A national assessment of underground natural gas storage: identifying wells with designs likely vulnerable to a single-point-of-failure

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Abstract

The leak of processed natural gas (PNG) from October 2015 to February 2016 from the Aliso Canyon storage facility, near Los Angeles, California, was the largest single accidental release of greenhouse gases in US history. The Interagency Task Force on Natural Gas Storage Safety and California regulators recently recommended operators phase out single-point-of-failure (SPF) well designs. Here, we develop a national dataset of UGS well activity in the continental US to assess regulatory data availability and uncertainty, and to assess the prevalence of certain well design deficiencies including single-point-of-failure designs. We identified 14 138 active UGS wells associated with 317 active UGS facilities in 29 states using regulatory and company data. State-level wellbore datasets contained numerous reporting inconsistencies that limited data concatenation. We identified 2715 active UGS wells across 160 facilities that, like the failed well at Aliso Canyon, predated the storage facility, and therefore were not originally designed for gas storage. The majority (88%) of these repurposed wells are located in OH, MI, PA, NY, and WV. Repurposed wells have a median age of 74 years, and the 2694 repurposed wells constructed prior to 1979 are particularly likely to exhibit design-related deficiencies. An estimated 210 active repurposed wells were constructed before 1917—before cement zonal isolation methods were utilized. These wells are located in OH, PA, NY, and WV and represent the highest priority related to potential design deficiencies that could lead to containment loss. This national baseline assessment identifies regulatory data uncertainties, highlights a potentially widespread vulnerability of the natural gas supply chain, and can aid in prioritization and oversight for high-risk wells and facilities.

Introduction

Each year nearly 28 000 billion standard cubic feet (Bcf) of processed natural gas (PNG) composed primarily of methane (CH4), ethane (C2H6), other hydrocarbons, and sulfurous odorants flow through the US natural gas supply chain. Approximately 13% of PNG produced annually is injected back into underground storage reservoirs, which are either depleted hydrocarbon fields, depleted aquifers, or solution-mined salt caverns [1]. Underground natural gas storage (UGS) facilities contain 4300 Bcf in working capacity and provide a critical link in PNG operations as they bridge imbalances between supply
and demand and mitigate ratepayer cost volatility [1–3]. Domestic natural gas production has grown 50% in the past decade and PNG storage has recently reached all-time highs [4]; however, the 2015 Aliso Canyon UGS incident has prompted new scrutiny of the nation’s natural gas storage infrastructure [3].

Between October 2015 and February 2016, an estimated 99 638 (± 9300) metric tons (mt) (5.0 Bcf) of methane were released into the atmosphere from a failed storage well operating at the Aliso Canyon UGS facility near Porter Ranch, California [5, 6]. The 118-day leak resulted in the evacuation of 5790 households, and has raised new health concerns for proximate populations [7]. The emissions from the incident constitute the single greatest accidental release of climate forcing gases in US history [6] and accounted for 2.0 million metric tons of CO₂ equivalent, or about 6% of the 2015 US natural gas transmission and storage emissions from the US Environmental Protection Agency’s (EPA) Greenhouse Gas Inventory (GHGI) [8]. If incorporated into the GHGI, this single incident would increase the methane emissions attributed to storage wells by 770% from the 1999–2014 baseline of 14 879 mt yr⁻¹ [9].

Unintentional gas migration from UGS operations has caused fatalities, fires and explosions, evacuations, exposure to noxious odors, tropospheric ozone production [10], and releases of climate-forcing gases [11, 12]. A 2009 review of underground gas storage incidents cited 200 unintended gas migration events in the US to date [13]. The majority of unintended releases at UGS facilities, including the Aliso Canyon release, were associated with well integrity problems [11–17] (supplementary information (SI) available at stacks.iop.org/ERL/12/064004/mmedia). Presently, well-level data on incidents is not widely available and is inconsistently reported among states, limiting the opportunity to assess the rate of UGS well failure risk [13, 17].

The Aliso Canyon #25 Standard Sesnon (#25 SS) well failure is believed to have originated from the subsurface well casing [3, 18]. The well—originally completed in 1954 as an oil-producing well and repurposed for UGS in 1972—was vulnerable to a single-point-of-failure (SPF) along a portion of its production casing because: (1) a single full-length well casing was exposed directly to the outside rock formation from 990–6960 ft.; (2) gas was intentionally moved through both the outer well casing, and the inner production tubing (SI text). Injecting and withdrawing gas through both the production tubing and casing was a common practice at Aliso Canyon and has recently been identified as a common practice at other UGS facilities, particularly at older wells [3], which typically have narrower pipe diameters. An additional factor that may have contributed to loss of containment was the removal of a sliding sleeve valve in 1979 that was intended to provide a connection between the tubing and the tubing-casing annulus [3].

From industry surveys, only 3%–5% of active UGS wells utilize safety valves or sleeves below the surface [19]. The combination of these factors effectively bypassed the passive barrier protection provided by the inner production tubing, rendering the well’s structural integrity commensurate to that of a single casing at 990–6960 ft.

Following the Aliso Canyon incident, the 2016 Protecting our Infrastructure of Pipelines and Enhancing Safety (PIPES) Act mandated that the Pipeline and Hazardous Materials Safety Administration (PHMSA) promulgate minimum Federal standards for UGS operations by June 22, 2018 [18]. The Interim Final Rule (IFR)—Pipeline Safety: Safety of Underground Natural Gas Storage Facilities notes that the lack of minimum downhole regulations at UGS facilities presents an immediate threat to safety, public health, and the environment [20]. Some states had adopted regulations, but only for ‘in-state’ facilities that do not send gas into the interstate market [49 U.S. C. § 60104(c)]. Several states have no safety regulation for UGS facilities, and others only regulate facilities in specific geologies (e.g. salt caverns) [3]. Following the Aliso Canyon incident, California has amended design, construction, and maintenance measures to help ensure that current SPF wells do not pose an immediate threat of loss of control of fluids [21]. To inform PHMSA’s rule-making process, an Interagency Task Force (ITF) on Natural Gas Storage Safety was formed to study three primary areas of concern: integrity of UGS wells, public health and environmental effects from natural gas storage leaks, and energy reliability. One of the highest priority recommendations regarding well integrity was to ultimately phase out UGS well with SPF designs [3].

Modern production and UGS wells typically contain a nested set of structural elements (e.g. casing, tubing, cement, packers, and wellheads) to form multiple barriers that collectively function to achieve zonal isolation [22]. According to the IFR, an uncertain portion of active UGS wells, like the #25 SS, are repurposed production-type wells that are facing obsolescence issues, and likely exhibit vestiges of original construction (e.g. lack of corrosion-resistant coatings) [20]. Therefore, based upon common practices prevalent during previous well construction eras [23], a portion of repurposed UGS wells may be particularly likely to exhibit designs vulnerable to SPF. Additionally, wells not designed for UGS are also more likely to lack corrosion-resistant coatings, utilize threaded pipe couplings, and exhibit insufficient strength safety margins for steel casings [20].

Identifying the prevalence of wells with design deficiencies such as single barriers would reduce vulnerability of UGS systems. Despite forthcoming regulations and reliance on UGS, baseline well-level information is not readily available, and according to the IFR, there is currently no effective means to ensure compliance with safety standards [20]. The absence of
such data impairs a systematic risk assessment and stakeholder management of UGS, along with refinement of EPA’s GHGI [9, 24]. Improving our understanding of disparate state and Federal UGS wellbore data can aid in reducing uncertainties, and methods presented herein provide a tractable approach towards baselining national UGS well-level activity.

Here, we develop a national dataset of UGS well activity in the continental US to assess regulatory data availability and uncertainty, and perform a first-order assessment of well-level design deficiencies. To do so, we develop a framework to join disparate Federal- and state-level UGS data, and apply an indicator method to identify repurposed wells and those more likely to exhibit a SPF well design.

Methods

Storage field data
The Energy Information Administration of the US (EIA) maintains the Oil and Gas Field Code Master List, which provides standardized field names and codes for all identified oil and gas fields in the US [25]. We relied on the April 2016 EIA-191 M Monthly Underground Gas Storage Report to identify active UGS operations and matched these operations with state-level well data [1]. The EIA aggregates UGS operations by field and reservoir codes. However, not all states adhere to constant distinctions between subterranean fields and reservoirs. Moreover, a portion of UGS operations reported by the EIA contain either duplicate field or reservoir names/codes, which indicates co-located operations within a single facility. Therefore, we include counts of unique UGS ‘fields/reservoirs’ and ‘facilities’ containing multiple co-located field-reservoirs where applicable. For interpretability, we refer to ‘fields’ hereafter as the subterranean entities as implied in the EIA 191 M list, whereas ‘facilities’ refer to UGS operations that have been joined to wells as per our methods described herein (see figure 1).

Storage well data
For most states, UGS well data were available via web download. Four states required academic use agreements via direct correspondence (SI table 3). The ‘well type’ variable was the primary indicator of a storage-related function [e.g. storage, injection (gas), monitoring storage]. Well types not explicitly related to PNG storage, such as liquefied gas storage, were excluded. To determine activity state, most states provided a ‘status’ indicator (e.g. active, plugged and abandoned, inactive, shut-in, etc.) that was used to determine the current activity state of a well.

Well-to-field join
Under the assumption that active storage wells and storage fields coincide, we attempted to join wells and fields based upon the availability and quality of well records. The data joining process is displayed in figure 1. Where applicable, well data were standardized using geodatabase aggregation and included location information, type, status, activity dates, depth, an indicator of whether a well was assigned to a facility, and unique state-well identifier (e.g. API #).
Determining well construction date
Well construction dates were generally included in state databases. We compared spud dates—the date of initial ground penetration—with permit and completion dates to determine whether completion or permitting reflected the original completion or permit, or subsequent re-completions or re-permitting. Completion occurred within a year of the spud date in 92% of 949 wells for which both spud and completion dates were available (SI figure 2), which suggests that these completion dates obtained largely reference the original completion of the well. Based on this relationship, we assigned the year of the oldest activity date for each well to proxy as the year of original construction.

Identifying well-level deficiencies
Repurposed storage wells were defined as wells that were originally designed for hydrocarbon production (or other non-UGS function) and were later converted to storage. To determine whether a well was designed for storage or repurposed, we compared the well’s construction date to its associated field storage designation date. The storage designation date (when the facility began injecting PNG) was obtained from the 2013 Oil and Gas Field Code Master List [25] (the most recent edition containing designation years). We examined the entire distribution of well construction dates in relation to their respective facility designation dates. From these observations, wells that predate their facility designation date by at least three years were treated as repurposed, and wells within two years of facility designation date, were treated as designed for storage.

Confirmation of SPF design would require individual well histories, which are not readily available at the national scale. Therefore, we employed an indicator method to identify well-level deficiencies inferred from initial well use, and common construction practices at the time of drilling. Based upon recommendations by the ITF, we chose a well construction date of pre-1979 to indicate the likelihood of a SPF design [3]. Therefore, repurposed wells with a construction date before 1979 were classified as particularly likely to exhibit a SPF design. We also utilized well construction eras from King and King [23] to provide context in identifying other potential well-level design deficiencies. We also compared well depth to well age to help corroborate initial well use, and to provide an internal data validation within state.

Results

Data quality and completeness
As of July 2016, the EIA reported 384 active and 23 inactive underground gas storage field-reservoirs associated with 131 unique company names within the continental US. Of these 384, 18 contained at least one duplicate field name or derivative (e.g. Lee 2; Lee 8; Lee 11) totaling 48 entries. Thus, the 384 active field-reservoirs were contained within 354 geographically confined UGS facilities. We identified 18 396 total UGS-related wells, with 14 138 ‘active’ status UGS wells successfully joined to 317 active UGS facilities in 29 states (figure 1). Thus, 37 active UGS fields were unable to be joined to a single active UGS well. The counts above exclude the four Alaskan facilities and the 82 UGS facilities that have been abandoned, classified as inactive, or are no longer in use [26]. Of the 14 138 active UGS facilities identified, 12 440 are sited in depleted fields, with 1561 sited in aquifers and 137 in salt caverns. Eighty-two percent (82%) of active UGS wells are located in the East and Midwest regions (figure 2), driven in part by the heavy dependence on UGS during the winter season. Of the inactive status wells, 1702 were reported as ‘abandoned,’ ‘plugged,’ or ‘plugged & abandoned.’ For more detailed state-level metadata see SI tables 3 and 4.

A portion of UGS wells (n = 1390) including all wells in Iowa (n = 709) and most Nebraska wells (n = 103) reported an ‘unknown’ activity status. Some of these wells were successfully joined by field name to active UGS facilities, indicting active operations. However, because the well activity status could not be verified, these wells were not included in final active UGS well counts. PA, NY, IA, MN, NE, and TX recorded ‘unknown’ as a potential well status.

A portion of states (14 out of 29) reported specific storage-well function (e.g. monitoring/observation, injection/withdrawal). Texas provided only injection-type storage wells coinciding with EPA’s Underground Injection Control program, therefore withdrawal-only and monitoring wells were not enumerated. Oklahoma did not report a ‘storage’ well type, and only post-1984 wells were digitized and available for download as of February 11, 2016. These 15 states equated to 6483 total active UGS wells, with 1313 explicitly listed for injection, 695 listed for monitoring/observation, and the remainder listed as ‘storage’ excluding Oklahoma.

Ohio UGS wells data did not include field names/codes with well records; therefore, the 3318 UGS Ohio wells were joined geospatially to facilities via company system maps (figure 1, SI table 4). Eight other states had joined discrepancies that necessitated further match validation by visual inspection of company system maps (figure 1, SI table 3).

Availability of well construction activity dates varied by state (SI table 3). Of the 14 138 active UGS wells identified, 12 667 or approximately 89% contained at least one relevant construction activity date (e.g. permit, spud, completion). Only 949 UGS wells reported at least two activity dates (see SI figure 2). Approximately 60% of wells included a completion date, 35% contained permit dates, and 18% had valid spud dates. Louisiana was the only state to
provide a date for a workover-type event. Kansas did not report well construction dates for 330 active UGS wells—the most of any state—while Mississippi did not provide well construction dates for any of its 175 UGS wells. Notably, intrastate facilities, which connect to fewer wells than interstate facilities (5122 vs. 7021) have a higher rate of missing dates (table 1).

There are 76,639 entries in the 2013 EIA Oil and Gas Field Code Master List, with 951 entries coded as ‘STOR’ in their remarks section indicating the field has been utilized for a storage function. Of these, 274 are listed as either ‘unknown’ or ‘wildcat’ fields across 18 states, and only 84 of the 951 indicate abandonment. Of the 354 active fields identified above, 337 reported the date the field began storage operations (designation date). The median designation year for these storage fields is 1963. Of the 12,667 wells with a valid construction date, 12,144 connect to a field that contained a valid storage designation date. Thus, well-level design deficiencies were assessed from 12,144 active UGS wells (see figure 1).

Overall, excellent well drilling depth data was provided by most states with 22 of 29 states reporting at least 95% coverage. Notable exceptions include Mississippi who did not report well depths and California with only 60% of wells reporting (SI table 3).

**Table 1.** Active UGS well counts by initial well use by facility-level category.

| Facility & Type | UGS Wells | UGS-Designed Repurposed | Wells Missing Facility Date | Missing Well Date |
|----------------|-----------|-------------------------|----------------------------|------------------|
| Total          | 12,144    | 9,429 (78%)             | 2,715 (22%)                | 559              | 1,471           |
| Interstate     | 7,021     | 5,386                   | 1,985 (28%)                | 355              | 673             |
| Intrastate     | 5,122     | 4,042                   | 1,480 (29%)                | 304              | 798             |
| Aquifer        | 1,151     | 1,078                   | 73 (7%)                    | 87               | 323             |
| Depleted Field | 10,950    | 8,315                   | 2,635 (31%)                | 428              | 1,091           |
| Salt Cavern    | 43        | 36                      | 7 (16%)                    | 44               | 57              |

* reflects only active UGS wells that contain both well construction date and facility storage designation date.

Comparing UGS well construction dates to their respective facility designation date reveals a peak of new well constructions that coincides with new UGS facility designations (figure 3). Of these, 1,065 (9%) wells were constructed in the same year as their facility commenced storage operations, and 2,633 (22%) of all UGS wells were constructed within the first two years of a UGS facility designation (figure 3). The increase in
well construction within the year prior to storage designation of their respective facility suggests that these wells were likely designed for the storage operations, or were re-completed for storage purposes. Data on well construction in the five years prior to facility storage reveal a local minima of new well construction at roughly two years before facility storage designation. While some wells constructed more than two years before storage designation may be designed for storage, a two-year cut-off of UGS-design wells is supported by the distribution of well construction relative to its facility designation in figure 3. Therefore, wells drilled at least three years before their respective facility storage designation date were classified as repurposed UGS wells.

Figures 4(a) and 4(b) rank facilities by storage designation date, and include joined active wells by construction dates. There are 114 active UGS facilities that contain only UGS-designed wells (active wells with construction dates after or within two years of the facility designation date). The shaded box in figure 4(a) displays the 57 facilities that do not report a storage designation date, but did successfully join to active UGS wells with valid construction dates ($n = 559$). Though a portion of these wells may be repurposed, they were not included in final counts of repurposed wells. Figure 4(a) displays the 160 UGS facilities that contain at least one repurposed well.

Facility age and well age are positively associated, indicating that facility age helps to predict the distribution of well ages (Pearson’s $r = 0.48$, $p < 0.0001$); however, facility age does not significantly predict of the presence of repurposed wells ($t = 0.031$, $p = 0.975$). Among facilities with at least one repurposed well, facility age is strongly correlated with well age (Pearson’s $r = 0.72$, $p < 0.0001$). We observed that a majority of facilities continue to construct new UGS-designed wells after beginning storage operations, yet new well construction does not preclude operation of older, repurposed wells.

Of the 12 144 active UGS wells with adequate date information, 2715 (22% of 12, 144; 19% of active UGS wells) are classified as repurposed, of which 97% (2635) were sited in depleted oil/gas fields (table 1). An additional 266 wells with an ‘unknown’ status joined to an active facility would be classified as repurposed if the well status were to be confirmed. Thus, considering the 1994 active wells that did not contain valid well or field dates, and the 266 unknown status repurposed wells, the 2715 figure may underestimate the total number of repurposed UGS wells based upon this identification method. States that report an explicit storage well function account for 1135 of the 2715 repurposed wells; among these 241 were labeled as ‘observation’ or ‘monitoring,’ 41 were labeled as ‘injection,’ and the remainder were listed as ‘storage.’

Repurposed wells are often older than UGS-designed wells (figure 3). The median age of repurposed wells is 74, compared to a median age of 48 years for UGS-designed wells and their age distributions are significantly different [$X^2 (111, N = 12129) = 7.2 \times 10^3$, $p < 0.0001$]. These results also reflect a decrease in UGS well construction over the last 30 years and a continued reliance on older wells.

Active repurposed wells can be found in 160 UGS facilities in 19 states, with 88% located in OH (902), MI (638), PA (370), NY (315), and WV (166) (figure 6). These 160 facilities connect to 79% of the total active wells and 51% of the working gas capacity in the US. Wells counts and locations of facilities with unknown status repurposed wells are indicated in gray in figure 6. Percent of wells missing sufficient date information to determine initial use is displayed in figure 6 at the state level (green pallet). Darker greens represent the percentage of wells either missing a well construction date or are connected to a facility missing designation date. Less than 10% of wells in OH, MI, PA, NY, and WV contain missing date information; however, universal activity date definitions are lacking.

An estimated 2694 of 2715 UGS repurposed wells were constructed prior to 1979, indicating these wells are particularly likely to exhibit SPF designs. Therefore, 99% of repurposed wells shown in figure 6 also meet our age-based indicator for exhibiting a SPF design, and with 88% constructed before 1960, there is a likelihood that these wells exhibit other well-design deficiencies as indicated in table 2. Notably, 661 active repurposed wells across 10 states were constructed before 1929—before well pressure-control systems and other containment methods were
utilized. An estimated 210 active repurposed wells were constructed before 1917—before cement zonal isolation technologies were employed. These wells are located in PA, OH, NY, and WV and represent the highest priority related to potential design deficiencies that could lead to containment loss and should warrant further investigation.

Drilling well depth generally increases over time for all UGS wells ($r = -0.25$, $p < 0.0001$) (Figure 7(a)). However, this relationship is stronger for UGS-designed wells ($r = -0.38$, $p < 0.0001$) compared to repurposed wells ($r = -0.19$, $p < 0.0001$). While depth is associated with initial well design (repurpsement), well age is a much stronger predictor of well design, explaining 37% of the variance compared to less than 1% for well depth. Nonetheless, well depth is important to consider in terms of wellbore integrity as pressures and temperatures generally increase with depth.

To further examine age and depth relationships, Figure 7(b) categorizes repurposed wells by the top five states harboring repurposed wells. The clustering of wells by age, depth, and state particularly for MI, WV, and OH indicates a form of internal data corroboration between well depth and age variables. This concordance supports generalizability of findings related to initial use and design deficiencies at a state

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**Figure 4.** (a) Active UGS facilities with only UGS-designed wells. The gray-shaded box of figure 4(a) represents the facilities and associated wells where facility storage designation dates were not available. (b) Active UGS facilities with at least one active repurposed well as indicated by an individual well construction date predating facility storage operations by at least three years. Red circles indicate the date a facility began storage operations. Black diamonds indicate individual well construction dates.

**Figure 5.** Active UGS well age distributions by year, colored by well design as per figure 3, with repurposed wells in dark brown, UGS-designed wells in gray, and wells drilled within two years before facility conversion to storage in yellow.
level. In contrast, NY and PA wells tend not to cluster to the same degree, which may indicate greater geologic heterogeneity and historical drilling practices, or a higher degree of data uncertainty related to date information.

**Discussion**

This study presents an April 2016 census of active UGS wells concatenated from disparate state, federal, and company data and information, and provides a baseline for assessing obsolescence issues related to UGS wells. We document error sources, discrepancies across 29 separate wellbore databases, and highlight key limitations and areas in need of further investigation. State-level UGS wellbore datasets contained numerous reporting inconsistencies that limited data concatenation, and our attempt to characterize data quality and uncertainties adds to a limited literature on the subject [24, 27, 28]. Overall, the majority of state regulatory bodies harboring UGS operations provide public access to standard wellbore data and information, with certain exceptions related to download restrictions, paywalls, use waivers. UGS wellbore data from eight states contained important missing variables (e.g. field name, activity status, date information) that limited the well-to-field join

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**Table 2.** Active UGS wells categorized by initial design and well construction eras adapted from King and King [23].

| Time Era                          | Pre Zonal Cement Isolation (pre 1917) | Pre Well Containment (1917–1929) | Pre Gas Tight Couplings (1930–1959) | Pre Modern Cement (1960–1969) | Pre Additional Barriers; Cementing Full Strings (1970–2004) | Improved Well Integrity Assessments (2005–2015) | Total |
|----------------------------------|--------------------------------------|----------------------------------|-------------------------------------|-------------------------------|-------------------------------------------------------------|-------------------------------------------------|-------|
| Potential for pollution from well construction | High | Moderate | Moderate | Moderate | Lower | Lower | — |
| UGS-Designed                    | 1 | 2 | 2683 | 2373 | 3938 | 430 | 9429 a |
| Repurposed                       | 210 | 451 | 1737 | 214 | 103 | 0 b | 2715 |
| Facility Date Unknown            | 1 | 45 | 102 | 70 | 172 | 133 | 523 |

a 1567 active wells did not contain a valid construction date.
b The youngest repurposed well was constructed in 1994.

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Figure 6. Counts of repurposed wells per facility symbolized by orange markers. Of the 2715 repurposed wells shown, 2694 (99%) were constructed prior to 1979, indicating a particular likelihood to exhibit SPF designs. Percent of active UGS wells missing sufficient date information is indicated at the state level by green shading. Gray markers indicate active facilities that contain at least one repurposed ‘unknown’ status well. Callout numbers represent counts of repurposed wells by state and includes active and unknown status well counts where applicable.
process. Generally, these data variables were obtained following personal correspondence with data providers, with exceptions (see SI table 3). Most UGS wellbore datasets contained good coverage for: field name, status, location, operator, depth, one activity date, and API# where applicable. Generally, key missing variables included explicit storage well function, workover history, testing history, date types, and additional activity dates. Explicit characterization of well-level spatial uncertainty was beyond the scope of this study, though the peak signal between UGS field designation dates and well construction dates indicates a degree of temporal agreement between EIA field data and state well-level data. Similarly, documented imparity in data availability and quality across states and over time contributes to reducing availability heuristic and can aid regulators and stakeholders in identifying best practices.

Wellbore-level data typically does not contain information related to design elements, mechanical integrity testing, or other information necessary for a rigorous assessment of well integrity, therefore the inability to test certain assumptions remains a key limitation of this study. Given this lack of data, we developed an indicator method designed to evaluate the presence of previously identified well design deficiencies that can contribute to containment loss, using data that is consistently available on a nationwide basis. There is a potential for misclassification in identifying well design deficiencies such as SPF, however most of the assumptions in our methodology are likely conservative (see SI table 2).

We relied on findings and recommendations by the ITF report on Natural Gas Storage Safety, the IFR, and the recent regulatory amendments applying to California’s UGS wells.

This assessment of UGS well deficiencies is limited in scope to original well design elements such as wells not designed for UGS and wells exhibiting limited passive barrier protections. The focus on wellbore integrity assessed here is in agreement with previous studies [11–15, 29]. Our attempt to identify initial well design and SPF designs are supported by previous studies [23, 30], the Interagency Task Force on Natural Gas Storage Safety [3], and the recent regulatory amendments applying to California’s UGS wells [21]. The pre-1979 well construction date as a proxy for single barrier design is supported by limited studies of well- and barrier-failures in certain locations [3, 23, 30]. Kell [30] showed that Ohio wells constructed prior to 1983 were more than twice as likely to leak (0.1%) compared to post-1983 wells with a failure rate of 0.035%. Similarly, in Texas, wells constructed before 1983 were five times more likely to leak (~0.02%) than wells constructed after 1983 (~0.004%) [30]. Though age alone does not pose a hazard if integrity is managed, further information on UGS well-level incidents is needed to assess UGS well age as a causal factor.

Our dataset contains nearly 5000 more active UGS wells than cited in the ITF report [3]. The source of this discrepancy is unclear, and is particularly apparent for OH, MI, WV, PA, and IA. Further, the methodology applied here likely underestimates the total number of active UGS wells because our estimate excludes: (1) wells with an unknown status that join to active storage fields; (2) wells not coded as ‘storage’ that may also be connected to storage formations (e.g. production/withdrawal only); and, (3) full storage-related well data from AK, TX, OK, and TN. Likewise, both the number of repurposed wells and the number of wells that that exhibit single barriers are likely underestimated due to the potential misinterpretation of completion date proxying for original well construction. Additionally, explicit well function was available for only 6483 active UGS wells limiting our ability to distinguish between active injection and monitoring wells that may explain a portion of the count discrepancy.

Studies are in progress to evaluate various aspects of the natural gas midstream infrastructure [31] and

Figure 7. (a) Active UGS wells by age and depth below surface categorized by likely initial well design. (b) Repurposed wells colored by select states only by age and depth below surface.
improve existing emissions estimates and source apportionment for natural gas production and storage activities [32]. While greater precision has been achieved in attributing atmospheric methane to oil and gas emissions and fugitive leaks [33–36], the GHG can be further improved by refining infrastructure and activity data from this sector [37]. This UGS database with identified uncertainties can improve characterization of both UGS field and well activity. With potential secondary and tertiary uses of subsurface reservoirs likely to increase in the future, data and results presented herein can inform hazard identification and risk assessments for geologic storage of CO$_2$, underground fluid disposal, and compressed air storage [17].

**Conclusion**

The natural gas leak at the Aliso Canyon facility highlights the immense hazard potential that a single UGS well can possess. We identified 2715 active UGS wells across the US that, like the failed well at Aliso Canyon, were not originally designed for gas storage. The 99% of repurposed wells constructed prior to 1979 are particularly likely to exhibit certain design deficiencies including single passive barrier protection. An estimated 210 active repurposed wells were constructed before 1917—before cement zonal isolation methods were utilized. These wells are located in PA, OH, NY, and WV and represent the highest priority related to potential design deficiencies that could lead to containment loss.

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