

# An Overview of Seabed Storage Methods for Pipelines and Other Oil and Gas Equipment

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In the construction of subsea oil and gas developments, it is increasingly common that subsea oil and gas equipment will be installed in subsea well before final hookup and production. Installation of wellheads, subsea hardware, pipelines, and surface facilities (platforms, FPSO, FLNG, connected terminals, or gas plants) are increasingly driven by independent cost and vessel availability schedules; this gives rise to requirements that the subsea facilities must be stored in the seabed for a specific time. In addition, schedule delays, particularly in the installation or startup of the connected platform, FPSO, FLNG, or onshore plant may cause unexpected extensions of the intended storage period. Currently, there are two methods commonly used for storage subsea facilities in the seabed: dry parking and wet parking. Each method has its own risks, challenges, and implications for the facility life and its integrity. The corrosion management and preservation method selection is a crucial factor to be considered in choosing the appropriate storage method and achieving a successful seabed storage. An overview of those factors is presented, along with a discussion on the internal corrosion threats and assessments.

**Keywords:** seabed storage, dry parking, wet parking, corrosion, microbial, chemical treatment

## 1. Introduction

The oil and gas industry is trending towards an increasing number of deep water developments, complex production facilities (e.g. FLNG) and hotter and more corrosive production sources requiring the use of corrosion resistant alloy (CRA) material clad and lined pipelines. Wellheads, subsea facilities and pipelines are increasingly being installed in separate operations, to take advantage of cost savings and vessel availability – these operations may be several years apart. The facilities can only be put into production (and exposed to the final corrosion control method) when the parent production facility – the host platform, floating production storage and offloading (FPSO), floating liquefied natural gas (FLNG) vessel, oil terminal or gas plant is available. Even if the installation process goes precisely to plan, the subsea assets may be installed several years before production begins. However, due to the ever increasing complexity of the production facilities, extended delays in delivery/startup are often encountered. This must be factored into the design and specification of seabed storage operations.

When the seabed storage goes wrong the consequences can be significant. The subsea facilities can be in a damaged condition with compromised integrity even before production is commenced. Even in mild cases, costly additional inspection and fitness-for-purpose assessments become necessary. In more severe examples, the design life of the equipment may be reduced, or equipment repair, replacement, or startup delays may be necessary. In a subsea development where billions of dollars have been invested, this risk has to be managed to an acceptable level. This paper describes the crucial factors that determine the success of seabed storage. The internal and external corrosion threats during seabed storage are discussed. Then guidelines are presented for the selection of the appropriate corrosion management and preservation strategies.

## 2. Storage Method Options

There are two common methods for storage of production equipment in seabed: “dry parking” and “wet parking”.

Dry parking is a method whereby the equipment is filled with gas. The gas could be dehydrated air or an inert gas such as nitrogen and may be at atmospheric pressure, or pressurised above hydrostatic ambient to resist in-leakage.

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**Table 1 Principal advantages and disadvantages of seabed storage method**

| Storage method | Filled Medium                                                | Advantages                                                                                                                                                                                                                                                                                                                                                                                                | Disadvantages                                                                                                                                                                                                                                                                                                                                                                                                   |
|----------------|--------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Dry Parking    | Inert gas (dry air, membrane nitrogen or cryogenic nitrogen) | <ul style="list-style-type: none"> <li>Effectively zero corrosion risk (oxygen or MIC) without in-leakage of seawater.</li> <li>No environmental impact disposing of biocide treated water or ethylene glycol (MEG)</li> </ul>                                                                                                                                                                            | <ul style="list-style-type: none"> <li>High risk of in-leakage of seawater, due to the high hydrostatic pressures. The use of gel plugs and double isolations would alleviate this somewhat, but the reliability of the sealing would have to be confirmed.</li> <li>Requires a large air dryer or inert gas generation spread or transport and storage of large quantities of inert gas to site.</li> </ul>    |
|                |                                                              | <ul style="list-style-type: none"> <li>Lower chloride content than seawater gives a lower theoretical corrosion risk.</li> <li>Lower initial solids and bacteria loading, particularly if sourced from municipal or drinking water supplies</li> </ul>                                                                                                                                                    | <ul style="list-style-type: none"> <li>Cost and logistics: for offshore flooding, potable water must either be shipped offshore or generated on site.</li> <li>Requires offshore storage.</li> <li>Lower density than seawater – will be displaced by raw seawater when an item is opened for tie-in or in the event of a leak.</li> </ul>                                                                      |
| Wet Parking    | Treated Seawater                                             | <ul style="list-style-type: none"> <li>Ready availability: No storage requirements offshore.</li> <li>No density gradient: the density of the flooding medium will be the same as the ocean, so much lower amounts of raw seawater ingress during tie-ins or in the event of a leak.</li> </ul>                                                                                                           | <ul style="list-style-type: none"> <li>Potentially more corrosive than MEG or potable water due to chloride (salt) content.</li> <li>Higher native bacteria loading, requiring greater biocide treatment, and a higher probability of MIC in the event of treatment failure.</li> </ul>                                                                                                                         |
|                |                                                              | <ul style="list-style-type: none"> <li>Manufactured product, so clean unless contaminated during shipping.</li> <li>Natural weak corrosion inhibitor.</li> <li>Sufficiently pure MEG will inhibit bacterial growth relative to potable or seawater.</li> <li>Probably the best flooding fluid for corrosion prevention.</li> <li>May not need to be displaced with fresh MEG prior to startup.</li> </ul> | <ul style="list-style-type: none"> <li>Cost.</li> <li>Requires bulk shipping to the field if used for riser or flowline flooding, and on-site storage.</li> <li>Environmental impact of disposal of the wet parking MEG if the chemical treatment or resultant contamination renders the MEG unfit for re-use as hydrate inhibitor or unable to be passed into the downstream production facilities.</li> </ul> |
|                | Potable or Demineralised water                               | <ul style="list-style-type: none"> <li>Lower chloride content than seawater gives a lower theoretical corrosion risk.</li> <li>Lower initial solids and bacteria loading, particularly if sourced from municipal or drinking water supplies</li> </ul>                                                                                                                                                    | <ul style="list-style-type: none"> <li>Cost and logistics: for offshore flooding, potable water must either be shipped offshore or generated on site.</li> <li>Requires offshore storage.</li> <li>Lower density than seawater – will be displaced by raw seawater when an item is opened for tie-in or in the event of a leak.</li> </ul>                                                                      |

In wet parking, the filling medium is a non-corrosive liquid, such as MEG, chemically treated potable water, or chemically treated seawater.

Table 1 summarises the storage methods, and associated principal advantages and disadvantages.

### 3. Corrosion Threats and Assessment

The principal potential risks of corrosion during subsea storage are discussed below.

#### 3.1 External corrosion

The risks of external corrosion due to seawater exposure during seabed storage (irrespective of the method chosen) are effectively the same as during normal operation. The potential corrosion rates are arguably lower due to lower temperatures, but the solution is the same application of anti-corrosion coatings and cathodic protection that will have been provided for the operational design life.

There are two minor additional threats inherent in seabed storage. The first is to ensure that the additional subsea exposure from the storage period is included in the CP design life; for example, a facility with a 20 year design life plus a 2 seabed year storage period will need

**Table 2 Concentration of bacteria in natural waters**

| Location                      |                                               | Concentration (cells/ml) |
|-------------------------------|-----------------------------------------------|--------------------------|
| Sea water                     | Continental Shelf & upper 200 m of open ocean | $5 \times 10^5$          |
|                               | Deep water (below 200 m)                      | $5 \times 10^4$          |
|                               | Deep water below (320 m)                      | $10^2$                   |
| Fresh waters and saline lakes |                                               | $10^6$                   |
| Potable water                 |                                               | $10^5$                   |

a CP system designed for 22 years, not 20.

The second is to ensure that all equipment installed for subsea storage has sufficient cathodic protection. The CP potentials on each piece of stored equipment must be verified after installation. A subtle threat is where equipment is interdependent for CP protection – i.e. one piece of equipment (e.g. a tie-in spool) relies on anodes on an adjacent piece of equipment (e.g. a manifold or pipeline) to provide the necessary CP current. If the dependant equipment (the tie-in spool) is not installed connected to the CP-providing item, the dependant equipment will not be protected. A design check must be carried out to ensure that each individually-installed piece of equipment has sufficient CP for the storage period. This may entail adding temporary storage anodes for disconnected dependant items.

### 3.2. Internal corrosion

#### 3.2.1 microbiologically induced corrosion (MIC)

Microorganisms can directly or indirectly affect the integrity of many materials used in oil gas systems, such as carbon steel, stainless steels, duplex stainless steels, as well as nominally corrosion resistant alloys such as alloy 825 and alloy 625. Viable microorganisms can be found over a surprisingly wide range of temperature, pressure, salinity, and pH, and are prevalent in seawater, potable water (to a lesser degree) and can even be found in industrial chemicals such as MEG. The bacteria concentration in natural waters is shown in Table 2 [1].

The bacteria that is responsible for MIC attack is not the planktonic (floating bacteria), but is the sessile bacteria (which attaches to the metal surface). During the colonization process, planktonic microbes from the aqueous phase quickly adhere to exposed metal surface and proceed to generate a slime made up of excreted extracellular polysaccharides (EPS). The slime envelopes the organisms and creates conditions for further development of microbial communities and possible MIC. The slime holds wa-

ter, collects nutrients, and recruits other microbes as well as particulates and other debris from the liquid phase. The slime also protects the organism from direct exposure of biocides at dosages that would readily kill planktonic organisms freely suspended in the water phase.

MIC does not occur as soon as a biofilm has been established. There is a lag phase during which the bacteria in the biofilm become adjusted to their environment. Industry experience with hydrotest corrosion failures suggests that it takes more than a week for a mature biofilm to establish itself in untreated seawater, and more than a month for filtered seawater [1].

Three main classes of bacteria are implicated in MIC in seawater and MEG environments. All are naturally present in seawater and (to a lesser degree) MEG and potable water, and are likely to be present in any oil and gas equipment.

##### 3.2.1.1 sulphate reducing bacteria (SRB)

There are several theories as to how sulphate reducing bacteria cause corrosion. In cathodic depolarization theory (CDT) the bacteria metabolise sulphate ions from the surrounding environment, releasing sulphide compounds and forming iron sulphide [2]. The iron sulphide produced accelerates the local corrosion rate through the creation of a more efficient cathode. In contrast, the bio-catalytic sulphate reduction (BCSR) theory proposed by Gu *et al.* [3] argues that the sulphide produced by the SRB is not the direct cause of the corrosion. The corrosion occurs when the biofilm hinders the supply of nutrients from the bulk fluid, so the SRB directly metabolise iron from the metal surface. Other possible corrosion mechanisms are oxygen concentration cells and forming insoluble sulphides when metal ions combine with sulphur [4].

Additionally, the biofilm contains a homogeneous population of SRB. As biofilms are widely heterogeneous, they will almost certainly contain APB, many of which thrive in anaerobic environments, so any given biofilm has the potential to cause significant corrosion.

### 3.2.1.2 acid-producing bacteria (APB)

APB release aggressive organic (acetic, succinic, isobutyric, etc.) or inorganic (sulphuric) acids as by-products of metabolism, which cause corrosion beneath the colonies formed by these bacteria. APB can also generate a biomass material that can lead to under-deposit corrosion, or fouling of downstream systems.

### 3.2.1.3 general aerobic bacteria (GAB)

General Aerobic Bacteria is less corrosive in their own right than SRB or APB, but can cause crevice corrosion due to oxygen and concentration gradients between the colony and the bulk fluids. They can also cause bio-fouling.

### 3.2.2 oxygen and chloride corrosion

Dissolved oxygen in seawater is one of the most constituents affecting corrosion since it is the principal reactant involved in the cathodic reaction and is involved in the passivation reaction that occur for most metals and alloys in seawater [5,6]. It was reported that as low as 50 ppb, oxygen had created pitting corrosion in natural gas and crude oil production [7].

The effect of the dissolved oxygen level on corrosion is dependent on the metal. For metals that form passive films like stainless steel and aluminium, a high oxygen content is favourable in that it helps to delay the initiation of pitting on the metal surface. However, once pitting is initiated, the propagation rate is increased with oxygen content in the seawater [5,6].

Chlorides accelerate corrosion by increasing the electrical conductivity of the water so that the flow of corrosion currents is facilitated. Chlorides also reduce the effectiveness of natural protective films, which may be permeable to small ions.

Seawater, even when drawn from medium depths, contains dissolved oxygen, and all seawater contains high lev-

els of chloride salts. Table 3 shows the most encountered form of corrosion form of various materials immersed in seawater [8,9]. Alloy 825, 22 chrome duplex or AISI 316L are highly susceptible to internal corrosion from raw seawater with the possible form in pitting, galvanic and crevice. All would be severely corroded by medium or long term exposure to raw seawater. Deoxygenated seawater is likely to be tolerable by alloy 825 and 22 chrome duplex. AISI 316L is much more likely to suffer unacceptable corrosion. As the oxygen is irreversibly consumed by the scavenger chemical and cannot be replaced without in-leakage, there is little time dependency in oxygen corrosion management.

MEG is manufactured oxygen free by the source chemical plant, and therefore non corrosive. However it is likely that even with significant precautions taken during delivery (e.g. inert gas blanketing of storage tanks, purging of equipment), the MEG will become oxygenated during decanting, storage, transport to site, and injection into the pipeline or riser.

Internal corrosion of solid or clad alloy 625 items is unlikely when exposed to oxygenated MEG. Alloy 625 is normally considered near immune to seawater corrosion in a non-flowing environment at the ambient conditions on the seabed. A small amount of pitting corrosion is possible, particularly on welds. Corrosion inhibitor is unlikely to be effective in preventing any corrosion.

The risk of corrosion in 25 chrome duplex items exposed to oxygenated MEG is fairly low, with a small chance of crevice corrosion depending on temperature. The thin walled umbilical cores and riser carcasses are particularly vulnerable to corrosion.

Deoxygenating the flooding water or MEG using oxygen scavenger is highly likely to remove any residual risk of oxygen corrosion in alloy 625 and 25 chrome duplex, however little practical information of the behaviour long term exposure to deoxygenated MEG or seawater is available in the public domain. It is highly likely that internal

**Table 3 Corrosion form of various materials immersed in seawater**

| Material        | Corrosion Form      |                   |         |          |         |
|-----------------|---------------------|-------------------|---------|----------|---------|
|                 | Generally resistant | General Corrosion | Pitting | Galvanic | Crevice |
| Carbon Steel    |                     | •                 |         |          |         |
| Stainless Steel |                     |                   | •       | •        | •       |
| 22 Cr Duplex    |                     |                   | •       | •        | •       |
| 25 Cr Duplex    | •                   |                   |         |          |         |
| Alloy 625       | •                   |                   |         |          |         |
| Alloy 825       |                     |                   | •       | •        | •       |

oxygen corrosion can be controlled by the oxygen scavenger.

### 3.3 Chemical treatments for wet parking

The primary method of corrosion control during wet parking operations is chemical treatment of the flooding medium. The three main classes of chemical treatment are as follows:

#### 3.3.1 biocide

Biocide serves two purposes when used to manage bacterial corrosion.

The first purpose, which occurs when the biocide is first introduced into the fluid or equipment, is to kill as many existing bacteria as possible. This provides an immediate mitigation of the bacterial corrosion threat based purely on the numbers of bacteria. However it is important to note that biocide will never kill all bacteria in any system. Some will be naturally immune, and some will be protected in colonies by slime layers.

The second function, which occurs more in the long term, is a *bio-stat* function; the chemical maintains a lethal environment, and prevents the surviving bacteria from growing, reproducing or spreading. As soon as the concentration of biocide falls below lethal values, bacteria can start to re-colonise the equipment, and cause corrosion. Unlike oxygen scavenger, which is an irreversible reaction, biocide must be maintained at lethal levels for the entire duration of the wet parking period.

Biocide is naturally consumed over time, even in a stagnant wet parked system. The consumption rate is dependent on many factors such as biocide type, environmental pH, water cleanliness, bacterial loading, presence of oxygen, and temperature. The rate of consumption of the biocide is difficult to predict accurately, making calculating the required dose highly uncertain and introducing an inevitable risk of failure of the treatment before the end of the storage period. This is why it is common industry practice to specify a biocide dose suitable for twice the maximum anticipated wet storage period.

The dosage of biocide is critical, and must be carefully monitored and controlled when it is added to the storage fluid. In addition, oxygen scavenger may react with biocide, consuming one or both so the mixing of the chemicals must be carefully designed and controlled. Like any chemical dosage, a detailed procedure must be written, and comprehensive quality assurance programme put in place to ensure a correct and effective dose.

Historically, wet storage periods have been restricted to 1-2 years at most. Given proper specification, qualification and application of the biocide, industry experi-

ence is generally successful in preserving equipment for these periods. However, recent practice as described in the introduction to this paper has seen the intended or contingency storage periods beginning to push well beyond 2 years. This is uncharted territory for biocide performance, with little experience or laboratory data available to determine the appropriate chemical or dose. Extensive laboratory qualification is required before attempting extended wet storage, and consideration should be given to methods of circulating, re-treating or refreshing the storage medium mid-way through the storage period where feasible.

#### 3.3.2 oxygen scavenger

Oxygen scavenger is a substance that is injected into a flooding medium to remove dissolved oxygen and render it non-corrosive. Typical oxygen scavenger chemicals are hydrazine, sodium bisulphite or ammonium bisulphite. These irreversibly react with any free dissolved oxygen in the storage fluid, so that (with no in-leakage), once oxygen has been reduced to an acceptable level, it will remain so effectively indefinitely.

Oxygen scavenger is injected at a level determined stoichiometrically by the initial level of dissolved oxygen in the storage fluid. The dosage is effectively independent of the seabed storage period. As sulphite based oxygen scavengers provide a food source for microbial corrosion, and may interfere with the performance of some biocides, it is essential that oxygen scavenger must not be overdosed, and that no more than the minimum dose able to reduce the oxygen to non-corrosive levels (below 20 ppb) is used [10].

The most critical success factors in oxygen scavenger treatment are ensuring that:

- The oxygen scavenger is dosed correctly prior to injection. The calculated dose must be sufficient to consume the native dissolved oxygen, plus any oxygen from air already in the item itself. The metering must be carefully controlled and constantly monitored during the flooding or filling operation. Any off-specification fluid must be discarded and not injected. Samples should be taken to verify the correct dosage via chemical assay.
- The oxygen scavenger is properly mixed and distributed into the storage fluid.
- The storage fluid is not exposed to oxygen (air) after being treated with oxygen scavenger, as this will re-oxygenate the fluid and render the treatment ineffective.
- Treated fluid must completely fill all void spaces in the item being filled. No air gaps or air locks must

be permitted to remain.

- The duration of storage has little or no bearing on the decision to use oxygen scavenger, as the oxygen corrosion it prevents is generally rapid, and consumes the oxygen irreversibly. Once the initial dissolved oxygen is consumed by corrosion, no further damage will occur. The amount of damage is directly proportional to the amount of oxygen allowed into the system.

### 3.3.3 corrosion inhibitor

Corrosion inhibitor is sometimes also added to flooding water, but recent practice has moved away from this as (a) most corrosion inhibitors are only marginally effective against oxygen corrosion, (b) corrosion inhibitors are ineffective against bacterial corrosion, and (c) corrosion inhibitors generally require flow to function well. They are often packaged with biocides and oxygen scavenger in combined preservation chemicals, but should not be considered as mandatory.

## 4. Corrosion Prevention

### 4.1 Dry parking internal corrosion prevention

#### 4.1.1 seawater in-leakage

Dry parking would be a major operation, and a full design review is required to determine the equipment and design required to implement it.

Facilities to inject and accurately meter oxygen scavenger into the flooding MEG or seawater, and to take samples for testing will be required on the vessel performing the flooding.

For all storage methods, the greatest threat comes from in-leakage of raw seawater after the equipment is laid on the seabed. To prevent this, all leak paths to the ocean must be provided with double blocks, or pressure tested diverless connectors. Failure to provide this level of isolation exposes all equipment to a significant corrosion hazard.

#### 4.1.2 microbial corrosion

Dry parking effectively removes any threat of microbial corrosion if the target dewpoint is achieved. The main threat is associated with seawater in-leakage, described above.

#### 4.1.3 oxygen and chloride corrosion

Preventing internal oxygen and chloride corrosion during dry parking relies upon eliminating water. Pipelines will generally be installed dry. Ideally, this would be maintained and the pipeline put straight into dry parking without exposing it to water. However the need for

hook-up or tie-in to other subsea facilities, or pressure testing prior to storage generally requires the pipeline to be flooded. In this case, the pipeline must be fully dried before dry parking. The usual sequence of events is to bulk dewater the pipeline with a pig train (usually including one or more MEG swabs). Then dehydrated gas (air or nitrogen) is passed through the pipeline until the exiting gas reaches the desired dewpoint (usually circa 5-10 °C below the local minimum ambient seabed temperature). A vacuum may be drawn on the pipeline to assist in drying. Once the dewpoint target is achieved, the pipeline or system is sealed for the duration of the storage period. Dehydration of pipelines and subsea facilities is a common and relatively technically straightforward process, but the infrastructure is extremely costly, and the operation can be time consuming. Deployment of air dehydration or nitrogen generation spreads, plus the optional vacuum drying spread is a major undertaking and cost.

Dry parking (performed properly) will effectively eliminate any threat of internal corrosion from oxygen or chlorides as long as the specified gas dewpoint was achieved and no in-leakage occurred.

### 4.2 Wet parking corrosion prevention

#### 4.2.1 MEG

##### 4.2.1.1 microbial corrosion

MEG is sterile when manufactured, but it may be contaminated with corrosive bacteria during transport (e.g. from inadequate tank cleaning), decanting, injection or from bacteria already present in the subsea equipment itself. MEG is not as effective a bacteria growth medium as seawater, and generally has less nutrient present, but bacteria growth is nonetheless possible.

The requirement for biocide treatment of MEG should be determined by the material of the item being stored, the length of storage required, and the initial cleanliness of the item itself and the MEG.

Items made of higher grade corrosion resistant alloys (e.g. Alloy 625, Alloy 825, 25 Chrome Duplex) do not generally require biocide in MEG unless either the storage period is extremely long (> 2 years) or the MEG or item is suspected to be badly contaminated with bacteria. Shorter term storage, clean MEG or clean systems are less likely to require biocide. Carbon steel, stainless steel or lower grade corrosion resistant alloys such as 22 Chrome Duplex will generally require biocide when stored with MEG, unless the storage period is short (< 1 year).

##### 4.2.1.2 oxygen and chloride corrosion

The requirement for oxygen removal from MEG is mar-

ginal, and practice varies. In small flooding volumes, short flooding durations, high grade stainless or CRA applications or where the MEG is naturally supplied oxygen free, deliberate oxygen removal is often not required. Larger volumes, lower grade stainless or carbon steels or heavily oxygenated MEG would be more likely to require oxygen removal.

It should be noted that specialised oxygen scavengers are required for MEG service, and these may have a substantially longer reaction time, and require higher dosage than oxygen scavengers used to treat potable or seawater.

#### **4.2.2 potable water**

##### **4.2.2.1 microbial corrosion**

Potable water contains much lower levels of bacteria than seawater and is chlorinated which acts as a mild biocide. The initial level of bacteria is comparable or lower than MEG. It contains lower levels of sulphates and organic matter, so results in lower levels of bacteria growth and MIC risk than seawater, again comparable to MEG.

##### **4.2.2.2 oxygen and chloride corrosion**

Oxygen removal for potable water flooding is not required by the many industry standards due to the reduced corrosion risk associated with the lower chloride levels. For higher grade corrosion resistant alloys (e.g. alloy 625, alloy 825, 25 and 22 chrome duplex), oxygen scavenger would not be required. Carbon steel and lower grade stainless steels would generally require oxygen scavenger.

#### **4.2.3 seawater**

##### **4.2.3.1 microbial corrosion**

Seawater inherently contains large quantities of SRB, APB and GAB. The naturally occurring sulphates in seawater, plus organic matter provide food sources for growth, and seawater is a better growing medium for bacteria than MEG. Seawater flooding poses a greater MIC threat than MEG. Biocide treatment of seawater is mandatory for any storage application, except for extremely high grade corrosion resistant alloys (e.g. alloy 625, titanium) with relatively short storage times (< 1 year).

##### **4.2.3.2 oxygen and chloride corrosion**

It is conventional practice to treat flooding seawater with oxygen scavenger to eliminate the risk of oxygen corrosion. This is particularly relevant to carbon steel, but is also relevant to lower grades of stainless steel (e.g. AISI 316L and 22 chrome duplex) which may suffer crevice corrosion in oxygenated fluids.

## **5. Corrosion Monitoring During Storage**

### **5.1 Dry parking**

As discussed above, seawater leakage becomes the greatest threats on dry parking method. Therefore, inspection and monitoring should be taken with the focus on:

- In-leakage detection.
- Contingency plan for displacing raw seawater with treated in the event of a leak.

### **5.2 Wet parking**

Irrespective the fluid medium used in wet storage method, below are the corrosion monitoring that should be taken.

#### **5.2.1 bacteria monitoring**

For bacteria monitoring, steps that should be taken include:

- Testing during flooding.
- Keeping samples of the original fluid.
- Taking samples from the stored item where possible.
- Contingency plan for re-dosing, circulation or replacing flood fluid if bugs are detected or for long duration storage.

#### **5.2.2 oxygen monitoring**

The monitoring of oxygen level is only required during flooding – no further testing needed.

## **6. Preservation Method Assessment**

### **6.1 Dry parking**

Dry parking is a high performance, but potentially high risk method of storage. It has been used successfully in the past (i.e. Malampaya project), but it is a much less common option than wet parking. The primary benefits of dry parking are that:

- Systems with few or no potential leak paths – systems that are mechanically complete and have been pressure tested. Systems with temporary seals (lay down heads, flanges etc.) still in place are far more prone to leak.
- Applications where a large surface facility (e.g. a platform) particularly with a source of dehydrated gas is already available to supply the drying medium, or on projects where drying is already required as part of the pre-commissioning plan. Mobilising a full dehydration spread just for storage is unlikely to be economic.
- Shallow water applications, as the interventions required to connect and operate large diameter down lines for gas delivery and vacuum drying are more difficult in deep

water applications unless a surface facility is available.

- Smaller volume applications, as dehydrating large volumes and generating large volumes of dry gas is time consuming and expensive.

## 6.2 Wet parking

### 6.2.1 MEG

MEG is commonly used to flood smaller items of sub-sea facilities such as wellheads, jumpers, the production manifold, MEG flying leads, MEG umbilical cores, etc. These items are generally flooded before installation.

MEG is most suited for:

- Medium to long term storage, as bacterial growth is much less likely than other methods.
- High value assets, where the lower corrosion risks justify the cost of the MEG
- Gas projects using MEG as a hydrate management fluid, where the MEG can be collected and recycled into the anti-hydrate MEG system after startup. Note: the effects of any treatment chemicals on the MEG regeneration system must be checked before this is applied. In addition, MEG from the flooding may contain elevated levels of dissolved metal or salts, and so may prohibitively increase exchanger fouling and scaling in the MEG regeneration system during startup. It may also increase filtration requirements if corrosion solids or biomass are generated during the flooding period. If the MEG cannot be recycled, the attractiveness of this option is somewhat diminished.
- Smaller volume systems, as transport and storage of MEG is expensive
- Less environmentally sensitive areas, or projects where recovery and disposal of the flooding medium is feasible, as otherwise disposal of large quantities of treated MEG can be problematic.
- Systems with lower grade corrosion resistant alloys (e.g. 22 Chrome Duplex) or stainless steel clad linepipe (e.g. AISI 316, 317 or 321).

### 6.2.2 treated potable water

Potable water storage is most suited to projects where:

- Smaller volume systems or larger volume systems where potable water is readily available, for example pipelines traversing onshore, or near shore locations. Transporting or generating large quantities of potable water offshore may not be feasible or economic in other circumstances.
- Environmentally sensitive regions where disposal of MEG or biocide treated water is challenging.
- Systems with lower grade corrosion resistant alloys (e.g.

22 Chrome Duplex) or stainless steel clad linepipe (e.g. AISI 316, 317 or 321).

- Regions with excessively contaminated local seawater.

### 6.2.3 treated seawater

Treated seawater is historically the most common seabed storage medium. Ready availability on-site, and the low cost of filtration and chemical treatment, coupled with the generally acceptable reliability of the chemical treatments makes it the first choice for most offshore projects. Treated seawater is most suitable for:

- Large volume systems, due to the low costs and infrastructure requirements.
- Carbon steel or high grade corrosion resistant alloy systems.
- Short to medium term storage.
- Lower value assets.
- Systems which are more corrosion tolerant (e.g. high corrosion allowance steel pipe).
- Systems where samples can be taken during the storage period to verify the biocide performance
- Systems which can be readily inspected after storage.

It is less suitable for:

- Systems with lower grade corrosion resistant alloys (e.g. 22 Chrome Duplex) or stainless steel clad linepipe (e.g. AISI 316, 317 or 321) which are highly sensitive to seawater corrosion and failures of chemical treatments.
- Systems requiring cleanliness (e.g. MEG injection pipelines or systems with MEG recirculation) as some degree of corrosion is likely, potentially leading to fouling of filters and injectors or iron scaling of regeneration reboilers.
- Long term storage (> 2 years) or projects with higher uncertainties in the duration of the storage period.

## 7. Conclusions

This paper discusses the options, advantages, costs and risks of common methods of seabed storage for subsea facilities. The following conclusions are drawn:

1. Dry parking carries the lowest corrosion risk if the seal can be maintained (no seawater ingress), however is relatively high risk in most circumstances, and relatively technically difficult and costly. It is a specialised technical option for specific circumstances.
2. Wet parking with MEG is commonly used to flood smaller items of sub-sea facilities. The use of MEG is a medium cost, high reliability option for bigger items or long term storage, and is particularly attractive if the flooding MEG can be re-used.
3. Potable water flooding is technically feasible. However



the small advantages of using potable water when compared to properly treated seawater or MEG are often outweighed by the cost and effort required to ship or generate bulk potable water offshore. It is again, a specialised option, most suited to sensitive materials, long term storage, or environmentally sensitive areas.

4. Seawater flooding remains the most common method of seabed storage for most systems with the exception of those containing stainless steels. It is sufficiently reliable for short-medium term storage, but only given rigid adherence to chemical qualification, treatment and injection quality standards, and continuous monitoring where possible. Longer term storage with seawater becomes technically questionable, requiring extensive chemical qualification trials.

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