

## Surface modification and electrostatic charge of polystyrene particles

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### Abstract

Particle surface modification by poloxamer adsorption can significantly alter the electrostatic charge, adhesion behaviour and consequently handling properties of a material. The charge reduction on polystyrene spheres achieved by this modification technique is dependent on the concentration, molecular weight and conformation of poloxamer at the particle surface. Adsorption isotherms of poloxamers on polystyrene particles follow a Langmuir profile and there is an apparent correlation between the extent of adsorption and ability of poloxamer to reduce electrostatic charge. Surface analysis techniques, X-ray photoelectron spectroscopy and Time of Flight Secondary Ion Mass Spectrometry have generated data on the thickness of the adsorbed poloxamer layer and provided evidence to suggest that the polypropylene oxide component of the poloxamer adsorbs to the polystyrene surface and there is a polyethylene oxide rich outer surface which may influence the charge alteration. © 1999 Elsevier Science B.V. All rights reserved.

**Keywords:** Adsorption; Poloxamers; Polystyrene particles; Electrostatic charge and adhesion; Surface analysis

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### 1. Introduction

Initial investigations (Cassidy et al., 1996; Cassidy and Rowley, 1997a) have indicated that the electrostatic charging propensity of particulate systems can be altered by modifying the surface of the particles. The modification procedure involves

the physical adsorption of polymers onto the surface. The preliminary work focused on the surface modification of a hydrophobic drug, and demonstrated that the electrostatic behaviour of the drug could be successfully controlled. The extent and degree of control has been shown to be polymer type and concentration dependent and also the molecular weight of surface modifier may have a significant role (Cassidy et al., 1996; Cassidy and Rowley, 1997a).

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Numerous parameters, e.g. the molecular weight of adsorbate, the number and position of functional groups, the nature of the solvent with regards to solvent power, physical and chemical properties of the adsorbent such as shape, porosity, surface area, polarity and surface energy, affect the adsorption process (Sato and Ruch, 1980) and the role of surface modification in the control of electrostatic properties of particles is as yet, little understood.

Further work (Cassidy et al., 1998) has concentrated on the electrostatic charging tendency of a model particulate system, polystyrene spheres, on which the adsorption technique has been applied. The work presented here is a continuation of the polystyrene study and the principal aim was to examine the effect of surface treatment by polymers on polystyrene with respect to electrostatic phenomena, particle adhesion, adsorption extent and mechanism. Poloxamers which are non-ionic surfactants existing as ABA block copolymers of polyethylene oxide–polypropylene oxide–polyethylene oxide (PEO–PPO–PEO), were chosen as adsorbates or surface modifiers as they are widely used and readily available in a range of molecular weights and their aggregation behaviour has been comprehensively studied (Wanka et al., 1990; Alexandridis et al., 1994a; Alexandridis and Hatton, 1995). The use of poloxamers is diverse and includes their incorporation in creams and aqueous suspensions as dispersion stabilizers and flocculants and they have attracted increasing attention as surface modifiers for their role in controlling the organ distribution of colloidal particles (Illum and Davis, 1984; Rudt and Muller, 1993; Hillery and Florence, 1996). In an attempt to produce polymeric drug carrier particles that would avoid recognition by the phagocytic cells of the immune system, 60 nm polystyrene particles have been successfully coated with poloxamine 908 (Davis et al., 1986; Illum et al., 1987) and various poloxamers (Rudt and Muller, 1993; Hillery and Florence, 1996). The polymers adsorb on the surface of the particles making the surfaces more hydrophilic and presumably non-charged so that they escape recognition *in vivo*. The rationale behind using amphipathic PEO–PPO copolymers as opposed

to a PEO homopolymer is based on research in colloidal systems where amphipathic copolymers have demonstrated effective steric stabilization, thought to arise from the anchoring of the hydrophobic PPO chain to the particle surface and subsequent stabilization by the protruding PEO chains (Tadros, 1982; Pirma, 1992). In addition, the capacity for electrostatic charge reduction by poloxamers has been shown to be greater than that of other polymers (Cassidy et al., 1996).

The adsorbent employed was polystyrene which as spheres have been well characterised with respect to size, shape and surface groups. The use of adsorbed polymers to modify the sedimentation behaviour and rheological properties of colloidal dispersions of polystyrene has also been extensively studied (Kayes and Rawlins, 1979; Baker and Berg, 1988; Faers and Luckman, 1994). Polystyrene particles used in this study however were much larger and more representative of samples encountered in powder processing and manufacture rather than those employed for drug delivery purposes.

It is envisaged that detailed investigation of the adsorption process on polystyrene particles, the role of adsorbed poloxamer in electrostatic phenomena and characterisation of the treated and untreated polystyrene using surface analysis will provide a clearer understanding of the mechanism by which electrostatic charge alteration occurs.

## 2. Experimental

### 2.1. Materials

Polystyrene divinyl benzene copolymer (PS) (product name: PLgel) supplied as a loose white powder from Polymer Laboratories (Shropshire, UK).

The size and size distribution of the particles were determined by laser light diffraction (Malvern Mastersizer 2600) employing dilute poloxamer solution as dispersant. The mean diameter was determined as 54.4  $\mu\text{m}$  (Lot No. 50M-SOLID-2). The 10th, 50th and 90th centile were 39.8, 56.2 and 62.3  $\mu\text{m}$ , respectively.

The poloxamers—Synperonics; F77, F87 and F127—were obtained from ICI (Wilton, UK) as waxy flakes. The molecular weights of the poloxamers were approximately 6500, 7500, and 13 000 for F77, F87 and F127, respectively. All have a 70% polyethylene oxide (PEO) content.

The poloxamers were size fractionated (125–180  $\mu\text{m}$ ) by size reduction and sieving and the samples were further air jet sieved (Alpine) to remove fines. Particle size range was confirmed using optical microscopy image analysis (VIDS), prior to charging studies.

## 2.2. Methods

### 2.2.1. Treatment of polystyrene with poloxamers

Known quantities of PS particles, which are insoluble in water, were agitated in a shaking incubator with solutions of poloxamer of known concentration in the range 10–200  $\text{mg l}^{-1}$  for 24 h at  $25 \pm 0.5^\circ\text{C}$ , when equilibrium was attained. Recent studies of equilibration conditions of different concentration poloxamer/PS and poloxamer/drug systems in these laboratories, have indicated that equilibrium is achieved within 4–5 h and is maintained for at least 50 h in most cases and up to 120 h for some systems.

The powder was separated from the liquid by either filtration for a large quantity of material or decanted and centrifuged at 3600 rpm (MSE Mistral 1000) for 25 min when equilibrating smaller amounts. The polymer concentration in the supernatant was determined by UV spectrophotometric analysis at  $\lambda_{\text{max}}$  of 495 nm, from the colour of iodine–polymer complexes by using a method similar to that of Baleaux (1972). Values were compared with a calibration curve and the assay was reproducible (cv < 5%) and linear in the range 10–100  $\text{mg l}^{-1}$ . The amount of poloxamer adsorbed per gram of PS was calculated by solution depletion based on the difference between initial and final (equilibrium) concentrations.

### 2.2.2. Charging of polystyrene (PS), poloxamers and treated PS

The electrostatic charge of PS and treated PS was determined using a cyclone particle charging apparatus which consists of a cyclone separator, Faraday well and electrometer.

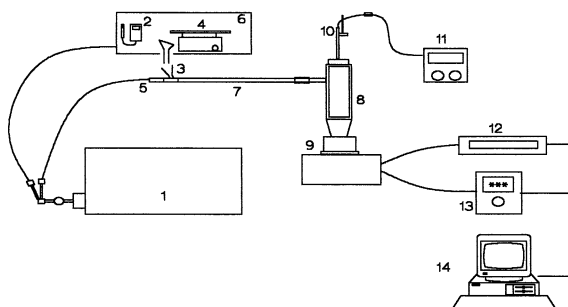
A schematic diagram of the apparatus is shown in Fig. 1.

The sample was fed into the apparatus under controlled conditions (< 6% relative humidity; 20–25°C) using dry air supplied by a compressor at a flow rate of 8  $\text{m s}^{-1}$  and the powder became electrostatically charged on contact with the stainless steel inner cyclone surface. The cyclone apparatus is a closed system enabling atmospheric conditions to be controlled, maintained and monitored throughout each sample run. The powder was separated from the carrier air and deposited in the Faraday well (consisting of an inner aluminium cup, capacity 0.05 l, insulated from outer earthed vessel) connected to an electrometer (Keithley 610C) and force compensation load cell (Precisa 400M) for charge ( $Q$ ) and mass ( $m$ ) measurement, respectively. The results are expressed as specific charge ( $\text{nC g}^{-1}$ ) and presented as the mean and standard deviation of five determinations. Statistical analysis to evaluate differences in the mean specific charge of samples was undertaken using a  $t$ -test for values with unequal variance.

Adhesion of treated and untreated material to the inner cyclone surface was assessed using a qualitative scale represented by numbers 0–3; where 0 indicates absence of adhesion; 1, mild adhesion; 2, moderate adhesion and 3, extensive adhesion.

### 2.2.3. X-ray photoelectron spectroscopy measurements

XPS spectra were obtained using an automated VG Escascope (VG Scientific, Ltd., East Grinstead, Sussex, UK) employing Mg  $K\alpha$  X-rays with a photoelectron take-off angle of  $90^\circ$  with respect to the sample platen surface. Samples of PS and treated PS were prepared by lightly pressing a microspatula tipful of powder onto double-sided tape on a sample stub and removing any loose material with an air duster. The poloxamer was prepared as a spin cast film from  $\text{CHCl}_3$ . The analysis diameter of each sample was 1100  $\mu\text{m}$  and a single measurement was performed in each case. The determination of the overlayer thickness of poloxamer on the PS spheres was calculated using two models: (i) employing the overlayer



1 Compressor	7 Feed pipe	13 Electrometer
2 Relative humidity probe	8 Cyclone	14 Computer
3 Venturi funnel	9 Faraday well and balance	
4 Vibratory feeder	10 Pitot tube	
5 Ionisation nozzle	11 Flow meter	
6 Sealed chamber	12 Balance electronics	

Fig. 1. Cyclone apparatus for electrostatic charge measurement of bulk powders.

signal intensity and comparing it with the pure poloxamer signal intensity, and (ii) using peak fitting of the Carbon 1s spectrum to calculate the intensity fractions of the carbon components due to the surfactant and PS substrate.

#### 2.2.4. ToF SIMS studies of poloxamer coated polystyrene

Samples were analysed by Time of Flight Secondary Ion Mass Spectrometry using a PHI 7200 spectrometer (Physical Electronics Inc., Minnesota, USA). A single positive and negative ion spectrum was acquired over the  $m/z$  range 0–1000 from a fresh area of sample in each case using a 200  $\mu\text{m}$  analysis area. A total primary ion dose of ca.  $1 \times 10^{12}$  ions  $\text{cm}^{-2}$  was used. The primary ions were  $\text{Cs}^+$  at 8 keV. The static SIMS sampling depth is approximately 1 nm. Samples of the treated PS were prepared as for XPS studies, whereas the PS and poloxamer were prepared as spin cast films on Si from toluene and water, respectively.

### 3. Results and discussion

The results of the charging studies are presented in Table 1 for PS particles and size fractionated poloxamers and in Table 2 for PS treated with different concentrations of F77, F87 and F127. The treatment concentrations were chosen from the adsorption isotherm, two that lie on the increase in the profile (10 and 30  $\text{mg l}^{-1}$ ) and two that lie on the plateau region (100 and 200  $\text{mg l}^{-1}$ ). These are initial treatment concentrations and therefore corresponding equilibrium concentrations are lower but are located in similar re-

Table 1  
Charge results of poloxamers and PS

Sample	$Q/m$ (nC $\text{g}^{-1}$ )	Adhesion
F77 (125–180 $\mu\text{m}$ )	+4.4 (1.5)	0–1
F87 (125–180 $\mu\text{m}$ )	+12.0 (4.5)	0–1
F127 (125–180 $\mu\text{m}$ )	+15.6 (1.7)	0–1
PS (60 $\mu\text{m}$ )	–15.4(3.2)	1–2

Table 2  
Charge results PS and surface modified PS spheres

Sample	Amount adsorbed (mg g <sup>-1</sup> )	Amount adsorbed (mol g <sup>-1</sup> × 10 <sup>-7</sup> )	Cyclone $Q/m$ (nC g <sup>-1</sup> )	Adhesion
PS (60μm)	–	–	–15.4 (3.2)	1–2
PS+F77 (10 mg l <sup>-1</sup> )	0.07	0.11	–17.4 (5.3)	1–2
PS+F77 (30 mg l <sup>-1</sup> )	0.47	0.72	–12.4 (3.1)	1–2
PS+F77 (100 mg l <sup>-1</sup> )	0.87	1.34	–8.6 (2.6)	1
PS+F77 (200 mg l <sup>-1</sup> )	1.12	1.72	–6.4 (0.6)	1
PS+F87 (10 mg l <sup>-1</sup> )	0.20	0.27	–10.5 (2.3)	1–2
PS+F87 (30 mg l <sup>-1</sup> )	0.75	1.00	–4.5 (1.7)	1–2
PS+F87 (100 mg l <sup>-1</sup> )	1.53	2.04	–2.4 (0.7)	0–1
PS+F87 (200 mg l <sup>-1</sup> )	1.58	2.10	–2.1 (0.5)	0–1
PS+F127 (10 mg l <sup>-1</sup> )	0.16	0.12	–9.2 (4.3)	1
PS+F127 (30 mg l <sup>-1</sup> )	1.12	0.86	–3.5 (2.1)	1
PS+F127 (100 mg l <sup>-1</sup> )	2.50	1.92	–1.6 (0.6)	0–1
PS+F127 (200 mg l <sup>-1</sup> )	3.16	2.43	–2.1(1.3)	0–1

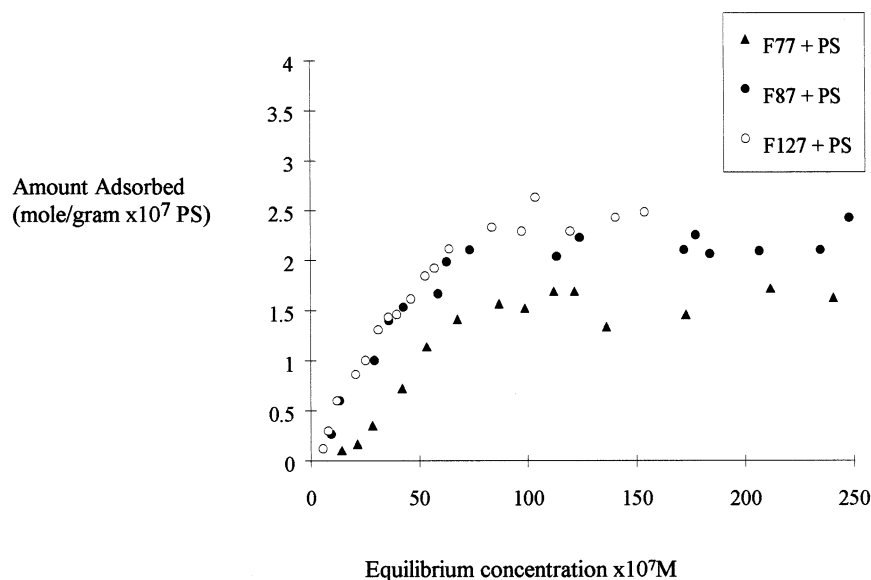


Fig. 2. Adsorption isotherm of F77, F87 and F127 on PS at 25°C.

gions on the adsorption profile. To facilitate a comparison of the effect of molecular weight of polymer on adsorption and charge, concentrations on the isotherm are expressed in moles. The molecular weights of the polymers are given in Section 2.1. The adsorption isotherms of F87, F77 and F127 on PS at 25°C are presented in Fig. 2.

### 3.1. Adsorption isotherms

The equilibrium concentration of poloxamer was plotted as a function of the amount adsorbed for F77, F87 and F127 modified PS (Fig. 2). Each point on the adsorption isotherms is the mean of three determinations of samples equilibrated with

the same initial concentrations up to a maximum of  $200 \text{ mg l}^{-1}$ .

All the isotherms exhibit a Langmuirian profile where there is a sharp increase in the amount adsorbed at low concentration followed by a plateau region for the three poloxamers. From this plot a comparison of the amount adsorbed with regard to the molecular weight of polymer can be ascertained. The isotherms for F87 and F127 are similar in shape and magnitude with respect to polymer adsorption up to a maximum where the plateau regions are evident, although the plateau is slightly higher for F127. The amount adsorbed is much less for F77 than the other polymers at all treatment concentrations, for example, the adsorption plateau values are approximately  $1.5$ ,  $2.0$  and  $2.1 \text{ mol} \times 10^{-7} \text{ g}^{-1}$  PS for F77, F87 and F127, respectively. In addition, the maximum adsorption occurs at a higher equilibrium concentration of approximately  $75 \times 10^{-7} \text{ M}$  as opposed to  $50 \times 10^{-7} \text{ M}$  for F87 and F127. In general there is a rapid rise in adsorption of non-ionic surfactants around the critical micelle concentration (cmc) (Alexandridis et al., 1994a,b; Baker and Berg, 1988) with maximum adsorption occurring after the apparent cmc has been reached (Kayes and Rawlins, 1979). The adsorption results are in contrast to previous work with copolymers, where a decrease in the amount adsorbed was found with increasing molecular weight of poloxamer (Kayes and Rawlins, 1979). The work of Kayes and Rawlins shows adsorption isotherms of poloxamers F38, F68, F88 and F108 on polystyrene latex (312 nm) where the maximum adsorbed amount for F38 is about twice that of the other polymers. However, there does not appear to be a significant difference between the profiles for F68, F88 and F108. The extent of adsorption was greater for all four poloxamers than that obtained in the investigation reported here possibly due to the size and surface nature of the adsorbent and some differences in experimental conditions such as pH. Further studies (Cassidy and Rowley, 1997b) using a homologous series of poloxamers, the hydrophobic polypropylene oxide unit remaining constant while the ethylene oxide chain length increased have demonstrated that there may be compromise

between the increasing length of the ethylene oxide chain, which results in decreased adsorption, and the molecular weight of the polymer which appears to result in increased adsorption.

### *3.2. Charge and adhesion results of poloxamers and PS*

The three poloxamers charged electropositively against the stainless steel inner cyclone surface with more positive specific charge values as the molecular weight of polymer increases. There were significant differences in charge values ( $P < 0.001$ ) comparing F127 with F77 and ( $P < 0.02$ ) comparing F87 with F77. The increase in positive charge of F127 over that exhibited by F87 was not statistically significant. Adhesion to the contact surface was only just apparent in the cyclone for the size fractionated poloxamer powders.

PS, however, exhibited electronegative charging in the cyclone and adhesion was mild to moderate. The spheres exhibited good flow and transport properties in the cyclone apparatus at  $8 \text{ m s}^{-1}$  and  $> 80\%$  of the sample was deposited in the Faraday well.

### *3.3. Charge results of surface modified PS systems*

The specific charge results presented in Table 2 indicate that when PS was treated with poloxamers F87 and F127, there was a reduction in negativity of the mean specific charge using the cyclone technique for charge measurement. The charge reduction was statistically significantly different from the charge value exhibited by PS alone for all concentrations of treated material. Additionally, adhesion of PS to the contact surface was markedly reduced by treatment with polymer. The charge results determined in the cyclone for the F77/PS system also show a charge reduction with increasing concentration of polymer. This charge reduction is only significantly different from the electrostatic charge of PS alone for the two higher concentrations ( $100$  and  $200 \text{ mg l}^{-1}$ ) of modified particles. Adhesion was also reduced for the treated material although not to the same extent as with F87 and F127. The

amount adsorbed in  $\text{mg g}^{-1}$  of PS was less for F77 than F87 and F127 and may account for the higher charge values with this system. Comparison of the charge of modified material with respect to the amount adsorbed in  $\text{mol g}^{-1}$  indicates that the charge reduction capacity of the three poloxamers increases with increasing molecular weight of polymer ( $1.34 \times 10^{-7} \text{ mol g}^{-1}$  of F77 produced a charge of  $-8.6 \text{ nC g}^{-1}$ ,  $1.00 \times 10^{-7} \text{ mol g}^{-1}$  of F87 lowered the charge to  $-4.5 \text{ nC g}^{-1}$  and  $0.86 \times 10^{-7} \text{ mol g}^{-1}$  of F127 reduced the specific charge to  $-3.5 \text{ nC g}^{-1}$ ). As shown in Table 1, the powder samples of F87 and F127 exhibited greater positive charges which may account for the greater ability to produce a lower net negative charge on the bulk samples. Addi-

Table 3

XPS results including overlayer thickness for F77 surface modified PS spheres

Sample	Overlayer thickness, d (nm)	
	Overlayer signal model	Peak fitting model
PS+F77 (10 $\text{mg l}^{-1}$ )	0.4	0.3
PS+F77 (30 $\text{mg l}^{-1}$ )	0.3	0.3
PS+F77 (100 $\text{mg l}^{-1}$ )	0.6	0.6
PS+F77 (200 $\text{mg l}^{-1}$ )	0.5	0.7

Table 4

XPS results including overlayer thickness for F127 surface modified PS spheres

Sample	Overlayer thickness, d (nm)	
	Overlayer signal model	Peak fitting model
PS+F127 (10 $\text{mg l}^{-1}$ )	0.5	0.4
PS+F127 (30 $\text{mg l}^{-1}$ )	0.7	0.7
PS+F127 (100 $\text{mg l}^{-1}$ )	0.8	1.1
PS+F127 (200 $\text{mg l}^{-1}$ )	1.2	1.4

tionally, all the poloxamers have the same ratio of PEO to PPO groups although with increasing molecular weight the length of the chains increase and it is possible that it is the length of the PEO chain protruding from the particle surface which actually influences the charge reduction capacity.

The charging results correlate with isotherm data; where the plateau between 100 and 200  $\text{mg l}^{-1}$  is concurrent with no further significant reduction in magnitude of negative charge on PS particles for the three polymers studied. In addition, F77 had the lowest uptake on to the particles and was least effective in specific charge reduction. F87 and F127 have widely different molecular weights (7500 and 13 000, respectively) and yet the amount adsorbed was only slightly greater for F127 and only significantly greater at two concentrations. F127, however, demonstrated the best charge reduction ability, which may be influenced by longer PEO chains at the surface of the treated particles (see Section 3.4.1), as it appears less dependent on the amount of poloxamer adsorbed.

### 3.4. Surface analysis results

#### 3.4.1. X-ray photoelectron spectroscopy

Tables 3 and 4 present the overlayer thickness of PS treated with F77 and F127, respectively as determined using XPS data.

The results suggest that the average overlayer thickness was in the range 0.3–0.7 nm for F77 treated PS depending on the polymer treatment concentration and 0.4–1.4 nm for F127 treated material. Correlation can be drawn with the adsorption results where it was demonstrated that the uptake of F77 was approximately half that of F127. The models applied were derived with the assumption of flat and smooth surfaces and therefore when applied to non-flat surfaces they may overestimate the thickness of the overlayer. Corrections were made to the oxygen signal intensity used with the overlayer signal model for the presence of O as sulphonated end groups in the PS surface and for the slight presence of a contaminant silicone, polydimethylsiloxane. The former would have no effect on the peak fitting model which uses the C1s photoelectron peak envelope

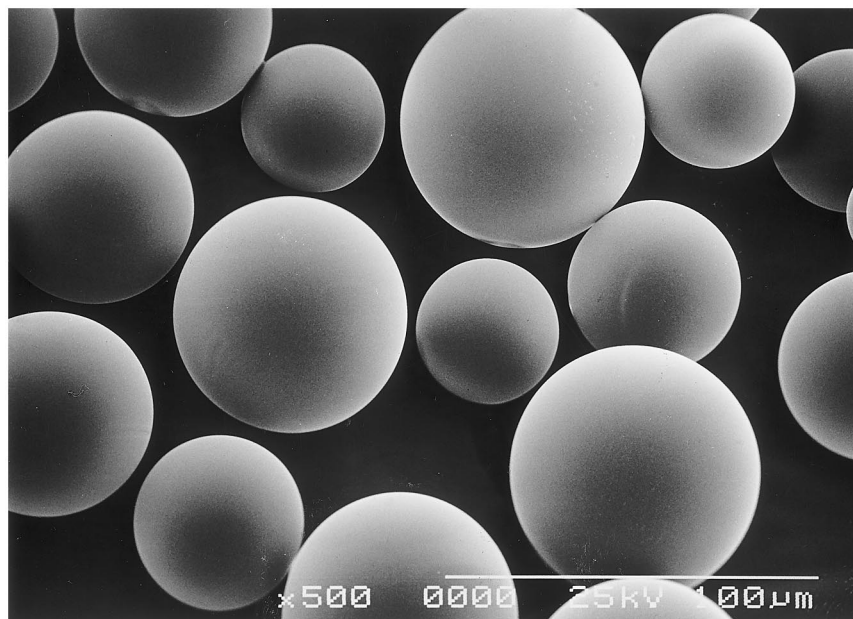


Fig. 3. Untreated PS ( $\times 500$ ).

whereas the presence of a silicone would only have a small effect on the peak fitting model and would tend to slightly underestimate the overlayer thickness. The results indicate, however, that the layer thickness increases with increasing PEO chain length and/or molecular weight and are consistent with many others which have demonstrated that the layer thickness of PEO–PPO–PEO copolymers adsorbed onto polystyrene latex particles increases as the molecular weight of the PEO component increases (Kayes and Rawlins, 1979; Baker et al., 1989; Baker and Berg, 1988; Faers and Luckman, 1994; Li et al., 1994). It is believed that the PPO component of the polymer adsorbs as a compact coil or lies flat on the hydrophobic surface and has a negligible contribution to the thickness of the adsorbed layer (Kayes and Rawlins, 1979; Faers and Luckman, 1994).

Photomicrographs, Figs. 3–5 provide evidence that the actual coverage of surfactant on the polystyrene spheres is not of an even distribution and is of non-uniform thickness, although even at high magnification it would be unwise to suggest that these images demonstrate that there are areas

where there is no coverage at all, although this is a possibility. It may be the case that the surface is covered by a monolayer of surfactant with further patches of multilayer buildup at higher concentrations. More detailed surface analysis investigations, Time of Flight Secondary Ion Mass Spectrometry (ToF SIMS) has provided further evidence of the distribution of poloxamer at the particle surface.

#### 3.4.2. Time of Flight Secondary Ion Mass Spectrometry

In order to interpret the ToF SIMS data, the spectra for the PS and F127 samples will be discussed in the first instance. Fig. 6 shows the positive ion ToF SIMS spectrum of the PS substrate. It is not consistent with pure PS but does contain the characteristic peaks of polystyrene (i.e.  $m/z + 91, 103, 115, 128, 165, 178$ ). Additional peaks in the spectra are due to the Si wafer substrate, the  $\text{Cs}^+$  primary ion at  $m/z + 133$ , polymer chain end groups and residual stabilisers/emulsifiers from the PS sphere production process. Fig. 7 is the positive spectrum for F127, respectively recorded from a thin film cast from



aqueous solution. Prominent characteristic peaks for the poloxamer can be observed at  $m/z + 45$ , 59, 87 and 99. The peak at  $m/z$  45 is mainly due

to the PEO component in the poloxamer and 59, 87 and 99 due to the PPO component. Fig. 8 shows a positive spectrum of a  $100 \text{ mg l}^{-1}$  F127

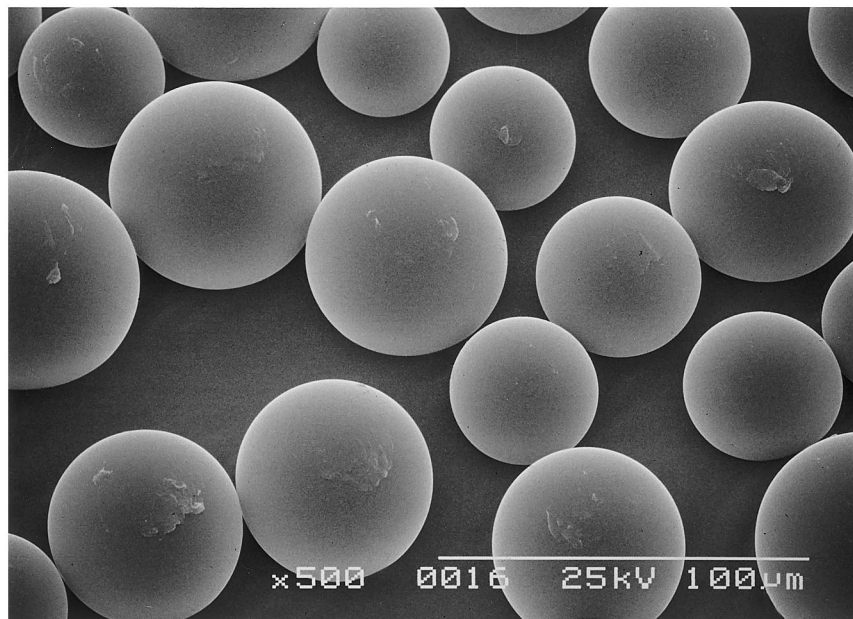


Fig. 4. PS treated with F127 ( $200 \text{ mg l}^{-1}$ ,  $\times 500$ ).

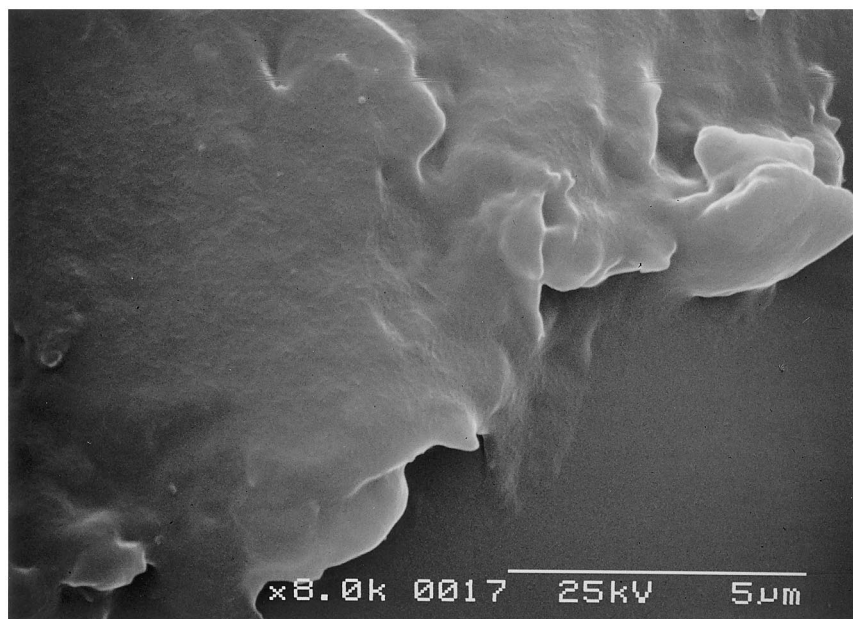


Fig. 5. PS treated with F127 ( $200 \text{ ml}^{-1}$ ,  $\times 8.0 \text{ k}$ ).

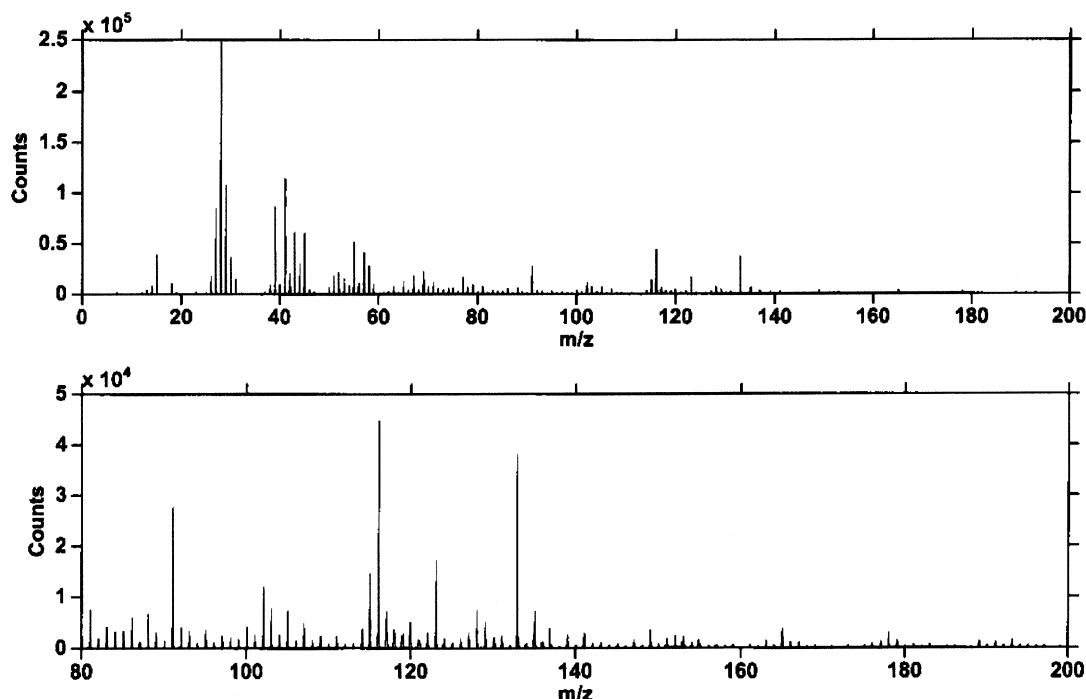


Fig. 6. Positive ion (+) ToF SIMS spectrum of PS spheres on Si spin cast from toluene 0.1% (w/w) solution.

treated sample and this is representative of the spectra for all treated samples. The spectra are dominated by the F127 peak at  $m/z$  59 and there is low but significant intensity in the  $m/z$  91 characteristic of PS for all four treated samples. This indicates that the poloxamer overlayer is relatively thin and may be localised. Additionally, the 59:91 and 45:91 peak area ratios have provided information on the poloxamer:polystyrene surface area ratio whereby a thick continuous layer of poloxamer on PS would be indicated by a value close to that for pure F127 and a thin layer by a value nearer to that for PS. Table 5 shows that both sets of ratios for the treated samples are higher than pure PS but significantly lower with respect to F127. This is consistent with very thin and possibly non-uniform coverage of PS by F127. These results also suggest that there is little apparent change to the surface coverage by the PEO components as the poloxamer concentration increases but the PPO component does demonstrate an increase between the 30 and 100 mg l<sup>-1</sup> poloxamer treated samples. Further treatment of

results, i.e. dividing the intensities of the PEO peak and PPO peaks by the total ion intensity shows that the PEO component changes little with increasing poloxamer concentration, whereas the PPO component shows a definite increase. Also the PEO:PPO peak intensity ratio shown in Table 5, decreases as poloxamer concentration increases, due to an increase in PPO peak intensity rather than a decrease in PEO peak intensity. The fact that the PEO peak relative intensity remains fairly constant as the F127 concentration increases probably indicates that the PEO component is not adsorbed to the PS surface and it is the PPO component which is closest to the PS surface. Hypothetically therefore as subsequent layers build up the next PPO components are adsorbed onto either PEO or PPO rather than PS and the observed fragmentation relative intensities would be expected to be different to that from the initially adsorbed layer. Such change in fragmentation would be expected to continue as the adsorbed layer thickness was increased until some 'equilibrium' thickness had been attained. The

subsequent PPO components would then be adsorbing on a more hydrophilic surface than PS and would presumably desorb more readily during the SIMS experiment. This would account for the increased PPO relative ion intensity. More experimental data is required to shed further light on the conformation of F127 on hydrophobic and hydrophilic surfaces perhaps using molecular modelling or producing thin films of F127 on flat substrates and employing angle resolved XPS.

ToF SIMS imaging of the  $10 \text{ mg l}^{-1}$  treated sample only, was recorded over a  $400 \times 400 \mu\text{m}$  area using a liquid metal ion gun using  $\text{Ga}^+$  ions at 25 keV. Results on a test sample with a spatial resolution of ca.  $1.5 \mu\text{m}$  indicated the surface composition was uniform for all species with no obvious features such as bare patches observed. This may be confirmation of the XPS surface coverage results which suggest that at this concentration the particles are covered by one monolayer. However, approximately only one quarter of a particle surface was interrogated by this

method and the higher concentration treated samples were not analysed.

#### 4. Conclusions

The charge and adsorption investigations demonstrate unequivocally that polystyrene spheres undergo a concentration dependent reduction in electrostatic charge with adsorbed poloxamer which supports the previous work undertaken with phenylbutazone (Cassidy and Rowley, 1997a). The ability to produce the reduction in charge increases with increasing molecular weight of poloxamer which may be related to the extent of adsorption and is possibly influenced by the orientation of the PEO functional groups of the poloxamer at the particle surface. Surface chemical analysis has established that the overlayer thickness of poloxamer on PS required to alter electrostatic charge is extremely thin. The layer thickness increases with increased adsorp-

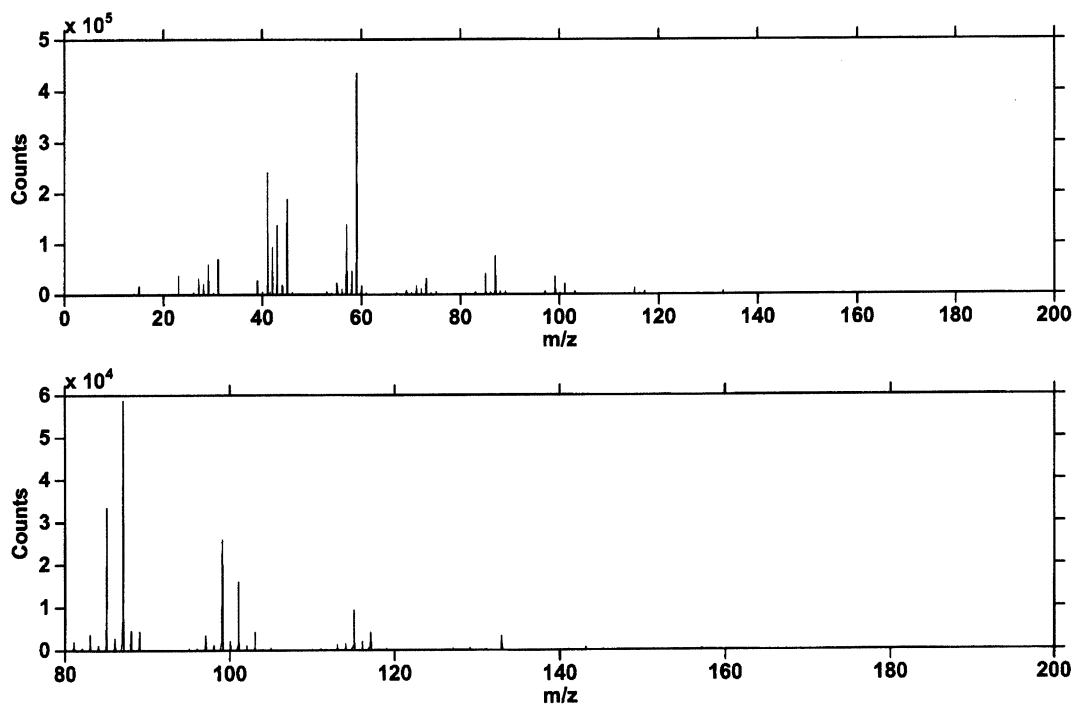


Fig. 7. Positive ion (+) ToF SIMS spectrum of F127 on Si spin cast from water.

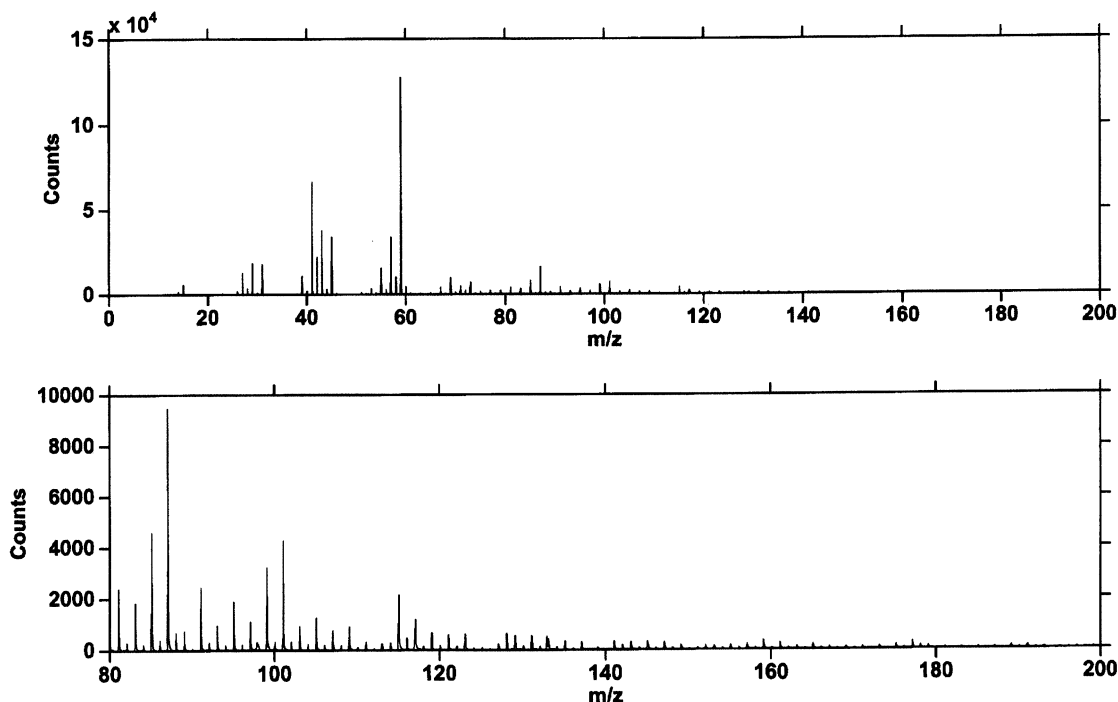


Fig. 8. Positive ion (+) ToF SIMS spectrum of 100 mg l<sup>-1</sup> F127 treated PS spheres.

tion of poloxamer and supports adsorption data obtained by the solution depletion method. Fractional coverage results indicate that adsorption is multilayer although SEM evidence suggests that the distribution of poloxamer at the particle surface is not homogenous at high concentration. SIMS spectroscopy has also indicated relatively thin coverage of the PS surface by F127 but could not completely rule out the possibility of uncovered patches. SIMS imaging however on the 10 mg l<sup>-1</sup> treated sample indicated uniform distribu-

tion of F127. SIMS results seem to support continuous albeit thin coverage for all F127/PS treated samples. There was evidence that the PPO component of the F127 molecule initially adsorbs onto the PS surface and produces a PEO rich outer surface. Subsequent layers may also build up with the PPO component to the inside and the PEO chains protruding. Further work may help to establish if there is a requirement of at least one monolayer at the surface to facilitate adsorption and contribute to the charge reduction ability

Table 5  
Peak area ratios of PEO (*m/z* 45) and PPO (*m/z* 59) to PS (*m/z* 91)

Peak ratio	Sample					
	PS	10mg l <sup>-1</sup>	30mg l <sup>-1</sup>	100mg l <sup>-1</sup>	200mg l <sup>-1</sup>	F127
45:91	0.33	5.88	4.62	5.28	4.87	233.4
59:91	0.13	15.7	15.19	20.24	19.8	546.3
45:59 (PEO:PPO)	—	0.37	0.3	0.26	0.25	0.43
45:Total	—	0.03	0.04	0.03	0.03	0.07
59:Total	—	0.08	0.12	0.12	0.14	0.17

and exactly what concentration is required to produce this monolayer. It is anticipated that if electrostatic charging in relation to the orientation and distribution of the polymer at the particle surface is more fully understood then it will be possible to control or reduce the electrostatic charge on many hydrophobic materials including drugs, by the addition of a minute amount of a non-toxic hydrophilic polymer using this adsorption technique.

## References

- Alexandridis, P., Holzwarth, J.F., Hatton, T.A., 1994a. Micellization of poly(ethylene oxide)–poly(propylene oxide)–poly(ethylene oxide) triblock copolymers in aqueous solutions: Thermodynamics of copolymer association. *Macromolecules* 27, 2414–2425.
- Alexandridis, P., Athanassiou, V., Fukuda, S., Hatton, T.A., 1994b. Surface activity of poly(ethylene oxide)–poly(propylene oxide)–block–poly(ethylene oxide) copolymers. *Langmuir* 10, 2604–2612.
- Alexandridis, P., Hatton, T.A., 1995. Poly(ethylene oxide)–poly(propylene oxide)–poly(ethylene oxide) block copolymer surfactants in aqueous solutions at interfaces: thermodynamics, structure, dynamics and modelling. *Colloid. Surf. A: Physicochem. Eng. Asp.* 96, 1–46.
- Baker, J.A., Berg, J.C., 1988. Investigation of the adsorption configuration of poly(ethylene oxide) and its copolymers with poly(propylene oxide) on model polystyrene latex dispersions. *Langmuir* 4, 1055–1061.
- Baker, J.A., Pearson, R.A., Berg, J., 1989. Influence of particle curvature on polymer adsorption layer thickness. *Langmuir* 5, 339–342.
- Baleaux, M.B., 1972. Chimie Analytique-Dosage colorimétrique d'agents de surface non ioniques polyoxyéthylènes à l'aide d'une solution iodo-iodurée. *Comptes Rendus Acad. Sci. (Paris)* 274, 1617–1620.
- Cassidy, O.E., Rowley, G., Nguyen, H., 1996. The effect of surface modification on electrostatic charge of a particulate system. *Eur. J. Pharm. Sci.* 4 (Suppl.), S65.
- Cassidy, O.E., Rowley, G., 1997a. The effect of drug surface modification by adsorbed polymer on electrostatic charge. *Proc. Pharm. Tech. Conf.* 16 (3), 5–11.
- Cassidy, O.E., Rowley, G., 1997b. Adsorption of poloxamer on polystyrene spheres in relation to electrostatic properties. *J. Pharm. Pharmacol.* 49 (Suppl. 4), 72.
- Cassidy, O.E., Rowley, G., Fletcher, I.W., Davies, S.F. and Briggs, D., 1998. Adsorption of copolymers on model polystyrene particles in relation to electrostatic properties. *Proceedings of the World Congress on Particle Technology III (CD-ROM)*.
- Davis, S.S., Douglas, S., Illum, L., Mak, P.D.E., Müller R.H., 1986. Targeting of colloidal carriers and the role of surface properties, in: Gregoriadis, G., Senior, J., Poste, G. (Eds.), *Targeting of drugs with synthetic systems*, Plenum Press, New York, 123–146.
- Faers, M.A., Luckman, P.F., 1994. Rheology of polyethylene oxide polypropylene oxide block-copolymer stabilized latexes and emulsions. *Colloid. Surf. A: Physicochem. Eng. Asp.* 86, 317–327.
- Hillery, A.M., Florence, A.T., 1996. The effect of adsorbed poloxamer 188 and 407 surfactants on the intestinal uptake of 60-nm polystyrene particles after oral administration in the rat. *Int. J. Pharm.* 132, 123–130.
- Illum, L., Davis, S.S., 1984. The organ uptake of intravenously administered colloidal particles can be altered using a non-ionic surfactant (Poloxamer 338). *FEBS Lett.* 167, 79–82.
- Illum, L., Davis, S.S., Müller, R.H., Mak, E., West, P., 1987. The organ distribution and circulation time of intravenously injected colloidal carriers sterically stabilized with a block copolymer: Poloxamine 908. *Life Sci.* 40, 367–374.
- Kayes, J.B., Rawlins, D.A., 1979. Adsorption characteristics of certain polyoxyethylene–polyoxypropylene block copolymers on polystyrene latex. *Colloid. Polym. Sci.* 257, 622–629.
- Li, J.T., Caldwell, K.D., Rapoport, N., 1994. Surface properties of Pluronic-coated polymeric colloids. *Langmuir* 10, 4475–4482.
- Pirra, I. (Ed.), 1992. *Polymeric surfactants*, Surfactant Science Series, Marcel Dekker, New York.
- Rudt, S., Muller, R.H., 1993. In vitro phagocytosis assay of nano- and microparticles by chemiluminescence. II. Effect of surface modification by coating of particles with poloxamer on the phagocytic uptake. *J. Control. Release* 25, 51–59.
- Sato, T., Ruch, R., 1980. *Stabilization of Colloidal Dispersions by Polymer Adsorption*. Marcel Dekker, New York.
- Tadros, F.T., 1982. Polymer adsorption and dispersion stability. In: Tadros, F.T. (Ed.), *The Effect of Polymers on Dispersion Properties*. Academic Press, London, pp. 1–18.
- Wanka, G., Hoffmann, H., Ulbricht, W., 1990. Phase diagrams and aggregation behaviour of poly(oxyethylene)–poly(oxypropylene)–poly(oxyethylene) triblock copolymers in aqueous solutions. *Colloid. Polym. Sci.* 268, 101–117.