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# Corrosion and cleaning of offshore deluge systems

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# Corrosion and cleaning of offshore deluge systems

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This report presents the findings of a literature review of the issues surrounding the corrosion of offshore firewater deluge systems as well as inspection and cleaning methodologies which may be used. Contributions of case studies from offshore operators is included, detailing their experiences of corrosion of deluge systems and cleaning methods and maintenance schedules.

The report also includes the findings from corrosion tests performed at HSL on carbon steel coupons immersed in proprietary chemicals used to clean deluge systems and compares these results to corrosion tests carried out in sea water.

The findings of the report were that:

- There was no evidence that cleaning mechanically sound deluge pipework would result in damage to that pipework.
- There was no evidence to suggest that any one cleaning method is more suitable than another.
- Corrosion observed in deluge systems is due to long term exposure to seawater following wet testing.
- Where practical, flushing deluge piping with potable water after wet testing is recommended to removed pooled sea water and salt deposits.

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# EXECUTIVE SUMMARY

## Objectives

This project had two main objectives. The first was to conduct a review of the available literature regarding deluge systems. This was also intended to incorporate case studies supplied by operators covering their experience of corrosion of deluge systems and the methods they use to maintain them.

The second objective was to conduct electrochemical tests on corrosion coupons manufactured from carbon steel (the most common material used to manufacture deluge system pipework). The testing was to be carried out in seawater and in proprietary chemicals used to clean deluge systems.

## Main Findings

No evidence has been found, either during corrosion testing or in the literature review, to suggest that cleaning chemicals will cause perforation of otherwise sound pipes.

Corrosion testing found that the total metal loss for a carbon steel corrosion coupon immersed in proprietary cleaning chemicals over a 24 hour period was in the region of 10 microns. This would be unlikely to cause perforation of a carbon steel pipe in a deluge system unless it was already severely wasted due to prior corrosion.

These results were backed up by a review of the available literature available pertaining to the chemical cleaning and corrosion of materials used to manufacture deluge systems.

Corrosion testing was carried out using coupons which were fully immersed in artificial seawater. The results showed that if a coupon was fully immersed, the total metal loss over a one year period could be of the order of 50 microns. Conditions inside deluge pipes are likely to be more aggressive than the test conditions due to bioorganisms being present in seawater, but not present in the artificial seawater used for testing. Additionally the fact that the pipe surfaces are not fully immersed, but more often subject to a moist, humid environment comprising both wetting and drying and thermal cycling makes the conditions inside deluge piping likely to be more aggressive than the test conditions.

## Recommendations

If pipes are mechanically sound, then they should be cleaned using any suitable means. There is no evidence to suggest any one cleaning method is more suitable than another.

Corrosion observed in deluge systems is due to long term exposure to seawater pooling in pipes following wet testing.

Where practical, flushing deluge pipes with potable water after wet testing is recommended to remove seawater pools and salt deposits.

# 1 INTRODUCTION

## 1.1 BACKGROUND

Offshore fire protection deluge systems are critical components of the fire protection measures on offshore installations. Lord Cullen's report [1] on the Piper Alpha disaster identified corrosion of the firewater deluge system as a significant failing, leading to blocked nozzles and pipework. HSE has identified that instances of blocked nozzles are still high, with corrosion products within the systems being the primary cause. The cleaning of carbon steel deluge system pipework, required to maintain it in a fit for purpose state, has been raised by some operators as a cause for concern. Some operators believe there is the potential for chemical treatments to cause corrosion of the systems they are designed to treat.

A previous study carried out for HSE in 2003 [2], which investigated the materials used for deluge systems, made some suggestions for design improvements which could be made to reduce the incidence of nozzle blockages, however the frequency of nozzle blockage has been report by some operators to be very high. Cleaning was not addressed in that study, and testing only briefly discussed.

## 1.2 AIMS AND OBJECTIVES

The purpose of this investigation was:

1. To review the available literature regarding internal corrosion and cleaning of deluge systems and to gather information about current cleaning practices from cleaning service providers.

2. To gather information from the operators/asset owners relating to their experiences with the integrity of deluge systems.

3. To carry out electrochemical tests on samples of typical deluge pipe material to assess their corrosion rates when exposed to artificial seawater and cleaning chemicals, prepared in a representative way.

It is intended that the information gathered will be used to clarify the issues surrounding the corrosion of deluge systems and assist operators in making decisions about cleaning regimes and processes in order to adequately maintain these safety critical systems.

The literature review presented here was based on literature available in 2012.

# 2 LITERATURE REVIEW

## 2.1 DELUGE SYSTEMS OVERVIEW

Water deluge systems are employed on offshore installations as a means of active fire protection in hydrocarbon processing areas. They are used to minimise the consequences of fire or explosion. Regulation 13 of the Offshore Installations (Prevention of Fire and Explosion, and Emergency Response) Regulations 1995[3], requires that measures are taken to protect personnel from the effects of fire and explosion on an offshore installation. These measures are explained further in the Approved Code of Practice and Guidance document (ACOP) relating to these regulations, published by HSE [4]. According to the ACOP the term 'measures' includes active fire protection such as deluge systems. The objective of active systems should be to deliver the required quantities of the fire-fighting media within the required time to the required locations.

According to ISO 13702:1999 [5] they are intended to control fires and limit their escalation; to reduce the effects of a fire to allow personnel to either undertake emergency response activities or evacuate (Evacuation, Escape and Rescue – EER); to extinguish the fire where it is considered safe to do so; and to limit damage to structures and equipment. This standard also sets out the requirements to ensure that these systems are maintained in a state such that they are fit for purpose. Such maintenance involves inspection, testing and cleaning.

## 2.2 DELUGE SYSTEM DESIGN

Deluge systems may be manual, automatic or both depending on their location, and the size and type of fire expected. They are attached to the firewater ring main and water delivered by the firewater pump system. The pressure flow rate and pattern must be sufficient for the anticipated requirements in the particular area that the system is intended to protect. The water used in these systems is generally untreated seawater, or chlorine treated seawater dosed at the inlet to the seawater pump, without corrosion inhibitor additions.

Fixed deluge systems can protect in different ways, with the four broad types defined in ISO 13702 as:

- Area protection
- Equipment protection
- Structural protection
- Water curtains

The design of deluge systems is detailed in NFPA 15 'Standard for Water Spray Fixed Systems for Fire Protection'[5]. Systems are designed to deliver sufficient pressure and flow at the nozzles in order to perform one of the four tasks listed above effectively. Nozzle size, location and orientation are selected as part of this design. The systems are designed not only to provide sufficient water, but also to do so in a set time, determined by the fire analysis of each area to be protected.

ISO 13702 states that "*the sizes of nozzle and associated pipework should be selected to avoid blockage caused by corrosion products or build up of salt deposits after testing*". It also goes on to suggest that systems should be designed to be self-draining. It is therefore important to avoid dead legs or low points in the system or to ensure that these can be drained after testing. The nozzles may be fitted with strainers, however if these are considered by the operators to be a contributing factor to blockage, these may have been removed. Nozzles are available which have been designed to minimise blockage, however this does not remove the need for maintenance to avoid perforation of the pipes due to corrosion.

Deluge systems are generally operated as dry systems, in that water is only introduced to the pipework downstream of the deluge valve when the system is operated, either for testing or in the event of a fire. After this testing, however, the water discharged through the system results in the walls of the pipes remaining wet, giving rise to a corrosion risk due to the moist environment, which may also result in pooling in the bottom of the pipes.

For this reason ISO 13702 states that: "*means should be provided to enable the testing of deluge valve performance without discharging firewater through the pipework and nozzles.*"

## 2.3 CORROSION AND SCALING ISSUES

It has been observed that many offshore operators have found on testing of their deluge systems that the nozzles have become blocked, causing inadequate flow rate and distorted spray patterns. The major cause of blockages had been found to be corrosion products, however, marine organisms and scaling may also contribute.

Deluge systems use seawater, which is more corrosive than potable water due to the dissolved solids which it contains [7,8]. The most aggressive ionic species in seawater is generally considered to be the chloride ion, however sulphates play an important part when sulphate reducing bacteria (SRB) are present.

Deluge systems are normally kept 'dry' in that there is no water in the system until it operates. After testing of the system, however, the pipe walls will be wet, and there may also be pooling in the bottom of the pipes. With no airflow within the pipes, this moisture will remain, and with the presence of a large air space in the pipes, relative to the volume of water, ample oxygen will be present to create corrosive conditions. Additionally, if thermal cycling occurs then evaporation and condensation in the pipes will enhance local corrosion rates.

It is well documented that calcium and bicarbonate ions can cause scale build up within the pipes, and whilst this may potentially offer some protection from corrosion, reduces the cross-sectional area of the pipes leading to reduced flow rate. Scales can also give rise to locally aggressive conditions beneath them if they are not well adhered, leading to under deposit corrosion. Localised under deposit corrosion can occur in both carbon steel and stainless steels. In normally passive materials such as stainless steels, this can lead to pitting corrosion.

Microbial films will form within hours on both metallic and non-metallic surfaces when left in stagnant untreated seawater [9]. These will not only foul pipes in their own right, but can become sites for fouling by larger marine organisms, e.g. mussels. The films caused by these bacteria can create a locally aggressive environment beneath them due to differential aeration or pH, production of aggressive compounds such as organic acids, deposits of conducting metal compounds such as sulphides creating cathodic deposits and removal of inhibitors from the metal surface (commonly nitrate inhibitors) resulting in under deposit corrosion [10]. If SRB are present then these can be particularly damaging, and if they are present at the base of a biofilm can be protected by it from biocide treatments. SRB can result in very aggressive pitting of carbon steel due to the formation of a conductive iron sulphide film which creates a local cathode, setting up local galvanic cells. In stainless steels the presence of SRBs in seawater results in microbial assisted chloride induced pitting. Locally acidic conditions develop under the film, resulting in very aggressive pitting rates.

In copper-nickel alloys, the sulfides released by SRBs are known to interfere with protective film formation resulting in pitting [11]. Clean seawater must be used for first use to ensure stable film formation.

Macro and microbiological deposits are usually controlled by either periodic or continuous chemical treatment in production pipework. Physical means, such as strainers are used to remove large-scale organisms such as mussels and other shellfish. Commonly used biocides are oxidising biocides such as chlorine (by electrolytic chlorine generation). Chlorination is efficient, cheap and relatively environmentally friendly, however it can be difficult to achieve a balance between biological control and increased corrosion rates. Stott [12] reports that it is very common to find that biocides are under or overdosed, both of which can result in increased corrosion rates. Other biocide treatment packages are available, the purpose of which is only to control the bacteria, minimising its effects, not to remove it. The only effective way to prevent biological films forming appears to be by regular mechanical cleaning, preventing them from becoming established. No mention was made of the effectiveness of chemical cleaning for removal of biological films.

## 2.4 MATERIALS

The design of deluge systems is governed by NFPA 15, which lists suitable materials for use in the systems for both pipework and nozzles. These materials are: carbon steel, either uncoated or hot dipped zinc coated (galvanised); stainless steel; copper or copper alloy. No suggestion is made of the sort of materials which should be used for deluge systems in ISO 13702 or in the Offshore Installations Regulations, 1995. The Offshore Installation Regulations 1980 [13] (a redraft of the earlier SI 611) state simply that materials used for deluge systems should either be corrosion resistant or suitably protected from corrosion and that the systems must still be functional in the event of an emergency (i.e. fire resistant). The study conducted for HSE in 2003 [2] found that the two main types of pipework used for offshore deluge system was lined or galvanised mild steel or cupronickel. Information gained in the current survey paints a more complex picture, with systems comprising mixed materials as replacement of corroded sections takes place. In these instances, in order to reduce the risk of galvanic corrosion, insulating spools are used. These are typically sections of either a suitable non-metallic pipe or metallic pipe with a thick coating on them, placed between the dissimilar metal pipework [14]. The spools may be glass flake lined, powder coated or rubber lined [15].

Composite pipes are available and have been used in the Norwegian North sea sector [16], but it is not known how widespread their use is in United Kingdom (UK) installations. New products such as elastomer pipes are also now available, and have been used on installations off western Australia and in the North Sea [17].

### 2.4.1 Carbon steel

Carbon steel has been widely used for the construction of offshore deluge systems pipework. Carbon steel, however, corrodes readily in seawater, with typical corrosion rates of approximately 0.13 mm per year when fully submerged in quiescent sea water [19]. Wetting and drying cycles increase corrosion rates and the likelihood of pitting, with corrosion rates in these circumstances an order of magnitude higher than general corrosion rates.

Hot dipped galvanised steel or steel protected by other suitable coatings should be used, in order to provide corrosion resistance. Fusion bonded epoxy coated carbon steel pipe is also available and offered by one deluge system manufacturer [18]. Galvanised pipe however has only a limited lifespan after which the zinc layer is consumed and the pipe is no longer corrosion resistant. This will occur during the intended lifespan of the deluge systems and should be taken into account in planning the maintenance schedule.

Lined or coated carbon steel pipe may have a lower corrosion allowance, permitting the use of thinner walled pipe with the advantage of weight savings and lower costs. Coatings, however, can be easily damaged during installations and can’t be guaranteed to be holiday free, both of which may give rise to pitting corrosion. Joined pipe sections will need to be coated in situ to prevent crevice corrosion at the joints.

### 2.4.2 Corrosion resistant alloys

If corrosion resistant materials are selected at the design stage, then long term cost benefits may be realised during the lifetime of the system. Due to the greater cost of these materials it would be unlikely to be economical to fully replace a carbon steel system already installed unless a cost-benefit analysis shows otherwise. Use of these alloys as replacement sections in an existing carbon steel system does occur, as discussed above.

Stainless steel (316) is resistant to uniform corrosion but susceptible to pitting in seawater, and to crevice corrosion [19].

Copper-nickel alloys such Cupro-nickel 90/10 have good resistance to aqueous chloride ions in untreated seawater and have good crevice corrosion resistance [19,20] though their resistance to biofouling may be over-exaggerated. Whilst copper is toxic to shellfish, the effects are much less pronounced in bacteria [21]. They can suffer pitting due to sulphide production under films of SRB, particularly new pipework exposed in the first few weeks of operation. It can take several weeks for the protective oxide film to form in an aqueous environment, and the presence of sulphides in the environment interferes with this film formation, resulting in pit formation. Once affected, the alloy may never form a stable oxide film, with sulphides remaining in the film, leaving the alloy susceptible to pitting [11].

Titanium piping has been used in the Norwegian sector since 1993, and has recently been used in the Swedish sector [22]. The formation of a titanium dioxide protective layer on its surface makes them effectively immune to pitting and crevice corrosion in seawater. Localised corrosion has not been found to occur under biofilms making it very suitable for seawater service. Published corrosion rates are typically of the order of nanometers per year, therefore it is likely that no corrosion allowance is necessary. According to Shrier [23], titanium may be cathodically polarised if coupled to anodic materials such as steel, which may give rise to hydriding; the formation of brittle $TiH_2$ needles, reducing its ductility and fracture toughness.

### 2.4.3 Other materials

The most common forms of composite pipes used offshore are glass fibre reinforced polymer (GRP) pipes, such as glass fibre reinforced epoxy (GRE, manufactured to meet fire resistance standards [24]. These options have the advantage of being corrosion resistant, easier to handle with low material and installation costs, coupled with weight savings. They are not immune to biofouling, with the possibility of degradation due to secretions from marine organisms.

Synthetic elastomeric pipes are available [25], claiming 20 years service. No details of the materials or reinforcement used were found during this reveiw, but the connectors used are manufactured from titanium. The cost is claimed, at the time of carrying out this survey, to be lower than installing cupro-nickel pipes and the manufacturer's publications [26] claim resistance to seawater, sediments and a maintenance free service life of up to 30 years.

## 2.5 MAINTENANCE, INSPECTION AND TESTING

ISO 13702 states that firewater should be treated to prevent growth of marine organisms which may impair performance of pumps; this will also benefit the firewater ring main and deluge system. As mentioned in section 2.3 of this report, dosing of the water with chlorine is the most commonly used method, along with mesh strainers to remove shellfish. The use of copper and copper alloys reduces the likelihood of shellfish attachment.

The Offshore Installations regulations, 1995, states in Regulation 19 that all plant on offshore installations must be maintained in an efficient state, in efficient working order and in good repair, and that examinations should be carried out, using suitable techniques, including testing where appropriate—

(a) to assess its suitability for the purpose for which it is used or provided;

(b) to assess its actual condition; and

(c) to determine any remedial measures that should be taken.

It is important to not only maintain the deluge systems pipework, but also the deluge valves and pumps and the firewater ring main and pumps, as all of these could introduce corrosion products and fouling into the deluge systems.

The Offshore Installations Regulations, 1980, suggested a scope of examinations which included ensuring all piping and nozzles downstream of the control valve are clear. There are two ways to achieve this goal; visual examination of the pipe internals and wet testing.

### 2.5.1 Visual Examination

The only practical means for internal visual examination of deluge pipes is boroscopy, preferably accessing the pipe internals via nozzle attachment points to avoid breaking joints. This can only be carried out at accessible points on the deluge system, and so cannot be comprehensive and thorough and must only be regarded as indicative of the general condition of the pipe.

### 2.5.2 Testing

NFPA 25 [27] requires that deluge systems be tested as a minimum on a yearly basis at full flow rate to test sprinkler patterns, water volumes and delivery rates. This testing includes inspection of the nozzles and removal, inspection and cleaning of nozzles strainers. Mainline strainers should be removed and inspected every 5 years. Section 10.2.1.4 does allow other maintenance intervals to be set dependant on the results of visual inspection and operational tests. HSE Offshore Information Sheet, OIS/1/2010 [28] states that the currently accepted criteria in the UK offshore industry is a failure criterion of 5% nozzle blockage. Several blocked nozzles on one leg of an area deluge is also a failure criterion.

Wet testing is not popular with operators, as it requires that all equipment which may be affected by the water spray be protected. This can be a time consuming process, and if not performed efficiently can give rise to other corrosion issues such as corrosion under insulation as well as affecting electrical equipment.

Full system wet tests are generally carried out with seawater, some of which will remain within the pipe after testing. This residual water can remain causing internal corrosion and biological contamination thus giving rise to nozzle blockages on subsequent tests. In ideal circumstances, the system would be tested with fresh water rather than seawater, however on large installations this is not likely to be possible. In this event it would be prudent to ensure that the system is flushed with fresh water after testing to remove salt water.

Dry testing has been proposed as a replacement for the wet testing regime with inspection intervals reduced to minimise the corrosion risks associated with wet testing [27]. This process would take the form of reassessing the system against its original design, visually inspecting it, performing a wet test and then cleaning and inhibiting the system after which visual inspection alone would be performed on an annual basis. Wet testing would take place at increased intervals, after which it would be treated with inhibitor and then visually examined. This technique may be suitable for newer systems or those which have demonstrated few problems in the past. It may not be suitable for older systems or those with a history of poor corrosion performance. A dry testing regime would have to be well designed and implemented so that critical areas of the system are examined.

Analysis of the results of testing may prove useful in terms of establishing where blockages occur so that reoccurring blockages can be investigated, allowing the cause to be established and addressed. Analysis of scales or corrosion product removed during testing or cleaning may also yield useful information about the measures that need to be taken to prevent reoccurrence, such as water treatment to control marine organism growth.

## 2.6 CLEANING METHODS

### 2.6.1 Chemical cleaning

Circulation cleaning is the most common method of chemical cleaning used, as it allows fresh chemicals to reach all surfaces in the systems being cleaned. Flow rate and temperature are controlled to achieve optimum cleaning efficiency. Fill and soak cleaning, followed by flushing is generally only used where high fouling of the pipes has occurred. The two systems are sometimes used alternately [30]. Chemical cleaning usually involves the use of a mixture of different chemicals in order to achieve efficient cleaning and to reduce corrosion. A typical chemical cleaning solution can contain a proprietary mix of acids, bases, complexing agents, oxdising agent, reducing agents, organic solvents, corrosion inhibitors and surfactants.

Corrosion deposits are usually removed with acids, either inorganic (mineral) or organic. Strong acids are hazardous to handle and can be difficult to control for cleaning purposes. A current provider of chemical cleaning uses an organic acid based cleaning solution. This is preferable to using inorganic acids as it is a ‘weak’ acid and so has lower safety and environmental risks associated with its handling (it is biodegradable). All cleaning acids must be inhibited before use to minimise attack of the base metal; organic acids are also often used with complexing agents, either chelants or sequestrants, in order to complex the metallic ions into water soluble forms. These acids are usually circulated at a relatively low flow rate; too high a flow rate can remove passive films resulting in erosion of the base metal in the case of passivating metals or alloys. According to McCoy [31], citric acid is the most suitable acid for cleaning metal pipework made from carbon steel, stainless steel, cupro-nickel and titanium. It is not suitable for use on zinc-galvanised pipes.

Corrosion inhibitors added to the acids to protect the base metal work by either interfering with the corrosion reactions at the metal surface, or by forming a physical barrier to reactants. These are usually mixtures of organic compounds and can be classed as anodic, cathodic or general inhibitors.

Alkalis may be used to degrease the surfaces prior to scale removal and may be used after descaling to neutralize any acidic residues left on the surfaces and to passivate surfaces.

As discussed in section 2.3, biocide treatments would generally be applied continuously to the fire water, however unless carefully dosed, this may not be effective. Other chemicals applied during the cleaning process would be a mixture of higher concentrations of organic non-oxidising biocides with surfactants to aid their penetration of the biofilm. Unless these treatments are performed regularly, however, biofilms can easily re-establish in favourable conditions (stagnant seawater at ambient temperatures).

Advantages of chemical cleaning are that the system does not require joints to be broken in order to clean it. The cleaning process can take place without any dismantling of the pipework. Many chemical treatments (degreasing, descaling, biocide treatment and passivation) can be combined in one package.

Disadvantages of chemical cleaning is that the entire deluge system will be offline during the cleaning process, and the chemicals used can be hazardous and require careful handling and disposal. Where systems contain mixed materials or have internal coatings, chemicals must be selected to avoid attack of the materials or coatings.

### 2.6.2 Mechanical cleaning

**Abrasive cleaning** has been used for cleaning industrial pipework for many years. For particularly hard scale, rotating cutters have been used, as has blasting using abrasive particles such as sand or steel shot. Neither of these techniques appears to be used for cleaning deluge pipes at the time of writing. One mechanical method of cleaning for deluge systems which is currently used is a rotating brush system.

All of these methods require the removal of deposits after cleaning, so the system has to be flushed with water at some point after the mechanical process.

**High pressure water jetting** is a common technique for cleaning pipework, however does not appear to be used for cleaning deluge systems. This may be because the layout of the deluge pipework poses difficulties in passing a pressurised hose through the elbows of the system.

The advantages of mechanical cleaning are that it avoids the use of strong acids or alkalis, reducing risks to the personnel performing the cleaning. Mechanical cleaning can be quicker than chemical cleaning, and in the case of the dry techniques can be performed such that only the part of the system being cleaned is out of action. Temporary bypass connections can be made, allowing the deluge system to remain live during the cleaning process. According to one source [31] regular mechanical cleaning appears to be the most efficient way of controlling biofilms, however the intervals at which it should be carried out are not suggested, and this is likely to vary depending on the nature of the film.

The main disadvantage of mechanical cleaning is that it can scour away any protective layers or coatings on the pipe internals. In the case of passive layers, this can be followed by rapid corrosion if moisture is present, until the passive layer is re-established, and so inhibitors should be used in the cleaning or jetting water to prevent corrosion occurring. Water jetting and dry blasting are hazardous activities due to the high pressures involved and so safety precautions must be taken. The solids generated during the cleaning process must be collected and removed from the installation. Access is required to all parts of the system in order to ensure it is thoroughly cleaned, and on some installations this may be difficult. Challenging geometries may also make it difficult to ensure adequate cleaning.

## 2.7 INFORMATION FROM OPERATORS

Only two responses were obtained from operators in this current study regarding their systems. These responses highlighted concerns that the operators had regarding repairs carried out on their systems and the problems that may be faced when cleaning is carried out. It appears to be common to replace corroded areas of pipework with dissimilar metals. These sections must be insulated to prevent the creation of a galvanic corrosion cell. Both chemical treatments and mechanical treatments must be selected carefully to avoid preferential corrosion.

Due to the lack of responses from operators on this study, data gathered for a previous study for HSE has been re-evaluated in accordance with the objectives of the current study. This data, along with the recently gathered data indicated that for Cu-Ni systems chemical cleaning is not commonly carried out.

All operators stated that they carry out annual surveys of deluge systems, however the common frequency of wet testing was 2 years. The wet testing frequency appeared to be influenced by the extent of nozzle blockage found at previous wet tests.

One operator reported blockage of nozzles by large-scale debris such as fish.

# 3 ELECTROCHEMICAL TESTING

## 3.1 TEST METHOD

Coupons of carbon steel with dimensions 60mm by 30mm by 5mm were prepared and the surfaces polished to a 600 grit finish. The edges were sealed with non-leachable silicon sealant, as was a 7 mm strip on each face of each specimen at the top, where the electrical connection was made. This resulted in each sample having an exposed surface area of 3180 $mm^2$. Twelve coupons were tested, four for each test condition as shown in Table 1. Coupons 9 to 12 had all been immersed in seawater and allowed to corrode in quiescent conditions for four weeks.

Artificial seawater was prepared using the procedure detailed in section 6 of ASTM D1141-98 [32].

A chemical cleaning solution was prepared using constituent chemicals sourced from a cleaning company who maintain deluge systems. The chemicals were prepared in accordance with the company's procedures for cleaning to ensure that the properties of the final solution reflected their use in practice. (NOTE: The test conditions used were laboratory conditions to ensure repeatability of the test method, they were not intended to recreate the actual conditions during the cleaning process).

Both the seawater and cleaning solution tests were carried out in quiescent conditions. Both types of solution were open to air. The coupons were fully immersed in the test solutions throughout testing and left undisturbed between test intervals.

**Table 1. Corrosion test programme**

| Sample no. | Material | Environment | Test Day 1 | Test day 2 | Test Day 7 |
|---|---|---|---|---|---|
| 1 | Polished CS | Seawater | $E_{corr}$/LPR | | $E_{corr}$/LPR |
| 2 | Polished CS | Seawater | $E_{corr}$/LPR | | $E_{corr}$/LPR |
| 3 | Polished CS | Seawater | $E_{corr}$/LPR/Tafel | | $E_{corr}$/LPR/ Tafel |
| 4 | Polished CS | Seawater | $E_{corr}$/LPR/Tafel | | $E_{corr}$/LPR/ Tafel |
| 5 | Polished CS | Cleaning soln | $E_{corr}$/LPR | $E_{corr}$/LPR | |
| 6 | Polished CS | Cleaning soln | $E_{corr}$/LPR | $E_{corr}$/LPR | |
| 7 | Polished CS | Cleaning soln | $E_{corr}$/LPR/Tafel | $E_{corr}$/LPR/Tafel | |
| 8 | Polished CS | Cleaning soln | $E_{corr}$/LPR/Tafel | $E_{corr}$/LPR/Tafel | |
| 9 | Pre-corroded CS | Cleaning soln | $E_{corr}$/LPR | $E_{corr}$/LPR | |
| 10 | Pre-corroded CS | Cleaning soln | $E_{corr}$/LPR | $E_{corr}$/LPR | |
| 11 | Pre-corroded CS | Cleaning soln | $E_{corr}$/LPR/Tafel | $E_{corr}$/LPR/Tafel | |
| 12 | Pre-corroded CS | Cleaning soln | $E_{corr}$/LPR/Tafel | $E_{corr}$/LPR/Tafel | |

Electrochemical testing was performed using a computer controlled PAR VersaStat 3 potentiostat, a silver/silver chloride reference electrode and a graphite counter electrode. The test programme consisted of open circuit measurement performed for an hour in order to establish a stable corrosion potential, $E_{corr}$, on every sample. This was followed on all samples by linear polarisation resistance (LPR) in order to determine the polarisation resistance, $R_p$. On day 1 of testing, two samples of each set of four then underwent cathodic and anodic polarisation in order to determine the Tafel coefficients and allow $i_{corr}$ and, therefore, corrosion rates to be calculated. On day 2 or 7 of testing, however, all four samples in each set underwent cathodic and anodic polarisation.

This testing was conducted in broad agreement with ISO 17475, ASTM G59, ASTM G5 and ASTM G61[33-36]. The data gathered was analysed using VersaStudio software, with corrosion rate calculations performed in agreement with ASTM G102 [37].

## 3.2 RESULTS

The results obtained from the test programme are summarised in Table 2. A more detailed table of the results can be found in the Appendix. The results in Table 2 show the total metal loss, in mm, which would be expected in one year for carbon steel immersed in seawater. It can be seen from the results that the initial corrosion rate recorded on day one has dropped to almost half of that value on day 7. It is well documented that carbon steel immersed in quiescent seawater will typically exhibit a decrease in corrosion rate due to the formation of corrosion products on its surface.

The total metal loss based on one 24 hour cleaning cycle being carried out has also been determined for both polished coupons and pre-corroded coupons. The results show significantly smaller amounts of metal loss regardless of whether the steel has a layer of corrosion on its surface.

**Table 2. Results showing expected average metal loss in carbon steel by exposure period**

| Material | Environment | Time | Corrosion Loss in mm | |
|---|---|---|---|---|
| | | | Over 12 months | Over 24 hr Cleaning Period |
| Carbon Steel | Seawater | Day 1 | 0.095 | - |
| | | Day 7 | 0.051 | - |
| Carbon Steel | Chemical Cleaning Solutions | Day 1 | - | 0.008 |
| | | Day 2 | - | 0.012 |
| Pre-Rusted Carbon Steel | Chemical Cleaning Solutions | Day 1 | - | 0.010 |
| | | Day 2 | - | 0.011 |

## 3.3 ASSESSMENT

The results show that, although the base metal is attacked during chemical cleaning, the amount of metal loss during the process is negligible. There is little likelihood of deluge pipes being perforated by cleaning solutions unless so much wastage had occurred prior to cleaning that the pipes were only several microns thick. Any pipes which had wasted to such an extent would not be sufficiently strong enough to retain any fluid introduced into them, including seawater, and would be likely to fail during a wet test prior to cleaning.

The amount of uniform metal loss due to seawater exposure estimated from this testing may be considered conservative (i.e., relatively high) compared with in-service conditions because the measurements were taken within a week and, typically, initial uniform corrosion rates are higher than longer-term ones under similar conditions. Conversely, it is arguable that fully submersing the coupons, albeit under aerated conditions, is less aggressive than the wet-dry cycling that might be experienced under in-service conditions. Corrosion due to wet-dry cycling, however, is likely to be more localised or patchy, rather then uniform in nature, and it is well documented that localised corrosion occurs at much higher rates than uniform attack. On balance, the seawater-corrosion rates measured during these tests do not necessarily reflect those seen under in-service conditions and, most likely, under-estimate in-service corrosion; however, it should be noted that the tests were comparative in nature (i.e., metal loss due to seawater compared with metal loss due to chemical cleaning).

# 4 CONCLUSIONS AND RECOMMENDATIONS

No evidence has been found, either during corrosion testing or in the literature review, to suggest that cleaning chemicals will cause perforation of otherwise sound pipes.

Corrosion testing found that the total metal loss for a carbon steel corrosion coupon immersed in proprietary cleaning chemicals over a 24 hour period was in the region of 10 microns. This would be unlikely to cause perforation of a carbon steel pipe in a deluge system unless it was already severely wasted due to prior corrosion.

These results were backed up by a review of literature available regarding chemical cleaning and corrosion of materials used to manufacture deluge systems.

Corrosion testing was carried out using coupons which were fully immersed in artificial seawater. The results showed that if a coupon was fully immersed, the total metal loss over a one year period could be of the order of 50 microns. Conditions inside deluge pipes are likely to be more aggressive than the test conditions due to bioorganisms being present in seawater, but not present in the artificial seawater used for testing. Additionally the fact that the pipe surfaces are not fully immersed, but more often subject to a moist, humid environment comprising both wetting and drying and thermal cycling makes the conditions inside deluge piping likely to be more aggressive than the test conditions.

Corrosion observed in deluge systems is due to long term exposure to seawater remaining in pipes following wet testing and system use. Flushing deluge pipes with potable water after wet testing is recommended to remove seawater pools and salt deposits.

Replacement of pipes piecemeal may not be the best overall solution, and a cost benefit analysis should be carried out looking at complete replacement of the systems versus continued repair and cleaning costs, along with the implications of nozzle blockages (system downtime, material costs, safety risk factors). Where pipes are replaced piecemeal, care must be taken in material selection to avoid galvanic couples.

Analysis of the results of testing may prove useful in terms of establishing where blockages occur so that reoccurring blockages can be investigated, allowing the causes to be established and addressed.

If pipes are mechanically sound, then they should be cleaned using any suitable means. There is no evidence to suggest any one cleaning method is more suitable than another.

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# 6 APPENDIX

**SEAWATER DAY ONE**

| Coupon | Material | Environment | File | Tests | Ecor | Rp | Ba | Bc | Beta | Icor | SA | icor | CR | CR | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | V (Ag/AgCl) | ohms | V/dec | V/dec | V/dec | (A) | $m^2$ | $A/m^2$ | µm/y | mm/y | |
| 1 | **CS** | **Seawater** | C1 Seawater D1 | Ecor, LPR | -0.633 | 98 | | | 0.025 | 2.59E-04 | 0.0032 | 8.15E-02 | 95 | 0.095 | |
| 2 | **CS** | **Seawater** | C2 Seawater D1 | Ecor, LPR | -0.693 | 111 | | | 0.025 | 2.29E-04 | 0.0032 | 7.20E-02 | 84 | 0.084 | |
| 3 | **CS** | **Seawater** | C3 Seawater D1 | Ecor, LPR, Tafel | -0.598 | 94 | 0.130 | 0.100 | 0.025 | 2.61E-04 | 0.0032 | 8.22E-02 | 96 | 0.096 | |
| 4 | **CS** | **Seawater** | C4 Seawater D1 | Ecor, LPR, Tafel | -0.666 | 93 | 0.080 | 0.245 | 0.026 | 2.82E-04 | 0.0032 | 8.87E-02 | 104 | 0.104 | |
| | | | | Average | -0.648 | 99 | | | 0.025 | | | 0.081 | | **0.095** | **mm in 1 year** |
| | | | | Std Dev | 0.041 | 8 | | | | | | 0.007 | | 0.008 | |

**SEAWATER DAY SEVEN**

| Coupon | Material | Environment | File | Tests | Ecor | Rp | Ba | Bc | Beta | Icor | SA | icor | CR | CR | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | V (Ag/AgCl) | ohms | V/dec | V/dec | V/dec | (A) | $m^2$ | $A/m^2$ | µm/y | mm/y | |
| 1 | **CS** | **Seawater** | | Ecor, LPR | -0.724 | 153 | 0.080 | 0.120 | 0.021 | 1.36E-04 | 0.0032 | 4.29E-02 | 50 | 0.050 | |
| 2 | **CS** | **Seawater** | | Ecor, LPR | -0.723 | 137 | 0.080 | 0.130 | 0.022 | 1.57E-04 | 0.0032 | 4.94E-02 | 58 | 0.058 | |
| 3 | **CS** | **Seawater** | | Ecor, LPR, Tafel | -0.725 | 164 | 0.080 | 0.120 | 0.021 | 1.27E-04 | 0.0032 | 4.00E-02 | 47 | 0.047 | |
| 4 | **CS** | **Seawater** | | Ecor, LPR, Tafel | -0.723 | 138 | 0.070 | 0.115 | 0.019 | 1.37E-04 | 0.0032 | 4.31E-02 | 50 | 0.050 | |
| | | | | Average | -0.724 | 148 | | | 0.021 | | | 0.044 | | **0.051** | **mm in 1 year** |
| | | | | Std Dev | 0.001 | 13 | | | | | | 0.004 | | 0.005 | |

**CHEMICAL CLEANER DAY ONE**

| Coupon | Material | Environment | File | Tests | Ecor | Rp | Ba | Bc | Beta | Icor | SA | icor | CR | CR | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | V (Ag/AgCl) | ohms | V/dec | V/dec | V/dec | (A) | $m^2$ | $A/m^2$ | µm/y | mm/y | |
| 5 | **CS** | **Chemical** | | Ecor, LPR | -0.640 | 5 | | | 0.049 | 9.71E-03 | 0.0032 | 3.05E+00 | 3567 | 3.567 | |
| 6 | **CS** | **Chemical** | | Ecor, LPR | -0.642 | 7 | | | 0.049 | 6.93E-03 | 0.0032 | 2.18E+00 | 2548 | 2.548 | |
| 7 | **CS** | **Chemical** | | Ecor, LPR, Tafel | -0.637 | 7 | 0.250 | 0.210 | 0.050 | 7.09E-03 | 0.0032 | 2.23E+00 | 2605 | 2.605 | |
| 8 | **CS** | **Chemical** | | Ecor, LPR, Tafel | -0.640 | 6 | 0.240 | 0.200 | 0.047 | 7.91E-03 | 0.0032 | 2.49E+00 | 2905 | 2.905 | |
| | | | | Average | -0.640 | 6 | | | 0.049 | | | 2.487 | | 2.906 | mm in 1 year |
| | | | | Std Dev | 0.002 | 1.0 | | | | | | 0.400 | | 0.467 | |
| | | | | | | | | | | | | | **Average** | **0.008** | **mm in 24 hr period** |

**CHEMICAL CLEANER DAY TWO**

| Coupon | Material | Environment | File | Tests | Ecor | Rp | Ba | Bc | Beta | Icor | SA | icor | CR | CR | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | V (Ag/AgCl) | ohms | V/dec | V/dec | V/dec | (A) | $m^2$ | $A/m^2$ | µm/y | mm/y | |
| 5 | **CS** | **Chemical** | | Ecor, LPR | -0.631 | 4 | 0.270 | 0.200 | 0.050 | 1.25E-02 | 0.0032 | 3.93E+00 | 4589 | 4.589 | |
| 6 | **CS** | **Chemical** | | Ecor, LPR | -0.634 | 4 | 0.290 | 0.230 | 0.056 | 1.39E-02 | 0.0032 | 4.38E+00 | 5124 | 5.124 | |
| 7 | **CS** | **Chemical** | | Ecor, LPR, Tafel | -0.630 | 5 | 0.270 | 0.200 | 0.050 | 9.99E-03 | 0.0032 | 3.14E+00 | 3672 | 3.672 | |
| 8 | **CS** | **Chemical** | | Ecor, LPR, Tafel | -0.633 | 5 | 0.310 | 0.220 | 0.056 | 1.12E-02 | 0.0032 | 3.52E+00 | 4112 | 4.112 | |
| | | | | Average | -0.632 | 5 | | | 0.053 | | | 3.743 | | 4.374 | mm in 1 year |
| | | | | Std Dev | 0.002 | 0.6 | | | | | | 0.535 | | 0.625 | |
| | | | | | | | | | | | | | **Average** | **0.012** | **mm in 24 hr period** |

**CHEMICAL CLEANER ON PRE-RUSTED SPECIMENS DAY ONE**

| Coupon | Material | Environment | File | Tests | Ecor | Rp | Ba | Bc | Beta | Icor | SA | icor | CR | CR | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | V (Ag/AgCl) | ohms | V/dec | V/dec | V/dec | (A) | $m^2$ | $A/m^2$ | µm/y | mm/y | |
| 9 | **Rusted CS** | **Chemical** | | Ecor, LPR | -0.638 | 5 | | | 0.052 | 1.04E-02 | 0.0032 | 3.28E+00 | 3835 | 3.835 | |
| 10 | **Rusted CS** | **Chemical** | | Ecor, LPR | -0.634 | 6 | | | 0.052 | 8.70E-03 | 0.0032 | 2.73E+00 | 3196 | 3.196 | |
| 11 | **Rusted CS** | **Chemical** | | Ecor, LPR, Tafel | -0.629 | 5 | 0.330 | 0.220 | 0.057 | 1.15E-02 | 0.0032 | 3.61E+00 | 4218 | 4.218 | |
| 12 | **Rusted CS** | **Chemical** | | Ecor, LPR, Tafel | -0.640 | 6 | 0.270 | 0.180 | 0.047 | 7.83E-03 | 0.0032 | 2.46E+00 | 2876 | 2.876 | |
| | | | | Average | -0.635 | 6 | | | 0.052 | | | 3.022 | | 3.531 | mm in 1 year |
| | | | | Std Dev | 0.005 | 0.6 | | | | | | 0.520 | | 0.607 | |
| | | | | | | | | | | | | | **Average** | **0.010** | **mm in 24 hr period** |

**CHEMICAL CLEANER ON PRE-RUSTED SPECIMENS DAY TWO**

| Coupon | Material | Environment | File | Tests | Ecor | Rp | Ba | Bc | Beta | Icor | SA | icor | CR | CR | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | V (Ag/AgCl) | ohms | V/dec | V/dec | V/dec | (A) | $m^2$ | $A/m^2$ | µm/y | mm/y | |
| 9 | **Rusted CS** | **Chemical** | | Ecor, LPR | -0.635 | 5 | 0.290 | 0.210 | 0.053 | 1.06E-02 | 0.0032 | 3.33E+00 | 3892 | 3.892 | |
| 10 | **Rusted CS** | **Chemical** | | Ecor, LPR | -0.638 | 5 | 0.270 | 0.230 | 0.054 | 1.08E-02 | 0.0032 | 3.40E+00 | 3969 | 3.969 | |
| 11 | **Rusted CS** | **Chemical** | | Ecor, LPR, Tafel | -0.640 | 5 | 0.270 | 0.210 | 0.051 | 1.03E-02 | 0.0032 | 3.23E+00 | 3775 | | |
| 12 | **Rusted CS** | **Chemical** | | Ecor, LPR, Tafel | -0.635 | 6 | 0.270 | 0.260 | 0.058 | 9.60E-03 | 0.0032 | 3.02E+00 | 3527 | | |
| | | | | Average | -0.637 | 5 | | | 0.054 | | | 3.244 | | 3.931 | mm in 1 year |
| | | | | Std Dev | 0.002 | 0.5 | | | | | | 0.165 | | 0.054 | |
| | | | | | | | | | | | | | **Average** | **0.011** | **mm in 24 hr period** |

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# Corrosion and cleaning of offshore deluge systems

This report presents the findings of a literature review of the issues surrounding the corrosion of offshore firewater deluge systems as well as inspection and cleaning methodologies which may be used. Contributions of case studies from offshore operators is included, detailing their experiences of corrosion of deluge systems and cleaning methods and maintenance schedules.

The report also includes the findings from corrosion tests performed at HSL on carbon steel coupons immersed in proprietary chemicals used to clean deluge systems and compares these results to corrosion tests carried out in sea water.

The findings of the report were that:

- There was no evidence that cleaning mechanically sound deluge pipework would result in damage to that pipework.
- There was no evidence to suggest that any one cleaning method is more suitable than another.
- Corrosion observed in deluge systems is due to long term exposure to seawater following wet testing.
- Where practical, flushing deluge piping with potable water after wet testing is recommended to removed pooled sea water and salt deposits.

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