Corrosion and cathodic protection engineering expertise applied to an offshore regasification terminal

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Abstract

This paper reviews how corrosion and cathodic protection engineering expertise is applied in many forms and at various levels to ensure the integrity of Adriatic LNG terminal. The terminal includes an offshore gravity based structure (GBS) for offloading, storing and regasifying the LNG and a pipeline to export the natural gas to the national grid. The deep knowledge of corrosion degradation mechanisms and Non-Destructive Testing (NDT) is essential for developing and managing the Risk Based Inspection (RBI) process on pressure piping and equipment. The knowledge of the behavior of different materials exposed to different internal and external conditions allows to screen the most critical items and optimize the inspections. The know-how on concrete degradation mechanisms drives the optimization of concrete coring and the assessment of the durability of the structure. The assessment of the resistance of steel structures exposed to offshore environment is also an important result of the application of corrosion engineering. Furthermore, the expertise in cathodic protection is deployed in the ambit of periodical underwater inspections of the metallic structures anchored to the GBS and of the offshore and onshore pipeline sections. Broadly speaking, the engineering approach to issues such as integrity and inspections is discussed and reviewed.

Keywords: integrity, risk based inspection, cathodic protection, durability.

Introduction

The Adriatic LNG (ALNG) Terminal (Figure 1), located about 15 kilometers offshore the Italian coastline in the Northern Adriatic Sea, is a unique facility utilizing innovative technology to provide a safe and efficient offshore LNG offloading, storage and re-gasification capability. The terminal is a large gravity based structure (GBS) resting on the seabed at 29 meters mean sea level. The structure is 180 meters long by 88 meters wide, with a height of about 47 meters.

The plant has a regasification capacity of 8 billion cubic meter per year, approximately 10% of the country's yearly natural gas consumption.

The GBS contains two LNG storage tanks with a total working capacity of 250,000 cubic meters, approximately twice the capacity of a conventional LNG carrier. Major process equipment includes four loading arms, four in-tank LNG pumps, five high-pressure send-out pumps, four Open Rack Vaporizers (ORV's) which use seawater as the heating medium, a Waste Heat Recovery LNG Vaporizer (WHRV) which uses waste heat from the turbine generators, and two Boil-Off Gas (BOG) compressors.


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Figure 1: The Adriatic LNG Terminal.

Risk Based Inspection of pressure piping and equipment

In order to continue to pursue safe and reliable operation as well as optimal management of inspection related costs, Adriatic LNG and Cescor s.r.l. developed a risk-based approach focused on prevention of potential loss of containment from pressure vessels, atmospheric storage tanks and piping in processing and utility facilities.

The RBI methodology optimizes the inspection activities in order to rationalize inspection frequencies and the required level of accuracy, producing as a main result the development of an effective inspection plan: the inspection optimization process reduces the overall inspections costs and increases the level of confidence in detecting equipment degradation phenomena which might produce potential failures.

The RBI methodology, originally developed and commonly applied for upstream oil and gas assets, has been adapted for the case of an offshore LNG regasification terminal.

The RBI process includes the following steps:

i. data and information collection,
ii. definition of homogeneous piping circuits,
iii. definition of expected degradation mechanisms and related probabilities of occurrence,
iv. risk assessment,
v. inspection program and inspection plan,
vi. inspection execution,
vii. inspection data analysis.

The accomplishment of the risk assessment step implies the deployment of a specific knowledge of the behaviour of each type of material exposed to different internal and external conditions. For the case of ALNG a number of material classes are involved: carbon steels, stainless steels, titanium and GRP. The list of fluids is also wide and includes process fluids such as cryogenic LNG, natural gas, seawater, water/glycol mixture plus a number of utility fluids such as diesel, fuel gas, potable water, sodium hypochlorite, nitrogen, instrument and plant air, etc. In addition, items installed on the offshore terminal can be bare, coated or thermally insulated. A specific coating is applied as a function of the involved component. Thermal insulation is adopted for cold service and hot service. In both cases two layers are usually observed: the external layer, which is a sort of barrier (made of stainless steel or a polymeric resin), and the inner layer, where different materials are adopted for the two cases, in the first one cellular glass, polyurethane foam or mineral wool, in the second one cellular glass or perlite silicate. In addition, the materials may be exposed to a wide range of operating conditions.

The possible degradation mechanisms depend on the combination of several factors, including:

- the material of construction;
- the type of transported fluid;
- the operating conditions;
- the environmental conditions in which the component operates.

For the elaboration of inspection programs and inspection plans a deep knowledge of corrosion degradation mechanisms and NDT is essential. In general, degradation mechanisms have preferential locations where they take place in a vessel, storage tank or along a pipe and the knowledge of these locations is very important for inspection planning and optimization. The application of a NDT unsuitable to detect a possible degradation mechanism certainly leads to wrong results; at the same time, the application of a suitable NDT to the wrong location may lead to misleading results as well.

The output of the inspection planning is the identification of the most suitable non-destructive technique for the detection of a specific type of degradation mechanism. Different types of techniques are available: some are aimed at the identification of metal loss due to general corrosion while others at identification of crack-like defects. Moreover, the definition of an adequate number of measurements is another critical aspect of inspection planning: the inspection of a too small area or the collection of a small sample of measurements may lead to miss a potentially critical damage while the execution of too many measurements results in a waste of time and economical resources. The purpose and the final target of the inspection planning is to find the best possible balance between these two opposite factors. An example of inspection optimization for a pressure vessel is reported in Figure 2.

The corrosion engineering expertise is also helpful in supervising the execution of the inspections. The role of Company representative during an inspection campaign is the key in ensuring the successful accomplishment of the objectives and targets of the campaign. In addition, the verification of the compliance of the executed activities with those recommended into the inspection plan is another important responsibility of the Company representative.

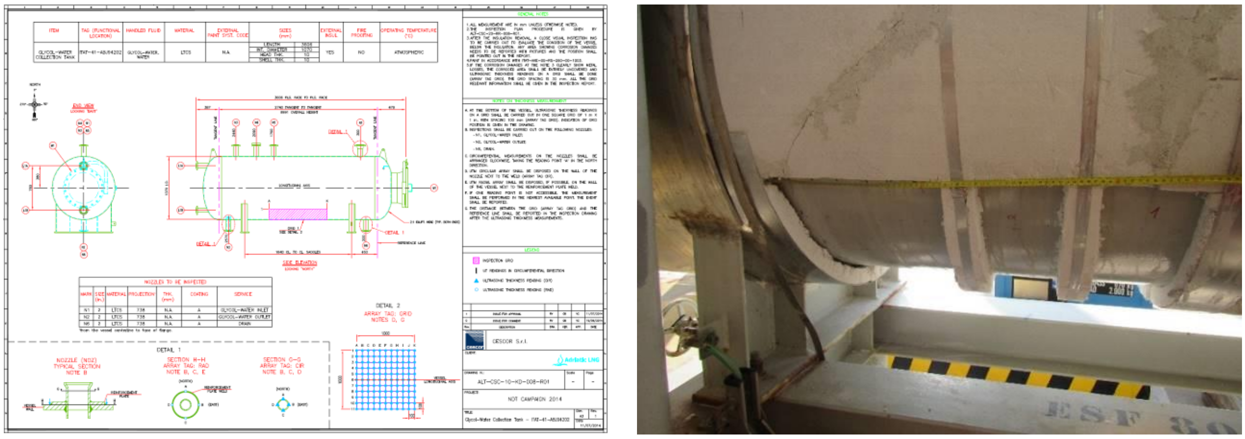

Figure 2: Example of inspection optimization.

Finally, inspection data interpretation requires engineering capabilities and specialistic expertise to get the most from the collected data in terms of knowledge of the actual status of the inspected component. Moreover, expert judgements regarding the integrity of a component shall be in charge of qualified corrosion and materials engineers.

<u>Concrete durability</u>

The Gravity Based Structure (GBS) is a huge "box" made of reinforced concrete immersed in seawater for about half of its height. The reinforcement system counts different levels of steel reinforcements (stirrup, main steel reinforcements, post tensioned steel reinforcements) which are all embedded in the middle of the lateral and inner walls. The inner structure of the GBS is made up by a number of adjacent compartments located at two different elevation levels and characterized by different dimensions and functions. Some of them are void, some host pumps or other components, some are filled with sand and seawater for ballasting purposes, others work as storage tanks for utility fluids like potable water and fire water.

In addition, the underwater section of the external walls of the GBS are equipped with galvanic anodes which provide protection to all the underwater metallic structures electrically connected to the anodes.

Concrete is porous to air and seawater, thus, as a function of the external environment, steel reinforcements may suffer from corrosion (as detailed below). In particular, the time for corrosion to occur depends not only on the exposure conditions, but also on the thickness of the concrete cover and the permeability characteristics of the concrete cast.

The know-how on complex concrete structures, their degradation mechanisms and their durability was deployed in a number of ways, such as:

- Assessment of degradation mechanisms for concrete structures;
- Preparation of the job specification for concrete coring;
- Supervision to the execution of concrete coring;
- Analysis of the concrete laboratory results;
- Assessment of the durability of the concrete structures.

Steel reinforcements in concrete are normally protected by a thin and adherent oxide layer which is formed by interaction of iron with the alkaline environment (pH = 13) of the concrete. Corrosion in concrete can start and propagate due to the mechanism of carbonation or contamination with chlorides.

Carbonation of concrete leads to complete dissolution of the protective layer due to the effect of CO_2 in the acidification of the pH of the concrete around the steel; chlorides, instead, cause localized breakdown when they are present in very large amounts at the steel surface.

The assessment of concrete degradation mechanisms comprises all the specific exposure conditions met in the GBS.

The GBS structure is exposed to different external environments (i.e. atmosphere, splash zone and immersion in seawater) which contain different amounts of chlorides and oxygen. Chlorides-induced corrosion show itself as follows:

- Aerial zone: for parts exposed to the atmosphere, oxygen can easily penetrate into the concrete cover, but chloride penetration is relatively low. On the other hand, when the concrete contains some cracks, the penetration of chlorides can be accelerated and corrosion rates may be increased. Localized corrosion of steel reinforcements starts when the chloride ion concentration in the concrete around the reinforcements reaches a critical threshold, which is between 0.4 and 1.0 % in weight with respect to cement (incubation time).
- Splash zone: in the splash zone, the concrete walls are exposed to alternating wetting and drying conditions. In the wetting periods, due to the high tide level or waves / salt water sprays, water penetrates into the concrete by capillary absorption or by permeation. In the drying periods, the evaporation of water, which occurs much more slowly, leaves in the pores the salts originally dissolved in the water and, in the meantime, promotes the oxygen ingress. Once chloride contamination level reaches a critical threshold for corrosion initiation, corrosion rates can be quite high with stabilization of macrocells connecting contaminated areas with passive rebar where the availability of oxygen is high.
- Immersed zone: for water immersed reinforced concrete structures, corrosion rates are generally lower compared to structures exposed to atmosphere. In this condition the concrete pores are completely filled with water and due to negligible oxygen diffusion rate the corrosion rate is very low or negligible, independently of the anodic reaction. However, if the immersed concrete structure is severely cracked or otherwise locally damaged, localized corrosion on steel reinforcements can initiate also in submerged zones. A specific case in which corrosion can also occur in immersed concrete structures is the one of concrete walls with one side exposed to chloride containing water and the other side exposed to air. To stop corrosion, it is sufficient to weaken or to stop the macro-cell circulating current. This is easily obtained by applying a cathodic protection system on the side of the reinforcement exposed to the seawater.

In addition, post tensioned steel reinforcements, installed in galvanic ducts filled with mortar, may be subject to corrosion phenomena that lead to the initiation and propagation of cracks. Atomic hydrogen can be produced by the cathodic reaction of a corrosion process. Then the atomic hydrogen can penetrate to the metal lattice and accumulate near the crack tip, which can lead to failure without warning. The risk of hydrogen-induced stress-corrosion cracking (HI-SCC) of post tensioned steel reinforcements was assessed.

Concrete coring was required to check the concrete characteristics with respect to the design requirements and for the purpose to assess the durability of the structures. The GBS is a huge structure and during construction different concrete castings were required. Project documentation showed that different mix designs were used for the different concrete castings.

The objectives of the concrete coring campaign (see Figure 3) were:

- To measure the chloride diffusion coefficient, D, which characterizes the chloride penetration resistance typical of concrete casting;
- To measure maximum penetration of chloride at specific location (especially in correspondence of “splash zone”, the most critical area). This measurement assesses the actual chloride penetration and is helpful to verify the chloride penetration modeling used;
- To assess the carbonation depth into concrete (aerial part).

Figure 3: Concrete coring campaign.

The job specification for concrete coring of GBS and mooring dolphins covers the following aspects:

- Procedure for core drilling;
- Selection of locations for core drilling, taking into account accessibility issues along the external vertical walls of the GBS;
- Dimensions and number of core drilling samples;
- Procedure for concrete repairing;
- Personnel and instrumentation requirements.

Personnel with a recognised competence and know how in concrete coring were also required to participate to the coring campaign for coordination and supervision. In fact, the compliance with the coring specification was a priority for ALNG.

Finally, all the available data, included the results of the laboratory analysis on drilling samples, were used to carry out a durability assessment of the GBS concrete. The study was a comprehensive assessment of the status of the GBS. The exposure conditions of all the concrete walls have been considered: boundary walls, internal walls at different levels, slabs at different elevation (top, middle, bottom).

The results of drilling samples laboratory analysis were used to estimate the time necessary for chlorides to reach the stirrups, the main steel reinforcements and the internal ducts containing the post tensioned steel reinforcements.

Recommendations were also provided to cope with potential and ascertained criticalities.

Integrity assessment of steel structures exposed to marine environment

In addition to pressure piping and equipment, a number of structural steel components are installed on the offshore terminal (see Figure 4). Some of them, for example the flare boom, ladders, handrails, are exposed to the marine atmosphere only while others, like the breasting structures, the boat landing and the riser protector, are partially immersed in seawater, partially exposed to the splash zone and partially exposed to the offshore atmosphere.

The correct and expert application of ISO 9223 and ISO 9224 standards allows to estimate the corrosion rate for the most common engineering metals for structural applications exposed to the atmosphere. Carbon steel, zinc, copper and aluminium are the engineering materials considered by the standards.

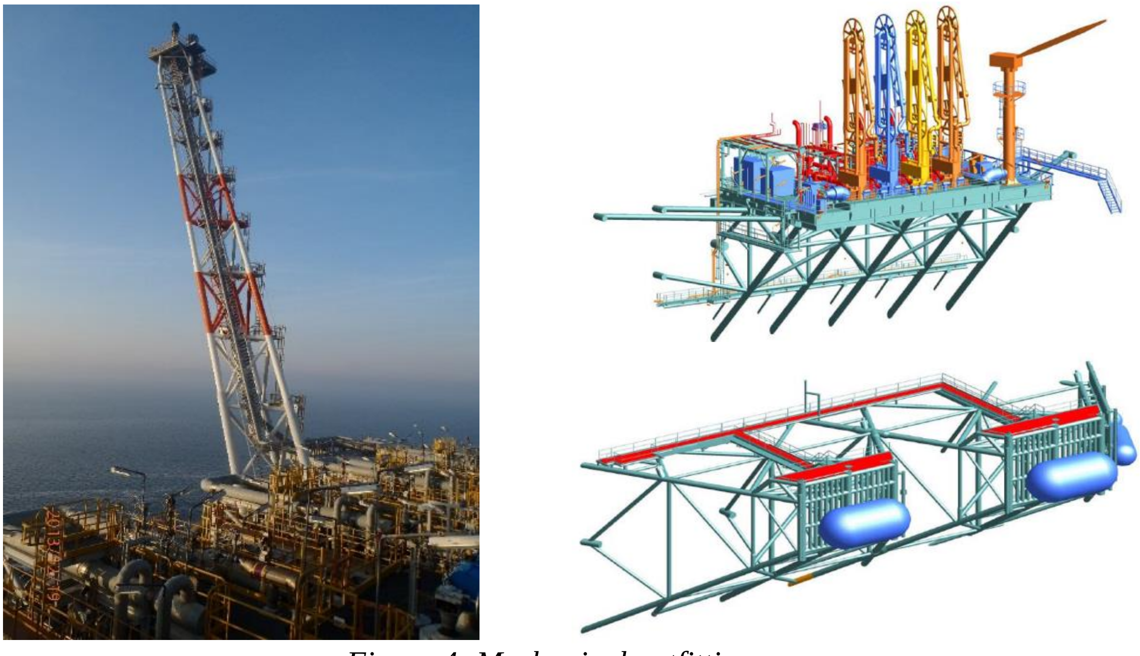

Figure 4: Mechanical outfitting.

ISO 9223 classifies the aggressiveness of the atmosphere into 6 categories of corrosivity based on the one-year corrosion effect. The standard also allows the calculation of the first-year corrosion rate (also referred to as the *dose-response function*) based on annual average environmental parameters like temperature, relative humidity, chloride deposition and SO_2 deposition.

Long term exposure corrosion rates can be estimated by applying ISO 9224 standard. For most metals and alloys exposed to natural outdoor atmospheres, corrosion rate decreases with exposure time because of the accumulation of corrosion products on the surface of the metal exposed. The progress of attack on engineering metals and alloys (when the total damage is plotted against exposure time on logarithmic coordinates) is usually observed to be linear for the first period of exposure while it tends to progressively decrease for longer exposure time.

Estimation of the cumulative metal loss due to corrosion over the design life of a bare metallic structure exposed to the atmosphere can be reasonably estimated by applying the approach proposed by ISO 9224.

The correct application of the ISO 9223 and ISO 9224 standards and the interpretation of the numerical results are within the expertise and responsibilities of a corrosion and material engineer.

Cathodic protection inspections of offshore structures

Underwater metallic structures protected against seawater corrosion through the application of a cathodic protection system are:

- Riser, expansion loop and offshore pipeline;
- Mechanical outfitting (e.g. breasting structures, boat landing, riser protector, etc.);
- Metallic reinforcement bars and plates embedded in the GBS concrete structure.

The concrete metallic reinforcement bars and the immersed part of mechanical outfitting are protected against corrosion by a cathodic protection system made of galvanic anodes installed on the immersed part of the external walls of the GBS. The galvanic anodes are electrically connected to the concrete reinforcement bars and in turn to the mechanical outfitting.

The riser is also electrically connected to the anodes installed on the GBS walls while the expansion loop, located at the base of the riser, and the offshore section of the pipeline are equipped of their own bracelet galvanic anodes.

The expertise in cathodic protection was deployed to perform a number of activities related to the cathodic protection inspections of immersed metallic structured.

The first activity is the preparation of the job specifications for CP underwater inspections, documents which define:

- The requirements for general and close visual inspections (see Figure 5);
- The requirements for potential measurements;
- The guidelines for randomly sampling galvanic anodes to be inspected;
- The requirements for anodes survey;
- The requirements for data reporting;
- Check lists for data collection.

Figure 5: Underwater close visual inspection of mechanical outfitting.

Personnel with recognized certification and technical background in cathodic protection were also deployed for the coordination and the supervision of the offshore inspection campaigns. In addition to the Company representative role, the supervision of the inspection campaign also had the possibility to verify the accurate execution of the inspection and the compliance with all the requirements set into the job specifications.

Finally, analysis and interpretation of cathodic protection inspection data as well as the comparison with cathodic protection data from previous inspection campaigns is within the duties and responsibilities of a well-trained and certified cathodic protection engineer. The data interpretation is a very important activity which gives value to the economic resources and the organizational efforts invested into the preparation and execution of an inspection campaign.

Onshore cathodic protection inspections

The pipeline connecting the offshore GBS to the onshore Metering Station in Cavarzere is about 30 km long. For about half of its length the pipeline run onshore through cultivated fields, grasses and rural areas. The pipeline crosses and intercepts rivers, lagoons, streets, railways and high voltage cables.

The maintenance requirements for an onshore buried pipeline are well defined by the international normative.

Certified cathodic protection personnel are being deployed regularly at site for three years for carrying out periodical interventions (ordinary maintenance) such as on/off potential measurements, 24-hours interference registrations at rail crossings, checks and regulations on T/R operating parameters, verifications of the efficiency of insulating joints, etc.

In addition, in 2015, the Close Interval Potential Survey (CIPS) in combination with the Transverse Gradient Method (TGM) with a spacing of 5 meters were jointly applied (as required into the pipeline equipment strategy) for the verification of the correct protection status of the pipeline and the possible presence of defects in the external coating.

A more high-profile application of the cathodic protection expertise was the verification of the interference with high voltage aerial cables parallel to the pipeline. The intervention was requested by ALNG to compare the present degree of interference with the one that will establish as the result of the imminent burying of the high voltage cables in a trench that will run parallel to a section of the pipeline.

Also in this case the CP know-how was applied for data interpretation and comparison with respect to data from previous inspections.

Material consultancies

Maintenance operations on the offshore terminal sometimes require specific support from the material and corrosion discipline to cope with some unexpected problems.

One example was the request for selecting the most adequate material for the anchoring bolts and nuts of the passage ways grids exposed to the tides and waves. Two alternative solutions have been proposed. In both cases the material selection for the involved components has been performed considering the requirements on mechanical properties and the need to avoid galvanic phenomena and protective coating damages.

Another request was the material review of the Waste Heat Recovery Unit in light of modifications of the water/glycol mixture circulating into the close system. The presence of residual oxygen and chlorides into the mixture required a verification with respect to the operating conditions and the construction materials, mainly carbon steel, 304L stainless steel and 316L stainless steel. For carbon steel, the compatibility of the available corrosion allowance with respect to the maximum expected oxygen corrosion was carried out while the risk of Stress Corrosion Cracking (SCC) for stainless steel component was assessed.

Conclusions

The practical cases described into this paper show and demonstrate how the corrosion and cathodic protection engineering expertise can be applied in many forms and at various levels to ensure the integrity of a huge and complex offshore structure along its service life.

The competence on materials, corrosion and cathodic protection proves to be more and more important in the modern oil and gas industry and it turns out to be more and more useful and necessary to manage ordinary maintenance operations and successfully implement periodical inspection programs.

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