Chapter 1

What risks do California's underground gas storage facilities pose to health, safety, environment, and infrastructure?

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ABSTRACT

1.0 INTRODUCTION

The general purpose of underground gas storage (UGS) is to meet varying demand for natural gas (predominantly methane, CH_4) over daily to seasonal time scales. The California UGS system in 2017 comprises 12 UGS facilities, four in southern California, seven in northern California, and one in central California with a total capacity to store just under 400 Bcf of natural gas. The California UGS reservoirs are all in depleted hydrocarbon reservoirs where natural gas is under high pressure (e.g., >1000 psi (~7 MPa) for most facilities). The handling and containment of high-pressure natural gas, which is highly flammable and explosive, entails risk. Each UGS facility in California is a combination of surface and subsurface systems designed to compress, inject, contain, withdraw, and process natural gas through wells that access the deep pore space of the storage reservoirs. The subsurface part of UGS comprises the reservoir for storage, the caprock (seal) for keeping buoyant gas from flowing upward, the overburden (rock above the caprock or reservoir) which contributes to additional storage security, and the well. We consider the wellhead to be part of the subsurface and surface parts of the UGS system, the latter of which also included flowlines connecting the wells to centralized compression and gas processing facilities. This chapter (Chapter 1) consists of six separate sections that stand alone but are also integrated to describe the risk posed by UGS in California and the mitigation of this risk.

1.1 CHARACTERISTICS OF CALIFORNIA UNDERGROUND GAS STORAGE FACILITIES

We have identified and searched multiple databases and other public sources to gather information to characterize the state of underground gas storage (UGS) in California. Gas injection via gas storage wells occurred in 13 facilities in California in 2015 prior to the Aliso Canyon well blowout ("well blowouts" in California are defined as "the uncontrolled flow of well fluids and/or formation fluids from the well"; Hauser and Guerard, 1993). Gas injection via storage wells ceased in the Montebello facility at the end of 2016 with the approval of the operator's application to inactivate the injection permit. Three of the four remaining facilities in southern California store gas in depleted oil reservoirs. The remaining facility, along with the one in central and seven in northern California, store natural gas in depleted gas reservoirs. The southern California facilities withdraw original-in-place oil and gas condensates in varying ratios relative to stored gas withdrawn. Various aspects of the facilities utilizing oil reservoirs differ from those utilizing gas reservoirs. For instance, the oil reservoir storage sites have deeper wells installed longer ago, more vertical wells such that wellheads are distributed more widely across the field, and they operate at a lower pressure as a fraction of the initial pressure.

UGS facilities utilizing depleted gas reservoirs are operated by either an investor-owned utility or an independent (non-utility) company. These groups of facilities generally vary from each other, with the independent facilities using wells installed more recently, gas handling plants farther from the storage well field, and longer pipelines, both connecting from the transmission line to the plant and from the plant to the well field. The differences between the three groups of facilities (utility-owned depleted oil reservoirs, utility-owned depleted gas reservoirs, and independently owned depleted gas reservoirs) provide the opportunity to study variations in risk between the groups, and potentially adapt approaches to managing risk utilized in one group of facilities to another group.

A substantial portion of the gas stored in southern California has been via wells installed six to nine decades ago. It does not appear that there is any regulatory limit to the age of a well component utilized for UGS. Temporal failure statistics should be developed for various components and utilized to determine the reasonable life expectancy of, and a time-varying monitoring schedule for, each type of component.

The data utilized to arrive at these characterizations typically do not have quality flags, nor is there a public record of data-quality protocols applied. Outliers exist in the data suggestive of errors, and there are inconsistencies between datasets that indicate errors. A unified database should be developed to avoid these inconsistencies, and a data-quality protocol including data-quality flags should be applied to the database. However, while some of the data inaccuracies may degrade the precision of UGS characterization in this report, the datasets are sufficiently consistent to provide confidence that our characterizations are accurate. We have compactly summarized key characteristics of California UGS facilities in a risk table presented in Section 1.7

1.2 FAILURE MODES, LIKELIHOOD, AND CONSEQUENCES

We review the main failure modes, likelihood of failure, and the consequences of failure of UGS in California. For the purposes of this section, failure is most commonly loss-of-containment (LOC), but it can also be damage to a well or other component that affects health and safety, the environment, or facility operations without LOC. The reason LOC is the main focus is that UGS involves containing through multiple repeated operations (compression, injection, storage, withdrawal, decompression, processing, utilization) of a highly flammable gas at very high pressure. In the subsurface part of UGS, well integrity and reservoir integrity are needed to contain natural gas. Well integrity failures can occur for many reasons, but failure of cement seals and corrosion of casing are two of the main causes of subsurface LOC. Reservoir integrity relies on caprock sealing and lack of transmissive faults, both of which have been known to fail at UGS systems in the past. In the surface part of UGS, failure can occur by damage to pipelines, valves, seals, and many other components relied upon to contain high-pressure gas in the aboveground infrastructure of UGS facilities. Some California UGS facilities identified here are located in regions with particular hazards, among which are seismic, landslide, flood, tsunami, and wildfire hazards, all of which are external events that can affect UGS infrastructure. Human and organizational factors are widely cited as a cause of incidents at industrial facilities such as UGS sites. The likelihood of failure of UGS facilities can be qualitatively estimated by the record of reported incidents in California, which suggests an incident of severity significant enough to have been reported will occur on average 4.1 times per year somewhere in California, and most of these incidents will be due to well integrity failures. But these statistics must be used cautiously, because the overall number of events is relatively small and reporting of incidents has not been regulated or standardized. The consequences of LOC incidents can be catastrophic, as in the case of large releases such as occur during well blowouts or flowline rupture with ignition, or they can occur without impacts to safety but with potential long-term impact to environment, as in the case of chronic low-flow-rate leakage of methane in the context of its role as a greenhouse gas. Dispersion of any emitted gas will occur by air entrainment and surface winds. The dispersion of leaked natural gas and resulting downwind concentrations relevant to ignition and explosivity can be modeled very accurately, provided that local wind and leakage flow rate data are available. Analysis of dispersion of leaked natural gas suggests that the footprint of methane concentrations between the lower and upper flammability limits can be expected to exceed the size of the clustered surface infrastructure (e.g., a compressor pad, gas-processing facility pad, or the clustered wellheads on pads of multiple deviated wells) for large but not impossible leakage fluxes, meaning that the surface infrastructure is vulnerable to explosion hazard. Subsurface leakage of natural gas, e.g., by annular overpressurization, can allow natural gas to flow into underground sources of drinking water (USDW) typically at much shallower levels than the storage reservoir. There are recorded incidents of natural gas leaking to surface that must have encountered USDW, although specifics of the impacts have not been assessed to our knowledge. In general, we believe adherence to the new regulations proposed by California Division of Oil, Gas and Geothermal Resources (DOGGR) will strongly reduce the likelihood of well integrity failures.

1.3 CAPACITY OF UGS SITES: EFFECTS OF AGE AND STORAGE INTEGRITY

The capacity of UGS reservoirs can be affected by the age of the facility through (i) the effects of formation damage and related reservoir processes, (ii) the loss of reservoir integrity through well or caprock seal failure. Any unintended impedance to the flow of fluids into or out of a wellbore (reduction in permeability) is referred to as formation damage (Petrowiki, 2017). Age-related processes affecting depleted oil and natural gas reservoirs include formation damage, grain alteration due to partially fluid-supported sediments, changes in reservoir pressure conditions, and changes in fluid contacts within the pore spaces of the reservoir. Of these, the factor with the greatest potential to affect storage capacity is formation damage, as it affects the productivity of a depleted oil and gas reservoir during gas withdrawal. Operators should carry out proactive approaches to identifying, addressing, and properly mitigating formation damage in advance of the reduction in formation permeability to avoid loss of gas storage reservoir capacity.

The majority of the depleted oil and gas fields converted to UGS in California were originally discovered and developed for oil and natural gas production from 1929 to 1958. Consequently, the majority of the wells used for UGS in California are older wells (see Section 1.1) and these have required extensive well work-overs targeting a variety of integrity-related issues, such as quantity and quality of cement and corrosion of casing.

Well work-overs, themselves, can provide inherent risk and have the potential for accidental releases. The age of these wells and historic well construction practices dramatically increase the likelihood for LOC. Five gas storage fields within the Los Angeles area have experienced gas migration issues due to age of the wells, improperly plugged and abandoned wells that served as avenues for gas migration out of the reservoir, and reliance on repurposed gas storage wells. At the depleted Montebello oilfield in Los Angeles, gas had been injected by SoCalGas at a depth of 7,500 feet since the early 1960s (Bruno, 2014). Gas injection ceased in 1986 after significant gas seeps were discovered at the surface within a large housing development above the gas storage reservoir (Khilyuk et al., 2000). Soil-gas analysis had detected the presence of imported and processed storage gas, several homes were purchased and demolished, and soil-gas extraction system was installed (Miyuzki, 2009).

When old wells are taken out of service due to age or integrity failures, the capacity of a gas storage reservoir is impacted unless new gas storage wells are drilled and completed to retain gas storage capacity and deliverability. Regarding effects on capacity of reservoir integrity in depleted oil and gas field storage operations, the initial confining zone/caprock is relatively secure, as evidenced by hydrocarbon retention (based on the thick cap that acts as a robust seal in preventing migration from the gas storage reservoir), but the seal can sometimes become degraded over time with repeated pressure and stress cycling. The maximum operational reservoir pressure may need to be reduced to manage reservoir integrity problems, thereby impacting capacity. By assessing gas storage reservoir integrity using a holistic approach (i.e., utilizing multiple methodologies such as geophysical logging and pressure testing), the number of incidents associated with loss of storage integrity can be dramatically reduced with the added benefit of maintaining storage capacity.

1.4 Human health hazards, risks, and impacts associated with underground gas storage in California

In Section 1.4, we assess the environmental, public, and occupational health hazards associated with underground gas storage (UGS) in California. We use four primary approaches: (1) an analysis of air toxic emission data reported to regional air districts and to the state; (2) a proximity analysis of populations near UGS facilities and their potential exposure to toxic air pollutants and natural gas fires and explosions using numbers, density, and demographics of people in proximity to UGS facilities and air dispersion modeling; (3) an assessment of air quality and human health impact datasets collected during the 2015 Aliso Canyon incident; and (4) an assessment of occupational health and safety hazards associated with UGS. The approach we take follows the general recommendations of the National Research Council to compile, analyze, and communicate the state of the science on the human health hazards associated with UGS in California.

Human health hazards of underground gas storage include exposures to toxic air pollutants as well as to explosions and fires during normal operations and/or large loss-of-containment (LOC) events. There is also a possibility of subsurface migration of gases and other fluids associated with gas storage into groundwater resources that may be used currently or in the future for drinking water and other uses that can form exposure pathways to people.

Our assessment of the scientific literature, available air pollutant emissions inventory, air pollution and human health monitoring datasets, and population characterization for community and occupational exposures indicate the following:

1. There are a number of human health hazards associated with UGS in California that are predominantly attributable to exposure to toxic air pollutants and gas-fueled fires or explosions during large LOC events. However, many UGS facilities also emit multiple health-damaging air pollutants during routine operations — formaldehyde in particular, which is of concern for the health of workers and nearby communities.

2. Large LOC events (e.g., the 2015 Aliso Canyon incident) can cause health symptoms and impacts in the nearby population and are a key challenge for risk management efforts.

3. UGS facilities located in areas of high population density and in close proximity to populations are more likely to cause larger population morbidity attributable to exposures to substances emitted to the air than facilities in areas of low population density or further away populations.

4. During large LOC events, if emitted gases are ignited, the explosion hazard zone at UGS facilities can extend beyond the geographic extent of the facility, creating flammability hazards to nearby populations.

5. Workers on site are likely exposed to higher concentrations of toxic chemicals during both routine and off-normal operations, and workers on site have greater chance of exposure to fire or explosions during LOC events.

6. There is uncertainty with respect to some of the mechanisms of human health harm related to the 2015 Aliso Canyon incident and other UGS LOC events in the future. This is mostly attributable to the lack of access to data on the composition of stored gas in the facilities and limitations of air quality and environmental monitoring during and after these events. While our research team attempted repeatedly to obtain the relevant gas composition data, we were unsuccessful.

7. California-specific as well as other peer-reviewed studies relevant to California on human health hazards associated with UGS facilities are critically scarce.

Multiple recommendations emerged from our research that could help to reduce the risk of UGS facilities in California, and would greatly benefit the effectiveness of risk managers to protect nearby human populations from the health risks of environmental exposures sourced from UGS facilities. Our recommendations include but are not limited to the following:

1. Require that the composition of gas withdrawn from the storage reservoir over time be disclosed, along with any chemical use on site that could be leaked, intentionally released, or entrained in gas or fluids during LOC events.

2. Require facility-specific meteorological (e.g., wind speed and direction) data-collection equipment be installed at all UGS facilities.[1]

3. Require that improvements to air quality and human health monitoring approaches be implemented both during routine operations and during LOC events.

4. Require that steps be taken to decrease exposure of nearby populations to toxic air pollutants emitted from UGS facilities during routine operations and LOC incidents. These steps could include the increased application and enforcement of emission control technologies to limit air pollutant emissions, the replacement of gas-powered compressors with electric-powered compressors to decrease emissions of formaldehyde, and the implementation of science-based minimum-surface setbacks between UGS facilities and human populations.

5. Require that UGS workplaces conform to requirements of CalOSHA and federal OSHA (Occupational Safety and Health) to protect the health and safety of on-site workers. On-site workers that include but are not limited to employees, temporary workers, independent contractors should fall under these regulations regardless if operators are legally bound to comply.

1.5 ATMOSPHERIC MONITORING FOR QUANTIFICATION OF GHG EMISSIONS AND UGS INTEGRITY ASSESSMENT IN CALIFORNIA

At the time the incident was discovered at Aliso Canyon in fall 2015, there was no reported quantitative operational monitoring program for ambient methane or other trace gases at Aliso Canyon (or any other UGS facility in California). A variety of methane measurement methods was deployed in the months that followed to improve confidence in the SS-25 well leak rate as it evolved in response to efforts to control the well and reduce reservoir pressure by gas withdrawal. These methods include complementary airborne surveys using low-altitude *in situ* sampling and high-altitude remote sensing as follows: (1) total methane emissions were determined using an aircraft equipped with a Picarro *in situ* methane analyzer flying cylindrical patterns around the facility, and (2) spatially resolved emissions from individual infrastructure components were estimated using an aircraft equipped with JPL's Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG). Both airborne methods have since been applied to other UGS facilities in California: total facility methane emissions were measured at selected facilities roughly 40 times from June 2014 through

1. The California Air Resources Board (CARB) implemented regulations effective October 1st, 2017 requiring continuous measurement of meteorological conditions at UGS facilities.

August 2017. Local methane emissions were measured roughly 80 times from January 2016 through August 2017 with the AVIRIS-NG method. UGS facilities are also subjected to daily surveys of all wellheads with hand-held gas analyzers, offering the ability to find small concentration anomalies at wellheads. Together, these measurements provide relevant information on current UGS facility emissions, discussed below in the context of greenhouse gas (GHG) emissions as well with regards to integrity implications.

In general, methane (CH_4) emissions from UGS facilities are a potential concern for climate change because methane is a powerful GHG. Methane emissions from the total California natural gas supply chain from production to combustion should be carefully controlled below ~3% of the total amount used if short-term (~20 yr) climate impacts are to be minimized. We compared the recent airborne measurements of methane emissions from gas storage facilities with annual GHG reporting by the UGS operators to the California Air Resources Board. Taken together, the mean emissions of roughly 1,060 kg/hr (~9.3 $GgCH_4$ (~0.5 Bcf annually)) from the active UGS facilities in California are approximately 7.8% of total natural gas-related methane emission estimated by the California Air Resources Board (CARB), and ~2.6 times the CARB estimate for gas storage-related methane emissions. Those emissions are dominated by three facilities: Honor Rancho, Aliso Canyon (after the SS-25 leak repair), and McDonald Island, which contribute 45%, 16%, and 14%, respectively, to the UGS total. We conclude that UGS-related methane emissions appear to be a small part of both California's methane and total GHG emission inventories. However, the ongoing methane emissions from California UGS facilities are roughly equivalent to having a 2015 Aliso Canyon incident every 10 years. This, combined with super-emitter (defined as anomalous relative to expectation) activity at three facilities, suggests a mitigation opportunity for meeting the state's short-lived climate pollutant mitigation targets in the natural gas sector.

Measurements of natural gas emissions at UGS facilities also provide an atmospheric tracer that can enable efforts to monitor the integrity of surface and subsurface infrastructure—potentially offering early warning to minimize the impact of leaks and avoid LOC and other hazardous situations for some failure modes. Methane in particular is both the primary constituent of natural gas and can be measured by a variety of methods to identify, diagnose, and guide responses to integrity issues. Methane emissions are also qualitatively indicative of emissions of toxic compounds (e.g., benzene), though relationships vary across reservoirs. There are many methane measurement methods that can be applied to UGS leak detection; however, they have differing capabilities and limitations. Several of these methods have been successfully demonstrated in operational field conditions at Aliso Canyon, Honor Rancho, and other facilities, including several examples that illustrate the potential for coordinated application of multiple synergistic observing system "tiers."

1.6 RISK MITIGATION AND MANAGEMENT

To address risk mitigation and management of UGS facilities in California, we carried out review and analysis of three related topics: (1) review of key elements that must be included in an effective risk management plan (RMP) for a UGS facility; (2) a discussion of potential additional practices that could improve UGS integrity; and (3) a review and evaluation of regulatory changes under way by DOGGR covering UGS integrity, with comments on the new California Air Resources Board (CARB) methane monitoring regulations for context. We outline the elements of a well-conceived site-specific RMP that must be based on a formal quantitative risk assessment (QRA), and we provide guidance on methodologies to perform rigorous risk assessment. We also provide guidance on a range of other attributes that a RMP must contain. Underlying effective risk management is the idea that there are risk targets or goals, the attainment of which guides risk mitigation activities. Our analysis includes a critique, with recommendations, of the draft DOGGR UGS regulation published May 19, 2017. Some of the specific recommendations relate to the requirements for a site-specific RMP at an UGS site, including the need for each UGS facility to perform a quantitative risk analysis, to perform regular training of the operational staff using written procedures, and to collect failure data and off-normal event data to be compiled in a publicly available database. The current DOGGR draft regulation should explicitly address the importance and role of human and organizational factors as well as safety culture. Another recommendation relates to the need for DOGGR or the industry to develop risk targets or goals to guide decision-making, while still other recommendations relate to specific sections of the draft regulations that require various monitoring and measurement activities to assess and mitigate well integrity issues.