MICROBIAL CORROSION OF PIPE LININGS

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WRC Report No. 432/2/99
ISBN 1 86845 478 9
ISBN SET NO 1 86845 479 7

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EXECUTIVE SUMMARY

In a previous project carried out by the CSIR for the WRC titled "**Microbial Corrosion of Common Piping Materials in the PWV area**" which examined the extent of micro-organisms in the corrosion of common piping materials, the possibility of microbial corrosion on coating systems was reported and led to the current project.

The objectives of this study were to critically determine whether various coating/lining systems were susceptible to microbiological attack; to determine the effects of sulphate reducing bacteria (SRB) in degradation of coating/lining systems and to recommend remedial measures if microbiologically influenced corrosion (MIC) proved to be occurring on the lining systems. Any form of severe corrosion can lead to leaks and bursts with the associated costs of water loss and pipe replacement more so if improper or defecive coating/lining systems are applied.

After a total of 36 months, exposure of different coating/lining systems and other metallic coating materials in both raw water systems and stagnant potable water systems no microbiological degradation of the coating/lining systems occurred. In every case however, where the coating/lining failed MIC was detected on the substrate. It is therefore crucial that linings systems for immersed condition are correctly specified and applied.

A common preventative measure is to line or coat pipelines but this can be an expensive waste of time and money if these sytems are applied incorrectly or defectively because corrosion and leaks can still occur. The results of this study clearly show that linings and coatings used under immersed conditions can fail resulting in MIC by SRB of the substrate material irrespective of its compositon.

ACKNOWLEDGEMENTS

The research in this report was funded by the Water Research Commission and entitled:

MICROBIAL CORROSION OF PIPE LININGS.

The Steering Committee responsible for this project, consisted of the following persons:

Mr H.C. Chapman	-	Ex-WRC (Chairman)
Mr D. Huyser	-	WRC (Committee Secretary)
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The financing of the project by the WRC and the contribution of the members of the Steering Committee is gratefully acknowledged.

LIST OF FIGURES

LIST OF ABBREVIATIONS

CFu	-	Colony Forming Units
CSIR	-	Council for Scientific and Industrial Research
DWAF	-	Department of Water Affairs and Forestry
EDS	-	Energy Dispersive Spectroscopy
LTD	-	Limited
MIC	-	Microbiologically Influenced Corrosion
MPE	-	Multipurpose Epoxy
PWV	-	Pretoria, Witwatersrand, Vereeniging
SEM	-	Scanning Electron Microscopy
SRB	-	Sulphate Reducing Bacteria
TAPC	-	Total Aerobic Plate Count
TVL	-	Transvaal
WRC	-	Water Research Commission

LIST OF TABLES

1. INTRODUCTION

Internal corrosion of pipes conveying various types of water results in huge losses of water in South Africa. The situation is clearly unacceptable due to our limited water resources, and ever-increasing demand for clean, safe drinking water. Many municipalities and other authorities have traditionally used uncoated steel pipe to convey water. However, in general, our waters are becoming more corrosive necessitating the use of linings to prevent internal corrosion.

Sulphate reducing bacteria (SRB) play a major role in the corrosion of steel materials conveying potable waters. Most studies are concerned with the effect of the growth of these micro-organisms on the quality of the water in the distribution systems. However, limited information is available on the effect of these bacterial growths on the coating systems of metal pipelines. Coatings and lining systems in steel pipelines and non-metallic piping have been used extensively as a means of corrosion prevention, but no information exists on whether these materials are susceptible to breakdown caused by microbes.

Microbiologically-influenced damage of organic materials may occur by a combination of direct and indirect mechanisms. Microbial growth on pipes coated with organic or inorganic linings may have operational consequences as well as causing damage to the pipes, even if direct or indirect degradation does not occur.

Improving material qualities and corrosion protection technologies in combination with the knowledge and recommendation of the correct material for the correct location, a great number of failure due to incorrect use or specification of coatings/linings can be reduced or even avoided thus minimising microbial attack on the substrates.

The objectives of the project were as follows:

- To determine if different coating/lining systems were susceptible to microbiological attack.
- To determine the effects of SRB in degrading coating/lining systems.
- To recommend measures if MIC proved to be occurring on these coating/lining systems.

2. MATERIALS AND METHODS

2.1 Test Sites

2.1.1 Flow-loop for potable water

- CSIR (Pretoria)

2.1.2 Pontoons for raw water

- Roodeplaat Dam (Pretoria)
- Kleinplaas Dam (Stellenbosch)
- Vaal Dam

2.1.3 Once-through flow system (Stagnant Condition)

- CSIR (Cottesloe)
- Vaal Dam
- Western Transvaal Regional Water Company (Klerksdorp)

2.2 Experimental Procedure

2.2.1 Flow-loop for portable water (Refer K5/381)

Two flow loops were constructed from 50mm diameter polypropylene tubing. The flow loops were approximately 22mm high (equivalent to a six stoney building) and each loop was in excess of 45m long. Potable water was pumped through the loops by two pumps situated at the base of the facility. The one flow loop contained water of ambient temperature whereas the water flowing through the second loop was heated with a geyser. The flow loops were operated on a continuous basis between Monday morning and Friday afternoon and were left full of water over the weekend. In this way, a simulation of actual service conditions was obtained since there were periods of reticulation system when the water was static inside the pipe.

2.2.2 Once-through flow system (Stagnant Condition)

Cold potable water was fed through a Feenix (1 bar) pressure regulator and then through a manifold and polypropylene tanks (volume 501) containing immersed specimens. In order to progress with this research under stagnant conditions i.e. flow rate non-existant water circulation was stopped.

2.2.3 Pontoons in raw-water

Specimens were supported in test racks which were attached onto a floating pontoon. The specimens were exposed at three levels in each dam. The top level was in the splash zone (with half the specimen being immersed), the second level was approximately three meters below the surface and the third level was in the mud or silt zone of the dam.

2.3 Materials

2.3.1 Coating Systems (Raw Water)

Specimens of nominal dimensions 150 x 100 x 3mm were prepared accordingly. In addition to uncoated 3CR12, carbon steel, galvanised and organic coated specimens were exposed. Different surface exposure preparations in the three dams are presented in the progress report of project K5/381. The range of materials tested is listed in Table 1.

2.3.2 Organic linings and non-metallic piping materials (Flow-loop System)

The materials used in the flow-loop system were presented in the final report of project K5/381, submitted to WRC in February 1996.

2.3.3 Once-through flow system (Stagnant Condition)

Some samples consisted of mild steel panels coated with "Copon" Plascon Evans Paints (Tvl) Limited - Copon EP2300. This is a polyamide cured epoxy containing synthetic iron oxide pigment. The epoxy coating cures to a semi-gloss finish and is used extensively as a multicoat lining on pipelines, valves, gates and pumps. Other samples were cut from 50 mm nominal diameter mild steel pipe (approximately 15 cm long) and lined on the inner surface with organic metarials while the outer surcface was left uncoated. The whole pipe sample was imersed in the tanks. The organic coatings used were polyamide cured epoxy, 1 coat solvent free epoxy, plascon hot coat and penguard epoxy.

In addition three grades of cast iron were used namely grey cast iron, malleable cast iron and spheroidal graphite cast iron. The cast iron specimens were prepared and the edges were painted to avoid edge effects.

TABLE I: **Summary of alloys and coatings for dam water exposure**

Base Alloy	Surface Preparation	Metallic Coating	Organic Coating		
			AECI	Chemrite	Plascon
Mild Steel	Abrasive blasted	None	Vinyl Epoxy M.P.E.	Epoxy M.P.E.	Vinyl Epoxy M.P.E.
Mild Steel	Abrasive blasted	Galv.	Vinyl Epoxy	-	Vinyl Epoxy
Mild Steel	Abrasive blasted	Zn Sprayed	Vinyl Epoxy	-	Vinyl Epoxy
Mild Steel	Abrasive blasted	Al Sprayed	Vinyl Epoxy	-	Vinyl Epoxy M.P.E.
3CR12	Pickled/Passivated	None	M.P.E.	-	Vinyl Epoxy M.P.E.
3CR12	Blasted/Passivated	None	Vinyl Epoxy M.P.E.	-	Vinyl Epoxy M.P.E.

M.P.E. = Multi-purpose Epoxy

2.4 Methods

An arrangement was made with DWAF personnel such that they accompanied the CSIR personnel to the different dam sites for each evaluation. Detailed photographic records of the exposed samples after removal from the dams, the flow-loop and once-through flow system (stagnant) were compiled, as well as photographs showing the different stages of experimental investigation.

Samples collected from different sites were kept moist for microbiological sampling and analysis. This was in the form of water samples, corrosion products and swabbing on the internal surfaces of pipes (organic lining) and the external surfaces of the exposed panels with various coating systems. Tests performed on these samples identified the absence/presence of sulphate reducing bacteria (SRB) , total bacterial counts in the water and identification of other bacterial species.

The surfaces of the different generic coatings were visually examined. Notes were made on their appearances. When necessary corrosion products were analysed by Energy Dispersive Spectroscopy (EDS) which is linked to the SEM to identify major corrosive species. This was done for all the test sites.

3. RESULTS

The mild steel panels and the zinc coated samples exposed in raw waters at the three dams showed signs of general corrosion (Figures 1(a) and 1(b)). The top right hand corner of most of the coated panels (which was not coated) also showed preferential corrosion attack. Massive corrosion product was evident and the presence of SRB was positively identified using standard microbiological techniques. The surfaces of these panels after cleaning showed deep pits which are common when microbiological attack has occurred. Visual examination of the galvanised and the zinc coated samples from the dams indicated general corrosion and isolated tubercles on the surface. The removal of the corrosion product showed the local depletion of the protective zinc layer (Figures 2(a) and 2(b)). The zinc coated samples from photos Roodeplaat Dam showed total depletion of the coating with red rust evident (Figure 1b - RZ20). Vinyl-coated galvanised samples from the Vaal Dam showed isolated tubercles and massive tubercles on the edges which resulted in failure of the vinyl coating (Figures 3(a) and 3(b)).

The samples with different non-metallic (i.e. organic) coatings showed no obvious signs of biodegradation in general. Different coatings showed no obvious coating defects or microbial attack except at different parts of the panels. The presence of edge attack as shown in Figures 4(a) and 4(b) (samples RGPV15 and RPE 15) showed the presence of SRB after culturing. In other samples, surface attack was evident and the substrate was exposed to microbial attack (Figure 5(a) - sample RA 15). SRB's were isolated at the superficial tubercles with corrosion product which were black brown in colour. Figure 5(b) shows a surface coating defect (cracking) and isolated blisters which have not penetrated the substrate. These defects seem not to have been favourable for the growth of SRB. Isolated pits were evident on samples RGAV 15, RZ 7 and RGAV 7 after cleaning showing typical morphology of MIC, see Figures 6(a) and 6(b).

The "copon" coated samples exposed under stagnant conditions at Cottesloe showed the absence of SRB on the corrosion products whereas SRB were detected at the other sites. Generally, the coatings still looked good and no obvious biodegradation was evident (Figures 7(a) and 7(b)).

The internally lined piping materials showed blisters and cracking along the weld. The cracking on the coating showed some brown corrosion product (Figure 8(a)) which tested positive for SRB while Figure 8(b) shows the internally lined pipe sample after cleaning.

Copon coated samples exposed under stagnant conditions at Klerksdorp and the Vaal Dam (after 60 months) showed the presence of tubercles (brown corrosion product) along the scribed areas. These tested positive for the presence of SRB. The cleaned samples showed coating defects and blistering as shown in Figures 9(a), 9(b), 10(a) and 10(b).

Figures 11(a) and 11(b) are coated cast-iron samples exposed under stagnant conditions at the Klerksdorp and Vaal Dam sites. These samples showed deteriorated coatings, resulting in massive corrosion product. These proved favourable for SRB growth and corrosion attack.

The EDS analyses of the corrosion products varied from site to site. The brown and black corrosion products from samples showed the presence of sulphur (S) and chloride (Cl) as dominant corrosive elements. Other elements detected were silicon (Si) and calcium (Ca). The results from the Western Transvaal Regional Water Company site showed the presence of more chloride than any other site. (Figures 12(a), 12(b), 12(c), 12(d) and 12(e)).

The results of the microbiological analysis showed that the total bacterial plate counts varied from one site to another as shown in Table II. Roodeplaat Dam showed higher bacterial counts and the poorer quality of the water can be noted on the appearance of the panels removed from the dam (massive algae, calcium carbonate and slimy organisms).

TABLE II:

Site	*TAPC (Cfu/mℓ)	Dominant Bacteria
Roodeplaat Dam	$3,5 \times 10^6$	a) Seratia liquetaciens b) Klebsiella
Kleinplaas Dam	$6,8 \times 10^4$	Pseudomonas cepacia
Vaal Dam	$8,0 \times 10^5$	Pseudomonas aloaligenes

* **TAPC** = Total Aerobic Plate Count

* **Cfu/mℓ** = Colony Forming Units

4. DISCUSSION

After 24 months of exposure at Vaal Dam and 36 months at Roodeplaat and Kleinplaas Dams it was not possible to rank the corrosion performance of the various generic coating systems and non-metallic piping materials based on microbiological corrosion. The water quality of different dams played a major role in influencing failures of generic coating systems (this aspect is discussed in more detail in project K5/381). Although the research was meant to look into microbiological effects there seemed to be a number of factors affecting the coatings such pinholes and lack of adhesion. Such defects can lead to favourable condition for growth of SRB.

Uncoated mild steel panels, zinc coated, galvanised vinyl-coated and galvanised (hot-dipped) panels showed poor corrosion resistance and microbiological corrosion was evident. A breakdown of the coating system be it organic or inorganic would allow rapid localised corrosion by micro-organisms at the breakdown site, as would pinholes or other anomalies. This might spread to the whole surface of the panel affecting the substrate. Blisters were evident on some coatings and most of them were dry at the interface between the coating and the substrate, but some were filled with a clear liquid. Microbiological isolation tests showed that the environment beneath such blisters was not favourable for the growth of SRB.

Deteriorated coating systems also showed mixed biofilms of fungi, actinomycetes and bacteria surrounded by large amounts of slime. Heavy microbial growths, and particularly the slimes were often associated with severe blistering and cracking of the coating/lining. These observations and results support the hypothesis that microorganisms act as detergents on the surface of the coatings by excreting metabolites. Slimes were also found to contain large amounts of metabolites and these may cause considerable deterioration of coating systems.

The mild steel pipes from the flow-loop system showed massive tubercles and their surfaces after cleaning showed signs of shallow pits associated with the SRB. The galvanised pipes showed signs of depleted zinc coating and were progressively corroding. The internally lined pipes showed a better corrosion resistance and no obvious defects caused by microbes. Any signs of microbial presence as proved by the positive result from the SRB isolation test were mainly due to the stagnant environment in the system (flow-loop) and uncoated steel pipes as part of the system.

Stagnant conditions are favourable for the growth of SRB because of the absence of water flow and oxygen. This was shown by the presence of SRB in the corrosion products although the coated/lined samples seemed unaffected. There may be a considerable microbiological activity in the liquid itself or material resulting in the formation of metabolites that will cause deterioration of the coating systems (Ridgeway 1981).

The presence of certain chemical species is indicative or supportive of the diagnosis of microbiological corrosion. When monitoring for microbiological corrosion, one should determine load conditions, including the presence of water, and water quality (pH, salts, CO_2 and sulphate) viable micro-organisms in liquids and especially on metal surfaces, and operational conditions. Ridgeway detected the presence of five major elements from X-Ray energy scans of tubercles on defective coating systems. These were Si, P, S, Ca and Fe with smaller quantities of the elements Zn, Mg, Al, K and Mn. We found similar elements in this study (Ridgeway 1981).

Bacterial populations are dynamic by nature, with continuous cell division and death of cells. They can be expected to occur in a constant state of flux, in terms of numbers, in terms of physiological state of the cells and in terms of their species composition and interact. The results obtained proved that bacterial populations in water are dynamic. They react to external conditions and other environmental factors. In all samples only one or two species attained any form of dominant position, while others held temporary positions. The production of H_2S is also not a concrete proof of the presence of SRB as this could be produced by other bacteria e.g. Pseudomonas etc (Rothwell 1979).

5. CONCLUSIONS

1. SRB play a major role in the corrosion of mild steel, galvanised steel, zinc coated, vinyl-galvanised coated and zinc-vinyl coated exposed in raw dam waters and in potable waters.

2. No obvious biodegradation of non-metallic coating and non-metallic piping materials was observed after 24 months (Vaal Dam) and 36 months (Roodeplaat and Kleinplaas Dam) exposure. The time period may have been insufficient to allow for the detecion of changes/deterioration in the organic materials cuased by the microbes)

3. Coating defects will initiate microbiological attack on the substrate.

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Figure (1a): Mild Steel samples from Vaal Dam.

Figure 1(b): Zinc coated samples from Roodeplaat Dam.

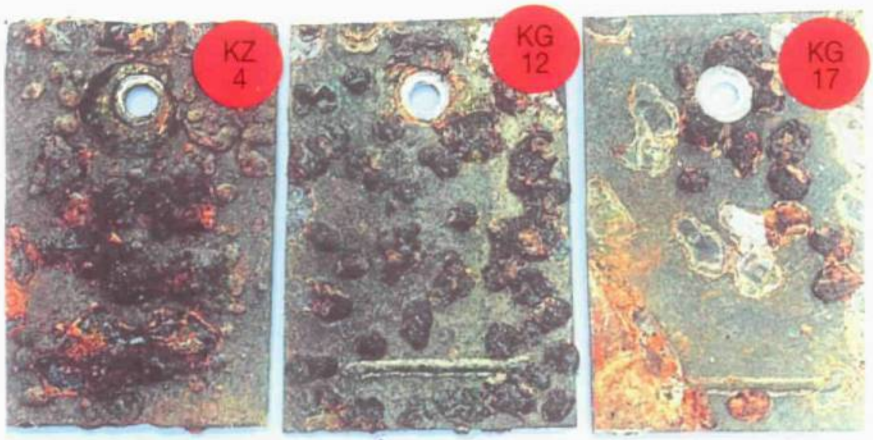

Figure 2(a): Galvanised and Zinc coated samples from Kleinplaas Dam.
Note: Isolated tubercles.

Figure 2(b): Galvanised and Zinc coated samples after cleaning.
Note: Local depletion of zinc coating.

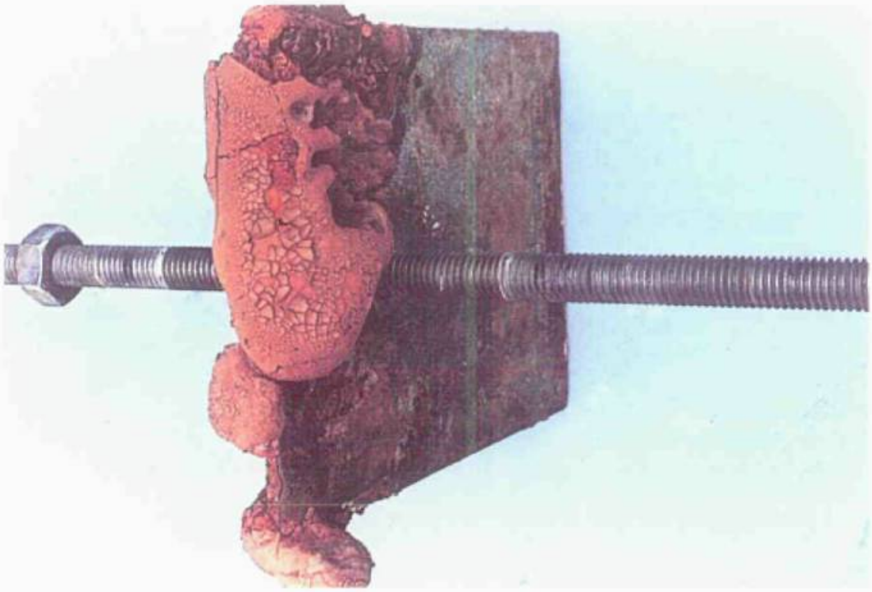

Figure 3(a): Zinc-vinyl coated sample from Vaal Dam.
Note: Massive tubercles along the edges.

Figure 3(b): Coating defects and highly corroded Zinc-vinyl-coated sample from Vaal Dam.

Figure 4(a): Coating defect at the bottom edge (arrowed) **(RGPV 15)**.

Figure 4(b): Failed coating at the edge **(RPE 15).**
Note: Corroded edges (arrowed).

Figure 5(a): Non-metallic coated samples from Roodeplaat. **Note:** Isolated tubercles throughout the surface **(RA 15),**and corrosion product (black/brown).

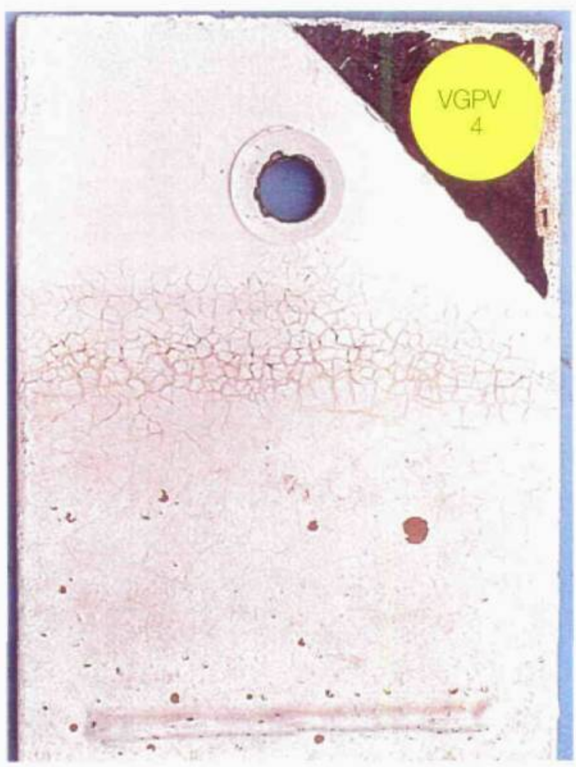

Figure 5(b): Non-metallic coated sample from Vaal Dam.
Note: Cracked coating defect.

Figure 6(a): Galvanised-vinyl-coated sample from Roodeplaat Dam.
Note: Isolated pits and edge effect.

Figure 6(b): Zinc coated **(RZ 7)**and Galvanized-vinyl-coated samples from Roodeplaat Dam. **Note: (RZ7)**zinc coating removed and **(RGAV7)** with isolated pits.

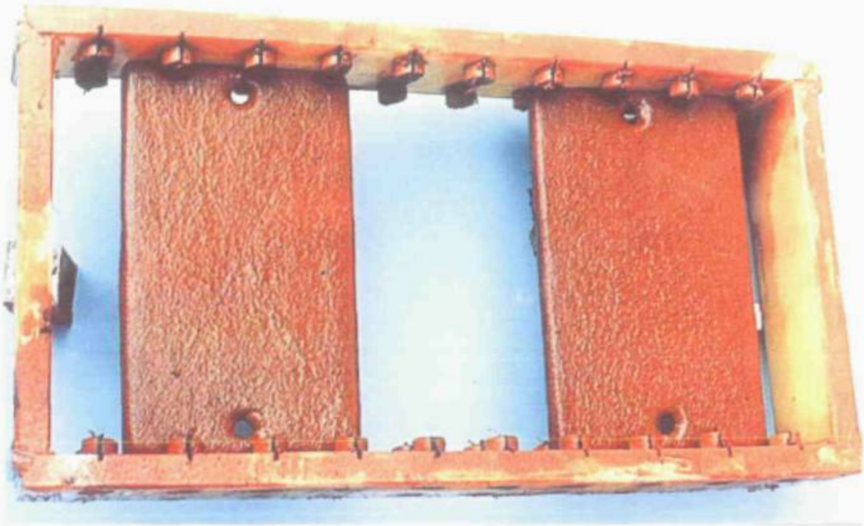

Figure 7(a): Coated samples exposed under stagnant conditions covered with brown surface deposits (Cottesloe).

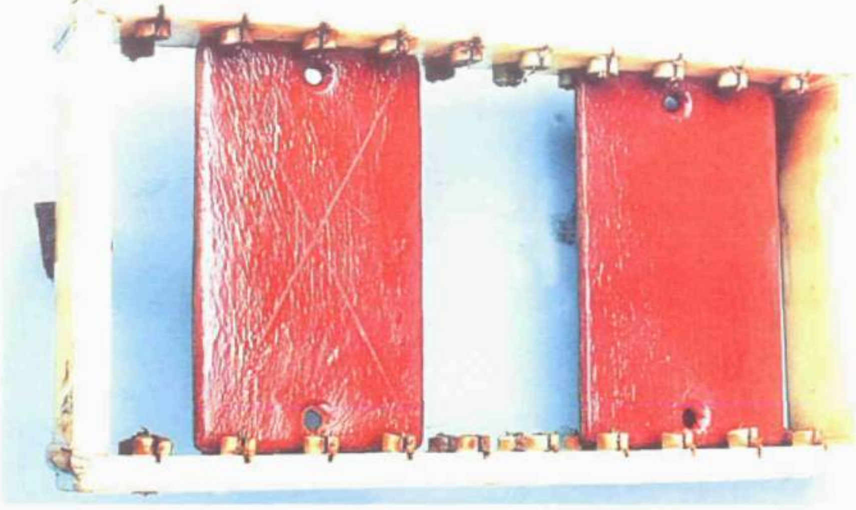

Figure 7(b): Cleaned coated samples exposed under stagnant conditions showing unaffected coating (Cottesloe).

Figure 8(a): Internally lined pipe sample from stagnant condition (Cottesloe)
Note: Cracking along weld.

Figure 8(b): Internally lined pipe sample after cleaning from stagnant condition.

Figure 9(a): Coated samples from the stagnant conditions covered with corrosion product at Western Transvaal Regional Water Company.

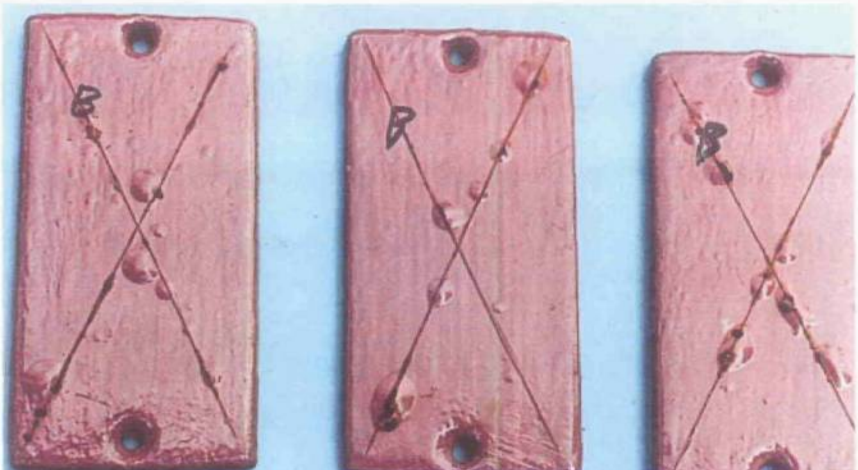

Figure 9(b): Coated samples exposed under stagnant conditions after cleaning at Western Transvaal Regional Water Company.
Note: Blisters where coating failed.

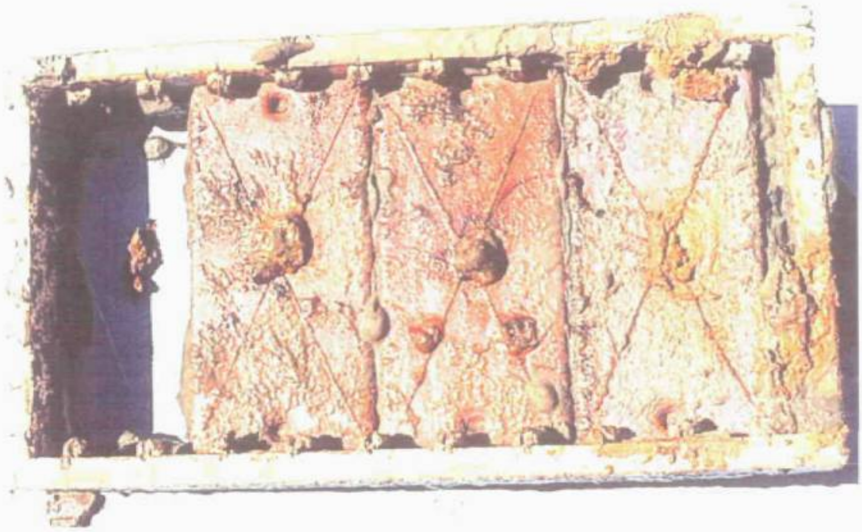

Figure 10(a): Coated samples exposed under stagnant conditions at vaal Dam.
Note: Tubercles at scribed areas.

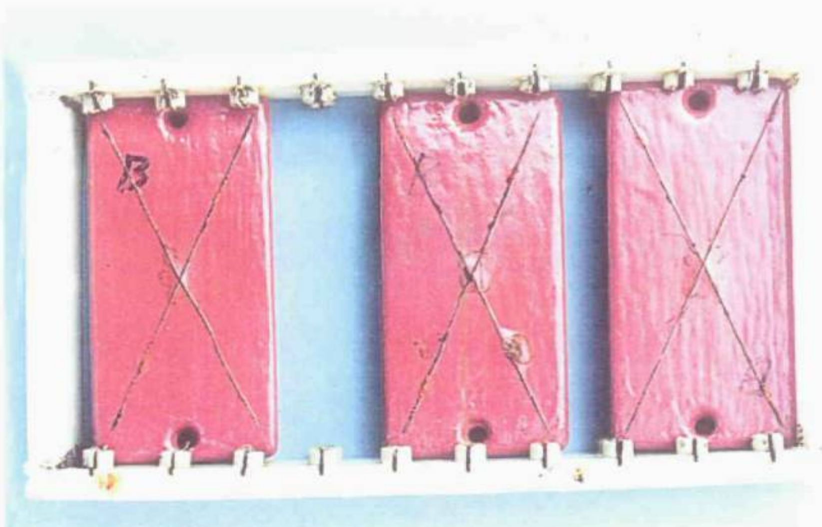

Figure 10(b): Coated samples exposed under stagnant conditions after cleaning at Vaal Dam.
Note: Blistering at scribed areas.

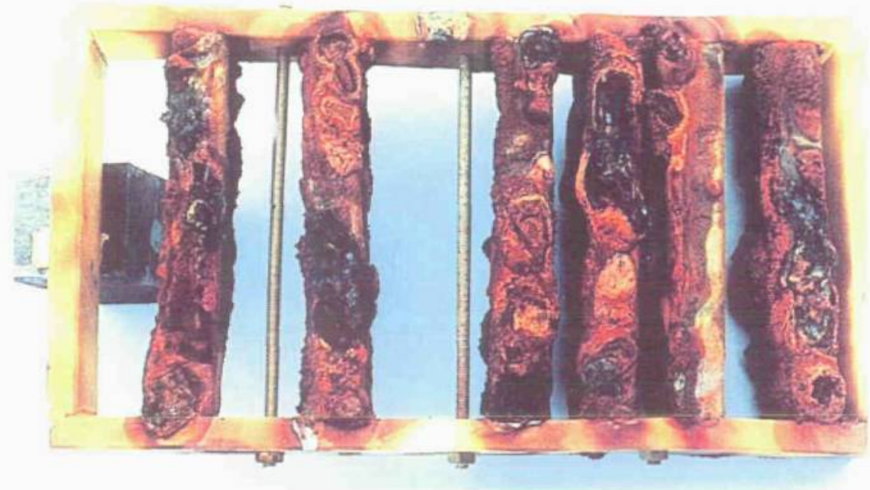

Figure 11(a): Edge coated cast-iron samples exposed under stagnant conditions at Western Transvaal Regional Water Company. **Note:** Massive tubercles and brown/black corrosion product.

Figure 11(b): Edge coated cast-iron samples exposed under stagnant conditions at Vaal Dam. **Note:** Corrosion product (black/brown).

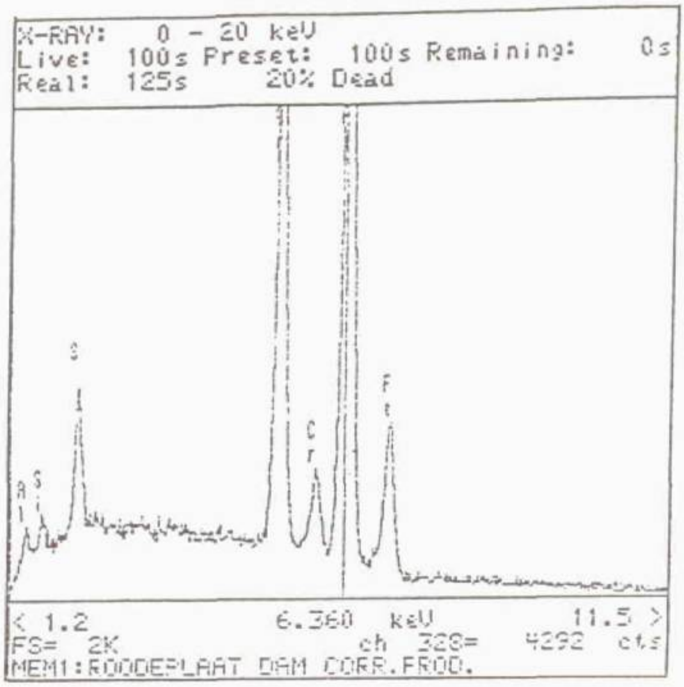

Figure 12(a): EDS analysis of corrosion product (Roodeplaat Dam).

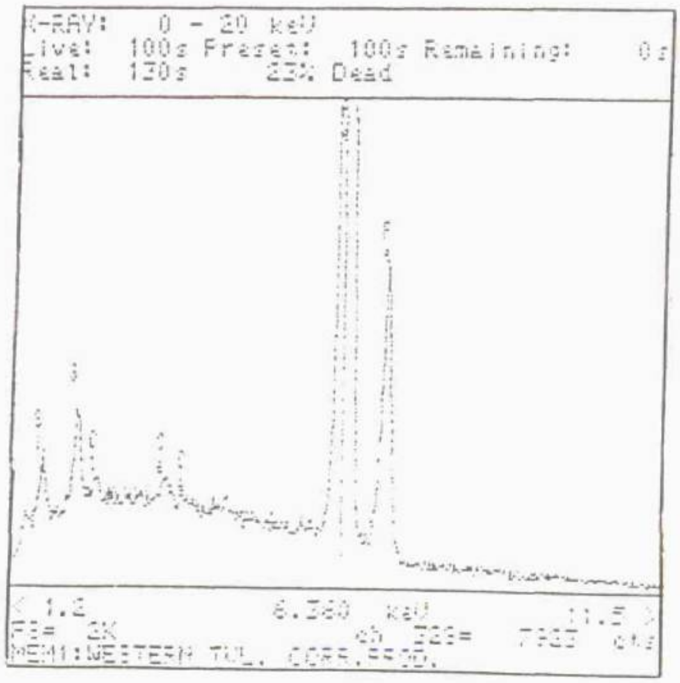

Figure 12(b): EDS analysis of corrosion product (Western Transvaal Regional Water Company).

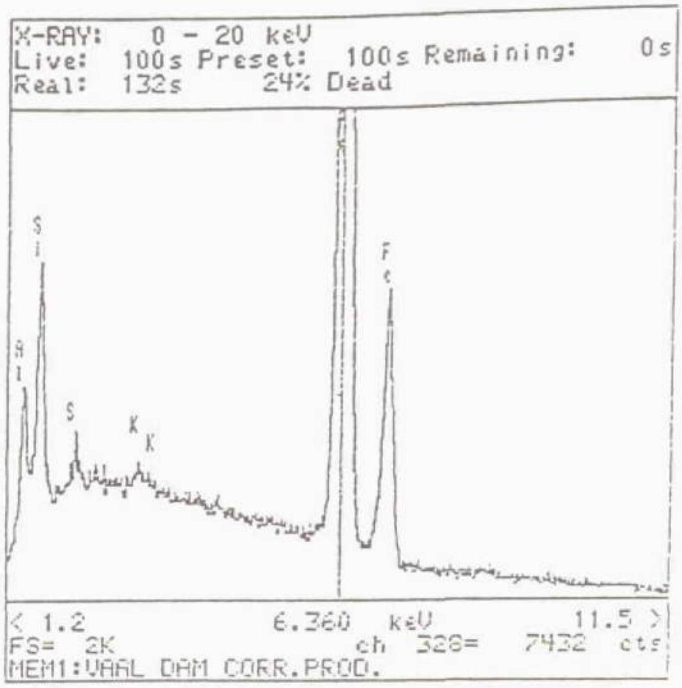

Figure 12(c): EDS analysis of corrosion product (Vaal Dam).

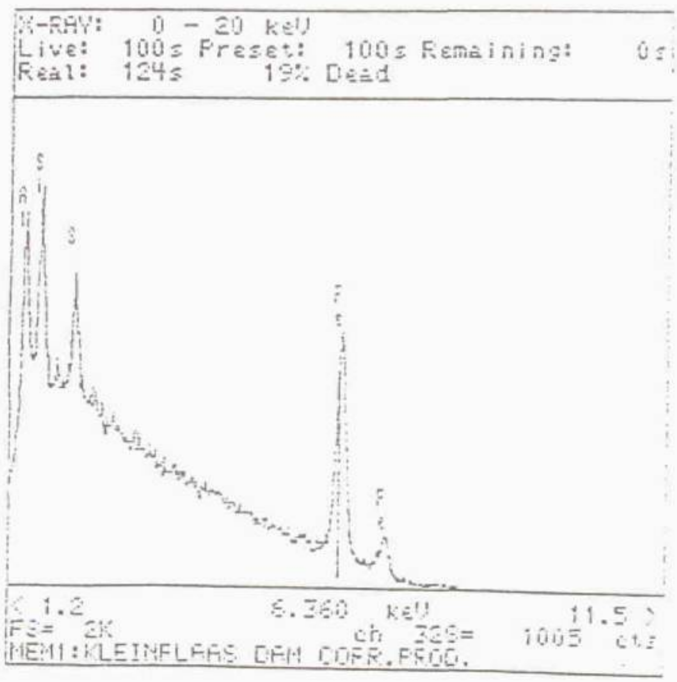

Figure 12(d): EDS analysis of corrosion product (Kleinplaas Dam).

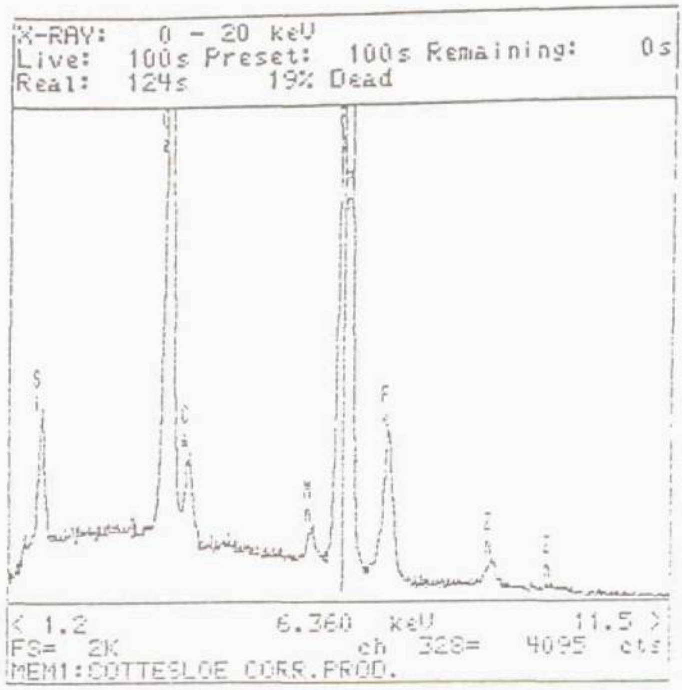

Figure 12(e): EDS analysis of corrosion product (Cottesloe).

APPENDIX 1

Literature Review

LITERATURE REVIEW

MICROBIAL CORROSION OF LININGS AND COATINGS

CONTENTS

1. INTRODUCTION

Protective coatings and linings are unique speciality products which represent the most widely used method of corrosion control. The function of a protective coating or lining is to separate two highly reactive materials i.e. to prevent strongly corrosive industrial fumes, liquids, solids from contacting the reactive underlying substrate of the structure. The coatings or linings act as a barrier to prevent either chemical compounds or corrosion current from contacting the substrate. In general coatings are relatively thin films separating the two reactive materials.

The infection of a painted surface by moulds manifests itself in two ways. The growth may consist of mycelium which consists of fine filaments or coloured spots with spongy structure or a combination of both. Frequently it is difficult to distinguish fungus growth from dirt collection.

The failures due to "vegetation" on paint films are discolouration, which may look like staining or spatting, holing and flaking off, but may occasionally be mistaken for checking. The defects may remain visible after the fungi have died. While discolourations are more obvious on whitish films, mould growth can also be unsightly on red and brown oxide paints.

The activity of bacteria may lead to black discolouration of films and to corrosion of metals. Bacteria need food for their development and multiply only in the water phase. But more moisture and a higher optimum growth temperature (for many bacteria about 37°C) is required. Little damage from bacteria should be experienced at a relative humidity below 70 to 72%.

The species, Desulfovibro desulphuricans, which flourishes only in the absence of oxygen, has the ability to reduce sulphates to sulphides and cause the formation of black sulphide. A slight hydrogen sulphide smell may be noticeable.

2. BIOLOGICAL FAILURE

Mostly in biological failure, the bacteria or fungi merely live on the surface of the coating and do not necessarily affect its resistance. The second type is where the micro-organisms actually use the coating for food and derive their energy from it. Under certain conditions, coatings can be rapidly disintegrated by this type of action. The latter coatings are all organic and usually of the oil type, e.g. alkyds, polyamide epoxies and coatings which use biodegradable plasticizers. In these cases, the portion of the coating which is used for food is the cause of the difficulty, even though the resin portion of the coating might be inert under other circumstances.

3. MECHANISM OF MICROBIOLOGICAL ATTACK

Biodeterioration of other materials point to excreted metabolites on the surface being responsible for their breakdown. Micro-organisms may remove certain ingredients from the film or they may cause other chemical reactions to take place within it. The properties of the coating may be such that it becomes prone to the physical causes of blistering (Funke, 1981; Leidheiser, 1982).
Some of the observations in this study support this hypothesis:

- The coating becomes hard and brittle showing that the micro-organisms have altered the chemical composition of the film, either by leaching out components or by chemical reactions.

- When examined blisters are often dry at the interface between the paint and the metal but are sometimes filled with liquid. Microbiological investigation has shown that this liquid is frequently sterile. In a few cases bacteria were present, commonly in pure culture, and when isolated and used as a test organism did not produce deterioration of the coating.

4. DETERIORATION OF COATINGS BY EXCRETED, CELL-FREE METABOLITES

Stranger-Johannessen[1991] have shown that in paint tests carried out in a humidity chamber, incubated with a fungal spore suspension, zinc chromate prevented microbiological growth and showed no signs of paint failure. In contrast the zinc phosphate composition displayed severe blistering and supported a strong fungal growth.

Other observations indicated that soluble fungal metabolites diffusing from the infected blocks caused the deterioration of the coatings. This suggests that to bring about blistering and loss of adhesion micro-organisms do not need to be in direct contact with the paint surface. Micro-organisms are also known to produce a vast variety of alcohols, glycerine, ketones, acetone, solvents, polysaccharides, enzymes, antibiotics, amino acids, etc. (Costerton & Greesy, 1986: White At. Al. 1986).

5. BIODETERIORATION OF SURFACE COATINGS

Micro-organisms are known to bring about undesirable changes in the properties and structures of some materials. These undesirable changes are normally the result of breakdown of organic molecules into inorganic compounds.

Harris (1964) has carried out a number of investigations into microbiological attack of pipeline coatings. Through field tests he was able to conclude that populations of a number of hydrocarbon-utilising bacteria were higher near to the pipe, but at the same depth. More conclusively he was able to demonstrate, in the laboratory, that hydrocarbon-utilising bacteria were able to grow on certain asphalt enamels in the presence of mineral salt solutions though coal-tar enamels supported only slight growth.

Parkhurst (1967) also carried out growth tests of micro-organisms on pipe coatings and pipe wrappings and her results reinforce those of Harris (1964). Parkhurst (1967)

concludes that, generally, the simpler the composition of the coating or wrapping the less susceptible to microbial attack it becomes.
Harris has found various bacterial and fungus growths beneath coatings; however, it is not certain whether these were due to biodeterioration or mechanical breakdown of the coatings.

Wittenburg (1971) and Quayle (1971) have considered the possible mechanisms of hydrocarbon degradation by various organisms and Zobell (1964) has considered hydrocaborn assimilation by various SRB. The occurrence of fungal growth on polymers and plasticisers has been surveyed by Brown (1946). Stahl and Pessen (1953) have shown attack of plasticizer by Pseudomonas aeruginosa. Most of the earlier investigations drew the conclusion that synthetic polymers alone are not utilised as carbon sources by micro-organisms and that plasticisers, fillers, stabilisers and pigments added during processing are responsible for the unrealibility of some polymers to bacterial and fungal attack. However, the mere presence of growth on the polymeric material does not necessarily indicate that deterioration has occurred or will occur.

6. BLISTERING AND LOSS OF ADHESION CAUSED BY MICRO-ORGANISMS

In the 1970's an investigation was made into the action of micro-organisms on anti-corrosive coatings. A large number of bacteria, actinomycetes and fungi were found on deteriorated coatings in humid air, sea water, fresh water, and tanks. Stranger-Johannessen (1980, 1986) showed that after incubation, failures including loss of adhesion, blistering and flaking could be reproduced. Some paints were also found to be particularly prone to microbiological attack including polyamide, epoxy resin, chlorinated rubber, water and solvent based alkyds and coal-tar paints.

7. ORGANIC MATERIALS

Microbial damage of synthetic materials as well as detrimental effects on the properties and functions of products made of plastics has been recognised for sometime. Based on theoratical considerations as well as practical experience synthetic materials can be:

* degraded directly by micro-organisms (in which these, or their components, act as C^- and N^- sources)

* damaged indirectly by microbial metabolites (degradation of synthetics by acids, bases or enzymes; colour changes due to microbial pigments)

Microbiologically caused damage of synthetic materials may occur also by combination of direct and indirect mechanisms.

Some plasticisers are very sensitive to microbial attack, e.g. esters of phthalic, sebacic, and fatty acids as well as complex compounds. Microbial degradation of ester-based plasticisers can take place by the action of eco-enzymes (esterases). The compounds formed by the splitting of esters, i.e. acids, and alcohols can be utilized as carbon sources. However, plasticisers resistant to microbial attack are known and include glycol derivatives and epoxy-tetrahydrophthalates, and others. Microbial attack on additives may also cause changes in the physical properties of materials (embrittlement and change in bonding, tensile and tearing strengths).

Plastics are often attacked by Pseudomonas aeruginosa, Serratia marcescens as well as Micrococcus, Bacillus and Streptomyces species. The bacterial attack occurs mainly in water and soil.

Details regarding damage of some specific plastics by micro-organisms are given below:

- Polyethylene

  Polyethylene (PE) has a good to very good stability towards microbial degradation depending on its molecular weight: above 10 000 it is especially stable. The surface of PE changes colour under the action of some fungi e.g. Aspergillus oryzae.

- Polypropylene

The sensitivity towards microbial degradation is similar to that of PE. Growth of fungi has been observed but no changes in chemical properties reported.

- Polystyrene

This plastic is known to be very stable. Growth of fungi can be encouraged by tissue surface.

- Polyvinyl chloride

Bacteria and fungi attack acid - PVC only very slightly. Some PVC - powders show fungicidal properties. Colour changes caused by microbial effects are often observed on PVC.

- Polyesters

The stability of polyesters towards microbial attack depends mainly on the acids used i.e. di or polycarboxylides. Phthalic acid esters, economically the most important group, are resistant to microbial degradation.

- Polyurethanes

The resistance of polyurethanes (PU) towards microbial degradation depends on the chemical structure which can vary considerably. PU bases on polyethers are generally more resistant than those on polyesters. The microbial attack occurs mostly by the action of esterases. Microbial degradation of PU-structures occurs successively in the following order: free isocyanides, urea, amide groups, uretharic groups, isocyanic acid.

- Polyamides

These thermoplastic polycondensates contain linear polymer chains spiked at regular distances with carbon amide groups. Information concerning microbial degradation of polyamide tends to be contradictory.

Table III, shows the relative stability of the polymeric materials to microbial attack.

TABLE III: RELATIVE STABILITY OF POLYMERIC MATERIALS TO MICROBIAL ATTACK (Dolezel, 1978)

Materials	Stability
Polyethylene	1 - 2
Polypropylene	1 - 2
PVC-softeners	2 - 3
Vinyl chloride-vinyl acetate	1 - 3
copolymers	1
Polyvinyfluoride	1
Polytrifuorchlorethelene	1
Polytetrafuorethylene	3
Polyvinyl alcohol	1
Polystyrene	1 - 2
Polymethylmethacrylate	1 - 2
Polyamides	3
Polyurethanes	1
Epoxy resins	1 - 2
Polyesters (glass fibre reinforced)	1 - 3
Phenol-formaldehyde resins	1 - 3
Urea-formaldehyde resins	2 - 3
Melamine-formaldehyde resins	2 - 3
Cellulose derivatives	2 - 3
Natural rubber	2 - 3
Butadiene-styrene rubber	2 - 3
Butadiene-acrylonitrile rubber	1
Butyl rubber	1 - 2
Polychloroprene rubber	2 - 3
Polysulphide rubber	

N.B 1 = very stable
2 = medium stable
3 = less stable

8. RESISTANCE TO BACTERIA AND FUNGUS

There are two ways in which bacteria and fungi can affect a coating. First, where they settle on any dirt that has accumulated on the surface of a coating, they tend to live and thrive. This increases dirt buildup and dramatically detracts from the appearance of the coating. They also attack the coating itself and form colonies or areas which not only become unsightly, but which may actually be penetrated by corrosive conditions. Almost everyone is familiar with the dark, blotchy fungus growth on some coatings. These fungus colonies are living on one or more of the coating ingredients and can eventually lead to premature coating breakdown. The susceptibility of coatings to such biological activity can often be offset by the addition of bactericides and fungicides to the coating itself during manufacture.

Under some conditions, catastrophic coating failures can occur because of biological activity. One such failure occurred when a polyamide coating was applied to a concrete sewer manhole. Polyamide epoxies have good resistance to water and good adhesion to concrete. In this case however, the coating is affected within nine months to a year due to bacterial action. An amide cured epoxy, however was unaffected by these factors. The difference is that the polyamide part of the molecule is vulnerable to biological attack, therefore making polyamide coatings unsatisfactory for severe conditions.

Underground conditions can also lead to coating breakdown due to bacteria attack. If a coating contains organic sulfide, they are often subject to breakdown by SRB. Sulphur cements were used to join sewer pipe until it was discovered that sulphur - active bacteria used the cements for food with the development of additional quantities of H_2S gas.

Extensive testing was done in this area during World War II to develop coatings that could be used in tropical climates where biological activity created some serious problems. It was found that coatings for use in any area suspected of fungus or bacterial growth should be formulated with resins, pigments, plasticizes, etc., which in themselves cannot be used by biological organisms for food.

9. SELECTION OF RESISTANT MATERIALS

Using corrosion-resistant materials is another method of preventing MIC. Identifying suitable materials includes researching the performance of materials used in similar environments and, as necessary, in-situ testing of candidate materials. The influence of the methods of fabrication, installation, and testing on the potential for MIC in the completed system must also be considered. Resistant material alternatives include protective linings, non-metallics, or upgraded metallic alloys.

Protective organic linings, such as coal-tars or asphaltic bitumen-based materials, applied to the interiors of carbon steel piping will prevent or retard corrosion, including MIC. However, the performance of these lining materials depends on their composition and long-term durability as well as pinhole-free application.

The pigments and resins of some organic coating systems can actually serve as food source for some bacteria, enhancing their growth. Some coating systems incorporate fillers or biocides that increase resistance to such micro-organisms (Dittmer, 1975) when long-term durability is a concern. A breakdown of the coating system would allow rapid localized corrosion by any micro-organisms at the breakdown site, as would pinholes or other anomalies (Stahl, 1953).

While MIC will degrade some plastics and plastic composites, several are reported to be resistant to MIC and could be used to prevent MIC in piping systems (Dittmer, 1975). In general, increased resistance for plastic products is achieved with increased polymer chain cross-linking. One plastic material reported to be "unaffected by bacteria or fungi or does not promote or support algae or bacteric growth" is extra-high molecular weight, high-density polyethyle (EHMW - HDPE). Early and unexpected failures of anti-corrosive organic coatings often occur and in many cases there is no obvious reason for the failure.

Harris (1966) described failures on underground oil, gas pipes in different soils and under different climatic conditions. Blistering and loss of adhesion occurred and water was found beneath the coating in which micro-organisms from the surrounding soils were present.

10. PREVENTION OF COATING DETERIORATION WITH ANTIMICROBIAL ADDITIVES

When biocidal anti-corrosive paints are in contact with liquids they may prohibit slime formation reducing the risk of metabolites coming into contact with the surface. There is considerable microbiological activity in the liquid itself sufficient metabolites may be present in sufficient quantity and cause deterioration even on broadly protected paints.

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