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THE ROLE OF BIOFILMS IN MICROBIAL CORROSION

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INTRODUCTION

Planktonic bacteria, in pure cultures in rich media, have formed the basis of microbiological studies since the times of Pasteur and Koch. Recently, direct observations of bacteria growing in a wide variety of natural industrial and pathogenic situations have shown that these organisms actually grow predominantly in multispecies biofilms attached to available surfaces[1,2]. These biofilm microorganisms have now been shown to differ fundamentally from their planktonic counterparts in their physiology and cell wall structure and in their susceptibility to antibacterial agents.

The value of studies on pure cultures of bacteria has been proven by the control of disease and the development of vaccines, antibiotics and genetically engineered organisms. Unfortunately, this knowledge has not assisted us in controlling the negative effects of bacteria in industrial systems. It has become clear that bacteria exhibit a plasticity of form and function when they grow in biofilms.

BIOFILM GROWTH

The biofilm performs several functions vital to the survival of its constituent organisms. The polysaccharide anchors the microorganisms to a surface. The biofilm traps nutrients from the bulk solution and makes them available to the bacteria (Fig. 1) and antagonistic molecules (biocides, surfactants, antibiotics, etc.) are captured and retarded by the anionic fibres of the exopolysaccharide (Fig.1). The biopolymer also shields the bacteria from predators, bacteriophage and immune system factors[3].

The biofilm plays an important part in concentrating enzymes that act on insoluble substrates. Plant matter in cattle rumen demonstrates this effect very dramatically because the cellulose is colonized by cellulolytic bacteria such as Fibrobacter succinogenes within 15 minutes. These bacteria produce cellulases and hemicellulases which are held near the cellulose surface by the developing digestive biofilm and the bacterial attack on this insoluble substrate is, therefore, focused at specific locations. A second important effect is noted in these celluloytic biofilms. Bacteria must have a means of disposing their metabolic products for maximum efficiency. The Fibrobacter succinogenes produce butyrate as an end product of cellulose degradation. If Treponema (a butyrate utilizer) are added to the biofilm the rate of cellulose degradation is sharply accelerated[4]. The biofilm allows the syntrophic species to be positioned in relation to each other to achieve rapid removal of the end product.

This syntrophy can be noted in the metabolism of soluble substrates. Bacteria in upflow anaerobic sludge blanket (UASB) digesters form highly structured particles. The particles were recently found to consist of a complex microbial consortium. The mantle population consists of heterotrophs which break down the complex substrates to butyrate and propionate which is consumed by acetogens in an inner layer. The core of the particle consisted of Methanotrix which utilized the acetate. The full development of these complex consortia requires several months, but, once formed, they can degrade organic matter and produce methane at a prodigious rate[5].

CORROSIVE FACTORS IN BIOFILMS

When biofilms develop on metallic surfaces they can create conditions conducive to corrosion. The presence of adjacent microcolonies of different types of bacteria contributes to the formation of local anodes and cathodes due to differences in eH, pH, or other ions (Fig. 2). It has been demonstrated that these colonies can produce measurable potential differences at different points on the surface[6]. The polysaccharides from different bacteria can have differing chelating abilities that produce concentration cells at the metal surface[7].

We have seen that the biofilm positions bacteria and their enzymes at solid surfaces. When contaminated industrial systems form biofilms, the heterotrophic population dominates the upper layers. The lower layers are comprised of bacteria that can remove metabolic end products as we have seen in degradative processes. The bacteria that perform this function in nature often also have the capacity to utilize hydrogen produced by other bacteria. In corrosive biofilms, the hydrogenase positive organisms are positioned in the bottom of the biofilm, where hydrogen is being formed as the cathodic reaction product (Fig.3).

Removal of this cathodic hydrogen depolarizes the corrosion cell, greatly accelerating the corrosion rate. Many of the hydrogenase positive bacteria, such as sulfate-reducing bacteria, are also sulfidogens. The H_2S produced precipitates iron sulfide which is itself a powerful cathodic depolarizer. Growth of this active iron sulfide and bacteria complex results in formation of a very large cathode relative to the anode (Fig.4). A large cathode/anode ratio results in extremely rapid localized attack. The effect of hydrogenase positive bacteria on corrosion has been shown in many field[8] and laboratory[9,10], situations.

The incidence of microbial corrosion is more widely accepted than the various mechanisms proposed to account for it. However, a consensus has now developed in which the basic structure of the bacterial biofilms now known to be virtually ubiquitous in aquatic systems is itself invoked as the corrosion mechanism. Local bacterial microcolonies constitute anodes and cathodes within these biofilms, which also show remarkable heterogeneity in other physiological properties, and the biofilm itself becomes an integral part of the "corrosion cell". It is easy to accept that a physico-chemical corrosion cell can cause pitting corrosion and we now realize that the biofilm represents a mechanism whereby bacterial anodes and cathodes can be held in juxtaposition to the metal surface, and to each other, along with their retained products (iron sulphides), so that a very active classic corrosion process can be initiated and sustained by a bacterial biofilm. Because planktonic bacteria could not, by definition, establish classic corrosion cells in a metal surface it is true to say that biofilm formation is an absolute sine qua non of microbially influenced corrosion.

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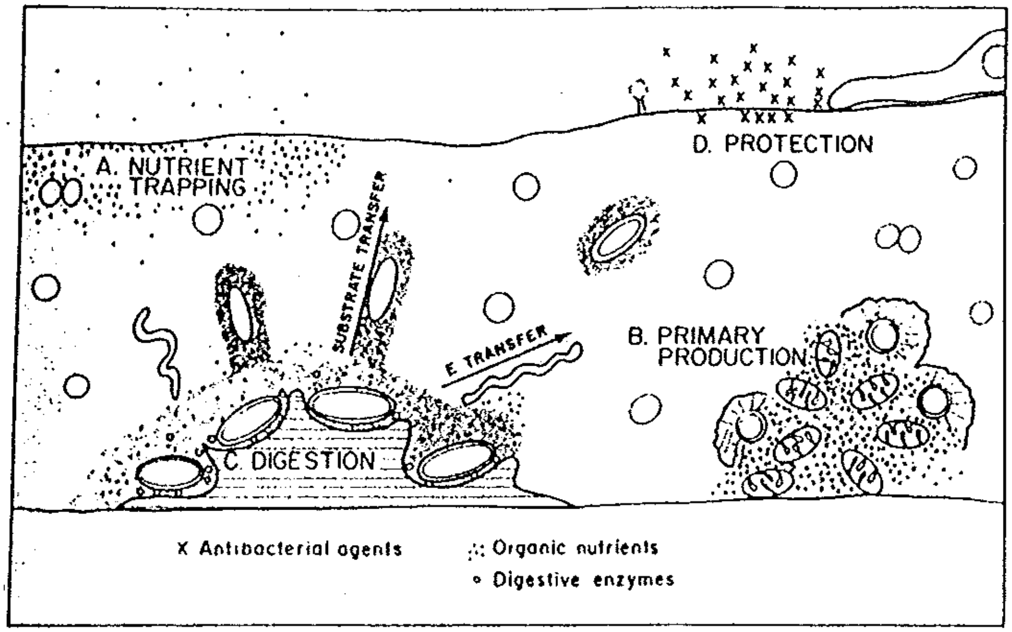
A. NUTRIENT TRAPPING
SUBSTRATE TRANSFER
D. PROTECTION
E TRANSFER
B. PRIMARY PRODUCTION
C. DIGESTION
X Antibacterial agents
Organic nutrients
Digestive enzymes

FIG. 1.

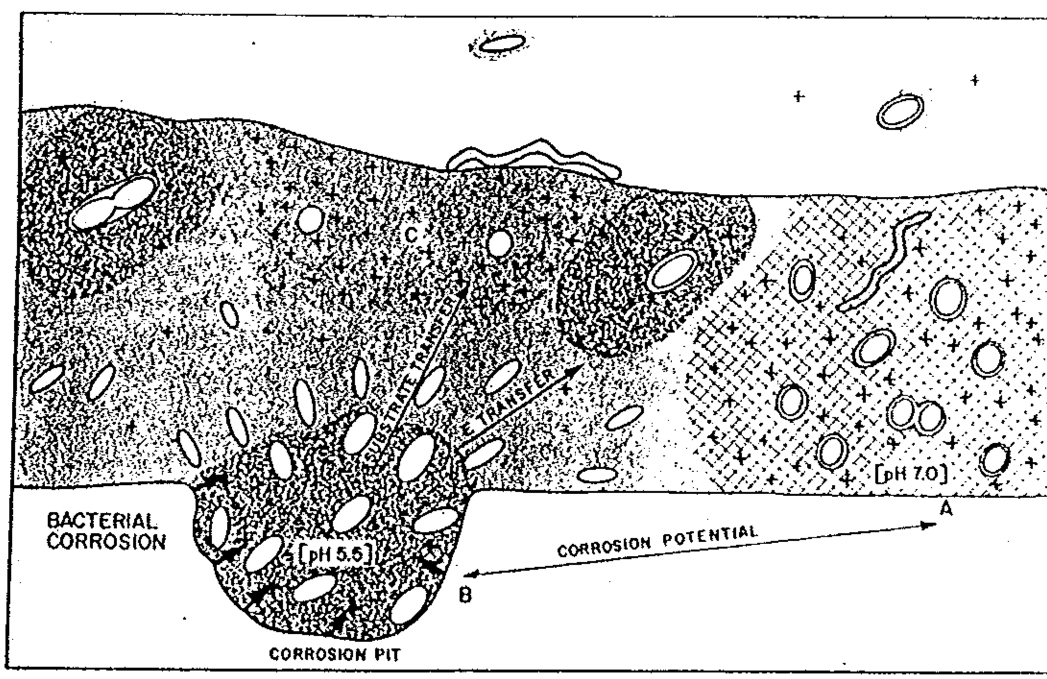
C
SUBSTRATE TRANSFER
E TRANSFER
[pH 7.0]
A
BACTERIAL CORROSION
[pH 5.5]
CORROSION POTENTIAL
B
CORROSION PIT

FIG. 2.

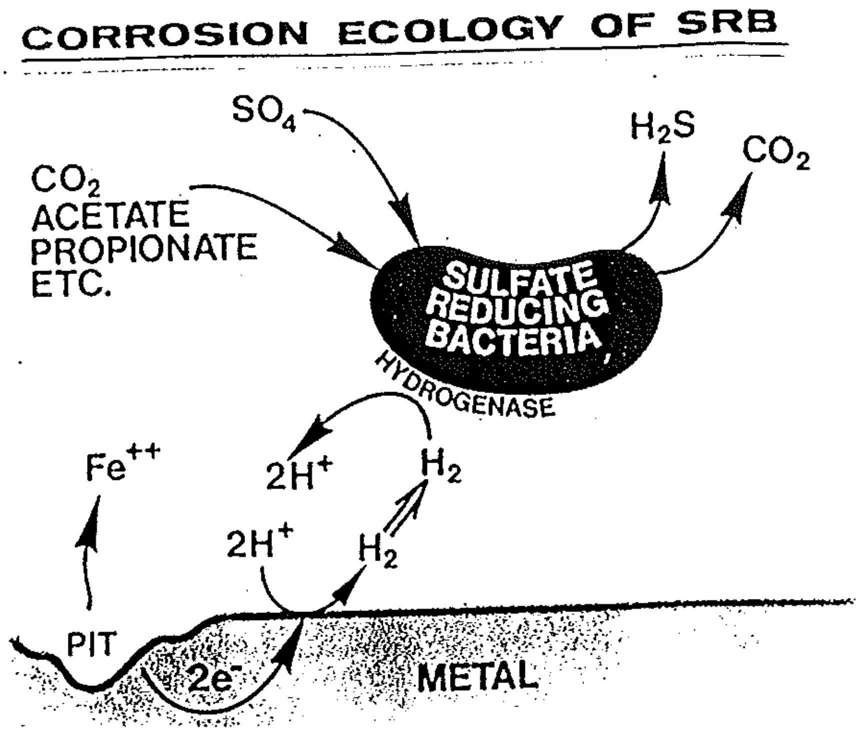
CORROSION ECOLOGY OF SRB
SO_4
H_2S
CO_2
CO_2
ACETATE
PROPIONATE
ETC.
SULFATE REDUCING BACTERIA
HYDROGENASE
Fe^{++}
$2H^+$
H_2
$2H^+$
H_2
PIT
$2e^-$
METAL

FIG. 3.

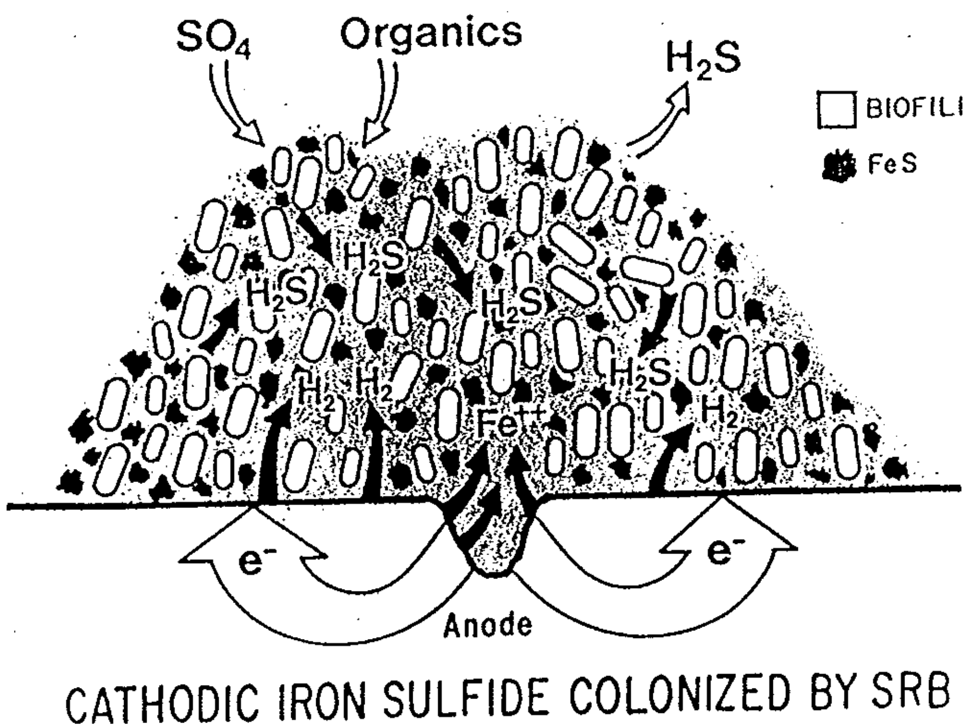
SO_4
Organics
H_2S
BIOFILI
FeS
H_2S
H_2
Fe^{++}
e^-
e^-
Anode
CATHODIC IRON SULFIDE COLONIZED BY SRB

FIG. 4.