exploring the key properties of hydrophobicity and charge density of additives, consideration wasn't given to toxicity or other factors affecting applicability. Any subsequent treatment required to remove additives used would increase the barrier for implementation, so identifying bio-compatible alternatives would greatly increase the feasibility of the concept. Amines are ubiquitous in the environment and there are many potential options of biological origin. The biological activity of some compounds would make them unfeasible so careful planning would be needed, but more benign examples such as choline salts and some hydrophobic amino acids (e.g. phenylalanine or tryptophan) could be effective for this process with lower environmental impact than synthetic amines.

Appendices

The effects of alkylammonium counterions on the aggregation of fluorinated surfactants and surfactant ionic liquids

Supplementary Material

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1 Surface Tension Analysis

A complete set of the surface tension data obtained is presented below, annotated with the regions and slopes used to obtain the surface excess at the cmc and the area per molecule.

2 SANS Analysis

Data were fit using one of two models: a) lamellar paracrystalline stack, or b) ellipsoidal micelles. For lamellar systems, the model presented by Nallet *et al.* was applied.¹ This formalism comprises a form factor representing the lamellar membranes, $P(q)$ and a structure factor that describes their relative spacing and interaction, $S(q)$ as a function of the average inter-lamellar spacing, d :

$$I(q) = 2\pi \frac{P(q)S(q)}{dq^2} \quad (1)$$

The form factor representing the lamellae is given by:

$$P(q) = \frac{2\Delta\rho^2}{q^2} (1 - \cos(q\delta) \exp(-q^2\sigma^2/2)) \quad (2)$$

where $\Delta\rho$ is the difference in scattering length density between the bilayer and solvent, δ is the bilayer thickness, and σ is a parameter fixed at $\sigma = \delta/4$.

The structure factor representing the interactions between lamellae in the system is given by:

$$S(q) = 1 + 2 \sum_1^{N-1} \left(1 - \frac{n}{N}\right) \cos(qdn) \exp\left(-\frac{2q^2d^2\alpha(n)}{2}\right) \quad (3)$$

where N is the number of lamellar plates and n refers to the ' n 'th layer and α is given by:

$$\alpha(n) = \frac{\eta_{cp}}{4\pi^2} [\ln(\pi n) + \gamma_E] \quad (4)$$

where γ_E is Euler's constant. The Caillé parameter,² η_{cp} is

$$\eta_{cp} = \frac{q_0^2 k_B T}{8\pi \sqrt{K\bar{B}}} \quad (5)$$

Table S1: Neutron scattering contrast parameters including scattering length density (SLD) for the materials involved in this study. Note that the calculations are performed for the precursor neutral species; little change is expected upon proton transfer.

Material	Density (g cm ⁻³)	SLD ($\times 10^{10}$ cm ⁻²)
Deuterium oxide	1.11	6.373
Ammonia	0.73	-0.479
Perfluorooctanoic acid	1.80	3.816
Methylamine	0.70	-0.845
Ethylamine	0.69	-0.655
<i>n</i> -Propylamine	0.72	-0.584
Isopropylamine	0.72	-0.584
Dimethylamine	0.67	-0.636
Diethylamine	0.71	-0.515
Di- <i>n</i> -propylamine	0.74	-0.462
Trimethylamine	0.67	-0.543
Triethylamine	0.73	-0.455
Tri- <i>n</i> -propylamine	0.76	-0.415

where q_0 is the scattering vector of the first Bragg peak, k_B and T are the Boltzmann constant and the temperature respectively, K is the membrane bending elasticity and $\bar{B}$ is the membrane compression modulus.

For ellipsoids, the following form factor $P(q, a)$, was used:³

$$P(q, a) = \frac{3\Delta\rho V(\sin[qr(R_{eff})] - qr \cos[qr(R_{eff})])}{[qr(R_{eff})]^3} \quad (6)$$

where $\Delta\rho$ is the scattering length density difference between the ellipsoid and solvent, V is the ellipsoid volume, and

$$R_{eff} = \sqrt{R_b^2(\sin \alpha)^2 + R_a^2(\cos \alpha)^2} \quad (7)$$

wherein R_a and R_b are the semi-major and semi-minor axes of the ellipsoid respectively and α is the angle between the semi-major axis and the q vector.

References

- [1] F. Nallet, R. Laversanne, D. Roux, Modelling x-ray or neutron scattering spectra of lyotropic lamellar phases: interplay between form and structure factors, J. Phys. II France 3 (1993) 487–502.
- [2] A. Caille, X-ray scattering by smectic-a crystals, C. R. Hebd. Acad. Sci. Paris B 274 (1972) 891–893.
- [3] M. Kotlarchyk, S.-H. Chen, Analysis of small angle neutron scattering spectra from polydisperse interacting colloids, The Journal of chemical physics 79 (5) (1983) 2461–2469.

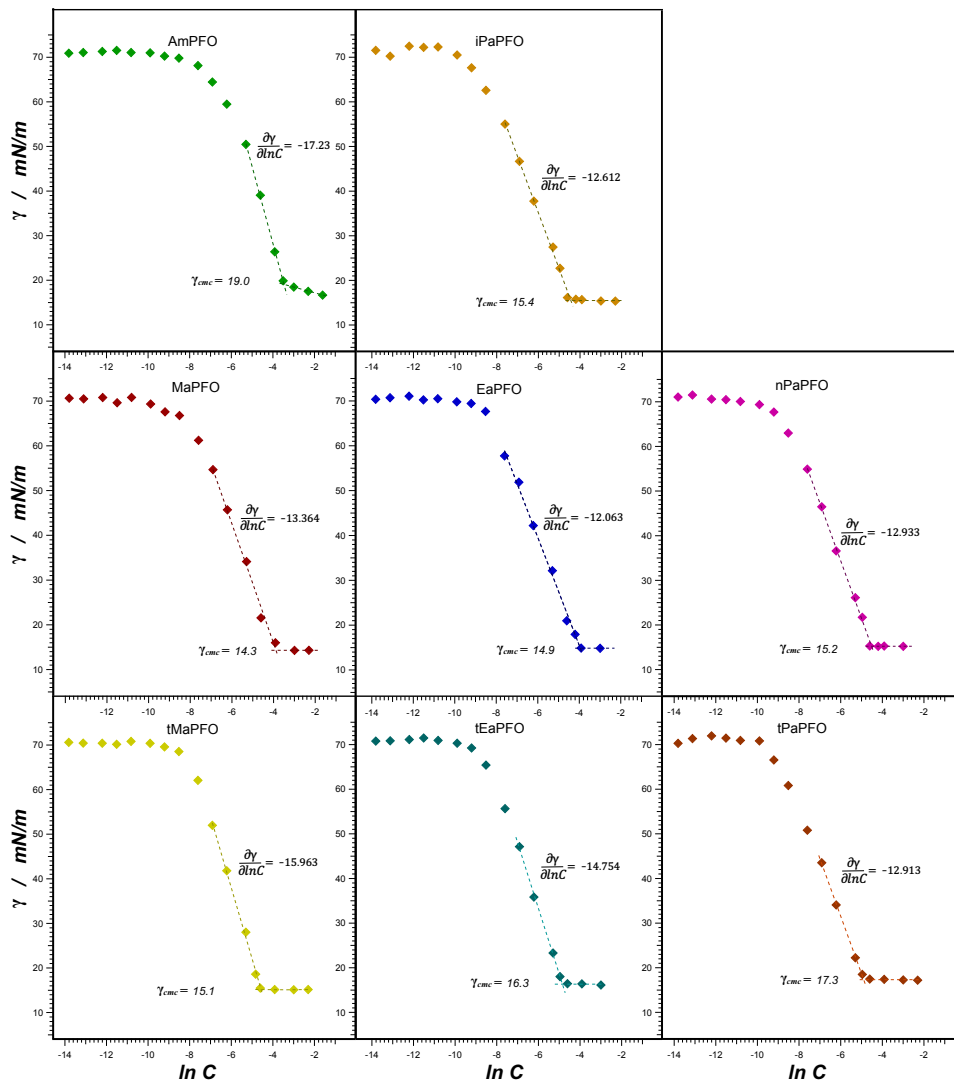


Figure S1: Surface tension analysis of the alkyl ammonium perfluorooctanoate compounds studied. Surface tension analysis for the di-substituted alkyl ammonium PFOs has been previously reported, and values were obtained from the literature as referenced in the text of the main paper.

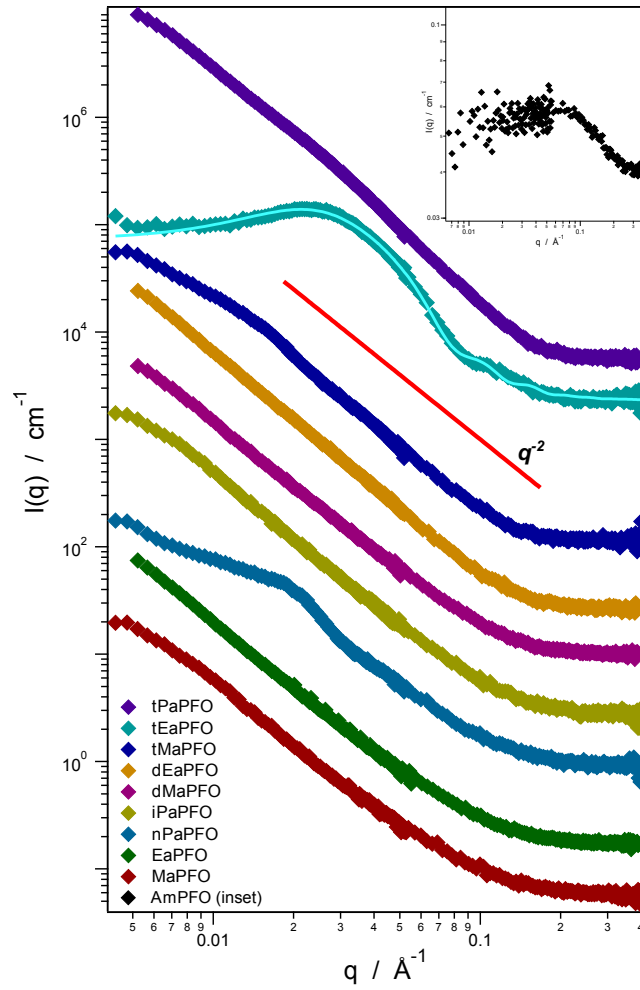


Figure S2: SANS spectra of 2% solutions of the different PFO compounds. The spectrum for AmPFO is inset for clarity.

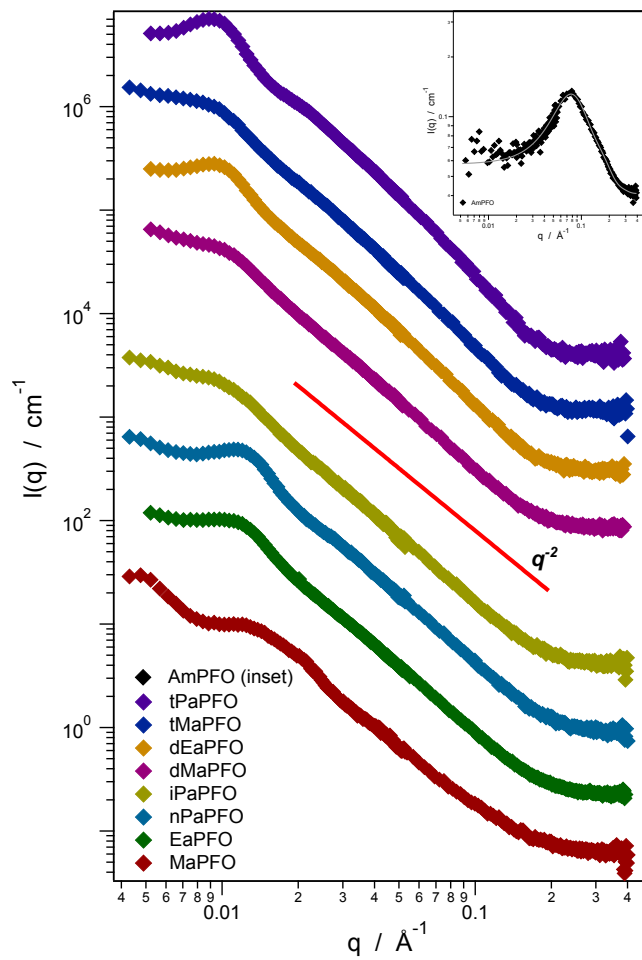


Figure S3: SANS spectra of 5% solutions of the different PFO compounds. The spectrum for AmPFO is inset for clarity.

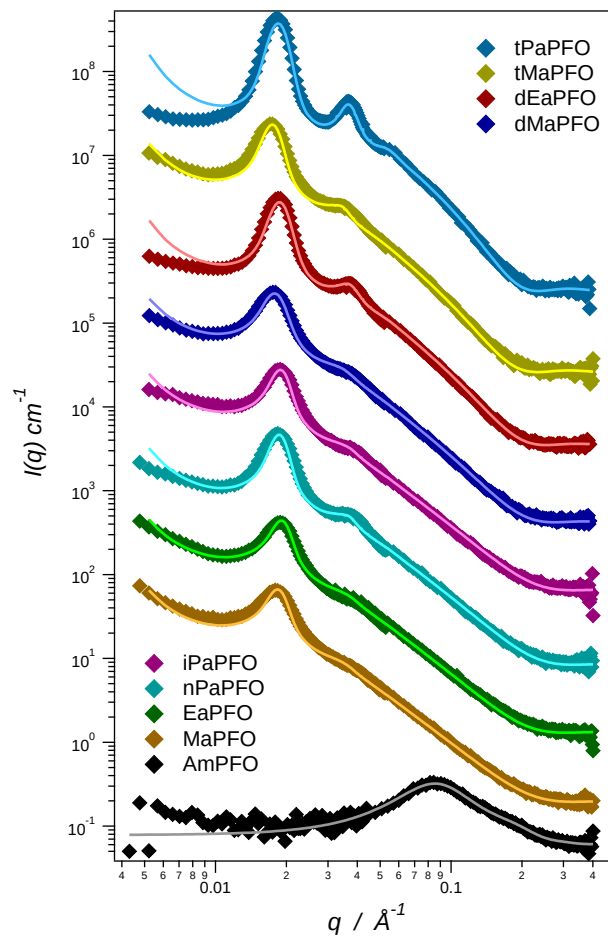


Figure S4: SANS spectra of 10% solutions of the different PFO compounds.

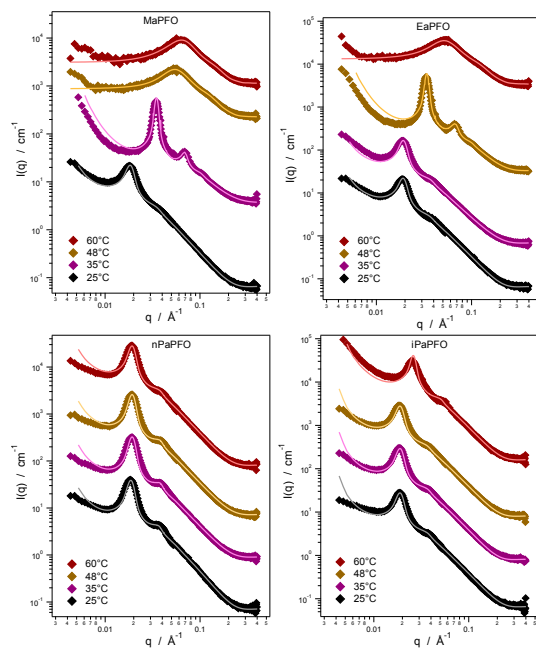


Figure S5: SANS spectra of 10% solutions of the primary ammonium PFO compounds as a function of temperature.

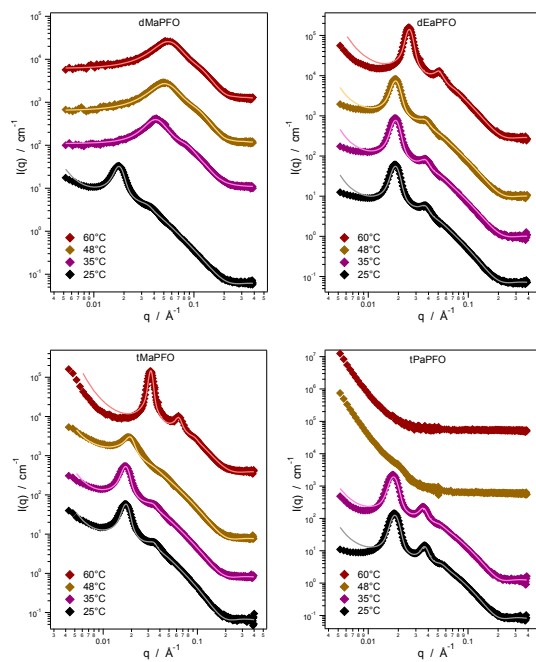


Figure S6: SANS spectra of 10% solutions of the secondary and tertiary ammonium PFO compounds as a function of temperature.

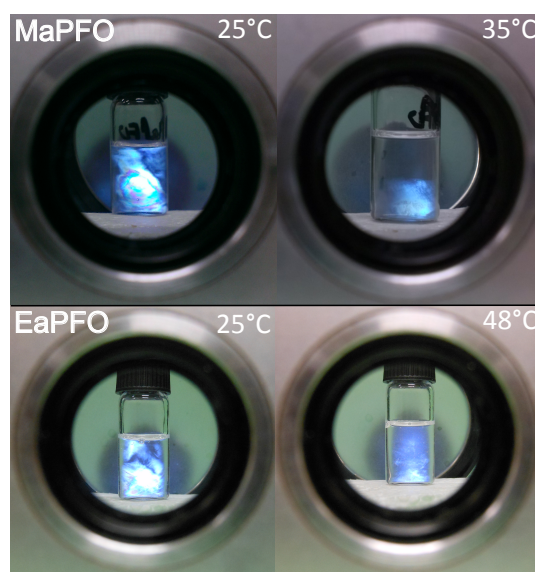


Figure S7: 10% solutions of MaPFO and EaPFO analysed through crossed polarising filters. After incubation for 10 minutes at noted temperatures, MaPFO showed a phase separated microemulsion, while the EaPFO sample showed no phase separation, but a noticeable change in birefringence.

Increased surface activity and foaming of dilute perfluorooctanoate solutions by addition of organic amines

Supporting Information

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Surface tension analysis

Stock amine surface tension

Figures S1 and S2 present the equilibrium surface tension of mono- and di-amino *n*-alkanes as a function of concentration.

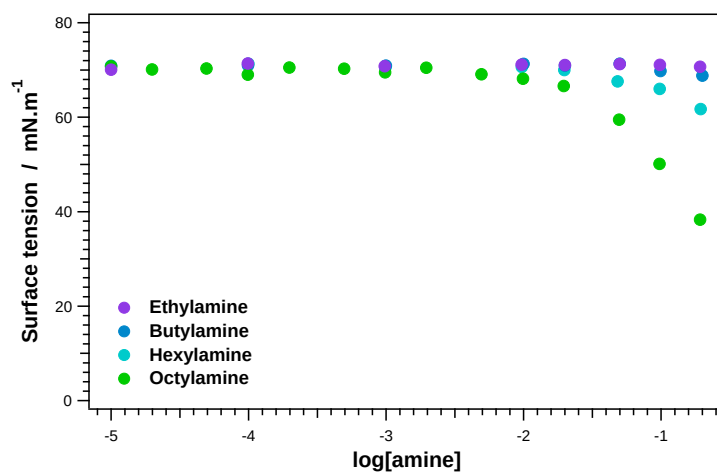


Figure S1: Surface tension of monoamine solutions as a function of concentration in water.

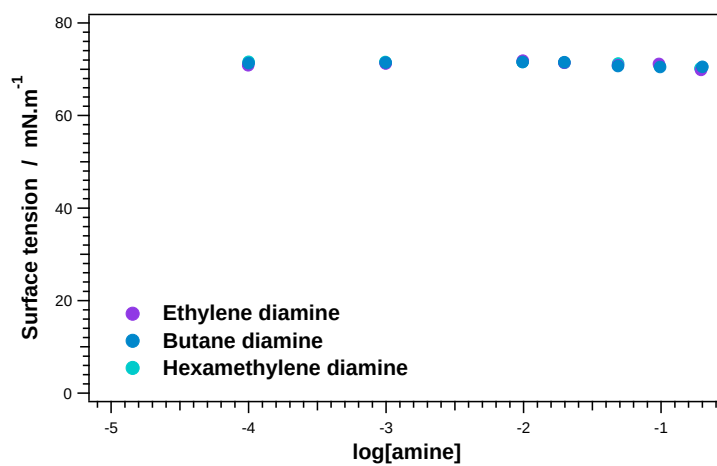


Figure S2: Surface tension of diamine solutions as a function of concentration in water.

Dynamic surface tension

For more detailed kinetic measurements, bubble pressure tensiometry was undertaken using a Krüss BP100 bubble pressure tensiometer. Measurements were obtained with the same conditions as equilibrium samples, utilising 0.1 mM NaPFO with 1 mM amine solutions and pH adjusted to pH = 5. Measurements were taken on a time-range from 0.01–200 s with pH adjustment made immediately prior to dynamic surface tension tests.

Diffusion analysis

Table S1: Apparent diffusion coefficient, D_{app} , for 0.1 mM NaPFO solutions containing 1 mM various additives. Where two values are present for a particular condition, this reflects that two gradients were present in the early-time dynamic surface tension data.

Additive (1 mM)	$D_{app} / \text{m}^2\cdot\text{s}^{-1}$
Sodium chloride	8.64×10^{-11}
Ethylamine	9.32×10^{-11}
Butylamine	4.01×10^{-10}
Hexylamine	1.08×10^{-10}
	3.23×10^{-9}
Octylamine	9.32×10^{-11}
	6.30×10^{-9}
Calcium dichloride	4.60×10^{-10}
Ethylene diamine	2.82×10^{-10}
Butane diamine	2.82×10^{-10}
Hexamethylene diamine	7.38×10^{-10}

A thorough examination of surfactant diffusion is difficult as they are multi-component and do not lend themselves to an easy theoretical analysis. In this work the approximations described by Joos and Rillaerts¹ (based on work from Bendure²). This uses the change in surface pressure to approximate the diffusion coefficient assuming there is no barrier to adsorption at the interface from the equation:

$$\Pi = 2RTC_0 \left(\frac{Dt}{\pi} \right)^{\frac{1}{2}} \quad (1)$$

with the surface pressure Π defined as:

$$\Pi = \gamma_0 - \gamma_t \quad (2)$$

where γ_0 is the solvent surface tension, γ_t is the surface tension at time t , C_0 is the surfactant concentration, R is the molar gas constant and T is temperature. This model is used for the early time period where diffusion to the interface is assumed to be diffusion-limited. Plotting the surface pressure as a function of $t^{-1/2}$ then gives a linear profile in the early time region and the gradient can be solved for the apparent diffusion coefficient, D_{app} . We refer to this as 'apparent diffusion' since this is likely not a true value of the diffusion, but is used to compare the dynamic behaviour of the systems analysed with each other, rather than to find an absolute diffusion values.

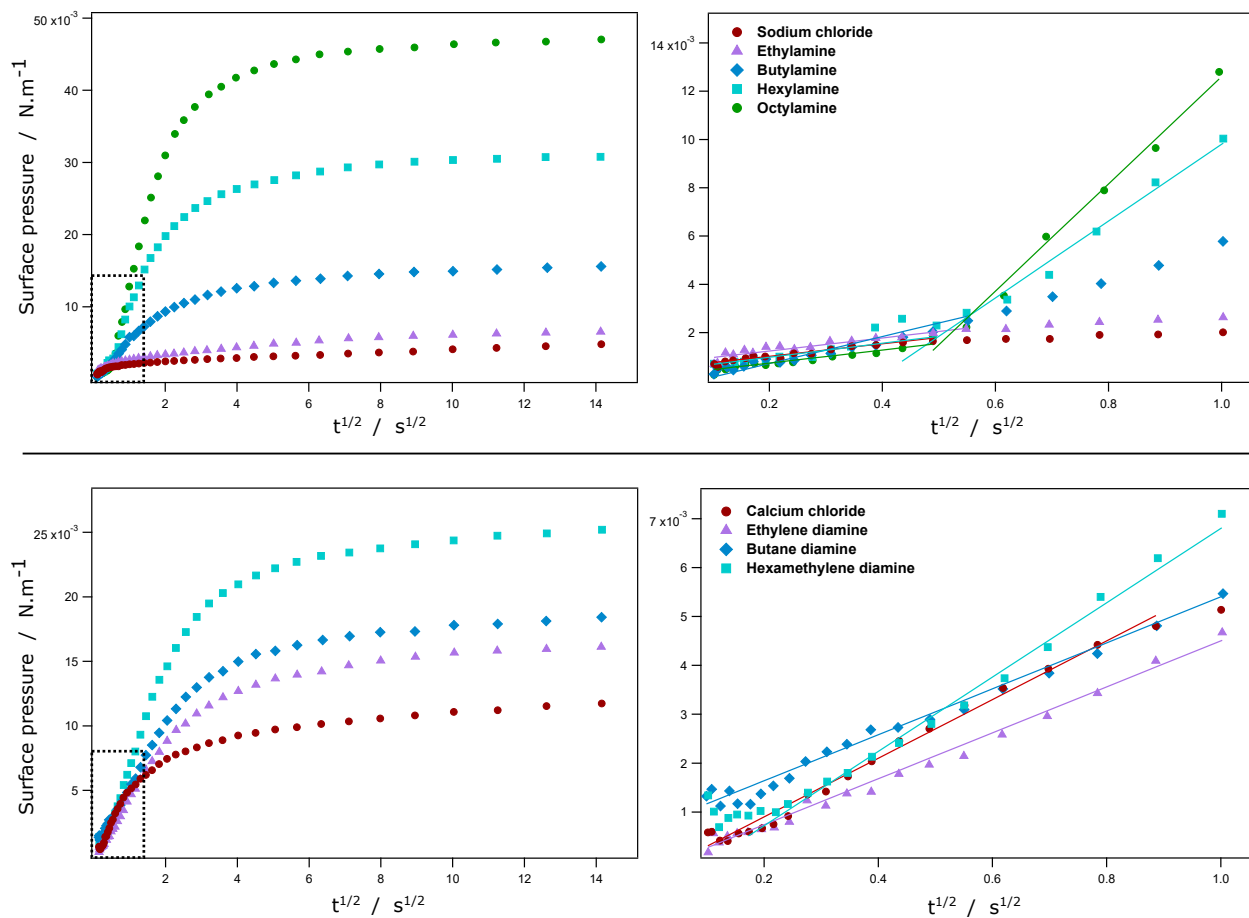


Figure S3: Dynamic surface tension for 0.1mM NaPFO solutions with 1mM of additives at pH 5 as a function of $t^{1/2}$. The early time region is expanded on the right, with linear regressions used to calculate the apparent diffusion.

Further foam extraction data

References

1. P. Joos and E. Rillaerts, *Journal of Colloid and Interface Science*, 1981, **79**, 96 – 100.
2. R. L. Bendure, *Journal of Colloid and Interface Science*, 1971, **35**, 238 – 248.

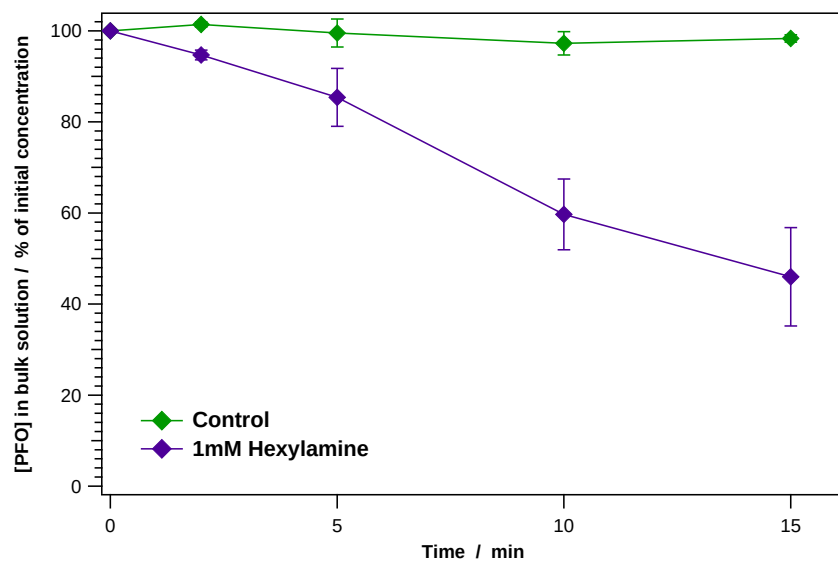


Figure S4: Foam extraction measurements with error bars of one standard deviation ($n=5$).