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Analysis of Occurrences at Underground Fuel Storage Facilities and Assessment of the Main Mechanisms Leading to Loss of Storage Integrity

Evans, David J.[1]
British Geological Survey, Keyworth, Nottingham, UK
Schultz, Richard A.[2]
Petroleum and Geosystems Engineering, The University of Texas at Austin, Austin, Texas, 78712 USA

ABSTRACT: Unintentional releases of natural gas to the surface or subsurface environment are recognized as a challenge to the safe and reliable operation of underground fuel storage facilities, including for natural gas. Previous studies have documented some of the occurrences at such facilities and assessed leakage or failure mechanisms along with their degree of severity, in part to inform risk-based assessments of subsurface geologic storage of fuels and wastes (such as carbon dioxide). This paper summarizes the past occurrences and several hundred others of varying severity (from nuisance/non-hazardous to catastrophic), that have occurred or earlier ones that have come to light since a previous study of Evans [1] was undertaken. Worldwide, these have occurred at facilities developed in salt cavern (~320), porous rocks (aquifer and depleted hydrocarbon field – ~40 and ~600 respectively), mined hard-rock cavern (~50) and storage facilities of as-yet to be determined type (~7). The present work includes categorizing the fuel type (natural gas, LPG, NGL's, crude oil), type, nature and severity of any leakage for both above ground and subsurface incidents, all of which provide key parameters to risk probability assessments.

Worldwide, a total of 1023 occurrences at underground fuel storage facilities are documented, of which 706 involve natural gas facilities. Of these, 63% can be attributed to subsurface causes (38% to well integrity, 25% to geological or subsurface integrity causes) and 36% to surface causes including pipeline and wellhead issues. It is important to note that not all involve product loss: only 588 occurrences are linked with migration or leakage of product, of which only 428 occurred to, or at, the surface. Together, the 1023 occurrences provide evidence of problems that do occur and which could contribute to a more serious occurrence and thus their recognition informs risk assessments. In the US, a total of 817 occurrences are documented, of which 538 are linked to migration/leakage of product, with 397 occurrences to, or at, the surface. Some 599 occurrences involved natural gas facilities. Of these, 59% can be attributed to subsurface causes (33% to well integrity, 26% to geological or subsurface integrity causes) and 38% to surface causes. In the US, the highest numbers of occurrences are found in California, Pennsylvania, and Texas, with product losses and related issues occurring in depleted oil and gas fields and in solution-mined salt cavern facilities.

1. INTRODUCTION

Natural gas (methane) has rapidly become a critically important component of US and other countries' economies, providing an important energy source for industrial, commercial, and electrical generation sectors as well as for residential heating (e.g. [2,3]). Natural gas has traditionally served the seasonal winter-heating market, but is increasingly being called upon to help meet shorter-term peak demand in the summer-cooling market as use for electrical generation increases and to provide a steady and reliable backup for renewable power, such as wind and solar, which are characterized by intermittent or variable supply [4]. Because the storage capacity in the above-ground pipeline network is insufficient to meet these demands, natural gas is stored in large underground facilities. Many fuels are stored in underground fuel storage (UFS) facilities and under-ground natural gas storage (UGS) form the majority of these storages, both in the US and throughout the world.

Based upon US Energy Information Administration (EIA) data (as of October, 2016: https://www.eia.gov/ dnav/ng/ng_stor_cap_dcu_NUS_a.htm), more than 400 UGS facili-

[1] Email: dje@bgs.ac.uk
[2] Email: oriongeo@gmail.com

Table 1. Numbers of UGS facilities worldwide and USA only (based upon IGU, 2006 and EIA (2016: https://www.eia.gov/dnav/ng/ng_stor_cap_dcu_NUS_a.htm).

Storage type	Worldwide (number, %age)	USA (number, %age)
Depleted field	454/75	329/79
Aquifer	87/14	47/11
Salt cavern	64/11	39/9
Abandoned mine	1/<1	–
Totals	607	381*

* USA totals exclude estimate for abandoned mines; data as of 2015

ties exist in the US, with an additional smaller number in Europe and elsewhere (**Table 1**). In the US, the majority (329, or 79%) of the 415 UGS facilities utilized depleted oil and gas fields; 47 (11%) occupied depleted ground-water aquifers, and 39 (9%) were in solution-mined mined salt caverns. Porous-rock (i.e., reservoir) storage thus represented 91% of UGS fields, with solution-mined salt caverns comprising the remainder. An additional number of UFS facilities are in converted hard-rock mines. Such storages, in addition to mined hard rock caverns and converted mines, provide an additional number of UFS facilities.

The identification and assessment of risks to product loss at UFS and UGS facilities lies at the heart of risk management programs that are currently being used and expanded throughout the storage industry. The Aliso Canyon blowout in southern California during winter 2015–2016 has focused national attention in the US on the safety and reliability of UGS facilities and has motivated new federal and state regulations that require risk management plans. Because risk is commonly considered to involve some combination of occurrence and likelihood of product leakage, having an accurate database of natural gas leakage occurrences constitutes a fundamental element of risk assessment (e.g. [5]).

The work reported in this paper aims to help inform the debates relating to safety and risks associated with UFS and UGS facilities. We have compiled a database comprising details of 1023 occurrences at UFS sites worldwide. These occurrences are documented in over 20 categories to aid ready analysis of differing categories or variables such as location, fuel type, cause, and severity. We present a summary of these data in this paper. In the future, more detailed statistical assessments are planned, from which it is anticipated that greater understanding of the main causal mechanisms and areas of risk will emerge.

2. BACKGROUND STUDIES

Over the years, individual incidents at underground fuel storage (UFS) sites have made local news or media reports (e.g. the 1973 Elk City, Oklahoma, LPG storage incident; [6]), some have appeared in safety authority reports (e.g. the NTSB 1992 Brenham salt cavern incident report), US State geological reports (Illinois aquifer storage sites; [7]) and others in the scientific literature (e.g. gas migration at the Beynes and St Illiers aquifer storages, France; [8,9]). Prior to the current work, a number of studies into the occurrence and frequency of the release of hydrocarbons from underground storage had been undertaken. Bérest [8,10] analyzed 10 'accidents' related to a variety of causes at mainly salt cavern storages, but also aquifer and mined rock facilities. In 1998, an ad hoc working group was established by Marcogaz[3] to exchange information and establish a database on, and define failure rates at, European underground gas storage operations. Its purpose was to "help to prove to the public and to national authorities the high safety level of UGS, to dissipate fears of people bordering UGS sites and to contribute to reducing the requirements of authorities by implementing the SEVESO II Directive[4] in each national Law system." The 'Marcogaz' study [11], identified incidents based upon criteria defining major accidents in Annex VI of the 1999 COMAH Directive[5], however, no sites were specifically identified. The study concluded:

- 6 accidents occurred due to surface processes over a cumulative period of 970 years, the probability for major accidents on surface facilities of UGS sites being calculated at $6x10^{-3}$ accident/year/site;

[3] Technical Association of the European Natural Gas Industry (http://www.marcogaz.org/)

[4] European Council Directive 96/82/EC of December 9, 1996 on the control of major accident hazards involving dangerous substances and is a European Union law aimed at improving the safety of sites containing large quantities of dangerous substances. Also known as the Seveso II Directive, after the Seveso disaster, it replaced the Seveso Directive and was itself modified by the Seveso III directive (2012/18/EU).

[5] The Control of Major Accident Hazards Regulations 1999 (COMAH) implemented the Seveso II Directive and came into force in Great Britain (GB) on April 1, 1999. Most recent revisions were made in 2015, which implement the majority of the Seveso III Directive (2012/18/EU) in GB.

- 5 accidents occurred due to faulty wells over a cumulative period of 100,155 years, the probability for major accidents on wells of UGS sites being calculated at $5x10^{-5}$ accident/year/well; and
- 1 accident occurred that resulted in severe injury due to well problems over a cumulated period of 100,155 years, the probability of major accidents resulting in severe injury on wells being calculated at $1x10^{-5}$ accident/year/well.

The Marcogaz European UGS study represents an important, but limited source of information. Except for two accidents causing injuries, all other cases of accidents were classified "major accident" because of the release of gas or material damage inside the UGS facility. The report claims there had been no deaths inside or outside a UGS facility, yet does not contain reference to the Ketzin incident for which one fatality is reported (N.J. Riley, 2007, pers. comm.; [1,12]).

In the mid-2000s, CO_2 storage investigations drew on experiences at underground gas storage facilities to assess safety and containment of potential storage sites. Key works at the time identifying storage incidents at both porous rock and salt cavern storage sites included [13,14,15]. In 2008 the UK Health and Safety Executive (HSE) commissioned a report on underground fuel storage incidents to inform land use planning, which documented 67 incidents or problems at UFS facilities, linked to differing causes [16]. This was followed by the study of Evans [1], which built on the HSE report and compared failure rates with other areas of the energy supply chain and was at the time, perhaps the most extensive survey of storage incidents, their causal mechanisms and mitigation strategies. Since then CCS studies and risk analyses have utilized these baseline studies from gas and other hydrocarbon storage facilities (e.g. [17,18]).

The values compiled by EIA and discussed above do not include the estimated 70 additional UGS facilities developed in mined hard-rock caverns and abandoned coal mines. A worldwide survey of underground mines re-purposed for oil and gas storage [97] lists eight abandoned mines that have been used for hydrocarbon storage [20] globally, including six mines in the US, that were used for hydrocarbon storage as of 1995 (their table 4). Of those eight mines, only three (one in the US and two in Belgium) were used to store natural gas from as early as 1961 [21,22]. These numbers may be low, as at least five more LNG gas storage facilities located in mined rock caverns were reported separately from Ohio alone, with gas leakage reported from one of these in 2013 [23]. A report to the US Department of Energy in 1998 [24] cited from an unpublished earlier study that as of 1991, a total of 1122 underground storage caverns were in operation in the US for LPG storage; of these, 70 were in hard-rock caverns and 1052 were in salt caverns.

Although wells constitute a fundamental risk element for integrity and product loss, the geological and geomechanical integrity of the reservoir in UGS facilities is also of primary concern [25]. Gas or liquids can escape confinement to their intended subsurface zone by means of multiple mechanisms including accessing faults and fracture sets [25,26], failure of confining zone sequences, and structural spill points. Failures of reservoir integrity and leakage of gas are well documented for all main types of gas storage facility (depleted oil and gas fields, aquifers, and salt), along with storage in abandoned mines [1,27,28,29]. Risk registers can be assessed and mitigated following practices developed in the oil and gas industry [30], geothermal [31,32], and carbon dioxide sequestration [33,34,35,18] industries, and these must be informed by accurate data on leakage mechanisms and rates. As discussed in the literature (e.g. [1]), leakage occurrences from UGS and UFS facilities have occurred through a number of causes. Many can be related to a loss of well integrity, whereas others can be attributed to a loss of subsurface integrity (such as caprock failure or salt movement) or operations (for example, procedures not followed). Many occurrences are related to multiple causes and not all leakage occurrences can be attributed solely to a loss of well integrity. In many cases, the facilities were operated according to established guidelines, while at others operators failed to follow procedures. In all cases the risk of leakage occurrences could potentially be reduced by improved guidelines for wells, geologic characterization, and operations.

In a study of porous-rock storage integrity, 22 leakage occurrences from a total of ~485 porosity-storage facilities worldwide could be attributed to natural gas leakage through the caprock/top-seal sequence, corresponding to about 10% of all reported leakage occurrences investigated in that study [17]. Of these, half were due solely to failure of the caprock/top-seal sequence itself, a quarter were due solely to undetected or incorrectly characterized faults or fractures in the sequence, and the remaining quarter were due to a combination of caprock failure and seal-bypass mechanisms.

In the wake of the massive Aliso Canyon, California blowout, new US federal regulations have been put into place for all US intrastate and interstate UGS facilities. The Interim Final Rule (IFR) released by the Pipeline and Hazardous Materials Safety Administration (PHMSA) in December 2016 [36] applied an initial set of common minimum standards (based on the American Petroleum Institute's [API] Recommended Practices RP 1170 and 1171) that all operators are expected to comply with. The goal of the new Federal regulations is to increase reliability of the combined pipeline and storage system. Leakage occurrences noted in the IFR include Hutchinson/Yaggy (2001), Moss Bluff (2004), and Aliso Canyon (2015–2016). The State of California has separately revised its regulations for its intrastate storage facilities in response to this occurrence.

As part of a US natural-gas industry initiative, the American Gas Association published a position paper [37] to accompany the pair of API RP 1170 and 1171 that were incorporated into the IFR. This "white paper" relates that unplanned releases of natural gas from underground storage wells, while rare, have indeed occurred. Porous-rock storage was considered but not natural gas storage in solution-mined salt caverns or mined caverns. On the basis of a literature search and an informal survey of operators that included nearly 14,000 wells contained in 226 fields, representing a sampling of over 80 percent of US natural gas storage wells, a total of 61 well-related leakage incidents were tabulated from 1950 through 2010, corresponding to an average of 10.2 per decade or nearly 1 per year. Of these, 15 (25%) involved injuries, 4 (7%) involved fatalities, and 21 (34%) inconvenienced the public through road closures, water supply replacements, building damage and evacuation of homes to some degree. Of the 51 occurrences that included an estimated length of time taken to resolve the incident, 23 were resolved within 1–2 days, 17 were resolved within a month, and 11 took longer than a month to resolve. Of all occurrences, about 33% were related to well interventions (e.g. testing, maintenance, or related work), 36% were downhole leaks, 11% were related to design or manufacturing defects, 8% were attributed to wellhead or gathering line issues, and 2% were of undisclosed origin. The industry white paper interprets a subset of these data (i.e. occurrences that occurred since 1990, corresponding to 27 or 44% of all occurrences listed, but also including the Aliso Canyon occurrence in 2015–2016, which took more than 3 months to resolve) as indicating that the likelihood of leakage occurrences in the future should be considered from a process safety perspective as "very unlikely," "extremely unlikely," or "remote." The data subset just referred to, with 28 leakage occurrences over a 15-year period, would average 11.2 occurrences per decade or 1.9 occurrences per year, corresponding to a somewhat higher incidence rate than was obtained by using the longer-term values. The industry interpretation of well-related leakage occurrences may be contrasted with the critical nature of such occurrences concluded, for example, by industry regulators such as PHMSA as noted in its IFR [36].

Clearly, all reports show that leakage occurrences and ultimately accidents do occur at underground natural gas storage facilities of all types and differing terminologies have been used to describe various occurrences. How-ever most commonly used is 'accidents', which carries undesirable connotations. As noted by Bérest [8], subsidence associated with salt cavern deformations (salt creep and closure) can, for example, be spectacular but such movements do not always affect the stability of the overlying ground or endanger lives. Bérest suggests therefore, that although such movements were not fully expected by the designers and they often had not inconsiderable impacts on the economics of the facilities, the word "accident" is something of a misnomer insofar as there may be no danger to persons or property from any particular occurrence or situation. For the purposes of this paper and to avoid any connotation or implication, the non-generic word 'occurrence' is used here when referring to underground storage events identified in the literature and discussed in this paper.

3. CURRENT WORK

Compiling accurate numbers for natural gas and hydrocarbon leakage is a challenging undertaking. Although some occurrences are well documented, others are known only anecdotally, as through media reports; many others may not be well documented if they were not publicized by operating companies, or constitute part of litigation documents. Nevertheless, the work reported here provides (to the authors' knowledge), the most current and comprehensive compilation of occurrences at storage facilities and their main root causes. As such, we believe that it provides the best foundation from which decisions and regulations regarding product loss rates from underground fuel, and in particular natural gas facilities, can be made. These data can also be used to inform the reliability of other subsurface sequestration efforts such as carbon dioxide (e.g. [17,18]).

Data relating to occurrences at UFS sites summarized and presented in this paper represent data in the public domain, compiled following exhaustive searches both online and in the scientific and safety literatures. Since the study by Evans [1], further occurrences have happened and most importantly, more information has become available online, though scanned reports and contemporary newspaper articles being made available. This work documents a total of 1023 occurrences at UFS and UGS facilities of very varying nature, cause and severity. Important to note is that a significant number do not involve leakage of product and an even smaller number involve leakage to, or at, surface (see below).

The database is constructed in such a way that if an occurrence involved more than one well or cavern, then it is recorded as an entry comprising the number of wells or caverns involved for that one site and problem. To illustrate this point, during a routine inspection of a storage well in March 2015, the operator of the Rough gas storage field in the UK (Centrica) identified a potential issue with well integrity. Importantly in this instance, no serious leakage of the wells was determined and no accident occurred. However, the situation resulted in an immediate reduction in operating pressure at the field and led to a reduction in working gas volume from 3.7 bcm (130.7 bcf) to 3.1 bcm (109.5 bcf) [38,39]. Rough is a depleted offshore gas field converted to natural gas storage operations in 1985 and has thus been operating for over 40 years. It was feared by the operator that the problem, linked to aging infrastructure, affected all Rough wells on the two platforms. The situation prompted a testing program of all wells, during which a 'containment envelope failure' in one well occurred at a lower pressure than expected. This prompted a full 42-day shutdown of the facility in June 2016, which was extended in July 2016, initially until March/April 2017, although since then some wells have been allowed limited withdrawal capacity over winter 2016. The testing revealed that 28 wells were operating at pressures higher (3500 psi) than originally certified (3000 psi). This case, therefore, is recorded as an identical entry for 28 wells, with the main cause being well integrity, but including a subsidiary category of operational issues (the gradual increase in storage pressures to those above which the wells were certified).

The current study provides the data with which to assess likely leakage mechanisms, main risks to storage integrity and the potential consequences of any storage failures. Occurrences of varying severity are found from storage types involving porous rocks (depleted hydrocarbon fields and aquifers), salt caverns, abandoned mines and mined rock caverns (non-salt). A sixth category comprises occurrences where the storage type is unconfirmed. A number of important incidents not previously mentioned in the scientific literature have been identified, demonstrating subsurface failure mechanisms and impacts on surface infrastructure. Importantly in some cases, mitigation measures are also available. The stored fuel type comprises natural gas, town gas (a legacy industry term for flammable gaseous fuel made from coal), ethylene, ethane, oil and HVL's (highly volatile liquids: including natural gas liquids and LPG) and empty (i.e. when not filled with product, but either at atmospheric pressure or filled with brine). A number of minor problems associated with one of the two operational salt cavern compressed air energy storage (CAES or CAS) facilities (Huntorf facility; [40]) are included, as they demonstrate problems which are also encountered at natural gas storages. Again where fuel type is unknown, these are recorded in a category unconfirmed.

Although many occurrences are linked to more than one cause, the main causal mechanism behind each occurrence is noted and assigned to one of six categories:

1. Subsurface/well integrity
2. Subsurface/caprock-reservoir integrity
3. Above-ground infrastructure – mechanical failure
4. Above-ground infrastructure – both
5. o Operational – e.g. at the Belle River storage facility where productivity decreased over time in several (at least 4) wells across field with operational problems rendering several 35 mmscfd wells inoperable; inspection of well sites revealed safety valve control lines had lost hydraulic pressure, resulting in 150 mmscfd lost deliverability from field [41], or

   o Human error (e.g. a serious gas leak at the Rough storage field in 1998, starting point of which was failure of a flange during maintenance work that was blamed on managerial mistakes [42]), and
6. 'Unconfirmed' cause.

The operational/human error categories are in fact often difficult to differentiate as many operational occurrences result from some sort of human error. The category 'subsurface/caprock-reservoir integrity' includes migration of stored product in the subsurface and covers a range of scenarios that can result in loss of storage integrity and product in the subsurface, but which does but not necessarily involve loss of caprock integrity. It may or may not lead to leakage to surface. In the case of depleted fields or aquifers, this can involve:

- Migration laterally into (or out of) areas of the trapping structure not previously considered, or into adjoining fields due to lateral reservoir connections. This could be through

  o Poor understanding of the reservoir as in e.g. the Sabinsville, Pennsylvania, USA, Shirley storage field, West Virginia, USA and Žukov, Czech Republic depleted storage fields [43,44,45] respectively and in some aquifer storages, including the Gourney-sur-Aronde gas storage in France, where injected gas preferentially migrated to the southeastern and northwest limbs of the anticlinal trap [9,46].

  o Operational issues such as the operation of storage reservoirs at pressures that cause previously unanticipated gas migration into distant regions of the structure, but which in the case of e.g. the Lansing Storage Field did not involve leakage to surface. Migration arose due to periods of prolonged high pressure when less gas was withdrawn than anticipated. This led to gas being driven into regions of the reservoir with lower permeability and/or porosities [47]. In such cases, recovery of the storage gas is difficult and may involve complete loss, or operating at lower pressures to permit remigration back into the main area of the reservoir. In the case of the Downs storage field, Pennsylvania, leakage at surface was deemed to have arisen due to storage pressures being too high. Original discovery pressure of field was 1760 psi in discovery well LW #14, but from start of injection in well LW #19 on May 16, 1975 to June 13, 1975, 270 mcf gas injected at shut-in pressure of 3004 psi, which caused leakage from the field (A. Theodos, pers. comm. 2015).

- Migration out of storage area or into deeper and/or shallower reservoirs either via faults (e.g. the Dunajovice storage field, Czech Republic; [46]), poor caprock seals (e.g. the Pleasant Creek storage field, California, USA, Cunningham storage field, Kansas, USA and Hrušky storage field, Czech Republic; [45,48,49,50]), or wells, within the same storage field (e.g. the Tioga storage field, Pennsylvania, USA; [51,52]), or involving adjacent fields due to lateral continuity of the reservoir (e.g. the Žukov storage field; [45]). An end-member of this category is the example from Leidy Field (Pennsylvania, USA) in 1969 (A. Theodos, 2008 pers. comm.; [1]). Gas initially migrated from storage via five storage wells at 850 m3 (30,000 ft3) per day and later from 13 other wells. This led to a high-pressure build-up of gas in sandstones at shallower levels that caused fracturing of the rock over several square miles and led to the severing of casing in 30 other wells. Extensive surface blowouts in gas and water wells occurred, with gas continuing to escape for up to six weeks. Wells vented up to 56,634 m3 (2 mcf) per day and an estimated 113.3 mcm (4 bcf) of gas was ultimately lost until pressures were reduced and down-hole plugs were set in wells.

In the case of salt caverns and abandoned mines/mined rock caverns, 'subsurface/caprock' also includes loss of cavern/void integrity, where the void is compromised either through:

- Migration of stored product and/or water from caverns in non-salt rocks, as e.g. at the Demopolis propane storage facility [10], the Marcus Hook refinery, Pennsylvania USA (when faulty moni-toring led to too much propane being pumped into a cavern which leaked into basements nearby; [53]), the Todhunter Propane Terminal, Middleton, Ohio, USA [23] and the Kajaani oil storage facility in Finland [54].

- Spalling from the walls or roof areas

  o most commonly found in salt caverns of the US Strategic Petroleum Reserve (SPR) salt cavern storages (e.g. [55,56,57]; see below), but has occurred in other salt cavern storage facilities, e.g. at the Loop storage facility, west Texas, where a 60 m roof collapse occurred [58],

  o but also includes rock fall problems reported in mined HVL cavern storages in non-salt rock caverns in e.g. the Jinzhou oil storage in China [59] and the Elgas LPG storage cavern facility in Australia [60,61];

- Major inflows of groundwater due to intersecting regions of poor rock quality, which required major bolting and/or grouting, e.g. at the Padur Strategic oil storage, India [62].

- Collapse of the cavern either during

  o construction, where poor site characterization is often linked to the problem, as is uncontrolled leaching. At Bayou Choctaw (Louisiana) a cavern failed due to uncontrolled leaching that led to collapse of overburden into the developing cavern. Problems were experienced at Clovelly and Napoleonville (Louisiana), due to insufficient site characterization, with caverns being constructed too close to the edge of a salt dome and encountering 'host rock' in the cavern walls. In 2003, storage authority was rescinded for four caverns at the Mont Belvieu Cavern LLC facility due to their outer walls being too close to the salt dome edge [63].

  o during operation and which may be linked to uncontrolled leaching, as in the case of the failure in 1995 at Mineola, East Texas (USA), which resulted from communication between two caverns and led to a major release of propane [64,65]. The storage facility was operated in brine compensation mode and failure occurred partly as a result of (undetected) dis-solution of the intervening salt cavern wall during the injection of undersaturated brine accompanying each cavern's emptying-filling cycle. The accident resulted from human error on a number of counts:

    - firstly, enlargement of the caverns and a narrowing of the intervening salt wall by the injected brine that went unnoticed, which led to errors in storage volumes and metering of the LPG volume;
    - secondly, one cavern was held at much lower pressure than the adjoining one, which contributed to pressure induced failure of the thinned intervening cavern wall; and
    - thirdly, failure to re-open a safety valve

Table 2. Severity rating of underground fuel storage occurrences applied in this study.

Severity	Category	Description
1	***Insignificant/nuisance***	operational issues that were easily rectified or repaired, not involving leakage of product fire/explosion/blowout, injury, evacuees, fatalities or leading to financial losses
2	***Minor/ disruptive***	issues including minor/small leakages/surface release, cavern instabilities that were rectified or repaired, vapour flash, but no real financial loss, fire/explosion/blowout, injury, evacuees or fatalities
3	***Moderate (1)***	issues including substantial losses through subsurface leakages, but not involving surface release, leading to financial losses, but no fire/explosion/blowout, injury, evacuees or fatalities
4	***Moderate (2)***	issues including substantial operating problems (including shut-down, closure of caverns &/or loss of roof salt) or substantial losses through subsurface leakages, involving surface release, gas in observation or water wells, or pipeline leakages, leading to financial losses, ± fire/explosion/blowout, but no injury, evacuees or fatalities
5	***Significant***	issues including significant leakages/losses and surface release, fire/explosion/blowout leading to financial losses, minor numbers of injured/injuries (1–5), but no evacuees, fatalities or serious property damage
6	***Serious***	issues mainly involving significant surface release, fire/explosion/blowout, greater number of injured/serious injury (5–10), evacuees (<50) and/or serious property damage/financial losses but no fatalities
7	***Major***	issues mainly involving large-scale surface release through well or surface pipelines, ± fire/explosion/blowout, high numbers of evacuees (50–500), large number of injured/serious injury (10–15) and/or significant property damage/financial losses, but no fatalities
8	***Catastrophic***	issues mainly involving devastating surface release at facility through well or surface pipelines, fire/explosion/blowout, cratering, fatalities, high number of injured (>15) and/or evacuees (>500) and major property damage/financial losses

monitoring wellhead pressure and poor design of the gas detection system.

From the descriptions available, the individual occurrences are also graded in terms of severity using a rating of one to eight: one being insignificant/nuisance, eight being catastrophic (**Table 2**). We have adopted the 1–8 scale as we believe it undoes some of the range compression noted in scales limited to 1–5 that are commonly used in risk-management approaches such as risk matrices [5,66].

Category 1 occurrences (insignificant/nuisance) involve no leakage or ultimately any real hazard. They include, for example, reported problems with corrosion of three 1-inch siphon pipes that inject biocide to counter bacteria-causing corrosion and which had entered a pipeline at the Huntingburg storage field [67], and a brush fire that broke out at Aliso Canyon in October 2016, but for which ultimately structures were not threatened by the fire and no injuries were reported [68]. They are included firstly to illustrate a problem, some of which could develop and potentially cause or contribute to more serious operational problems at facilities in the future, and secondly to ensure that all problems encountered are represented for reasons of impartiality and to avoid skewing of the data. Category 2 occurrences (minor/disruptive) include the majority of the 229 very minor non-hazardous leaks and problems reported associated with depleted field storage sites in California between October 26, 2015 and February 5, 2016 (**Table 3**). These came to light only as a result of inspections ordered on January 26, 2016 by the California Public Utilities Commission's (CPUC) Safety and Enforcement Division (SED) following the Aliso Canyon incident in October 2015. The CPUC directed all California natural gas storage operators to immediately inspect all natural gas storage facilities for leaks and report the information to the State (the SED employed its own classification rating/grading off leaks – **Table 3**). Of the 229 leaks reported, 95% percent (218) were non-hazardous and required only minor responses such as tightening or lubricating valves. Eight were "Grade 1", meaning that they potentially posed a safety hazard. Those eight leaks have been addressed: six leaks were repaired and two leaks no longer existed because related wellhead components no longer held gas (although components must be repaired before gas is reintroduced).

Incidents noted as primary motivation for the US federal and California regulatory changes in 2016 such as Brenham (1993), Hutchinson/Yaggy (2001), Moss Bluff

Table 3. California Public Utilities Commission's (CPUC) SED January 2016 Leak Survey Directive – Summary Results, March 2016 (based upon CPUC [69]).

Facility	Operator	Leaks Found	Leaks Repaired	SED Classification	Location of Leak	Remedial Actions
Aliso Canyon	SoCalGas	66	66	Minor non-hazardous	Above ground	Tightening, adjustment, lubrication or replacement of parts or piping.
La Goleta	SoCalGas	17	17	Minor non-hazardous	Above ground	Tightening, adjustment, lubrication or replacement of parts or piping.
Honor Rancho	SoCalGas	1	1	Non minor non-hazardous	Above ground	Tightening, adjustment, lubrication or replacement of parts or piping.
		13	13	Minor non-hazardous	Above ground	Tightening, adjustment, lubrication or replacement of parts or piping.
Playa Del Rey	SoCalGas	3	3	Minor non-hazardous	Above ground	Tightening, adjustment, lubrication or replacement of parts or piping.
Montebello	SoCalGas	6	6	Minor non-hazardous	Above ground	Tightening, adjustment, lubrication or replacement of parts or piping.
Wild Goose Storage	Wild Goose Storage Inc.	27	21	3 (High priority) 8 (Medium priority) 16 (Low priority)	All above ground	21 leaks repaired and corrective actions begun to address remaining six leaks but final repair had not been completed by March 2016.
Lodi	Lodi Gas Storage LLC	0	0	Not applicable	Not applicable	Not applicable
Central Valley Gas Storage	Central Valley Gas Storage LLC	2	2	Grade 3	Above ground	Repaired on 2/4/16 and 2/5/16
Gill Ranch Storage	Gill Ranch Storage LLC	10	1	1 (Grade 2) 9 (Grade 3)	Above ground	Grade 2 leak was repaired 2/9/16. Grade 3 leaks were scheduled to be repaired within 60 days.
Los Medanos	PG&E	23	23	8 (Grade 1) 18 (Grade 2) 58 (Grade 3)	Above ground	Seven leaks were awaiting remedial action. PG&E completed remediation of 17 leaks of the 24 leaks as of 3/6/2016. The remaining 2 Grade 1 leaks had blown down and were not leaking at time of report, but required assistance from third party vendor to complete the repair.
Pleasant Creek	PG&E	29	29		Above ground	
McDonald Island	PG&E	32	25		23 (Above ground) 1 (Below ground)	
Totals		229				

(2004) and Aliso Canyon (2015) fall into Category 8: catastrophic, involving major product loss, damage, high numbers of evacuees, injuries but including fatalities (any fatality results in a level 8 rating). In between categories 1 and 8, the ratings are based on escalating problems reported and increasingly related to migration of product, its release to surface and the impact any leak had on above ground infrastructure and people. A number of occurrences involving subsurface migration into areas of depleted gas fields and which did not result in surface release but required applications to expand existing field boundaries are classed as Category 3: moderate (1). Such occurrences include the storage fields Alden [70,71], Colony-Welda [72], East Cheyenne/West Peetz, Weaver and Victory [73,74], Epps [75] (Coleman, 1992), West Unionville [76] and Huntsman-West Engelland [77] storage fields. On occasion the migration of gas in the subsurface has led to production of storage gas in adjacent fields: so-called 'corner shooters' of Jahns [78]. This type of migration of gas has also led to overpressuring of wells and surface compressors and/or pipelines in adjacent producing fields, causing shut-ins, at e.g. the Colony-Welda Field [79]. These occurrences merit a severity rating of 4: Moderate (2), as they involve migration from the storage horizon to both deeper and shallower reservoir levels, and from there to infrastructure and/or surface, but did not lead to serious product escape, blowouts, fires or casualties (e.g. Illinois aquifer storage leakages [7,80]; leakage at the Waseca-Waterville aquifer storage, Minnesota, USA in the 1970s [75] and in 2001, communication between a fuel storage cavern and a brine cavern at Spindletop [63]).

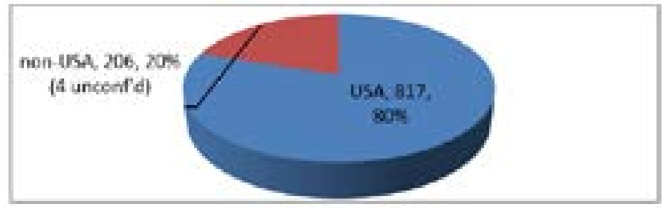
The previously cited Leidy depleted oilfield incident is from this family of occurrences, and despite major product loss is included as Category 4 only because it did not, on current limited evidence and given the date (1969), involve evacuees, injuries or fatalities. Categories 5–7 involve differing levels of loss, damage, number of evacuees, injuries or fatalities associated with any particular occurrence. They include (refer also Evans [1]): Category 5 (Cairo Gas Storage facility, Iowa, USA – 1981, two blasts on feeder pipelines carrying gas to injection wellheads [81] and 1989 well blowout at Karlshamn LPG mined rock storage facility, Sweden [82]), Category 6 (2003 salt cavern well leaks, Magnolia gas storage facility, Louisiana, USA, [83] and 2014 salt cavern well leak, Prud'homme natural gas storage facility, Canada [84]), Category 7 (2010 salt cavern failure/loss of integrity and leakage to surface near wells, Eminence storage field, Mississippi, USA [85], 1980 salt cavern well, Mont Belvieu storage facility, Texas, USA [86] and 1953 aquifer storage leak [caprock], Herscher storage field, Illinois [7]). Major Category 8 incidents are already referred to elsewhere in this paper.

For the purposes of this paper, the following sections summarize the occurrences by country (USA [undivided] and non-USA), and USA occurrences, by US State, with a further breakdown for natural gas only.

4. OCCURRENCES: WORLDWIDE AND ALL FUEL TYPES

The number of occurrences worldwide total 1023 of which the majority are from the USA (817/80%; **Fig. 1a**). These occurrences have been found to occur from as early as the 1940s (Playa del Rey in California; [87,88]), to very recently: Aliso Canyon in 2015 and at the UK Rough gas storage facility in 2016.

Non-USA occurrences number 158 in Europe, with 44 from other countries (**Fig. 1b**). Albeit skewed somewhat by the checks required following the Aliso Canyon incident, occurrences are most prevalent in depleted oil and gas fields, be it in the USA or overall (603 or 59% of all documented occurrences; Fig. 2a-c), being almost twice that of the next most common storage type (salt caverns: 322 or 31%; **Fig. 2a**).



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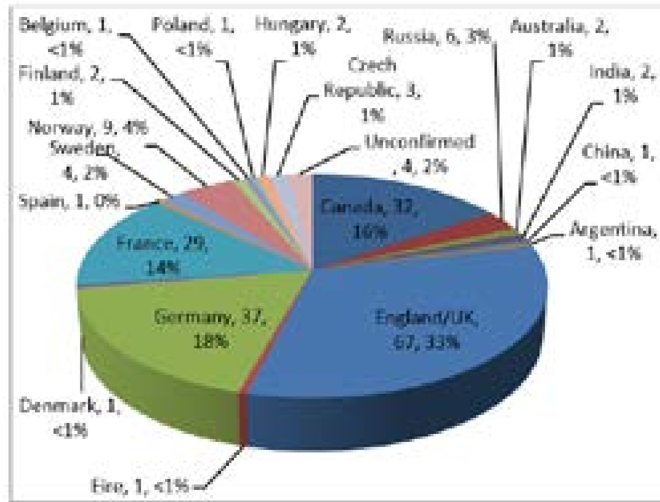


b

Fig. 1. UFS occurrences by country. a) USA and non-USA undivided (n = 1023), b) breakdown for non-USA occurrences, by country (n = 206, including 4 unconfirmed).

Comparing these all fuel figures to the number of UGS facility types worldwide, it can be seen that 59% of occurrences at depleted fields compares with such facilities comprising approximately 75% of UGS facilities worldwide (**Table 1**, **Fig. 2a**). For aquifers the comparison is 4% and 14%, and for salt caverns 31% and 11%. It thus appears that for UFS, salt caverns have an occurrence rate above their percentage share of UGS facility numbers, both worldwide and in the USA (**Figs. 2b** and **c**).

Looking at occurrences by fuel type (**Fig. 3**), worldwide natural gas is the most common stored fuel involved (706 or 69% of the occurrences; **Fig. 3a**), with HVL's (181/18%) and oil (107/11%) storages making up the majority of the remaining cases. Gas is also most common by USA or non-USA countries (**Figs 3b** and **c**).

Figure 4 illustrates the breakdown of occurrences in terms of the severity for the USA (undivided) and non-USA facilities. The most common level of severity is Category 2 (minor/disruptive; 436/43% of occurrences) which, as noted above and as illustrated by US numbers in **Figure 4b** (383/47% of occurrences), reflects largely the 229 minor and non-hazardous leaks found during checks ordered by the CPUC post-the 2015 Aliso Canyon incident. Without those examples, Category 4 occurrences would represent the most common

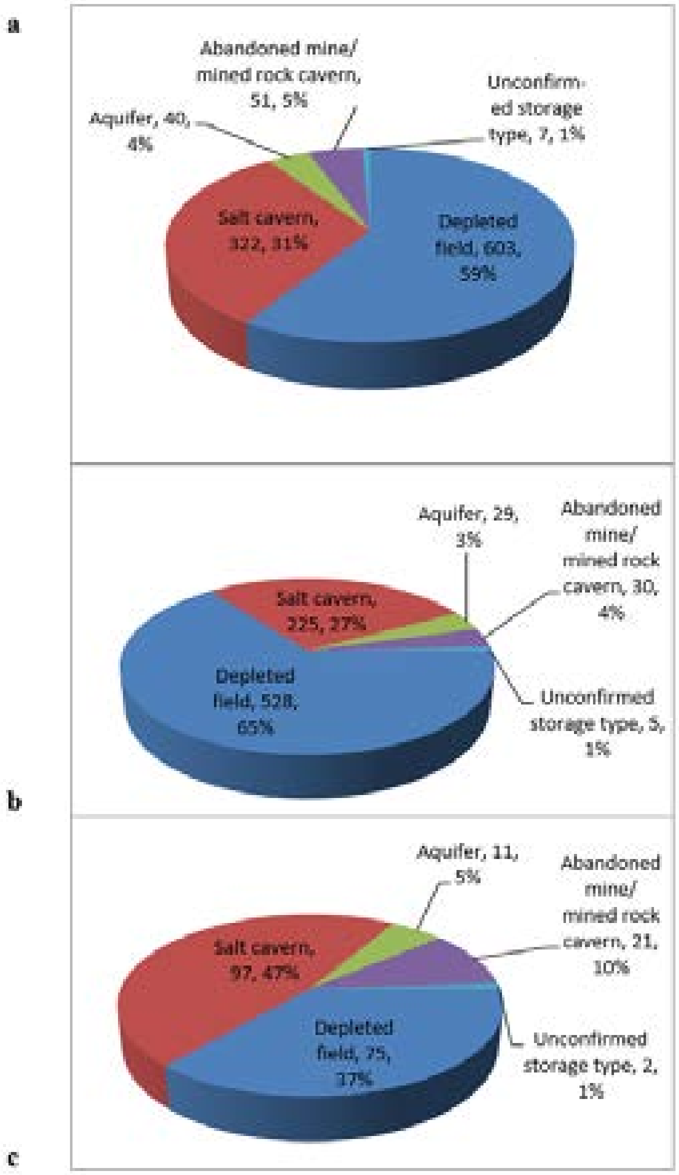


Fig. 2. Breakdown of worldwide occurrences by storage type (totals 1023). a) occurrence by storage type worldwide – USA and non-USA undivided, b) occurrence by storage type USA (undivided), c) occurrence by storage type, non-USA.

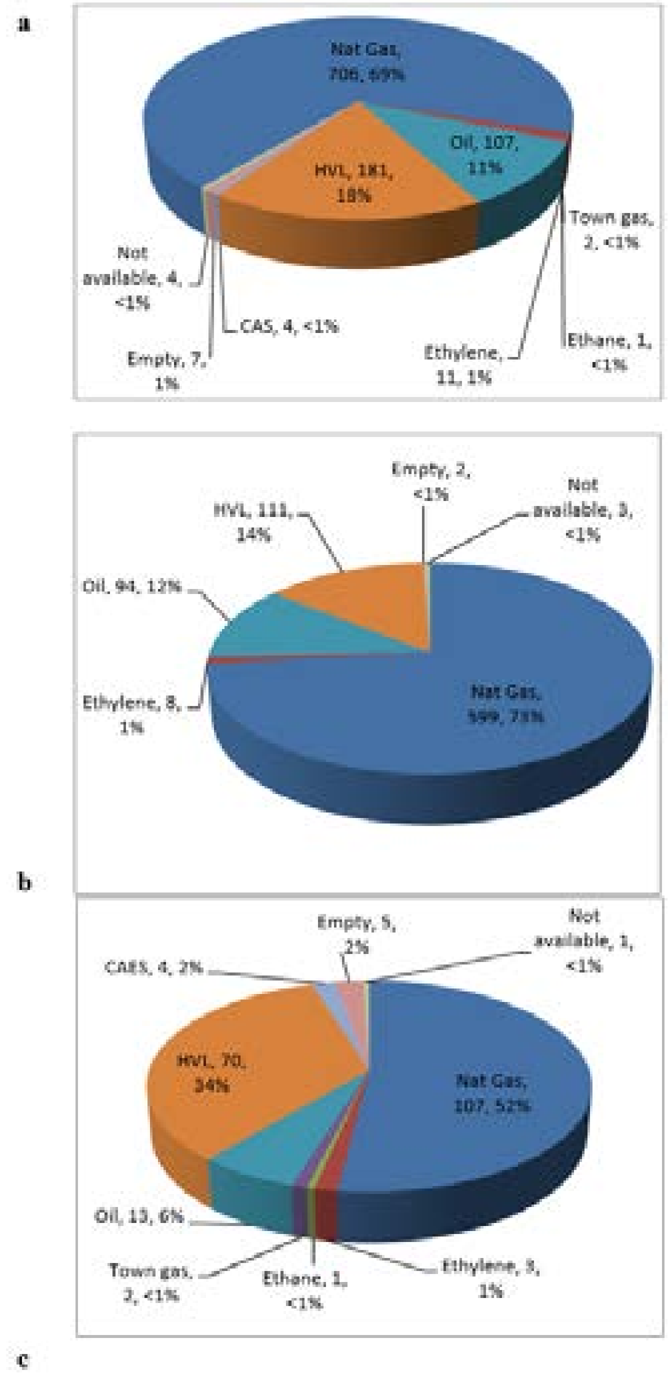


Fig. 3. Breakdown of occurrences by fuel type (totals 1023, includes compressed air [CAES]). a) occurrence by fuel type worldwide – USA and non-USA undivided, b) occurrence by fuel type USA (undivided), c) occurrence by fuel/energy type, non-USA (undivided).

group and be in-line with the non-USA (**Figs. 4b** and **c**). Major and catastrophic occurrences account for 38 (~4%) of the 1023 occurrences at UFS facilities. Occurrences rated as severity category 1 occurrences (insignificant/nuisance and not involving leakage) total 118 (~11%) of the occurrences.

Occurrence by storage type and severity (**Fig. 5**) reveals salt caverns to have the highest number of Category 7 and 8 occurrences (9 and 14 respectively; **Fig. 5c)**. The greatest number of Category 2 occurrences (326), occur in depleted fields (**Fig. 5a**) and again, this is strongly influenced by the 229 minor and non-hazardous leaks found during post-2015 Aliso Canyon checks. Depleted fields also provide the greatest number of Category 3 severity occurrences (326).

The number and breakdown of fuel stored versus severity of occurrence are illustrated in Figure 6 for the three main fuel types. This figure clearly reveals that occurrences involving natural gas far outweigh other stored fuel types (706 of 1023 occurrences documented; **Fig. 6a**). Despite this, in terms of severity, HVL's (including ethylene and ethane) have been associated with 20 a

b

c

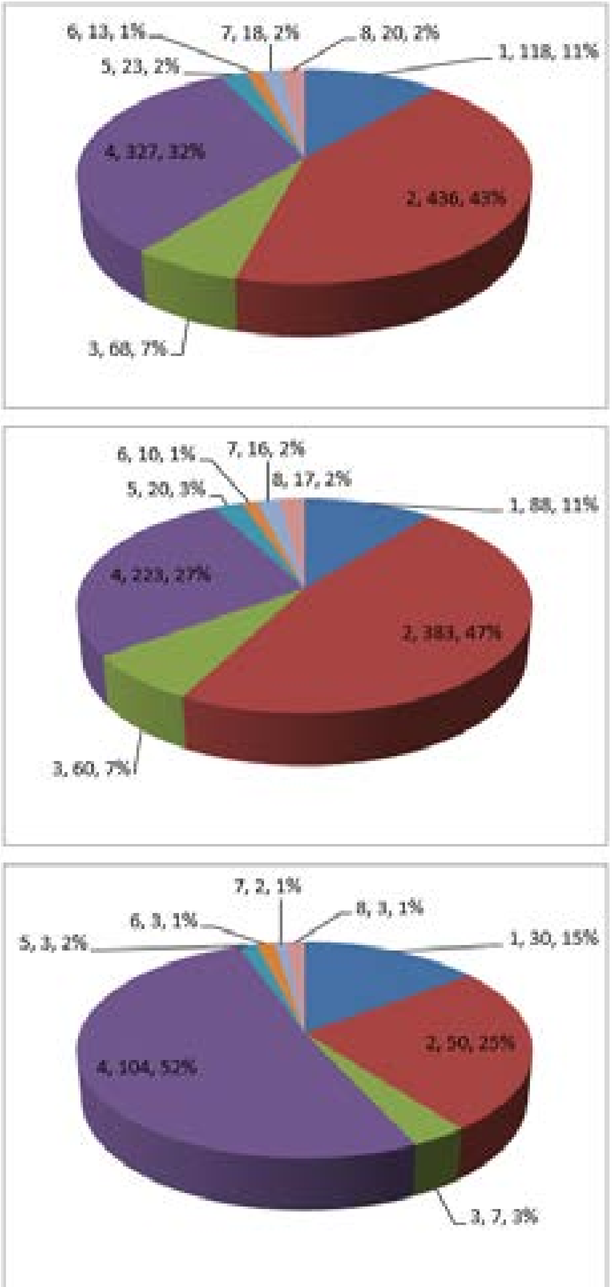


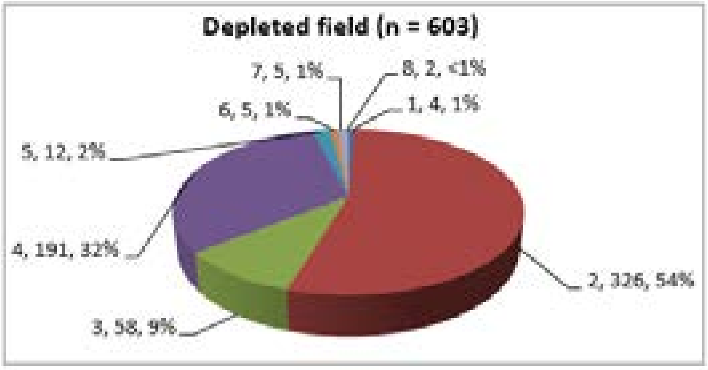
Fig. 4. Diagrams illustrating breakdown of occurrences, worldwide, by severity (categories 1 [insignificant/nuisance] to 8 [catastrophic]). Number and percentage of each category, shown as [category of severity, number, percentage]. a) figures, worldwide – and USA (undivided), including four occurrences of unconfirmed country, b) figures for the USA, undivided (*n* = 817), c) figures for non-USA (undivided, *n* = 202; excluding unconfirmed [*n* = 4]).

occurrences of category 7 (10) or 8 (10) levels (**Fig. 6c**). Whereas natural gas has been associated with only 15 major occurrences of category 7 (8) and 8 (7) level, with only three category 8 occurrences (no category 7) during oil storage (**Fig. 6b**). The latter has the most number of category 1 occurrences, largely reflecting the problems encountered with hanging strings in the US Strategic Petroleum Reserve (SPR) salt cavern storages and with which no leakage occurred (e.g. [55,56,57]).

Figure 7 illustrates the breakdown of evacuees, injuries and fatalities by storage type. Whilst the greatest number of fatalities at any one single release incident was in 1969 at the Ranson depleted gasfield storage site, Pennsylvania, USA (four dead, seven injured; [89]; A. Theodos, pers. comm. 2008, 2015), salt cavern storage is associated with the greatest number of casualties (16/57% of total fatalities, 76/61% of total injured). However, two of these fatalities were not related to storage operations or product leakage: one occurred during construction (Aldbrough, UK, 2005; [90]) and a second in September 2011 when elevated pipes were struck during grass cutting operations at the cavern 5 site of the Bryan Mound SPR, Texas [91]. They are included for completeness and to illustrate process failures that could potentially have led to more serious incidents, particularly in the case of Bryan Mound.

Salt caverns are also associated with the greatest number of Category 7 (9) and 8 (14) severity occurrences (**Fig. 5**), albeit two of Category 8, were not directly storage/leakage or operations related. Whilst numbers are small, this indicates that salt cavern storage carries increased risk, perhaps reflecting more the single point failure mode and higher stored product release rates that can form locally high concentrations of released product in the form of gas clouds, e.g. the 1993 Brenham incident. Since 2009, four Category 7 or 8 severity incidents at mined (non-salt) rock caverns have come to light: at the Todhunter terminal, Ohio, USA (2005, HVL and related to above ground operational issues, with one fatality; [92]); the Marcus Hook Refinery, Pennsylvania, USA (1978, HVL and related to subsurface storage integrity linked with operational issues – overfilling; [53]); the Mid American Pipeline Company, Iowa, USA (1975, HVL and related to above ground infrastructure when a chiller unit used to cool the HVL before storage failed, releasing HVL's that ignited, killing two employees and injuring three others; [93,94]); the Padur oil storage, India (2013, oil and subsurface integrity [rock falls, with one fatality] during construction and not during storage operations; [62]).

The breakdown of occurrences by cause illustrates the most common causal mechanism in UFS results from loss of subsurface well integrity (385 or 38% of occurrences; **Fig. 8**). The numbers involving subsurface integrity is also a significant category (259, 25%) and together, the subsurface is linked to 644 (63%) of the occurrences. Above ground surface infrastructure, operational and human error are detailed as the main cause in 370 (36%) of the occurrences, suggesting that the subsurface environment and associated infrastructure represents an important area of consideration during any risk assessment or analysis.



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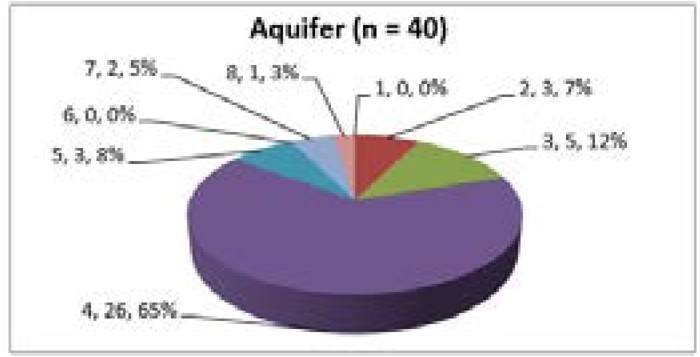

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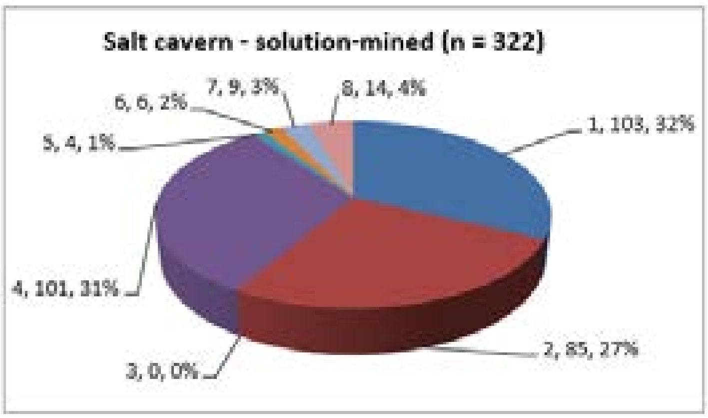

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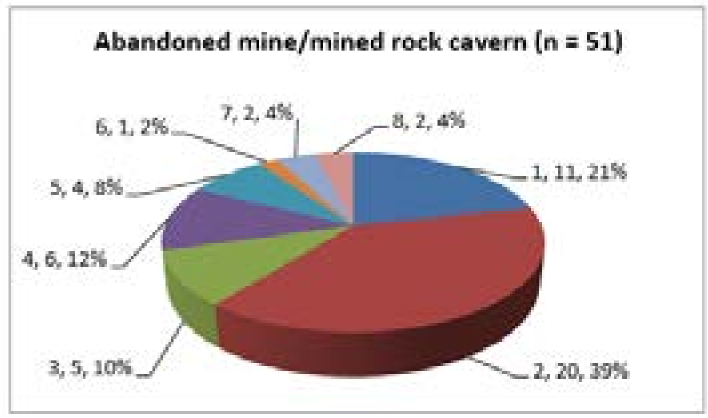

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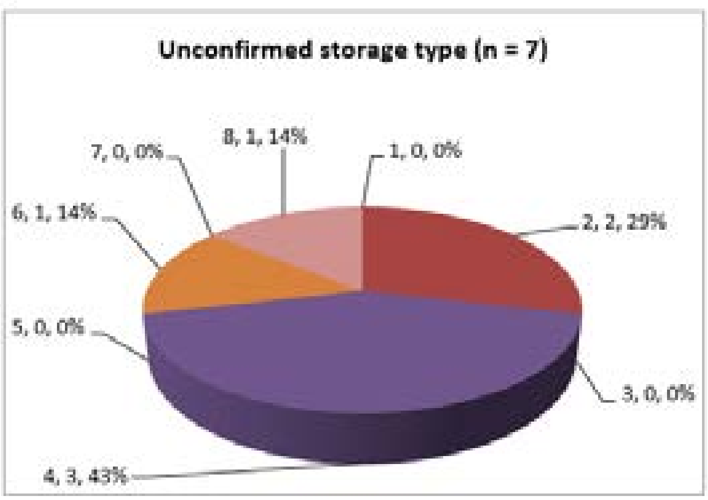

e

Fig. 5. Breakdown of storage type, worldwide by severity (categories 1 [insignificant/ nuisance] to 8 [catastrophic]). Number for each category shown in order: severity category, number, percentage. a) depleted field, b) aquifer, c) salt cavern, d) abandoned mine/mined rock cavern, e) unconfirmed storage type.

One newly discovered Category 8 incident involving HVL's reveals how one subsurface release of product can lead to another mechanism, escalating an incident. Leaks from caverns via wells at the Petal underground HVL ('alkyfeed') storage facility, Mississippi, USA, caused an explosion, massive fire and created a large crater (J.R. Craddock, pers. comm. 2017). The incident led to fracturing of a shallow pipeline above the crater, which caused the release of more HVL (propane) from the pipeline that was feeding a Delta Underground Storage Company cavern, which was being filled at the time. The pipeline release contributed to a major Category 7 or 8 accident in its own right. To add to the severity of the incident, hydrocarbons contained within several LP trailer transports and a gasoline tanker, which was dragged into the crater, also fueled the fire. The incident led to 14 injured (burns) and ~200 evacuated. Incredibly, no fatalities were reported. The whole incident clearly illustrates the close ties and potential dangers of storage facilities and their intimately related infrastructure. Such accidents might serve as examples of how above-ground infrastructure could be designed and constructed differently to avoid similar major incidents in the future.

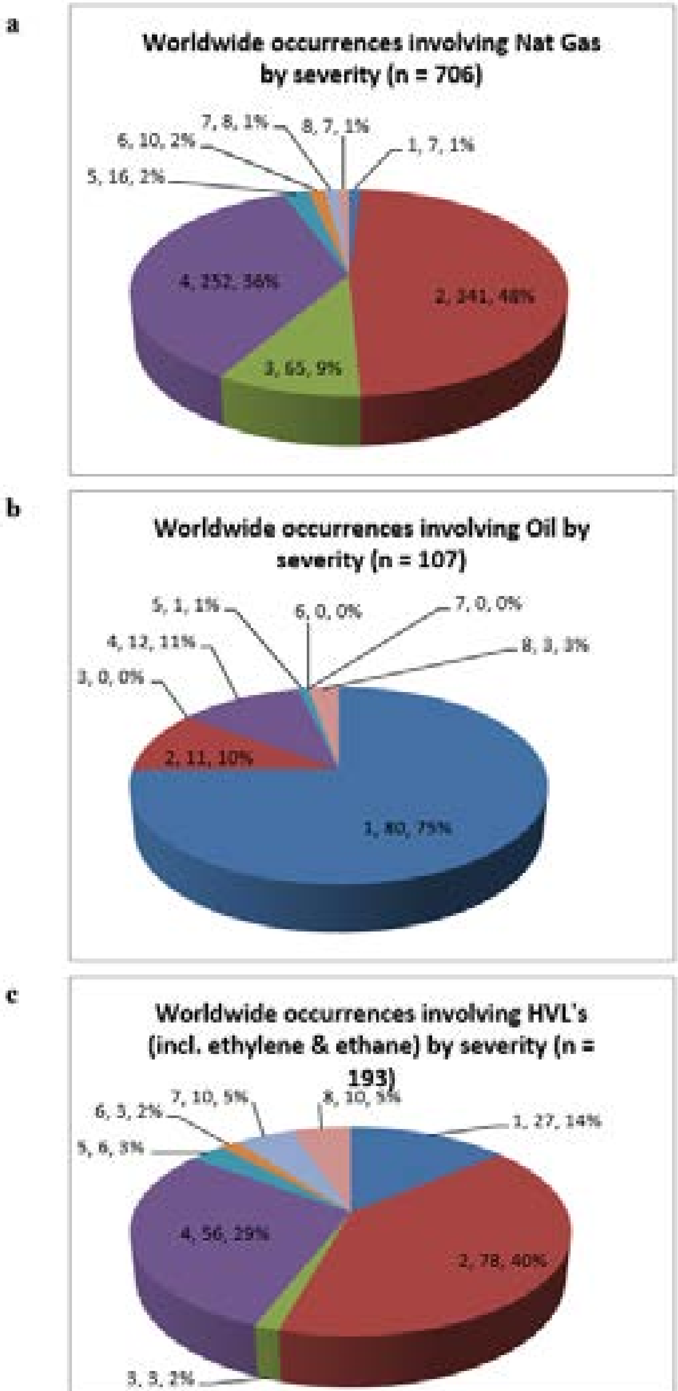

Fig. 6. Breakdown of stored product by severity (categories 1 [insignificant/nuisance] to 8 [catastrophic]). Number for each category shown in order: severity category, number, percentage. Note: not shown Town Gas ($n = 2$), CAS ($n = 4$), empty cavern ($n = 7$) or unconfirmed ($n = 4$).

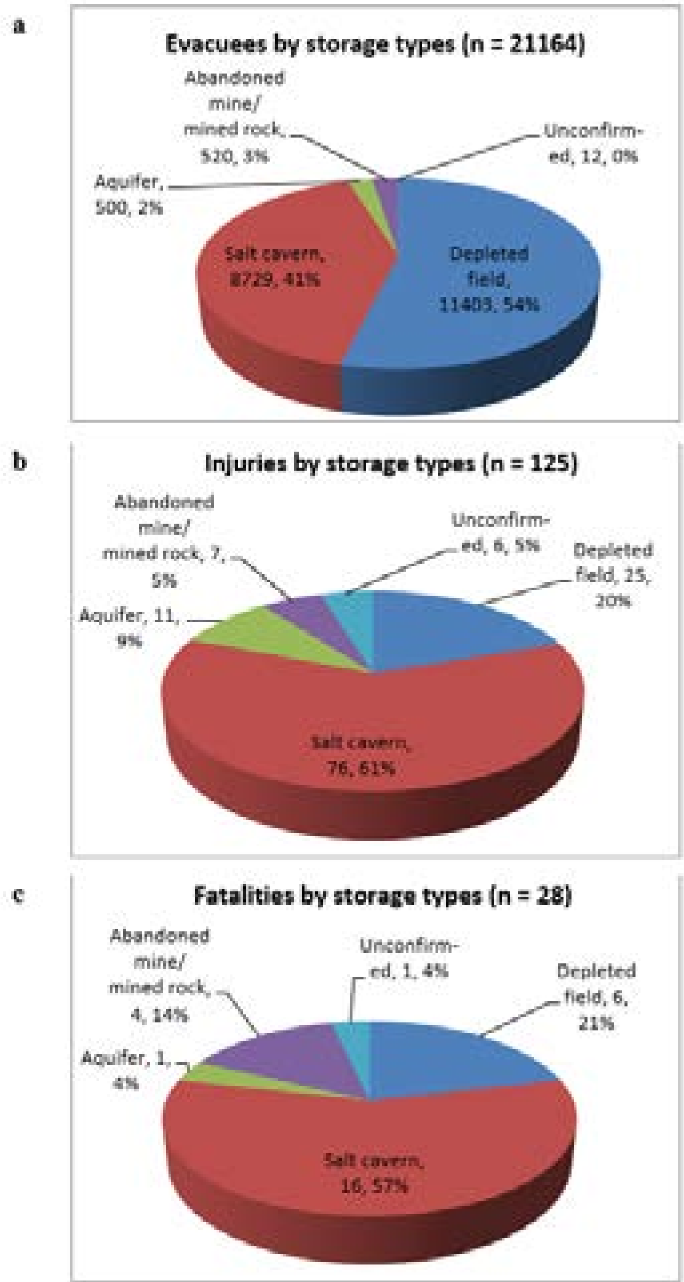

Fig. 7. Breakdown of the numbers, worldwide, for evacuees, injuries and fatalities arising from occurrences at the differing storage types. Refer also Tables 5 and 8 for figures relating to USA only. Note: fatalities include three deaths not related to storage activities (two during construction at the Aldbrough (UK) and Padur storages and one at the Bryan Mound SPR, but are included for completeness).

Table 5 illustrates the numbers of worldwide occurrences linked with migration or leakage of product in the subsurface (588), and those occurrences linked with product leakage to, or at, the surface (428). Of these leakages, 93 were accompanied by a fire, with 81 involving a fire and explosion.

5. OCCURRENCES: USA

The previous section introduced worldwide data for the various storage, fuel type, degree of severity and failure types, including for the USA as a whole. In this section we present a summary of occurrences by US State, focusing mainly on those associated with natural gas storage. As detailed above, the total number of occurrences in the USA, for all fuel types found to date is 817 (Tables 4 and 5), with the highest occurrences being from the

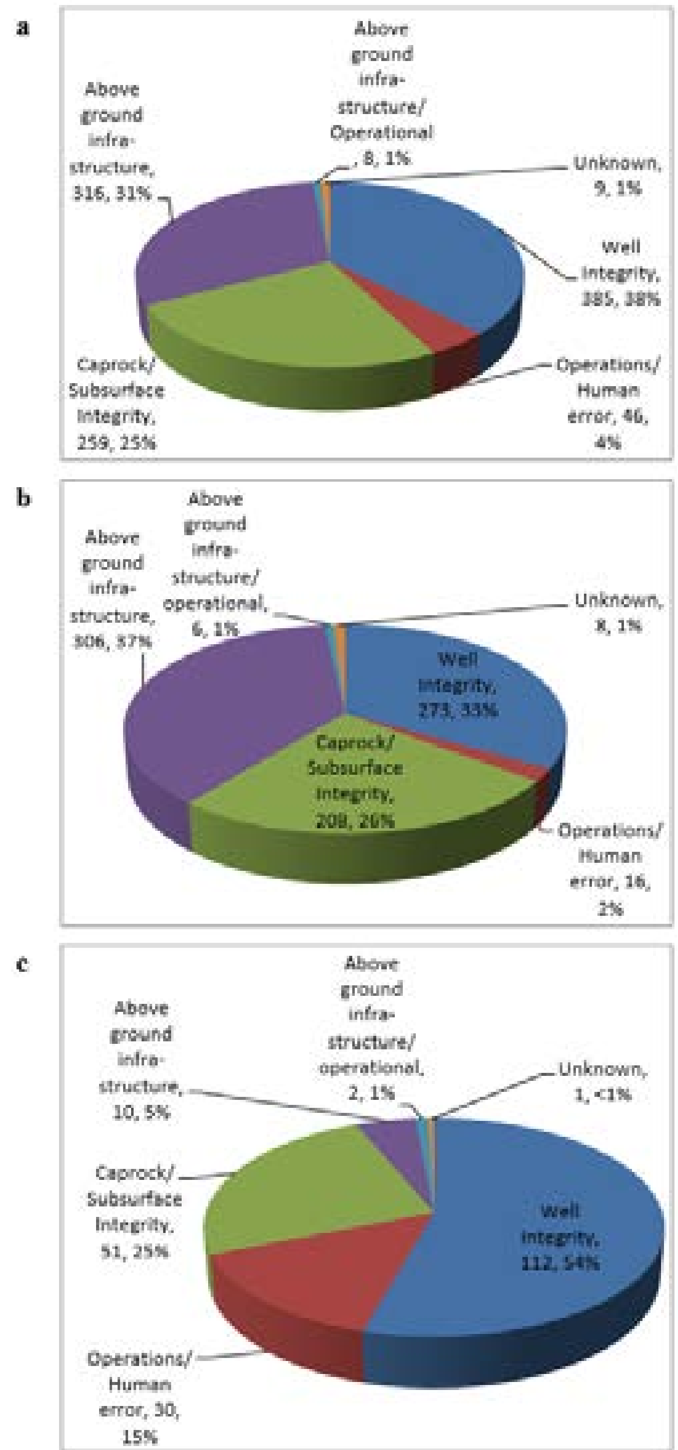

Fig. 8. Diagrams illustrating occurrences, worldwide, for UFS facilities by the main causal mechanism. a) values, worldwide - USA and non-USA undivided (n = 1023), including four occurrences of unconfirmed country, b) figures for the USA, undivided (n = 817), c) figures for the non-USA (undivided; n = 206).

states of California, Texas and Pennsylvania (349/43%, 126/15% and 76/9% respectively; **Table 4**, **Fig. 9a**).

The breakdown by fuel types reveals occurrences at US storages are dominated by three main fuel types (**Table 4**, **Fig. 9b**): natural gas, which is linked with the highest number of occurrences (599/73%), HVL's (including ethylene: 119/15%) and oil (94/12%). In terms of the storage types involved (all fuels), depleted fields comprise the most occurrences (528/65%), with salt cavern storage linked to 225 (27%) of occurrences (Table 5, Fig. 9c). Aquifers and abandoned mines/mined rock storages account for 29 (5%) and 30 (4%) of cases respectively.

In terms of the causes behind the occurrences at US storage sites, the most frequent are related to above ground infrastructure (306/37%; **Fig. 9d**, **Table 5**), with a further 22 having some above ground link, through operational or human error. However, with a combined total of 481 (70% of occurrences), subsurface issues relating to the integrity of the well (273/33%) and subsurface storage environments (208/26%) are clearly important contributors to occurrences and problems encountered at fuel storage sites (**Fig. 9d**, **Table 5**).In terms of severity, the overall breakdown for the US in each storage type is illustrated for all fuel types in **Table 6** (see also **Fig. 9c** and **f**). Of note is that salt cavern storage has the highest number of occurrences rated in terms of severity level 8 (catastrophic; 13), with depleted fields only having been associated with two such types of occurrence: at the depleted field sites of the Ranson storage field, Pennsylvania, USA (1969, four dead, seven injured; [89]) and Aliso Canyon (2015; prolonged and major product loss with high numbers of evacuees (11, e.g. [2]).

The severity of occurrences at UFS sites in relation to storage type and the main causal mechanism is summarized in Table 7. In terms of causal mechanisms, the most frequent is subsurface well integrity, which has been linked with nine of the category 8 occurrences in UFS across all storage types (being in depleted field and salt cavern storage incidents). The two other Category 8 occurrences are linked with a mined rock storage (1975 at Mid American Pipeline Company terminal, Iowa; [94]) and unconfirmed storage type (in 1947 at Marion, Osceola County, Michigan; [95] – see below).

Table 5 illustrates the numbers of US occurrences at Table 5 illustrates the numbers of US occurrences at UFS sites linked with migration or leakage of product in the subsurface (538) and those occurrences linked with product leakage to, or at, the surface (397). Of these leakages, 80 were accompanied by a fire, with 71 involving a fire and explosion. When natural gas alone is considered, 599 occurrences have been found across the various storage types (**Fig. 9e**, **Tables 8** and **9**). The breakdown for such occurrences, by US State, shows the vast majority of the these have arisen in California (342/57%), with Pennsylvania emerging with the next highest figures

Table 4. Breakdown of occurrences for all fuel types by US State.

US State	*NG*	*Ethylene*	*Oil*	*HVL*	*Empty*	*Not available*	*Totals*
Not available	17	0	0	0	0	1	18
Alabama	0	0	0	2	0	0	2
Arizona	0	0	0	1	0	0	1
California	342	0	0	7	0	0	349
Colorado	7	0	0	0	0	0	7
Georgia	0	0	0	1	0	0	1
Illinois	15	0	0	2	0	0	17
Indiana	7	0	0	1	0	0	8
Iowa	6	0	0	4	0	0	10
Kansas	18	0	0	33	0	0	51
Kentucky	3	0	0	0	0	0	3
Louisiana	15	1	20	5	2	0	43
Michigan	18	3	0	1	0	1	23
Minnesota	1	0	0	0	0	0	1
Mississippi	10	0	0	6	0	0	16
Missouri	1	0	0	2	0	0	3
Nebraska	2	0	0	0	0	0	2
New Mexico	2	0	0	0	0	0	2
New York	13	0	0	6	0	0	19
Ohio	6	0	0	16	0	0	22
Oklahoma	2	0	0	1	0	0	3
Pennsylvania	75	0	0	1	0	0	76
Texas	28	4	74	19	0	1	126
Utah	2	0	0	2	0	0	4
Virginia	0	0	0	1	0	0	1
West Virginia	7	0	0	0	0	0	7
Wyoming	2	0	0	0	0	0	2
Totals	***599***	***8***	***94***	***111***	***2***	***3***	***817***

(75/13% of occurrences; **Fig. 9e**). It is not surprising to find that, in terms of storage type, the most occurrences involving natural gas are linked with depleted fields (520/87%; **Table 9**, **Fig. 9f**), with the two main contributors, California and Pennsylvania (**Fig. 9e**), having significant numbers of depleted field storage sites: indeed, California has only this type of storage. Of the other storage types, salt cavern storage is linked to only 45 (8%) of natural gas occurrences (**Fig. 9f**). For aquifer sites the number of occurrences total only 29 (5%) in the USA (**Fig. 9f**), although these are all (5%) in (5%) in the USA (**Fig. 9f**), although these are all associated with natural gas: the majority being from Illinois (15; **Tables 8** and **9**, **Fig. 9e**).The breakdown of occurrences involving natural gas storage arising from the principal subsurface causal mechanisms of well integrity and subsurface storage/caprock integrity is shown by state for each storage type in **Figure 10**. California has the greatest number of occurrences related to well integrity in depleted fields (93/57%; **Fig. 10a**), whereas Kansas and New York have the greatest number related to issues concerning subsurface integrity (16/25% and 10/16% respectively; **Fig. 10b**).

The State of Texas tops the lists in both subsurface categories for natural gas storage (**Figs. 10c** and **d**). Illinois, with limited alternative storage types, heads the list for occurrences involving subsurface integrity during gas storage operations (**Figs. 10e** and **f**). In terms of severity, **Table 9** illustrates the breakdown for US occurrences by storage type involving only nat-

Table 5. Summary of the main causes linked with occurrences at US fuel storage sites, numbers linked with migration and ultimately leakage at surface, evacuees and/or casualties.

Storage type (USA only, all fuel types)		Causes and numbers by storage						Number by storage type				Number by storage type		
		Subsurface - well integrity	*Subsurface - storage integrity*	*Operational/ human error*	*Above ground infrastructure*	*Above ground infrastructure/ operational*	*Unknown*	*Occurrences leading to leakage/ migration in subsurface*	*Occurrences leading to leakage/ migration at surface*	*Leading to fire*	*Leading to explosion*	*Evacuees*	*Injuries*	*Fatalities*
Porous rock	***Depleted field (total = 528)***	166	69	6	282	4	1	392	282	27	37	11372	23	6
	Aquifer (total = 29)	5	15	1	6	0	2	29	19	11	10	0	2	0
Mined voids	***Salt cavern - solution-mined (total = 225)***	101	101	8	9	2	4	86	67	31	18	8430	73	15
	Abandoned mine/mined rock cavern (total = 30)	1	23	1	5	0	0	27	25	8	5	520	7	3
Unconfirmed (total = 5)		0	0	0	4	0	1	4	4	3	1	0	6	1
Totals		273	208	16	306	6	8	538	397	80	71	20322	111	25
		481		328			8							
Worldwide (USA & non-USA, undivided, n = 1023)		385	259	46	316	8	9	588	428	93	81	21164	125	28

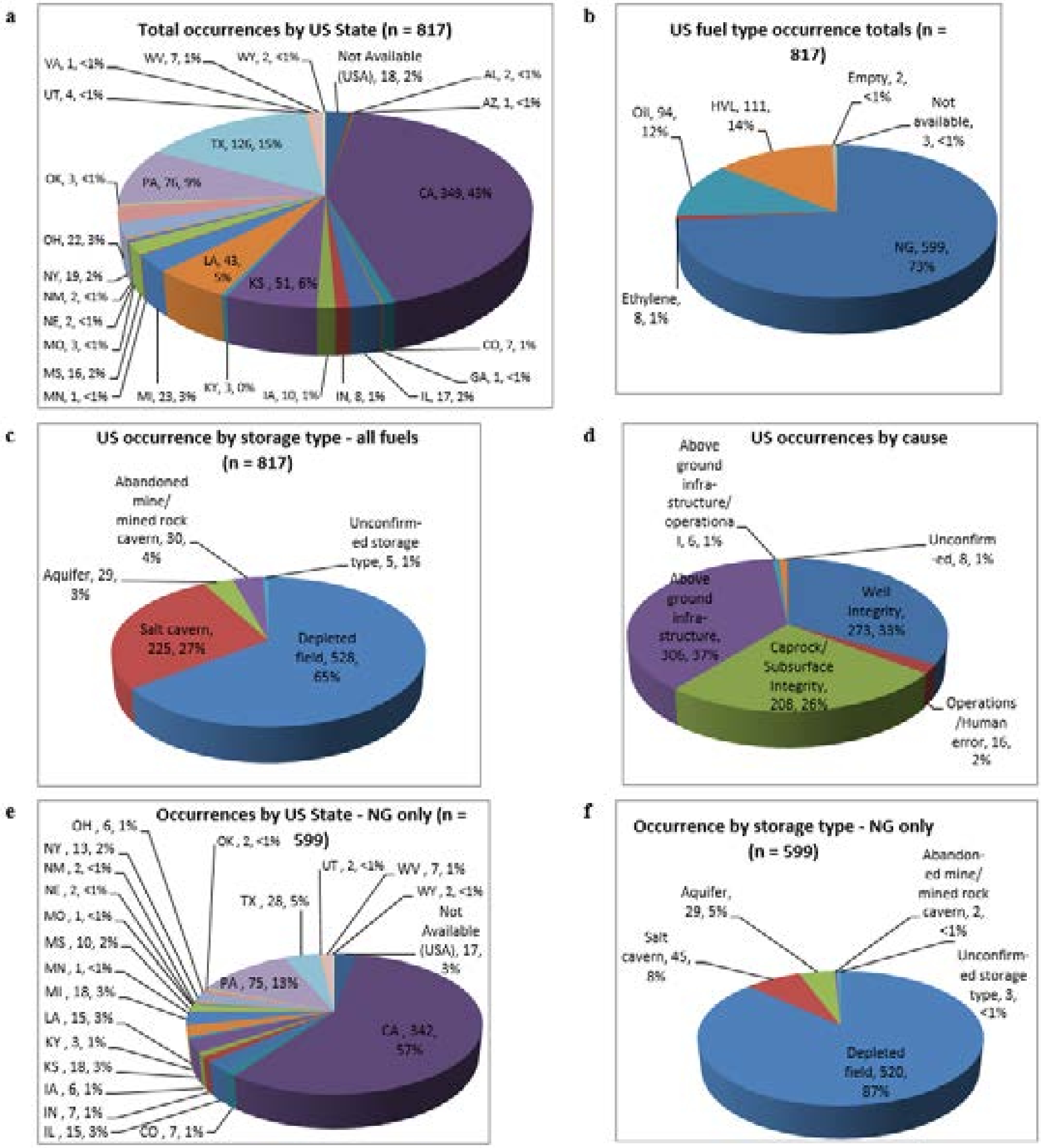

Fig. 9. Breakdown of occurrences for the USA by US States. a) occurrence by State, b) occurrence by fuel type, c) occurrence of all fuels by storage type, d) occurrence of all fuels by cause, e) occurrence by State for natural gas only, f) occurrence by storage type for natural gas only.

ural gas. In addition to the Ranson and Aliso Canyon incidents, there have been two category 8 occurrences at salt cavern storages: the infamous Hutchinson/Yaggy incident (2001) and the Moss Bluff incident in 2004. There are also reports of an occurrence at an unconfirmed storage type at Marion, Osceola County, Michigan, USA on November 30, 1947, when an explosion occurred at a compressor station for a natural gas storage facility. One worker was killed, six others were injured and gas services were interrupted in the area [95]). Believ-

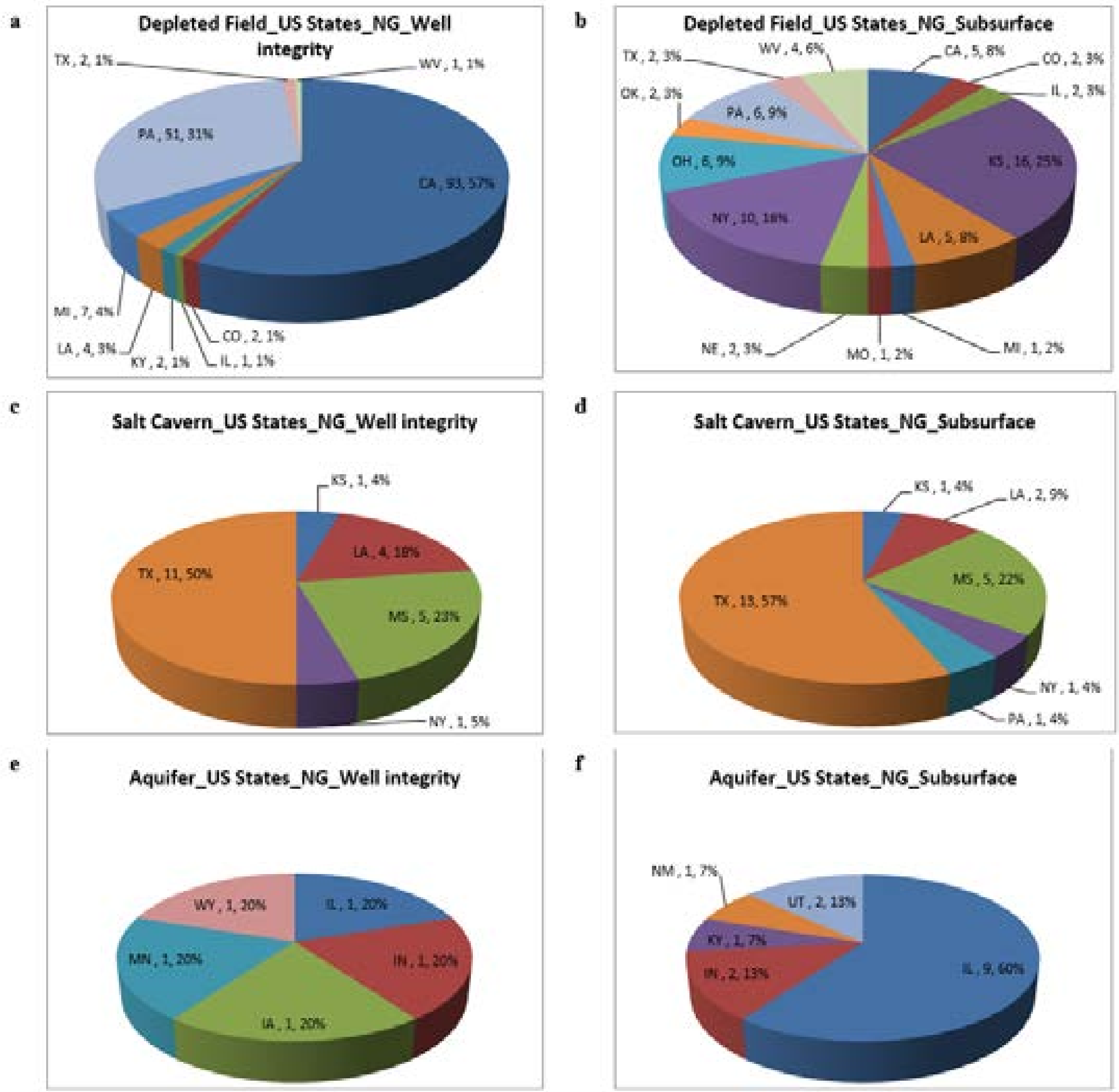

Fig. 10. Breakdown of occurrences at US natural gas storage sites, based on US State, storage type and cause (well or subsurface integrity). a and b) depleted field, c and d) salt cavern, e and f) aquifer storage. Note that abandoned mines and unconfirmed storage type total only 4 and 5 occurrences respectively.

ing this to have been an underground storage site, then given its age (pre-dating salt cavern storages), it is likely to have been a depleted hydrocarbon field facility.

The severity of occurrences at UGS sites in relation to storage type and the main causal mechanism is summarized in **Table 10**. As discussed above, the high incidences of occurrences in both California and Pennsylvania is understandable when it is considered that the main storage type in both states is the depleted field and where the number of old, deteriorating oil and gas wells is extremely high. Many of the occurrences in California have taken place in what are now heavily populated areas, where housing has encroached and in places, built near and over old oil and gas fields and long-abandoned wells, the locations for many of which are unknown. In addition to the Aliso Canyon incident (2015), gas has migrated from the reservoir to the surface at a number of other storage fields, which

Table 6. Summary of severity of US occurrences by storage type for all fuel types.

Storage type (USA, all fuel types; n=817)		Severity category (sub-totals)								Totals
		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	
Porous rock	***Depleted field***	4	324	53	125	12	4	4	2	528
	Aquifer	0	1	3	21	3	0	1	0	29
Mined voids	***Salt cavern - solution-mined***	83	41	0	71	3	5	9	13	225
	Abandoned mine/mined rock cavern	1	15	4	4	2	1	2	1	30
Unconfirmed		0	2	0	2	0	0	0	1	5
Totals		***88***	***383***	***60***	***223***	***20***	***10***	***16***	***17***	***817***

has resulted in the abandonment of some, including the El Segundo field in the 1970s, due to new housing and safety reasons [96]). However, as discussed earlier, the numbers are somewhat skewed by the requirements imposed on operators following the 2015 Aliso Canyon incident.

In the case of Texas, a large number of well problems are recorded from the various salt cavern hosted US SPR caverns, most notably the Bryan Mound storage site. Problems have also occurred at the Big Hill, West Hackberry and Bayou Choctaw (e.g. [55,56,57]). The salt caverns are constructed in domal salt structures that have experienced large salt block falls from the cavern wall and roof regions that have impacted and damaged the hanging casing strings on numerous occasions. Bryan Mound has the greatest propensity with at least 54 occurrences and 43 string failures, West Hackberry ranked second with 11 occurrences and nine hanging string failures, Bayou Choctaw has experienced five occurrences with two string failures, and Big Hill has had only one significant failure. The damage to the strings indicates that the blocks of salt may have attained appreciable velocities after spalling from the cavern walls. The vast majority of these cases are classified as level 1 in terms of severity, but illustrate problems that do occur to both the installed infrastructure (well components) and in the subsurface storage environment (cavern walls and roof) and could lead or contribute to more serious incidents.

Table 10 illustrates the numbers of US occurrences at UGS sites linked with migration or leakage of product in the subsurface (432) and those occurrences linked with product leakage to, or at, surface (305). Of these product leakage to, or at, surface (305). Of these leakages, 42 leakage to, or at, surface (305). Of these leakages, 42 were accompanied by a fire, with 47 involving a fire and explosion.

6. CONCLUSIONS AND IMPLICATIONS

As with other areas of the energy supply chain, incidents and accidents occur at UFS facilities, including UGS sites. The protracted Aliso Canyon incident of 2015 in California brought underground gas storage and its safety to national and worldwide attention. Building on earlier compilations of occurrences at UFS sites, and in the light of the Aliso Canyon incident, we have presented the results of an exhaustive search for occurrences at such storage facilities. Since the previous research in 2009, more data have been made available through online sources such that a database of occurrences now totals 1023 documented cases. These are of very varying nature, type and severity, with occurrences found in all the man storage types. The most severe to catastrophic incidents, involving major product loss or damage to above-ground infrastructure, large numbers of evacuees, injuries and fatalities are rare, with only 16 of the severest category 8 found. A number of these did not involve storage operations directly, but were either during construction of the facility (Aldbrough, UK and Padur, India 2014]), or occurred during operation of the site, with no link to leakage or release of stored product (e.g. at Bryan Mound, 2011). However, Aldbrough and Padur reveal problems with storage horizon integrity or above-ground process failures which could have led to more serious incidents during storage operations and so have been included here for completeness in terms of identifying categories during risk assessment.

Since the 2009 review published by Evans (2009), only one major incident rated as category 7 or 8 severity level has been found for depleted field storage: in 2015 at Aliso Canyon, California, USA, and linked to well integrity. For salt cavern storage, four occurrences of this severity have been found (2010–2013 Eminence [Mississippi – subsurface (cavern) integrity]; 2011 Bryan Mound SPR, Texas [above ground, one fatality, but not involving leakage from storage; 2011 Mont Belvieu West, Texas [above

Table 7. Breakdown of US occurrences by storage type, main causal mechanism and severity for all fuels.

Storage type		Main causal mechanism	Severity								
			1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	
Porous rock storage	**Depleted field**	***Well Integrity***	0	55	3	98	2	3	4	1	166
		Operations/Human error	1	2	0	3	0	0	0	0	6
		Caprock/Subsurface Integrity	0	6	50	11	1	0	0	1	69
		Above ground infrastructure	3	261	0	9	8	1	0	0	282
		Above ground infrastructure/ operational	0	0	0	4	0	0	0	0	4
		Unconfirmed	0	0	0	0	1	0	0	0	1
		Sub totals	***4***	***324***	***53***	***125***	***12***	***4***	***4***	***2***	***528***
	Aquifer	***Well Integrity***	0	1	0	4	0	0	0	0	5
		Operations/Human error	0	0	0	1	0	0	0	0	1
		Caprock/Subsurface Integrity	0	0	3	11	0	0	1	0	15
		Above ground infrastructure	0	0	0	3	3	0	0	0	6
		Above ground infrastructure/ operational	0	0	0	0	0	0	0	0	0
		Unconfirmed	0	0	0	2	0	0	0	0	2
		Sub totals	***0***	***1***	***3***	***21***	***3***	***0***	***1***	***0***	***29***
Mined voids	**Salt cavern - solution-mined**	***Well Integrity***	20	27	0	35	1	5	5	8	101
		Operations/Human error	0	1	0	5	2	0	0	0	8
		Caprock/Subsurface Integrity	63	7	0	30	0	0	1	0	101
		Above ground infrastructure	0	3	0	0	0	0	3	3	9
		Above ground infrastructure/ operational	0	0	0	0	0	0	0	2	2
		Unconfirmed	0	3	0	1	0	0	0	0	4
		Sub totals	***83***	***41***	***0***	***71***	***3***	***5***	***9***	***13***	***225***
	Abandoned mine/Mined rock cavern	***Well Integrity***	0	1	0	0	0	0	0	0	1
		Operations/Human error	0	0	0	0	0	0	1	0	1
		Caprock/Subsurface Integrity	1	14	4	3	0	0	1	0	23
		Above ground infrastructure	0	0	0	1	2	1	0	1	5
		Above ground infrastructure/ operational	0	0	0	0	0	0	0	0	0
		Unconfirmed	0	0	0	0	0	0	0	0	0
		Sub totals	***1***	***15***	***4***	***4***	***2***	***1***	***2***	***1***	***30***
Unconfirmed		***Well Integrity***	0	0	0	0	0	0	0	0	0
		Operations/Human error	0	0	0	0	0	0	0	0	0
		Caprock/Subsurface Integrity	0	0	0	0	0	0	0	0	0
		Above ground infrastructure	0	1	0	2	0	0	0	1	4
		Above ground infrastructure/ operational	0	0	0	0	0	0	0	0	0
		Unconfirmed	0	1	0	0	0	0	0	0	1
		Sub totals	***0***	***2***	***0***	***2***	***0***	***0***	***0***	***1***	***5***
Totals			**88**	**383**	**60**	**223**	**20**	**10**	**16**	**17**	**817**

ground pipeline failure with one fatality]). One other previously unreported catastrophic incident has been found during the present study: in 1986 at the Petal salt cavern facility, Mississippi, USA: an interesting incident that started out related to subsurface well integrity later escalated into a major incident after above ground infrastructure was affected following surface crater formation. This incident illustrates very clearly how one cause can lead to other causes that may not have been foreseen or anticipated when plant was designed and constructed. Since 2009, four level 7 or 8 severity incidents at mined rock caverns have come to light at the Todhunter terminal,

Table 8. Summary of the main causes linked with occurrences at US natural gas storage sites, numbers linked with migration and ultimately leakage at surface, evacuees and/or casualties.

Storage type - USA, natural gas only		Subsurface - well integrity	Subsurface - storage integrity	Operational/ human error	Above ground infrastructure	Above ground infrastructure/ operational	Unknown	Occurrences leading to leakage/ migration in subsurface	Occurrences leading to leakage/ migration at surface	Leading to fire	Leading to explosion	Evacuees	Injuries	Fatalities
Porous rock	Depleted field (total = 520)	163	64	6	282	4	1	390	281	27	36	11372	23	6
	Aquifer (total = 29)	5	15	1	6	0	2	28	19	11	10	0	2	0
Mined voids	Salt cavern - solution-mined (total = 45)	22	23	0	0	0	0	10	2	2	0	730	1	2
	Abandoned mine/mined rock cavern (total = 2)	1	1	0	0	0	0	2	0	0	0	0	0	0
Unconfirmed (total = 3)		0	0	0	3	0	0	2	3	2	1	0	6	1
Totals		191	103	7	291	4	3	432	305	42	47	12102	32	9
		599												

Ohio, USA (2005, HVL and related to operational issues); Marcus Hook Refinery, Pennsylvania, USA (1978, HVL and related to subsurface issues); Mid American Pipeline Company, Iowa, USA (1975, HVL and related to above ground infrastructure); Padur oil storage, India (2013, oil and subsurface integrity [rock falls, with one fatality] during construction and not during storage operations).

The occurrences found to date are many and varied, with differing levels of severity and cause. Many occurrences can be attributed to one main cause, but with other causes having made some contribution; e.g. many sub-surface incidents are also linked to human error and/or operational issues such as overpressuring of reservoirs or caverns, poor site characterization and definition of the storage horizon, such as either salt dome boundaries or depleted field limits.

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REFERENCES

1. Evans, D.J., 2009. A review of underground fuel storage events and putting risk into perspective with other areas of the energy supply chain, In *Underground gas storage: Worldwide experiences and future development in the UK and Europe*, D.J. Evans and R.A. Chadwick, Editors, Geological Society: London, 173–216.
2. US Department of Energy, 2016. Ensuring safe and reliable underground natural gas storage. Final report of the Interagency Task Force on natural gas storage safety, October 2016, 83 p. Report available at http://energy.gov/sites/prod/files/2016/10/f33/Ensuring%20Safe%20and%20Reliable%20Underground%20Natural%20Gas%20Storage%20-%20Final%20Repor..._0.pdf.
3. States First, 2017. Underground gas storage regulatory considerations: A guide for state and federal regulatory agencies, Interstate Oil and Gas Compact Commission, Ground Water Protection Council; in press.
4. Black and Veatch Management Consulting, LLC,

Table 9. Summary of severity of occurrences by storage type for natural gas only.

Storage type (USA, natural gas only)		**Severity**								**Totals**
		1	***2***	***3***	***4***	***5***	***6***	***7***	***8***	
Porous rock	***Depleted field***	4	318	53	123	12	4	4	2	520
	Aquifer	0	1	3	21	3	0	1	0	29
Mined voids	***Salt cavern - solution-mined***	2	9	0	28	0	3	1	2	45
	Abandoned mine/mined rock cavern	0	1	1	0	0	0	0	0	2
Unconfirmed		0	1	0	1	0	0	0	1	3
Totals		***6***	***330***	***57***	***173***	***15***	***7***	***6***	***4***	***599***

2016. A bridge to the future: The increasing role of natural gas storage in energy reliability, 31 p.

5. Hubbard, D.W., 2009. *The failure of risk management: Why it's broken and how to fix it*. Wiley: New York, 281 p.

6. Milwaukee Journal, 1973. Milwaukee Boulders Suddenly Fill Oklahoma Pasture. *The Milwaukee Journal*, Wednesday February 28, 1973, p. 3. https://news.google.com/newspapers?nid=1499&dat=19730228&id=JUwaAAAAIBAJ&sjid=wSgEAAAAIBAJ&pg=6719,3939798&hl=en.

7. Buschbach, T. C., and D. C. Bond, 1974. Underground Storage of Natural Gas in Illinois—1973. Illinois Petroleum 101, Illinois State Geological Survey, Department of Registration and Education, Urbana, Illinois, 84 p.

8. Bérest, P., 1990. Accidents in underground oil and gas storages: case histories and prevention. *Tunnelling and Underground Space Technology* **5**: 327–335.

9. Mari, J.L. Huguet, F. Meunier, J. and Becquey, M., 2011. Natural gas storage seismic monitoring. *Oil and Gas Science and Technology* **66**: 9–20.

10. Bérest, P., 1989. Accidents of underground oil and gas storages — case histories and prevention. In: Nilsen, B. and Olsen, J. (eds) *Proceedings International Conference Storage Gases in Rock Caverns*. Balkema, Rotterdam, 289–301.

11. Joffre, G-H. and A. Le Prince, 2002. Database for major accidents on underground gas storage facilities. MARCOGAZ Report; DES.ST-GHJ/TLA-2000.00023. http://marcogaz.org/information/index_info3.htm.

12. Fay, R.O., 1973. The Elk City Blowout. *Oklahoma Geology Notes* **33**, no. 4, August 1973, 135–151.

13. Benson, S., 2005. Chapter 25: Lessons learned from industrial and natural analogs for health, safety and environmental risk assessment for geologic storage of carbon dioxide. In: THOMAS, D.C. AND BENSON, S.M. (eds), *Carbon dioxide capture for storage in deep geologic formations*, volume 2, Elsevier, 1133–1141.

14. Benson, S. and Hepple, R., 2005. Chapter 28: Prospects for early detection and options for remediation of leakage from CO_2 storage projects. In: THOMAS, D.C. AND BENSON, S.M. (eds), *Carbon dioxide capture for storage in deep geologic formations*, volume 2, Elsevier, 1189–1203.

15. Perry, K.F., 2005. Natural gas storage industry experience and technology: Potential application to CO_2 geological storage. In *Carbon dioxide capture for storage in deep geologic formations: Results from the CO_2 capture project*; volume 2: Geologic storage of carbon dioxide with monitoring and verification, S.M. Benson, C. Oldenburg, M. Hoversten and S. Imbus, Editors, Elsevier: Amsterdam, 815–825.

16. Evans, D.J., 2008. A review of underground fuel storage events and putting risk into perspective with other areas of the energy supply chain, British Geological Survey, Keyworth, Nottingham NG12 5GG, UK.

17. Bruno, M.S., K. Lao, J. Diessl, B. Childers, J. Xiang, N. White, and E. Van der Veer, 2014. Development of improved caprock integrity analysis and risk assessment techniques. *Energy Procedia* **63**: 4708–4744.

18. Pawar, R.J., G.S. Bromhal, J.W. Carey, W. Foxall, A. Korre, P.S. Ringrose, O. Tucker, M.N. Watson, and J.A. White, 2015. Recent advances in risk assessment and risk management of geologic CO_2 storage. *International Journal of Greenhouse Gas Control* **40**: 292–311.

19. Peila, D. and Pelizza, S., 1995. Civil reuses of underground mine openings: A summary of international experience. *Tunneling and Underground Space Technology* **10**: 179–191.

20. Khan, A.R., P.J. Anderson, and B.E. Eakin, 1967. Cavern storage of liquefied natural gas. Paper WPC-12534 presented at the *7th World Petro-*

Table 10. Breakdown of US occurrences by storage type, main causal mechanism and severity for natural gas only.

Storage type		**Main causal mechanism**	**Severity**									**Totals**
			1	***2***	***3***	***4***	***5***	***6***	***7***	***8***		
Porous rock storage	**Depleted field**	***Well Integrity***	0	53	3	97	2	3	4	1		163
		Operations/Human error	1	2	0	3	0	0	0	0		6
		Caprock/Subsurface Integrity	0	2	50	10	1	0	0	1		64
		Above ground infrastructure	3	261	0	9	8	1	0	0		282
		Above ground infrastructure/ operational	0	0	0	4	0	0	0	0		4
		Unconfirmed	0	0	0	0	1	0	0	0		1
		Sub totals	***4***	***318***	***53***	***123***	***12***	***4***	***4***	***2***		***520***
	Aquifer	***Well Integrity***	0	1	0	4	0	0	0	0		5
		Operations/Human error	0	0	0	1	0	0	0	0		1
		Caprock/Subsurface Integrity	0	0	3	11	0	0	1	0		15
		Above ground infrastructure	0	0	0	3	3	0	0	0		6
		Above ground infrastructure/ operational	0	0	0	0	0	0	0	0		0
		Unconfirmed	0	0	0	2	0	0	0	0		2
		Sub totals	***0***	***1***	***3***	***21***	***3***	***0***	***1***	***0***		***29***
Mined voids	**Salt cavern - solution-mined**	***Well Integrity***	1	4	0	12	0	3	0	2		22
		Operations/Human error	0	0	0	0	0	0	0	0		0
		Caprock/Subsurface Integrity	1	5	0	16	0	0	1	0		23
		Above ground infrastructure	0	0	0	0	0	0	0	0		0
		Above ground infrastructure/ operational	0	0	0	0	0	0	0	0		0
		Unconfirmed	0	0	0	0	0	0	0	0		0
		Sub totals	***2***	***9***	***0***	***28***	***0***	***3***	***1***	***2***		***45***
	Abandoned mine/Mined rock cavern	***Well Integrity***	0	1	0	0	0	0	0	0		1
		Operations/Human error	0	0	0	0	0	0	0	0		0
		Caprock/Subsurface Integrity	0	0	1	0	0	0	0	0		1
		Above ground infrastructure	0	0	0	0	0	0	0	0		0
		Above ground infrastructure/ operational	0	0	0	0	0	0	0	0		0
		Unconfirmed	0	0	0	0	0	0	0	0		0
		Sub totals	***0***	***1***	***1***	***0***	***0***	***0***	***0***	***0***		***2***
Unconfirmed		***Well Integrity***	0	0	0	0	0	0	0	0		0
		Operations/Human error	0	0	0	0	0	0	0	0		0
		Caprock/Subsurface Integrity	0	0	0	0	0	0	0	0		0
		Above ground infrastructure	0	1	0	1	0	0	0	1		3
		Above ground infrastructure/ operational	0	0	0	0	0	0	0	0		0
		Unconfirmed	0	0	0	0	0	0	0	0		0
		Sub totals	***0***	***1***	***0***	***1***	***0***	***0***	***0***	***1***		***3***
Totals			**6**	**330**	**57**	**173**	**15**	**7**	**6**	**5**		**599**

leum Congress, 2-9 April, Mexico City, Mexico.

21. Piessons, K. and Dusar, M., 2003. CO2 sequestration in abandoned coal mines. *Proceedings 2003 International Coalbed Methane Symposium*, Tuscaloosa, paper 0346, 11 p.

22. Piessons, K. and Dusar, M., 2004. Feasibility of CO2 sequestration in abandoned coal mines in Belgium. *Geologica Belgica* **7**/3–4: 165–180.

23. Hunt, S., 2013. Regulation of underground propane storage is murky. The Columbus Dispatch,

Monday March 11, 2013 7:11 a.m. http://www.dispatch.com/content/stories/local/2013/03/11/regulation-of-underground-propane-storage-is-murky.html.

24. PB-KBB, Inc., 1998. Advanced underground gas storage concepts: Refrigerated-mined cavern storage. Final Report to US Department of Energy, contract number DE-AC26-97FT34349.

25. Katz, D.L. and M.R. Tek, 1981. Overview on underground storage of natural gas. *Journal of Petroleum Technology* **33**: 943–951.

26. Chen, M., T.A. Buscheck, J.L. Wagoner, Y. Sun, J.A. White, L. Chiaramonte and R.D. Aines, 2013. Analysis of fault leakage from Leroy underground natural gas storage facility, Wyoming, USA. *Hydrogeology Journal* **21**: 1429–1445.

27. United Nations Economic Commission for Europe, 2013. Study on underground gas storage in Europe and Central Asia. United Nations, Geneva.

28. Ding, G., C. Li, J. Wang, H. Xu, Y. Zheng, Q. Wanyan and Y. Zhao, 2015. The status quo and technical development direction of underground gas storages in China. *Natural Gas Industry* **B 2**: 535–541.

29. Kron, N.D. and D.H. Malone, 2015. Three-dimensional geologic model of the Pecatonica gas storage field, Winnebago County, Illinois. Wo*rld Journal of Environmental Engineering* **3**: 121–125.

30. Yang, C., W. Jing, J.J.K. Daemen, G. Zhang and C. Du, 2013. Analysis of major risks associated with hydrocarbon storage caverns in bedded salt rock. *Reliability Engineering and System Safety* **113**: 94–111.

31. Dusseault, M.B., 2011. Geomechanical challenges in petroleum reservoir exploitation. *KSCE Journal of Civil Engineering* **15**: 669–678.

32. Ghassemi, A., 2012. A review of some rock mechanics issues in geothermal reservoir development. *Geotechnical and Geological Engineering* **30**: 647–664.

33. Streit, J.E. and R.R. Hillis, 2004. Estimating fault stability and sustainable fluid pressures for underground storage of CO_2 in porous rock. *Energy* **29**: 1445–1456.

34. Rutqvist, J., 2012. The geomechanics of CO2 storage in deep sedimentary formations. *Geotechnical and Geological Engineering* **30**: 525–551.

35. Zoback, M.D. and S.M. Gorelick, 2012. Earthquake triggering and large-scale geologic storage of carbon dioxide. *Proceedings of the US National Academy of Sciences* **109**: 10,164–10,168.

36. US Department of Transportation, Pipeline and Hazardous Materials Safety Administration, 2016. Pipeline safety: Safety of underground natural gas storage facilities. Interim Final Rule, Docket No. PHMSA-2016-0016, Federal Register, Vol. 81, No. 243, Dec. 19, 2016, p. 91860–91873; details of the PIPES Act available at https://www.congress.gov/bill/114th-congress/senate-bill/2276/text.

37. Joint Industry Task Force (American Petroleum Institute, American Gas Association, and Interstate Natural Gas Association of America), 2016. Underground natural gas storage: Integrity and safe operations, 83 p.: July 2016. Report available at http://www.energyinfrastructure.org/energy-101/natural-gas-storage.

38. CMA, 2016. Rough gas storage undertaking review: Final report. Competition and Markets Authority (CMA) report, 22 April 2016, 87 p. https://assets.publishing.service.gov.uk/media/571a2323e5274a201400000f/Rough_gas_storage_undertakings_review_final_report.pdf.

39. Stokes, D. and Spinks, O., 2016. Rough storage issues remain a structural threat. Online report by Timera Energy, 29 August 2016. http://www.timeraenergy.com/rough-storage-issues-remain-a-structural-threat/.

40. Crotogino, F., Mohmeyer, K-U. & Scharf, R. 2001. Huntorf CAES: More than 20 years of successful operation. *SMRI Spring Meeting*, Orlando, Florida, April 15–18, 2001, 7 p.

41. Brown, K.G., and D.E. Miekle, 1995. The Value of Wellhead Electronic Flow Measurement in Gas Storage Fields. Society of Petroleum Engineers, *SPE Eastern Regional Meeting*, September 18–20, Morgantown, West Virginia, SPE-31000-MS, 15 p.

42. Macalister, T., 1998. North Sea gas plant came close to disaster. *The Independent Online*, Monday June 8, 1998. http://www.independent.co.uk/news/north-sea-gas-plant-came-close-to-disaster-1163708.html.

43. FERC, 2012a. Dominion Transmission Inc. V Order issuing certificate. United States of America Federal Energy Regulatory Commission (FERC), 141 FERC ¶ 61,183, Docket No. CP12-59-000, Issued November 30, 2012, 14 p. https://www.ferc.gov/EventCalendar/Files/20121130155259-CP12-59-000.pdf.

44. FERC, 2007. Equitrans, L.P. — Order issuing and amending certificates. United States of America Federal Energy Regulatory Commission (FERC), 141 FERC ¶ 61,183, Docket No. CP05-18-000, Issued June 21, 2007, 17 p. https://www.ferc.gov/whats-new/commmeet/2007/062107/C-4.pdf.

45. Buzak, F., 1992. Carbon isotope study of gas migration in underground gas storage reservoirs, Czechoslovakia. *Applied Geochemistry* **7**: 471–480.

46. Blondin, E. and Mari, J.L., 1986. De-

tection of gas bubble boundary movement. *Geophysical Prospecting* **34**: 73–93.

47. FERC, 2012b. Natural Gas Pipeline Company of America LLC (NGPCA) — Order issuing certificate, authorizing abandonment, and authorizing an increase in storage deliverability. United States of America Federal Energy Regulatory Commission (FERC), 139 FERC ¶ 61,119, Docket No. CP11-547-000, Issued May 17, 2012, 21 p. https://www.ferc.gov/whats-new/comm-meet/2012/051712/C-1.pdf.

48. Jones, V.T. and Drozd, R J., 1983. Predictions of oil and gas potential by near-surface geochemistry. Bulletin American Association of Petroleum Geologists 67, 932–952.

49. Jones, V.T. and Pirkle, R.J., 2004. http://www.eti-geochemistry.com/FinalVersion1.10.htm.

50. Brown, W.E., 2009. Northern Natural Gas Co. V. L.D. Drilling, Inc. (d.kan. 2009) memorandum and order, Wesley E. Brown, Senior District Judge, May 1, 2009, 22 pp. https://casetext.com/case/northern-natural-gas-co-v-ld-drilling.

51. Breen, K.J., Révész, K., Baldassare, F.J. and McAuley, S.D., 2007. Natural gases in ground water near Tioga Junction, Tioga County, North-Central Pennsylvania—Occurrence and use of isotopes to determine origins. U.S. Department of the Interior, U.S. Geological Survey, Scientific Investigations Report 2007-5085, 75 p. http://pubs.usgs.gov/sir/2007/5085/pdf/sir2007-5085.pdf.

52. Révész, K., Breen, K.J., Baldassare, F.J. and Burruss, R.C., 2010. Carbon and hydrogen isotopic evidence for the origin of combustible gases in water supply wells in north-central Pennsylvania. *Applied Geochemistry* **25**: 1845–1859.

53. Maykuth, 2015. Deep under Marcus Hook refinery, new importance for massive old caverns. The Philadelphia Inquirer, Updated: May 3, 2015 — 1:09 a.m. EDT. http://www.philly.com/philly/business/energy/20150503_Deep_under_Marcus_Hook_refinery__new_importance_for_massive_old_caverns.html.

54. Neste, 2012. The only way forward. Neste Oil annual report, 2012. 312 pp. www.2012.nesteoil.com.

55. Munson, D.E., M.A. Molecke, and R.E. Myers, 1998. Interior cavern conditions and salt fall potential. Solution Mining Research Institute (SMRI) *Spring Meeting*, April 19–22, New Orleans, Louisiana. http://www.osti.gov/bridge/servlets/purl/650136-U4fH7n/webviewable/.

56. Munson, D.E., S. Bauer, C. Rautman, B. Ehgartner, and A. Sattler, 2003. Analysis of the massive salt fall in Big Hill Cavern 103. Sandia Report Nos. SAND2003-0703, 35 p. http://prod.sandia.gov/techlib/access-control.cgi/2003/030703.pdf.

57. Munson, D.E., 2006. Features of West Hackberry SPR Caverns and Internal Structure of the Salt Dome. Sandia Report Nos. SAND2006-5409, 81 p. http://prod.sandia.gov/techlib/access-control.cgi/2006/065409.pdf.

58. Seni, S.J. and Johnson, D.O., 2005. Regulatory response to recent events effecting three gas storage facilities in Texas. AGA Annual Meeting 2005. http://www.aga.org/NR/rdonlyres/D5AF8AFC-9C14-4C67-939C-42D06D5B8121/0/0504SSENI.pdf.

59. Zhuang, D.Y., Tang, C.A., Liang, Z.Z., Maa, K., Wang, S.Y. and Liang, J.Z., 2017. Effects of excavation unloading on the energy-release patterns and stability of underground water-sealed oil storage caverns. *Tunnelling and Underground Space Technology* **61**: 123–133.

60. You, T., J.C. Kandel, and N. Gatelier, 2003. Underground storage in Sydney, some uncommon rock mechanics features of an uncommon project in Australia. ISRM 2003 – Technology roadmap for rock mechanics, *South African Institute of Mining and Metallurgy*, 1359–1364.

61. de Ambrosis, L.P. and Kotze, G.P., 2004. Stress induced roof collapses during construction of the Sydney LPG storage cavern. Proceedings 9th Australia New Zealand Conference on Geomechanics, Auckland, New Zealand, 159–165. http://www.ghd.com/PDF/Roof%20Collapses%20During%20Construction%20of%20LPG%20Storage%20Cavern.pdf.

62. Pillai, R.K., 2014. Safety measures adopted in underground cavern storage of crude oil too prevent disasters. ISPRL presentation 1 January 2014. http://www.google.co.uk/url?sa=tandrct=jandq=andesrc=sandsource=webandcd=3andved=0ahUKEwjgpqvAtbPRAhWC8YMKHemyDhoQFggpMAIandurl=http%3A%2F%2Fwww.cidm.in%2Fpresentations%2Frajan.ppsxandusg=AFQjCNGBVQAgj0Z4YGJRG0usHiDTO9dfcg.

63. Johnson, D.O., 2008. New developments in solution mined storage cavern operations in Texas. Solution Mining Research Institute (SMRI) *Fall conference*, October 12–14, Austin, Texas, 105–117.

64. Bérest, P. and Brouard, B., 2003. Safety of salt caverns used for underground gas storage. *Oil and Gas Science and Technology* **58**: 361–384.

65. Warren, J.K., 2006. Evaporites: *Sediments, resources and hydrocarbons*. Springer-Verlag, Berlin.

66. Cox, L.A., 2008. What's wrong with risk

matrices? *Risk Analysis* **28**: 497–512, doi:10.1111/j.1539-6924.2008.01030.x.

67. City of Huntingburg, 2012. City of Huntingburg gas storage field Q and A, 7/26/12, Exhibit A. Notes from Huntingburg Utility Board/ Common Council meeting Thursday, July 26, 2012, 7:00 pm, 7 pp. http://www.huntingburg-in.gov/egov/documents/1394122910_58484.pdf.
68. Kurzweil, A. and Burrous, C., 2016. Brush fire scorches 28 acres at Aliso Canyon gas facility near Porter Ranch. Posted 5:18 a.m, October 19, 2016, Updated at 01:28 p.m., October 19, 2016. http://ktla.com/2016/10/19/brush-fire-scorches-28-acres-at-aliso-canyon-gas-facility-near-porter-ranch/.
69. CPUC, 2016. Leak Survey Results – March 16, 2016. Results from California Public Utilities Commission (CPUC) Jan. 26, 2016, Safety and Enforcement Division (SED) directive. http://www.cpuc.ca.gov/General.aspx?id=10456.
70. FERC, 2012c. Southern Star Central Gas Pipeline, Inc. — Order amending certificate. United States of America Federal Energy Regulatory Commission (FERC), 139 FERC ¶ 62,161, Docket No. CP11-481-000 and CP11-481-001, Issued May 30, 2012, 6 p. http://fda.complianceexpert.com/2.11185/2012-issuances/southern-star-central-gas-pipeline-inc-139-ferc-62-161-2012-1.356969.
71. FERC, 2015. Southern Star Central Gas Pipeline, Inc. — Order issuing certificate. United States of America Federal Energy Regulatory Commission (FERC), 150 FERC¶62,073, Docket No. CP14-542-000, Issued January 30, 2015, 6 p. http://thompsonenergyexpert.com/ferc-issuances/2015-issuances/southern-star-central-gas-pipeline-inc-150-ferc-62-073-2015-1.381599.
72. FERC, 2006. Southern Star Central Gas Pipeline, Inc. — Order amending certificate. United States of America Federal Energy Regulatory Commission (FERC), 115 FERC ¶ 61,219, Docket No. CP06-49-000, Issued May 19, 2006, 17 p. https://www.ferc.gov/CalendarFiles/20060519193354-CP06-49-000.pdf.
73. FERC, 2014. East Cheyenne Gas Storage, LLC — Order amending certificate. United States of America Federal Energy Regulatory Commission (FERC), 148 FERC ¶ 62,138, Docket No. CP14-486-000, Issued August 14, 2014, 7 p. http://thompsonenergyexpert.com/ferc-issuances/2014-issuances/east-cheyenne-gas-storage-llc-148-ferc-62-138-2014-1.376136.
74. FERC, 2016. East Cheyenne Gas Storage, LLC — Order issuing certificate. United States of America Federal Energy Regulatory Commission (FERC), 155 FERC ¶ 61,236, Docket No. CP16-25-000, Issued June 2, 2016, 13 p. https://www.ferc.gov/CalendarFiles/20160602172056-CP16-25-000.pdf.
75. Coleman, D.D., 1992. The use of geochemical fingerprinting to identify migrated gas at the Epps underground gas storage field. *67th Annual Technical Conference and Exhibition of the Society of Petroleum Engineers*, Washington, DC, October 4–7, 1992, SPE 24926, 725–734.
76. Mantia, R.W., 1989. West Unionville storage field, a case study. In: Tek, M.R. (ed), *Underground Storage of Natural Gas: Theory and Practice*, North Atlantic Treaty Organisation, Kluwer Academic Publishers, 405–427.
77. Coleman, D.D., 1989. Geochemical fingerprinting: identification of storage gas using chemical and isotopic analysis. In: Tek, M.R. (ed), *Underground storage of natural gas: Theory and practice*, North Atlantic Treaty Organisation, Kluwer Academic Publishers, 327–338.
78. Jahns, A.F., 2007. Application by Sacramento Natural Gas Storage, LLC for a certificate of public convenience and necessity for construction and operation of natural gas storage facilities and requests for related determinations: supplement to proponent's environmental assessment. Application No. 07-04-013 (filed April 9, 2007).
79. FERC, 1993. Reese Exploration Inc v. Williams Natural Gas Company United States of America Federal Energy Regulatory Commission (FERC), 983 F. 2d 1514. Numbers Nos. 91-3230 and 91-3231, January 19, 1993, 13 p. http://openjurist.org/983/f2d/1514/reese-exploration-inc-v-williams-natural-gas-company.
80. Coleman, D. C., W. F. Meents, C- Li. Liu, and R. A. Keogh, 1977. Isotopic identification of leakage gas from underground storage reservoirs — A progress report. *Illinois Petroleum* **111**, Illinois State Geological Survey, Department of Registration and Education, Urbana, Illinois.
81. The Bulletin, 1981. Gas blast repeat angers neighbors of storage site. The Bulletin, Oregon, Friday April 7, 1981, p. 13. https://news.google.com/newspapers?nid=1243&dat=19810417&id=r10zAAAAIBAJ&sjid=EPcDAAAAIBAJ&pg=3282,3616502.
82. Hamberger, U., 1991. Case history: Blowout at an LPG storage cavern in Sweden. *Tunnelling and Underground Space Technology* **6**: 119–120.
83. State of Louisiana, 2007. Oil Insurance Limited versus Dow Chemical Company, Dow Hydrocarbons and Resources Inc., Frank's Casing Crew Rental Tools Inc. and Grey Wolf Drilling Company. State of Louisiana Court of Appeal, First

Circuit, 2007 CA 0418. Judgment Rendered, November 2nd 2007, 10 p. http://www.la-fcca.org/Opinions/PUB2007%5C2007-11/2007CA0418Nov2007.Pub.17.pdf.

84. Hazardex, 2014. Canada gas facility explosion and fire prompts evacuation. Web article, 13 October 2014. http://webcache.googleusercontent.com/search?q=cache:fMneVvR-VDiEJ:www.hazardexonthenet.net/article/84899/Canada-gas-facility-explosion-and-fire-prompts-evacuation.aspx+&cd=22&hl=en&ct=clnk&gl=uk.

85. Wellinghoff, J., P.D. Moeller, J.R. Norris, C.A. LaFleur, and T.T. Clark, 2013. Order approving abandonment, amending certificate authority, and granting clarification. United States of America Federal Energy Regulatory Commission (FERC) decision relating to Transcontinental Gas Pipe Line Company, LLC. Docket Nos. CP11-551-000 and RP12-993-001. Issued February 7, 2013, 39 p. http://www.ferc.gov/EventCalendar/Files/20130207144002-CP11-551-000.pdf.

86. Bérest, P., B., Brouard and J.G. Durup, 2001. Tightness tests in salt cavern wells. *Oil and Gas Science and Technology* **56**: 451–469.

87. SoCalGas, 2004. Southern California Gas Company's application to value and sell surplus property at Playa del Rey and Marina del Rey (A.99-05-029). Environmental impact report, June 4, 2004 (Draft), prepared for the California Public Utilities Commission, Energy Division, San Francisco, CA, 525 p.

88. Chilingar, G.V. and B. Endres, 2005. Environmental hazards posed by the Los Angeles Basin urban oilfields: an historical perspective of lessons learned. *Environmental Geology* **47**, 302–317.

89. Lebanon Daily News, 1969. Natural gas is believed cause of fatal blast. Lebanon Daily News, July 5, 1969, p. 24. https://newspaperarchive.com/us/pennsylvania/lebanon/lebanon-daily-news/1969/07-05/.

90. BBC, 2005. Probe after man crushed to death. British Broadcasting Corporation (BBC) News Website, Monday, 8 August 2005. http://news.bbc.co.uk/2/hi/uk_news/scotland/4132092.stm.

91. US Department of Energy, 2011. Fatality at the Strategic Petroleum Reserve Bryan Mound site, September 13, 2011. U.S. Department of Energy Office of Health, Safety and Security Accident Investigation Report, November 2011, 116 p. https://energy.gov/sites/prod/files/2014/04/f14/November_2011_Final_AI_Report-Fatality_%20at_SPR.pdf.

92. PHMSA, 2011. Failure investigation report — TEPPCO propane fire, 9/18/2005. US Department of Transportation, Pipeline and Hazardous Materials Safety Administration (PHMSA) Office of Pipeline Safety, Central Region, Failure Investigation Report, 12/15/2011, 11 p. http://phmsa.dot.gov/staticfiles/PHMSA/DownloadableFiles/TEPPCO%20HL%20OH%202005-09-18%20508.pdf.

93. Ohsann, T. and van Nostrand, G., 1975. Two killed as explosion rips gas pipeline company. The Daily Iowan, Friday January 24 1975, vol. 107, Nos 132, p. 10. http://webcache.googleusercontent.com/search?q=cache:p.k26Oh5WOBQJ:dailyiowan.lib.uiowa.edu/DI/1975/di1975-01-24.pdf+andcd=1andhl=enandct=clnkandgl=uk.

94. NTSB, 1993. Highly Volatile Liquids Release from Underground Storage Cavern and Explosion, Mapco Natural Gas Liquids Inc., Brenham Texas, April 7, 1992. National Transportation Safety Board (NTSB) Accident Report, NTSB/PAR-93/01, PB93-916502.

95. Wikipedia, 2017. List of pipeline accidents in the United States (1900–1949). https://en.wikipedia.org/wiki/List_of_pipeline_accidents_in_the_United_States_(1900%E2%80%931949.

96. Khilyuk, L.E., G.V. Chilingar, J.O. Robertson, Jr. and B. Endres, 2000. *Gas migration: Events preceding earthquakes*. Gulf Publishing Company, Houston, Texas.