LETTER

A national estimate of U.S. underground natural gas storage incident emissions

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Abstract

The 2015 Aliso Canyon storage well blowout was widely reported as the worst natural gas leak in the history of the United States (U.S.) and released ∼0.1 million metric tons of methane (CH4), a potent greenhouse gas. Although storage well fugitive emissions are estimated in the U.S. Environmental Protection Agency’s annual Greenhouse Gas Inventory, the inventory does not include historical estimates of anomalous large emission events other than Aliso Canyon or smaller incident related CH4 releases. A total of 129 underground natural gas storage (UGS) incident-related events between 1940 and 2016 were compiled from various federal/state agencies and literature reviews. Incident emissions were estimated based on best available information, such as direct operator reports, the monetary cost of gas lost, or modeling of the escaping gas at sonic speeds. There are 387 active UGS fields in three types of reservoirs: salt caverns, aquifers, and depleted oil and gas (O&G) fields. 65% of events were in the depleted O&G fields, which account for 79% of storage fields. Texas recorded the highest number of incidents (20), 14 of which were in salt dome reservoirs. The incident emissions showed a heavy-tailed emission pattern with CH4 releases up to 29 billion cubic feet (8.2 × 108 m3). The top seven events contributed 98% of the total estimated/measured CH4 emissions.

1. Introduction

Natural gas, an important bridge fuel source for the next decade, is primarily composed of methane (CH4, 76%–92% by volume) (US EPA 2020). However, fugitive and vented CH4 creates environmental pollution problems and has a global warming potential 28–36 times of carbon dioxide on a 100 year horizon (Masson-Delmotte et al 2021). Research in different regions consistently shows current municipal, state, and national greenhouse gas (GHG) inventories underestimate the actual CH4 emissions (Alvarez et al 2018, Sargent et al 2021, Tyner and Johnson 2021). The emission gaps could be attributed to under-characterized sources (Saint-Vincent and Pekney 2019), temporal variations in emission rates over time and intermittency (Vaughn et al 2018), non-ideal current inventory data input models (Rutherford et al 2021), and heavy-tailed emitters (Zavala-Araiza et al 2018).

The 2015 Aliso Canyon blowout drew public attention to underground natural gas storage (UGS) management and directly led to revised safety regulations (PHMSA 2020). The well blowout lasted 112 d and released 0.1 MMt (million metric tons) CH4 due to a breached 7″ (18 cm) casing (Conley et al 2016). The faulty storage well in the Aliso Canyon field used the space between well tubing and casing to transport more gas and meet the rising demand for natural gas. This practice was not typical and increased the risks of well failure (Folga et al 2016). The CH4 volume lost was about 1/4 of the annual CH4 emissions from the whole South Coast Air Basin (Wunch et al 2016).

There are three main reservoir types for UGS fields, i.e. depleted oil and gas (O&G), salt dome, and aquifer. UGS built at depleted O&G fields can take advantage of existing wells and other associated infrastructure. A typical UGS facility contains well heads, transmission pipelines, a compressor station, and, in some cases, other equipment such as dehydrators.
UGS facilities are primarily owned and operated by interstate/intrastate pipeline companies, local distribution companies, and independent third parties. If the facility faces the interstate market, it is subject to the United States (U.S.) Department of Transportation (DOT) and the Federal Energy Regulatory Commission regulations; otherwise, it is regulated by the state. Currently, there are over 14,000 active storage wells distributed across 387 UGS fields in the continental U.S., and recent studies suggest that around 200 wells were constructed before 1917, when the cement zonal isolation method was adopted; Michanowicz et al. suggested these wells might rupture in the same fashion as the well responsible for the Aliso Canyon accident (Michanowicz et al. 2017).

So far, the UGS research has focused on risk assessment of single-point-of-failure designed wells (Michanowicz et al. 2017) and UGS facilities (Folga et al. 2016), well integrity assessment (Freifeld et al., 2016), top-down airborne measurements of UGS facilities (Thorpe et al. 2020), historical CH₄ occurrence frequencies from different storage reservoir types (Schultz et al. 2020), and air pollutant emissions from the Aliso Canyon blowout (Garcia-Gonzales et al. 2019). The risk assessment studies help understand causes leading to historic incidents at UGS facilities and minimize future CH₄ release potential.

Historical data are particularly sparse for quantifying blowout emissions from storage wells or incident-related emissions at UGS sites. Satellite remote sensing has only recently been put into practice to estimate large well blowout emissions from space (Casworth et al. 2021). The current U.S. GHG inventory uses emission factors of onshore production wells to approximate emissions from storage wells (Smith et al. 2019). No historical emissions for anomalous events other than the Aliso Canyon blowout have been incorporated as of this writing. For this paper, an UGS incident database was compiled from available public resources. We discuss (a) the spatial distributions of UGS facilities and related incidents, (b) types of incident causes, and (c) the overall CH₄ emission pattern.

2. Methods

We define UGS incident events as the closure or cessation of operation of the UGS facility due to an incident (Folga et al. 2016). The compiled database is largely based on Folga et al. (2016), and has 129 incident records from 1940 to 2016. 78 entries were from the Pipeline and Hazardous Materials Safety Administration (PHMSA), a DOT agency (PHMSA 2020). Literature reviews provided another 51 records (Folga et al. 2016). The retrieved incidents cover a wide range of operational malfunctions due to various equipment and assets in the UGS complex. Examples include gas leaks from pipelines related to UGS, gas escaping from breached casing, gas migration through soil fissures, faulty overburden, over-pressure, and other operational failures.

PHMSA entries have detailed incident descriptions, cause, duration, pipeline diameter, operational pressure, etc. The information was used to estimate CH₄ emitted per incident. Literature reviews yielded a broad year range of incidents, from 1940 to 2013 (Evans 2009, Folga et al. 2016). The legacy incidents typically did not have comprehensive event records, and thus, no reliable method for estimating emissions. Eighteen out of the 51 incidents identified in the literature review were not estimated due to lack of sufficient information.

PHMSA reporting formats can be grouped into three time spans 1984–2001, 2002–2009, and post 2009. Different formats led to different methodology to estimate lost gas volumes. Gas release volume was directly reported for events after 2009. Cost of gas lost was reported for incidents between 2002 and 2009. The total property damage cost was reported for the events between 1984 and 2001. This oldest time span contained 20 incidents, and only limited information was available. We used operator reported emissions for UGS events where such information was available. For events with gas loss cost available, the U.S. Energy Information Administration (EIA) monthly wellhead gas price was used to calculate the gas volume (EIA 2020b). To confirm the reliability of this method, we compared EIA wellhead prices with the operator-reported price in PHMSA events since 2009. The prices matched, indicating this estimation method is reliable.

For events with no direct gas loss reported or detailed narratives to infer gas volume, we proposed an intuitive method based on fluid mechanics. As the gas pressures inside natural gas equipment, such as pipelines, are orders of magnitude higher compared to ambient pressure, the escaped gas from leak spots or rupture areas will have high speed, but no more than sonic due to conservation of mass, momentum, and energy (Lin 2002). Escaped flows are choked if a further reduction in pressure downstream does not lead to a higher exiting speed, and the maximum velocity will be the sonic speed at existing environmental conditions. The threshold pressure ratio (upstream/downstream) is called the critical pressure ratio, above which the exiting flow can be assumed to have a sonic escaping speed. This assumption can simplify the gas volume estimation, as the other required parameters (such as leak cross section area and event duration) are readily available from PHMSA records. The critical pressure ratio between upstream and downstream flows is 1.9 for the natural gas stream, significantly lower than the typical pressure ratios (~50) used in the natural gas supply chain (Li et al. 2020a). Assuming the gas exits at sonic speed, the multiplication of sonic speed, duration, and cross-sectional area yields the gas volume.
3. Results and discussions

There are 387 active UGS fields in U.S. (EIA-191 2020). The working gas capacity ranges from 24 million cubic feet (MMcf) \((7 \times 10^5 \text{ m}^3)\) to 164 billion cubic feet (Bcf) \((5 \times 10^9 \text{ m}^3)\). The base gas capacity also spans four orders of magnitude, from 21 MMcf \((6 \times 10^5 \text{ m}^3)\) to 144 Bcf \((4 \times 10^9 \text{ m}^3)\). Overall, 308 fields \((79\%)\) are depleted O&G reservoirs. Salt dome and aquifer fields each account for about 10% of the total. Depleted O&G reservoirs are the most common type and are distributed across the U.S. The other two types, salt domes and aquifers, are more region-specific. Figure 1 shows the aquifer storage fields are mainly near the Great Lakes, and the salt dome fields are mostly in Texas, Louisiana, and Mississippi. The number of aquifer and salt dome storage fields are 44 and 36, respectively.

Within the compiled incident dataset, figure 2 shows Texas has the highest number of incidents \((20)\), but also the third highest number of storage fields in any state \((30)\). Salt dome reservoirs accounted for 14 of the studied incidents. The remaining six incidents that occurred in Texas were in the depleted O&G fields. California ranks second in incident count, with 16 incidents in the dataset. All California incidents were in the depleted O&G fields, as all the active reservoirs in California are this type of UGS. Illinois is distinct from the other states, with all but one incident in the aquifer storage fields. Similarly, Indiana has all four incidents in the aquifer fields. The other top ten states have mostly depleted O&G fields or a small portion of salt dome-related incidents. On a per storage site basis, California has the highest incident ratio per capita of 1.1. Texas ranks second with a ratio of 0.7, and Illinois follows with a value of 0.6. Texas, California, and Illinois are the three most critical states based on absolute incident count and incidents per capita.

3.1. Incident count and cause

PHMSA events were examined specifically, as they contained detailed narratives for the incidents. The narratives were used to infer incident causes. Figure 3 shows that PHMSA incidents counts show an increase after 2006. Before 2006, the event count for a single year was 1, 2, or none. The significant increase of incident count for the last decade is partially related to the technological advance of horizontal drilling and hydraulic fracking (Vengosh et al 2014). The U.S. is experiencing a shale gas boom and dry natural gas production increased by 70% in the last two decades (EIA 2020a). More natural gas production
has contributed to increased throughput across the whole natural gas supply chain. For example, mid-stream compressor stations require compressors of larger size or greater horsepower to compress and transport more gas from the production segment to downstream distribution centers.

The most common failure mechanism was pipeline corrosion. For 1984–2001 events, ‘other’ was listed as the most common cause and corrosion was second. The other two causes were construction/material defect and damage by outside force with separate counts of four and three. Thus, we have a less clear understanding of the cause of legacy UGS failures and sparse event logs for emission estimates. Corrosion is an important root cause for pipeline failures, as pipeline leak frequency shows
a strong dependence on pipeline material and age (Weller et al. 2020, Li et al. 2020b). The main types of external pipeline corrosion are galvanic, atmospheric, stray current, microbiological, and selective seam. Galvanic corrosion occurs when two different metals are in electrical contact with each other. Stray currents come from distribution power lines, railway systems, and alternating current. Selective seam corrosion is localized corrosions along the weld bond line.

Corrosion accounts for 44% of post-2009 incidents, 47% for 2002–2009, and 30% for 1984–2001. Equipment failure was the second most common cause listed for post-2009 cases. Equipment failure could occur in control/relief equipment, compressor or compressor-related equipment, threaded or non-threaded connections, etc. Other causes, such as natural force and excavation damages, led to a maximum of three incidents per year. Natural force events include earthquakes, heavy rains/floods, lightning, extreme temperature, high winds, trees/vegetation roots, and snow/ice impact. Excavation damages occur during various types of work performed by excavation tools such as trencher and drilling equipment. The work type includes O&G site development, building construction, road work, etc. For 2002–2009 cases, pipeline corrosion was again the main cause of failure, resulting in eight incidents. The rest of the incidents during this time were nearly evenly distributed across a variety of causes. For 1984–2001 cases, only four categories were identified, and each had about the same weight. Excavation damage was included in the ‘damage by outside force’ factor.

3.2. Emission estimates
The 129 compiled events come from diverse reporting sources with different information to estimate CH₄ emissions. Figure 4(A) shows the gas cost and volume are highly correlated with $R^2$ of 0.96. Using this cost-to-volume estimation method, emissions rates for 17 events were calculated. Gas cost ranged from $0 to $600,000, and 93% of events had gas cost below $100,000. The gas cost of $0 indicates the operator reported the monetary value of gas lost for an event was zero.

For PHMSA events before 2002, no gas cost was provided, so we used the sonic speed escape method to estimate the gas volume that was lost. The first example we validated the method was the 2015 Aliso Canyon storage well blowout event. The event released $1.4 \times 10^8$ m$^3$ of CH$_4$ in 112 d due to a breached 7” (18 cm) casing with an operational pressure of $1.7 \times 10^7$ Pa. The sonic speed calculation provided a gas volume estimate of $9.7 \times 10^7$ m$^3$, about 32% lower than the official reported value (Conley et al. 2016). The reported emissions were based on airborne mass balance flights with an uncertainty of about 20% to 30% (Conley et al. 2016, 2017). Our proposed sonic speed estimation reached a reasonable agreement with the reported emissions. We further validated the method by analyzing PHMSA events for which directly reported volume emissions were available. Figure 4(B) shows the sonic-based estimates are mostly within one order of magnitude relative to the operator reported volumes. The method underestimates one event by more than an order of magnitude. Events such as gas explosion following
blowout or underground gas migration, such as the Hutchinson, KS downtown gas event, would typically have follow-up gas releases from damaged equipment due to explosion or unknown migration durations, respectively (Evans 2009). All these could complicate the total gas release volume, resulting in inaccurate modeling and emissions estimations using the sonic speed method. Thus, the sonic speed method was only adopted when other methods such as gas economical value or remote sensing were not viable.

3.3. Heavy-tailed emission pattern

In emissions estimates from UGS incidents, we observed a heavy-tailed emission pattern, which has been observed in various segments of the natural gas supply chain (Brandt et al 2016, Omara et al 2016, Saint-Vincent et al 2020). The heavy-tailed emission pattern refers to the disproportionately large share of the total measured emissions taken up by the few largest emitters. Figure 5 shows the UGS incident emissions ranged from 0 to $8.2 \times 10^8$ m$^3$. Incidents with 0 m$^3$ emissions imply that no gas escaped to the surface. The largest emission event occurred at the West Greenville storage field in Kentucky (Evans 2009). The incident was related to tubing failures. The storage well blowout incident was due to a slipped and dislodged packer and resulted in major fire, destroying vehicles and the rig. Eventually, the well was killed and plugged.

The cumulative mass of CH$_4$ released from the whole compiled UGS dataset was 0.9 MMt. And the newest U.S. EPA national inventory estimated about 8.4 MMt of CH$_4$ from the O&G segment in 2020 (US EPA 2022). It is not fair to directly compare these two values due to the difference in the time range. UGS incidents can also lead to fire and explosion events which would combust and convert the majority of rapid released CH$_4$. We examined five specific years (1980, 2004, 2015, 1969 and 2006) with the highest annual CH$_4$ emissions from UGS incidents. Each year also turned out to have one of the top five UGS incidents. The year 1980 had the largest emission event at the West Greenville storage field in Kentucky. The annual UGS emissions in 1980 contributed about 10% of the national O&G supply chain emissions (EIA 2011). In 2004, the UGS emissions accounted for 1.5% of the O&G total emissions. The year 2015 had the Aliso Canyon storage blowout event and the total UGS emissions were about 1.2% of the national emissions. There were no national inventory estimates for 1969. UGS incidents in 2006 contributed 0.2% of the national O&G emissions. Overall, CH$_4$ emissions from UGS incidents are not negligible and need to be included in future inventories.

The typical regulatory implication regarding CH$_4$ reduction, based on the observation of super-emitters in natural gas infrastructure, is shifting priorities to fix the heavy-tailed emitters (EPA 2021). Most of the UGS incident emissions were small ($<3 \times 10^5$ m$^3$, 10 MMcf), and only a few large events had emissions on the order of $10^6$ m$^3$. A high priority is to conduct comprehensive risk assessment for UGS construction and operation and to perform routine maintenance and safety checks for risk factors associated with UGS failure incidents.

The major limitation of the study is the lack of detailed narratives for legacy events. The sonic speed method for emissions estimation was adopted for some of these events, but the emission estimates could deviate from actual values by an order of magnitude.

4. Conclusion

We compiled a U.S. UGS incident database of 129 cases from 1940 to 2016. Using various methods, we estimated emissions for 109 (84%) of those events.
A heavy-tailed emission pattern is observed, where the top seven events contributed 98% of the total estimated CH\(_4\) emissions from all events. All 129 events have already occurred and caused monetary and life losses. Yet lessons can be learned from these events in order to prevent future UGS incidents. Findings from this study will help understand CH\(_4\) emissions from historic storage well blowout and UGS-related incidents, contribute to data gaps in the U.S. GHG inventory, and provide more accurate data input for global transport models.

**Data availability statement**

The data that support the findings of this study are available upon reasonable request from the authors.

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