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Assessment of Failure Mechanisms in an Industrial Firewater Pipeline: A Case Study

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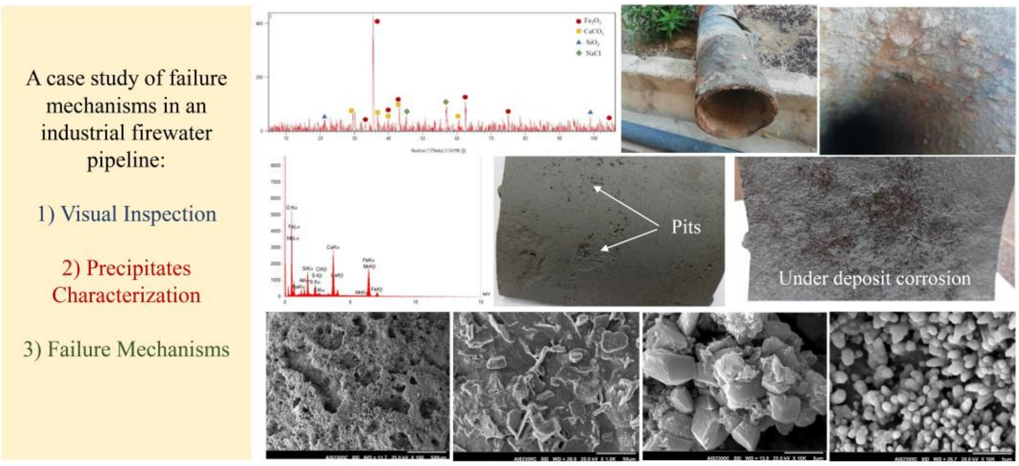
ABSTRACT

In this case study, the major mechanisms contributing to failure of a petrochemical firewater (FW) pipeline were assessed. The outer surface of FW pipe exhibited general corrosion and formation of noticeable pits due to separation of wrapping coating. The results of XRF, EDS, and XRD analysis demonstrated the presence of Fe_2O_3, $CaCO_3$, SiO_2, and NaCl indicating the presence of iron oxide (Fe_2O_3) and silica (SiO_2) as corrosion products, and $CaCO_3$ and NaCl as sediments found in water. The formation of deposits (precipitates) on the whole internal surface of the pipe and occurrence of general corrosion, under-deposit corrosion, and tuberculation was confirmed by visual inspection and microscopic examination (SEM). The deposits formed in the pipe may originate and/or accelerate corrosion through forming oxygen depleted area under deposit, playing as anodic region compared to the surrounding area and lead to more aggressive corrosive attack under the deposit. Moreover, the tubercles were the main reason of formation of oxygen concentration cells as the oxygen-deficient sites beneath the tubercles playing as anodic regions and surrounding areas act as cathodic regions resulting in localized corrosion.

GRAPHICAL ABSTRACT



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Introduction and background

Pipeline systems are regarded as a fundamental section of the industry infrastructure due to their undeniable role in the supply and transportation of fluids [1]. Various failures are occurring in pipelines such as corrosion [2], creep [3], fatigue [4], and other fracture types leading to failure of equipment. Failure in pipelines is generally described as the occurrence of bursts along a pipe or several other pipes in a network [5-7], whereas some other researchers [8, 9] claim that pipe break or even leakage should be introduced as a form of failure. All in all, pipeline failure can be defined as 'the unintended loss of pipeline contents' [10].

The firewater (FW) piping is a strategic section of a firefighting system in petroleum refineries and petrochemical plants. The FW pipeline in chemical industries carries fresh or recycled water in stagnant load conditionsto neutralize the severity of fire(s) during uncontrolled processing chemical reactions such as leakages. Firewater distribution systems, or would better be called firewater systems (FWS), as dead-end systems consisting of pipeline networks with hydrants at essential locations playing a crucial role in guaranteeing the safety of industrial units, large hospitals, substantial academic and research institutions. Notably, the water stagnancy in firewater pipelines is unavoidable since that water is not in continuous use for service. A regular circulation would be highly beneficial for solving this issue in the plant [11]. Generally, FWS is kept in stagnant condition with a pressure range of 1-1.5 kg/cm^2. In firefighting conditions, high pressures of 10-12 kg/cm^2 are applied to spray water with an optimal force [12].

Despite the diversity of pipeline materials, carbon steel is still regarded as the most reliable material utilized for extraction, transportation, and conservation of various chemicals, hydrocarbon products, acids, and water [2]. Carbon steel pipe has been widely employed for chemical processing industries' fresh or recycled water services [12, 13]. Reportedly, corrosion may gradually diminish the wall thickness of carbon steel pipeline steadily or in the localized area leading to a rise of hoop stress. This stress may result in bulging, buckling, deformation, and rupture [14].

In recent years, the internal corrosion of firewater (FW) pipelines - mainly made of carbon steel and buried in the ground - has been a tremendous challenge in industrial plants since these pipes should be used in service for long years. Thus, assessment of failure mechanisms and prediction of the remaining life of FW pipelines utilized in industrial applications are of great importance since the failure and leakage of pipes during an emergency may lead to unpredicted conditions and cause social-economic losses and catastrophes. For instance, Sobral *et al*. [15] proposed frequent inspection of firefighting equipment, which led to remarkable failure mitigation. Shankar *et al*. [16]

Cast iron pipes are also employed in water distribution systems due to their low cost, ease of fabrication, and suitable corrosion resistance. Cast or ductile iron pipes used in these systems usually have an average life of 50–75 years [17]. Despite the prolonged usage of cast iron in such piping systems, the aged pipes were confronted with deterioration due to corrosion and increasing risk of failure [18]. Shankar et al. [16] indicated the loose spherical deposits, in which rust layers were constituted of iron oxide, silica, and spherical nodules covered with network structures. Moreover, there was no significant decrease in the pipe thickness confirmed by the detailed corrosion characterization, although there were remarkable signs of graphitic corrosion, microbes and rust formation [16]. Nowadays, stainless steel has been utilized in firewater piping, due to its excellent corrosion resistance in cold, flowing, low-chloride containing water.

Corrosion and scale-forming are two of the most critical problems in firewater distribution networks [19]. Several factors encompassing flow conditions, aggressive anions, biological activity, water composition, and quality, and dissolved oxygen are regarded as the most influencing parameters on corrosion and scale-formation of pipelines. The dissolved oxygen is of great importance [20, 21], since it could accelerate the pitting corrosion. The internal corrosion of steel water pipelines is highly under the impression of different corrosion mechanisms, such as uniform corrosion [22, 23], localized attacks [2, 14], microbiological corrosion [13, 24], top of the water line corrosion (TWLC) [25, 26], and tuberculation [27-29]. TWLC and tuberculation are two essential mechanisms for degradation in firewater steel pipelines. TWLC causes severe localized corrosion on the top portions and facilitates the conditions for the pump system discharge and a significant reduction in the water flow or even makes it come to an end [30]. Regarding tuberculation, the term "tubercle" is defined as a small rounded prominence, referring to iron corrosion products on the steel surfaces in contact with oxygenated water [31]. The failure analysis of a low carbon steel fire water pipeline in a petrochemical plant was assessed byvisual inspection, microscopic examination, chemical and water analyses conducted by Al Subai *et al.* [14]. Their findings indicated the presence of some leakages and severe deep pits at the top internal section of the pipeline associated with deposits found at the bottom internal surface of the pipe due to severe oxygen corrosion attack at the top section of the pipe. In contrast, the bottom surface of the pipe suffered from under deposit corrosion.

To a large extent, in industrial aqueous environments containing crude oil and water, microbe metabolisms result in microbiologically influenced corrosion (MIC) [32]. In the early stages, MIC damages are accompanied by a biofilm formation over the surface [33]. Microorganisms colonies usually lead to localized corrosion with the appearance of pitting damages [34]. MIC has marked its trace on firewater pipeline systems (FPS's) failures, and since early 1990 the concern of MIC in FPS's has noticeably increased due to multiple premature failures [24]. The combined availability of essential nutrients and supportable operating conditions provided an ideal case for different types of corrosion causing microorganisms to grow in FPS's [35]. The literature reveals many firewater failures due to microbial activities [36-38]. Early reports of MIC failures in FPS often concluded that damage was primarily due to stagnant water conditions and the presence of sulfate-reducing bacteria (SRB) [36, 37]. This stagnant water can also facilitate the growth of anaerobic bacteria leading to localized corrosion and precipitation of organic debris along with corrosion products [12]. Moreover, thiosulphate significantly reduces the pitting corrosion resistance of stainless steel in a suitable condition with a chloride and sulphate [39, 40]. Balamuragan *et al.* [12] conducted a physicochemical analysis of the freshwater used for a firewater system in which the presence of aggressive ions as well as corrosive bacteria in the system was confirmed, and less corrosion rate occurred in the experimental situation (without changing the water) suggesting the firewater reservation for longer intervals for superior corrosion management. [12].

Many researchers have made an enormous effort to predict the remaining life and assess the failure mechanism of buried FW pipes pipeline by proposing various models, though seldom comprehensive research has yet been conducted to achieve practical methods in this domain [41]. Monte Carlo simulation indicated the reliability of analysis applications conducted in literature [42-44]. Sinha *et al.* developed a model using a simulation-based probabilistic neural network analysis to assess the failure possibility of aging pipelines in corrosive media [45]. Moreover, a semi-probabilistic approach conducted by Noor *et al*. [46] was applied for forecasting the residue strength of submarine pipelines exposed to internal corrosion in which the maximum permissible operating pressure of the corroding pipelines was estimated based on a series of pigging data demonstrating the corrosion pit location and dimension.

In this case study, the water in the pipe is transferred from the river in the vicinity of the petrochemical plant, which is stored in huge tanks and then transferred to other sections. Reportedly, the quality of income water utilized for cooling water in the complex is controlled through filters by adsorbing solid particles and using corrosion inhibitors. At the same time, there is no particular purification done on the water flowing in the fire pipelines, which are generally at stagnant condition. Consequently, this facilitates the high potential of deposition (precipitation) in the pipeline leading to several types of corrosion features. The firewater pipelines are buried in the ground to be protected against corrosion wrapped by coating and held under cathodic protection. In the following case study, the authors made an effort to conduct an inspection of a failed fire water pipeline and investigate the deposits formed in the pipe by visual inspection, microscopic and structural investigation, and chemical analysis through SEM, EDS, XRF, and XRD analyses to understand the deposits characteristics on the corrosion type occurring on the external and internal surface of the pipeline and find out the contributing failure mechanisms.

Experimental

Materials and Methods

Fire Pipeline Material Characterization and Condition

The material characterization results indicated that the firewater service line pipe was constructed of mild carbon steel seamed pipe or galvanized steel pipe for water piping SGP[1]-E (E.L) fabricated by electrical resistance welding (ERW) with standard thickness, the maximum operating pressure of 10 kg/cm^2, and corrosion allowance (CA) of 1 mm. Notably, the water in the pipe is stagnant, and only in the case of any fire emergency, the water is pumped to relevant sections. Thus, there is no freshwater with a specific flow rate flowing in the pipe.

The preparation of precipitations for characterization and lab analysis

To invesigate the precipitates and to attain a deep understanding of proactive corrosion mechanisms in fire water pipelines and to assess the chemical composition and morphology, the precipitates and corrosion products were analyzed using the SEM, EDX, XRD, and XRF analysis.

Results and Discussion

As illustrated in Figure 1a, the destruction of pipe wrapping coated on the outer surface and also formation of huge amount of precipitation and tubercles (Figure 1b and c) are clearly observed in the inner surface of the pipelines. Tubercles can be explained as complex deposits colonies, including: metal oxides, remaining of living microorganisms, and corrosion products [47].

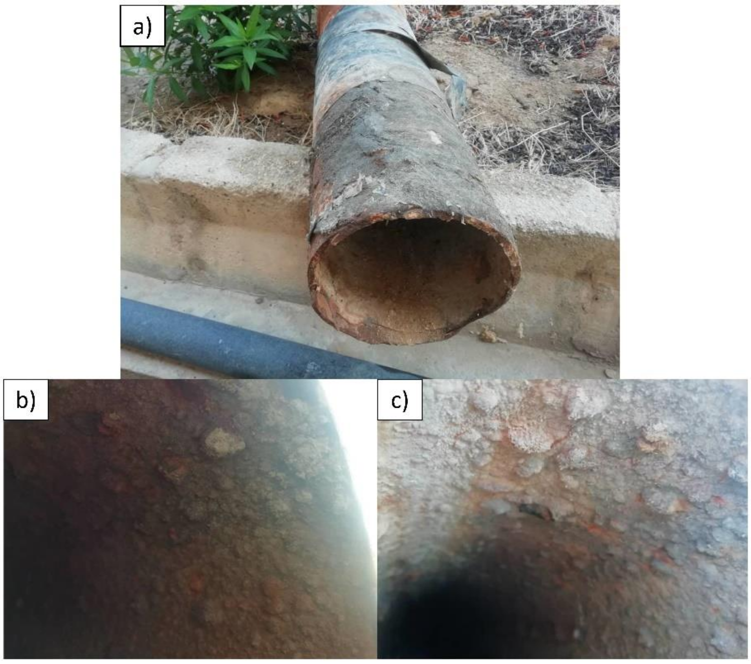

Figure 1. The field illustrates the destruction of external coating (Wrapping) and the formation of vast amounts of deposits and tubercles

Some parts of the corroded pipeline underwent the soft sandblast, and according to ASTM G1, ASTM E 407, and ISO 8407, the precipitates and corrosion products were cut off, and the corroded inside and outside section of the pipe was sent for microscopic inspection and analysis (Figure 2 and 4).

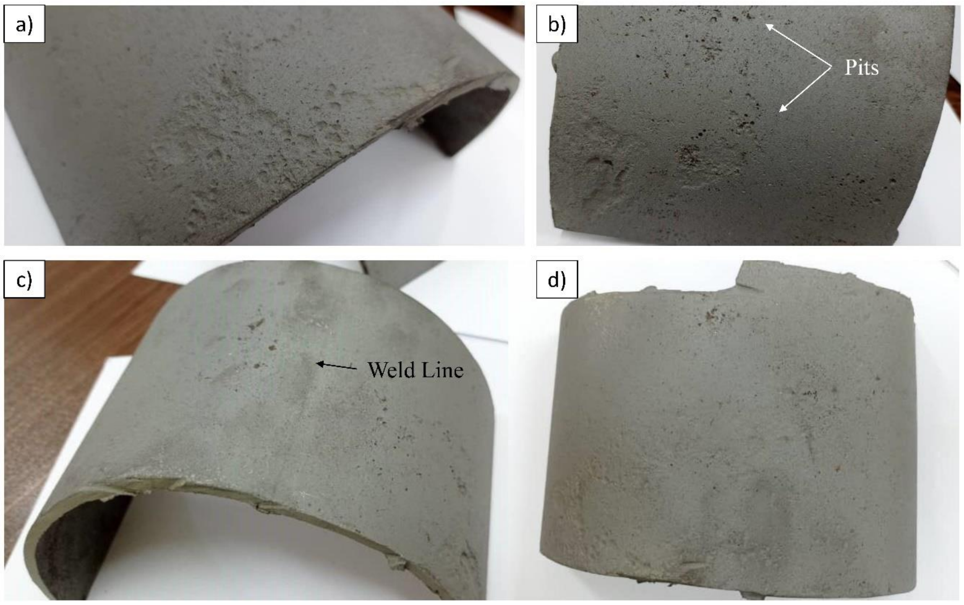

Figure 2. The external surface of the firewater pipeline after removing the deposits

Figure 3. The firewater pipeline's external (Bottom and Top) surfaces after removing the deposits

As demonstrated in Figures 2 and 3, the occurrence of corrosion, appearance of pits, and reduction in thickness in some regions of the pipe's external surface is vividly observed. The leading cause of corrosion ing on the external surface could be the destruction of wrapping coating employed under cathodic protection system.

Figure 4. The internal surfaces of the firewater pipeline after removing the deposits

As seen in Figure 4, it is observed that the combined forms of general and localized corrosion have been occurred on the inner surface, indicating the severity of corrosion progress under the formed deposits and corrosion products. According to visual inspection and literature findings, there are three significantfeatures of corrosion observed on the internal surface of the firewater pipeline sample: general corrosion, under-deposit corrosion, and tuberculation. Tuberculation is originated from forming tubercles which are created due to oxygen concentration cells as the oxygen-deficient sites beneath the tubercles that may play a role as anodic regions and surrounding areas act as cathodic regions and finally result in acute localized corrosion. Tubercles can also reduce the flow and enhance the pumping costs, consequently turning into remarkable efficiency reduction of the firewater pipelines [27, 31].

Deposits formed in the piping system can originate and accelerate corrosion by forming an oxygen-depleted area under deposit, which may play as anodic region compared to the surrounding area, leading to more aggressive corrosive attack under the deposit and occurrence of pitting.

Figure 5 depicts the corroded area of the weld line exhibiting the higher susceptibility of corrosion of weld line due to higher energy of this sensitized zone prone to intergranular corrosion.

Figure 5. The corroded region around the weld line of the firewater pipeline

Figure 6. The internal (Bottom and Top) surfaces of firewater pipeline after removing the sediments

The internal (Bottom and Top) surfaces of the firewater pipeline after removing the precipitates in Figure 6, depict the occurrence of corrosion on the internal surface of the pipelines under the precipitates formed during the service.

Figure 7 shows the sample prepared from the precipitates (sediments) formed on the internal surface of the FW pipeline to characterize the elements and compounds that sediments are made of. The visual inspection of these deposits exhibits a brownish and white/yellowish color which may be a sign of forming iron oxide (Fe_2O_3 or Fe_3O_4) and $CaCo_3$ (Calcium Carbonate), respectively. For further examinations, these deposits were analyzed by EDS, XRD, and XRF analyses, and the corresponding results are discussed in the following.

Figure 7. The sample of deposits formed on the internal surface of the firewater pipeline

SEM observation and analysis

As in Figure 8, the surface morphology of deposits in different areas is reproducible. A wide range of various morphologies such as filaments and spherical particles at four different resolutions is observed. The surface morphology in some areas is compact compared to other regions in which a porous structure and separated deposits are observed. The formation of precipitates could mitigate the corrosion process. However, the existence of porosities in precipitates results in the creation of dead zones, concentration polarization, and oxygen concentration cells; for instance, due to the formation of tubercles which leads to under-deposit corrosion.

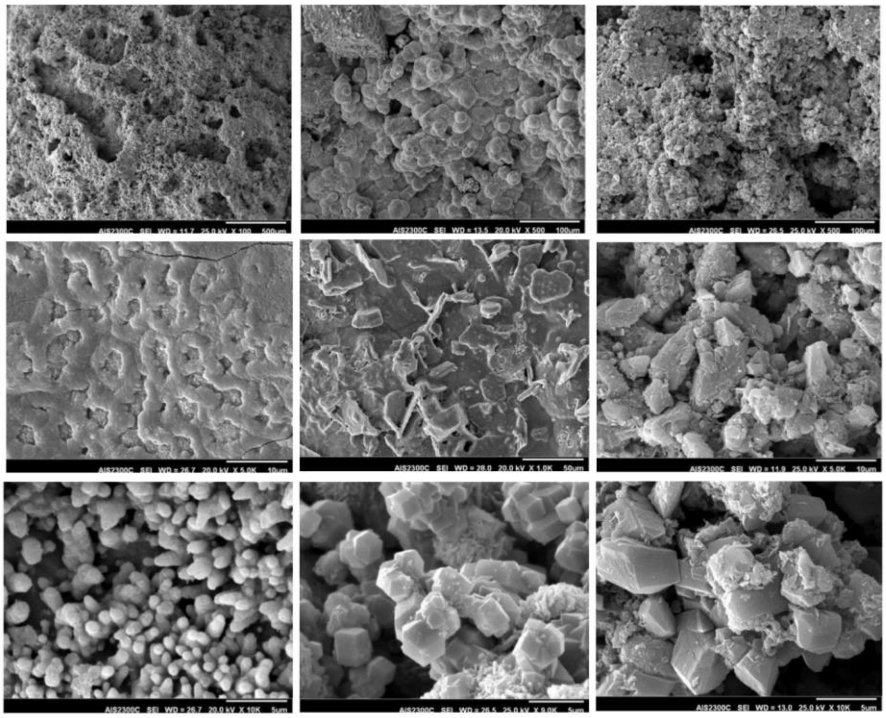

Figure 8. SEM images of precipitates deposited on the internal surface of the FW pipeline at various magnifications

EDS Analysis

According to Figure 9 and Table 1, the primary peak intensities indicate the presence of major elements: Fe, O, Ca, Si, Mn, and minor elements: S, Cl, Al, and Na.

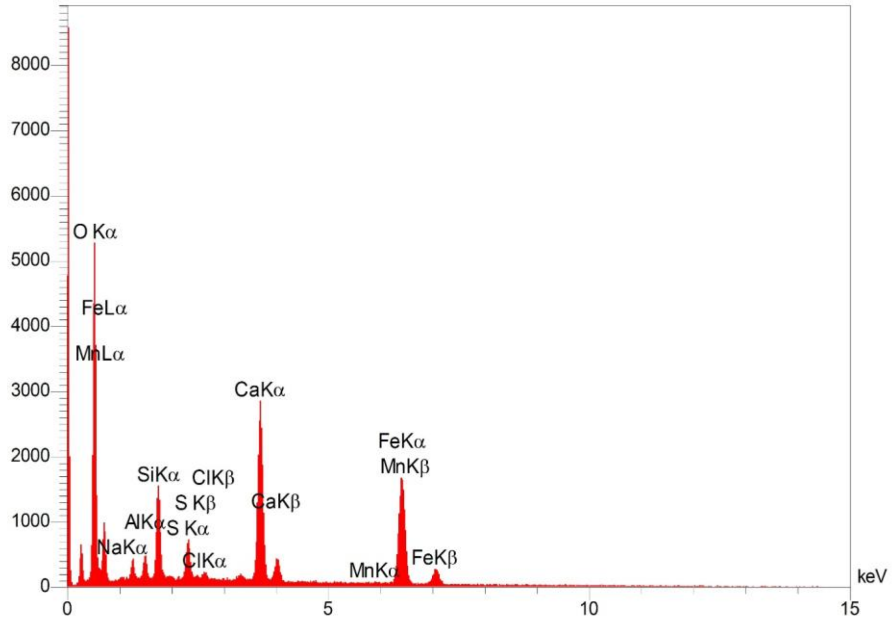

Figure 9. The EDS graph of precipitates deposited on the internal surface of the FW pipeline.

Table 1. The EDS graph of the sediments formed on the internal surface of the FW pipeline.

	Element	O	Si	Fe	Ca	Al	S	Na	Cl	Mn
Deposit Sample	Wt. %	50.16	8.70	14.05	15.53	3.42	4.17	2.05	1.31	0.61

XRD and XRF analyses

XRD Results

As it is evident from the XRD graph in Figure 10, the significant phases detected in the precipitate sample formed on the internal surface of the pipe are Fe_2O_3, $CaCO_3$, SiO_2, and NaCl, indicating the presence of iron oxide (Fe_2O_3), silica (SiO_2) calcite ($CaCO_3$) as corrosion products and NaCl as water sediment. The presence of Si, Ca, S, and P apart from Fe and O and the SiO_2 and Fe_2O_3 in rust layers were affirmed in a cast iron firewater pipe [16]. Moreover, high amounts of O and Ca and the presence of other elements and compounds are consistent with another study's results in which Calcite ($CaCO_3$) and Magnetite (Fe_3O_4) were detected as the major phases in the deposits formed on the bottom surface of the pipe [14].

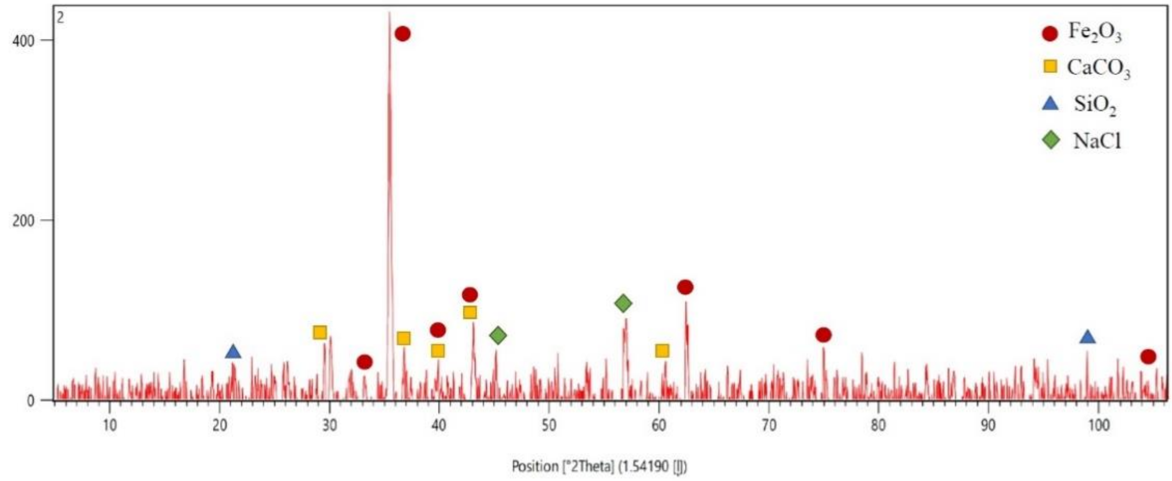

Figure 10. XRD pattern of precipitates formed on the inner surface of FW pipeline

Owing to the porous nature of corrosion products and tubercles such as Fe_2O_3 in particular, electrolyte and aggressive anions can readily attack the surface under them and cause the severe form of corrosion. Furthermore, aggressive anions enhance the electrical conductivity of water, leading to a remarkable increase in corrosion rate.

XRF results

The XRF results in Table 2, show the compound analysis of sediments (deposits). As seen in Table 2, the presence of Fe_2O_3, SiO_2, CaO, and other minor compounds is evident, which is in consistent with the XRD results.

Table 2. The XRF results of the deposits formed on the internal surface of the FW pipeline

	Compounds	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**Na_2O**	**K_2O**	**TiO_2**	**MnO**	**P_2O_5**
Deposit Sample	**Wt.%**	3.273	0.316	50.116	13.951	0.39	N	0.058	0.058	0.105	0.055

	Minor elements	**S**	**Cl**	**Ba**	**Co**	**Cr**	**Cu**	**Mo**	**Ni**	**Sr**	**V**	**Zn**	**Zr**	**Ce**	**La**	**Pb**
Deposit Sample	**ppm**	22694	4271	N	N	43	N	8	6	133	25	N	6	N	N	111

Conclusion

The main mechanisms contributing to the failure of a petrochemical firewater (FW) pipeline were assessed using SEM, EDS, XRF, and XRD analysis. The external surface of FW pipe indicated pitting corrosion due to the separation of wrapping coating during the service under cathodic protection. The XRF, EDS, and XRD analysis results showed the presence of Fe_2O_3, $CaCO_3$, SiO_2, and NaCl, indicating the presence of iron oxide (Fe_2O_3) and silica (SiO_2) as corrosion products, and $CaCO_3$, CaO, and NaCl as sediments found in water. Visual inspection and microscopic examination (SEM) confirmed the occurrence of general corrosion, under-deposit corrosion, and tuberculation on the whole internal surface of the pipe. The tubercles were the main reason for the formation of oxygen concentration cells as the oxygen-deficient sites beneath the tubercles play as anodic regions and surrounding areas acting as cathodic regions resulting in localized corrosion. Moreover, deposits formed in the piping system may originate and accelerate corrosion by forming oxygen-depleted area under deposit, which may play as an anodic region compared to the surrounding area leading to more aggressive corrosive attack under the deposit and pitting on the pipe wall.

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Disclosure statement

The authors reported no potential conflict of interest.

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