14

Vapor Phase Corrosion Inhibitors for Oil and Gas Field Applications

Benjamín Valdez-Salas[1], Michael Schorr-Wiener[1], and Nelson Cheng[2]

[1] *Instituto de Ingeniería UABC, Universidad Autónoma de Baja California, Departamento de Materiales Avanzados y Corrosión, Calle Normal s/n BLVD. Benito Juárez Col. Insurgentes Este, Parcela 44, Mexicali, Baja California, 21100, Mexico*
[2] *Magna International Pte Ltd, 10H Enterprise Road, Singapore, 629834, Singapore*

14.1 Introduction

Petroleum is a mixture of hydrocarbons extracted together with water containing corrosives agents: H_2S, CO_2, organic acids, and salts (chlorides and sulfates). The equipment and machinery of the oil and gas industry (OGI) are fabricated, mainly from carbon steel (CS), which is prone to corrosion. Therefore, corrosion inhibitors including vapor phase corrosion inhibitors (VPCIs) have high significance.

Nowadays, it is generally accepted that in the natural and industrial environments, corrosion and pollution are interrelated harmful processes since many water, air, and soil pollutants accelerate corrosion, and corrosion products such as rust, oxides, and salts also pollute water bodies at ports, rivers, dams, canals, and shipyards. Both are pernicious processes that impair the durability of the infrastructures assets, the industry efficiency and profitability and the quality of the environment [1–4]. Therefore, it is essential to develop and to apply corrosion engineering control methods and techniques, in particular those being environment friendly [5].

Oil and gas industry requires varied engineering materials, structures, installations, equipment, and machinery that should function with industrial efficiency and labor safety to assure its economic performance [6, 7]. The economic and social relevance of the OGI are evident by the activities of the diverse international and national professional associations, R&D institutions, and industrial enterprises involved (Table 14.1). Lately, the threat of terrorism has pushed the petroleum industry to the forefront of efforts to preserve the available supply fuels as sources of energy.

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Table 14.1 A list of associations and organizations dealing with oil and gas industries.

Institutes, associations, organizations	Abbreviation	Website
Society of Petroleum Institute	SPE	www.spe.org
American Petroleum Institute	API	www.api.org
International Standards Organization	ISO	www.iso.org
International Maritime Organization	IMO	www.imo.org
National Association of Corrosion Engineers	NACE	www.nace.org
IDE Technologies	IDE	www.ide-tech.com
Organization of Petroleum Exporting Countries	OPEC	www.opec.org
Petroleos Mexicanos	PEMEX	www.pemex.com
American Society for Testing and Materials	ASTM	www.astm.org
Israeli Institute for Energy and Environment	IIEE	www.energy.org.il
World Corrosion Organization, China	WCO	corrosion.org
European Federation of Corrosion	EFC	www.efcweb.org

14.2 Magna International VPCIs

Magna International with headquarters in Singapore consists of several enterprises located in Australia, Canada, Indonesia, China, and South Korea and maintain a closed collaboration with several universities located in the countries mentioned earlier and the Corrosion and Advanced Materials Department at the University of Baja California. The company is one of the world's leaders devoted to the critical field of corrosion-prevention technology. One of its main products is vapor corrosion inhibitors, known as VAPPRO, which stands for Vapor-Phase-Protection, suitable for environmental, industrial, defense, and commercial fields, including the OGI [8–10]. Magna VAPPRO products are accessible through the North Atlantic Treaty Organization and its Master Cross Reference List (NATO MCRL). NATO Stock Numbers are assigned to these VPCI products to facilitate their quoting. The VAPPRO products are made conform to the requirements of the European Union (EU) Directive on Restriction of Hazardous Substances (RoHS), which control the use of harmful chemicals that may be noxious to the environment and consumer's well-being. VAPPRO VPCIs have been tested and certified by the Bureau Veritas, a well-known organization dealing in quality, health, safety, and environment (QHSE) for the benefit of the general public [11–13]. Magna worldwide operations are based on the application of the ISO 9001-2000, ISO 14001-2004, and ISO 9001-2008. Magna provides VPCI and service in many countries including the NATO countries, Asia, Pacific, and Europe zones, maintaining a high level of science, technology, and innovation, for the creation of novel products in the demanding twenty-first century.

In the last three decades, Magna International has been focused in the research and development of advanced and green formulations of vapor biocorrosion inhibitors (VBCIs). They include green VPCI and VPCI based on organic molecules on carriers such as hydrocarbon solvents in impregnated papers and in plastic films.

14.3 Corrosion and Its Control in OGI

14.3.1 Fundamentals of Corrosion

Corrosion and deterioration of industrial equipment occurs by an interaction between the surface of the material and the corrosive factors of its environment. Corrosion and pollution are harmful processes that are strongly intertwined since many pollutants, e.g. SOx, NOx, H_2S, NH_3, CH_4, COx, Ox, and acids accelerate corrosion, and corrosion products such as rust, oxides, and soluble salts pollute water bodies such as lakes and rivers [14, 15]. Frequently, corrosion, scaling, and fouling phenomena appear simultaneously in OGI; they interact and influence each other. Scaling and fouling have a marked effect on corrosion, often associated with fluid velocities. They originate in the environments, depending on their chemical and biological composition, their interaction with the equipment surface, and plant operational conditions such as pH, flow regime, temperature, and pressure [16]. Prevention and mitigation of these forms of corrosion require adequate methods and techniques, including VPCI.

Crude petroleum extracted from field wells can be contaminated with corrosive, poisonous H_2S that requires special equipment and processes to eliminate it, before arriving at the refinery. The pH value of seawater is ~8 and the concentration of dissolved oxygen (DO), the main corroding agent, varies from 4 to 6 mg/l as a function of temperature and flow regime. Fluids contaminated with H_2S, a reductant, are slightly acidic and corrosive toward steel; therefore H_2S should be excluded by mechanical or chemical methods. Unless prevented, corrosion and the buildup of scale and biological fouling impact negatively on the OGI operation and in extreme cases even lead to equipment shutdown.

Corrosion is an electrochemical process that takes place on metallic surfaces by reaction with the environment. The dominant factors are DO concentration, temperature, and salinity. The overall corrosion process is the combination of two reactions: anodic and cathodic, a reduction–oxidation process that takes place simultaneously at the metal–fluid interface. For Fe at neutral or alkaline pH, the reactions are as follows:

Anodic reaction:

$$2Fe \rightarrow 2Fe^{2+} + 4e^- \quad (14.1)$$

Cathodic reaction:

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \quad (14.2)$$

The overall corrosion reaction:

$$2Fe + O_2 + 2H_2O \rightarrow 2Fe(OH)_2 \quad (14.3)$$

Ferrous hydroxide, $Fe(OH)_2$, will further oxidize to ferric hydroxide, $Fe(OH)_3$, and eventually turn to rust, $Fe_2O_3 \cdot xH_2O$. On the basis of the appearance of corrosion phenomena on the metal surface or in the geometry of the equipment, corrosion is classified as uniform when the metal corrodes at the same rate resulting in a uniform decrease of thickness or localized when corrosion appears at a specific area in a part of the equipment. Corrosion results from differences in factors such as aeration, concentration, pH, humidity, solids content, and fluid velocity.

Atmospheric corrosion in OGI installed in coastal zones is driven by the effect of marine aerosols containing humid particles of NaCl. It is promoted by the formation of moisture layers on metal surfaces and by the chemistry of these layers. Climate change influences the macro and micro effects that act on the metal wet surfaces. The time of wetness (TOW) is a variable used to determine the time when the surface was wet at conditions over 80% of relative humidity. Furthermore, hygroscopic salts absorb moisture and form deliquescent salt particles, which can greatly accelerate the corrosion of metals. Corrosion damage increases maintenance expenses and generate problems during operation to extract crude petroleum.

Corrosion inhibitors that slow down anodic, cathodic, or both the reactions are, respectively, called anodic, cathodic, and mixed inhibitors. In the case of VPCI and VBCI, they form films over the metallic surface by adsorption of organic salt ions in the presence of humidity reducing the extent of corrosion.

14.3.2 Oil and Gas Industries

Oil and gas constitute the lifeblood of modern civilization; they assure the prosperity and security of the world. Petroleum is a mixture of hydrocarbons, extracted together with water, salts, and gases from wells. Water contains corrosive agents: CO_2, H_2S, organic acids, chlorides, and sulfates. Wells with H_2S are called sour wells, and sweet wells are those with CO_2. The petroleum industry consists of a complex system of operations, starting with crude oil extraction from wells, onshore, and offshore, its conveyance by pipelines to treatment plants, and its refining to produce many oil derivatives such as gas, gasoline, kerosene, naphtha, and asphalt [17–22]. A great variety of chemical products that include plastics, fertilizers, pesticides, solvents, pharmaceuticals, and cleaning agents are obtained from crude petroleum, acting as a vital raw material for these industries. Oil refineries apply fractional distillation to produce diverse derivatives, with gasoline as the most valuable.

The sectors of the natural gas (NG) industry are drilling, production, storage, transportation, and distribution; all suffer from corrosion. NG is extracted from land and marine wells, containing salty and briny water and corrosive gases, H_2S, and CO_2. During oil refining, corrosion augments due to the formation of HCl, H_2S, CO_2, and O_2. The acids are neutralized by the addition of alkali to reach a pH level of 7.0–7.5 [23–26]. Wet corrosion can be controlled by applying passivating, neutralizing, and adsorption types of VPCIs. Gasoline contaminated with water causes corrosion in transport systems and motor vehicles, which can be treated with VPCIs formulated with esters of carboxylic or phosphoric acids, following the regulation in accordance with NACE TM-01-72 and ASTM D6651. The formation of black deposits, constituted by corrosion powders, iron sulfides, iron oxides, and iron carbonates produced by corrosion attack of H_2S, CO_2, and O_2 in wet NG, has been detected in NG conducting pipelines. Application of a combination of VPCIs, more effective dehydration, and process control contributed to the solution of this problem.

The practical use of VPCI in diverse sectors and facilities of the OGI is schematically shown in Figure 14.1. The VPCI are actively implemented to prevent, mitigate, and control corrosion in numerous industries and natural locations. The influence of VPCI technology is presented in recently published books [28].

14.3.3 OGI Sectors

The petroleum industry presents a great diversity in its installations, equipment, operations, and processes, according to its sectors:

- *Gathering*: The crude is extracted from land and marine wells and send by pipelines, short or long, to the cleaning and processing facilities. Floating production, storage, and offloading vessels assist in oil gathering from the marine, steel platforms.
- *Refining*: In huge steel towers, applying a fractionation process, reforming yields gases, gasoline, kerosene, naphtha, jet fuel, and diesel oil. Refining processes involve distillation, catalytic reforming and cracking, alkylation, isomerization, and hydrotreating.
- *Transportation*: Oil and gas are transported by pipelines, tankers/barge, truck, and rail (Figure 14.2). Crude oil is transported from the producing countries to the consuming countries in petroleum steel tankers. They are cheaper and more efficient than submarine pipelines. In their trip back, the tanker holds are filled with seawater to provide adequate stability.
- *Storage*: Aboveground storage tanks are stationary cylindrical containers and are made of steel with a metallic roof. They are located near refineries, for the delivery of fuels to the consumers. Corrosion appears particularly at the bottom of the tanks due to the sedimentation of corrosive salty waters.
- *Equipment*: All these sectors require the application of varied equipment to handle the chemicals needed to produce fuels. They comprise the wells with their casings, tubes, pumps, and valves; the wellheads with complex Christmas tree, heat exchangers, tubings, or corrugated plates; and for coolers, the numerous pipelines of different wall thickness and diameter and the instruments and tools for measuring temperature and pressure of the fluid flowing in these equipment.

The sectors of the NG industry are drilling, production, storage, transportation, and distribution; all suffer from corrosion. The world crude oil production is 82 million barrel/day and the world consummation is 87.4 million barrel/day, which indicate the prominent position of this industry. When processing crude, production facilities must separate oil from the gas and water that reside within the geologic formation. After separation, a small portion of the gas is flared off; some is used to generate electrical power for the oilfield work. However, most

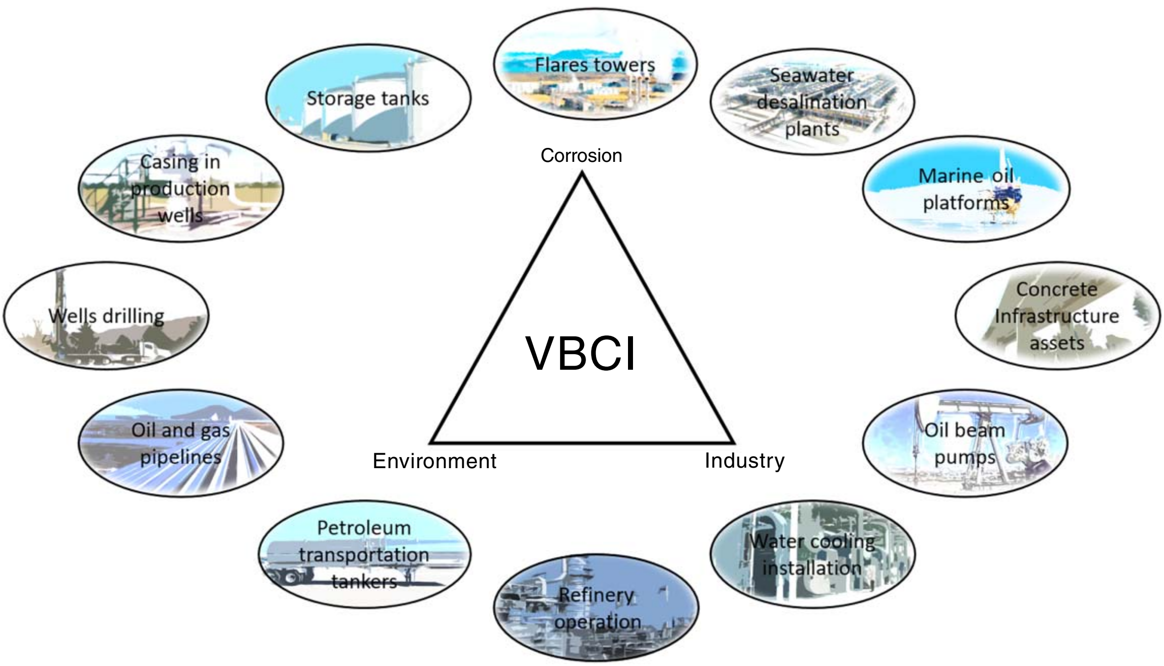


Figure 14.1 Schematic illustration of the several varieties of VPCI applications in different sectors of the oil and gas industries. Source: Cheng et al. 2017 [27]. Copyright@Intechopen. https://creativecommons.org/licenses/by/3.0/. Licensed under CCBY 3.0.

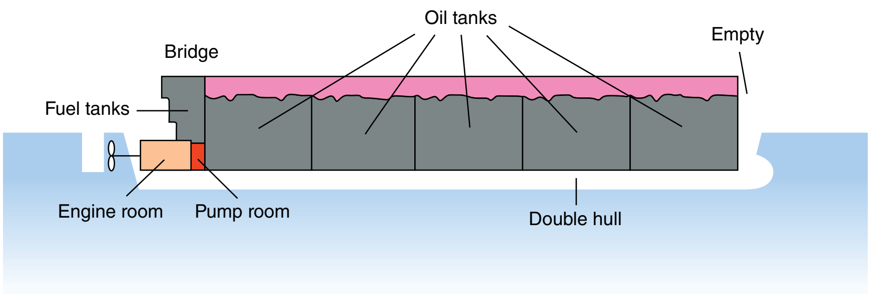


Figure 14.2 Tankers for transportation of crude petroleum from producer country to consumer country. On its return the tanker's holds are filled with VPCI containing seawater. Source: Cheng et al. 2017 [27]. Copyright@Intechopen. https://creativecommons.org/licenses/by/3.0/. Licensed under CCBY 3.0.

of the gas (as well the water) is reinjected into the formation to help maintain pressure and enhance recovery of additional oil.

Other significant product of the petroleum industry are the tar sands (also called oil sands) that consist of huge sand deposits impregnated with bitumen. The oil is removed from the sand applying high-temperature steam and piped off to a refinery, to obtain useful fuels. Special corrosion and heat-resistant engineering materials are selected for fabrication of this industry equipment used in these vast field operations.

14.3.4 Corrosiveness of Oil and Gas Products

The corrosivity of petroleum and its combustible derivatives depends mainly on three critical factors: traces of water containing salts such as chlorides and sulfates, H_2S (toxic and corrosive gas produced by decomposition of sulfur bearing components), and CO_2 reacting as carbonic acid.

Crude oil and many of its derivatives form films on the metallic surfaces at ambient temperature avoiding corrosion. Water is required for the corrosion process and its solubility in hydrocarbon media is very limited. However, they can become corrosive when high temperatures are applied in the refining processes. Water, as previously mentioned appears in crude oil, and it can be absorbed during the transportation, storage, or distribution, depending on relative humidity and temperature in the surrounding environment. Small quantities of water do not condense and remain in the form of micro emulsion or solubilized, and this makes its elimination more difficult. Some organic compounds have the ability to form stable emulsions with the water present in oil and fuels diminishing the corrosiveness.

The dissolution of air in oil would promote the corrosion of the metallic equipment applied in oil processing. The gaseous components in air such us oxygen, nitrogen, CO_2, and SO_2 can partially dissolve in fuels. Purging with an inert gas, chemical oxygen scavengers, and degassing with vacuum are some of the methods used to eliminate oxygen from the liquid media.

Not all the oil components are corrosive; some organic compounds such as amines and carboxylates act as corrosion inhibitors promoting the formation of passive layers on the metallic surface. Corrosion of ferrous and non-ferrous alloys used in the OGI can be controlled with the use of corrosion inhibitors that prevents the dissolution of metals. Many of these substances provoke the formation of impurities that block filters and pipelines [29].

14.3.5 Metals and Alloys in OGI

There is an extended list of metallic alloys that are used in the OGI. Many of these alloys exceed the required mechanical properties, are heavy and brittle, and sometimes do not fulfill the corrosion resistance requirements. CS is the most used and its mechanical properties can vary with the carbon content, heat treatment, and the alloying chemistry.

Cast irons contain 10 times more carbon than CS alloys that make it very brittle by the formation of graphite in the form of nodules or flakes. It is used in oil and gas operations with the exception of water service.

Use of high cost corrosion resistance alloys (CRAs) are justified when their application reduces the maintenance expenses and assure long service time, without corrosion damage. NACE define CRAs as those alloys whose mass loss is at least one magnitude order lower than CS. CRAs include stainless steel, titanium, nickel-based alloys, cobalt-based alloys, copper, aluminum, and their alloys.

14.4 Vapor Phase Corrosion Inhibitors

14.4.1 Fundamentals

Inhibition, in general, is a process aimed to restrain an activity in natural and industrial areas. In medicine, inhibitors arrest the action of an organ or tissue in the human body, e.g. they bind to enzymes to decrease activity. Recommendations for the appliance or norms of inhibition are recorded in psychology manuals to improve human behavior. In water, scale inhibitors maintain salts in solution, to avert deposits or mineral scale, under which corrosion might appear [30–32].

VPCI is an economical and useful tool to control corrosion in OGI industrial facilities such as soil pipelines, concrete structures, and electronic devices. VPCIs contain organic and inorganic chemical compounds and able to vaporize and condense in the presence of moisture forming thin films on metallic surfaces that protect against corrosion deterioration (Figure 14.3).

VPCI volatilize into the air and inhibit corrosion on metallic materials and metals-based products, particularly during shipment and storage. They are cost effective and help conserve resources, and then they are incorporated into packaging materials [34, 35]. The corrosion rates of reactive metals, e.g. iron, are decreased by a modification of their surface with the mentioned organic molecules. This is the useful function of adsorbed VPCI; their inhibition efficiency (IE) can reach up to 98%. There is special interest in developing biodegradable, nontoxic, natural VPCIs.

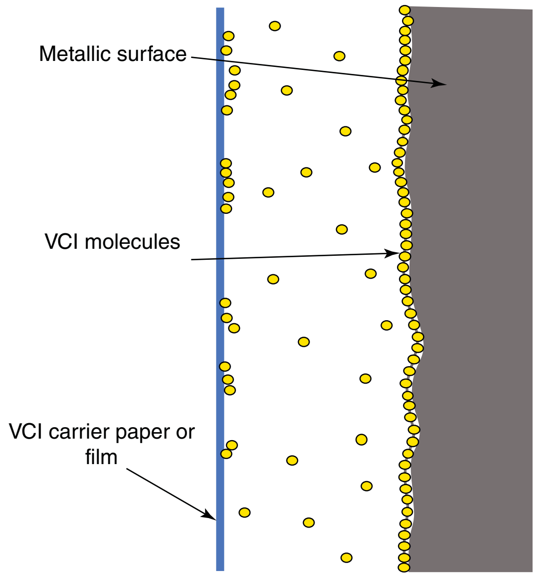


Figure 14.3 VPCI molecules are absorbed on the steel surface forming an anticorrosive film. Source: Reproduced with permission from Gangopadhyay and Mahanwar [33]. Copyright 2018, Springer Nature.

Types of VPCI include amines, nitrite of amines, amine carboxylates, heterocyclic compounds (thiazole, triazole, pyrrole, mercaptans, imidazoline, etc.), carboxylic acid esters, acetylenic alcohols, and mixtures or reaction products of these substances. Currently the use of certain amines and nitrites has been prohibited, by environmental and health regulations, since they can form nitrosamines, which can produce cancer. Figure 14.4 shows the structure of some typical VPCIs.

VPCIs are generally classified into three groups based on their corrosion control mechanism as:

- Anodic, oxidizing (forms passive layer on the metal surface)
- Cathodic (reducing DO in the water)
- Adsorbed, film forming inhibitors

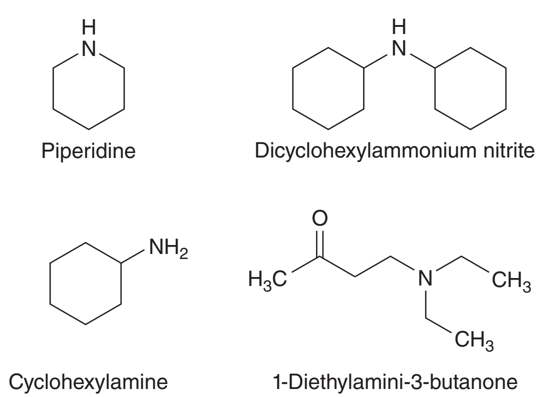


Figure 14.4 Chemical compounds used for the production of volatile corrosion inhibitors. Source: Cheng et al. 2017 [27]. https://www.intechopen.com/books/corrosion-inhibitors-principles-and-recent-applications/vapor-inhibitors-for-corrosion-protection-in-humid-and-saline-natural-and-industrial-environments. https://creativecommons.org/licenses/by/3.0/. Licensed under CCBY 3.0.

The concept "bio" in the new green VPCI products, means that the active component of the VBCI is of biological origin and therefore environmentally friendly. This basic conception converts the VBCI as equivalent to "green" corrosion inhibitors.

14.4.2 VPCI Application in OGI

The transport of crude oil and their derivatives is an important, economical segment of the vast petroleum industry. Enormous steel tankers (Figure 14.2) deliver petroleum products. In their way back the tankers hold are full of seawater containing VPCI. Tables 14.2 and 14.3, respectively, show details of VPCI products of various international companies and the products of Magna International.

Table 14.2 Corrosion inhibitors' producers and products.

Producer	Country	Product
Tianjin Hi-Perferal Advanced Material Co., Ltd.	China	VBCIs and VCIs range of products
VCI 2000	USA	Imidazoline corrosion inhibitor
Daiwa Kassei	Japan	Anti-corrosion oils
Protective Packaging Corporation	USA	Corrosion protection, aircraft protection
Armor-VCIs	USA	Metal rescue, dry coat, desiccants
Daubert Cromwell	USA	VCI military packaging, VCI paper, VCI film, and bags
Green Packaging Inc.	USA	VCI paper, VCI emitters, and desiccants
Zerust Excor	USA	Zerusts VCIs: packaging films, kraft packaging paper
Cortec Corporation	USA	VPCI for oil, gas, and process industries
MetPro	Mexico	VCI: stretch film, paper

Table 14.3 Magna International VBCI and VPCI registered products.

Product	Main application	Characteristics
VBCI-844CCV	Seawater hydrostatic testing	Provides contact, colloid, and vapor inhibition
Vappro 841	Ferrous and non-ferrous metals	Protection in recessed areas
Vappro 842	Detection of leaks during hydro testing	No need to dry the piping
Vappro 844	Corrosion inhibition of seawater equipment	System after flushing
Vappro 848	Additive for heat exchangers fluids	Does not contain chromates or nitrites
Vappro 849	Treatment of closed-loop cooling system	Replacement of nitrite based inhibitors

14.4.3 Testing and Monitoring of VPCI

The protection properties of the VPCIs can be evaluated by laboratory tests simulating the relevant environmental and industrial conditions being dealt with [36, 37]. The application of national and international test standards is important since our results can be compared with different laboratories or industrial experience. The recommended standard organizations are [38, 39]:

ASTM	American Society for Testing and Materials
NACE	National Association of Corrosion Engineers
BSI	British Standards Institution
EN	European Standards (European Norms)
ISO	International Standards Organization

ASTM standards include:

G1	Preparing, cleaning, and evaluating corrosion test specimens
G3	Electrochemical measurements in corrosion testing
G4	Conducting corrosion test in field applications
G5	Potentiostatic and potentiodynamic anodic polarization measurements
G31	Laboratory immersion corrosion testing of metals
G59	Conducting potentiodynamic polarization resistance measurements

NACE standards:

RP0300/ISO 16784-1	Corrosion of metals and alloys. Corrosion and fouling in industrial cooling water systems
TM 0169	Laboratory corrosion testing of metals
SP 0308	Inspection methods for corrosion evaluation of conventionally reinforced concrete structures.
TM 0208	Laboratory test to evaluate the vapor-inhibiting ability of volatile corrosion inhibitor materials for temporary protection of ferrous metal surfaces
RP 0775	Preparation, installation, analysis, and interpretation of corrosion coupons in oilfield operations

BSI.ISO standards:

BSI.ISO 11844-3:2006	Corrosion of metals and alloys
BSI.EN ISO 7539-7:2009	Corrosion of metals and alloys
BSI.ISO 4404:1998	Corrosion petroleum and related products

Additionally, the VPCI performance is evaluated following the practice and standard methods utilized to determine the vapor inhibitor ability (VIA). The most commonly used practice is the 4031 described in the US federal standard, FED-STD-101. Some practice applied to evaluate the VIA are based on the previously mentioned method like the NACE TM0208-2013 or the German test method, TL 81305-002. There are many reports in the literature applied for VPCI performance evaluation techniques [40] that are composed of several steps, as detailed in the following text.

Specimen cleaning procedure is performed applying the recommendations of test 4031, FED-STD-101. Each sample is immersed in a tank or container of hot mineral spirits followed by immersion in methanol, allowed to dry in clean air, and then stored in a desiccator until ready to use. The test solution consists of a glycerin/water mixture with a mass ratio of 1 : 2.

Setup of chamber for VPCI materials includes the use of glass jars or Erlenmeyer flasks depending on the selected test method. In this test, the moisture saturation period is the most important factor. During this time, the relative humidity (%RH) should increase the saturation of the closed container. Heating of the test chamber is sometimes required by the evaluation technique applied. After a saturation period, the specimen temperature is diminished to condense water on its surface and to form a VPCI protective film.

14.4.4 Research and Development

A detailed search of the VPCI literature, published in the period of 2012–2019, has been carried out and is summarized in Table 14.4 [33, 41–53].

Table 14.4 Summary of reported VPCIs.

References	Year	Application	Class/type
[41]	2019	Suppression of steel, brass, and copper corrosion	Mixture of polyaniline and benzoic acid
[42]	2018	Ferrous and non-ferrous and alloys	27 inhibitors reviewed
[43]	2018	Inhibition of mild steel	Grape pomace extract
[33]	2018	Inhibitors for metal coatings	12 inhibitors mentioned
[44]	2017	Atmospheric inhibition of carbon steel	Mono-terpenoid phenol
[45]	2015	New approach for VCI	Anodic, cathodic, mixed
[46]	2014	Packaging	Passivation, adsorption, precipitation
[47]	2013	Atmospheric inhibition of ferrous and non-ferrous metals	1-(Morpholino)(phenyl) methyl-benzotriazole
[48]	2013	Atmospheric corrosion	Liquid and gas phase
[49]	2013	Atmospheric corrosion of ferrous and non-ferrous metals	Schiff and Mannich bases
[50]	2012	Metal corrosion	VCI vapors
[51]	2012	H_2S corrosion of steel	Amines
[52]	2012	Atmospheric corrosion of ferrous and non-ferrous metals	Synthetic inhibitors
[53]	2012	Metal corrosion	Volatiles

We have performed a few laboratory investigations to assess the use of aqueous and ethanolic extracts form plants encountered in the arid regions of the State of Baja California, denominated Creosote (*Larrea tridentata*) and *Pachycormus discolor*, in HCl solutions. The inhibition action of an ethanol extract of the Creosote Bush in aqueous HCl was evaluated and found to be effective on CS surfaces. HCl is generally employed for pickling to remove carbonate scales from steel surfaces [29, 41].

Table 14.5 lists several VPCIs that have sufficient vapor pressure to protect metal surfaces forming an absorbed film. For instance, dicyclohexylammonium nitrate is used for prevention of steel corrosion, packaging applications, due to its chemical stability, volatility, vapor transport, and diffusion [33, 41–53]. A review published by Ansari et al. describes the protective action of VPCIs on ferrous and non-ferrous metals [42]. Gangopadhyay et al. reviewed the use of VPCIs for temporary corrosion protection, as coatings for metals [33]. Figure 14.5 shows images of pipes with and without VPCI coating.

Wiley Series in Corrosion has published in the last decade valuable books on corrosion control in the environment and industry. They include two books devoted completely to corrosion inhibitors:

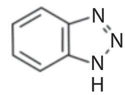
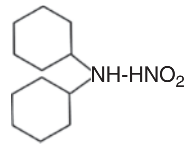
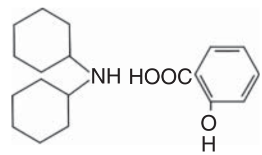
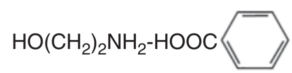
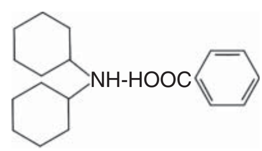
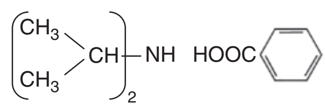
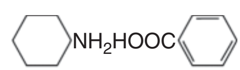
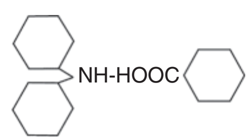
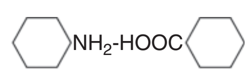
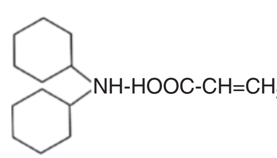
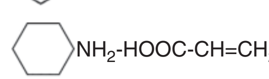
- V.S. Sastri, *Green Corrosion Inhibitors: Theory and Practice.*
- S.K. Sharma, *Green Corrosion Chemistry and Engineering, Opportunities and Challenges.*

The book *Green Corrosion Inhibitors: Theory and Practice* presents guidelines for testing the toxicity, biodegradation and bioaccumulation for corrosion inhibitors, standards for their environmental testing, and models to use in industrial practice. Sastri called the environment-friendly corrosion inhibitors "green," but toxic inhibitors are termed "gray." An additional classification of corrosion inhibitor considers them as hard, soft, and borderline.

S.K. Sharma promotes the scientific and technological aspects of "Green Chemistry." His book *Green Corrosion Chemistry and Engineering: Opportunities and Challenges* is dealing with environmental and industrial corrosion problems and their solutions, mainly by the application of VPCIs. Two types

Figure 14.5 Pipes covered with VPCI packaging and uncovered. Source: Reproduced with permission from Gangopadhyay and Mahanwar [33]. Copyright 2018, Springer Nature.

Table 14.5 Summary of VPCIs and their structure.

Volatile corrosion inhibitor	Abbreviation	Structure
Benzotriazole	BTA	
Dicyclohexylammonium nitrite	DICHAN	
Dicyclohexylammonium salicylate	DICHA-SA	
Monoethanolamine benzoate	MAE-BA	
Dicyclohexylammonium benzoate	DICHA-BA	
Diisopropyl ammonium benzoate	DIPA-BA	
Cyclohexylamine benzoate	CHA-BA	
Dicyclohexylammonium cyclohexane carboxylate	DICHA-CHC	
Cyclohexylamine cyclohexane carboxylate	CHA-CHC	
Dicyclohexylammonium acrylate	DICHA-AA	
Cyclohexylamine acrylate	CHA-AA	
Sodium nitrite		$NaNO_2$

Source: Reproduced with permission from Gangopadhyay and Mahanwar [33]. Copyright 2018, Springer Nature.

of VPCI are described: (i) VPCI produced by mixing chemical components with anticorrosion properties, with anodic, cathodic, and absorption protection mechanisms, and (ii) VPCI obtained from natural plants, wastes from agricultural crops, and by extraction technology from vegetables. Petroleum-based VPCI need to be replaced by VPCI obtained by extraction with solvents derived from vegetable such as soy and canola oils. These VPCIs are biodegradable, contributing to maintain a healthy environment [54, 55].

14.5 Conclusions and Outlook

Selection of the most appropriate VPCI for corrosion prone systems is based on its cost; ease of availability, worker's safety, chemical stability, and saving in maintenance. The choice should be made in accordance with the corrosion expert knowledge and experience, and it is a compromise between technological and economic criteria. Proper use of VPCIs in combination with a system of automated corrosion sensors is an effective means of preserving machinery, equipment, and vehicles related to the OGI, during long-term storage, with savings in maintenance costs.

The novel group of VPCIs known by a registered trademark VBCI, meaning vapor biocorrosion inhibitor, are intensely promoted and distributed throughout all the national companies of Magna International. They are considered environmentally friendly, cost efficient, and suitable for the varied sectors of OGI. As more VBCI turn up in OGI, and the testing and evaluation methods improve, new knowledge will shed light on their application [27, 56, 57].

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