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Statistical analysis of incidents on onshore CO_2 pipelines based on PHMSA database

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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

The development of an integrated network for the management of carbon dioxide requires knowledge and optimization of all Carbon Capture Utilization and Storage (CCUS) aspects, including pipeline transport. Safety is one of the aspects that should be addressed prior CCUS facilities come in operation; the risk for people should be assessed to ensure it is below an acceptable level. In some cases, a quantitative risk assessment (QRA) is required by the approval authority. Normally the risk assessment is based on the use of statistical/historical data. However, for CO_2 handling systems the operating experience is limited compared to hydrocarbon transporting systems and, for this reason, hydrocarbon pipeline statistics are normally used as a proxy. The only database that contains records on CO_2 pipelines is the PHMSA since in the U.S. several CO_2 pipelines have been constructed since the 1970's, essentially for Enhanced Oil Recovery operations. There is limited statistical data available compared to the hydrocarbon pipelines experience and therefore care should be taken when undertaking the frequency analysis. In this work an analysis of incidents data related to the onshore CO_2 pipelines in the U.S. between 1985 and 2021 reported by the Pipeline Hazardous Material Safety Administration (PHMSA) of the U.S. Department of Transportation is presented. The aim of the study is to analyze the records contained in the PHMSA database to provide an estimate of a specific CO_2 pipeline failure rate to be used in quantitative risk assessments. Concerns and limitations of the data have been also discussed.

1. Introduction

The development of a CO_2 transportation network is object of interest as a necessary crosscutting topic in the whole Carbon Capture and Storage industry. CO_2 pipeline development is an important aspect for the realization of all decarbonization CCUS projects. In the International Energy Agency (IEA) Sustainable Development Scenarios (SDS), carbon capture utilization and storage (CCUS) accounts for 9% of the cumulative emissions reductions needed globally by 2050 (International Energy Agency, 2019). This implies a rapid scale-up of CCUS deployment, from around 30 Mton of CO_2 currently captured each year to 2300 Mt per year by 2040 (Global CCS Institute, 2020). More than 30 commercial CCUS facilities have been announced in the last three years, mainly in Europe and the United States, but also in Australia, the People's Republic of China, Korea, the Middle East and New Zealand. Projects now nearing a final investment decision represent an estimated potential investment of around USD 27 billion, more than double the investment planned in 2017 (International Energy Agency, 2020). The development of CCUS projects according to IEA is off track as expected; some of the main problems are related to public perceptions and costs as well as the lack of experience from most of the contractors. Despite natural gas pipeline are nowadays distributed for more than 500,000 km in the U.S. (Duncan and Wang, 2014), carbon dioxide pipelines only reached 8000 km in 2013. One of the most important aspects that should be evaluated during the design of a CO_2 transmission pipeline is the risk for people (Gant et al., 2014; Mocellin et al., 2015; Vitali et al., 2021; Witlox et al., 2014). Safety issues are in fact, one of the principal factors that can drive the public perception of CCUS projects (Cox et al., 2020; L'Orange Seigo et al., 2014). In addition to this, compared to the existing CO_2 pipeline network in the US, especially in Europe the new pipelines may cross populated areas; thus, a risk assessment becomes a fundamental milestone in the project approval process. One of the steps of a quantitative risk assessment consists in the evaluation of the probability of the possible accidental scenarios. For this purpose, the analysis of historical

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incident data is fundamental for identifying the main causes, failure modes and related failure frequency of the pipeline. For oil and gas pipelines there are a number of available failure database which are created and managed by different institutions: Pipeline and Riser Loss of Containment (PARLOC), Clean Air and Water in Europe (CONCAWE), the UK Onshore Pipeline Operators' Association (UKOPA), the European Gas Pipeline Incident Data Group (EGIG), PHMSA, HSE hydrocarbon release database (HCRD). For CO_2 pipelines the operating experience is limited compared to oil and gas; therefore, there is limited statistical data available and care should be taken when undertaking the frequency analysis (DNV-GL, 2013a). Particular considerations should be given to (DNV-GL, 2013b) the relevance of historical incident data including similar CO_2 pressure and temperature conditions, impurities present to similar levels, materials, construction. This is one of the main limitations associated to a risk analysis for CO_2 pipelines as historical data for gaseous/dense phase CO_2 service systems and components is significantly less robust than for other mature industries. Different approaches have been proposed for the estimation of the failure frequency for CO_2 pipelines. In some instances, failure rates of natural gas pipelines have been used (Lam and Zhou, 2016), while in other cases an estimation of the failure rate from the PHMSA database has been proposed (Gale and Davison, 2004; Koornneef et al., 2009; McGillivray et al., 2014; Wang and Duncan, 2014). (Gale and Davison, 2004) in their study, reported that CO_2 pipelines in U.S. have a frequency of incident of 0.32 events per 1000 km per year, whereas natural gas and hazardous liquid pipelines have an incident frequency of 0.17 and 0.82 events per 1000 km per year respectively. This study accounted data up to 2001. DNV RP-J202 (Det Norske Veritas (DNV), 2010) suggested that statistics for internal corrosion derived from natural gas pipeline can be applied if strict control of water content in CO_2 pipelines is adopted (keep water level below saturation). DNV-RP-F104 (DNV GL, 2017), states that frequency analysis should examine the available historical incident data in depth to extract and use the most relevant data for a specific CO_2 pipeline project. According to (Koornneef et al., 2009), cumulative failure rates (puncture plus rupture) assumed within studies on risks of CO_2 pipelines show a range within one order of magnitude, i.e. from 1.2×10^{-4} to 6.1×10^{-4} km^{-1} year. However, it must be considered that the work has been published in 2009. In 2011, during the development of the ROAD project (NL), a Quantitative Risk Assessment (QRA) has been performed by (Dijkshoorn; Kaman, 2011) and included a failure frequency evaluation. The failure frequency considered in the study for onshore CO_2 pipeline was 1.97×10^{-3} km^{-1} year.

Many authors referred to PHMSA database for frequency failure evaluation of carbon dioxide pipelines during the last years. The failure rate calculated on PHMSA database are in the range of 1.7×10^{-4} km^{-1} year (Gale and Davison, 2004) to 6.1×10^{-4} km^{-1} year (Koornneef et al., 2009). In this work, the incidents reported in the latest version of the PHMSA have been analyzed and categorised with particular focus on the last 16 years since more detailed information was collected over this period. Considerations on the consequences on people, environment and operations have been included, moreover, based on this analysis an updated estimation of the failure frequency is proposed.

2. Methodology

2.1. Data collection and review

The Pipeline and Hazardous Materials Safety Administration (PHMSA) manages the U.S. national regulatory program to assure safe transportation of hazardous material by pipeline. According to the pipeline safety regulations (49 CFR 191/195), loss of containment incidents need to be communicated through an incident report within 30 days of a pipeline incident. The PHMSA defines as significant incidents those that:

- involve fatalities or injuries requiring in-patient hospitalizations
- have $ 50,000 or more in total costs (including loss to the operators or the others, but excluding cost of gas lost)
- results in release of 50 barrels or more of product,
- result in an unintentional fire or explosion.

It should be noted that the reporting threshold of $ 50,000 for property damage has not been changed or adjusted for inflation since 1984. The PHMSA reports are publicly available in different datasets: 1968–1985, 1986–2001, 2002–2009, 2010-onwards (U.S. Department of Transportation, 2022). Each dataset has a different format and also the information required in the incident form has changed over the years: starting from 2010 significantly more details need to be provided in the report. This allows a more in-depth analysis of the incidents and associated causes. The importance of incident reporting has been enforced also with a significant increment of the civil penalty for each violation (from $25,000 to $100,000 in 2010, according to 49 USC 60122). According to current regulation for reporting accident in the US, title 49, subtitle B, Chapter I, Subchapter D, part 195, 195.50: "an accident report is required for each failure in a pipeline system subject to this part in which there is a release of the hazardous liquid or carbon dioxide transported resulting in any of the following":

- Explosion or fire not intentionally set by the operator.
- Release of 5 gallons (19 L) or more of hazardous liquid or carbon dioxide, except that no report is required for a release of less than 5 barrels (0.8 cubic meters) resulting from a pipeline maintenance activity if the release is: not otherwise reportable under the section, confined to company property or pipeline right-of-way and cleaned up promptly, death of any person, personal injury necessitating hospitalization or estimated property damage, including cost of clean-up and recovery, value of lost product, and damage to the property of the operator or others, or both, exceeding $50,000.

The Accident Report for Hazardous Liquid pipeline systems provided from U.S. Department of Transportation Research and Special Programs Administration specifies that: if the spill is small, that is, the amount is at least 5 gallons but less than 5 barrels, only the first page of the report must be filled, unless the spill is to water. For this reason, small spill reported in the database will contain fewer details than larger ones. The accident report until 2010 required the selection of the commodity spilled between:

- Gasoline, diesel, fuel oil or other petroleum product, which is a liquid at ambient conditions;
- HVLs/other flammable or toxic fluid, which is a gas at ambient conditions;
- CO_2/N_2 or other non-flammable, non-toxic fluid, which is a gas at ambient conditions;
- Crude oil.

The latest update of the accident report form (from 2010) requires more data input; commodity released details have been expanded and populated with more accurate data such as:

- Crude oil
- Refined and/or Petroleum Product (non-HVL) which is a Liquid at Ambient Conditions
- HVL or Other Flammable or Toxic Fluid which is a Gas at Ambient Conditions
- CO_2 (Carbon Dioxide)
- Biofuel/Alternative Fuel (including ethanol blends)

In particular, carbon dioxide has been included as an independent commodity type; this feature improved the accuracy of the data available in the latest dataset, namely from 2010 to 2021.

The PMHSA database for *Hazardous Liquid pipeline systems* utilized in this work has been accessed the April 7, 2022. Full records of hazardous liquid pipeline systems have been downloaded then only carbon dioxide related data have been analyzed.

2.2. Data analysis

This study focused on analyzing the PHMSA incident data related to CO_2 pipelines operating in the US from 1994 to 2021. More than 30 CO_2 pipelines are operating in the U.S., with six crossing provincial/state boundaries and one crossing an international border into Canada. In the incident reports, pipelines from 10 states of the U.S. have been included, namely located in Texas (TX), Oklahoma (OK), North Dakota (ND), Mississippi (MS), Utah (UT), Wyoming (WY), Kansas (KS), Colorado (CO), Louisiana (LA) and New Mexico (NM). Pipeline failure rates are usually defined based on kilometers of installed pipeline; this provides an indication of the operating experience and the size of the data sample. Incident statistics are more reliable when are based on large data samples. If compared to hydrocarbon pipelines, operational experience and pipeline exposure is limited and updated incident data is scarce for CO_2 pipelines. According to the PHMSA more than 8000 km of onshore pipelines have been installed in the U.S. from 1968 to 2020, mostly for enhanced oil recovery (EOR) applications. More than 550,000 km of hydrocarbon pipelines are operational. In Fig. 1 the evolution of total mileage of CO_2 pipeline in the U.S. from 2004 to 2020 has been reported in km (U.S. Department of Transportation, 2022). In the U.S. the first pipelines constructed to transport CO_2 dates back to 1963, however the majority of the infrastructure was built between 1980 and 1990. The graph starts from 2004 as yearly detailed data for previous period cannot be retrieved from the database.

The evolution of the mileage of carbon dioxide pipeline in the US generally shows an increasing trend from 2004 to 2014, with a maximum of 8490 km of pipeline. The development after 2014 shows an almost constant value. Policies and economic interest were the main driving factor in the development of CO_2 pipelines, since most of the operating pipelines in the United States are related to enhanced oil recovery (EOR) activities. The total length of installed pipeline is fundamental to calculate the exposure. Exposure is calculated as the length of installed pipeline multiplied by its exposed duration and is expressed in kilometers-years. Considering the uncertainty on the installed pipeline length, the pipeline operating experience (expressed in km-year) to be used for the failure frequency calculation is estimated starting from 1985. The exposure evolution during the last 16 years is reported in Fig. 2.

With regards to the recorded incidents involving CO_2 pipelines, between 1994 and 2021, a total of 113 incidents related to onshore CO_2 transmission pipelines were reported to PHMSA database. Fig. 3 shows the number of incidents recorded for CO_2 pipeline in the period 1994–2021. Incident database indicates date and place of each reported

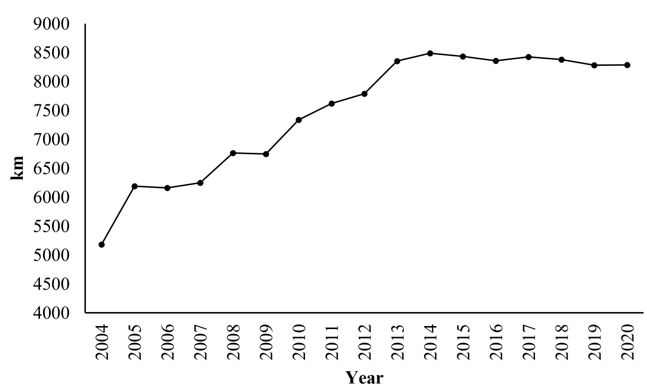

Fig. 1. Evolution of total kilometers of CO_2 pipeline in the USA from 2004 to 2020.

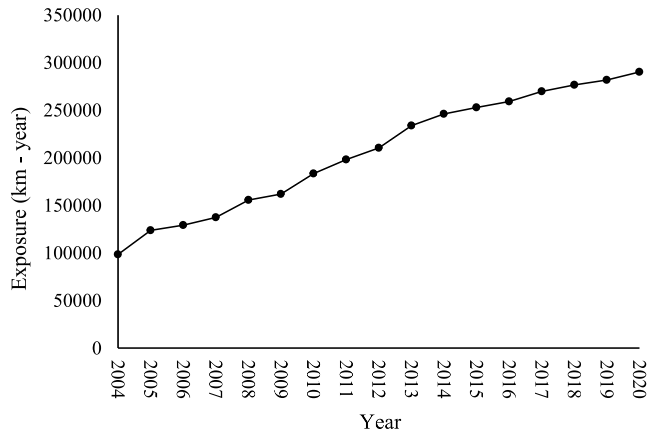

Fig. 2. Exposure evolution CO_2 pipeline in the USA from 2004 to 2020.

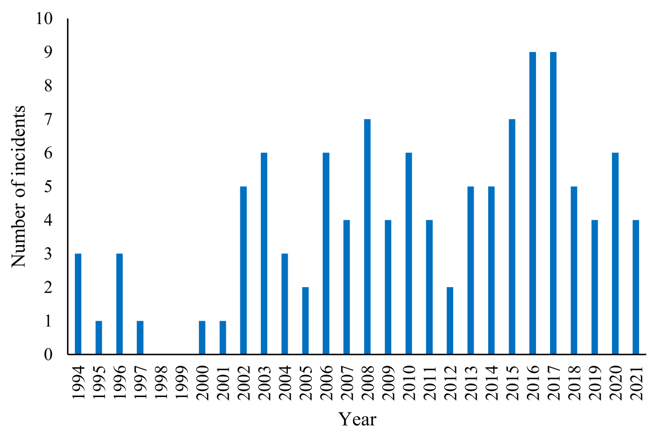

Fig. 3. Number of incidents recorded for CO2 pipelines in the U.S.A. (1994–2021) from PHMSA.

incident by the pipeline's operators. It should be noted that, since the database was accessed in April 2022, the incidents reported in the year 2022 are not included in this analysis. Moreover, the mileage data were available until 2020, for this reason the frequency failure calculation is based on data up to 2020.

No incidents were recorded in 1998 and 1999, the maximum number of incidents has been recorded in 2016 and 2017 with a total of 9 incidents for each year. The minimum (non-zero) number of incidents were recorded in 1995, 1997, 2000 and 2001 with a single occurrence for each year. The average number of incidents reported for each year from 2004 to 2021 is 5.11 incident/year. None of the recorded incidents resulted in fatalities. According to PHMSA data, only one incident resulted in an injury, however no details are included in the narrative of the incident report. This is an important difference with respect to accidental scenarios involving hydrocarbon pipeline releases. As highlighted in other studies (Lam and Zhou, 2016; Siler-Evans et al., 2014; Vetter et al., 2019), a significant percentage of pipeline accidents (gas and hazardous liquids) resulted in injuries and/or fatalities.

However, no conclusion can be directly drawn from the statistical analysis of the PHMSA incidents with respect to the negative impact on human health that such releases can pose. It should be noted that this outcome (zero fatality and zero injury) can be strongly affected by the fact that most of these pipelines are in remote locations and that the negative effects of CO_2 on people are also dependent on the time of exposure whereas some accidental scenarios involving hydrocarbons (i.e. fire and explosions) may result in immediate injuries/fatalities. Moreover, for the largest CO_2 incident recorded from 2010 in the

PHMSA, the Satartia accident in 2020, the incident report did not clearly report injuries even though the narrative contains reference to 46 hospitalizations that were actually recorded following the release.

With regards to incident consequences to the environments and asset/operations some considerations could be made based on the amount of CO_2 released in the atmosphere and the duration of the shutdown to restore operations.

This information can be extracted from the PHMSA database. On a total of 113 events registered, 45 required the pipeline shutdown, in 52 cases no shutdown was necessary and for the remaining 16 cases no information is available. Due to the higher level of detail, information contained in the database from 2010 to 2021 have been analyzed to understand the consequences of the incidents. Results in terms of incident date, time, location, duration of the line shutdown, CO_2 released in the atmosphere have been analyzed.

The incidents recorded in the period 2010–2021 have been analyzed in terms of location and commodity spilled. The grey states are the ones where at least one incident has been registered between 2010 and 2021. Data reported in barrels from the database has been divided by a factor 50 to ease the representation. The total released volume has been calculated including the estimated release caused by the incident and the following intentional releases adopted by the operator to safely start-up again and reach normal operations. Data shows that the largest number of released barrels occurred in 2017 in Wyoming, for the period considered. However, most of the CO_2 releases happened intentionally during the safe blowdown/controlled release, adopted prior to the start-up of the system following the incident repairs. This is the case for most of the incidents reported in the database, where the largest amount of CO_2 released in the atmosphere was vented following the rupture or the leak repair by the operators.

For this reason, the amount of barrels released in the atmosphere cannot directly be used to assess the entity of the incident/damage.

The analysis of the shutdown period following the incident could be used to assess the economic consequence of such incidents. In Fig. 5, the incidents already reported in Fig. 4 that required a shutdown of the line are now represented. The shutdown occurred in the grey states, and the amount of shutdown hours has been reported with markers.

The average number of shutdown hours, when required, is around 53 h (around 2 days), with a visible exception of a single case that occurred in 2020. Indeed, the largest incident from 2010 has been registered at Satartia, in the Yazoo County, Mississippi, the February 22, 2020. The incident required a shutdown of the pipeline for 246 days and 200 people living nearby have been evacuated that day; 46 people were taken to the hospital. According to the PHMSA data, the incident has been caused by natural force damage, particularly heavy rains/floods, that led to major damage of the pipeline welding. The carbon steel pipeline has been installed in 2009 and was operative for Enhanced Oil Recovery purposes. The metallurgic analysis conducted following the incident concluded that the soil movement (caused by unusually high rainfall averages) upstream of the failure location induced axial stresses sufficient to cause an overload condition and resulted in the pipeline rupture. Moreover, it is reported that unexpected release occurred during the restoring of normal operations; indeed, on October 7, 2020, during the planned operations necessary to reconnect the segment, the blowdown valve froze in the open position due to internal ice formation (caused by Joule-Thomson effect). Following an emergency notification in the area, the valve thawed enough to allow it to be closed only the day after at 6 p.m. with an estimated CO_2 release of 41,177 barrels.

Compared to the average shutdown duration estimated by (Hainen et al., 2020) for all hazardous liquid pipelines (7 days), the average shutdown period for CO_2 pipelines is considerably shorter (around 2 days).

With respect to consequences, another consideration in the data aggregation is the failure mode of the pipeline in each incident. Depending on the period, different release type failure modes were identified in the incident form: leak, pinhole, connection failure, crack, seal or packing, rupture and other. A release type is further classified as a weld, pipe, component/connection, valve, relief valve. Considering the differences in forms for the various reporting periods, the release types identified were mapped into the following failure modes:

- Leak – pinhole: for all the incidents with a leak size sufficiently small to be considered a pinhole (around ½"), based on the info reported in the form;
- Leak: for all incidents where the size of the leak is not clearly stated or is >½";
- Rupture: for all incidents indicated as rupture;
- Relief valve: for all the incidents where the release was due to the inadvertent opening of a relief valve due to an upset or to a malfunction of the valve itself;
- No info.

As reported in Fig. 6 out of a total of 113 incidents from 1994 to 2021 for CO_2 services, a large percentage (19%) is associated to relief valves

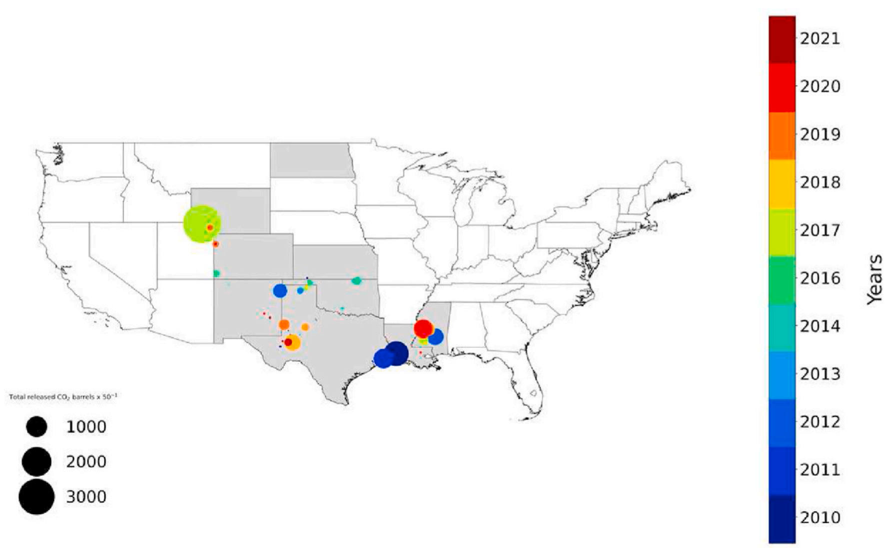

Fig. 4. Incidents location and reported spilled barrels related to CO_2 pipelines from 2010 to 2021.

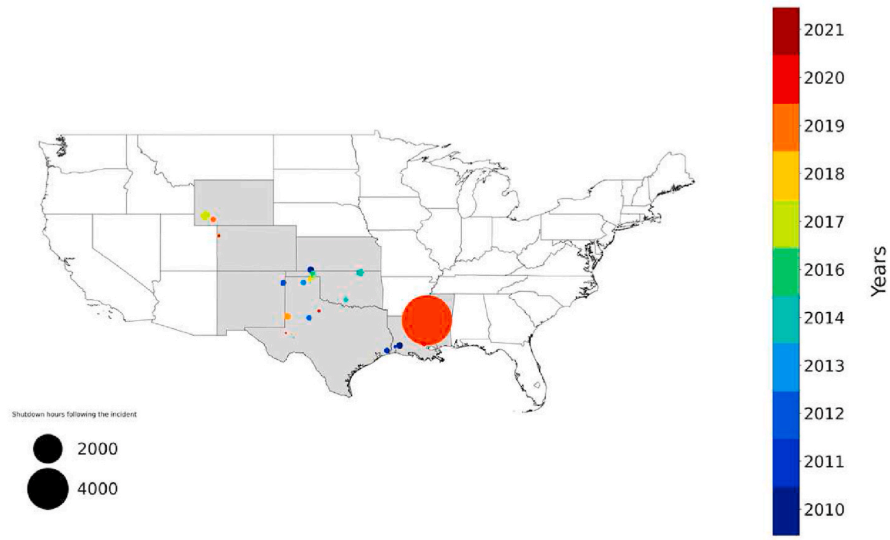

Fig. 5. Incidents location and consequent shutdown hours related to CO_2 pipelines from 2010 to 2021.

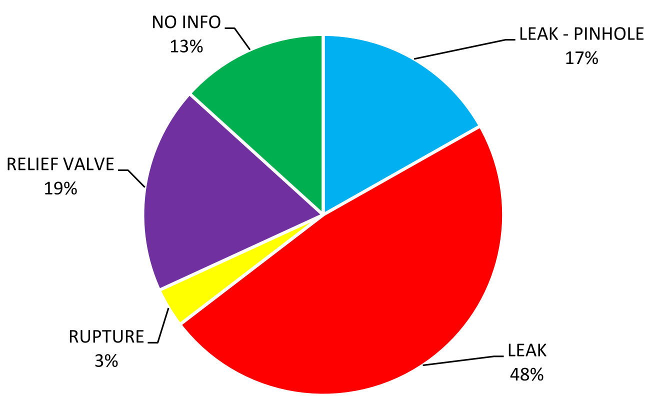

Fig. 6. Release type distribution for CO_2 pipeline incidents (1994–2021).

discharging in unwanted conditions and only a small percentage (3%) is associated to ruptures.

Amongst the information reported in the incident form, there is the incident cause, sub-cause and incident description which is of paramount importance to further analyze the data and identify the major categories of failures. As reported by (Lam and Zhou, 2016), the incident form has changed over the years as well as the number of fields required. In the latest form, in use since 2010, 8 incident causes can be selected, while several sub-causes can be added to better describe the incidents. Table 1 provides the list of the main causes and sub-causes. The main causes available are corrosion, natural force damage, excavation damage, other outside force damage, material failure of pipe or weld, equipment failure, incorrect operation, other accident cause.

Despite the differences that can be envisaged through the modification of the module from 1994 to 2021, 8 different causes of the incidents reported for carbon dioxide pipelines have been identified. The incident causes have been aggregated in classes to overcome to classification differences between the old report format and the post-2010 detailed module. Based on the analysis of the 113 recorded incidents involving CO_2 pipelines in the period 1994–2021 the incident cause distribution is reported in Table 2.

"*Equipment failure*" has been identified as the most frequent incident cause reported in the database, with 52 occurrences, accounting for 46.02% of the total events. 22 incidents have been attributed to "*material failure of pipe or weld*", that constitute 19.47% of the total. "*Corrosion*", that includes internal corrosion as well as external, counts 12 reported incidents (10.62%), followed by "*other accident cause*" (9.73%), "*incorrect operations*" (8.85%), "*excavation damage*" (1.77%), "*other outside force damage*" (1.77%) and "*natural force damage*" (1.77%). Fig. 7 shows the percentage distribution of the incident causes over the total events reported. The ones classified as "*corrosion*" were 12, 9 of which have been attributed to "*external corrosion*", while no information has been reported for the remaining 3 incidents. Amongst the incidents classified as "equipment failure", 30.77% has been attributed to the "*malfunction of control/relief equipment*", while 25.00% to "*non-threated connection failure*". A single case has been reported explicitly as "*icing of relief valve*". It should be noted that for 11 cases, occurred before 2009, the sub-cause was not reported.

As reported in Table 2 most incidents (approx. 45%) occurred due to causes related to equipment malfunction, however, not all releases reported in this category are real incidents/leaks due to failures. Many of these cases (more than 30%) are associated with pressure or thermal relief valves relieving in unwanted conditions ("*malfunction of control/relief equipment")*. Considering that relief valves discharge into atmosphere these have been reported as incidents as they are unwanted releases. However, in most database for hydrocarbon release frequency these would not classify as incidents. This suggests that the calculated release frequency is conservative since these incidents have not been filtered out. The remaining incidents falling in this category are associated with the failure of small components such as nipples, seals, gasket, O-ring that led to 'small' releases.

The second main cause is material related defects (more than 20% of the incidents); in many cases, the failure occurred at a weld and resulted in minor releases. However, in some instances the failure occurred in a pipe segment and resulted in more significant releases.

The third contribution is corrosion. In most incidents reported, external corrosion originated the failure (i.e., damage to the coating, failure of the cathodic protection) which resulted in a leak (not rupture). This is an important aspect as one major concern for CO_2 pipelines is internal corrosion due to the presence of impurities in the carbon dioxide stream that can affect the material. Corrosion is a significant threat to pipeline integrity with water playing a major role in carbon steel pipelines. Based on best practices it seems to be generally accepted that corrosion will be insignificant in CO_2 transport pipelines as long as the water content is well below the water solubility. Existing CO_2 pipelines such as U.S. pipelines reported in PHMSA database, usually apply a strict

Table 1
Failure causes included in the accident report model from 2010.

Incident Cause	Incident Sub-cause
Corrosion	Internal corrosion
	External corrosion
Natural force damage	Earth Movement (not due to heavy rains/floods)
	Heavy rains/floods
	Lightning
	Temperature
	High Winds
	Other natural force damage
Excavation damage	Excavation damage by operator
	Excavation Damage by operator's contractor
	Excavation Damage by Third-Party
	Previous damage due to excavation activity
Other Outside Force Damage	Nearby industrial, man-made, or other fire/explosion as primary cause of accident
	Damage by car, truck, or other motorized vehicle/equipment not engaged in excavation
	Damage by boats, barges, drilling rigs, or other maritime equipment or vessels set adrift or which have otherwise lost their mooring (*)
	Routine or normal fishing or other maritime activity not engaged in excavation (*)
	Electrical arcing from other equipment or facility
	Previous mechanical damage (not related to excavation)
	Intentional damage
	Other outside force damage
Material Failure of Pipe or Weld	Construction, installation, or fabrication-related
	Original manufacturing-related
	Environmental cracking-related
Equipment Failure	Malfunction of control/relief equipment
	Pump or pump-related equipment
	Threaded connection/coupling failure
	Non-threaded connection failure
	Defective or loose tubing or fitting
	Failure of equipment body (except pump), tank plate, or other material
	Other equipment failure
Incorrect Operation	Damage by operator or operator's contractor not related to excavation and not due to motorized vehicle/equipment damage
	Tank, vessel, or sump/separator allowed or caused to overfill or overflow
	Valve left or placed in wrong position, but not resulting in a tank, vessel, or sump/separator overflow or facility overpressure
	Pipeline or equipment over-pressured
	Equipment not installed properly
	Wrong equipment specified or installed
	Other incorrect operation
Other Accident Cause	Miscellaneous
	Unknown

(*) = not applicable to onshore pipelines.

Table 2
Distribution of incidents causes between 1994 and 2021 for carbon dioxide pipelines reported in PHMSA.

Incident Cause	No. of incidents	Percentage of the total (%)
Equipment failure	52	46.02
Material Failure of Pipe or Weld	22	19.47
Corrosion	12	10.62
Other accident cause	11	9.73
Incorrect operation	10	8.85
Excavation damage	2	1.77
Other outside force damage	2	1.77
Natural force damage	2	1.77

control in water content and some of them are operated with dry CO_2. Some research (Brown et al., 2014) endorsed the theory to control water content to prevent corrosion. However, it is important to remark that water solubility depends on process conditions such as temperature and pressure, and it is also related to cross chemical reactions and interactions with other fluid components present in the mixture. (Timothy Fout and Steve Herron, 2013) suggest limiting the water content to 500 ppmw; however further investigation assessed that this approach could be not conservative enough to operate in a safe window. Thus, the conservative approaches reported in recent literature suggest limiting the water content to 20–50 ppmw to prevent internal corrosion phenomena (Adu et al., 2019).

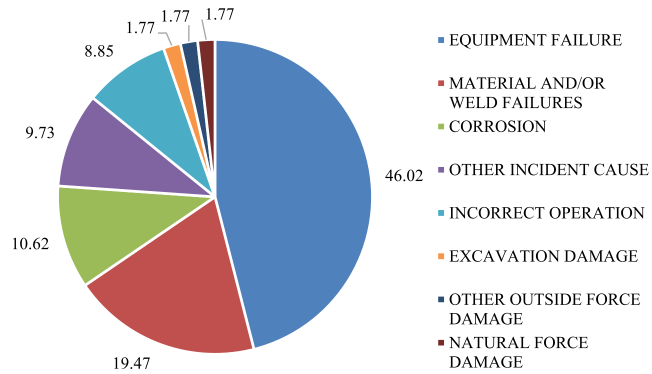

Fig. 7. Distribution of incidents causes between 1994 and 2021 reported in PHMSA.

3. Results - failure frequency

Considering all the recorded incidents in the PHMSA database and the calculated operating experience (km-year), it is possible to evaluate the CO_2 pipeline incident frequency. Fig. 8 reports the variation of the calculated incident frequency in the period 2004–2020 between a lower bound and an upper bound estimated considering different pipeline operating experience timeframe. The upper bound is based on pipeline operating experience since 1990, while the lower bound on operating experience since 1968. According to this data the incident frequency can vary between 2.53×10^{-4} event/year (lower bound) and 4.38×10^{-4} event/year (upper bound) with an average value of 3.76×10^{-4} event/year. This is in line with values reported in previous studies (Adu et al., 2019; Duncan and Wang, 2014; Koornneef et al., 2009).

The black line reported in Fig. 8 is based on pipeline operating experience since 1985 with a total of 290,084 km-year, the upper blue dashed line is based on pipeline operating experience since 1990 with 248,645 km-year, while the lower red dashed line is based on pipeline operating experience since 1968 with 430,981 km-year.

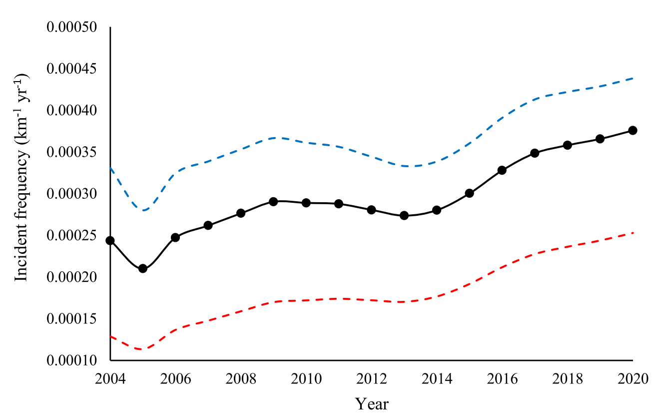

Fig. 8. Incident frequency trend (2004–2020) for CO_2 pipelines in the U.S.A. based on PHMSA.

4. Discussion

In Section 2, the incidents reported in PHMSA database related to CO_2 onshore pipeline from 1968 to 2021 have been analyzed. Results show that the incident frequency can vary between 2.53×10^{-4} event/year and 4.38×10^{-4} event/year with an average value of 3.76×10^{-4} event/year. It is important to highlight that all the above presented values for CO_2 pipeline are in the same range of failure rates reported for hydrocarbon pipelines. EGIG reports values in the range of 3.3×10^{-4} event/year with a reducing trend over the years, while UKOPA reports values in the range of 2.2×10^{-4} event/year with the same reducing trend over the years. Considering the available databases, three possible options to estimate the CO_2 pipeline failure frequency can be considered:

- Use data relevant to hydrocarbons pipeline
- Use data relevant to CO_2 pipeline
- Use data relevant to natural gas pipeline with correction factors.

In the first case the main concerns in using data relevant to different fluids are associated to the failure statistics due to internal threats (i.e. corrosion). There may be significant differences due for example to the presence of impurities (such as H_2O, H_2S, H_2) causing a corrosion risk significantly higher than in hydrocarbons pipelines. Moreover, the fracture propensity in CO_2 pipeline is not fully understood yet and therefore might be different from hydrocarbon pipelines for which there is consolidated knowledge in prevention and mitigation techniques.

In the second case the main issue is due to the very limited operating experience compared to the operating experience for hydrocarbon pipelines (more than 4 millions km-years in EGIG database). The third option could be considered as a hybrid implementation of the previously described methods. The use of the frequency failure related to natural gas pipelines may require correction factors to consider the differences between natural gas and carbon dioxide. Despite some aspects related to construction, maintenance and third-party, external factor could be potentially managed with same evaluation methods, while substantial differences between the two gases in terms of chemical properties and pressures should be assessed and accounted for.

5. Conclusions

In this work, the failure frequency associated to gaseous/dense-phase onshore CO_2 pipelines have been analyzed. The main uncertainty associated to a failure frequency analysis for CO_2 transportation systems is the availability of historical failure data for CO_2. The only recognized database that contains statistics on CO_2 pipeline incidents is the Pipeline and Hazardous Materials Safety Administration (PHMSA) from U.S. Department of Transportation. However, the limited operating experience, if compared with the database available for other hydrocarbon services such as natural gas, suggests adopting a cautious approach in the use of this specific data. In fact, CO_2 pipelines operating in the U.S. are approx. 2% of the overall pipeline network. A total of 113 incidents are reported from 1986 to 2021 for CO_2 services. Approx. 45% of incidents registered occurred due to causes related to equipment malfunction, more than 30% of these cases are associated with pressure or thermal relief valves relieving in unwanted conditions. The remaining incidents due to equipment failure are associated with the failure of small components that lead to minor releases. The second main cause is material related defects; most of the failures occurred at a weld and resulted in minor releases; in few cases the failure occurred in a pipe segment and resulted in more significant releases. The third contribution is related to external corrosion. According to the analyzed data, the incident frequency can vary between a lower bound of 2.53×10^{-4} event/year and an upper bound of 4.38×10^{-4} event/year with an average value of 3.76×10^{-4} event/year. The estimated values for CO_2 pipelines are in the same range of failure rates reported for hydrocarbon pipelines and represent a possible starting point in quantitative risk assessments.

Clearly, in view of the limited data availability and limitations as discussed in this paper, the estimated failure frequency from the PHMSA incident database shall be used with a cautious approach in a risk assessment and sensitivity analysis shall be carried out on a case-by-case basis. Similarly, failure frequency data relevant to hydrocarbon pipeline shall be used with care depending also on the characterization of the main differences between natural gas pipelines and carbon dioxide pipelines. Although PHMSA incident data is limited, it currently represents the only available dataset for CO_2 pipeline failures.

In this work some considerations on the consequences on people, environment and operations have been included. However, further analysis with respect to accident mechanisms and consequences will be beneficial to improve the interpretation of the incident data, the failure frequency estimation and the definition of potential 'high consequence areas' to correctly support the risk assessment process of new CCUS projects under development.

CRediT author statement

Matteo Vitali: Investigation, Methodology, Writing – original draft, Writing – review & editing. Cristina Zuliani: Investigation, Methodology, Writing – review & editing, Supervision. Francesco Corvaro: Project administration, Funding acquisition, Resources, Supervision. Barbara Marchetti: Project administration, Resources, Supervision. Fabrizio Tallone: Project administration, Funding acquisition, Supervision.

Declaration of competing interest

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.

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