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Most fatal oil & gas pipeline accidents through history: A lessons learned approach

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A R T I C L E I N F O

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A B S T R A C T

Pipelines are used throughout the world for oil & gas transportation purposes. This method of transport is reasonably safe, yet accidents keep occurring nowadays. It is important, for the safety of the oil & gas pipeline network, to remember the history that has led the industry to the actual development point. This research compiles the most fatal oil and gas pipeline accidents through history. Of the compiled accidents, the 10 most fatal are selected for a brief but precise review of their root causes and the lessons learned from them. The core objective of this paper is to learn from the experience of the documented pipeline failures, with the purpose of building a safer and

better future for the oil & gas pipeline transportation network.

1. Introduction

The failure of Oil and Gas Pipelines (OGP) is always an unfortunate incident because of the consequences that it entails: in some cases, the consequences may be economical, environmental or, in the worst imaginable condition, the accidents can provoke human losses [1]. The relative high safety that the OGP system has today could not have been achieved without the accidents that happened through history [2]. The causes that led to these accidents were, in some cases, not known before they took place and, therefore, could not have been investigated prior to the accident.

OGP can present fatal damage that leads to accidents in the form of a rupture or, more frequently, in the form of latent damage that can result in failure at a later date [3]. For this reason, the purpose of this paper is to beneﬁt from the fatal OGP failures that have been documented trough history, in order to avoid the need of further pipeline failures by learning from these unpleasant experi-ences. Therefore, the approach taken by this paper is considered as a Lessons Learned Approach or LLA [4].

This paper is structured as follows. In Section 2, the failure causes established by the most important pipeline failure databases are explained, along with the failure criteria adopted for this paper. Subsequently, Section 3 presents a review of the established causes of pipeline failure and the classiﬁcations adopted by the most relevant organizations in the ﬁeld. Furthermore, the classiﬁcation as-sumed by this paper is explained and justiﬁed. In Section 4, the pipeline accidents that entailed more than 20 fatalities through history are compiled, the 10 most fatal OGP accidents are presented, and an analysis of the lessons-learned from them is realized. Finally, in Section 5, the conclusions of this research can be found.

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2. History of OGP transportation

The construction of the world pipeline infrastructure, initiated with the use of wooden pipes [5]. These primal installations were ﬁrst replaced by lead pipes and subsequently by steel pipes in 1920, allowing the use of higher operating pressures [6]. According to the United States Department of Transportation, more than 50% of the installed pipe system was built between 1950 and 1969, which implies approximately 228,526,848 km of pipes out of a total of 492,459,264 km of the gas transmission system; about 5% was built before 1940 and, the rest, from 1970 to the present [7].

In 1960, advances in pipeline technology occurred with the introduction of pressure testing [8], then in the 1970s were im-plemented the application of thermomechanical processing to substitute the traditional heat treatment techniques in pipeline steels [9], leading to the development of X70 steel grade pipes [9,10]. According to the API criteria for pipe steel grades classiﬁcation, the “X” grade determines the conditions of the pipeline chemical composition and manufacturing, while the numbers following the “X” establish the minimum yield strength of the pipe in .000 s of psi [11]. Subsequently, accelerated cooling after controlled rolling was introduced to improve the strength levels (X80 steel) [6,10].

Advances in steel production and rolling practices (hot mechanical treatment, and aimed at the transformation of ingots into various proﬁles) occurred in the 1970s and 1980s through the control of the microstructure, further improvements of the rolling method and chemical additions [12–15]. These resulted in steels with higher yield strengths, which increase mechanical resistance for equal wall thickness [14,16].

Finally, the transition from the “vintage” to the modern era led to signiﬁcant changes in the supervision and control of the pipe system. The ﬁrst monitoring system was employed in 1965 [17], and, since then, there have been several generations of development. Sensors, remote controlled valves and speciﬁc software can control parameters, such as operating pressure and others, which fa-cilitate the control of the system and also improve the leak detection and ﬂow control functionalities [16,18–20].

Today, advanced high-strength steels such as APIX80, X100 and X120 are being evaluated for the potential application of high-pressure and long-distance gas transmission pipelines [10], such as the 3443.99 km pipe network in Alaska whose operating pressure is 2500 psi [6] or the new Nord Stream 2 1200 km link between Russia and Germany that is to be ﬁnished by the end of 2019 [21].

3. Causes of pipeline failure

OGP carry the responsibility of transporting hazardous products and, therefore, a failure in an OGP system can lead to signiﬁcant consequences such as ﬁre, explosions, environmental damage, and injuries or, in the worst imaginable condition, human casualties [22].

Various databases that collect data regarding pipeline failure exist throughout the oil & gas industry all over the world, as can be seen in Fig. 1. In North America, the spearhead OGP incident database is managed by the Pipeline and Hazardous Materials Safety Administration (PHMSA) [23], which is a branch of the United States Department of Transportation (DOT). In this region, pipeline operators are obliged by law to report to the DOT every event that involves an undesired release to the environment, while meeting any of the following criteria [24]:

Fig. 1. Existing OGP incident reporting databases.

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1. The incident involves a death or personal injury necessitating in-patient hospitalization 2. Estimated property damage, including cost of substance lost, of $50,000 or more

In Europe, the reporting of pipeline accidents is not mandatory by law. However, several pipeline operators decided to participate in the creation of a pipeline incident database in this region, in order to gather data and learn from the incidents that take place. As a result of this initiative, EGIG (European Gas pipeline Incident data Group) was born [24,25].

There are more OGP failure databases throughout the world, such as UKOPA (United Kingdom Onshore Pipeline Operators’ Association) in the UK, or PID (Pipeline Incident Database) in Canada [24]. In Fig. 1, the oﬃcial databases that exist nowadays with the purpose of OGP failure reporting are schematized.

The completely greyed out countries in the world map depicted in Fig. 1 do not have an established database system for reporting OGP incidents. It is very important to notice that a vast amount of the globe is in this condition, which means that it is easy for OGP failures that occur to go unnoticed. This is a very unfortunate situation that should be addressed, since learning from OGP failures, as this paper defends, can prevent future failures that may lead to catastrophic consequences.

The scientiﬁc community is not unaware of the importance of having an eﬃcient OGP failure reporting system. For instance, Castellanos et al. [26] took the OGP failure reporting system a step further, and made the eﬀort of developing a Failure Analysis Expert System (FAES) database supported by an algorithm through Artiﬁcial Neural Network (ANN). The fact that a uniﬁed database is yet to be established hinders the OGP industry need of joining eﬀorts to establish uniﬁed criteria that allows the identiﬁcation of the variables that induce failure in order to prevent it.

OGP failure is a relatively frequent occurrence [27], and the accidents in this ﬁeld are usually reported and thoroughly studied, yet no directives or regulations that determine in a uniﬁed manner the way of classifying the failures in OGP exist. One of the most simpliﬁed approaches, as described by Miao and Zhao [28] is to divide the main failure causes of pipeline into four groups: third-party damage, corrosion, design and construction error, and incorrect operation conditions. These aforementioned authors, report in their study that corrosion damage and third-party damage contribute the greatest to increment the likelihood of OGP failure.

In the following subsections, the categorization of incident causes that the PHMSA and the EGIG databases adopt aforementioned databases use are explained, since the criteria is not unanimous. The aforementioned databases have been selected for the criteria analysis since the authors strongly believe that, nowadays, these are the most impactful incident reporting databases in the OGP industry.

3.1. Failure causes identiﬁed by the PHMSA

The PHMSA establishes 8 diﬀerent categories of pipeline failure causes [29] which are brieﬂy described below:

• Corrosion: deterioration of a metallic pipeline that results from an electrochemical reaction with its environment, resulting in

metal loss in the pipe. The PHMSA diﬀerentiates the following speciﬁc types of corrosion (the speciﬁc types of corrosion not mentioned below are categorized as “corrosion”):

o External corrosion: corrosion that occurs due to the environmental conditions on the outside of the pipe, as a result of the interaction of the pipe with the soil, air or water that surrounds it. There are new approaches and techniques to detect this phenomenon at early stages by means of probabilistic approaches [30–33].

o Internal corrosion: corrosion that occurs due to the environmental conditions inside of the pipeline, as a result of the interaction of hydrogen sulﬁde, carbon dioxide, other chemicals, or even water, with the interior walls of the pipe [34–38].

o Stress Corrosion Cracking (SCC): formation of cracks as a result of the interaction of the mechanically stressed pipeline due its pressurized contents with its environment, that result in a marked decrease of the pipe load bearing capabilities, as have been very well documented, mainly caused by a mechanism of plasticity-induced crack growth or ductile tearing [39–42].

o Selective Seam Corrosion (SSC): localized corrosion attack along the weld line of pipelines joined by electric resistance welding (ERW) or electric ﬂash welding (EFW) processes, causing a crevice-like corrosion centered on the bondline of the pipe’s weld [43,44]. This problem mainly aﬀects pipelines manufactured from 1920 to 1970, since after that, the mentioned pipe joining techniques were no longer used [45]. It has been reported that SSC has a synergistic eﬀect with fatigue corrosion events [46]. Excavation damage: failure caused by digging inadvertently into a buried pipeline that sooner or later may lead to the sudden an

unexpected failure of the pipe [47–49].

Natural force damage: incidents caused by acts of nature such as ﬂooding [50,51], earthquakes [52–54] or lightning [55–57]. Other outside force damage: incidents caused by vehicle accidents, vandalism, sabotage, terrorism or as a result of another nearby accident [58–60].

Material/Weld failure: the pipeline fails due to defects, impurities on the metal, chemical composition and/or improper welding techniques [61,62].

Equipment failure: failure of a component or device other than the pipe [63,64].

Incorrect operation: failure induced by human factors, usually by a mistake made by one of the operators. This category includes actions like overﬁlling a tank, leaving a wrong valve opened, overpressuring a piece of equipment or incorrectly marking an area to be excavated [65,66].

All other causes: sub-causes out of category.

In Fig. 2, the incident distribution per cause from 2009 to 2018 of the incidents reported to the PHMSA database is shown [67].

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Fig. 2. PHMSA OGP incident distribution per cause in the 2009–2018 period [67].

Fig. 2 shows that in the USA the most frequent root cause in OGP failures in the last 10 years has been material/weld/equip failure (43%) by a signiﬁcant margin, followed by corrosion (17%).

3.2. Failure causes identiﬁed by the EGIG

The EGIG database has a smaller pipeline incident cause classiﬁcation, with 5 deﬁned categories, which are brieﬂy explained below.

• Corrosion: comprises all of the failures caused by all types of corrosion, although EGIG states that additional information re-

garding the speciﬁc corrosion mechanism needs to be provided in the report of each incident.

External interference: this category includes the failures provoked by digging, piling and ground works. It is very similar to the “excavation damage” category established by PHMSA.

Construction defect/material failure: this failure cause is equivalent to the “Material/Weld failure” used by PHMSA.

Ground movement: includes failures caused by dike break, erosion, ﬂood, landslide [68–70], mining, rivers or unknown but related to a movement of the terrain in which the pipe is installed.

Other and unknown: sub-causes out of category such as design error [1], maintenance error, lightning or unknown causes.

Fig. 3 shows the incident distribution per cause from 2007 to 2016 of the incidents reported to the EGIG [27].

As can be seen in Fig. 3, in the countries that participate in the EGIG database external interference has been the most frequent root cause of OGP pipeline failure (28%) in the 2007–2016 period, closely followed by corrosion (25%). Although it is not speciﬁed amongst the failure causes identiﬁed by the EGIG, there is a 4% of the reported failures that were caused by hot tap made by error, meaning that modiﬁcations in the pipeline were made whilst the pipe continued being in operative conditions. There is a notorious diﬀerence between the incident distribution per cause of the incidents in the USA (Fig. 2) and in Europe (Fig. 3), being the only signiﬁcant common factor that corrosion is the second most frequent cause in both cases.

3.3. Failure causes criteria adopted for this research

Since this study compiles the most lethal pipeline accidents through the world, the authors consider that, with clariﬁcation purposes, utilizing a nomenclature system that adapts to the failures reviewed is the best approach. With regards to the failure causes criteria adopted for this review, the authors have opted for an intermediate point between the two previously reviewed classiﬁcation systems. The reason behind this is that, given the characteristics of the accident data recompiled, the PHMSA approach would be too detailed, while the EGIG one would not be enough to cover all the particularities. The classiﬁcation of failure causes adopted for this review is explained below.

• Vandalism: accidents caused by thieves drilling into the pipe in order to steal fuel.

Uniform corrosion: failure caused by uniform thinning of the interior or exterior of the pipe due to uniform corrosion. Pitting corrosion: failure provoked by pitting corrosion of the pipe.

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Fig. 3. EGIG OGP incident distribution per cause in the 2007–2016 period [27].

• Third party: failure caused by construction works (digging, piling, ground works).

Flawed design: pipe failure due to a design mistake.

Mismanagement: failure induced by human factors, either a mistake by an operator or due to poor decision-making by the pipeline company.

Component failure: failure of one of the components of the pipe (e.g. valve, weld). The causes behind the failure are not speciﬁed and cannot be linked to either of the mechanisms exposed before.

Not deﬁned (ND): there is no available information regarding the causes behind the accident.

4. OGP accidents compilation and analysis

OGP accidents that have been compiled by this research are presented in Table 1, including data such as the date of the accident, location, number of fatalities (criteria of order), transported ﬂuids, the root cause of the event and the sources from where the data

Table 1

Most fatal OGP accidents through history.

Date

October 1998 November 1984 June 1989 December 2006 March 1937 April 1992

May 2006 June 2003 May 2008

September 2011 August 1970 November 2013 March 2004 November 1978 November 1996 July 2014 December 2010 March 1965 July 2004

June 2014 August 2013 October 1971

January 1976

Location

Lagos, Nigeria

San Juanico, Mexico Ufa, Russia

Lagos, Nigeria Texas, USA Guadalajara, Mexico Lagos, Nigeria

Abia, Nigeria Lagos, Nigeria Nairobi, Kenya Osaka, Japan Qingdao, China

Arkhangelsk, Russia Mexico DF, Mexico San Juan, Puerto Rico Kaohsiung, Taiwan Puebla, Mexico Quebec, Canada Ghislenghien, Belgium Andhra Pradesh, India Rosario, Argentina Renfrewshire, Scotland

Nebraska, USA

Fatalities

1078 650 643 466 309 252 143 105 100 100 79 62 58 52 33 32 29 28 24 23 22 22

20

Root cause

Vandalism Pitting corrosion Mismanagement Vandalism

ND

Flawed design Vandalism Vandalism Third party

Component failure Third party Uniform corrosion Vandalism Component failure Third party Uniform corrosion Third party

ND

Third party Mismanagement ND

ND

Flawed design

Substance

Gasoline LPG Natural Gas Oil

Natural Gas Gasoline Diesel Petrol

Oil Oil

Natural Gas Oil

Natural Gas Natural Gas Propane Propane

Oil

Natural Gas Natural Gas Natural Gas Natural Gas Natural Gas

Natural Gas

Sources

[72,73,74] [75,76,77] [72,78,79] [72,80,81] [72,82,83] [84,85,86] [72,87,88] [84,88] [84,88,89] [84,90,91] [84,92] [84,93,94] [84,95] [84,96] [72,97] [98,99] [84,100,101] [84,102,103] [104,105] [106,107,108] [84,109,110] [84,111,112]

[72,113]

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Fig. 4. Number of fatalities caused by the most lethal OGP accidents ordered chronologically.

was obtained. The criteria adopted by the authors was to take the highest published number, considering diﬀerent number of reported fatalities depending on the source: in this paper, 23 accidents were compiled, which caused a total of 4329 fatalities.

As can be seen in Table 1, Nigeria is very present in the top 10 of the most lethal OGP accidents through history, accounting for the 43% of the total number of fatalities. Trying to remedy these kind of situations, great eﬀort has been put recently towards mitigating the frequency of OGP failures in Nigeria [71].

In Fig. 4, the number fatalities of caused by the compiled OGP accidents is chronologically ordered by year.

From Table 1, it is indicated that the major proportion of the fatalities is located in the period 1984–2006, where almost 80% of

Fig. 5. Distribution of the fatalities of the most lethal OGP accidents by root cause.

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Table 2

Lessons learned from the 10 most fatal OGP accidents through history.

Accident (Fatalities)

Lagos, 1998 (1078)

San Juanico, 1984 (650)

Ufa, 1989 (643)

Lagos, 2006 (466) Texas, 1937 (309)

Guadalajara, 1992 (252)

Lagos, 2006 (143) Abia, 2003 (105)

Lagos, 2008 (100)

Nairobi, 2011 (100)

Lessons learned

• Pipeline incidents must always be notiﬁed immediately to the emergency services and the aﬀected population, in order to reduce their impact and the number of fatalities.

• Lack of maintenance in signiﬁcantly poor areas, can induce failure that leads to scavenging, which increments the impacts of pipeline breakdown. For this reason, properly designed and applied maintenance plans are always of vital paramount.

• The use of state-of-the-art eﬀective leak detection systems are crucial for the safety of gas and oil transport via pipelines. If the leak is quickly detected, then the probabilities of escalation are signiﬁcantly diminished.

• Material selection during design must take into consideration the potential of the pipe being subjected to suﬀer pitting corrosion. Therefore, a material that is not prone to pitting corrosion should be prioritized during the design stages in order to avoid accidents like this.

• Proper isolation techniques should be always designed with the purpose of containing possible accidents. This was not the case in this accident, allowing the initial blast propagation and causing a tremendous number of fatalities.

• Maintaining an intensive train schedule was prioritized over verifying the information given by a train driver pointing out that he noticed a very strong gas odor when transiting through the accident area. Therefore, it is sensible to state that human safety should be always situated over any kind of proﬁt, since the consequences, as happened in this case, can be catastrophic.

• Proper real-time telemetry information is vital to prevent confusions as the one that increased the impact of this accident. Not having enough data lead the operator to not be able to make an informed decision before raising the pressure of the pipe.

• Same as in the Lagos, 1998 accident.

• This accident caused one of the most important improvements towards ensuring gas transportation and consumption safety, due to the fact that, as result of this disaster, the mixing of “malodorants” with natural gas was made mandatory in the state of Texas, with other states quickly following [82].

• Although several gases were added “malodorants” as a consequence of this accident, there are still some that are completely unscented such as carbon monoxide, which in high enough concentrations, is highly lethal. For this reason, installing gas detectors in public buildings, such as schools, and even in private homes, is advisable.

• When ﬂammable materials such as gas & oil are involved, the risk of explosion should always be properly assessed before stating that no measures are to be taken. Moreover, when the risk of human casualties is involved precautions should be extreme.

• Design is one of the most important stages toward accident prevention since, as happened in this case, a design ﬂaw can cause severe consequences. For this reason, it is very important that designers have all the required information and know-how in order to be able to generate the most appropriate design.

• Same as in the accident occurred in Lagos, 1998.

• The response made by the company responsible of the pipeline when an incident is reported must be as quick and eﬀective as possible, and the potential risks can never be disregarded.

• Same as in the accident occurred in Lagos, 1998.

• Construction work should always be properly planned. Before starting any kind of digging, the responsible construction company must always gather all the updated information regarding the piping systems that run through the area.

• Exactly determining the failure mechanisms that led to any accident or incident is vital in order to learn from them. If this is not

done, the opportunity of reducing the likelihood of a similar accident happening again is discarded, placing human lives at risk.

the fatalities occurred, with 1998 being the most catastrophic.

Fig. 5 depicts the proportion of the fatalities that were caused by each type of failure.

It is notable point out that vandalism is the main root that signiﬁcantly has caused the highest proportion of the deaths, amongst the most baneful OGP accidents through history, adding up to an astounding ratio of 43%. Mismanagement and pitting corrosion are in contention for second place, with a ratio of 15% each. OGP accidents behind 9% of the total number of fatalities have a not deﬁned root cause, hindering the task of preventing repetition of the same type of accident in the future (Fig. 5).

The following subsections detail the 10 most fatal pipeline accidents through history, covering every pipeline accident that has entailed over 100 deaths. A description of each accident is made, analyzing the most relevant data and circumstances of each case, and, ﬁnally, after all the accidents analysis, the lessons learned from each accident are presented in Table 2.

4.1. October 1998 (Lagos, Nigeria) → 1078 fatalities

On October 17th, 1998, the most devastating accident on the history of oil and gas pipeline transportation occurred, with unprecedented mortality and extent of damage [114]. This accident is considered the third most fatal within the energy industries [72]. The death toll was furthermore increased due to the fact that farmers realized that the pipeline was leaking and notiﬁed other nearby villagers, who traveled to the pierced pipe to scavenge for fuel [72]. This fact was proven because many of the dead were holding a bucket, verifying that theft was going on during the incident, although some sources signal that it might have been possible that the failure was induced due to lack of maintenance and neglect [84]. Moreover, the government and oil companies involved did not make public the incident upon realization, causing a delay on the medical assistance arrival, which only happened after many had already died [72]. In Fig. 6, a picture of the aftermath of this accident is shown, where the buckets that were being used by the scavengers can be seen in the foreground of the image [74].

4.2. November 1984 (San Juanico, Mexico) → 650 fatalities

The most severe LPG (liqueﬁed petroleum gas) accident through history happened when a 12-inch pipeline transporting LPG

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Fig. 6. Fireﬁghters trying to extinguish a ﬁre after the 1998 pipeline blaze in Nigeria [74].

ruptured due to pitting corrosion, although the available information states that the causes of the accident are yet to be precisely deﬁned. The initial blast generated a series of chain-reaction explosions, which, combined with the fact that the pipeline crossed through a residential complex in the area of the failure, caused an impacting death toll [75]. Fig. 7 depicts the tanks blown in the San Juanico storage plant during the chain of explosions [77].

4.3. June 1989 (Ufa, Russia) → 643 fatalities

The third most impacting OGP accident regarding the number of casualties occurred during the night of the 4th of June 1989, when two passenger trains were crossing through a zone of natural gas contamination caused by a leak on the Western Siberia/Ural/ Volga pipeline. A spark from one of the train motors caused an explosion equivalent to 300 tons of TNT, which combined with the fact that the trains aﬀected by the accident were carrying a combined ﬁgure of over 1.300 passengers, caused the number of fatalities to skyrocket. In the literature, mismanagement is signaled as the primary cause of the incident, because the investigation following the accident concluded that, when the operators of the pipeline realized that the pressure through the line was dropping, decided to raise said pressure in order to compensate and maintain system stability, causing the broken section of the pipe to increase. This decision was made mainly because they lacked the resources and telemetry systems to detect a leak and there were no signals of the pressure drop being dangerous [115]. Fig. 8 depicts one of the trains involved in the accident in the derailed condition after the explosion [78].

4.4. December 2006 (Lagos, Nigeria) → 466 fatalities

This is the second OGP accident amongst the 4 more lethal that is located in the area of Lagos, Nigeria. The information regarding this accident is very limited, although the sources signal that the cause of the accident was very likely the same as in the most lethal pipeline accident through history: pipeline was vandalized with oil-theft purposes, leading more scavengers to turn up to the van-dalized area and increasing the number of fatalities [84]. The remnant ﬁre after the OGP accident can be seen in Fig. 9 [81].

Fig. 7. Tanks blown in the San Juanico LPG storage plant after the chain of explosions [77].

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Fig. 8. One of the trains derailed after the Ufa pipeline disaster [78].

Fig. 9. On the background, smoke and ﬂames after the December 6th pipeline accident [81].

4.5. March 1937 (Texas, USA) → 309 fatalities

It was a regular afternoon in the Consolidated High School, located in New London, Texas, when, several minutes before the end of the school day, the building was completely destroyed due to an explosion provoked by an undetected natural gas leak, causing the death of 309 people, of which 294 were students [72]. The investigation about the accident concluded that the cause of the explosion was that an electric wood-shop sander sparked unscented gas that had accumulated beneath and inside the walls of the school [82]. Fig. 10 depicts the aftermath of the New London School explosion, where the demolished building can be observed in the background of the image [82].

4.6. April 1992 (Guadalajara, Mexico) → 252 fatalities

Once again, an initial explosion causing a chain-reaction of several explosion was the recipe for a high death toll accident. The fact that impacts the most about this accident is that the gas leakage was noticed by the neighbors, who notiﬁed the company and led to a city worker being sent to inspect the area, discovering high amounts of gasoline fumes. However, the city major deemed that there was no risk of explosion and the evacuation was discarded [84]. The installation of a zinc-coated pipe with sewer purposes too close to the existing gasoline pipeline created the environment necessary for galvanic corrosion to occur, which led to the thinning of the gasoline pipe due to corrosion and the subsequent leak that led to the accident. The large number of casualties was caused because the highly combustible gas dispersed over a highly populated urban area [98]. The tremendous damage caused by the chain of

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Fig. 10. Aftermath of the New London School explosion [82].

explosions can be observed in Fig. 11 [85].

4.7. May 2006 (Lagos, Nigeria) → 143 fatalities

This accident was determined to have been caused by the pressurized petrol pipeline being previously punctured by thieves [84], and, therefore, vandalism is again the main reason of a lethal OGP accident located in Nigeria. The diesel that was leaking from the vandalized pipeline caught ﬁre, destroying three nearby villages [72].

4.8. June 2003 (Abia, Nigeria) → 105 fatalities

This accident, as the ones reviewed in Sections 4.1, 4.4 and 4.7, was caused by vandalism with thieving purposes. The case, however, has a deeper background, since the puncturing of the pipeline was astonishingly done two months prior to the accident, without the responsible company doing anything to remediate it, so the accident was far from instantaneous. Furthermore, locals claimed that they had informed the owner of the leak several days before the accident, but they failed in detaining the leak [84].

4.9. May 2008 (Lagos, Nigeria) → 100 fatalities

The ﬁrst accident on the list caused by third party occurred when a pipeline transporting diesel exploded in Ijegun, Lagos on May 2006, after it was damaged during construction works when an operator struck the pipeline with a bulldozer, causing it to rupture and subsequently explode. The explosion damaged the local Primary School and over 15 homes [84]. Fig. 12 depicts the ﬁreﬁghters trying to extinguish the ﬁre following the OGP pipeline explosion [89].

4.10. September 2011 (Nairobi, Kenya) → 100 fatalities

It was September 12th, 2011, when a pipeline operated by the Kenya Pipeline Company (KPC), which had been leaking oil

Fig. 11. Damage caused by the Guadalajara 1992 pipeline explosions [85].

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Fig. 12. Fireﬁghters trying to put down the ﬁre after the OGP pipeline explosion [89].

previously, caught ﬁre. The high death toll was caused, once again, due to the fact that locals were visiting the area of the incident to collect the leaking oil. A valve that had failed under pressure was signaled as the location of the leak [84]. However, the causes that led the valve to fail are not explained. In this kind of accidents, it is of paramount importance to pinpoint the reasons behind the valve failure. The reasoning behind this statement, is that it is highly likely that more valves than the one that failed are installed through the pipeline system, either in the same pipeline that failed, or in another transport systems throughout the world, so the failure could potentially reproduce. It is very diﬀerent that the failure was induced by a design ﬂaw on the valve, by some corrosion mechanism or due to subjecting the valve to a pressure higher than its capabilities. The gruesome consequences of this accident can be seen in Fig. 1, where a man is sitting devastated in the foreground of the picture after discovering that two of his children have perished as a result of the OGP failure [90] (see Fig. 13).

Table 2 presents, adopting a Lessons Learned Approach, LLA, by the authors, all the lessons learned from the most lethal OGP accidents through history that this paper has compiled and analyzed in the previous subsections.

5. Conclusions

OGP fatal accidents as the ones reviewed in this paper are the most undesirable and unfortunate incidents that can occur within the industry. However, the lessons learned from them play a critical role on the history and development of the pipeline transport system.

This paper has compiled a total of 23 OGP fatal accidents with more than 20 deaths that have occurred trough history, with a combined number of 4329 fatalities. Vandalism has proven to be the most life-detrimental root cause in these accidents, being the responsible for 43% of the fatalities, while mismanagement and pitting corrosion are neck-and-neck for second place, accounting each for 15% of the total number of deaths. The fact that the root cause behind the accidents responsible of 9% of the fatalities has not

Fig. 13. A man sits in a state of shock after discovering the remains of two of his children after the 2011 Kenya pipeline ﬁre [90].

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yet been deﬁned is a notable and preoccupying observation. Moreover, Nigeria has a prominent presence in the top 10 of the most lethal OGP accidents through history: 43% of the total number of fatalities occurred in this country.

The LLA taken to analyze the 10 most lethal OGP accidents has proportioned more than 15 lessons learned that are stated in this paper and pursue the objective of being always present for the OGP manufacturers, operators, and for the general population. The general population has had a signiﬁcate inﬂuence in the most lethal OGP accidents and, therefore, should be aware of the risks that OGP transportation implies.

As a ﬁnal conclusion, the authors state that it is highly advisable to beneﬁt from the experience of the documented OGP pipeline failures, learning from the past, with the purpose of building a safer and better future.

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The authors declare that they have no known competing ﬁnancial interests or personal relationships that could have appeared to inﬂuence the work reported in this paper.

References

[1] J.G. Ramírez-Camacho, et al., Assessing the consequences of pipeline accidents to support land-use planning, Saf. Sci. 97 (2017) 34–42, [https://doi.org/10.](https://doi.org/10.1016/j.ssci.2016.01.021) [1016/j.ssci.2016.01.021.](https://doi.org/10.1016/j.ssci.2016.01.021)

[2] G. Gabetta, G. Gori, The use of knowledge management to improve pipeline safety, Integrity of Pipelines Transporting Hydrocarbons, Springer, Dordrecht, 2011, pp. 1–16, , [https://doi.org/10.1007/978-94-007-0588-3\_1.](https://doi.org/10.1007/978-94-007-0588-3_1)

[3] W. Worthington, Monitoring for transient pressures in pipelines, Pipelines 2005: Optimizing Pipeline Design, Operations, and Maintenance in Today's Economy, 2005, pp. 886–898, , [https://doi.org/10.1061/40800(180)71.](https://doi.org/10.1061/40800(180)71)

[4] [N. Milton, The Lessons Learned Handbook: Practical Approaches to Learning from Experience, Elsevier, 2010.](http://refhub.elsevier.com/S1350-6307(19)31232-4/h0020) [5] [J.E. Brantly, History of Oil Well Drilling, Gulf Publishing Company, Book Division, 1971.](http://refhub.elsevier.com/S1350-6307(19)31232-4/h0025)

[6] [M. Torres, Microstructural Investigation of Vintage Pipeline Steels Highly Susceptible to Stress Corrosion Cracking, The University of Texas at El Paso, 2016.](http://refhub.elsevier.com/S1350-6307(19)31232-4/h0030) [7] J.F. Kiefner, M.J. Rosenfeld, The role of pipeline age in pipeline safety. INGAA, Oct, 2012. Available from: [https://www.ingaa.org/ﬁle.aspx?id=19307](https://www.ingaa.org/file.aspx%3fid%3d19307).

[8] H.A. Kishawy, H.A. Gabbar, Review of pipeline integrity management practices, Int. J. Press. Vessels Pip. 87 (7) (2010) 373–380, [https://doi.org/10.1016/j.](https://doi.org/10.1016/j.ijpvp.2010.04.003) [ijpvp.2010.04.003.](https://doi.org/10.1016/j.ijpvp.2010.04.003)

[9] I.De S. Bott, et al., High-strength steel development for pipelines: a Brazilian perspective, Metall. Mater. Trans. A 36 (2) (2005) 443–454, [https://doi.org/10.](https://doi.org/10.1007/s11661-005-0315-9) [1007/s11661-005-0315-9.](https://doi.org/10.1007/s11661-005-0315-9)

[10] D.B. Rosado, et al., Latest developments in mechanical properties and metallurgical features of high strength line pipe steels, Int. J. Sustain. Constr. Des. 4 (1) (2013), [https://doi.org/10.21825/scad.v4i1.742.](https://doi.org/10.21825/scad.v4i1.742)

[11] API (American Petroleum Institute), API Speciﬁcation 5L, 46th ed. Washington DC, 2018.

[12] S.K. Biswas, S. Chen, A. Satyanarayana, Optimal temperature tracking for accelerated cooling processes in hot rolling of steel, Dyn. Control 7 (4) (1997) 327–340, [https://doi.org/10.1023/A:1008268310234.](https://doi.org/10.1023/A:1008268310234)

[13] A.J. Deardo, Accelerated cooling: a physical metallurgy perspective, Proceedings of the Metallurgical Society of the Canadian Institute of Mining and Metallurgy, Pergamon, 1988, pp. 3–27, , [https://doi.org/10.1016/b978-0-08-035770-6.50006-4.](https://doi.org/10.1016/b978-0-08-035770-6.50006-4)

[14] M. Pontremoli, et al., Development of grade API X80 pipeline steel plates produced by controlled rolling, Met. Technol. 11 (1) (1984) 504–514, [https://doi.org/](https://doi.org/10.1179/030716984803275197) [10.1179/030716984803275197.](https://doi.org/10.1179/030716984803275197)

[15] M.V. Biezma, J.R. San Cristóbal, Letter to the editor: Is the cost of corrosion really quantiﬁable? Corrosion 62 (12) (2006) 1051–1055, [https://doi.org/10.5006/](https://doi.org/10.5006/1.3278238) [1.3278238.](https://doi.org/10.5006/1.3278238)

[16] [R.W. Revie (Ed.), Oil and Gas Pipelines: Integrity and Safety Handbook, John Wiley & Sons, 2015.](http://refhub.elsevier.com/S1350-6307(19)31232-4/h0080)

[17] [J.F. Kiefner, C.J. Trench, Oil Pipeline Characteristics and Risk Factors: Illustrations from the Decade of Construction, American Petroleum Institute, 2001.](http://refhub.elsevier.com/S1350-6307(19)31232-4/h0085) [18] [J. Aleksandersen, et al., The smart plug: a remotely controlled pipeline isolation system, The Eleventh International Oﬀshore and Polar Engineering Conference,](http://refhub.elsevier.com/S1350-6307(19)31232-4/h0090)

[International Society of Oﬀshore and Polar Engineers, 2001.](http://refhub.elsevier.com/S1350-6307(19)31232-4/h0090)

[19] [M.A. Westhoﬀ, Using operating data at natural gas pipelines, Proceedings: International Symposium on Transportation Recorders, (1999).](http://refhub.elsevier.com/S1350-6307(19)31232-4/h0095)

[20] I. Stoianov, et al., PIPENETa wireless sensor network for pipeline monitoring, Proceedings of the 6th International Conference on Information Processing in Sensor Networks, 2007, pp. 264–273, , [https://doi.org/10.1145/1236360.1236396.](https://doi.org/10.1145/1236360.1236396)

[21] [A. Goldthau, Assessing Nord Stream 2: regulation, geopolitics & energy security in the EU, Central Eastern Europe & the UK, European Center for Energy and](http://refhub.elsevier.com/S1350-6307(19)31232-4/h0105) [Resource Security. Strategy Paper vol. 10, (2016).](http://refhub.elsevier.com/S1350-6307(19)31232-4/h0105)

[22] [W.K. Muhlbauer, Pipeline Risk Management Manual, Gulf Publishing Company, 1996.](http://refhub.elsevier.com/S1350-6307(19)31232-4/h0110)

[23] Pipeline and Hazardous Materials Safety Administration. PHMSA [online], 2019. Available from: <https://www.phmsa.dot.gov/>(accessed 11 March 2019). [24] R. Bolt, Using or creating incident databases for natural gas transmission pipelines. Report of study group 3.4, 23rd World Gas Conference, Amsterdam, The

Netherlands, 2006, [https://doi.org/10.1115/ipc2006-10619.](https://doi.org/10.1115/ipc2006-10619)

[25] European Gas pipeline Incident data Group, EGIG [online], 2019. Available from: <https://www.egig.eu>(accessed 15 March 2019).

[26] V. Castellanos, et al., Failure analysis expert system for onshore pipelines. Part–I: Structured database and knowledge acquisition, Expert Syst. Appl. 38 (9) (2011) 11085–11090, [https://doi.org/10.1016/j.eswa.2011.02.153.](https://doi.org/10.1016/j.eswa.2011.02.153)

[27] European Gas pipeline Incident data Group, 10th Report of the European Gas pipeline Incident data Group [online], 2018. Available from: [https://www.egig.](https://www.egig.eu/reports) [eu/reports](https://www.egig.eu/reports) (accessed 20 June 2019).

[28] C. Miao, J. Zhao, Risk analysis for the urban buried gas pipeline with fuzzy comprehensive assessment method, J. Press. Vessel Technol. 134 (2) (2012), [https://](https://doi.org/10.1115/1.4004625) [doi.org/10.1115/1.4004625.](https://doi.org/10.1115/1.4004625)

[29] Pipeline Failure Causes, PHMSA [online], 2019. Available from: <https://www.phmsa.dot.gov/incident-reporting/accident-investigation-division/pipeline-failure-causes>(accessed 11 March 2019).

[30] M.V. Biezma, D. Agudo, G. Barron, A fuzzy logic method: predicting pipeline external corrosion rate, Int. J. Press. Vessels Pip. 163 (2018) 55–62, [https://doi.](https://doi.org/10.1016/j.ijpvp.2018.05.001) [org/10.1016/j.ijpvp.2018.05.001.](https://doi.org/10.1016/j.ijpvp.2018.05.001)

[31] I. Bertuccio, M.V. Biezma, Risk assessment of corrosion in oil and gas pipelines using fuzzy logic, Corros. Eng., Sci. Technol. 47 (7) (2012) 553–558, [https://doi.](https://doi.org/10.1179/1743278212y.0000000028) [org/10.1179/1743278212y.0000000028.](https://doi.org/10.1179/1743278212y.0000000028)

[32] B.T. Bastian, et al., Visual inspection and characterization of external corrosion in pipelines using deep neural network, NDT E Int. (2019) 102–134, [https://doi.](https://doi.org/10.1016/j.ndteint.2019.102134) [org/10.1016/j.ndteint.2019.102134.](https://doi.org/10.1016/j.ndteint.2019.102134)

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M.V. Biezma, et al. *Engineering Failure Analysis 110 (2020) 104446*

[33] H.P. Hong, Inspection and maintenance planning of pipeline under external corrosion considering generation of new defects, Struct. Saf. 21 (3) (1999) 203–222, [https://doi.org/10.1016/s0167-4730(99)00016-8.](https://doi.org/10.1016/s0167-4730(99)00016-8)

[34] E.O. Obanijesu, et al., Hydrate formation and its inﬂuence on natural gas pipeline internal corrosion rate, SPE Oil and Gas India Conference and Exhibition, Society of Petroleum Engineers, 2010, , [https://doi.org/10.2118/128544-ms.](https://doi.org/10.2118/128544-ms)

[35] E.O. Obanijesu, Modeling the H2S contribution to internal corrosion rate of natural gas pipeline, Energy Sour. Part A 31 (4) (2009) 348–363, [https://doi.org/](https://doi.org/10.1080/15567030701528408) [10.1080/15567030701528408.](https://doi.org/10.1080/15567030701528408)

[36] [A.M. Halvorsen, et al., pH stabilization for internal corrosion protection of pipeline carrying wet gas with CO2 and acetic acid, CORROSION 2003, NACE](http://refhub.elsevier.com/S1350-6307(19)31232-4/h0180) [International, 2003.](http://refhub.elsevier.com/S1350-6307(19)31232-4/h0180)

[37] M.N. Ilman, et al., Analysis of internal corrosion in subsea oil pipeline, Eng. Fail. Anal. 2 (1) (2014) 1–8, [https://doi.org/10.1016/j.csefa.2013.12.003.](https://doi.org/10.1016/j.csefa.2013.12.003) [38] C.R. Azevedo, Failure analysis of a crude oil pipeline, Eng. Fail. Anal. 14 (6) (2007) 978–994, [https://doi.org/10.1016/j.engfailanal.2006.12.001.](https://doi.org/10.1016/j.engfailanal.2006.12.001)

[39] W. Zheng, Eﬀects of hydrostatic testing on the growth of stress-corrosion cracks, 1998 2nd International Pipeline Conference, American Society of Mechanical Engineers, 1998, pp. 459–472, , [https://doi.org/10.1115/IPC1998-2053.](https://doi.org/10.1115/IPC1998-2053)

[40] J. Li, et al., Investigation of plastic zones near SCC tips in a pipeline after hydrostatic testing, Mater. Sci. Eng., A 486 (1–2) (2008) 496–502, [https://doi.org/10.](https://doi.org/10.1016/j.msea.2007.09.046) [1016/j.msea.2007.09.046.](https://doi.org/10.1016/j.msea.2007.09.046)

[41] S.Sh. Abedi, A. Abdolmaleki, N. Adibi, Failure analysis of SCC and SRB induced cracking of a transmission oil products pipeline, Eng. Fail. Anal. 14 (1) (2007) 250–261, [https://doi.org/10.1016/j.engfailanal.2005.07.024.](https://doi.org/10.1016/j.engfailanal.2005.07.024)

[42] J. Luo, et al., Stress corrosion cracking behavior of X90 pipeline steel and its weld joint at diﬀerent applied potentials in near-neutral solutions, Nat. Gas Ind. B 6 (2) (2019) 138–144, [https://doi.org/10.1016/j.ngib.2018.08.002.](https://doi.org/10.1016/j.ngib.2018.08.002)

[43] S.J. Luo, R. Wang, Identiﬁcation of the selective corrosion existing at the seam weld of electric resistance-welded pipes, Corros. Sci. 87 (2014) 517–520, [https://](https://doi.org/10.1016/j.corsci.2014.06.044) [doi.org/10.1016/j.corsci.2014.06.044.](https://doi.org/10.1016/j.corsci.2014.06.044)

[44] [G.T. Quickel, B.C. Rollins, J.A. Beavers, Analysis of seam weld related pipeline failures, Mater. Sci. Technol. 8 (2008) 514–523.](http://refhub.elsevier.com/S1350-6307(19)31232-4/h0220)

[45] J.F. Kiefner, Dealing with low-frequency-welded ERW pipe and ﬂash-welded pipe with respect to HCA-related integrity assessments, ASME 2002 Engineering Technology Conference on Energy, American Society of Mechanical Engineers, 2002, pp. 699–706, , [https://doi.org/10.1115/etce2002/pipe-29029.](https://doi.org/10.1115/etce2002/pipe-29029)

[46] M.D. Chapetti, J.L. Otegui, J. Motylicki, Fatigue assessment of an electrical resistance welded oil pipeline, Int. J. Fatigue 24 (1) (2002) 21–28, [https://doi.org/](https://doi.org/10.1016/s0142-1123(01)00111-6) [10.1016/s0142-1123(01)00111-6.](https://doi.org/10.1016/s0142-1123(01)00111-6)

[47] K.A. Macdonald, et al., Assessing mechanical damage in oﬀshore pipelines–Two case studies, Eng. Fail. Anal. 14 (8) (2007) 1667–1679, [https://doi.org/10.](https://doi.org/10.1016/j.engfailanal.2006.11.074) [1016/j.engfailanal.2006.11.074.](https://doi.org/10.1016/j.engfailanal.2006.11.074)

[48] [S. Duan, P. Shen, Analysis of nearby pipeline damage induced by deep excavation, Eng. Mech. 4 (2005) 79–83.](http://refhub.elsevier.com/S1350-6307(19)31232-4/h0240)

[49] C.E. Restrepo, J.S. Simonoﬀ, R. Zimmerman, Causes, cost consequences, and risk implications of accidents in US hazardous liquid pipeline infrastructure, Int. J. Crit. Infrastruct. Prot. 2 (1–2) (2009) 38–50, [https://doi.org/10.1016/j.ijcip.2008.09.001.](https://doi.org/10.1016/j.ijcip.2008.09.001)

[50] S. Girgin, E. Krausmann, Historical analysis of US onshore hazardous liquid pipeline accidents triggered by natural hazards, J. Loss Prev. Process Ind. 40 (2016) 578–590, [https://doi.org/10.1016/j.jlp.2016.02.008.](https://doi.org/10.1016/j.jlp.2016.02.008)

[51] E. Krausmann, et al., Industrial accidents triggered by earthquakes, ﬂoods and lightning: lessons learned from a database analysis, Nat. Hazards 59 (1) (2011) 285–300, [https://doi.org/10.1007/s11069-011-9754-3.](https://doi.org/10.1007/s11069-011-9754-3)

[52] M.J. O'rourke, Xuejie Liu, Response of buried pipelines subject to earthquake eﬀects, 1999. Available from: <http://hdl.handle.net/10477/588>.

[53] A. Hindy, M. Novak, Earthquake response of underground pipelines, Earthq. Eng. Struct. Dyn. 7 (5) (1979) 451–476, [https://doi.org/10.1002/eqe.](https://doi.org/10.1002/eqe.4290070506) [4290070506.](https://doi.org/10.1002/eqe.4290070506)

[54] S. Yoon, D.H. Lee, H. Jung, Seismic fragility analysis of a buried pipeline structure considering uncertainty of soil parameters, Int. J. Press. Vessels Pip. (2019), [https://doi.org/10.1016/j.ijpvp.2019.103932.](https://doi.org/10.1016/j.ijpvp.2019.103932)

[55] S.B. Cunha, Comparison and analysis of pipeline failure statistics, 2012 9th International Pipeline Conference, American Society of Mechanical Engineers, 2012, pp. 521–530, , [https://doi.org/10.1115/IPC2012-90186.](https://doi.org/10.1115/IPC2012-90186)

[56] P. Venturino, et al., Pipeline failures due to lightning, Eng. Fail. Anal. 64 (2016) 1–12, [https://doi.org/10.1016/j.engfailanal.2016.02.021.](https://doi.org/10.1016/j.engfailanal.2016.02.021)

[57] G.T. Quickel, J.A. Beavers, Pipeline failure results from lightning strike: act of mother nature? J. Fail. Anal. Prev. 11 (3) (2011) 227–232, [https://doi.org/10.](https://doi.org/10.1007/s11668-011-9447-y) [1007/s11668-011-9447-y.](https://doi.org/10.1007/s11668-011-9447-y)

[58] [G. Luft, Pipeline sabotage is terrorist's weapon of choice, Pipeline & gas journal 232 (2) (2005) 42–44.](http://refhub.elsevier.com/S1350-6307(19)31232-4/h0290)

[59] L. Kraidi, et al., Analyzing the critical risk factors associated with oil and gas pipeline projects in Iraq, Int. J. Crit. Infrastruct. Prot. 24 (2019) 14–22, [https://doi.](https://doi.org/10.1016/j.ijcip.2018.10.010) [org/10.1016/j.ijcip.2018.10.010.](https://doi.org/10.1016/j.ijcip.2018.10.010)

[60] J.R. Dancy, V.A. Dancy, Terrorism and oil & gas pipeline infrastructure: vulnerability and potential liability for cybersecurity attacks, ONE J 2 (2016) 579 [https://digitalcommons.law.ou.edu/onej/vol2/iss6/2.](https://digitalcommons.law.ou.edu/onej/vol2/iss6/2)

[61] J.L. Otegui, et al., Weld failures in sleeve reinforcements of pipelines, Eng. Fail. Anal. 8 (1) (2001) 57–73, [https://doi.org/10.1016/s1350-6307(99)00049-7.](https://doi.org/10.1016/s1350-6307(99)00049-7) [62] H.I. Shafeek, et al., Automatic inspection of gas pipeline welding defects using an expert vision system, NDT E Int. 37 (4) (2004) 301–307, [https://doi.org/10.](https://doi.org/10.1016/j.ndteint.2003.10.004)

[1016/j.ndteint.2003.10.004.](https://doi.org/10.1016/j.ndteint.2003.10.004)

[63] A. Aljaroudi, et al., Risk assessment of oﬀshore crude oil pipeline failure, J. Loss Prev. Process Ind. 37 (2015) 101–109, [https://doi.org/10.1016/j.jlp.2015.07.](https://doi.org/10.1016/j.jlp.2015.07.004) [004.](https://doi.org/10.1016/j.jlp.2015.07.004)

[64] L. Shi, C. Wang, C. Zou, Corrosion failure analysis of L485 natural gas pipeline in CO2 environment, Eng. Fail. Anal. 36 (2014) 372–378, [https://doi.org/10.](https://doi.org/10.1016/j.engfailanal.2013.11.009) [1016/j.engfailanal.2013.11.009.](https://doi.org/10.1016/j.engfailanal.2013.11.009)

[65] C.R. Azevedo, A. Sinatora, Failure analysis of a gas pipeline, Eng. Fail. Anal. 11 (3) (2004) 387–400, [https://doi.org/10.1016/j.engfailanal.2003.06.004.](https://doi.org/10.1016/j.engfailanal.2003.06.004) [66] [Z.H. Yang, C. Wang, H.U. Shi-Jie, Study on fuzzy comprehensive evaluation system of city gas pipeline based on AHP, J. Saf. Environ. 2 (2013).](http://refhub.elsevier.com/S1350-6307(19)31232-4/h0330)

[67] PHMSA, Pipeline Incident 20 Year Trends [online). Available from: <https://www.phmsa.dot.gov/data-and-statistics/pipeline/pipeline-incident-20-year-trends> (accessed 15 June 2019).

[68] J.Y. Zheng, et al., Failure analysis and safety evaluation of buried pipeline due to deﬂection of landslide process, Eng. Fail. Anal. 25 (2012) 156–168, [https://](https://doi.org/10.1016/j.engfailanal.2012.05.011) [doi.org/10.1016/j.engfailanal.2012.05.011.](https://doi.org/10.1016/j.engfailanal.2012.05.011)

[69] E.M. Lee, et al., Landslide-related ruptures of the Camisea pipeline system, Peru, Q. J. Eng. Geol. Hydrogeol. 42 (2) (2009) 251–259, [https://doi.org/10.1144/](https://doi.org/10.1144/1470-9236/08-061) [1470-9236/08-061.](https://doi.org/10.1144/1470-9236/08-061)

[70] [R. Bruschi, et al., Failure Modes for Pipelines in Landslide Areas, American Society of Mechanical Engineers, New York, NY (United States), 1995.](http://refhub.elsevier.com/S1350-6307(19)31232-4/h0350)

[71] A. Ambituuni, E. Ochieng, J.M. Amezaga, Optimizing the integrity of safety critical petroleum assets: A project conceptualization approach, IEEE Trans. Eng. Manage. 66 (2) (2018) 208–223, [https://doi.org/10.1109/tem.2018.2839518.](https://doi.org/10.1109/tem.2018.2839518)

[72] B.K. Sovacool, The costs of failure: A preliminary assessment of major energy accidents, 1907–2007, Energy Policy 36 (5) (2008) 1802–1820, [https://doi.org/](https://doi.org/10.1016/j.enpol.2008.01.040) [10.1016/j.enpol.2008.01.040.](https://doi.org/10.1016/j.enpol.2008.01.040)

[73] The Associated Press, Oil Pipeline Blows Up in Nigeria, Killing 250, The New York Times [online). 19 October 1998. Available from: [https://www.nytimes.](https://www.nytimes.com/1998/10/19/world/oil-pipeline-blows-up-in-nigeria-killing-250.html) [com/1998/10/19/world/oil-pipeline-blows-up-in-nigeria-killing-250.html](https://www.nytimes.com/1998/10/19/world/oil-pipeline-blows-up-in-nigeria-killing-250.html) (accessed 1 May 2019).

[74] Nigeria oil blast kills scores, BBC News [online], 2003. Available from: <http://news.bbc.co.uk/2/hi/africa/3009756.stm>(accessed 5 May 2019).

[75] J. Bhandari, et al., Modelling of pitting corrosion in marine and oﬀshore steel structures–A technical review, J. Loss Prev. Process Ind. 37 (2015) 39–62, [https://](https://doi.org/10.1016/j.jlp.2015.06.008) [doi.org/10.1016/j.jlp.2015.06.008.](https://doi.org/10.1016/j.jlp.2015.06.008)

[76] G. Arturson, The tragedy of San Juanico - the most severe LPG disaster in history, Burns 13 (2) (1987) 87–102, [https://doi.org/10.1016/0305-4179(87)](https://doi.org/10.1016/0305-4179(87)90096-9) [90096-9.](https://doi.org/10.1016/0305-4179(87)90096-9)

[77] R. Jimenez, A 25 años de las explosiones en San Juanico huele a gas y a olvido, El Universal [online). Available from: [https://archivo.eluniversal.com.mx/](https://archivo.eluniversal.com.mx/graficos/especial/EU_sanjuanico/index.html) [graﬁcos/especial/EU\_sanjuanico/index.html](https://archivo.eluniversal.com.mx/graficos/especial/EU_sanjuanico/index.html) (accessed 5 May 2019).

[78] J. Nevett, How the Ufa train disaster was overshadowed by Tiananmen Square, BBC News [online], 2019. Available from: [https://www.bbc.com/news/world-](https://www.bbc.com/news/world-europe-48510979)

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M.V. Biezma, et al. *Engineering Failure Analysis 110 (2020) 104446*

[europe-48510979](https://www.bbc.com/news/world-europe-48510979) (accessed 20 April 2019).

[79] On This Day: Ufa Train Disaster, The Moscow Times [online). Available from: <https://www.themoscowtimes.com/2019/06/04/on-this-day-ufa-train-disaster-a65865>(accessed 1 June 2019).

[80] Lagos pipeline blast kills scores, BBC News [online], 26 December 2006. Available from: <http://news.bbc.co.uk/2/hi/africa/6209845.stm>(accessed 1 June 2019).

[81] The Associated Press, Gas Line Explodes in Nigeria, Killing at Least 260, The New York Times [online], 2006. Available from: [https://www.nytimes.com/2006/](https://www.nytimes.com/2006/12/27/world/africa/27nigeria.html) [12/27/world/africa/27nigeria.html](https://www.nytimes.com/2006/12/27/world/africa/27nigeria.html) (accessed 20 April 2019).

[82] New London School Explosion, American Oil & Gas Historical Society [online], 2019. Available from: <https://aoghs.org/oil-almanac/new-london-texas-school-explosion>(accessed 22 April 2019).

[83] Natural gas explosion kills nearly 300 at Texas school, History [online). 13 November 2009. Available from: [https://www.history.com/this-day-in-history/](https://www.history.com/this-day-in-history/natural-gas-explosion-kills-schoolchildren-in-texas) [natural-gas-explosion-kills-schoolchildren-in-texas](https://www.history.com/this-day-in-history/natural-gas-explosion-kills-schoolchildren-in-texas) (accessed 10 May 2019).

[84] L. Zardasti, et al., Review on the identiﬁcation of reputation loss indicators in an onshore pipeline explosion event, J. Loss Prev. Process Ind. 48 (2017) 71–86, [https://doi.org/10.1016/j.jlp.2017.03.024.](https://doi.org/10.1016/j.jlp.2017.03.024)

[85] Sewers explode in Guadalajara, Mexico, killing hundreds, History [online], 13 November 2009. Available from: [https://www.history.com/this-day-in-history/](https://www.history.com/this-day-in-history/sewers-explode-in-guadalajara) [sewers-explode-in-guadalajara](https://www.history.com/this-day-in-history/sewers-explode-in-guadalajara) (accessed 10 May 2019).

[86] L. Méndez, Al menos 150 muertos tras 12 explosiones de gas en la ciudad mexicana de Guadalajara, EL PAÍS [online], 22 April 1992. Available from: [https://](https://elpais.com/diario/1992/04/23/internacional/703980013_850215.html) [elpais.com/diario/1992/04/23/internacional/703980013\_850215.html](https://elpais.com/diario/1992/04/23/internacional/703980013_850215.html) (accessed 14 May 2019).

[87] Hundreds killed in Nigerian pipeline explosion, The Guardian [online], 12 May 2006. Available from: [https://www.theguardian.com/world/2006/may/12/oil.](https://www.theguardian.com/world/2006/may/12/oil.business) [business](https://www.theguardian.com/world/2006/may/12/oil.business) (accessed 14 June 2019).

[88] Deadly Nigerian pipeline disasters, Reuters [online], 15 May 2008. Available from: <https://www.reuters.com/article/us-nigeria-pipeline-disasters/timeline-deadly-nigerian-pipeline-disasters-idUSL1566948020080515>(accessed 20 May 2019).

[89] Children killed in Nigeria blast, BBC News [online], 16 May 2008. Available from: <http://news.bbc.co.uk/2/hi/africa/7403525.stm>(accessed 21 May 2019). [90] Burned to death in Kenya pipeline ﬁre, The Telegraph [online], 2011. Available from: [https://www.telegraph.co.uk/news/worldnews/africaandindianocean/](https://www.telegraph.co.uk/news/worldnews/africaandindianocean/kenya/8758340/120-burned-to-death-in-Kenya-pipeline-fire.html)

[kenya/8758340/120-burned-to-death-in-Kenya-pipeline-ﬁre.html](https://www.telegraph.co.uk/news/worldnews/africaandindianocean/kenya/8758340/120-burned-to-death-in-Kenya-pipeline-fire.html) (accessed 22 April 2019).

[91] H. Lali, Kenya ﬁre: Nairobi pipeline blaze 'kills at least 75', BBC News [online], 12 September 2011. Available from: <https://www.bbc.com/news/world-africa-14879401>(accessed 22 June 2019).

[92] Gas Explosion at a Subway Construction Site, Failure Knowledge Database [online). Available from: <http://www.shippai.org/fkd/en/cfen/CB1012037.html> (accessed 18 June 2019).

[93] China oil pipe blast: Qingdao pipeline blast 'kills 44', BBC News [online], 23 November 2013. Available from: <https://www.bbc.com/news/world-asia-china-25050300>(accessed 15 May 2019).

[94] C. Aizhu, Sinopec oil pipeline blast kills 35 in eastern China, Reuters [online], 22 November 2013. Available from: <https://www.reuters.com/article/us-sinopec-blast/sinopec-oil-pipeline-blast-kills-35-in-eastern-china-idUSBRE9AL08E20131122>(accessed 15 May 2019).

[95] Search abandoned in Russia rubble, BBC News [online], 18 March 2004. Available from: <http://news.bbc.co.uk/2/hi/europe/3522832.stm>(accessed 20 June 2019).

[96] G. Mott, Pipeline explosion in Mexico kills 52, The Telegraph [online). Available from: [https://news.google.com/newspapers?nid=2209&dat=19781103&](https://news.google.com/newspapers%3fnid%3d2209%26dat%3d19781103%26id%3duhxSAAAAIBAJ%26sjid%3dJjUNAAAAIBAJ%26pg%3d4978%2c558758) [id=uhxSAAAAIBAJ&sjid=JjUNAAAAIBAJ&pg=4978,558758](https://news.google.com/newspapers%3fnid%3d2209%26dat%3d19781103%26id%3duhxSAAAAIBAJ%26sjid%3dJjUNAAAAIBAJ%26pg%3d4978%2c558758) (accessed 22 June 2019).

[97] Accident Report Detail PAR9701. National Transportation Safety Board (NTSB) [online). (accessed 1 July 2019). Available from: [https://www.ntsb.gov/](https://www.ntsb.gov/investigations/AccidentReports/Pages/PAR9701.aspx) [investigations/AccidentReports/Pages/PAR9701.aspx.](https://www.ntsb.gov/investigations/AccidentReports/Pages/PAR9701.aspx)

[98] H. Yang, et al., Conﬁned vapor explosion in Kaohsiung City–A detailed analysis of the tragedy in the harbor city, J. Loss Prev. Process Ind. 41 (2016) 107–120, [https://doi.org/10.1016/j.jlp.2016.03.017.](https://doi.org/10.1016/j.jlp.2016.03.017)

[99] Taiwan gas blasts in Kaohsiung kill at least 25, BBC News [online], 1 August 2014. Available from: <https://www.bbc.com/news/world-asia-28594693>(ac-cessed 25 May 2019).

[100] Deadly blast on oil pipeline in Mexico's Puebla state, BBC News [online], 20 December 2010. Available from: <https://www.bbc.com/news/world-latin-america-12034038>(accessed 22 June 2019).

[101] P. Rucker, Oil blast causes inferno in Mexican town, 28 dead, Reuters [online], 20 December 2010. Available from: <https://www.reuters.com/article/us-mexico-explosion/oil-blast-causes-inferno-in-mexican-town-28-dead-idUSTRE6BI1DT20101220>(accessed 12 June 2019).

[102] History through Our Eyes: March 1, 1965, explosion in LaSalle, Montreal Gazette [online], 1 March 2019. Available from: [https://montrealgazette.com/news/](https://montrealgazette.com/news/local-news/history-through-our-eyes/history-through-our-eyes-march-1-1965-explosion-in-lasalle) [local-news/history-through-our-eyes/history-through-our-eyes-march-1-1965-explosion-in-lasalle](https://montrealgazette.com/news/local-news/history-through-our-eyes/history-through-our-eyes-march-1-1965-explosion-in-lasalle) (accessed 25 June 2019).

[103] Rupture and ignition of a gas pipeline, La référence du retour d'expérience sur accidents technologiques [online). Available from: [https://www.aria.](https://www.aria.developpement-durable.gouv.fr/fiche_detaillee/27681_en/%3flang%3den) [developpement-durable.gouv.fr/ﬁche\_detaillee/27681\_en/?lang=en](https://www.aria.developpement-durable.gouv.fr/fiche_detaillee/27681_en/%3flang%3den) (accessed 20 June 2019).

[104] Z.Y. Han, W.G. Weng, Comparison study on qualitative and quantitative risk assessment methods for urban natural gas pipeline network, J. Hazard. Mater. 189 (1–2) (2011) 509–518, [https://doi.org/10.1016/j.jhazmat.2011.02.067.](https://doi.org/10.1016/j.jhazmat.2011.02.067)

[105] Fifteen die in Belgium gas blast, BBC News [online], 30 July 2004. Available from: <http://news.bbc.co.uk/2/hi/europe/3939087.stm>(accessed 22 June 2019). [106] K.B. Mishra, K. Wehrstedt, Underground gas pipeline explosion and ﬁre: CFD based assessment of foreseeability, J. Nat. Gas Sci. Eng. 24 (2015) 526–542,

[https://doi.org/10.1016/j.jngse.2015.04.010.](https://doi.org/10.1016/j.jngse.2015.04.010)

[107] GAIL pipeline blast in Andhra Pradesh, The Economic Times [online). Available from: <https://economictimes.indiatimes.com/nation-world/gail-pipeline-blast-in-andhra-pradesh/slideshow/37389290.cms>(accessed 1 July 2019).

[108] Killed in GAIL pipeline blast in Andhra Pradesh, PM Modi condoles deaths, India Today [online], 27 June 2014. Available from: [https://www.indiatoday.in/](https://www.indiatoday.in/india/south/story/gail-pipeline-fire-andhra-pradesh-east-godavari-198418-2014-06-27) [india/south/story/gail-pipeline-ﬁre-andhra-pradesh-east-godavari-198418-2014-06-27](https://www.indiatoday.in/india/south/story/gail-pipeline-fire-andhra-pradesh-east-godavari-198418-2014-06-27) (accessed 1 July 2019).

[109] Tragedia de Rosario: son 22 los muertos por la explosion, Clarín [online], 9 October 2013. Available from: <https://www.clarin.com/sociedad/tragedia-rosario-muertos-explosion_0_HydKKU7jD7e.html>(accessed 5 July 2019).

[110] Un escape de gas, la causa del estallido ocurrido en Rosario, La Nacion [online], 6 August 2013. Available from: <https://www.lanacion.com.ar/sociedad/un-escape-de-gas-la-causa-del-estallido-ocurrido-en-rosario-nid1608024>(accessed 5 July 2019).

[111] The day 22 died as explosion blasted shopping centre, The Herald Scotland [online], 19 October 2002. Available from: [https://www.heraldscotland.com/news/](https://www.heraldscotland.com/news/11913558.the-day-22-died-as-explosion-blasted-shopping-centre-event-the-clarkston-disaster-date-october-21-1971) [11913558.the-day-22-died-as-explosion-blasted-shopping-centre-event-the-clarkston-disaster-date-october-21-1971](https://www.heraldscotland.com/news/11913558.the-day-22-died-as-explosion-blasted-shopping-centre-event-the-clarkston-disaster-date-october-21-1971) (accessed 5 July 2019).

[112] Forty years on: Remembering the Clarkston Toll disaster, The Scotsman [online], 18 October 2011. Available from: <https://www.scotsman.com/news-2-15012/forty-years-on-remembering-the-clarkston-toll-disaster-1-1915939>(accessed 3 July 2019).

[113] Accident Report Detail PAR7606, National Transportation Safety Board (NTSB) [online). Available from: [https://www.ntsb.gov/investigations/](https://www.ntsb.gov/investigations/AccidentReports/Pages/PAR7606.aspx) [AccidentReports/Pages/PAR7606.aspx](https://www.ntsb.gov/investigations/AccidentReports/Pages/PAR7606.aspx) (accessed 26 June 2019).

[114] F.C. Onuoha, Why the poor pay with their lives: oil pipeline vandalisation, ﬁres and human security in Nigeria, Disasters 33 (3) (2009) 369–389, [https://doi.](https://doi.org/10.1111/j.1467-7717.2008.01079.x) [org/10.1111/j.1467-7717.2008.01079.x.](https://doi.org/10.1111/j.1467-7717.2008.01079.x)

[115] [D. Chernov, D. Sornette, Man-made Catastrophes and Risk Information Concealment, Springer, Switzerland, 2016.](http://refhub.elsevier.com/S1350-6307(19)31232-4/h0575)

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