1. Introduction

Biofilms serve beneficial purposes in the natural environment and in some modulated or engineered biological systems. For example, biofilms are responsible for the removal of dissolved and particulate contaminants in natural streams and in waste water treatment plants. Biofilms in natural water, called mats, frequently determine water quality by influencing dissolved oxygen content and by serving as a sink for toxic and/or hazardous materials. These mats may play a significant role in the cycling of chemical elements. Biofilm reactors are also used in some common fermentation processes, e.g., the "quick" vinegar process (Characklis and Marshall, 1990).

The initial step in biofilm formation is the attachment of the "first settlers" on the support. The aim of this contribution is to show how modification of support surfaces can be used to favour such attachment.

The attachment of microorganisms to solid surfaces may, in a first analysis, be thought of as an interaction between two smooth surfaces. It must be kept in mind that surfaces usually carry an electric charge which is neutralized at a certain distance in the solution, through a diffuse double layer. Within the latter, the concentration of ions with the same sign as that of the surface charge is lower compared with their concentration in the bulk solution, and the concentration of ions with opposite sign is higher.

As two surfaces approach each other, their tendency to associate may be evaluated by the DLVO theory, which allows the computation of their interaction potential energy. Dispersion forces (London forces) contribute generally to mutual attraction. The overlap of the diffuse double layers is responsible for electrostatic interactions at a separation distance of several tens of nm. For surfaces carrying charge of the same sign, the existence of a potential barrier decreases the probability that their encounter will give rise to formation of a firm bond. Since microbial cells are generally negatively charged in their natural medium, a situation of attractive electrostatic interaction exists only with positively charged carriers. For example, various species were described to adsorb to ion-exchange resins (Hattori and Hattori, 1985; Wood, 1980; Durand and Navarro, 1978). Bar et al. (1986), who used several kinds of ion exchangers to adsorb Acetobacter aceti, tried to show a relation between the amount of biomass adsorbed and the charge density of the resin.

Surface energy consideration enables to compute the free energy of adhesion between two surfaces, by regarding the transformation as a replacement of two solid-liquid interfaces by one solid-solid interface. The free energy of adhesion is negative, and thus adhesion is favoured,
when the surface energy of both solids is lower than that of the liquid medium; this is the case when the medium is an aqueous solution and both surfaces are hydrophobic. As interfacial free energies are computed from contact angles of liquids, their balance does not incorporate the contribution of electrostatic interactions between the two solid surfaces.

The fact that adhesion of microorganisms to various inert supports is governed by both electrostatic and hydrophobic interactions has been shown for biotechnologically relevant microorganisms (Mozes et al., 1987) as well as for soil bacteria (Van Loosdrecht et al., 1987a, 1987b). Electrostatic interactions act at a long distance (range of tens of nm, depending on the ionic strength) and control the rate at which surfaces can be brought close enough to form a firm bond. On the other hand, the balance of surface energies considers that, at the final state of the transformation, the two solids are in molecular contact; in a broader way, hydrophobic interactions depend on molecular organization and forces at short distances (less than 1 nm). At this stage, it must be realized that the surface of microorganisms is not smooth at a molecular level. While the overall interaction between a cell and a surface may be repulsive, cell appendages may bridge the distance between the cell and the surface due either to their more hydrophobic character, or their smaller radius, reducing the electric repulsion.

The picture becomes still more complicated if it is realized that the cell surface is neither smooth nor constituted of a compact solid but is made of macromolecules which keep a certain degree of mobility. The crucial influence of a capsule was observed in a comparison of different strains of Acetobacter acetii (Hermesse et al., 1988). Cells having a capsule were able to adhere to various siliceous or organic supports; cells without a capsule adhered only on supports treated to decrease the negative character of their surface.

Adsorption processes may change the electrical properties and the hydrophobicity of a substratum. The adsorption of macromolecules (proteins, polysaccharides) forms a conditioning film on the surface. The configuration and orientation of molecules within the conditioning film are influenced by the nature of the underlying substratum; there is evidence that the properties of the latter are marked through the thickness of the conditioning film (Busscher et al., 1989; Schakenraad and Busscher, 1989; J-L. Dewez, unpublished). The film of adsorbed polymers may convert the neat support/medium (solid/liquid) interface into a region of gel-like nature with which polymers or structures (e.g., fibrils) of the cell surface may interact. Zobell and Allen, already in 1935, described the concentration and adsorption of organic matter from seawater onto various solid surfaces, and the consequent enhanced attachment and growth of bacteria. The issue has been intensively investigated since then. A recent example is the study of Beech et al. (1989) who identified the involvement of specific macromolecules (extracellular polysaccharides, probably as lipopolysaccharides) in the initial stage of biofilm formation on metal surfaces.

Surface microroughness may help attachment of cells (Figure 1). This may be due to the increase of the surface area available for cell-substratum contact. Moreover, cells located inside pores are sheltered from shear forces; thereby their removal rate is reduced and retention of a larger amount of cells is assured. Verrier et al. (1987) showed that pores and crevices at the support surface improved initial adhesion of methanogenic bacteria to various polymers. Asther et al. (1990) noted that adhesion of Phanerochaete chrysosporium to various solid carriers improved when the roughness of the latter increased. The use of porous material as carrier for cell immobilization is rather common. For example, Opara and Mann (1988) used porous bricks and Navarro and Durand (1977) used porous glass to immobilize yeast; porous glass was also used by Bück et al. (1988) and Kreckeler et al. (1991) to immobilize bacteria. Messing and Oppermann