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Choosing the Right Coating System for Offshore Valves to Prevent External Corrosion

Karan Sotoodeh[1]

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Abstract
Corrosion is a common problem in the oil and gas industry. Environmental conditions outside of oil and gas facilities can cause external corrosion, which has severe negative consequences, such as human death, environmental pollution, loss of assets and production, fines and loss of reputation for companies. Therefore, the objective of this study is to prevent external corrosion in the offshore environment by selecting the appropriate coating system. The presence of chloride and seawater in offshore environments is one of the most common causes of external corrosion of valves, typically in the form of pitting corrosion and chloride stress cracking corrosion (CLSCC). External offshore corrosion can be prevented by selecting a suitable coating system, as this paper emphasizes. As a result of experimental results and standardization, zinc rich epoxy, thermal spray aluminum, and phenolic epoxy are widely used in the Norwegian offshore industry for offshore valves. This paper describes in greater detail how to select coating systems for offshore valves based on parameters such as operating temperature, insulation requirements, and valve body materials. The proposed methodology has been developed in accordance with the NORSOK M-001 standard as well as practical project specifications.

Keywords Zinc rich epoxy · Phenolic epoxy · Thermal Spray Aluminium (TSA) · Coating systems · Coating standardization

1 Introduction

There is a great deal of corrosion in the oil and gas industry which is undesirable [1, 2]. A corrosion-conscious approach is imperative for field operators, pipeline engineers, and designers to ensure smooth and uninterrupted delivery of oil and gas to end users since the lines and their component fittings will undergo material degradation due to corrosion [1–3]. According to the definition of corrosion, it is the gradual destruction of materials (mainly metals) caused by chemicals and/or chemical reactions with their environment [4, 5]. As a result of the processing of petroleum and gas, this may occur at any point in time [6]. Despite the fact that many different types of corrosion can occur in the oil and gas industry, they can generally be divided into two categories: internal corrosion and external corrosion. As a general rule, internal corrosion occurs in the oil and gas industry because of the presence of corrosive compounds such as carbon dioxide and hydrogen sulphide in produced oil and gas, and water and other corrosive media in piping and facilities [7, 8]. External corrosion occurs as a result of environmental conditions outside of oil and gas facilities. As the name implies, it is the natural interaction between the exterior surfaces of facilities, such as piping and valves, and the soil, air, or water surrounding them. External corrosion may be aggressive and persistent due to a variety of highly localized factors [9]. There are three types of corrosive external environments: offshore, underground, and under-insulation. The term "offshore" refers to areas that are located away from the coast. "Offshore" refers to oil fields and natural gas deposits that are developed under the sea in the oil and gas industry. Due to the presence of sea water and chlorides in the offshore environment, the external environment is highly corrosive, causing general corrosion, pitting corrosion as well as chloride stress cracking corrosion (CLSCC) [10]. There is no doubt that the main or dominant type of offshore corrosion is determined largely by the microstructure of the material. The majority of materials used for offshore valves fall into three main categories:

✉ Karan Sotoodeh
karan_sqi@yahoo.com

[1] Baker Hughes, Oslo, Norway

Fig. 1 An insulated actuated valve designed to conserve heat and protect personnel(Courtesy: Shutterstock)

Fig. 2 Severe corrosion under insulation (CUI) in the piping system(Courtesy: Shutterstock)

ferritic steels, austenitic steels, or a mixture of both. Steels such as carbon steels are ferritic steels, while stainless steel 316 is considered an austenitic steel. As its name implies, duplex stainless steel is ferritic-austenitic in composition. Additionally, the 6Molebdenum alloy that is used for valves installed on flare lines is considered super austenitic. In the offshore environment, carbon steels are more susceptible to general and pitting corrosion. Chloride stress cracking corrosion, however, is typically associated with austenitic stainless steels such as stainless steel 316. However, both duplex and austenitic stainless steels are susceptible to pitting corrosion. As with carbon steel, ferritic stainless steels are not used for offshore valves, but, as with carbon steel, they are more prone to pitting corrosion. Like austenitic stainless steel, super austenitic stainless steel is susceptible to pitting and chloride stress cracking corrosion. There is an underground corrosion problem that is associated with the piping and pipelines installed under the ground in the soil [11, 12]. It is important to note that underground piping ensures that fluid will not be interrupted by external factors such as roads, cars, or other facilities while it is being transported. Various reasons may justify the insulation of piping systems, including industrial valves, including keeping them warm or cold, preventing fires, protecting personnel from high temperatures, or isolating the source of noise from the pipes [13]. It is illustrated in Fig. 1 that an actuated valve has been installed on the piping system and covered with insulation in order to conserve heat and protect personnel. As a result of a variety of factors, such as rainfall, water and moisture are present in the offshore environment, which can pass through the coatings and accumulate on the surfaces of the pipes and valves, causing localized corrosion to occur [14]. According to Fig. 2, a piping system with a strainer and connected flanges has a severe CUI.

2 Research Problem, Novelty, Motivation, and Contribution

2.1 Research Problem

It is well known that corrosion is a constant problem in the oil and gas industry especially offshore and it is present in all projects. Corrosion, as mentioned in the introduction section, is an undesirable phenomenon with many negative consequences such as loss of human life, pollution of the environment, loss of production and assets, fines, and a loss of reputation for the company [15]. Every oil and gas plant has piping systems, including valves, which may account for approximately 25% of the initial cost [16]. By using various approaches, end users and contractors have attempted to prevent corrosion in various ways, such as selecting the most suitable material, selecting and applying coatings, providing cathodic protection, and making and using corrosion models [10, 17]. For piping and valves in the offshore oil and gas industry, the application of the coating is the most common method of preventing external corrosion. All types of corrosion mentioned in the introduction section, including pitting, CLSCC, and CUI, can be prevented by selecting the right coating system for the external surface of the piping. The coating is applicable to both piping and valve components installed under the sea as well as those installed on a ship or platform [18].

2.2 Novelty

A number of studies have been published in the last four years regarding the application of coatings to piping systems in the oil and gas sector. In a recent study, corrosion-resistant coatings for seawater piping components were examined [19]. The main study focus is on selection and application of internal coatings especially cemented carbide to prevent internal corrosion due to sea water flowing through the piping system [19]. In this study, there are two major limitations: first, it is limited to internal pitting corrosion rather than an external corrosion types, and as a consequence, it is limited to internal coatings rather than external coatings. In the other recent study, the focus is on the qualification of coatings used to prevent CUI [20]. During this study, it was determined that operating temperatures and thermal conditions play an important role in the selection of the proper coating [20]. Furthermore, various coating tests can be used to provide an indication of how the coating will perform in the real offshore environment [20]. As a result of this study, there are two major limitations: the first is that it is limited to CUI external corrosion type prevention and the second is that it does not provide any systematic approach or algorithm for selecting the appropriate coating based on various parameters such as operating temperatures. Another paper discusses the use of epoxy coatings such as phenolic epoxy to prevent CUI [21]. According to the paper, phenolic epoxy can be used up to 200 °C operating temperatures and adverse experiences have been reported regarding cracking and failure of phenolic epoxy [21, 22]. In this study, however, a major gap exists in providing a novel coating selection approach that can be applied to offshore oil and gas valves [23]. There has been a book published by the present author on coatings for pipes, valves, and actuators. The book examines the external types of corrosion as well as coating defects and systems applicable to piping and valves primarily in offshore environments. A separate chapter is devoted to preparing the surface of metal so that the coating adheres sufficiently to prevent premature failure of the coating. However, the book does not provide a systematic method for selecting the most appropriate coating based on various factors, including the material of the valves, the operating temperature, and the presence of insulation.

Based on the literature review, this paragraph summarizes what is known about the types and selection of coatings for corrosion prevention, as well as identifies gaps. According to the literature review in the previous paragraph, the following information is known:

- Application of corrosion-resistant coatings to piping systems in seawater to prevent pitting corrosion and CLSCC.
- Testing and qualification of coatings in accordance with various American Society of Test and Material (ASTM) standards for the prevention of CUI.
- An important consideration when selecting a coating system is the operating temperature.
- Using phenolic epoxy coatings to prevent CUI and cracking is a very common failure mode of this type of coating [24, 25].
- It is essential to prepare the surface of the metal substrate before applying a coating in order to prevent premature failure of the coating. In preparation, cleanliness and smoothness are important factors [23, 26].

As a result of the gaps identified, the following points have been highlighted:

- Coating systems that are applicable to valves in the offshore oil and gas industry.
- The application and limitations of each type of coating for industrial valves.
- How to select the best coating for offshore valves to prevent corrosion?
- How can one develop a chart for the selection of offshore valve coatings based on various parameters such as the type of valve material, the operating temperature, and the presence of insulation?

2.3 Motivation

This study is mainly motivated by the desire to prevent the negative consequences associated with external corrosion of offshore valves. The industrial valve is an important component of the piping system as it allows fluids to be stopped, started, and controlled. Additionally, some industrial valves have safety functions designed to prevent overpressure scenarios in the equipment and pipes [27–29]. The failure of valves due to corrosion or any other reason can put the plant's safety and reliability at risk. In addition, taking the necessary steps to prevent valve corrosion can help to ensure that a piping system is functioning properly and is free from costly damages caused by corrosion. It is possible for the piping to fail due to the valve, resulting in production loss, fluid assurance problems, and transportation issues.

2.4 Contribution

Coatings for industrial purposes have a wide variety of uses, with their primary purpose being to protect equipment, facilities and components from rust, corrosion, and degradation. The use of coatings in the oil and gas industry is essential to maintain the quality and integrity of the equipment and infrastructure [30]. It is also possible to use coatings to improve oil and gas production efficiency and safety, as well as reduce energy loss and improve energy efficiency. The safety and reliability of oil and gas plants in general, and industrial valves in particular, are extremely important issues that the present author has addressed in a couple of recent studies [31, 32]. Thus, this study proposes a comprehensive coating selection methodology to protect valves against external corrosion throughout its design life and during its operation. Due to the importance of protecting valves in oil and gas plants as expensive and critical assets, the following contributions have been made:

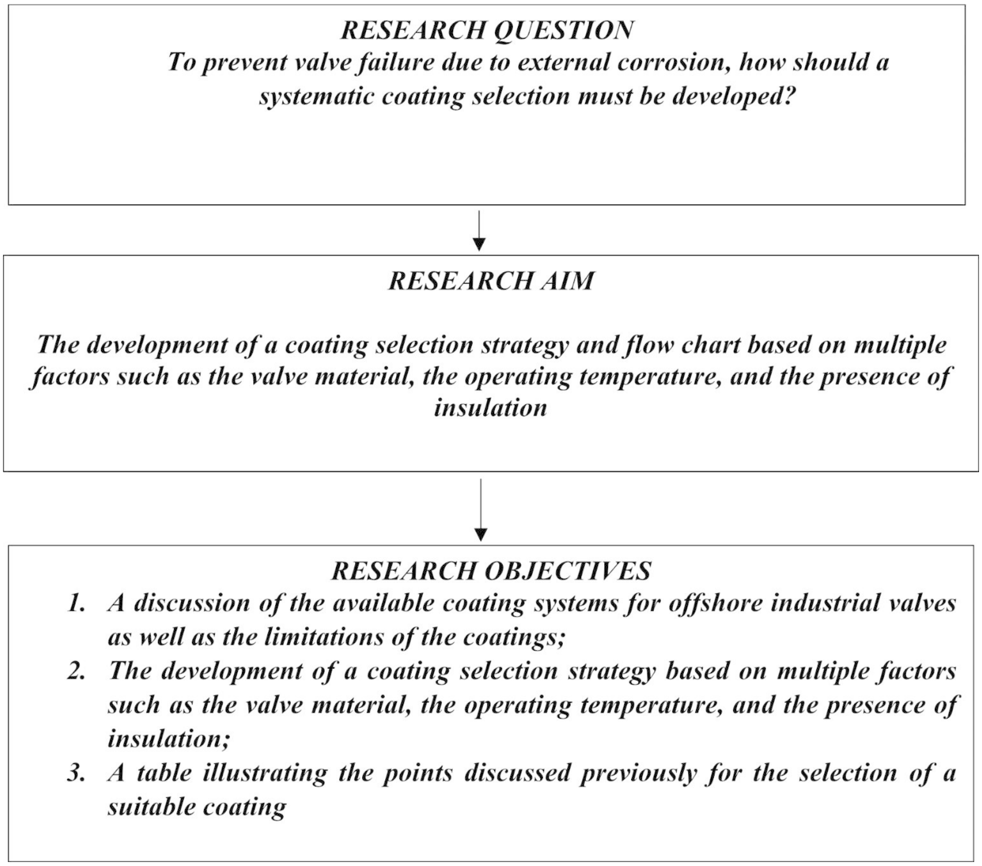
- Keeping humans and the environment safe from valve leaks caused by corrosion by taking into account the fact that many oils and gas valves carry fluids that are flammable, toxic, and hazardous;
- Protecting the environment from fires, explosions, and other adverse events caused by valve leaks;
- Ensure that there are no leaks from the valves that could result in the loss of expensive production fluid;
- Assuring that valves and piping systems are protected against damage and failure; and.
- Avoidance of fines and damage to the company's reputation.

3 Research aim and Objectives

This study is aimed at preventing valve failures caused by external corrosion in the offshore environment by applying suitable coating selection based on the requirements of material standards, industrial experiences, and relevant existing literature. A systematic approach is required to select coatings for offshore industrial valves, as discussed previously. To fill the gaps identified in previous studies, the following objectives have been developed.

- A discussion of the available coating systems for offshore industrial valves as well as the limitations of the coatings;
- The development of a coating selection based on multiple factors such as the valve material, the operating temperature, and the presence of insulation;
- A flow chart illustrating the points discussed previously for the selection of a suitable coating.

Figure 3 summarizes the research question, aim, and objectives.



RESEARCH QUESTION

To prevent valve failure due to external corrosion, how should a systematic coating selection must be developed?

RESEARCH AIM

The development of a coating selection strategy and flow chart based on multiple factors such as the valve material, the operating temperature, and the presence of insulation

RESEARCH OBJECTIVES

1. *A discussion of the available coating systems for offshore industrial valves as well as the limitations of the coatings;*
2. *The development of a coating selection strategy based on multiple factors such as the valve material, the operating temperature, and the presence of insulation;*
3. *A table illustrating the points discussed previously for the selection of a suitable coating*

Fig. 3 Formulation and summarization of the research questions, aim and objectives

4 Methodology

In order to select the suitable coating systems for offshore valves, this study incorporated both piping, valve and material standards as well as practical experience. Two steps are involved in the collection of data. In the first step, the following Norwegian petroleum standards are used:

- NORSOK M-501: Surface preparation and protective coating (Edition 6, 2012) [33].
- NORSOK M-001: Material selection (Edition 5, 2014) [34].
- NORSOK L-001: Piping and valves (Edition 4, 2017) [35].

In order of importance, the standards are listed from most important to least important. In the first one (NORSOK M-501), a discussion is given on the coating systems available for offshore facilities, including valves as well as their application. The NORSOK M-501 is an excellent reference for information on coating systems, applicable materials, operating temperature limits, and requirements for insulation [33]. It is not possible to use a single coating system for all valve components. In NOROSK M-501, nine coating systems (numbered from 1 to 9 with a letter in front) are introduced to cover all types of facilities, equipment, and components [33]. There are only four coating systems that can be applied to industrial valves; coating systems 1, 2 A, 6 C, and 7 [33]. The coating system 7 is applicable to submerged valves in the seas and oceans, which are beyond the scope of this research [33]. This study focuses on the valves installed on ships and platforms (topside valves), not the valves installed subsea. The coating selection for topside valves is more complex than that for subsea valves, since subsea valve coatings are standardized [36].

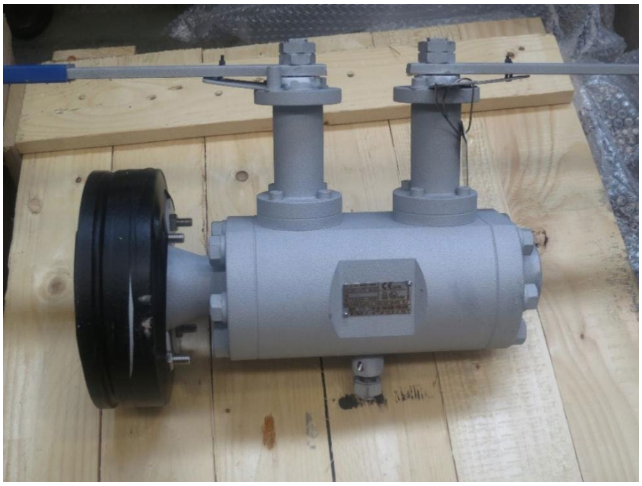


Fig. 4 A modular valve coated with TSA for offshore use(photograph by author)

This paragraph provides some general information and some limitations about coating types used for industrial valves in accordance with NORSOK M-501. A zinc-rich primer coat is included in coating system 1, and a minimum of three coats is required [23, 37, 38]. NORSOK specifies that zinc or zinc-alloy metal coatings can operate at a maximum temperature of 120 °C [23, 33, 37]. The use of zinc in primers is interesting for a number of reasons. Zinc is used as an anode or sacrificial metal in order to provide additional corrosion protection for steel surfaces, which is known as galvanic protection. Furthermore, zinc plays a crucial role in enhancing the durability of coatings by protecting them against corrosion in corrosive environments. The NORSOK standard divides coating system 2 into two categories [23]. The first system that applies to valves is system 2 A, which is thermal spray aluminum (TSA) or aluminum alloys [23]. There is a minimum thickness requirement of 200 micrometers for this coating. The NORSOK system 2 A coating is the most robust coating used on offshore valves. In system 2, powder or metal wire is melted and then sprayed on a metal surface in order to prevent corrosion. TSA is also known as metallization or metal coating [23, 39, 40]. A modular valve coated by TSA in gray color for an offshore project is shown in Fig. 4. The reason for this is that coating system 2 in general is widely used for various types of stainless steel, and stainless steel coatings should not contain metallic zinc. In fact, the melted zinc used in coating systems can cause corrosion to stainless steel. According to corrosion tests and data, molten zinc at a temperature of 500 degrees Celsius or higher is extremely aggressive to both ferritic and austenitic stainless steels when in contact for a short period of time. A stainless steel type 316, for example, can be greatly corroded when in contact with molten zinc; this is called liquid molten metal zinc corrosion. The NORSOK standard categorizes coating system 6 into three types of coating subsystems: 6 A, 6B, and 6 C. Coating system 6 C, also known as phenolic epoxy, is used on some offshore valves [23, 33]. Coating system 6 C, known as a phenolic epoxy or epoxy phenolic, is used to prevent corrosion under insulation (CUI). A phenolic epoxy coating has the advantage of being able to be applied in low pH (acidic) environments as well as in high-temperature applications where heat resistance is required. Phenolic can also improve epoxy's excellent solvent resistance and its hard, abrasion-resistant properties. In fact, Phenolics have good water and chemical resistance and epoxy has a high strength and adhesion, making the combination of the two very resistant to water or other corrosive substances.

There are a number of coating systems that can be applied to valves in the offshore industry. The coating system 1, zinc rich epoxy, is applied to non-corrosion resistant alloys (CRAs), cast iron, low temperature carbon steels, carbon steels, and low alloy steels. In the event that the operating temperature exceeds 120 degrees Celsius, the coating system must be upgraded to system 2 A, as described in the next section. As opposed to system 1, coating system 2 A can be applied to a variety of applications and materials, including carbon steel with operating temperatures exceeding 120 °C, where system 1 cannot be applied. The second application of TSA is when the valve materials are operating above the temperature limits specified in NORSOK M-001, which will be discussed in more detail in the following paragraph. The third application of TSA is to prevent corrosion under insulation (CUI) when phenolic epoxy cannot be used due to temperature restrictions. According to NORSOK M-501, phenolic epoxy is primarily used to prevent CUI, and it has a maximum operating temperature of 150 °C [23, 33, 41].

The second standard (NORSOK M-001) is important for this study in that it provides each and every material limitation for the operating temperature in offshore applications [34]. It should be noted that all valve materials listed in NORSOK M-001 standards, including carbon steel, austenitic stainless steel 316, 22Chromium (Cr) duplex stainless steel, 25Cr super duplex stainless steel, and 6 Molybdenum (6Mo) super austenitic stainless steel, except titanium, have limitations in offshore applications [34]. It is important to know that operating temperature is an influential factor on the corrosion rate [10, 42]. The American Petroleum Institute (API) 581 provides some information regarding the effects of operating temperature on the susceptibility of materials to chloride stress cracking corrosion and corrosion under extreme conditions (CUI) in marine (offshore) environments [43]. According to Table 16.2 M of API 581 standard, the risk of CUI is almost zero at operating temperatures as low as -12 °C and as high as 176 °C. Increasing the operating temperature from −8 to 71 °C increases the risk of CUI to its maximum at 71 °C. According to the same table, the risk of CUI decreases as the temperature rises from 71 to 176 °C and then reaches zero at that temperature [43]. According to API 581 Table 18.2, CLSCC susceptibility is correlated with operating temperature [43]. The risk of CLSCC is zero for operating temperatures less than 49 °C and greater than 149 °C. In the range of 49 to 93 °C operating temperatures, CLSCC is a high risk, while it is medium in the range of 93 to 149 °C operating temperatures [43]. If the operating temperature exceeds the limits specified in the NORSOK-M001 standard for all valve materials except carbon steel and titanium, the material must be coated [34]. A carbon steel valve must always be coated in an offshore environment, as it is the weakest material used for offshore valves [44]. As shown in Fig. 5, carbon steel valve gear boxes and handwheels remain uncoated in offshore environments, resulting in severe corrosion and rust. The corrosion resistance of titanium, especially in offshore environments, makes it unnecessary to coat the metal [45]. The maximum operating temperature at which austenitic stainless steel 316, 22Chromium (Cr) duplex stainless steel, 25Cr super duplex stainless steel, and 6 Molybdenum (6Mo) super austenitic stainless steel can be used without coating is 60 °C, 100 °C, 110 °C, and 120 °C, respectively [34]. Whenever these materials are exposed to temperatures above the given limits, they must be coated with NORSOK system 2 A, TSA.

The third standard used in this study is NORSOK L-001, which addresses specifications for piping and valves. In this standard, each type of valve has a unique code based on its type, size, pressure class, and special requirements [35].

A second step consisted of analysing the coating selection for industrial valves in a recent Norwegian offshore project called Johan Castberg. As part of the Johan Castberg

Fig. 5 Severe rust and corrosion on a valve handwheel and gear box made of carbon steel in the offshore environment (photograph by author)

Table 1 Coating selection for offshore valves summarized by the author based on NORSOK M-501

Material	*Operating temperature*	*Insulation requirement*	*Coating system*
Carbon steel	T ≤ 120 °C	No	1-Zinc rich epoxy
	T > 120 °C	No	2 A-TSA
	T ≤ 150 °C	Yes	6 C-Phenolic epoxy
	T > 150 °C	Yes	2 A-TSA
Austenitic stainless steel 316	T ≤ 60 °C	No	Not applicable
	T ≤ 60 °C	Yes	6 C-Phenolic epoxy
	T > 60°C	No or Yes	2 A-TSA
22Cr duplex	T ≤ 100 °C	No	Not applicable
	T > 100 °C	No	2 A-TSA
	100 °C < T ≤ 150	Yes	6 C-Phenolic epoxy
	T > 150 °C	Yes	2 A-TSA
25Cr super duplex	T ≤ 110 °C	No	Not applicable
	T > 110 °C	No	2 A-TSA
	110 °C < T ≤ 150	Yes	6 C-Phenolic epoxy
	T > 150 °C	Yes	2 A-TSA
6 Mo	T ≤ 120 °C	No	Not applicable
	T > 120 °C	No	2 A-TSA
	120 °C < T ≤ 150	Yes	6 C-Phenolic epoxy
	T > 150 °C	Yes	2 A-TSA
Titanium	Any	Any	Not applicable

project, a floating, production, storage, and offloading vessel (FPSO) was to be used to develop the project. Drilling for the project involved the drilling of 18 horizontal production wells and 12 injection wells [46]. A 280 km pipeline will transport the oil produced on the FPSO to Veidnes in the Nordkapp municipality of Finnmark county for processing. A new onshore oil terminal will be built in the North Norwegian region, making it the first of its kind. The project involved more than 7000 industrial valves of different types, including ball, gate, globe, and butterfly valves. Valve coatings were selected in accordance with NORSOK M-501 and Equinor, a client company specification. Due to the use of client specifications, the results of the coating selection system differed slightly from NORSOK M-501 due to a concept known as coating standardization. To provide better control and management of the valves, coating standardization is intended to reduce the variety of coating systems due to insulation requirements and operating temperatures. As will be discussed in more detail in the next section, standardization may increase the overall cost of coating.

5 Results

The main obstacle in the first step of methodology which is based on the use of standards is the difficulty in synthesizing all the conditions, including material type, operating temperature, and insulation presence, in order to determine in which circumstances one of the above-mentioned coating systems should be applied. As a result of this difficulty, all of the conditions discussed in three previous paragraphs have been summarized into the table below.

Table 2 Coating selection for offshore valves summarized by the author based on NORSOK M-501 and coating standardization

Material	*Operating temperature*	*Insulation requirement*	*Coating system*
Carbon steel	T ≤ 120 °C	No	1-Zinc rich epoxy
	T > 120 °C	No	2 A-TSA
	Any temperature	Yes	2 A-TSA
Austenitic stainless steel 316	T ≤ 60 °C	No	Not applicable
	T ≤ 60 °C	Yes	6 C-Phenolic epoxy
	T > 60°C	Yes or No	2 A-TSA
22Cr duplex	T ≤ 100 °C	No	Not applicable
	T > 100 °C	Yes or No	2 A-TSA
25Cr super duplex	T ≤ 110 °C	No	Not applicable
	T > 110 °C	Yes or No	2 A-TSA
6 Mo	T ≤ 120 °C	No	Not applicable
	T > 120 °C	Yes or No	2 A-TSA
Titanium	Any	Any	Not applicable

In Table 1, twenty scenarios can be generated based solely on the NORSOK M-501 standard for coating selection. According to the client specification and the contractor company, however, the aim was to reduce the coating selection scenarios for better management and handling of the valves during manufacturing and coating. To accomplish this goal, the following standardizations have been implemented: All insulated carbon steel valves are standardized to be coated by system 2 A (TSA). Consequently, the number of coating scenarios for carbon steel material has been reduced from four to three. In the case of 22Cr duplex valves, the client decided to standardize coating system 2 A (TSA) on all valves with an operating temperature above 100 °C, regardless of their insulation status. As a result, the number of scenarios has been reduced from four to two. It was decided by the client to standardize the coating system 2 A (TSA) for all 25Cr super duplex valves that operate above 110 °C, regardless of whether they are insulated. As a result, the number of scenarios has been reduced from four to two. There is also a standardization proposal for 6MO to take into account TSA (system 2 A) for all valves operating at temperatures above 120 °C, which reduces the number of coating scenarios from four to two. In Table 2, the coating selection scenarios are shown after they have been reduced from 20 to 13. The overall coating cost will increase due to the upgrade from system 6 C to system 2 A.

Thermal spray aluminum is characterized by its durability, corrosion resistance, and wear resistance. When aluminum is sprayed on a surface, it creates a barrier which prevents moisture, dust, dirt, and other environmental factors from damaging the underlying material. Thermal spray aluminum is also resistant to extreme temperatures and can be used on ferrous and non-ferrous metals. Moreover, thermal spray coating involves the use of pressurized high-heat gases to apply various coating materials. As a result of this process, the material bonds directly to the surface to form a coating that is resistant to corrosion, lubricity, thermality, and other factors. Usually, aluminum or aluminum alloy is selected over other materials such as zinc or zinc alloy. The reason for this is that aluminum has a low density of 2.70 g per cubic centimeter compared to zinc (7.14 g per cubic centimeter) and a high melting point of 668.37 °C compared to zinc's 419.53 °C. As a result, it is not easily ignitable and can be used in high temperature applications [47].

6 Discussion

As a result of the study, the results indicate that the coating selection for offshore valves is influenced by the operating temperature, the insulation requirements, and the valve material. There are two types of results generated; one is based on the NORSOK M-001 standard, whereas the other is based on both the NORSOK standard and practical experiences with a greater emphasis on coating standardization. The coating systems of various types of valves were studied under the same operating temperature, insulation and material conditions, and it was concluded that the type of valve does not affect the coating system in any way. Further, the same type of valves with the same operating temperature, material, and insulation were considered in one sample, but they were of different sizes. It was concluded that the size of the valve did not affect the coating system in any way. Thus, there is no connection or correlation between the valve coating and its size and type. This study is important in so far as its results provide a guideline as to how to select the best coating system for industrial valves in order to avoid corrosion and material failure of industrial valves, both of which can jeopardize the safety and reliability of both the valves as well as the piping systems which they are connected to. In the next paragraph, we will explain in more detail the main limitation associated with the results of this study.

One limitation of NORSOK M-501 and the proposed method above is that two other valve materials applicable to the offshore oil and gas industry, Inconel 625 and nickel aluminium bronze (NAB), are not listed in the NORSOK standard as they are not used in the Norwegian offshore industry. The Inconel 625 alloy is a high corrosion resistant nickel alloy that is commonly used in sour services containing a high concentration of hydrogen sulfide [48, 49]. Since Norwegian continental shelf crude oil is sweet, [50]. Inconel 625 isn't common for valve body materials and isn't covered by NORSOK M-501. It should be noted that NAB does not provide as high a level of corrosion resistance in offshore environments as titanium, therefore it is not common in Norwegian offshore industry and not covered by the same NORSOK standard [51]. To determine the coating requirements for these materials, the corrosion resistance of these materials should be compared with two materials that have a greater degree of similarity in corrosion resistance against chloride (offshore corrosion). Chemical composition and corrosion resistance of Inconel 625 are more like 6MO, while NAB is more like titanium. Comparing the corrosion resistance of Inconel 625 and 6MO in an offshore environment can be accomplished by calculating and comparing the pitting resistance equivalent number (PREN) for these two alloys. In accordance with ISO 15,156 standard, the value of PREN is calculated using Eq. 1 based on the chemical composition of these two alloys and elements, which includes chromium, melodeum, and nitrogen [49, 52].

Equation 1: Pitting resistance equivalent number (PREN) calculation.

$$PREN = Cr + 3.3\%\ Mo + 16N$$

Where: Cr: chromium; Mo: molybdenum; N: Nitrogen.

The chemical composition of 6MO and Inconel 625 is shown in Table 3.

As a result of Eq. 1, PREN for 6Mo and Inconel 625 is calculated as follows based on the chemical compositions given in Table 2:

$$PREN_{6MO} = Cr + 3.3\%\ Mo + 16N$$
$$= 20 + 3.3 \times 6 + 16 \times 0.21 = 43.16$$

$$PREN_{\text{Inconel 625}} = Cr + 3.3\%\ Mo + 16N$$
$$= 21.5 + 3.3 \times 8.5 = 49.55$$

The higher the PREN, the more resistant the material is to pitting corrosion (chloride corrosion) offshore. Inconel 625 corrosion resistance is therefore higher than 6Mo in offshore environments. Using the same coating requirements for Inconel 625 as for 6Mo in Table 1 would be conservative, but could work. As a result, the coating requirements for Inconel 625 are generated in the same way as those for 6MO in Tables 4 and 5.

Similar to titanium, NAB can be used for piping and valves handling corrosive sea water. "Corrosive sea water services" refer to sea water that contains a high level of chloride and/or operates at a temperature higher than 20 degrees Celsius when used for cooling [34, 51, 53]. Titanium and NAB exhibit very similar corrosion resistance against offshore environments [54]. Accordingly, NAB in

Table 3 Chemical composition of Inconel 625 and 6MO

	C	Mn	P	S	Cr	Ni	Mo	N
Super austenitic								
6MO (UNS S31254)	Max. 0.02	Max.1	0.03	0.01	20	18	6	0.21
Nickel alloys								
Inconel 625 (UNS N06625)	0.1	0.5	0.015	0.01	21.5	58	8.5	-

Note 1: C: Carbon, Mn: Manganese, P: Phosphor, S: Sulfur, Ni: Nickle

Note 2: UNS standards for Unified Numbering System for Metals and Alloys (UNS)

Table 4 Coating requirements for Inconel 625 without standardization

Material	*Operating temperature*	*Insulation requirement*	*Coating system*
6 Mo	T ≤ 120 °C	No	Not applicable
	T > 120 °C	No	2 A-TSA
	120 °C < T ≤ 150	Yes	6 C-Phenolic epoxy
	T > 150 °C	Yes	2 A-TSA
Inconel 625	T ≤ 120 °C	No	Not applicable
	T > 120 °C	No	2 A-TSA
	120 °C < T ≤ 150	Yes	6 C-Phenolic epoxy
	T > 150 °C	Yes	2 A-TSA

Table 5 Coating requirements for Inconel 625 with coating standardization strategy

Material	*Operating temperature*	*Insulation requirement*	*Coating system*
6 Mo	T ≤ 120 °C	No	Not applicable
	T > 120 °C	Yes or No	2 A-TSA
Inconel 625	T ≤ 120 °C	No	Not applicable
	T > 120 °C	Yes or No	2 A-TSA

the offshore environment does not require a coating in the same way that titanium does.

The results indicate that, in most cases (16 cases out of 20 as per Table 1) and (8 cases out of 13 as per Table 2), coating is required for offshore valves to prevent corrosion types that are typically pitting and CLSCC. This paper relies on standard and practical experiences to select the most appropriate coating, in contrast to a previous study that utilized fuzzy theory to select the best coating [55]. The other practical study focuses on using TSA for subsea gate valves, which is outside the scope of this study [56]. The present author recommends that a separate study be conducted in order to determine the best coating for subsea valves. Some topics, such as the preparation of metal surfaces prior to coating, the application of coating, and the thickness of the coating, are outside the scope of this study. It is very important to prepare metal substrates to prevent coating failure in terms of cleanness and surface roughness. For this reason, the present author has addressed this topic in a separate study [26, 57, 58].

In conclusion, two recommendations are made for future research: One is to evaluate the coating systems discussed in this study using a systematic engineering approach such as fuzzy analysis or value engineering or a similar approach. In addition, another study should be conducted on the selection of coating systems for subsea valves. Considering that subsea valves are installed kilometres under the ocean in remote areas and harsh environments with no access, safety and reliability of these valves are extremely important [59, 60]. It is extremely detrimental to the environment when subsea valves fail due to improper or inadequate coating in the seas and oceans [59, 60].

7 Conclusion

It is undesirable that there is a great deal of corrosion in the oil and gas industry. In offshore environments, corrosion of facilities and components, including industrial valves, is always a concern due to chloride present in the atmosphere and seawater splash. The valves are commonly coated with a protective coating to prevent external corrosion. It is of the utmost importance to choose a proper coating system for valves, and this is the primary aim of the research presented in this paper. In order to select the most appropriate coating system for offshore valves, three NORSOK standards are used. Coating systems are typically selected based on a variety of factors, including the type of valve body material, the operating temperature, and the degree of insulation required as summarized in Table 2. These factors are highlighted in a table along with a proposed coating system for each scenario, as well as twenty possible coating system selection scenarios. In practice, there is an effort to standardize coating scenarios in order to limit the variety of valve options, which makes it easier for manufacturers, inspectors and other parties to handle industrial valves. By standardizing coatings and reducing the number of coating systems from 20 to 13, another table is generated. The main challenge in the result was that no coating requirements were provided for Inconel 625 and NAB materials, which are widely used for offshore valves. Based on the results of the study, Inconel 625 can be considered to have the same coating requirements as 6MO and NAB does not require a coating in the same way as titanium.

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