

## THE WORLD OF SURFACE SCIENCE\*

D. O. SHAH

University of Florida

Gainesville, Florida 32611

## SYNOPSIS

The domain of surface science is perhaps one of the most interdisciplinary areas of modern science and technology. Monolayers provide a unique system to determine experimentally the cross-sectional areas of surface-active molecules and to study reactions and molecular interactions at surfaces. Surface chemical aspects of membranes, cornea and tear are discussed. The mechanism by which surface-active polymers stabilize a thick aqueous layer on cornea is elucidated.

The engineering applications of surface science range from agricultural sprays to oil recovery including areas such as catalysis, coatings, dispersions, electronics, flotation of minerals, lubrication, and retardation of evaporation from lakes and reservoirs. Among biomedical areas, the applications of surface science extend from anesthesiology to zoology including fields such as artificial implants, biomembranes, biolubrication, lipoproteins, lung surfactant, ophthalmology, pharmaceuticals and pharmacology.

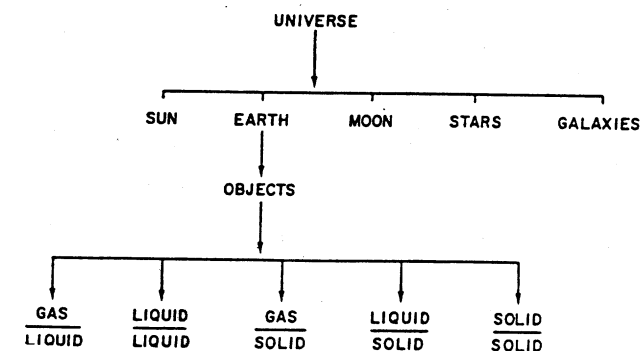


FIGURE 1. All objects are surrounded with one or more of these five interfaces.

\*This paper was selected by the Board of Judges of the Faculty Forum of the University of Florida for the "President's Scholar Award" for 1975-76.

**EDITOR'S NOTE:** In this issue, *CEE* continues a new department—ChE LECTURES. We intend to publish seminars and lectures on important areas of modern chemical engineering. If you feel that one of your seminars or lectures on a certain topic would have pedagogical or tutorial value and would be of general interest to our erudite readers, please send the manuscript to the editor for review. We would appreciate comments from our readers on this new department as well as suggestions for authors of papers.

ALTHOUGH THE importance of surface science has been recognized for more than a century, it is only during the last few decades that we have seen rapid advances in the understanding of surface phenomena. In this presentation I would like to review briefly various principles of surface science and where appropriate would like to present the highlights of the research carried out in my laboratory during the past decade.

Let me begin with a quotation of an oriental proverb which says, "The color of the world you see depends upon the color of the glass you look through." In general, a scientist attempts to look at the Universe through his own glass. When one looks at the Universe through the glass of surface science (Figure 1), one sees that it consists of Sun, Earth, Moon, Stars, Galaxies, etc. When one looks closer to the Earth, one finds that it is full of objects; and that each object is surrounded by a surface or an interface. Fortunately, all the interfaces can be grouped in five major classes, namely, gas/liquid, liquid/liquid, solid/liquid, solid/gas, and solid/solid. All objects are surrounded by one or more of these basic five interfaces. All of these interfaces have a common property called surface tension or surface free energy. There is also a class of compounds called surface-active compounds (or surfactants) that decreases strikingly the surface tension or surface free energy of these interfaces.

A surfactant molecule has two functional



Presently Dr. Shah is a professor of Chemical Engineering, Anesthesiology and Biophysics at the University of Florida.

He received his undergraduate training at the University of Bombay and subsequently his doctoral degree from Columbia University in 1965, where he worked in the laboratory of the late Professor J. H. Schulman.

He spent, subsequently, a year at NASA Ames Research Laboratory in California conducting research on chemical evolution and the origin of life, and surface chemical aspects of the origin of membranes. Later he moved to the Biological Oceanography Division of Columbia University and investigated the dispersion of oil-spills, retardation of evaporation and wave damping by thin films of surface active agents and surface chemical aspects of sea water.

Since 1970, he has been at the University of Florida with a joint appointment in Chemical Engineering and Anesthesiology Departments. Dr. Shah has published in the areas of biological and model membranes, chemical evolution and the origin of membranes, monomolecular films, foams, microemulsions, improved oil recovery, surfactant-polymer interaction, boundary lubrication and surface chemical aspects of lungs, vision and anesthesia.

Dr. Shah received the University of Florida's "Excellence in Teaching Award" in 1972-73, "President's Scholar Award" in 1975-76, and "Outstanding Service Award" in 1975-76.

parts, namely, a hydrophilic (water soluble) or polar part, and a lipophilic (oil soluble) or non-polar part. The lipophilic part is usually a long hydrocarbon chain. Schematically a surfactant molecule can be represented by a nonpolar (tail)

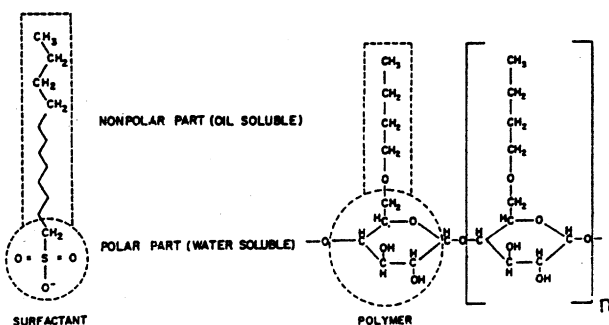


FIGURE 2. The structure of surface-active molecules. The broken line shows the separation of polar and non-polar parts of the molecule.

and a polar group as shown in Figure 2. A polymer also can be surface-active if it has two functional groups, one hydrophilic and the other lipophilic (Figure 2). The properties of a surface-active compound are determined by the balance between its hydrophilic and lipophilic characteristics. If the chain-length is relatively short (less than 12 -C-C- bonds in length), they are called water soluble surfactants since the polar group drags the entire molecule in water. However, when the chain-length is greater than 14 or 16 -C-C- bonds in length, the compounds are called insoluble surfactants. They do not dissolve in water because of the long hydrocarbon chains.

## MOLECULAR AGGREGATES

IF THE CONCENTRATION of a soluble surfactant in water is increased gradually, at a specific concentration of the surfactant, the solution properties such as osmotic pressure, surface

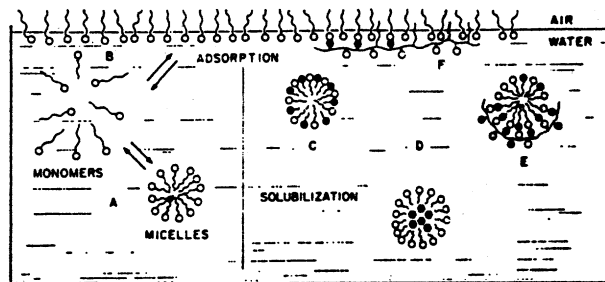


FIGURE 3. A schematic presentation of adsorption, micelle formation, and solubilization processes in surfactant solutions.

tension, viscosity, electrical conductivity, and density abruptly change [1]. This concentration is called critical micelle concentration (CMC). It has been established from theoretical considerations as well as experimental determinations that surfactant molecules begin to form aggregates, called micelles, when surfactant concentration is increased beyond the critical micelle concentration (Figure 3A). In general, the micelles are spherical aggregates of surfactant molecules about 40-100 Angstrom in diameter and are in equilibrium with single molecules (or monomers) in the bulk solution (Figure 3A). The critical micelle concentration depends upon the structure of surfactant molecules as well as physicochemical conditions such as temperature, pH, and the ionic composition of the solution.

If a soluble surfactant is dissolved in water, it tends to absorb at the gas/liquid, liquid/liquid, or solid/liquid interfaces. The adsorption phenom-

non results in a greater concentration of surfactant molecules at the interface as compared to that in the bulk solution (Figure 3B). For many surface-active drugs and pharmacological agents, their concentration at the membrane surface will be considerably greater than their bulk concentration [2].

The formation of micelles in an aqueous solution creates a local nonpolar environment within the aqueous phase. Oil soluble molecules such as dyes, pigments, nonpolar oils, or oil soluble vitamins can be dissolved within the micelles (Figure 3C, D). The solubilization of such molecules in micelles is greater if they also possess polar groups.

If a surfactant solution contains a surface-active polymer, then adsorption of the polymer can occur at the micellar surface (Figure 3E). The structure of lipoproteins, particularly low density lipoproteins in blood serum, resembles this situation in which a protein is adsorbed on the aggregates of lipid (i.e., biological surfactant or fat) molecules [3]. If a surface-active polymer is present in the solution, then a mixed, absorbed film of polymer and surfactant also can occur at the interface (Figure 3F). In several biological membranes, the protein-lipid association is believed to resemble this type of association [4].

Surfactant molecules can be considered as building blocks. One can make various types of structures of surfactant molecules by simply increasing the concentration of surfactant in water and adjusting proper physicochemical conditions such as temperature, pH, and the presence of various electrolytes [5, 6]. Figure 4 schematically shows various structures that are formed in the surfactant solution upon increasing the concentra-

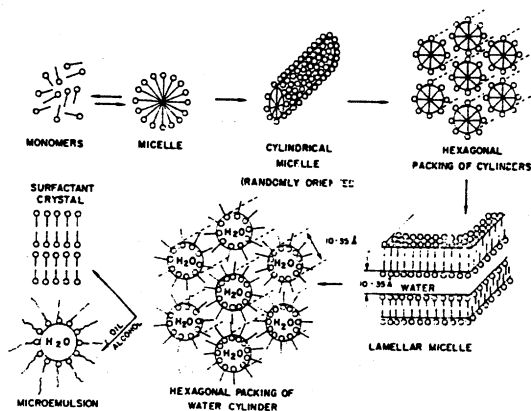


FIGURE 4. A schematic presentation of structure formation in surfactant solution depending upon the concentration of surfactant as well as physico-chemical conditions.

tion of a surfactant. Upon increasing the concentration of surfactant, spherical micelles become cylindrical and subsequently the cylindrical structures become hexagonally packed. If concentration is further increased, the lamellar structures are formed. Upon further addition of surfactant, the lamellar structures are converted to a hexagonal

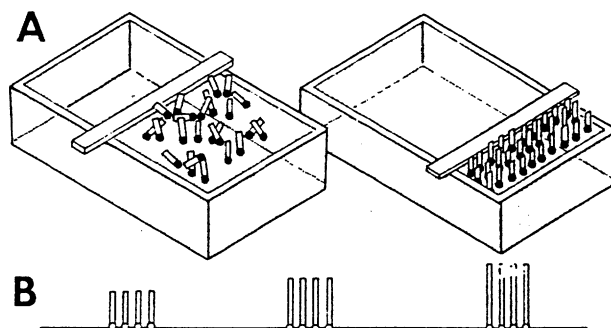


FIGURE 5. (A) schematic illustration of a monomolecular film at air-water interface.

(B) orientation of surface-active molecules with increasing chain-length at air-water interface.

packing of water cylinders. Upon addition of oil and a short-chain alcohol, one can convert such water cylinders into a water-in-oil microemulsion. The structures of these systems are well established from X-ray diffraction studies [7, 8]. It is possible to induce a transition from one structure to another by changing the physicochemical conditions such as temperature, pH, addition of monovalent or divalent cations in the surfactant solution [9]. The cylindrical and lamellar structures often are called liquid-crystalline phases since they have flow properties as liquids and a certain degree of crystallinity as solids. They have very unusual electrical and rheological properties [10-12]. It should be emphasized that the scheme shown in Figure 4 is a general scheme and a surfactant may skip several phases depending upon its structure and the physicochemical conditions.

## INSOLUBLE SURFACTANT AND MONOLAYERS

IF THE HYDROCARBON chains are sufficiently long (greater than 16 -C-C- bonds), the surface-active molecules will be insoluble in water. When such insoluble surfactants are dissolved in organic solvents, and a drop of the solution is placed on the water surface, these molecules will spread at the air/water interface. In general, the surfactant molecule does not evaporate because the polar group is anchored on the water surface and it does not dissolve because the long hydro-

carbon chain prevents the molecule dissolving into water. In this way, one can produce a monomolecular film of floating molecules of an insoluble surfactant at the air/water interface. In general, one can fill a tray of Teflon or plexiglas with water up to the rim of the tray. A measured quantity of surfactant solution in an organic solvent such as chloroform, benzene, or hexane can be placed by a microsyringe on the water surface. The solvent molecules evaporate or diffuse into the water leaving the insoluble surfactant molecules at the surface. A glass slide is placed at one end of the trough (Figure 5A). By horizontal movement of the glass slide one can compress this monomolecular film and bring molecules closer to one another. However, as the film is compressed, at a specific film area, the molecules will stand side by side with their polar groups in water and hydrocarbon chains in the air. By measuring the area of the film as well as calculating the number of molecules deposited on the surface, one can determine the average area per surface-active molecule in the monolayer. In a closed packed state, the average area per molecule is close to the cross-sectional area of the surfactant molecule. Thus, an insoluble monolayer is a system which allows the direct experimental determination of the cross-sectional area of the molecules.

Monomolecular films or monolayers represent a two-dimensional state of matter since their

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height, which is about 20-25 Angstrom, is negligible compared with their length and width. Analogous to the states of matter in three dimensions, monolayers also can exist as two-dimensional solids, liquids or gases and can undergo temperature-dependent phase transitions from one state to another [13, 14].

When the monomolecular film is compressed by moving the glass slide, the surface tension decreases (Figure 5A). The decrease in surface tension often is called surface pressure which indicates the state of compression of the monomolecular film. The higher the surface pressure,

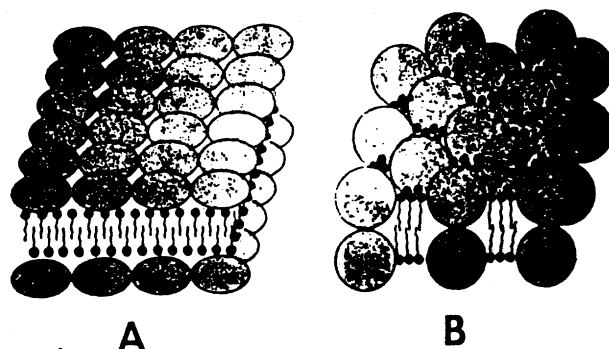


FIGURE 6. (A) Davson-Danielli model for structure of biological membranes.  
(B) Lipid-protein mosaic model for the structure of biological membranes.

the higher the state of compression of the monomolecular film. The surface tension is measured by a torsion balance from which a thin platinum blade is suspended in water at the air/water interface.

From the surface pressure measurements one can prepare a plot of surface pressure vs. average area per molecule. This plot is equivalent to pressure vs. volume curve for gases in three-dimensional state. In 1920, the concept of the specific molecular orientation at interfaces was a novel idea, but there was no experimental proof for this concept. Langmuir [15] used monolayer approach to establish that surface active molecules have a specific molecular orientation at the air/water interface. He studied monolayers of various fatty acids of different length containing 16 to 32 carbon atoms. Experimentally, he determined the cross-sectional area of molecules in the compressed monolayers of these fatty acids. To his surprise, he observed that although the fatty acids studied were of different chain-length, the cross-sectional area determined was the same for all fatty acids suggesting that they must be oriented vertically to the surface (Figure 5B). If they were oriented in any other way, the increasing chain length would have caused an increase in the average area per molecule. For establishing this concept of the specific molecular orientation at interfaces, Langmuir later was awarded a Nobel Prize [16].

#### APPLICATIONS OF MONOLAYERS

SINCE IT IS DIFFICULT to visualize at a molecular level how properties of a monolayer are related to various phenomena, I have prepared the following few diagrams to emphasize the role of monomolecular films in these phenomena.

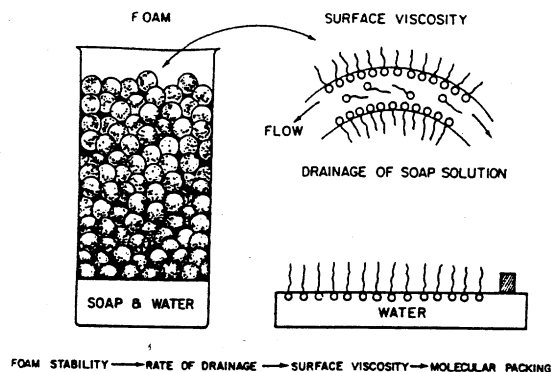


FIGURE 7. The schematic presentation of factors influencing foam stability.

Figure 6 shows two conceptual models for molecular arrangement of lipids and proteins in biological membranes [17, 18]. In the Davson-Danielli model (Figure 6A), the lipids (i.e., biological surfactant) are arranged as a continuous bilayer and protein is believed to be adsorbed on both sides of the lipid bilayer. The second model, (Figure 6B) which is based upon the current thinking about the structure of biological membranes, visualizes a discontinuous lipid bilayer interdigitated by protein molecules. Irrespective of which of these models is a more accurate description of molecular arrangement in membranes, the orientation and packing of lipid molecules in membranes are similar to that in monomolecular films of the lipids at the interface. Using a monolayer approach, one can determine lipid-lipid, lipid-protein and lipid-metal ion interactions that may occur in biological membranes [19-21].

Figure 7 schematically shows a foam column produced by a surfactant solution. The stability of the foam column depends upon the stability of individual soap bubbles. A soap bubble is a thin layer of surfactant solution which has the adsorbed film of surfactant on both sides of the soap film. The stability of the soap film depends upon the rate of drainage of solution in the film, which

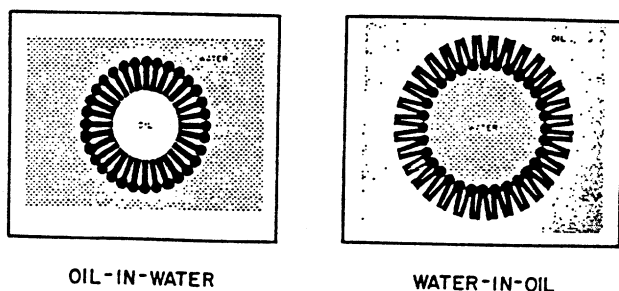


FIGURE 8. A schematic presentation for the structure of emulsion droplets and orientation of surface-active molecules at the oil-water interface.

subsequently depends upon the state of adsorbed surfactant film. We have observed [22, 23] that a closer packing of surfactant molecules in the adsorbed monolayer leads to a higher surface viscosity of the adsorbed monolayer, which subsequently decreases the rate of drainage of solution within the soap film, and hence increases the foam stability.

Figure 8 schematically shows the role of monolayers in stabilizing oil/water emulsions. It has been known that oil and water do not mix. However, if a surfactant is added to oil-water mixture, one can produce a relatively stable emulsion. Depending upon the relative amounts of oil and water as well as the physicochemical conditions, one can produce oil-in-water or water-in-oil type emulsion. In either case, each droplet is coated with a surfactant monolayer (Figure 8).

Figure 9 shows the role of the monomolecular film in boundary lubrication of metallic surfaces. Here a surfactant attaches itself to a metal surface due to the interaction between the polar

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group of the surfactant with the metallic surface. When such monolayer-covered surfaces slide against one another, the frictional forces decrease considerably. Since sliding of hydrocarbon chains past one another does not offer too much resistance, the coefficient of friction decreases strikingly. Moreover, the adsorption of such monomolecular film of surfactant on metal surfaces also protects the surface against wear from friction.

The monomolecular films of fatty acids or fatty alcohols also are employed for reducing evaporation of water [24]. In many countries such as Israel, India, and Australia this approach is used to decrease evaporation of water from lakes and reservoirs.

Figure 10 shows one of the concepts of surface science, namely, contact angle and wettability. When a drop of water is placed on wax, Teflon, or plexiglas, the drop rests on the surface with a finite angle called contact angle. If the contact angle is greater than  $90^\circ$ , the liquid does not wet the surface. If one adds a surfactant or "wetting agent" in water, the contact angle on wax or

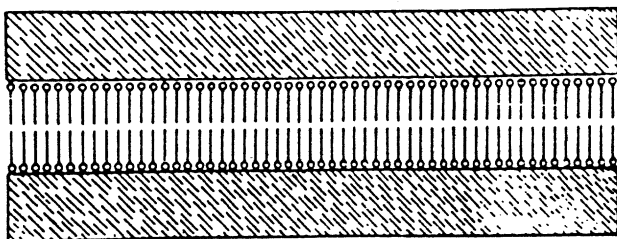


FIGURE 9. A schematic presentation of the orientation of surface-active molecules at the metal surface in boundary lubrication.

Teflon decreases dramatically and may approach zero. Hence, normally nonwettable surfaces can be wetted by water if surfactants are added to water [25, 26]. This phenomenon is of considerable importance in agricultural sprays since the herbicide or insecticide will not be effective if the drops from the spray do not stay on the leaves or fruits (because of their waxy surface) and fall on the ground. However, if one adds a surface-active agent to the spray, it changes the contact angle and permits droplets to stick and spread on the leaves and fruits providing protection from insects and other diseases (Figure 10). This phenomenon is also of central importance in the wetting of contact lenses and in many problems related to cornea and tears [27].

#### UNSATURATED FAT AND MOLECULAR AREA

AT PRESENT, considerable emphasis is placed on the desirability of "polyunsaturated fat" and the undesirability of "saturated fat and cholesterol" in diet. To determine the differences in the cross-sectional area and surface properties of lipid (fat) molecules with identical polar group but different degree of unsaturation in their fatty acid chains, we took lecithins from four different sources [28]. The four lecithins were, respectively, dipalmitoyl lecithin, egg yolk lecithin, soy bean lecithin, and dioleoyl lecithin. The first and the last lecithins were synthesized in the laboratory. Lecithin is a common component of biological tissues and membranes. As shown in Figure 11, the surface-pressure-area per molecule curves of these four lecithins were different suggesting that the nature of hydrocarbon chains influences the average area per molecule of lecithin. The order of average area per molecule is as follows: dipalmitoyl lecithin < egg lecithin < soy bean lecithin < dioleoyl lecithin. The fatty acid compositions of these four lecithins also were determined separately by the gas chromatography of fatty acids.

Figure 12 is a schematic presentation of these

four lecithins in monomolecular films based on monolayer and gas chromatography data. These results indicate that the degree of unsaturation or the presence of double bonds in fatty acid chains influences the average molecular area of lecithins and subsequently influences the intermolecular spacing between lipid molecules. If one assumes that the average area per molecule is a circle with a radius "r"; then the intermolecular spacing is  $2r$ . If we consider areas of  $51.9 \text{ \AA}^2$ ,  $73.8 \text{ \AA}^2$ ,  $78.1 \text{ \AA}^2$ , and  $87.5 \text{ \AA}^2$  per molecule at a surface pressure of 20 dynes/cm for dipalmitoyl, egg, soy bean, and dioleoyl lecithins, respectively; the corresponding intermolecular spacings are 8.1  $\text{\AA}$ , 9.7  $\text{\AA}$ , 10.0  $\text{\AA}$ , and 10.6  $\text{\AA}$  suggesting that a change of 0.3  $\text{\AA}$  to 1.5  $\text{\AA}$  in the intermolecular spacing is brought about by the degree of unsaturation of fatty acid chains. Further, we have shown that such small changes in intermolecular spacing strikingly influence the hydrolysis of lecithin monolayers when snake venom is injected under the monolayers. We have established that the degree of unsaturation of lecithins also influences their interaction with calcium ions in the solution as well as their association with cholesterol in monomolecular films (19, 21, 29, 30).

In summary, monolayers provide an extremely useful system to study cross-sectional area of surfactant molecules and to elucidate the effect of unsaturation on the intermolecular spacing, and

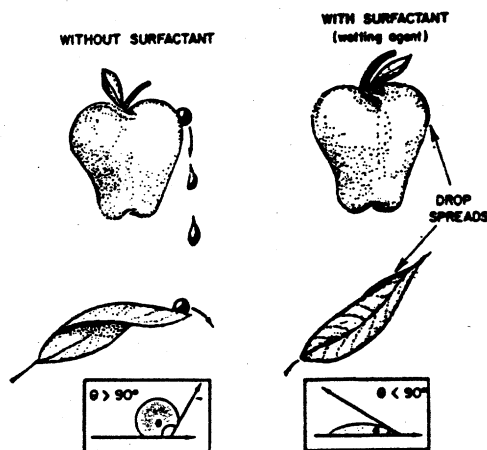


FIGURE 10. A schematic presentation of the role of contact angle and wettability in influencing the effectiveness of agricultural sprays.

hence on the reactions and molecular interactions at interfaces [31].

#### MONOLAYERS AND OIL SPILLS

The contraction of an oil spill is an interesting

application of monolayers.\* In the event of an oil-spill, the oil continues to spread because of the natural surfactant in the crude oil. These natural surfactants have a certain spreading pressure and, as a result, the oil continues to spread at the air/water interface. However, if one deposits a film of another surfactant with a higher spreading pressure around the oil-spill, then the deposited monolayer causes contraction of the oil-spill. In other words, the deposited film, having a higher surface pressure, causes the oil-spill to contract. The most fascinating message that comes out of this observation is that the monomolecular film of

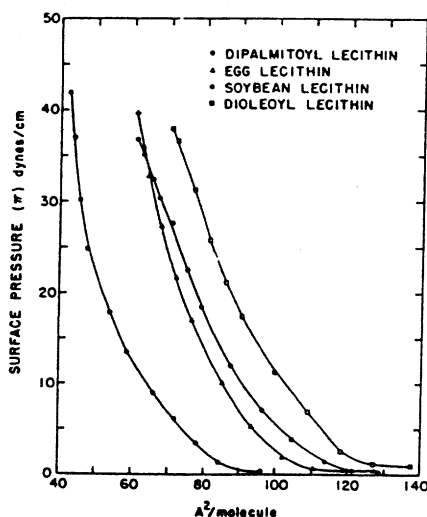


FIGURE 11. The surface pressure-area curves for four lecithins with different fatty acid compositions.

surfactant pushes a crude oil layer that is two million times thicker than its own thickness ( $\approx 25\text{\AA}$ ). This observation leads to the conclusion that for contraction of oil-spill, it is the spreading pressure that is a predominant factor and not the thickness of oil or surfactant layers. Spreading such a surface-active material around the oil-spill from a helicopter can prevent further spreading of the oil-spill and can thicken the oil layer at the air/sea interface and hence facilitate the collection procedures. Spreading of such films near the shore-line also can prevent the oil-spill from contaminating the beaches. Since we are using monomolecular films for this purpose, the danger of

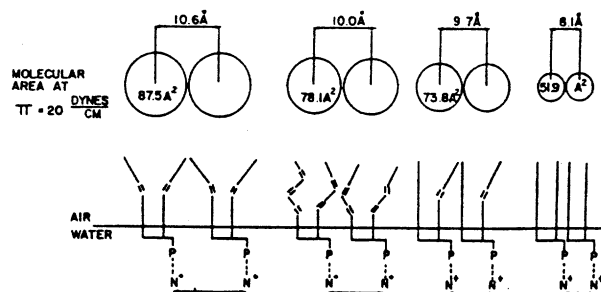


FIGURE 12. A schematic presentation of the effect of double bonds on the intermolecular spacing in lecithin monolayers.

contaminating the beaches with surfactant is extremely negligible and most of the surfactant used for this purpose would be biodegradable. Moreover, one would require extremely small amounts to produce monomolecular films.

Figure 13 shows the three-dimensional view of the application of surfactant solutions or microemulsions in tertiary oil recovery from petroleum reservoirs. Usually the oil wells are drilled in a five spot pattern in such a way that the microemulsions or surfactant solutions are injected into the central injection well. The surfactant formulation solubilizes the oils or decreases the interfacial tension at the oil/brine interface in the reservoir and displaces the oil towards the production wells at the four corners. If appropriate surfactants are injected, then the sandstone and rocks in the reservoir are cleaned and the oil is displaced effectively towards the production wells.

## SURFACE PROPERTIES OF POLYMERS AND TEAR SUBSTITUTES

IT IS FASCINATING that most of the phenomena mentioned previously such as retardation of evaporation, wettability of surfaces and lubrication take place every time we blink. Figure 14 schematically shows our concept [32, 33] of various phenomena that occur in the outer portion of the eye (i.e., cornea, tear, and the film of meibomian oil at the air/tear interface). Many people usually above 40 to 50 years of age suffer with a condition called "dry-eye syndrome." In this situation, the thickness of the tear film decreases considerably because of lack of fluid in the eyes. Between the blinks the thickness of the tear film decreases to such a low value that the tear film breaks and develops dry spots on the cornea. If one blinks under these conditions, there is considerable friction between the inside of the eye lid and the dry spots on the cornea. This may lead

\*Mr. A. Tamjeedi, an undergraduate student in Chemical Engineering, presented this paper at the Students AIChE Chapters competition at Baton Rouge, Louisiana and was awarded a second prize for his work in this area, 1973.



to damage of the corneal surface. Several pharmaceutical eye drops containing polymers are available to stabilize a thick layer of water on cornea. However, there is no scientific evaluation of the effectiveness of these available artificial tears or tear substitutes.

We studied the flow dynamics and the thickness of tear film in the eye using a slit-lamp fluorophotometer. The eye drops containing a fluorescent dye (fluorescein) are instilled into the eye of the patient or volunteer. In general, the intensity of fluorescence is related to the thickness of the tear film. We found that the tear-film thickness decreases between blinks due to drainage by gravity. However, if one adds a drop of a surface-active polymer solution (such as polyvinylalcohol (PVA), hydroxypropylmethylcellulose (HPMC)), or a commercially available tear substitute, the film thickness increases between blinks. Figure 15 schematically shows our explanation for the effect of polymers in thickening the tear film between blinks. A surface-active polymer would adsorb at the air/tear interface. When one blinks, this adsorbed film is compressed just like a monolayer spread on the tray filled with water (Figure 5). After the blink, the lid is moved upward, and the compressed film of the polymer spreads in the upward direction to occupy the clean surface at the air/tear interface. When the compressed film of polymer moves upward, it drags water as the sublayer. This phenomenon of surface flow from high surface pressure to low surface pressure is called *Marangoni effect*. To establish that water

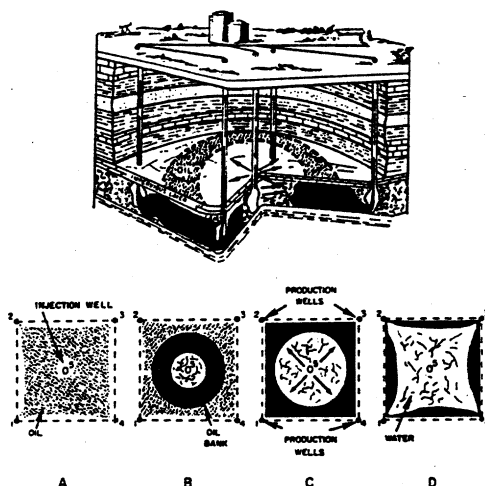


FIGURE 13. A schematic presentation of a petroleum reservoir. The lower part of the diagram shows how injection of a surfactant formulation moves the oil towards the four production wells.

can be dragged by a polymer film, a simple experiment using a glass slide was carried out as shown in Figure 16. One end of a wet glass slide was dipped into a polymer solution and it was observed that the polymer solution begins to climb on the wet glass slide. From fluorescence measurements, the thickness of the moving film was determined. To our surprise we found that the thickness of films of various polymer solutions measured in this system was the same as that measured in the eye. Table I shows the thickness of various polymer solutions dragged on a vertical glass slide. We

TABLE I

Polymer		Thickness ( $\mu\text{m}$ ) of water layer dragged by polymers*
Barnes-Hind wetting soln.	58 cp	22
Adapt†	70 cp	17
Presert†	18 cp	16
Lacril†	28 cp	14
Visculet†	130 cp	11
PVA	120 cp	18
PVA	20 cp	12
HPMC	120 cp	12
HPMC	20 cp	9
Monomolecular film of PVA		13

\*Surface Area of Trough =  $0.52 \text{ cm}^2$

†commercially available artificial tear solutions

also carried out similar experiments using a monomolecular film of Polyvinylalcohol (Table I). Here again, we found that the thickness of the layer of water dragged by a monolayer was 13 microns which is the same as the thickness of the layer dragged from the polymer solution. In other words, the increase in the thickness of the tears in the eye can be accounted for by a monomolecular film of polymer at the air/tear interface. This study again points out the importance of surface activity of polymers in assisting and providing comfort to patients with "dry-eye syndrome."

## APPLICATIONS OF SURFACE SCIENCE

• **Agriculture and food technology**—The effectiveness of various herbicides and insecticides in agricultural sprays are determined by their wetting of leaves and fruits. The presence of surfactants (wetting agents) in agricultural sprays strikingly improves the effectiveness of the sprays



and contributes to a greater production of crops. The emulsions also find considerable application in food products such as salad dressings, margarine, whipped cream, puddings, etc. Surface chemical aspects of protein-lipid associations also are important in determining the texture of food such as cakes and pastries and work is being done in this direction using the principles and techniques of surface sciences.

- **Energy**—The surfactant solutions and microemulsions are important in improving oil recovery from petroleum reservoirs. Another interesting application is in the area of combustion efficiency of various oils. Recently, it has been shown that if one injects a fine dispersion or emulsion of water and oil in furnaces, the efficiency of conversion of oil into heat is improved considerably. Although the exact mechanism is not established, the fact still remains that emulsification of oil and water improves the combustion efficiency.

- **Environment**—Principles and techniques of surface science find many applications in environmental problems. The dewatering of phosphate slimes, sludge formation, coagulation, and flocculation in many waste-water treatment plants rely on the surface interactions. The surface reactions and adsorption on activated carbon are very effective methods for removal of trace contaminants. Fibrous coalescers also are used for the removal of oil droplets from a few parts per million concentration in the effluent streams of many industries. Here the attachment of oil drops to the fiber and their subsequent coalescence play an important role in the separation of oil. The use of surface films as oil herder for the contraction of oil-spills has been discussed. The presence of films at the air/water interface also causes

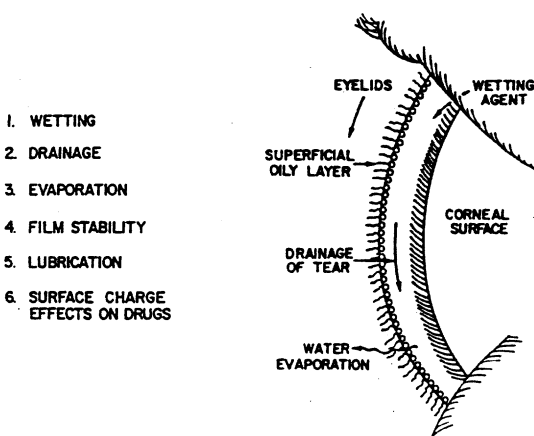


FIGURE 14. A schematic presentation of various surface phenomena occurring in the eye.

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wave-damping of small ripples. This observation has been used in developing the instrumentation for remote sensing of oil-spills. In all these systems and processes, the principles of physics and chemistry of surfaces and surface-active agents are involved.

- **Industries and engineering**—The surface science is involved in coating processes. For example, the production of magnetic tapes in which a dispersion of magnetic oxide is coated on polyester tapes. The stability of the dispersion and the strength of adhesion depend on the surface interactions. Other applications of surface science are found in the manufacture of inks, paints, pigments, nonstick cooking wares, etc. The textile industry also utilizes considerable quantities of surface-active substances in the form of wetting agents, emulsions, dye-solubilization and other processes. The contact angle and wettability also enters into water-proofing of textiles, roofing material and similar systems. Many lubricants also involve the use of hydrocarbon oils and various surface-active agents as additives. The physics and chemistry of thin films are used extensively in the electronics industry. As discussed previously, the production of petroleum and petrochemicals also utilizes many processes which are in the general domain of surface science. The field of catalysis is based on surface interactions between the substrate molecules and the catalyst surface. The formulations of soaps and detergents for household uses also are based on surface properties of surfactants. In the world about  $10^6$  tons of minerals are processed every year by the use of flotation technology which again relies on the adsorption of surfactant on mineral particles. Many office stationeries such as NCR papers (no carbon required papers) use microencapsulation of powders to coat these papers. The microencapsulation is one of the most interesting applications of surface and colloid science to industrial processes.

- **Biology and medicine**—Many principles and techniques of surface science are relevant to the understanding of the properties and functions of

biological membranes. It has been suggested [17] that the spontaneous formation of membranes played an important role in the origin of prebiological cells during the chemical evolution which was followed by the biological evolution. These techniques are being used to elucidate the mechanism of action of many drugs, anesthetic agents, and pharmacological agents on membrane properties. It has been established during recent years that conduction of electrical signal along a nerve fiber is strictly a surface phenomenon occurring in nerve cell membrane. As discussed previously the surface properties of polymers are also relevant to the performance of tear substitutes in the eye. These concepts can be also extended to the wetting of contact lenses and the comfort for the eye. The solubilization of oil soluble vitamins in

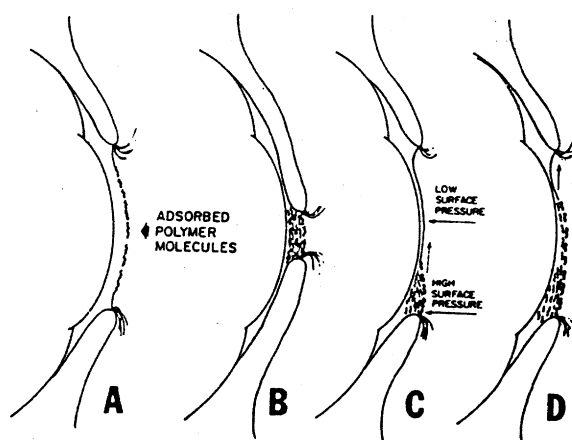


FIGURE 15. A schematic presentation of the effect of adsorbed polymer film at the air-tear interface in upward movement of water after a blink.

micelles, the fat absorption in intestine, lung stability and the function of pulmonary surfactant, synovial fluid and lubrication of bone joints, dental integuments, and the development of various nonthrombogenic surfaces for artificial organs and implants all draw significantly on surface science.

- **Pharmaceuticals**—Various pharmaceutical products such as ointments, skin lotions, creams, microencapsulation of drugs for sustained drug-delivery, birth control foams, etc. are being formulated and developed using principles and techniques of surface science. Some of these have been discussed previously.

In summary, I would like to emphasize that from the research activities I have carried out in the past decade, I have become convinced that the surface science is one of the most important facets

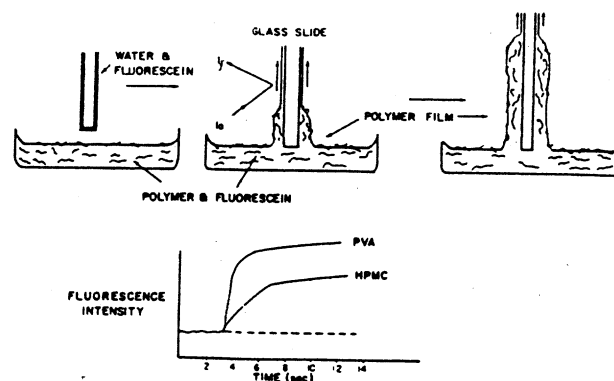


FIGURE 16. The slide technique used to measure the thickness of water layer dragged with a moving polymer film.

of science. It is related to many natural processes and systems; it is one of the unique branches of science that finds so many diverse and wide-ranging applications in engineering, biology and medicine.

It is only during the past few years that we have seen rapid advances in understanding the complexities and unique properties of surfaces. I believe we are still at the shores of surface science, and we have a whole ocean to explore! Over the years I have also become convinced in my belief that "research is an art. Just as an artist enjoys painting a picture, or a poet enjoys writing a poem, a scientist does research for his own enjoyment, regardless of its appreciation by others, although it is nicer when it is also appreciated and enjoyed by others." As I began this article with a quotation, I would also like to end it with a quotation from a poem by Tagore, which very appropriately says, "My friend, drink my wine in my own cup to appreciate its sparkling bubbles." □

## ACKNOWLEDGEMENTS

I would like to thank Professor Bolduc (Education), Professor Nevis (Electrical Engineering and Physics), Dr. Tham (Anesthesiology and Chemical Engineering), and Professor Walker (Chemical Engineering) for critically reviewing the manuscript and for many constructive suggestions. The financial support for the research presented here was provided by the National Science Foundation, National Institute of Health, Environmental Protection Agency, the Florida Heart Association, and the University of Florida, which is gratefully acknowledged.

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At present, Dr. Shah is the first **Charles A. Stokes Professor of Chemical Engineering and Anesthesiology** and is the **Director** of the Center for Surface Science and Engineering at the University of Florida. He received his undergraduate training at the University of Bombay, and his doctoral degree from Columbia University in 1965 under the direction of the late Professor J. H. Schulman, a pioneer in Surface and Colloid Science. Thereafter, he was awarded a NRC-NASA Resident Research Associateship to conduct research on chemical evolution and the origin of life at NASA Ames Research Center.

In 1970, he joined the University of Florida as an Assistant Professor, and was promoted to the position of Associate Professor in 1972. He later became a Full Professor in 1975. He has continued his research in areas of monomolecular films, foams, wettability and contact angle, dispersions in oil and aqueous media, surfactant-polymer interactions, boundary lubrication, nanoparticles of superconductors and magnetic materials, and surface phenomena in membranes, lungs, vision, and anesthesia. Dr. Shah has edited seven books on enhanced oil recovery, surfactant solutions, as well as macro- and microemulsions. He has published over two hundred research papers and reviews, and has presented about two hundred fifty papers at scientific meetings. He has delivered over three hundred seminars at academic institutions and industrial laboratories. Dr. Shah has served as a consultant to more than 50 corporate laboratories during the past twenty-five years.

Dr. Shah received the University of Florida's "**Excellence in Teaching Award**" in 1972, the "**President's Scholar Award**" in 1975, the "**Outstanding Service Award**" in 1976, the "**Best Paper Award**" at the International Congress of Chemical Technology in 1978, **Visiting Professorship in Chemical Engineering and Petroleum Engineering** at the Institute for Energy Studies at Stanford University in 1979, and the "**Outstanding Achievement Award**" from the Federation of Asian Indians in North America in 1980. He was invited as the **keynote speaker** at the European Symposium on Enhanced Oil Recovery in Bournemouth, England, in 1981. Dr. Shah received the "**Perry Brothers-Mallinckrodt Award**" from the Society of Cosmetic Scientists in 1982 for the best paper presented at the annual scientific meeting. He was invited to teach a short course on "**Surfactants and Their Use in Enhanced Oil Recovery**" at Imperial College, London, in 1983, and to present the **keynote lecture** at the meeting of the International Society for Contact Lens Research, in Cambridge, England, in 1984. Dr. Shah was appointed **Director** of the *Center for Surface Science and Engineering* at the University of Florida in November, 1984. He received the University of Florida's highest honor "**Teacher/Scholar of the Year 1984-85 Award**" and the "**President's Medallion for Excellence in Teaching and Scholarship**" in May 1985. Dr. Shah served as the **chairman** of the Department of Chemical Engineering during 1987-1991. He received the "**Florida Scientist of the Year Award**" in April 1988, and was invited to visit India during September 1988 on a three-week lecture tour as the **United Nations (UNIDO) Consultant**. The AIChE Students Chapter presented to Dr. Shah the "**World-Class Chairman Award**" and the University of Florida College of Engineering honored him with a plaque for **meritorious service** as the chairman and for **globally recognized professional contributions** to the field of surface science in 1991. He received the "**Vishwa-Gurjari 1992 International Award**" for distinguished achievement. In October 1992, Dr. Shah received the "**Florida Blue Key Distinguished Faculty Award**" and was requested to be the **Grand Marshal** of the 1992 Homecoming Parade. The Florida Academy of Science honored Dr. Shah as the "**Distinguished Florida Scientist of 1993**". In July 1993, he was presented the "**Pride of India Award**" by Mr. A. Ansari, India's Ambassador to the United Nations, on behalf of Swami Narayan Sanstha of the U.S.A. Dr. Shah received the "**1994 Best Paper Award**" of the American Oil Chemists' Society for his research paper on the *Molecular Mechanism for Destabilization of Foams*. He was invited to present a **plenary lecture** in honor of Professor Heinz Hoffmann at Wolfgang-Ostwald Colloquium for Colloid and Surface Science at Bayreuth, Germany during June 23-24, 1995. He organized and hosted at the University of Florida an **International Symposium on Micelles, Microemulsions, and Monolayers: Quarter Century Progress and New Horizons** during August 27-30, 1995 which was attended by 300 researchers from 25 countries. During 1995, Dr. Shah was invited to present a two-day intensive **short course on foam making and foam breaking** at the Procter & Gamble Research Centers in Cincinnati (USA), Caracas (Venezuela), Newcastle (UK), Brussels (Belgium), Rome (Italy), Kobe (Japan), and Manila (Philippines). Dr. Shah has been invited to serve on the **Editorial Board** of the Journal of Colloid and Interface Science, January 1, 1996. In 1996, Dr. Shah was appointed as the first **Charles A. Stokes Professor of Chemical Engineering**. He was invited to present a **plenary lecture** at the 4<sup>th</sup> World Surfactants Congress in Barcelona, Spain and was also an **invited lecturer** at the 11<sup>th</sup> Surfactants in Solutions Conference in Jerusalem, Israel in June, 1996. He received the **Professorial Excellence Award** from the University of Florida in 1996.