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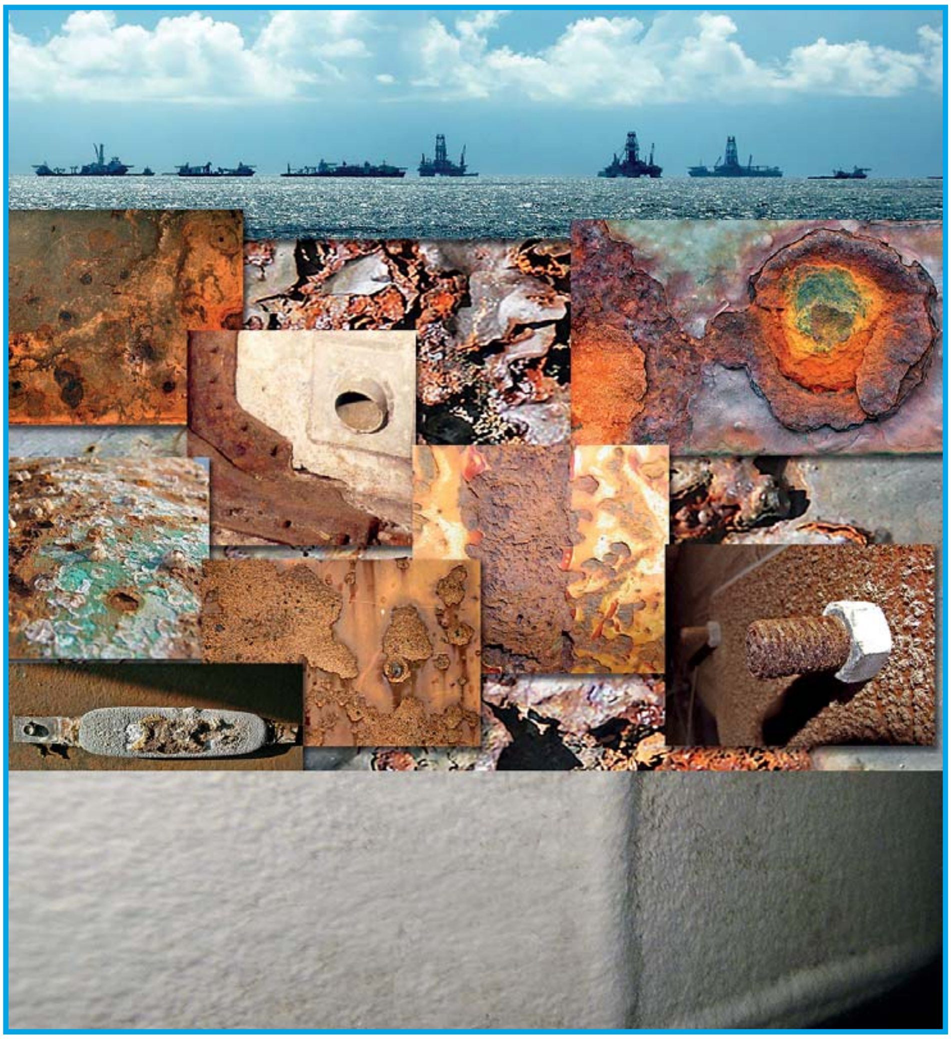
WHITE PAPER

Conquering Corrosion in Offshore Vessels



Best practices for corrosion prevention for the submerged hulls and tanks of offshore vessels, inside and out

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UNDERWATER TECHNOLOGY

Part I. Introduction

The corrosion problem

Offshore oil and gas exploration, production and storage vessels such as drill ships, floating storage and offloading units (FSOs), floating production, storage and offloading vessels (FPSOs), and the latest addition, floating liquefaction, re-gasification and storage units (FLRSUs) differ from bulk carriers, container ships, ferries and passenger vessels in that they are not expected to drydock frequently or routinely.

Whereas a ship that is drydocked every three or five years can have its anticorrosive coating system inspected and repaired regularly, an offshore vessel must go for much longer periods without such inspection and repair.

Whereas a very large crude carrier (VLCC), a container ship, a cruise ship or a naval vessel can expect to drydock at least once in a five-year period, an offshore vessel can be required to stay on station without drydocking for 20-40 years.

Another major difference is that offshore vessels tend to be stationary. A submersible or semisubmersible oil rig sits on the ocean bed or is tethered to one spot for extended periods of time. A drill ship, an FSO, FPSO or FLRSU is likewise expected to be stationary or move very little for years or decades.

Drydocking such vessels is a very time-consuming and expensive exercise. Their daily earning capacity is very high and each day out of service constitutes a huge loss. The procedure for getting this type of vessel into drydock, serviced and out of drydock can be very complicated, time-consuming and expensive, especially if thrusters have to be removed ahead of time, tanks have to be emptied and other preparatory actions taken. The drydock fees for an extended stay can mount up alarmingly. There are other major factors which have to be considered when prematurely removing FPSOs from their location such as the effect on a well.

Whereas a ship that is drydocked every three or five years can have its anticorrosive coating system inspected and repaired or replaced regularly, it is very desirable that an offshore vessel go for much longer periods without such inspection and repair or replacement. The extremely corrosive nature of saltwater, plus the corrosive effects of various living organisms, and of many cargoes, can take a particularly severe toll on the hull and the tanks of such vessels, inside and out, if steps are not taken to make sure that these are properly protected against such corrosion.

So, while corrosion protection is a vital issue for all ships and any metal structures immersed in or in contact with seawater, the case of offshore vessels and rigs is a special one with issues all of its own and with specific remedies and solutions. And the current requirements of the offshore oil and gas exploration and production industry in the second decade of the twenty-first century are particularly demanding.

These requirements extend, to some degree, to the tankers and VLCCs that carry highly corrosive petroleum products. The tanks of all these vessels, particularly with the now-required double hulls, are especially prone to severe corrosion. Corrosion protection is just as important inside the ship as on the outside hull, the splash zone (the area just above the water line where the highest corrosive forces are concentrated), and the superstructure of vessels and rigs subject to the onslaught of salt spray, condensation, extreme heat and other factors.

One among very many examples found readily to hand will serve to highlight the perilous nature of corrosion at sea. Even though strictly not an "offshore vessel," the case is relevant. On 12 December 1999, in severe weather, the Maltese registered tanker *Erika* split in two, 70 kilometers from the coast of Brittany, France, while carrying approximately 30,000 tons of heavy fuel oil. Some 19,800 tons of tarlike petroleum were spread across more than 250 miles of the Loire-Atlantic coastline. This was Europe's largest oil spill in two decades. This single oil spill was equal to the total amount of oil spilled worldwide in 1998. The economic consequences of the incident were felt across the region: a drop in the income from tourism and from fishing and a ban on the trade of sea products including oysters and crabs, added to the detrimental effects on the local population.

The final report on the disaster, issued in January 2000 by the French investigative agency Bureau d'Enquêtes sur les Accidents en Mer, concluded that severe corrosion had weakened the *Erika's* hull, causing the ship to flex in the storm and eventually to fracture. The *Erika* was about 25 years old.[1]

The following information comes from *The Handbook of Corrosion Engineering* by Pierre R. Roberge:

> Another example of major losses to corrosion that could have been prevented and that was brought to public attention on numerous occasions since the 1960s is related to the design, construction, and operating practices of bulk carriers. In 1991 over 44 large bulk carriers were either lost or critically damaged and over 120 seamen lost their lives. A highly visible case was the MV KIRKI, built in Spain in 1969 to Danish designs. In 1990, while operating off the coast of Australia, the complete bow section became detached from the vessel.
>
> Miraculously, no lives were lost, there was little pollution, and the vessel was salvaged. Throughout this period it seems to have been common practice to use neither coatings nor cathodic protection inside ballast tanks. Not surprisingly therefore, evidence was produced that serious corrosion had greatly reduced the thickness of the plate and that this, combined with poor design to fatigue loading, were the primary cause of the failure. The case led to an Australian Government report called "Ships of Shame." MV KIRKI is not an isolated case.
>
> There have been many others involving large catastrophic failures, although in many cases there is little or no hard evidence when the ships go to the bottom.[2]

Tankers seem to be very prone to failure due to corrosion.

> Each year between 1995 and 2001 an average of 408 tankers broke apart at sea or barely escaped that fate according to the International Association of Independent Tanker Owners (Intertanko). The leading cause was collision, but nearly as many suffered "structural/technical failures" – often a euphemism in industry circles for excessive corrosion.[3]

The cost of corrosion

Around the beginning of this millennium the

1 Corrosion Doctors. "Environmental Catastrophe: Sinking of the *Erika*," accessed 10 January 2013
2 Roberge, Pierre R., *Handbook of Corrosion Engineering* McGraw-Hill (2000) p4.
3 Martin, Richard, "The New Supertanker Plague," *Wired* 10.06 (June 2002).

US government ordered a two-year study on the cost of corrosion in the United States by industry sector, and on measures which could be taken to reduce that cost. A great deal of information emerged from this study. For example, the cost of protective coatings, organic and metallic, to protect metal against corrosion amounted to $108.6 billion.[4]

The total annual direct cost of corrosion to the US shipping industry was estimated at $2.2 billion. This broke down into the costs associated with new ship construction ($1.1 billion), maintenance and repairs ($0.8 billion) and corrosion-related downtime ($0.8 billion).

The cost of corrosion to the oil and gas exploration and production sector was estimated at $1.4 billion.

The data provided by the military services indicated that corrosion is potentially the number one driver in life-cycle costs. The total annual direct cost of corrosion incurred by military services for systems and infrastructure was approximately $20 billion.

The study came up with an estimate of a direct cost of $276 billion for the US economy, 3.1 percent of GDP, and an indirect cost of a further $276 billion, putting the total annual cost of corrosion to the US economy at $552 billion, 6 percent of GDP.

Accurate or rough, these figures make the point. Corrosion is very expensive!

A NACE report of about the same time period calculated that the average cost of corrosion protection due to new ship construction is $7.5 billion per year. This equates to approximately seven to ten percent of the cost of the vessel, and with chemical tankers it goes as high as thirty percent. The annual cost for repair and maintenance due to corrosion was estimated at $5.4 billion with an additional $5.2 billion cost associated with downtime.[5]

Vessels continue to be constructed of steel. Tankers are now required to be constructed with double hulls, introducing changes to operating conditions in ballast tanks, both positive and negative. There have been dramatic offshore advances into deep water. FPSO's are being installed with expectations of remaining on location for at least twenty years.

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Since there has been little progress in dealing with maritime corrosion since the early 2000s study referenced above, the cost of corrosion to the offshore sector has undoubtedly increased considerably.

A corrosion-prone industry

The sea is one of the most corrosive environments on earth. The chemicals stored or transported in the tanks of offshore vessels include some of the most corrosive of all. The combination means that the tanks and hulls of offshore vessels are subjected to highly corrosive elements, both inside and out.

Efforts to control corrosion

There are a number of different causes of corrosion in the metals used in the hulls and tanks of offshore vessels. These will be covered in detail below in Part III, The Problem of Corrosion.

The main methods of corrosion control in use are

- design of hulls and tanks to reduce corrosion
- choice of materials
- protective coatings
- cathodic protection systems
- the use of corrosion inhibitors.

Mild steel is the most common material used for hulls and tanks.

Protective coatings along with cathodic

4 US Federal Highway Administration (FHWA), “Corrosion Costs and Preventive Strategies in the United States,” Publication No. FHWA-RD-01-156 (2002).

5 Gerhardus Koch, *et al.*, “Corrosion Costs and Preventive Strategies in the United States,” NACE, (2002?).

protection are the methods most commonly used to combat corrosion.

The breakdown

The most usual sequence of breakdown in corrosion protection with resulting serious loss of steel and structural fatigue and failure is

1. the coating starts to break down for one or more of a number of reasons
2. this then exposes the underlying steel to corrosion
3. the cathodic protection system is inadequate to prevent the resulting corrosion
4. the corrosion sources combine and compound to accelerate the corrosion process so that in some cases the corrosion proceeds amazingly rapidly.

Coating failure on a semisubmersible rig using conventional antifouling paint.

This fatal downward spiral begins with a failure of the protective coating. This is the weakest link and the Achilles heel in corrosion protection. It is also the entrance point for dealing with the problem.

Breaking the cycle

So, how does one break this cycle?

Corrosion has been a known factor in shipping since metal was first used in the construction of ships' hulls. Research into its prevention began as soon as corrosion was detected as a threat.

And yet, despite some progress, judging by the factors listed above under "The corrosion problem" and "The cost of corrosion," the problem is still prevalent.

It may seem fanciful to say that the solution is available and is not even difficult, but this is in fact the case.

The key to solving the corrosion problem on ships' hulls and inside ships' tanks lies in the coating. A coating that provides an effective, long-lasting barrier between the steel and the corrosive elements such as seawater or various oil cargoes and does not fail is the simplest and most far-reaching answer to significantly reducing if not entirely eliminating the threat of corrosion on the hulls and in the tanks of offshore vessels.

The details of the problem and the solution are laid out clearly in the rest of this White Paper.

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Part II. Need for change

The subject of corrosion of offshore vessels is definitely not under control. This is a field which is currently wide open to workable solutions which mitigate or eliminate the corrosive effects of the marine environment and the chemicals stored and transported in ships' tanks on the mild steel from which these vessels and tanks are built.

There are reasons why the demand for such solutions is particularly acute and becoming more so at this time.

Following are some general observations presented by Ian Rowell of International Paint in a talk on Tankers and FPSO Corrosion given in 2004:

General Observations

- Floating Production Units have been in operation for over 15 years. Now nearly 200 in operation
- Units are increasingly operating in deeper water in locations that are more inaccessible
- The Costs of Offshore Coating Repair or Maintenance is significantly higher than New Construction –x15
- Units are operating in Hot Climates with very corrosive conditions.[6]

The following excerpts from an article by Steven Ferry published in 2012 demonstrate how and why oil and gas exploration and production are moving further and further offshore and describe the effect this is having on the offshore industry and the vessels that support it.

The world's demand for energy continues to rise and is now on a collision course with the stark reality that known oil reserves are dwindling, with most onshore oil reserves now mapped and being tapped.

Not that the oil and gas industry has not seen this coming. They have long realized that the energy future lies offshore, under the oceans of the world which comprise close to 71% of the Earth's surface. In fact, they have been working on technology to siphon the oil lying beneath increasingly deep waters since the first tentative steps were taken in the shallow bayous of Louisiana during 1940. Oil fields in shallower waters were tapped over the intervening years, to the point where it became imperative that the challenges of deep-water drilling be met and overcome.

Ratifying the oil and gas industry's outlook and approach, the greatest oil discovery in the last decade was made offshore.

And that is why the offshore drilling industry is a shining light in the maritime sector: capital outlays and discoveries, production and profits are all healthy. One area where significant improvements still can be made is in the mitigation of the lost production from, and high costs of maintenance of these rigs, ships and equipment, working as they are so remotely and in generally very challenging environments.

Let's look at some specifics.

General shipping new-builds are off, with 40% of dry bulk orders postponed in

6 Rowell, Ian, "Tankers and FPSO Corrosion," NIST Special Publication 1035, (April 2004), p 45.

2011, and 2012 and 2013 orders falling to an estimated 43 million dry weight tons each year.

Projected Energy Consumption

It is projected that world energy consumption (the majority of which is oil based) will grow by 53 percent from 2008 to 2035, and is projected to rise from 505 quadrillion British thermal units (Btu) in 2008 to 619 quadrillion Btu in 2020 and 770 quadrillion Btu in 2035 (see chart below).

…

"All the easy oil and gas in the world has pretty much been found. Now comes the harder work in finding and producing oil from more challenging environments and work areas." William J. Cummings, Exxon-Mobil.

...

The Offshore Future

Since offshore exploration and production began over 70 years ago in Louisiana, advancements in seismic and drilling technologies have seen the offshore industry developing fields in all parts of the globe and in ever-deeper waters, with a concomitant and steady increase in oil production.

Currently, approximately 30% of all the world's oil and gas comes from offshore units, and this share is expected to continue to increase. Just two years after the 2010 Deepwater Horizon spill and subsequent moratorium, deep-water drilling has regained its momentum in the Gulf of Mexico and is, once again, spreading around the world.

In fact, BP and other oil companies are now intensifying their exploration and production in the Gulf, which will soon surpass the levels attained before the accident. The reason for the resumption of such drilling is the inescapable and continuing high demand for energy.

Arctic Exploration

When Royal Dutch Shell sank five wells off Alaska recently, it was the first drilling in U.S. Arctic waters in decades. And encouraged by high commodity prices and shrinking sea ice, not only oil exploration, but the cruise and fishing industries as well, among others, are gearing up to tap the Arctic's riches, previously inaccessible because of the year-round ice. Also, shrinking summer Arctic ice is opening new and shorter shipping lanes, an open invitation to general shipping to chart Arctic courses.

The U.S. Geological Survey estimates that nearly 13% of the world's undiscovered oil reserves, and 30% of its undiscovered gas reserves, are to be found north of the Arctic Circle. That's 90 billion barrels of oil and 1,670 trillion cubic feet of natural gas. And these estimates don't include so-called unconventional oil and gas deposits, such as hydrocarbons found in shale rock, or methane hydrates on the sea floor.

While Arctic oil exploration is more challenging technically than any other environment, continuing high oil prices and advances in technology combine to fan the petroleum industry's interest in the region, with countries such as Canada, Russia, Norway, and Denmark (Greenland), whose northern areas all extend into the Arctic, being likely targets for future exploration.

Vessels and Rigs

It is clear that the migration to offshore exploration and production that has already begun will only gain momentum. It is also clear that, as it does, the demand for vessels and rigs will also continue to rise.

However, an unfortunate reality with these developments is that the farther from shore – such as into the Arctic (or Antarctic) – exploration and production takes oil companies, the farther vessels and rigs will find themselves from dry-dock for cleaning and servicing as needed, meaning significant downtime and lost production.[7]

At a 2004 workshop on Coatings for Corrosion Protection in Biloxi, Mississippi, Adolfo Bastiani, Vice-President Offshore Operations of MODEC International LLC, Houston, confirmed the industry's needs with regard to the longevity of corrosion protection:

The very concept of FPSO's is based on exploiting marginal oil fields and it is customary for all our clients to demand an FPSO that will operate in one location for 15 to 20 or even 25 years WITHOUT DRY-DOCKING. Adolfo Bastiani, MODEC

The very concept of FPSO's is based on exploiting marginal oil fields and it is customary for all our clients to demand an FPSO that will operate in one location for 15 to 20 or even 25 years WITHOUT DRY-DOCKING. Whether it is a new build or a converted hull, this long life expectancy is a tall order indeed. Besides no dry-docking, the contract is always quite demanding re downtime. Either zero or minimal few hours every month, the downtime does not allow the contractor any freedom for remedying corrosion wastage during operations, particularly in inaccessible areas of underwater hull, moorings, sub-sea structures and even cargo/ballast tanks. The rationale of not stopping production is fully understood by the contractor as this has substantial and often unbearable economic impact.

Right from FEED study, the contractor must ensure optimum corrosion protection for the operational life. In addition, he must take into account thickness of steel plating, such that if there is failure of paint coatings, the wastage caused by direct attack of corrosive seawater, still retains the integrity of the hull over the entire life expectancy. As always, all such studies are done and must be implemented under strict budgetary control.[8]

Following the Exxon *Valdez* oil spill in 1989, the US Congress passed the Oil Pollution Act of 1990 which, among other requirements, mandated a double hull for all new tankers operating in US waters. The consequences of the double hull requirement were heightened, not lessened, corrosion rates, as explained here:

Initially, ship owners anticipated corrosion rates to be similar to those encountered in single hulled ballast tanks. It was known that repairs and steel replacement would have to be performed after the third special survey when the ship was 15 years old; however owners of the early double-hulled tankers found significant corrosion and pitting at the first special survey after only 5 years [1]. The reasons for the accelerated corrosion accrue to the use of higher tensile strength steels in the newer ships which allow for thinner

7 Steven Ferry, "A Brighter, Greener Off-Shore Future," (2013).

8 Adolfo Bastiani, *Practical Experience*, NIST Special Publication 1035, Coatings for Corrosion Protection: Offshore Oil and Gas Operation Facilities, Marine Pipeline and Ship Structures, April 2004, p.29.

plates that flex more than the carbon steel plates used in the older tankers. Also, when a hot cargo, such as crude oil loaded in the Middle East, Africa, South Pacific the Gulf Coast and other high temperature regions, the cargo heats the ballast tanks. Without a double hull, the cargo would be cooled by seawater on the opposite side of the single hull. However, the double hull void space insulated the cargo, slowing its cooling. Ballast tanks, even when empty, have water (and often silt) in their bottoms, and condensing humidity throughout. The elevated temperature of the cargo increases the rate of corrosion within the ballast tanks, doubling it for every 10° C increase in temperature. Thus if the average temperature of a ballast tank is 20° C warmer than previously, the corrosion rate would be quadrupled.[9]

The main circumstances which drive the quest for better answers to corrosion on offshore vessels and structures are

- the increase in offshore operations and numbers of vessels involved in offshore oil and gas exploration and production
- a drive for lighter vessels which should be possible with better materials leading to reduced scantlings but which in practice apparently cannot be achieved because of corrosion wastage
- the increase in remoteness of these operations (deeper water) making it more inconvenient and expensive to drydock the vessels
- the opening up of Arctic regions to exploration and production with added harshness of environment and remoteness of operations
- the increasing concerns about the marine environment in general and the polar regions in particular.

Fortunately there are some answers which could go far in conquering the offshore corrosion problem.

9 Kenneth B. Tator, "Risk Assessment and Economic Considerations When Coating Ballast Tanks," *NISt Special Publication 1035, Coatings for Corrosion Protection: Offshore Oil and Gas Operation Facilities, Marine Pipeline and Ship Structures*, April 2004, p.101.

Part III. The corrosion problem

Note: The subject, as described below, appears to be very complex due to the number of variables involved, but will be simplified considerably in later sections of this White Paper. It is a complex subject and the number of variables involved is large, but that does not mean that a workable, simple solution to the problem doesn't exist. So, the reader should not be dismayed by the complexities as these will be clarified in later sections.

What is corrosion?

A great deal of energy is required to convert the iron ore extracted from the ground into mild steel in forms suitable for the construction of ships and other metal structures. This energy mainly takes the form of heat employed in smelting the ore. In the case of iron ore for example, temperatures of about 2282°F (1250°C) are required to convert the iron oxide ore into iron. This is not all: the iron produced needs to have carbon removed and some other elements added in order to make mild steel (or plain-carbon steel) which is the most common of structural metals. This requires melting the iron again and reprocessing it. The same is true for other metals, though in varying degree.

The energy required to make the transformation is stored in the resulting metal. The natural tendency of the steel (or other metal) is to release this stored energy and return to its most stable state. The chemical composition and appearance of the rust that develops on mild steel is almost identical to that of the most common iron ore.

The amount of energy required to create or refine the metal in the first place varies. For example, considerably more energy is required to convert iron ore to steel, or aluminum ore to aluminum than is required to refine copper, silver or gold. Thus iron and aluminum corrode more easily and rapidly than copper, silver or gold.

The process of corrosion is the return of a metal to its most stable state.

The fact and rate of corrosion are influenced by a number of factors such as the nature of the metal itself, the presence or absence of oxygen, the temperature, the speed of motion (for example a flow of water or other liquid over the metal), the proximity of other metals in a corrosive environment, the presence of electrical conductors such as salt or hard water or other corrosive elements, stray electrical currents, contact with various chemicals (for example in ships' tanks), stress, vibration, cavitation, the effect of micro and macro-organisms, and others.

For the purposes of this White Paper, we are interested in the corrosion of metals used in the construction of offshore vessels' hulls and tanks and the conditions they face which can accelerate, retard or prevent corrosion, as well as means of protecting them or reducing or preventing corrosion. Since almost all offshore exploration and production occurs in seawater, we are far more interested in the effects of saltwater than of fresh water. This limits the aspects of corrosion that need be covered. And since storage and transport tanks are used for specific cargoes or materials such as crude oil or liquid natural gas (LNG) we also concentrate on these as corrosive agents when it comes to tanks.

The result of corrosion of a ship's hull, frame, plates and tanks is loss of material and resulting structural weakness. Taken to extremes, corrosion can result in such a weakening of a ship's structure that it can sink. A corroded tank can become so flimsy that it no longer holds the liquid it is supposed to contain. A corroded hull can reach a point where it no longer keeps out seawater. A corroded rudder becomes less efficient and eventually, if not repaired or replaced, can simply fall off, rendering the vessel unsteerable and helpless.

Since the natural tendency of the materials used in the construction of the hulls and tanks of vessels is to corrode, measures must be taken to prevent this. It is a constant preoccupation for those responsible for designing, building, operating and maintaining vessels.

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The major factors

While the subject of the causes and manifestations of corrosion is very complex, this is not a chemistry lesson and our aim here is to provide a basic understanding of these as they affect offshore vessels and structures so that the remedies discussed later can be viewed in context.

Electrochemical causes

A liquid capable of conducting electrical currents is called an electrolyte. When some metals are immersed in water they are subject to aqueous (water-based) corrosion. We can call this marine corrosion. It is caused by flows of electrical current from one part of the metal to another part of the same metal or to a different metal. The current flows from one part of the surface of the metal, called the anode (negatively charged) to another point of metal called the cathode (positively charged) or between different metals. In this case (different metals) the baser or more active metal is the anode. The anode loses metal to the electrolyte as electrons flow between anode and cathode. In other words, the metal corrodes at the anode. The electrical circuit is completed by the metal itself. Seawater, because of its chloride content, is a particularly good electrolyte. So are various acids, which is why they are often used in batteries which operate on this principle.

Rain, condensation, various solutions can all be electrolytes and create a corrosive environment for metals.

The basic principle of corrosion is this electrochemical reaction.

The electrodes (anode and cathode) can be different metals or different parts of the same metal with different electrical potentials. It is the anode, the negative electrode, that corrodes.

The most important factor in all of this is that in order for corrosion to occur, it must be possible for a current to flow, for positively charged particles to leave the anode and flow through an electrolyte to the cathode. If the steel, aluminum or other metal were completely insulated from the liquid it is immersed in, it will not corrode.

Corrosion only occurs in areas that can act as anodes.

Any attempt to prevent corrosion must take this basic cause into consideration and, by whatever means, prevent this electrochemical reaction.

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Galvanic action

In terms of corrosion, galvanic action is a specific form of electrochemical reaction referring to the corrosive behavior of different metals in a corrosive environment where one metal has a higher electrical potential than the other. This brings us back to the relative amount of energy required to convert different types of ore into their corresponding metals. Aluminum requires more energy than iron which requires more energy than copper which requires more energy than silver which in turn requires more energy than gold. The metals which require less energy to refine are referred to as noble. Copper is relatively nobler than iron or aluminum, gold more noble than any of these. The effect of placing two of these metals in electrical contact in a corrosive medium is that the corrosion of the less noble metal is accelerated and the corrosion of the more noble metal is reduced or stopped. The following table shows the relative nobility of different metals.[10]

NOBILITY OF METAL IN SALTWATER

	Volts	
Magnesium	1.58	
Zinc	1.04	
Cadmium	.88	Less Nobility
Mild Steel	.79	
Aluminum alloyed	.71	
Lead	.52	
Tin	.50	
Brass	.31	
Stainless Steel	.24	More Nobility
Monel	.12	
Silver	.08	
Gold	.00	
Platinum	.00	

Data taken in saltwater @75) F. Voltage will vary with temperature, salinity, velocity, oxygen content and different metal alloys

The baser metal is the anode and the more noble metal the cathode. This is what lies behind the well-documented phenomenon of the very rapid corrosion of aluminum that occurs if it is painted directly with a copper-based antifouling paint. The corrosion of the aluminum is rapid and serious. When sailing ships were made of wood, the use of copper sheeting on the underwater hull to deter worms and prevent fouling was common. When this system was applied to the first steel hulls, the steel corroded very rapidly with disastrous consequences, much to the shock and dismay of their crews and owners. The same phenomenon was present on wooden sailing boats sheathed in copper or lead when the rudder pintle and fittings were of iron or steel – rapid corrosion and wasting away.

The relative size of anode and cathode has great bearing on the amount of corrosion which follows. Current flowing to a large area produces a less dense concentration of electric flow than if the same amount of current flows to a small area. Steel sheets fastened with copper rivets, the steel being the anode and the copper the cathode, since the flow will be relatively weak and the

10 Pro-Troll, Chapter VIII "The Chemistry of The Electric Charge on Your Boat," *Black Box Techniques*, http://www.protroll,com/books/?id=5&p_id=9, accessed 27 August 2013.

effects hardly noticed. However, reverse this and fasten copper plates with steel rivets and the steel rivets, the anodes, will rapidly corrode. The relatively large current generated, concentrating on a relatively small area will produce severe corrosion and the rivets will disappear and the sheets will fall off. It is a matter of current density.

To summarize, galvanic action refers specifically to the electrochemical reaction between two different metals in a corrosive medium.

Oxygen

The amount of dissolved oxygen present in an electrolyte can make a significant difference to the amount of corrosion that occurs. In the case of steel in water, for example, the areas where there is a higher concentration of oxygen become more cathodic and the areas of less oxygen become more anodic and therefore corrode more rapidly.

However, the effects of the presence or absence of oxygen on corrosion rate is complex, varying with different metals.

On certain metals such as stainless steel, aluminum and titanium, the presence of oxygen helps create a protective layer on the bare metal which greatly slows corrosion of the metal.

Not so in case of steel or most metals, where the more oxygen present, the greater the rate of corrosion.

The splash zone, or the area "between wind and waves" can be particularly corrosive due to the fact that this area is constantly being hit by highly aerated (lots of oxygen) seawater.

Aerobic and anaerobic conditions

The terms *aerobic* and *anaerobic* refer to the presence (aerobic) or relative absence (anaerobic) of oxygen. Corrosion can occur in aerobic or anaerobic conditions but is different in each case. The amount of oxygen present also affects different metals in different ways, as described under "Oxygen" above. Deaeration can greatly reduce corrosion in steel, for example, depending on the temperature of the water.

But there are even more variables here. In the absence of oxygen, the usual corrosion product on mild steel is FE3O4 which can be ½ V or more nobler than, and cathodic to, bare steel. So that the corrosion product of steel as a film on the steel surface could lead to significant corrosion of the underlying steel due to this new combination.

Hydrogen

Steel, particularly high strength steels used in construction of offshore structures (because the same strength can be attained with thinner high strength steels than with regular mild steel), can be weakened by hydrogen. The absorption of hydrogen can embrittle the steel. The sources of this hydrogen are an overdose of cathodic protection and the biocorrosion coming from sulphate reducing bacteria (SRB). A very full description of the causes and effects of hydrogen embrittlement of high strength steel can be found in the UK Health & Safety Executive publication *A Review of the Effects of Sulphate Reducing Bacteria in the Marine Environment on the Corrosion of Fatigue and Hydrogen Embrittlement of High Strength Steels*, by M. J. Robinson and P. J. Kilgallon of the Marine Technology Centre, Cranfield University, UK.[11] However, this is only a relatively minor factor in the overall picture of marine corrosion in the vessels and rigs used in the offshore oil and gas industry.

11 Robinson, M.J., Kilgallon, P. J., *A Review of the Effects of Sulphate Reducing Bacteria in the Marine Environment on the Corrosion Fatigue and Hydrogen Embrittlement of High Strength Steels*, Marine Technology Centre, Cranfield University, UK, for UK Health and Safety Executive (1998).

Atmospheric corrosion

Corrosion is certainly not limited to metals immersed in liquids. Sea spray, for example, is a highly corrosive environment. As already mentioned, the splash zone is particularly susceptible to corrosion. But the topside is also prone to corrosion, even if to a lesser degree than the splash zone or the immersed hull. High humidity with consequent condensation, spray, rain, all create a corrosive environment in which the electro-chemical conditions needed for corrosion to take place exist.

Fouling organisms

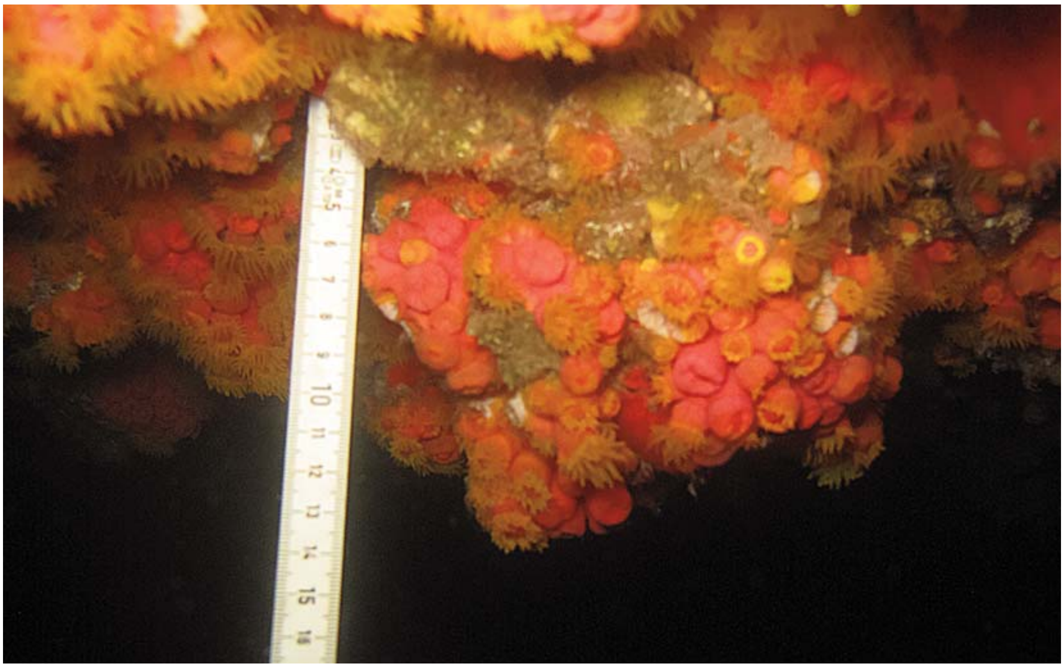
The presence of marine fouling, both micro- and macro-organisms, affects the rate of corrosion in various ways.

Fouling macro-organisms such as barnacles can damage all but the very toughest protective coatings, thus exposing an otherwise protected surface to the forces of corrosion. Once the coating has been compromised, corrosion can progress rapidly.

Marine organisms such as barnacles can affect the oxygen levels. A thick layer of marine organisms on a surface can reduce the amount of oxygen reaching the metal, thus protecting it. However, this can then promote the growth of anaerobic bacteria – bacteria which grow in the absence or near absence of oxygen. Some anaerobic bacteria reduce sulfates. Sulfate reduction has the byproduct of sulfides which can influence corrosion in certain metals. These bacteria substitute for oxygen in cathodic reactions.

Microbial corrosion

As described above, the waste products of bacteria can cause microbial corrosion of metals, known as Microbially Induced Corrosion or MIC. There are many types and varieties of bacteria involved and therefore of MIC. There are aerobic and anaerobic bacteria which cause corrosion in different ways. Two examples are sulfate-reducing bacteria (SRB)



Thick macrofouling rapidly develops on offshore vessels, even those, like this one, using conventional antifouling paint.

which cause sulfide stress cracking, and acid-producing bacteria (APB). SRB can cause corrosion under anaerobic conditions. APB act on metals just as an acid would.

Temperature

In general, higher temperatures result in greater corrosion. The rate of corrosion of steel almost doubles for every 10° C rise in temperature.[12]

Not all metals are equal

Different metals used in the construction of offshore vessels and rigs are affected by corrosion in different ways. In some cases these effects seem diametrically opposed. For example, aluminum, when it oxidizes, forms an even, protective layer of aluminum oxide, known as a passive film, which then acts to prevent further corrosion. It is self-protecting. However, at great depths in the Pacific Ocean, where oxygen is scarce, this oxide layer does not form and aluminum structures can corrode very rapidly. Conditions in the Atlantic at similar depths are not the same. On the other hand, steel, when it corrodes, forms the familiar red rust which is crumbly and porous and offers no protection from further corrosion. However, in the same Pacific Ocean low-oxygen depths, the corrosion of mild steel is much less than at sea level or near the surface where oxygen abounds.

Combinations of metals, depending on whether they are relatively noble (electrochemically inactive) or relatively base (electrochemically active) behave differently in a galvanic situation, where two dissimilar metals are in electrical contact in a corrosive environment (e.g., copper and steel in salt water). So, for example, in the unlikely event that the steel hull of a boat had a copper keel, the natural effect would be for the steel to corrode very rapidly while the copper hardly corroded at all. On the other hand, if the copper keel were to be exchanged for an aluminum one, the rate of corrosion of the iron would be greatly reduced and the aluminum would corrode rapidly. Aluminum is baser (more chemically active) than iron, which in turn is less active than copper, which is less active than silver, which is less active than gold.

Stainless steel behaves differently than mild steel. The two in combination behave differently than would a combination of bronze and mild steel.

Thus corrosion affects different metals and different combinations of metals in very different and sometimes surprising ways.

Types of corrosion

While the basic principles remain the same, there are many different types or manifestations of corrosion:

General corrosion is where the entire metal surface becomes corroded.

General corrosion.

12 SSPC, "Use of coatings to control corrosion of maritime structures," *Port Technology International* 32, 3 March 2011.

Pitting corrosion is a localized form of corrosion. This can be seen in at the bottom of cargo oil tanks or at the bottom of holds of bulkers. Deep pitting is not unusual.


Pitting corrosion.

Stress corrosion can be seen on metals that are under stress, and can result in cracking.

Crevice corrosion occurs, as the name suggests, in crevices such as where there are joints, in wire rope, bearings, sleeves, fastenings, the threads of bolts and other similar locations. This is compounded where the crevice is formed between dissimilar metals, such as a stainless steel cable passing through a steel hole, or a brass fitting attached to aluminum. Here we have galvanic corrosion accentuating the crevice corrosion.

Erosion corrosion, usually caused by flowing liquids.

Cavitation corrosion is a specialized form of erosion corrosion where the fluid dynamics are such that small bubbles or cavities implode against metal surfaces with tremendous force and heat and accelerate the corrosion process, sometimes alarmingly.


Cavitation erosion/ corrosion.

Galvanic corrosion occurs where two dissimilar metals are brought into electrical contact. The corrosion of the baser (less noble, more active) metal is accelerated.


Galvanic corrosion.

These and a number of other classifications and distinctions are used to describe different aspects of the same basic phenomenon. They are useful to the degree that they open the door to solutions to specific situations. For example, galvanic corrosion can be prevented by avoiding the use of different metals where an electrochemical reaction can occur. Don't use steel rivets in copper sheeting in saltwater or paint an aluminum hull with copper-based antifouling paint.

Corrosion zones

Different zones or areas of an offshore oil and gas exploration or production vessel or structure are subjected to different environmental conditions and are therefore more or less prone to corrosion. These zones can be divided up roughly into the following:

- Topside (atmospheric corrosion)
- Splash zone
- Submerged hull (outside)
- Inside the hull, single or double.
- Inside ballast tanks or cargo/ballast tanks.
- Inside cargo tanks where a variety of highly corrosive chemicals are stored and/or transported.

Complexity of the problem

In case the above section has failed to fully bring home the complexity and the multiplicity of factors which combine to make up "the corrosion problem" for offshore vessels and structures, the following extract from the 17th International Ship and Offshore Structures Congress of 2009, *Condition assessment of aged ships and offshore structures* should remove all doubt.

> Aging of ship structures may be defined as the progressive deterioration of structures as a result of normal operational use and environmental influences. The structural deterioration comes in the following forms:
>
> • Coating damage
> • Corrosion
> • Cracking
> • Deformations (dents), and
> • Changes in material properties.
>
> Coating damage
>
> Coating degradation can take the form of coating cracking, blistering, rust and flaking.
>
> Coating cracking takes place when structural deformation exceeds the elongation of the paint film. Blisters appear where an adhesion of the paint is locally lost. Blisters contain liquid, but there is no corrosion under the blister. Flaking refers to the lifting of paint from the underlying surface. The loss of paint adhesion is often a result of unsatisfactory surface preparation, incompatibility with under-layer and contamination between layers.
>
> Corrosion wastage
>
> Corrosion is the result of a chemical reaction between metal and the environment (water, cargo or consumables). Corrosion takes the form of general corrosion, pitting corrosion, stress corrosion cracking, corrosion fatigue, microbiological corrosion, galvanic corrosion, erosion corrosion, etc. (Boon et al 1997). General corrosion, which is the most common form of corrosion, spreads evenly over the surface of the metal.
>
> Pitting corrosion, which is localized corrosion, is often seen on the bottom of cargo oil tanks or in the hold structures of bulk carriers carrying coal and iron ore. The shape of the pits depends on the surrounding environment (Yamamoto 2008a). Microbes (bacteria) can cause corrosion, even on stainless steel, due to

their corrosive waste products. The most common bacteria are sulphate-reducing bacteria (SRB) and acid producing bacteria (APB). SRB cause corrosion under anaerobic conditions. Specific combinations of alloy and environment can lead to stress corrosion cracking when the metal is mechanically stressed while being exposed to the corrosive environment.

Galvanic corrosion occurs when two electrochemically dissimilar metals are physically connected and exposed to a corrosive environment. The less noble metal (anode) suffers accelerated corrosion attack. Erosion corrosion is usually caused by flowing fluid (water, cargo oil, etc) impinging at an existing corrosion cell. This kind of attack is dependent on the degree of liquid turbulence and velocity. In addition, corrosion may be aggravated in local areas of high stresses.

Rust is a corrosion product of an oxide and hydroxide generated to the surface of metal. Since the initial rust is porous and hygroscopic, the range of rusting expands and the paint film is destroyed. Rust is generated from the part where an adhesion of paint film is insufficient and a paint film is broken.

Many factors contribute to the degradation of coatings and corrosion. These contributing factors are: type of cargoes (acidity of the cargo), frequency of ballasting, frequency and method of tank cleaning, trapped water or oil, oxygen concentration, sulphur concentration, salinity of ballast water, temperature, humidity, pollution, trade route, structural flexibility, corrosion protection effectiveness, marine fouling, corrosion films, speed of flow, stray-current, cargo residues and mechanical abrasion, maintenance and repair, material of construction, microbial attack, sludge/scale accumulation, etc. (Gardiner et al 2003, Hu et al 2004, Panayotova et al 2004, 2007, RINA 2004). These factors act individually or in combination, and their influences are difficult to quantify. As a result, corrosion wastage of structural members is dependent on the location of the member (IACS 2005, Wang et al 2003a, 2003b, Yamamoto 2005, Paik and Melchers 2008).

Interaction of different degradation mechanisms

Corrosion and crack propagation can take place simultaneously. Crack propagation in corroded structures can be accelerated because the stresses in the structure increase as a result of corrosion wastage. Hydrogen cracking in anaerobic conditions may be strongly influenced by SRB. This cracking proves onerous for high-strength steels such as those used in the legs and spudcans of jack-ups. Mud and sludge in cargo oil tanks may provide the right circumstances for microbially influenced corrosion and resulting crack initiation (Rauta 2004).

Local dents are often the area initiating cracks. Removal of corrosion may be accomplished by scraping it off with the use of track-mounted cranes on a work deck. This scraping off process may significantly increase the loss of thickness initially caused by corrosion. Increased strains due to higher stresses as a result of thickness diminution or crack forming in combination with unaltered loads may stimulate corrosion.[13]

13 17th International Ship and Offshore Structures Congress 16-21 August 2009 Vol 2 p 314 - Condition assessment of aged ships and offshore structures.

While the subject of corrosion is highly complex in its details, causes and effects, nevertheless the problem from the viewpoint of those who operate vessels and immersed structures in the discovery and production of offshore oil and gas can be stated quite simply:...

Summary

While the subject of corrosion is highly complex in its details, causes and effects, nevertheless the problem from the viewpoint of those who operate vessels and immersed structures in the discovery and production of offshore oil and gas can be stated quite simply:

1. The natural tendency of most of the materials used in the construction of offshore vessels and structures is to corrode, resulting in wastage of material and weakening of the structures.
2. The sea is a severely corrosive environment.
3. The oil and gas cargoes stored and transported in tanks are often highly corrosive materials.
4. Therefore special measures need to be taken to protect the hull, inside and out, and the tanks of offshore industry vessels and structures to maintain structural integrity.
5. Because frequent drydocking of these vessels is not feasible, these special measures must be particularly effective and long-lasting without need of repair or replacement.

There is the problem. Is there an answer?

Part IV. Offshore hull and tank corrosion protection, past and present

From the first awareness of the fact of marine corrosion, efforts have been ongoing to solve the problem. Such is the nature of the human mind. Judging by the statistics and examples listed in the first two parts of this paper, however, these have not succeeded to the desired and required degree.

The main methods of corrosion control and prevention which have been attempted and are in use, often in combination, are

1. Choice of materials
2. Design of hulls and tanks
3. The use of corrosion inhibitors
4. Protective coatings
5. Cathodic protection systems
6. In-water cleaning of vessels and structures to remove fouling.

The main method addressed in this White Paper is protective coatings and their maintenance, which includes in-water cleaning. However, since these various methods are used in combination and some have specific applications, these are all worth examining individually and then in combination, even if the concentration is on coatings.

1. Choice of materials including the use of corrosion-resistant steel.

The material in general use for the hull envelope and ballast tanks of offshore vessels is normal, mild structural steel. It is the only material which is strong enough and economical enough for widespread use in constructing the hulls of ships.

More recently, corrosion-resistant steels have been introduced for use in cargo oil tanks. Different steels are used for the under deck than for the bottom of the cargo oil tank. These are not to be confused with corrosion-resistant alloys which are used for parts of ships. They are normal, weldable, high tensile shipbuilding steel and when in contact with seawater will corrode in the same way as the steel used on the hull. They have no benefit over normal mild steel if used on the hull or in ballast tanks. But they are an option for cargo oil tanks where they are less easily corroded than mild steel. The use of these steels is in part to comply with fairly recent IMO requirements for corrosion protection for cargo oil tanks of crude oil tankers contained in SOLAS II-1/3-11.[14]

A number of corrosion-resistant alloys have been developed and are in use on ships for fittings and equipment. However, the material in general use for the main hull and most tanks on offshore vessels and rigs continues to be mild steel.

This is so much the case that, for the purposes of this White Paper, the use of other materials such as stainless steels, copper and nickel alloys, titanium, aluminum can be disregarded. They exist and are important for specialized uses, but in the main, the hulls and tanks of offshore vessels and rigs continue to be constructed of mild steel with

14 IMO, MSC 87/26/Add.1, Annex 3, “Performance Standard for Alternative Means of Corrosion Protection for Cargo Oil Tanks of Crude Oil Tankers (2010).

no major shift in this practice envisaged. It is a matter of strength and economy.

2. Design of hulls and tanks to reduce corrosion potential or to maintain strength and integrity despite corrosion

For a considerable period of time, the general approach to dealing with corrosion in ships' hulls and tanks was simply to specify adequate scantlings, leave the steel bare and allow the corrosion to take its toll, replacing the steel when that toll reached the point where the structural integrity of the vessel was threatened.

The use of protective coatings and cathodic protection systems made it possible for classification societies and others to permit a reduction of those scantlings, on the understanding that the coatings and/or cathodic protection would be effective in limiting the corrosion wastage.

As explained earlier in this White Paper, a number of factors have arisen which encourage much longer intervals between drydocking of offshore vessels and rigs.

Today, in practice, many shipowners opt for full scantlings *plus* the protective coatings and cathodic protection. This multiple approach to protection from corrosion proves to be economically sound since steel replacement can be very expensive when one factors in the time spent in drydock to accomplish it or the cost of voyage or on-board repairs.

3. The use of corrosion inhibitors

Corrosion inhibitors are chemicals introduced into the internal parts of systems, such as piping, to reduce the corrosive effects of the fluids which are processed in those systems. They are not applicable to the outside hull. They can be used inside tanks. Their function is to reduce rather than prevent corrosion.

4. Protective coatings

As has been stated, if complete protection and isolation of the steel of the hull and tanks from corrosive elements can be achieved and maintained, there will be no corrosion.

The most reliable, effective and economically feasible means of protecting hulls and tanks from corrosion is through the use of protective coatings.

The most reliable, effective and economically feasible means of protecting hulls and tanks from corrosion is through the use of protective coatings.

When it comes to coatings for protecting hulls and tanks, the choice can appear bewildering: different types of coatings and coating systems and different brands of each type, all claiming to be the best, can make the final choice difficult.

There are three main approaches to coating steel in a saltwater environment, or three main coating types:

a. One approach is to create a barrier between steel and environment which is hard, impenetrable and impermeable, preventing the passage of any moisture, current, ions, electrons (in other words complete electrical insulation), chemicals or vapor from the environment to the underlying steel. This approach also assumes complete adhesion with no corrosive agents entrapped underneath. It also assumes that the coating will be durable, tough and flexible enough to continue to protect the steel for a long time. It is of course a lot to ask for from a very thin layer of material which must perform all these functions perfectly and for many years without failure.

b. The other two approaches assume that (a) cannot be achieved or maintained and try to deal with this in one of two ways. One way is to inhibit the effects of the corrosive elements which do penetrate the coating by reacting with the corrosive environment to create a protective film or barrier on the surface of the steel which will then prevent or at least slow down further corrosion. This approach has been in use for a long time, originally using an oil-based primer heavily loaded with red lead.

c. The other type of corrosion inhib-iting coating uses cathodically protective pigments in a base, usually in the form of additives in the primer. Particularly effective is an inorganic zinc-based primer such as a zinc-silicate, which is in very widespread use. These coatings work by shifting the potential of the corrosive elements which do penetrate the coating so that it is less cathodic and therefore less corrosive.

These different approaches are employed for different zones of the marine environment. The inhibitive and cathodic reducing approaches are not effective on the underwater hull or in ballast tanks where the steel is constantly immersed in seawater. Here the hard, impenetrable, impermeable barrier as described in (a) above is needed. The other two approaches tend to be more effective for the splash zone and topside where the wetting is sporadic and there is more likelihood of mechanical damage which obviously results in a penetration of the coating, creating a point from which corrosion can spread. These coating types then attempt to limit the extent and spread of the inevitable resulting corrosion.

Sometimes these approaches are attempted in combination, so a hard coating which attempts to provide an impenetrable barrier is used over a zinc-based primer, attempting a compromise. This approach is saying, “We’ll try to keep the corrosive elements away from the steel but just in case that doesn’t work, we’ll have a corrosion inhibiting primer as a back-up.” The corrosion inhibitor is just that, an inhibitor, not a preventer. Again, this approach is predicated on a failure of the coating to keep the steel fully isolated from corrosive elements.

The most prevalent type of hard coating is some form of epoxy. It is reasonably tough, fairly resistant to liquids, vapors and ions, fairly resistant to alkalis and salts and is easy to apply. However, epoxies do not tend to weather well. There are other resins in use. A more recent innovation is the use of polysiloxane (silicone) hybrid coatings, which blend organic resins such as epoxies with inorganic siloxanes. They have proved effective as topside paints. However, because all the synthetic resins in use are water absorbent and none of them meet the requirements described in (a) above, we are faced with the problems that make this White Paper necessary in the first place and which are described in its introductory parts. These coatings also do not last long enough to meet the requirements of the offshore oil and gas production vessels on the wetted hull, the splash zone and in ballast and cargo tanks.

There are a few other factors which affect the performance of coatings, such as the damage which can be done by ultraviolet light in the splash zone and topside, particularly to epoxy coatings. And there are many other types of coatings in use beyond the ones described above, different flavors and types of epoxy, other resins such as vinyls and polyesters.

Glassflake technology is available and in use and has proved to create very long-lasting and effective protection as will be explained later. The best coatings available are not necessarily in general use for a number of reasons. Preparation and application are key to the success of even the best coating.

The problem is really that the coatings in general use and the methods of application which prevail simply do not perform the job they are supposed to.

The problem is really that the coatings in general use and the methods of application which prevail simply do not perform the job they are supposed to. A compromise is then sought where the coating or the cathodic protection system attempts to mitigate the corrosive effects of the environment on the steel.

Faced with this admitted failure, observable in the real universe every day even when the results are not catastrophic, the owners and operators of offshore vessels and rigs have come to believe that the problem is not solvable.

5. Cathodic protection

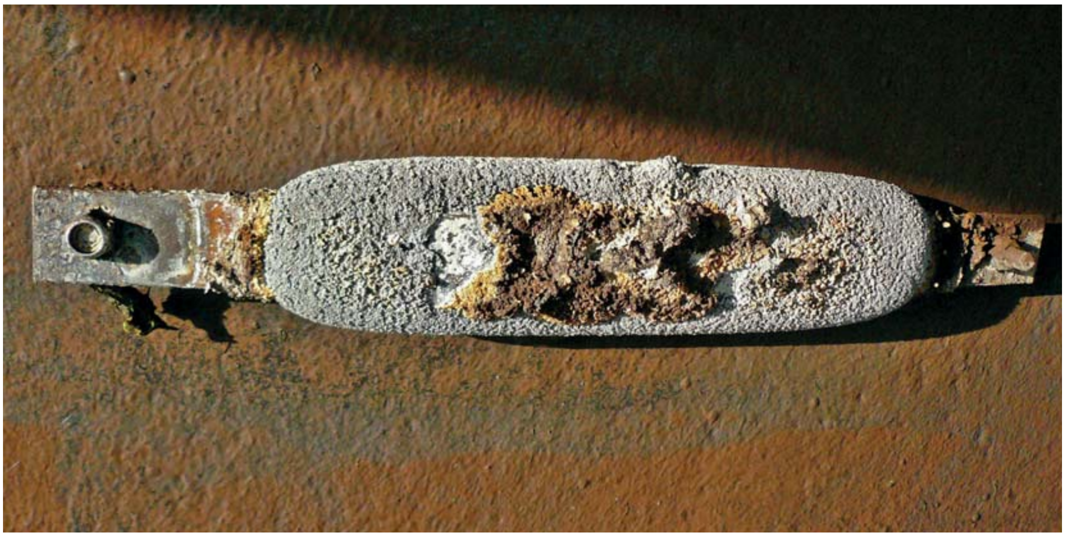
Cathodic protection works by balancing up the potential difference between the anode and cathode so that the electrochemical reaction is eliminated or reduced.

There are two ways to do this. One is by impressed current, where an external source of DC current is used to nullify the corrosive current being generated between the cathodes and anodes. The other is the use of “sacrificial” anodes, usually zinc or aluminum, strategically placed on the hull or in the tanks which utilize the galvanic action of metals with different potentials so that they become the anodes in the system instead of the steel on the hull or in the tank and are sacrificed to prevent corrosion of the steel.

This is particularly useful where the coating has failed to some degree and is no longer providing the protection it is supposed to. The cathodic system is then used to minimize the corrosion in the steel at those points of coating failure or inadequacy, holidays, blisters, flaking paint and other damage.

In theory a perfect cathodic protection system could conceivably retard all corrosion in bare steel. But this has not proven to be possible in practice.

An overcompensation on the part of a cathodic protection system can lead to a reverse of the anode/cathode relationship or to hydrogen embrittlement and weakening of the steel, particularly high strength steels. This can lead to cracking and failure.



Small sacrificial anode on vessel hull.

The most prevalent methods in use to reduce corrosion of the steel of ships' hulls and tanks are a combination of coating and cathodic system. These methods are based on an unspoken admission of failure on the part of coatings.

With all these possible answers and centuries of research and development and advanced physics and chemistry brought to bear, one may well ask why there is still such a major problem with corrosion, unsolved and apparently unsolvable.

The breakdown

The most usual sequence of breakdown in corrosion protection with resulting serious loss of steel and structural fatigue and failure is

1. the coating starts to break down for one or more of a number of reasons
2. this then exposes the underlying steel to corrosion
3. the cathodic protection system is inadequate to prevent the resulting corrosion
4. the corrosion sources combine and compound to accelerate the corrosion process so that in some cases the corrosion proceeds amazingly rapidly
5. the outcome is a long, costly stay in dry-dock or expensive on-board or voyage repairs involving extensive steel replacement long before the hoped for service life of the vessel has been reached.

This expensive and sometimes fatal downward spiral begins with a failure of the protective coating. It is the weakest link.

The following quote from a paper by Kenneth B. Tator of KTA-Tator, Inc. describes how this works.

Corrosion on the underwater hull begins with a failure of the coating.

> **Cracking of paint due to brittleness or loss of flexibility with aging is considered a primary factor in corrosion damage to the steel structures of ships' hulls, notably in seawater ballast tanks. This cracking is typically found in areas of coating stress concentrations such as sharp angles, fillet welds, transitions between structural details, weld toes, etc. Cracking is more severe for structural details made of high strength steel than for normal strength steel. This cracking is because thinner sheets of the high strength steel are used, and the lesser thickness results in greater flexing when the vessel is underway in rough seas.[15]**

The next section of this White Paper takes a more optimistic tone and examines the requirements of a fully effective solution to the problems of corrosion in offshore vessels, inside and out.

15 Kenneth B. Tator, "Risk Assessment and Economic Considerations When Coating Ballast Tanks," *NISt Special Publication 1035, Coatings for Corrosion Protection: Offshore Oil and Gas Operation Facilities, Marine Pipeline and Ship Structures*, April 2004, pp.102-3.

Part V: Real offshore corrosion protection

The key to solving the problem of steel corrosion in ships involved in offshore oil and gas exploration, production, storage and transportation is given in the following quote from *Marine Corrosion Causes and Prevention* by Francis L. Laque:

> **Since it has been demonstrated that electrochemical corrosion results from, or is accompanied by, a flow of current between anodic and cathodic surfaces, it should be possible to prevent corrosion by controlling the flow of corrosion currents. The ultimate objective is to suppress all current flowing from the anode in a corrosion cell.[16]**

While this is given as the theory for the workability of cathodic protection by sacrificial anodes or impressed current, there is another application for the theory. Attempts to prevent corrosion by cathodic protection alone have failed. Cathodic protection can help slow down corrosion rates and when used in combination with effective coatings helps reduce corrosion and the spread of corrosion where the coating is damaged, but on its own has not been able to prevent corrosion on steel.

However, if the steel could be fully coated with a tough, durable, impermeable and impenetrable coating which would stay on for the 25 - 40 year period required by the offshore oil and gas industry, then the corrosion problem would become a matter of mere historical interest.

However, if the steel could be fully coated with a tough, durable, impermeable and impenetrable coating which would stay on for the 25 - 40 year period required by the offshore oil and gas industry, then the corrosion problem would become a matter of mere historical interest.

How can one then protect the steel sufficiently to prevent corrosion entirely?

Glass

Glass is completely impermeable to liquids. It is entirely resistant to chemicals, acids, alkalies or salts. It is a complete electrical insulator. Nothing can get through it.

Unfortunately, despite all these wonderful properties, and the fact that one can entirely cover a metal with glass by fusion as in enamel, it is too rigid, brittle, fragile and expensive to be used in coating hulls and tanks to prevent corrosion.

The question is (or was) how to combine the valuable properties of glass with the tough, adhering and resistant qualities of the best synthetic resins.

Enter glass flakes.

Glass flakes were introduced into coatings around 1960. Since then they have gained popularity and have been used with a number of resins (polyester, epoxy, vinyl-ester) in many applications including marine corrosion protection, inside and outside ships.

By combining relatively large flakes of glass in a resin base in such a way that the flakes overlap each other, adhering firmly to the resin, in a fairly thick coating, one can achieve an impenetrable barrier which can protect steel from all the corrosive elements involved in the offshore oil and gas industry, both on the outside of the hull and on the inside of ballast and cargo tanks.

However, not all glassflake is equal, nor are all glassflake reinforced coatings, many of which exist.

16 Francis L. Laque, Marine Corrosion Causes and Prevention, John Wiley & Sons, (1975), p. 39.

Glassflake

All of the following factors are important in the effectiveness of a glassflake coating:

1. Type of glass used. There are several different types of glass that can be used for glassflake but C or ECR glass is the most chemically resistant and makes for a better glassflake reinforced coating. This glass is more expensive that other varieties and so raises the cost, but when considering cost one must take into account the life cycle of the hull and what longevity of corrosion protection one is seeking to obtain.

2. Method of manufacture. There are different ways to make glass flakes. One is called the bubble method. The other is the spun method. The spun method is more expensive but has many advantages in terms of quality and consistency. Again, the better product raises the cost somewhat, but when one compares the relatively slight additional cost of material and application to the huge expense involved in replacing corroded steel, the choice is obvious.

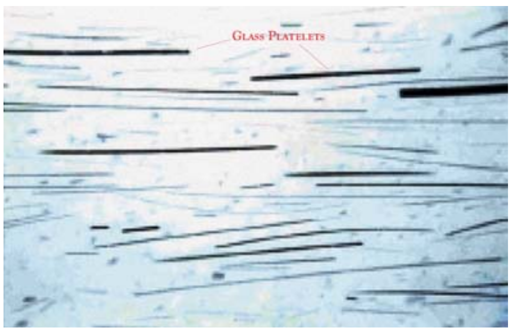
3. The size and aspect ratio of the flakes. In order for the glass to provide an impenetrable barrier, the flakes must be relatively large and have a large aspect ratio. Sometimes glassflake is micronized into a powder. This makes the eventual coating just as porous and permeable as if the glass were not there. The resulting coating has no value to the type of application being discussed here.

   Particles of a high aspect ratio e.g., low thickness to surface area, as for example with platelets or flakes, can overlap each other and extend the path length for diffusion in a film, presenting a barrier to the passage of moisture and gas diffusion by creating a tortuous path through it. Particles of a granular or spherical nature do not overlap and offer only limited resistance to diffusion through the film.[17]

4. Type of resin used. Although the glass itself is impervious to moisture and is capable of providing a complete barrier, in flake form the glass is not continuous. The type of resin used, the size and aspect ratio of the flakes (as in 1 above) and the proportions and final mix play a vital role in determining the effectiveness of the final coating and its ability to form a complete barrier between the steel it is protecting and the liquids, vapors, substances, ions and electrons it is protecting it from.

Traditionally, glass reinforced coatings have the longest life and offer the greatest protection against corrosion of any type of coating.

They can be used on the outside underwater hull of a ship, on the underwater gear such as rudders (they have the additional property of preventing cavitation damage to steel), stabilizer fins, nozzles, bulbous bows and other parts of the ship which are com-



Microscopic images of a high quality glassflake reinforced coating showing a high content of glass platelets with a large aspect ratio.

17 Simon J. Brigham & Charles Watkinson, "Understanding and Use of Glass Flake," Paint & Coatings Industry, 2 March 2009, p. 1.

pletely immersed. They can also be used inside ballast and cargo tanks. They can and should be used on the splash zone. They are not usually needed on the ship's superstructure.

An impermeable barrier

It is not enough to simply specify a "glass-flake reinforced coating," and hope that the rest of the details will take care of themselves. The success of glassflake reinforced coatings on the hulls of ships and inside ballast and cargo tanks depends on several factors:

1. type of resin
2. type of glassflake (type of glass and method of manufacture)
3. size and aspect ratio of the flakes
4. relative proportion of flakes to resin
5. the use of coupling or bonding agents to improve adhesion
6. the overall formula of the coating taking all the above and other factors into account
7. the thickness of the coating
8. the preparation of the surface to be coated (profile and cleanliness achieved prior to application)
9. the application itself (quality of application, conditions under which it is applied)
10. the maintenance of the coating during the life of the vessel.

If care is taken to optimize all of these points, (and it's not really as big an "if" as it appears) a near ultimate in corrosion protection can be achieved for the life of the vessel so protected.

Let's examine these in detail.

1. type of resin

This has been covered extensively earlier in this White Paper.

2. type of glass flake (type of glass and method of manufacture)

The type of glass required for the best results is C or ECR. This is chemical resistant glass.

The method of manufacture which creates the best glass flakes is the spun method. The bubble method, usually made from pre-melted glass marbles, has a tendency to produce curved flakes which are less desirable than flat, straight flakes, because they don't create the same impenetrable barrier. Product control is difficult with this method. On the other hand, the spun method produces very thin, flat flakes and lends itself to much tighter control of the final product.

3. size and aspect ratio of the flakes

Relatively large glass flakes are needed with a high aspect ratio (meaning that the surface area should be large in relation to the thickness of the flake). In particular granular or micronized glass is ineffective in terms of creating an impermeable coating.

4. relative proportion of flakes to resin

The proportion of glass flakes to resin is very critical. Impermeability increases with a higher glass content. However, too much glass will result in a coating that is insufficiently flexible to adhere to the steel and protect it. The correct ratio of glass to resin will produce the best results in terms of impermeability, toughness, abrasion resistance and surface hardness.

5. the use of coupling or bonding agents to improve adhesion

Treating the glass flakes with coupling or bonding agents improves tensile and flexural strength and reduces water absorption and vapor permeability even further, and thus should be included in the coating.

6. the overall formula of the coating taking all the above and other factors into account

The proper formula takes all of the above factors into account. The difference between a formula with all the above factors at optimum, compared to one where these factors have been shortcut or neglected is the difference between a coating which provides ultimate protection for the life of a vessel and one which fails rapidly.

7. the thickness of the coating

A thick coating, all other factors being equal, will provide better, longer-lasting protection than a thin one. A glassflake reinforced coating should be applied directly to the prepared metal to a thickness of 1000μm or more. With the right formula, this can be achieved by spraying on two coats, each of 500μm. Overcoat time is about three hours minimum, depending on conditions, and there is no maximum overcoat time which makes for a very flexible application schedule. Thicker coatings can be applied to provide longer protection.

Measuring the thickness of an underwater hull coating on a vessel in drydock.

8. the preparation of the surface to be coated (profile and cleanliness achieved prior to application)

Given a suitable coating, the most frequent cause of failure and subsequent corrosion is poor preparation of the steel. In order for the coating to work properly it must adhere thoroughly and uniformly to the entire surface with a sufficient key or profile to allow long-lasting adhesion and with a clean enough surface for the coating to bond firmly and permanently. The minimum standards required are therefore a 75μm profile and a cleanliness of SA 2.5 or SP 10 which is near white steel.

Gritblasting a hull prior to application of a glassflake coating.

A 75µm profile and SA 2.5 or better clean surface is needed for real corrosion protection.

9. the application itself (quality of application, conditions under which it is applied)

The coating must be applied correctly. This means that the preparation has been verified as uniformly adequate, that the prevailing temperature and humidity are within the specified range for application, that the spray equipment is thoroughly clean, that the right amount of catalyst is applied and properly mixed in and that the spraying is done evenly and correctly and the thickness verified. In between coats any flaws must be detected. After the second coat is applied, the overall film thickness must be verified and repaired where it is not adequate. None of this is demanding anything unusual; simply that the coating be standardly applied on a correctly prepared surface. Then the coating will perform as expected.

Application must be carefully monitored to make sure temperature and humidity is as specified.

10. the maintenance of the coating during the life of the vessel

Once the coating has been applied, the application verified and the vessel launched or undocked, there are still maintenance procedures that need to be observed in order to ensure that the coating continues to perform throughout its useful life. A glass-flake reinforced coating is usually slightly rough when first applied. When used on the outside hull, this can result in more friction than needed and also could lead to better adhesion of marine fouling organisms. Thus within a reasonable period of time, the hull should be cleaned underwater using special tools in order to clean and condition it. This first cleaning/conditioning removes any accumulated fouling and also smooths the surface, polishing the resin and leaving the glass more exposed. This type of coating can be cleaned as often as needed in the water without fear of damage to the coating but in fact resulting in a smoother hull. Because it is entirely non-toxic, cleaning does not present any environmental hazard. This conditioning or surface treatment leads to the name for this type of coating: Surface Treated Composite or STC.

Should the vessel need to drydock for any reason, the hull should be washed off and the coating inspected. Any mechanical damage should be touched up in order to restore the full integrity of the hull coating. This can be expected to be very minor.

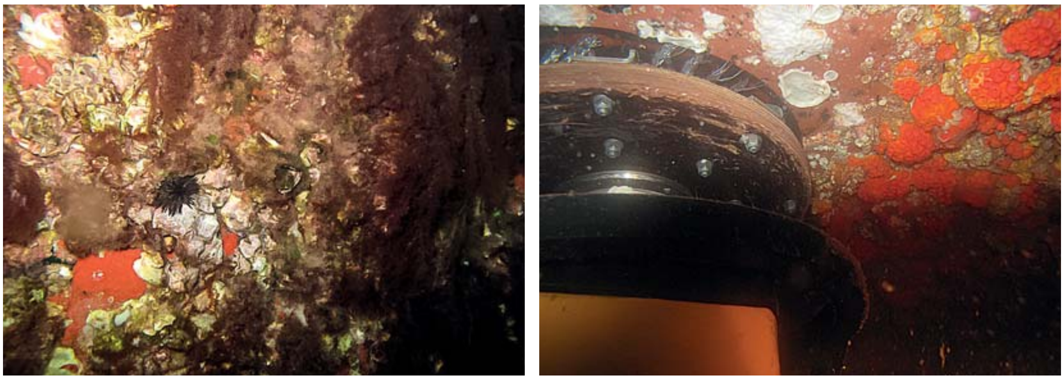
Benefits

A surface treated composite coating of this type offers many advantages in terms of corrosion protection both on the external hull and inside ballast and cargo tanks of offshore oil and gas exploration and production vessels. These benefits can be summarized in terms of

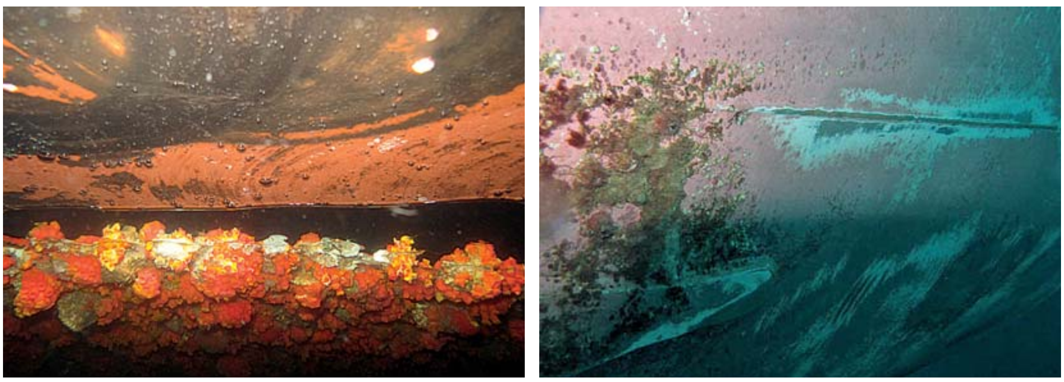
Underwater cleaning of a glassflake surface treated composite (STC) coating can easily be done without damage to coating or environmental hazard.

longevity, economy, safety and environmental.

1. A high quality, properly applied glassflake reinforced hull coating or tank coating of the type described above can provide protection from corrosion for 25 years or longer without need for drydocking to repair or replace the coating.
2. It will make the costly replacement of corroded steel unnecessary. This has a major impact on total ownership cost when one factors in the cost of the materials and labor, the expense of drydocking and the off-hire time avoided.
3. This type of coating can be cleaned as frequently as needed in the water without damage to coating or hazard to the environment. The coating remains as originally applied, becoming slightly smoother over time where it is on the hull and the hull is cleaned in the water. This helps in terms of weight and buoyancy of the vessel or rig and makes it possible for class inspectors to meet routine UWILD requirements. Fouling builds up very rapidly and heavily on a stationary structure such as a drilling rig or other offshore production or storage vessel, regardless of the type of coating in use, including biocidal antifouling coatings. Cleaning soft coatings such as AF or FR coatings is not practical for a number of reasons so a hard, cleanable, non-toxic coating has a great advantage in this respect.
4. The offshore vessel or rig maintains its structural integrity which is key to the safety of offshore operations.
5. Due to its non-toxic nature, an STC



Thick macrofouling rapidly develops on offshore vessels, even those, like this one, using conventional antifouling paint. Underwater cleaning of such hulls is difficult and causes damage to the coating as well as constituting an environmental hazard.



presents major advantages environmentally. This is an important point for offshore activities where impact on the environment often comes under close scrutiny.

6. The coating is easy to apply since it is sprayed directly onto prepared steel in two, three or four homogenous coats, each 500μm DFT, with a short overcoating time.
7. The coating has very low VOC content, another advantage from an environmental point of view.
8. If the coating is damaged mechanically, undercreep corrosion is virtually non-existent due to the very high adhesion level. Thus corrosion does not spread and the integrity of the coating is not compromised.
9. Although such a coating can and often is used in combination with cathodic protection, the work needed from the cathodic protection system is usually negligible, sacrificial anodes hardly losing any material, impressed currents kept very low.

It may appear to be more costly to prepare and coat an offshore vessel or rig in this fashion and with this type of coating. However, it is many times more costly to fail to protect such a hull or such tanks properly at newbuild stage and then find the coating failing, the steel corroding rapidly while the vessel is in service. In calculating costs it is necessary to look at total ownership cost, not simply compare the cost of different coating types and application methods.

The following quote from "Marine Corrosion Explained" on the Marine Corrosion Forum website summarizes this well:

> **Key factors in prevention of marine corrosion are design, selection of materials, construction, use and maintenance. Failings in any one of these may lead to a total failure to prevent attack, which once started may cost far more to correct or eliminate than any notional savings on materials achieved at the outset. In a recent survey corrosion was found to be responsible for 30% of failures on ships and other marine equipment. These are expensive errors arising from the selection and use of unsuitable materials and are compounded by ever increasing penalties on vessels, civil and military for breakdown and unnecessarily short intervals between outages for major repairs. On offshore platforms the cost penalty for replacement of failed equipment is several times that required for a similar onshore facility, and this does not take into account any losses of oil or gas production.[18]**

18 Marine Corrosion Forum, "Marine Corrosion Explained," http://www.marinecorrosionforum.org/explain.htm accessed August 2013.

Part VI. Ecospeed, Ecoshield, Ecolock

While there may be a number of superior coatings for the hulls and tanks of offshore oil and gas exploration and production vessels and structures, one in particular, Ecolock, meets all the above criteria and has been proven in action. Ecolock is an even tougher version of the hull performance coating, Ecospeed, a glassflake STC for general use, including ice-going vessels. Subsea Industries has developed and released Ecolock specifically for the long-term protection of the hulls of offshore vessels, as covered earlier in this White Paper.

Ecolock is a glassflake reinforced STC of the type described in Part V above, meeting all the specifications noted. It is additionally certified as an abrasion resistant ice coating[19] and DNV Class B1 rating as a ballast tank coating[20]. It is chemically resistant to a long list of substances including all those likely to be found in the cargo tanks of offshore vessels.

Ecoshield is a special formulation of the same glassflake reinforced coating which is designed specifically to protect rudders and running gear and to eliminate the damage to these parts caused by cavitation and

Ecospeed applied to a semisubmersible (above). Ecospeed being cleaned on the same vessel (below).

19 Lloyd's Register, "Recognized Ice Abrasion Resistant Coating," Certificate No.MNDE/20114335.
20 DNV, "Simulated Ballast Tank Testing of Ecospeed on Blast Cleaned Substrate," Report No. BGN-R2706374 (2006).

corrosion. Ecolock is a new formulation of the glassflake STC specifically designed for application to the hulls of offshore vessels as described in this White Paper. It is the answer to offshore hull protection.

With certain conditions, Ecolock provides a 25-year service life. As long as it is standardly applied, Ecolock comes with a 10, 15 or 20 year warranty if the coating has been maintained according to the specifications. The thickness of the coating can be increased to extend its longevity. None of these requirements are strenuous and are simply the conditions that need to be met for the coating to provide protection over the 25 year period involved.

Part VII. Next Step

To find out more about 25-year service life glassflake STC coating protection for your offshore vessel or fleet, call or email a request for a free consultation.

To find out more about Ecospeed, Ecoshield and Ecolock, visit the following websites:

www.ecospeed.be
www.ecospeed.us

If you would like to be added to the mailing list for future white papers on ship hull performance and related subjects and/or copies of the quarterly *Journal Ship Hull Performance* please go to the following link, register and state your preferences:

www.ShipHullPerformance.org

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