# Long-Term Viability of Underground Natural Gas Storage in California

## An Independent Review of Scientific and Technical Information

Chapter 1, Section 1.4
Human health hazards, risks, and impacts associated with underground natural gas storage in California

Seth B.C. Shonkoff [1,2,3], Lee Ann L. Hill[1], Eliza D. Czolowski[4], Kuldeep Prasad[5], S. Katharine Hammond[3], and Thomas E. McKone[3,6]

*[1] PSE Healthy Energy, Oakland, CA; [2]Department of Environmental Science, Policy and Management, University of California, Berkeley, CA; [3]Energy Technologies Area, Lawrence Berkeley National Laboratory, Berkeley, CA; [4]PSE Healthy Energy, Ithaca, NY; [5]National Institute of Standards and Technology, Gaithersburg, MD; [6]School of Public Health, University of California, Berkeley, CA*

California Council on Science and Technology

December 2017

# Long-Term Viability of Underground Natural Gas Storage in California

## An Independent Review of Scientific and Technical Information


*Jane C.S. Long, PhD, Independent Consultant*
*Steering Committee Co-Chair*

*Jens T. Birkholzer, PhD, Lawrence Berkeley National Laboratory*
*Steering Committee Co-Chair*

*Amber J. Mace, PhD, California Council on Science and Technology*
*Project Director*

*Sarah E. Brady, PhD, California Council on Science and Technology*
*Project Manager*

*Steering Committee Members*

*J. Daniel Arthur, P.E., SPEC, ALL Consulting L.L.C*

*Riley M. Duren, P.E., NASA Jet Propulsion Laboratory*

*Karen Edson, retired California Independent System Operator*

*Robert B. Jackson, PhD, Stanford University*

*Michael L.B. Jerrett, PhD, University of California, Los Angeles*

*Najmedin Meshkati, PhD, University of Southern California*

*Scott A. Perfect, PhD, Lawrence Livermore National Laboratory*

*Terence Thorn, JKM Energy and Environmental Consulting*

*Samuel J. Traina, PhD, University of California, Merced*

*Michael W. Wara, PhD, Stanford Law School*

*Non-Voting Ex Officio Steering Committee Members*

*Catherine M. Elder, M.P.P; Aspen Environmental Group (Technical Expert)*

*Jeffery Greenblatt, PhD; Lawrence Berkeley National Laboratory (Author)*

*Curtis M. Oldenburg, PhD; Lawrence Berkeley National Laboratory (Author)*

**Acknowledgments**

This report has been prepared by the California Council on Science and Technology (CCST) with funding from the California Public Utilities Commission.

 ISBN Number: 978-1-930117-86-0 

**About CCST**

The California Council on Science and Technology is a nonpartisan, nonprofit organization established via the California State Legislature in 1988. CCST engages leading experts in science and technology to advise state policymakers- ensuring that California policy is strengthened and informed by scientific knowledge, research, and innovation. CCST responds to the Governor, the Legislature, and other State entities who request independent assessment of public policy issues affecting the State of California relating to science and technology.

**Note**

The California Council on Science and Technology (CCST) has made every reasonable effort to assure the accuracy of the information in this publication. However, the contents of this publication are subject to changes, omissions, and errors, and CCST does not accept responsibility for any inaccuracies that may occur.

For questions or comments on this publication contact: California Council on Science and Technology 1130 K Street, Suite 280 Sacramento, CA 95814

916-492-0996

ccst@ccst.us www.ccst.us

Layout by a Graphic Advantage! 3901 Carter Street #2, Riverside, CA 92501

www.agraphicadvantage.com

## 1.4 HUMAN HEALTH HAZARDS, RISKS, AND IMPACTS ASSOCIATED WITH UNDERGROUND GAS STORAGE IN CALIFORNIA

### 1.4.1 Abstract

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 from 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[3].

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

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

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 to protect the health and safety of on-site workers. On-site workers that include but are not limited to employees, temporary workers and independent contractors should fall under these regulations regardless if operators are legally bound to comply.

### 1.4.2 Introduction

Section 1.2 of this report describes a number of underground gas storage (UGS) release mechanisms of high-pressure gas from the surface and subsurface parts of UGS systems. In this section, we extend the discussion of these potential emissions and releases to the environment to assess population exposures and summarize the associated hazards in the context of community and occupational health.

The documented human health hazards associated with UGS facilities include exposure to toxic air pollutants. These air-pollutant species are emitted through intentional and unintentional releases at and near the facility during normal operations, and minor and major loss-of-containment (LOC) incidents. Because of uncertainties about emissions and dispersion, addressing exposures and health impacts from LOC incidents is a major challenge for risk management. Another obvious human health concern for UGS facilities is the risk of exposure to fires, explosions, and secondary conflagrations attributable to the ignition of flammable natural gas, especially during large LOC events.

The human health hazards and risks from UGS facilities depend on the following factors:

a. Composition of stored, withdrawn, and stripped and compressed gas

b. Depleted hydrocarbon reservoir (DHR) type (e.g., depleted gas (DG) or depleted oil (DO))

c. Age and mechanical integrity of the subsurface and surface infrastructure

d. Type and number of gas compressors

e. Long-term expected emissions rate of chemical constituents from the wells

f. Magnitude and duration of emissions during LOC incidents

g. Atmospheric dispersion conditions during the period of release[4]

h. Number and density of gas storage, oil and gas production, and other wells in the vicinity of a loss of zonal isolation (i.e., subsurface LOC)

i. Activities, work and break locations of on-site workers and contractors

j. Location and density of downwind populations

k. Location of sensitive populations as represented by the very young, the elderly, women of childbearing age, schools, child care facilities, hospitals, and elderly care facilities in relation to the UGS facility; and

l. Prevalence of groundwater aquifers proximal to UGS facilities.

The approach we take to assess human health hazards and impacts follows the general recommendations of the National Research Council (1983; 1994; 1996; 2009) to compile, analyze, and communicate the state of the science on the human health hazards associated with UGS in California.

We divide our assessment on the public health dimensions of UGS storage into four approaches.

1. **Bottom-up approach using emissions inventories:** We first employ a bottom-up approach to explore hazards associated with UGS following the standard hazard assessment framework. In this approach, we characterize available data on the routine and off-normal emissions profiles of UGS facilities in California, and then identify chemical-specific human-health-relevant toxicity data, where available, and discuss chemical hazards based on annual mass emitted and toxicity.

2. **Identification and assessment of source-receptor relationships:** Our second approach to assessing public health hazards of UGS facilities uses source-receptor relationships and air dispersion modeling for routine emissions and LOC incidents. We employ source-receptor relationships to assess the physical hazards associated with explosion and flammability potential at UGS facilities in the case of large LOC incidents. In this approach, we evaluate potential exposures of nearby populations and other sensitive receptors to air pollutants emissions and potential fires and explosions from UGS facilities.

4. In the case of large emissions of flammable gases, atmospheric concentration and flammability of the gas and ignition source potential are the factors that determine the health and safety risks and impacts of fire/explosion.

3. **Aliso Canyon UGS Facility well blowout LOC Case Study:** We examine the 2015 Aliso Canyon incident involving the SS-25 well blowout as a community- and occupational-health case study of a large LOC incident. In this case study, we review and assess the air, environment, and human health impacts monitoring that occurred in the community nearby the Aliso Canyon storage facility and report findings, conclusions, and data gaps.

4. **Occupational aspects of UGS in California:** Finally, we examine the occupational health dimensions of UGS in California, identifying health and safety hazards facing workers in the context of routine activities and large LOC events (e.g., the 2015 Aliso Canyon incident).

We conclude this section with a summary of our key findings and conclusions as well as our policy and future research recommendations.

### 1.4.3 Framing the Hazard and Risk Assessment Process

Evidence-based policy and risk management plans for UGS sites require information on the hazards, risks, and impacts posed by these facilities. The terms *hazard*, *risk*, and *impact* are often used interchangeably in everyday conversation, whereas in a regulatory context they represent distinctly different concepts with regard to the formal practice of risk assessment and risk management. A *hazard* is defined as any biological, chemical, mechanical, environmental, or physical stressor that is reasonably likely to cause harm or damage to humans, other organisms, the environment, and/or engineered systems in the absence of control (Sperber, 2001). *Risk* is the probability that a given hazard plays out in a scenario that causes a particular harm, loss, or damage. (National Research Council, 2009). *Impact* is the particular harm, loss, or damage that is experienced if the risk-based scenario occurs. In the context of impacts related to exposure to radiation, food, water, or air, *hazard* can be considered an intrinsic property of a stressor that can be assessed through some biological or chemical assay. For example, a pH meter can measure acidity, particle disintegration counters can detect ionizing radiation, cell or whole animal assays, etc., can detect biological disease potency. These types of tests allow us to declare that a substance is acidic, radioactive, a mutagen, a carcinogen, or other hazard. *Hazard* can also refer to the potential for physical harm, as for example occurs when a person is exposed to fire or a collapsing building. However, defining the probability of harm requires a receptor (e.g., human population or high-value resource) to be exposed to the hazard, and often depends on the vulnerability of the population (or receptor based on age, gender, and other factors). As a result, risk is extrinsic and requires detailed knowledge (scenarios) about how a stressor agent (hazard) is handled, released, and transported to the receptor populations. In its widely cited 1983 report, the National Research Council first laid out the now-standard risk-analysis framework consisting of research, risk assessment, and risk management as illustrated in Figure 1.4-1 (National Research Council, 1983). The National Research Council proposed this framework to organize and evaluate existing scientific information for the purpose of decision-making. In 2009, the National Research Council issued an

updated version of its risk assessment guidance titled "Science and Decisions: Advancing Risk Assessment" (National Research Council, 2009). This report reiterated the value of the framework illustrated in Figure 1.4-1, but expanded it to include a solutions-based format that integrates planning and decision-making with the risk-characterization process. The National Research Council risk framework illustrates the parallel activities that take place during risk assessment and the reliance of all activities on existing research. These activities combine through the risk characterization process to support risk management.

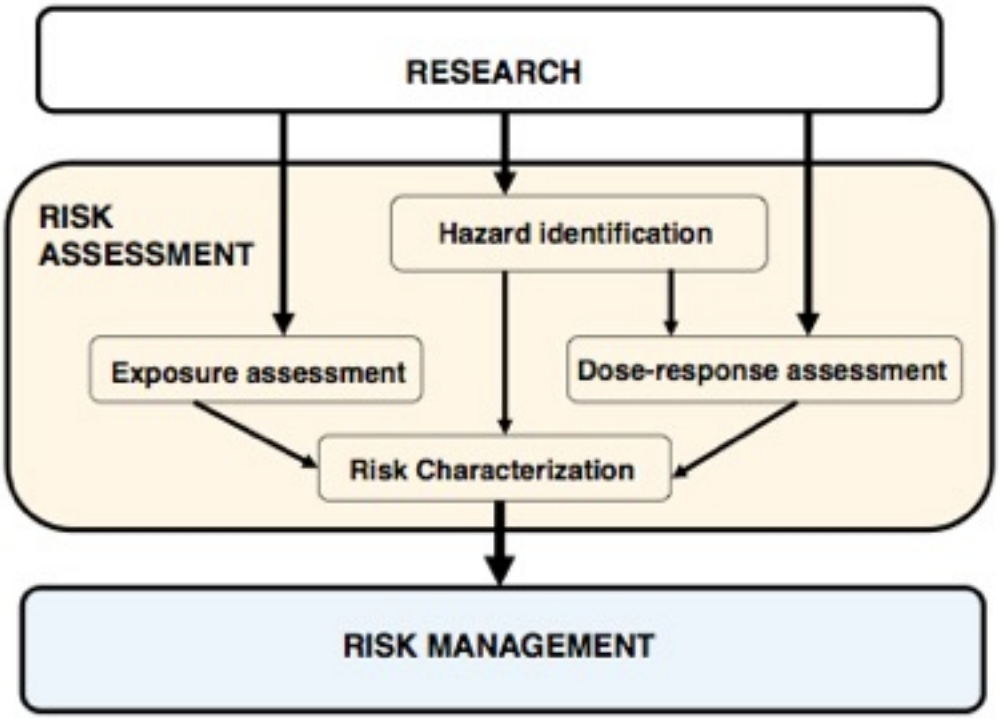


***Figure 1.4-1. The National Research Council (1983) Risk Analysis Framework.***

In using the framework in Figure 1.4-1, the first task in the risk analysis process is to identify features, events, and processes (FEPs) associated with an activity that could cause harm. These are called *hazards*. Any given hazard may or may not be a problem. It depends on the answers to two additional questions. First, is the hazardous condition likely to result in a population being exposed to the hazard? Second, what will be the impact if the hazardous exposure does occur (dose-response)? If we know the magnitude of a specific hazard exposure and the relationship between the magnitude of exposure and response or harm, then we can estimate the risk associated with that hazard. In cases where the hazardous condition is unlikely or where, even if it did occur, the harm is insignificant, then the risk is low. Risk is only high when the hazardous condition is both likely to occur and would cause

significant harm if it did occur. Of course, there are many combinations of likelihood and harm possible.

Formal risk analysis presents difficulties, because we often lack:

- Data on all the possible hazards
- Comprehensive understanding and definition of all of the failure scenarios
- Information on the likelihood and magnitude of exposure
- Data to support an understanding of the relationship between exposure (dose) and harm (response).

If a hazard has not been identified, then it is difficult to develop steps to mitigate potential harm in a risk management plan. In this case, a useful approach is to avoid the problem where possible, for example by choosing chemicals that are better understood, less toxic, or more controllable rather than choosing ones for which there is little toxicity information or poor understanding of the relationship between the hazard and risk to the environment and/or to public health. Options for addressing hazards when information is missing are discussed more in Section 1.6, which presents recommendations for risk management.

Although one can attempt to identify *all* hazards associated with UGS in California, it is important to note that this does not mean that all hazards that are identified present risks. A formal risk assessment is required to estimate risk associated with any given hazard. A formal risk assessment is a significant site-specific undertaking that is beyond what was possible in this report. However, this section, along with Section 1.6, describes the structure and content of a site-specific risk assessment for UGS sites. Among the goals of this section are to identify community and occupational hazards and highlight those where additional study may be warranted in the context of developing and implementing risk management and mitigation options for UGS operations.

### 1.4.4 Scope of and Approach to Community and Occupational Health Assessments

#### 1.4.4.1 Community Health Assessment Scope and Approach

This community health assessment (Section 1.4.7, 1.4.8, 1.4.10) evaluates health and safety hazards to communities near UGS facilities in California considering two emissions scenarios, routine and off-normal (e.g., loss-of-containment). The routine emissions scenario includes routine and modest but continuous or periodic (e.g., blow down of tanks and other equipment) emissions, while the off-normal emissions scenario includes a massive LOC release (e.g., the 2015 Aliso Canyon incident). For both scenarios, there are health and safety hazards to consider.

Regardless of the emissions scenario, a conservative approach is taken to estimate population and sensitive receptor (e.g., schools, daycare centers, elderly care facilities, etc.) exposure potential. We use radially symmetric buffers to identify potentially exposed populations near to actual California UGS facilities, regardless of average meteorological conditions. This conservative approach assumes that emissions—whenever they occur—may be dispersed in any direction by the currently prevailing winds and to various distances from each UGS facility.

We created the buffers using a two-tiered approach. Tier 1 includes any open (active or idle) wells within gas storage reservoirs. Tier 2 includes any well (active, idle, or plugged) in the field area that could serve as a potential conduit for gas migration.

At various buffer distances, we identify populations with potential for exposure from UGS facility emissions using total population counts. We also identify vulnerable populations and sensitive receptors, including schools, elderly care facilities, and daycare facilities located within buffers at various distances from each UGS facility.

During routine operations, the majority of methane emissions and co-emitted health-damaging air pollutant species come from above-ground infrastructure (see Section 1.5). However, given uncertain spatial estimates of above-ground infrastructure (e.g., compressor stations), this community health assessment assumes that compressors and other relevant above-ground infrastructure are located within the two-tiered boundaries created using well locations.

We lack detailed emissions information and gas composition data from the California UGS facilities to model dispersion of specific toxic air pollutants. To further clarify our community health assessment methodology, we use annual average wind roses and create asymmetric contours to identify how emissions are likely to disperse under average meteorological conditions. We then calculate the relative concentration of air pollutants/mass flow rate of emissions across space to spatially depict relative hazard in terms of exposure to nearby populations. We also use methane emissions data to model dispersion of methane at each site and to better estimate flammability and/or explosive potential (see Section 1.5). Finally, we include an assessment of the human health hazards and impacts of the Aliso Canyon SS-25 LOC event using available data.

#### 1.4.4.2 Occupational Health Assessment Scope and Approach

This occupational health assessment (Section 1.4.11) evaluates health and safety hazards to on-site workers at UGS facilities in California, including employees and contracted or temporary workers (contractors). The assessment in this section considers health and safety hazards associated with most routine and off-normal emissions scenarios, including LOC events. As with the community health assessment, the occupational health assessment focuses on health and safety hazards from potential exposures to toxic air pollutants, fire, and explosions.

Similar to the community health assessment, the lack of detailed emissions information and gas composition data from California UGS facilities limited the scope and detail of our assessment. Additionally, a lack of access to occupational air-monitoring data limited our capacity to consider whether on-site exposures posed a health risk to workers. Information was gathered from a variety of sources, including UGS facility site visits, operators, and state agencies.

### 1.4.5 Toxic Air Pollutant Emissions from UGS Facilities

UGS facilities emit compounds into the air that can come into contact with workers and nearby populations. Stored or pipeline gas may be released into ambient air intentionally (e.g., blowdowns) or accidentally (e.g., leaks, large LOC events). While natural gas is primarily methane ($CH_4$), a wide variety of substances are admixed with injected natural gas during residence in underground storage reservoirs in California, in particular in the depleted oil (DO) reservoirs. While the majority of these contaminants are removed during gas processing before delivery back into the natural gas distribution system, they can be emitted to the atmosphere/environment in the case where natural gas leaks out of the reservoir or any component of the surface infrastructure (e.g., flowline(s)) prior to gas processing, as occurred during the 2015 Aliso Canyon incident. Aboveground infrastructure, including compressor stations, also emit compounds into the ambient air during normal operations. This section uses available information from emissions inventories and available toxicity information to (1) identify known pollutants historically emitted from UGS facilities in California, (2) discuss acute and chronic toxicity for non-cancer and cancer endpoints associated with the identified chemicals, and (3) prioritize chemicals known to be emitted from UGS facilities by annual mass emitted and toxicity for future monitoring and risk assessment considerations. Data gaps and limitations are discussed.

#### 1.4.5.1 Characterization of UGS Facility Emissions

The California Air Toxics "Hot Spots" Information and Assessment Act (AB 2588) of 1987 requires quantification of emissions from stationary sources, including UGS facilities. The Air Toxics Hot Spots Program requires facilities to update emissions inventory data at least every four years, and requires reporting of both criteria pollutants (e.g., nitrogen oxides, sulfur oxides, carbon monoxide) and other toxic air pollutants that present a chronic or acute threat to public health. The California Air Resources Board (CARB) compiles and maintains a list of substances that must be reported under AB 2588, and evaluates substances listed by various government and scientific bodies (e.g., National Toxicology Program, International Agency for Research on Cancer, etc.) (CARB, 2016c). A full list of substances for which emissions must be quantified is presented in Appendix 1.A of the Emission Inventory Criteria and Guidelines Report (CARB, 2007).

UGS facilities report annual emissions by mass for criteria pollutants (tons/year) and toxic air pollutants (pounds/year) to regional air districts. Annual emissions by facility are then compiled by CARB and made publicly available via a Facility Search Engine (CARB,

2017a). South Coast Air Quality Management District (SCAQMD) also makes emissions data for facilities in their regional district publicly available through the Facility Emissions Search Tool (SCAQMD, 2017b). Of California UGS facilities in California, three operational facilities (Aliso Canyon, Honor Rancho, Playa del Rey) and one former facility that has indications of continued use (Montebello) are located within the SCAQMD, and have emissions reported online through both SCAQMD and CARB.

Emissions reporting may vary by regional air district. Facilities may report emissions from equipment (compressors, storage tanks, dehydrators, etc.) and processes using site-specific factors or default factors, if available. Routine (e.g., maintenance, blowdowns) and non-routine (shutdown, spills, equipment breakdown, etc.) are included in annual reporting, and facilities may be required to report emissions from all permitted and non-permitted equipment and processes. Facilities also may have the option to aggregate similar combustion sources (same type, same rating, same type of fuel). Air districts then calculate annual emissions based on throughput from the facility and reported natural gas releases.[5] Emissions from trucks associated with UGS facilities are not captured in the facility-specific emissions inventories. In SCAQMD, facilities are required to estimate annual emissions, even if no emissions fees are due, and to pay corresponding emissions fees if they exceed the thresholds. Operation profiles by equipment are not required for reporting (SCAQMD, 2014).

***Data Availability***

As of June 2017, SCAQMD reported emissions for UGS facilities from 2000 through 2016. CARB reported data for criteria pollutants for UGS facilities from 1987-2016, while toxic air pollutants data were available from 1996 through 2016. Between March and June 2017, data were extracted from the SCAQMD and CARB facility reporting tools using Facility ID to identify UGS facilities. SCAQMD data were copied directly from online tables, and CARB data were downloaded in available Excel files. Publicly available data were included in this assessment for emissions from on-site stationary sources. Emissions from mobile sources (e.g., trucking) are not publicly available for each facility. Table 1.4-1 and Table 1.4-2 show emissions data availability for criteria pollutants and toxic air pollutants by UGS facility and by year. Note that this discussion pertains to emissions (rates) rather than concentrations, which are required to be measured at wellheads and attached pipelines by CARB regulations (CARB, 2017c) for use in detecting leakage rather than quantifying the leakage rate.

5. Personal Communication, South Coast Air Quality Management District (SCAQMD). June 13, 2017; Personal Communication, Colusa County Air Pollution Control District. June 26, 2017; Personal Communication, Yolo-Solano Air Quality Management District. June 13, 2017

*Table 1.4-1. Criteria pollutant emissions data availability for UGS facilities in California. Data sources are specified when data are available from CARB or SCAQMD. Green = data available from one emissions inventory; red = no data available; yellow = data available from both CARB and SCAQMD; grey = site not in operation.*

| | FACILITY NAME | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **YEAR** | Aliso Canyon | Princeton Gas | Gill Ranch | Goleta | Honor Rancho | Lodi Gas | Kirby Hill | Los Medanos | McDonald Island | Montebello | Playa del Rey | Pleasant Creek | Wild Goose |
| **2016** | SCAQMD | | | | SCAQMD | | | | | SCAQMD | SCAQMD | | |
| **2015** | SCAQMD | CARB | CARB | CARB | | CARB | CARB | CARB | CARB | | | CARB | CARB |
| **2014** | | CARB | CARB | CARB | | CARB | CARB | CARB | CARB | | | CARB | CARB |
| **2013** | | CARB | CARB | CARB | | CARB | CARB | CARB | CARB | | | CARB | CARB |
| **2012** | | CARB | CARB | CARB | | CARB | CARB | CARB | CARB | | | CARB | CARB |
| **2011** | | | | CARB | | CARB | CARB | CARB | CARB | | | CARB | CARB |
| **2010** | | | | CARB | | CARB | CARB | CARB | CARB | | | CARB | CARB |
| **2009** | | | | CARB | | CARB | CARB | CARB | CARB | | | CARB | CARB |
| **2008** | | | | CARB | | CARB | CARB | CARB | CARB | | | CARB | CARB |
| **2007** | | | | CARB | | CARB | | CARB | CARB | | | CARB | CARB |
| **2006** | | | | CARB | | CARB | | CARB | CARB | | | CARB | CARB |
| **2005** | | | | | | CARB | | CARB | CARB | | | CARB | CARB |
| **2004** | | | | | | CARB | | CARB | CARB | | | CARB | CARB |
| **2003** | | | | | | CARB | | CARB | CARB | | | CARB | |
| **2002** | | | | | | | | CARB | | | | CARB | |
| **2001** | | | | CARB | | | | CARB | CARB | | | CARB | |
| **2000** | | | | CARB | CARB | | | CARB | CARB | | CARB | CARB | |
| **1999** | CARB | | | CARB | CARB | | | CARB | CARB | CARB | CARB | CARB | |
| **1998** | CARB | | | CARB | CARB | | | CARB | CARB | CARB | CARB | CARB | |
| **1997** | CARB | | | CARB | CARB | | | CARB | CARB | CARB | CARB | | |
| **1996** | CARB | | | CARB | CARB | | | CARB | CARB | CARB | CARB | | |
| **1995** | CARB | | | CARB | CARB | | | CARB | CARB | CARB | CARB | | |
| **1993** | CARB | | | CARB | CARB | | | CARB | CARB | CARB | CARB | | |
| **1990** | CARB | | | CARB | CARB | | | CARB | | CARB | CARB | | |
| **1987** | CARB | | | CARB | CARB | | | CARB | | CARB | CARB | | |

*Table 1.4-2. Toxic air pollutant emission data availability for UGS facilities in California. Data sources are specified when data are available from California Air Resources Board (CARB) or South Coast Air Quality Management District (SCAQMD). Green = data available for one emissions inventory; red = no data available; yellow = data available from both CARB and SCAQMD; grey = site not in operation.*

| | FACILITY NAME | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **YEAR** | Aliso Canyon | Princeton Gas | Gill Ranch | Goleta | Honor Rancho | Lodi Gas | Kirby Hill | Los Medanos | McDonald Island | Montebello | Playa del Rey | Pleasant Creek | Wild Goose |
| **2016** | SCAQMD | | | | SCAQMD | | | | | SCAQMD | SCAQMD | | |
| **2015** | SCAQMD | CARB | CARB | CARB | | CARB | | | CARB | | | | CARB |
| **2014** | | CARB | CARB | CARB | | CARB | CARB | CARB | CARB | | | | CARB |
| **2013** | | CARB | CARB | CARB | | CARB | CARB | CARB | CARB | | | | CARB |
| **2012** | | CARB | CARB | CARB | | CARB | CARB | CARB | CARB | | | | CARB |
| **2011** | | | | CARB | | CARB | CARB | CARB | CARB | | | | CARB |
| **2010** | | | | CARB | | CARB | CARB | CARB | CARB | | | | CARB |
| **2009** | | | | CARB | | CARB | CARB | CARB | CARB | | | | CARB |
| **2008** | | | | CARB | | CARB | CARB | CARB | CARB | | | | CARB |
| **2007** | | | | CARB | | CARB | | CARB | CARB | | | | CARB |
| **2006** | | | | CARB | | CARB | | CARB | CARB | | | | CARB |
| **2005** | | | | | | | | CARB | CARB | | | | CARB |
| **2004** | | | | | | | | CARB | | | | | CARB |
| **2003** | | | | | | | | CARB | | | | | |
| **2002** | | | | | | | | CARB | | | | | |
| **2001** | | | | CARB | | | | CARB | | | | | |
| **2000** | | | | CARB | | | | CARB | | | CARB | | |
| **1999** | CARB | | | CARB | CARB | | | CARB | | CARB | CARB | | |
| **1998** | CARB | | | CARB | CARB | | | CARB | | CARB | CARB | | |
| **1997** | CARB | | | CARB | CARB | | | CARB | | CARB | CARB | | |
| **1996** | CARB | | | CARB | CARB | | | CARB | | CARB | CARB | | |

### *Data Discrepancies*

Pollutant reporting varied by facility, by reporting agency, and by year. Certain facilities report only a few toxic air pollutants (e.g., Wild Goose, $n < 2$), while other facilities report a wider array of toxic air pollutants (e.g., Aliso Canyon, $n > 30$). These differences may be due to storage reservoir type (e.g., depleted oil vs. gas) or equipment used on site (e.g. gas-powered vs. electric-powered compressors); however, gas composition data and equipment-specific emissions reporting data are needed to explain differences between facilities. Data reported by SCAQMD and CARB for the same year and same facility also may differ (Table 1.4-3). Data vary in number of significant figures (decimal places) reported, due to the different way data are made publicly available (e.g., online tables, Excel files). Most emissions are determined using algorithms. This can be problematic, considering that

*in situ* monitoring of Honor Rancho and McDonald Island methane emissions suggests that emissions are 2.5 to 5 times higher than what is reported in the inventories, as discussed in Section 1.5.

***Table 1.4-3. Differences in reported annual emissions (pounds/year) between CARB and SCAQMD in 2015 for Playa del Rey, a UGS facility.***

| | | Playa del Rey Emissions (pounds/year) | |
|---|---|---|---|
| **CASRN** | **Pollutant Name** | **CARB** | **SCAQMD** |
| 7664-41-7 | Ammonia | 5110 | 239 |
| 71-43-2 | Benzene | 682 | 256 |
| 100-41-4 | Ethylbenzene | 129 | 78.1 |
| 110-54-3 | Hexane | 380 | 115 |

Data also vary by regulatory definition of pollutants. Lead is federally designated as a criteria pollutant, but is also listed as a toxic air contaminant (TAC) by the State of California. In the emissions inventories, lead is listed as a toxic air pollutant rather than a criteria pollutant. Methane, a potent greenhouse gas and the primary component of natural gas, is not required for reporting through the Air Toxics Hot Spots Program; however, methane was reported infrequently in the emissions inventories by a few UGS facilities. Pollutants are discussed as they are reported in the emissions inventories, as specified by the Air Toxics Hot Spots Program.

CARB and SCAQMD report pollutant ID, pollutant name, and annual mass emitted in tons or pounds. Pollutant ID aligns with Chemical Abstract Service Registry Number (CASRN), a unique numerical chemical identifier, unless the pollutant reported is a broad pollutant grouping (e.g., total organic gases (TOG), reactive organic gases (ROG)). Pollutant ID was available for all pollutants reported through emissions inventories, and was verified using Appendix 1.A of the Emission Inventory Criteria and Guidelines Report (CARB, 2007). CASRN were then assigned using pollutant ID or pollutant name using the Common Chemistry CAS Lookup tool maintained by the American Chemical Society (ACS, 2017).

Given data variability over time and at different UGS facilities, this assessment evaluates chemicals emitted from *any* UGS facility in California rather than focusing on facility-specific emissions. Facility-specific emissions summary tables can be found in Appendix 1.C.

***Top Pollutants Historically Emitted by Mass***

We examined pollutants historically emitted by mass across all UGS facilities in California from 1987 through 2015. Emissions data for 2016 were excluded, because data were unavailable for most UGS facilities. Emissions data were manually extracted from CARB through downloadable Excel files; if data were unavailable through CARB but were available through SCAQMD, data were extracted SCAQMD online tables. Criteria pollutant emissions reported by tons/year were converted to pounds/year to compare annual criteria and toxic air pollutant emissions. Pollutants were then sorted from highest to lowest

median annual emissions years reported across all UGS facilities between 1987 and 2015. A summary of available emissions data including criteria pollutants, toxic air pollutants, and pollutant groupings is presented in Appendix 1.C, Table 1.C-1

***Pollutant Groupings***

Fourteen broad pollutant groupings were reported by UGS facilities between 1987 and 2015. These broad groupings include multiple unique chemicals. Broad pollutant groupings reported by UGS facilities include total organic gases (TOG), reactive organic gases (ROG), total suspended particles (TSP), volatile organic compounds (VOC), and polycyclic aromatic hydrocarbons (PAH). Many pollutant groupings may contain individual chemicals with health significance; for example, reactive organic gases include ozone precursors, which present a respiratory hazard. However, given that these pollutant groupings contain multiple pollutants, each with differing annual emissions and toxicity, these 14 pollutant groupings were excluded from further analysis.

***Criteria Pollutants***

Criteria pollutants are found across the United States and are known to harm human health and the environment. The Clean Air Act requires the U.S. EPA to set National Ambient Air Quality Standards (NAAQS) for six criteria pollutants: nitrogen oxides, sulfur oxides, particulate matter (PM), carbon monoxide, ground-level ozone, and lead (U.S. EPA, 2017a). However, lead is listed as a toxic air pollutant under the Air Toxics Hot Spots Program, and ground-level ozone is not required for reporting in emissions inventories, and therefore is not included in this analysis. Criteria pollutant emissions in the Air Toxics Hot Spots Program were reported in tons per year and were converted to pounds per year to compare emissions across all pollutants. Criteria pollutant emissions data are included from 1987 through 2015.

***Toxic Air Pollutants***

Toxic air pollutants are reported from 1996 through 2015. Toxic air pollutants include those listed in Appendix 1.A of the Emissions Inventory Criteria and Guidelines Report that present a chronic or acute threat to public health (CARB, 2007; CARB, 2016c). Methane emissions were reported under the toxic air-pollutant designation by a few UGS facilities, but given that methane is not required for reporting under the Air Toxics Hot Spots Program as a compound that presents a threat to public health, it was removed from further analysis.

***Top Pollutants Historically Emitted by Mass***

Ninety-eight compounds (criteria, toxic, and pollutant groupings) were reported as emitted from UGS facilities in California between 1987 and 2015. Pollutant groupings (e.g., total organic gases, reactive organic gases) and criteria pollutants (e.g., nitrogen oxides,

sulfur oxides) were often ranked as the highest emitted compounds by mass. See full list in Appendix 1.C, Table 1.C-1. The health significance of these compounds is discussed in Section 1.4.6.

To identify and compare *specific* chemical compounds historically emitted by mass from UGS facilities in California, this analysis includes individual criteria and toxic air pollutants designated under the Air Toxics Hot Spots Program, but excludes broad chemical groupings. One criteria pollutant (carbon monoxide) and 82 toxic air pollutants were identified using classification by the Air Toxics Hot Spots Program. Compounds included polycyclic aromatic hydrocarbons (PAHs), nonmetals (excluding PAHs), and metals. The 83 pollutants, from here on referred to as "toxic air pollutants," were ranked by median annual emissions (pounds/year) that were calculated across UGS facilities and across all years of available data between 1987 and 2015. The top 25 toxic air pollutants historically reported by mass from UGS facilities are shown in Table 1.4-4. The health relevance of highly emitted compounds by mass is discussed in Section 1.4.6.

***Table 1.4-4. Top 25 toxic air pollutants historically emitted from UGS facilities from 1987 to 2015, ranked by median annual emissions (pounds/year).***

| | | Emissions (pounds/year) | | | |
|---|---|---|---|---|---|
| **Chemical Name[1]** | **CASRN[2]** | **Median** | **Min** | **Max** | **Toxic Air Contaminant (TAC)** |
| Carbon monoxide | 630-08-0 | 45,360 | 192 | 838,656 | N |
| Formaldehyde | 50-00-0 | 3,159 | 0.2 | 27,296 | Y |
| Ammonia | 7664-41-7 | 996 | 0.1 | 33,907 | N |
| Acetaldehyde | 75-07-0 | 392 | 0.0 | 4,499 | Y |
| Hexane | 110-54-3 | 250 | 0.2 | 7,638 | Y |
| Propylene | 115-07-1 | 245 | 7 | 9,608 | N |
| Methanol | 67-56-1 | 213 | 0.04 | 1,515 | Y |
| Acrolein | 107-02-8 | 206 | 0.02 | 2,833 | Y |
| Toluene | 108-88-3 | 198 | 0.002 | 2,246 | Y |
| m-Xylene | 108-38-3 | 190 | 0.2 | 801 | Y |
| Benzene | 71-43-2 | 171 | 0.04 | 1,970 | Y |
| Xylenes[1] | 1330-20-7 | 72 | 0.02 | 893 | Y |
| 1,2,4-Trimethylbenzene | 95-63-6 | 69 | 0.3 | 325 | N |
| 1,3-Butadiene | 106-99-0 | 57 | 0.004 | 244 | Y |
| Perchloroethylene | 127-18-4 | 51 | 24 | 277 | Y |
| Propylene oxide | 75-56-9 | 45 | 28 | 45 | Y |
| Trichloroethylene | 79-01-6 | 44 | 0.05 | 102 | Y |

1 Chemical grouping (xylenes) included for further analysis because it has health-based benchmark values established by federal and state agencies (Section 1.4.6).

2 Pollutant ID reported rather than CASRN.

| Chemical Name[1] | CASRN[2] | Emissions (pounds/year) Median | Min | Max | Toxic Air Contaminant (TAC) |
|---|---|---|---|---|---|
| Ethylene glycol | 107-21-1 | 27 | 11 | 40 | Y |
| Ethylbenzene | 100-41-4 | 25 | 0.01 | 291 | Y |
| Naphthalene | 91-20-3 | 24 | 0.002 | 106 | Y |
| 2,2,4-Trimethylpentane | 540-84-1 | 21 | 1 | 36 | Y |
| Silica, crystalline | 1175[2] | 18.3 | 18 | 18 | N |
| Biphenyl | 92-52-4 | 17.8 | 5 | 31 | Y |
| Diethylene glycol monobutyl ether | 112-34-5 | 12.9 | 12.9 | 12.9 | N |
| Phosphorus | 7723-14-0 | 12.7 | 3 | 23 | N |

1 Chemical grouping (xylenes) included for further analysis because it has health-based benchmark values established by federal and state agencies (Section 1.4.6).

2 Pollutant ID reported rather than CASRN.

Carbon monoxide, ammonia, and formaldehyde are the highest emitted toxic air pollutants historically emitted from UGS facilities in California. This trend is evident for each year in which compounds are reported between 1987 to 2015 (data not shown). Compounds with median annual emissions in excess of 200 pounds per year include hexane, acetaldehyde, propylene, methanol, and acrolein. Based on reporting requirements through the Air Toxics Hot Spots Program, compounds required for reporting through emissions inventories are anticipated to have health relevance and are associated with adverse health outcomes. Additionally, many pollutants reported in the emissions inventories are toxic air contaminants (TACs), air pollutants that may cause or contribute to an increase in mortality or in serious illness, or that may pose a present or future hazard to human health (California Legislative Information, 2017; Table 1.4-4). However, annual emissions do not provide mass fraction information (concentration) or spatial and temporal detail, which are necessary to conduct a detailed exposure or risk assessment. In summary, we observe that reported emissions as shown in Table 1.4-4 indicate chemicals of concern associated with UGS and provide a basis for setting priorities, but do not provide information on the concentration of these species in the stored gas or other emissions associated with UGS. This key input is needed to assess whether exposures from routine and LOC events are within health guidelines or high enough to require intervention.

### 1.4.6 Toxicity of Chemical Components with Public Health Relevance

#### 1.4.6.1 Approach to Ranking the Human Health Hazards of Chemicals Reported to Emissions Inventories

Chemical hazards stem from naturally occurring chemicals in storage reservoirs, chemicals used in maintenance for injection and production activities at UGS facilities, and chemicals used in the processing of stored gas to restore its quality as it is delivered to the transmission pipeline. Natural gas that is stored, processed, and distributed from UGS facilities contains

various chemical compounds, a number of which are associated with adverse health outcomes.

This section uses a bottom-up approach to explore chemical hazards associated with UGS in California. Given data availability and limitations, this approach focuses on chemical *hazards* that are likely to cause harm, rather than focusing on *risk*, the probability of a hazard to cause health harm (see Section 1.4.3).

For 83 individual pollutants reported as emitted by UGS facilities in California (including, but not limited to those listed in Table 1.4-4), we evaluate chemical hazards by (1) using annual mass emitted and *chronic* toxicity-weights to identify priority chemicals for future monitoring and risk assessment considerations; and (2) identifying chemical-specific, human-health-relevant *acute* toxicity data, where available, and discuss priority acute toxicants associated with UGS in California, which may be particularly relevant when discussing large LOC events.

***Toxicity-Based Emissions Ranking Approach***

In addition to evaluating mass of emissions from UGS facilities, it is important to also evaluate toxic potency of individual chemicals. Toxicity can be characterized as acute (short-term consequences from a single exposure or multiple exposures over a short period) or chronic (long-term consequences from continuous or repeated exposures over a longer period). Because of the significant number of chemical combinations required and lack of toxicological studies for most combinations, it was not feasible for us to evaluate the potential synergistic hazards with multiple pollutants. Even with high emissions and elevated toxicity, an exposure pathway is required to bring a compound into contact with the human receptor for an adverse effect to occur.

As mentioned previously, publicly available annual emissions data do not include spatial or temporal detail (such as emissions rates or mass fraction) to allow for a fully quantitative exposure or risk assessment. Instead, we use chemical-specific chronic (non-cancer and cancer) toxicity weights and acute toxicity health-based benchmarks established based on inhalation exposure. The ultimate goal of this assessment is to discuss different elements that relate to increasing hazard posed by chemicals associated with UGS in California.

### 1.4.6.2 Toxic Hazard Assessment for Chronic Non-cancer and Cancer Effects

Toxicity-weighted emission scores account for chemical-specific toxicity and size of releases. Toxicity-weighted emissions scores were calculated using median annual emissions data (pounds/year) from publicly available emissions inventories in California (see Section 1.4.4.) and EPA's Inhalation Toxicity Scores for individual chemicals (see Equation 1). U.S. EPA's Inhalation Toxicity Scores are chemical-specific toxicity weights for chronic non-cancer and cancer endpoints (U.S. EPA, 2017b). For more information about toxicity weights, see Appendix 1.C.

**Equation 1:**

*Median annual emissions (pounds/year) × EPA Inhalation Toxicity Score*[6] *= Toxicity-weighted emissions score*

### 1.4.6.3 Toxic Hazard Assessment for Acute Non-cancer Effects

This assessment includes evaluation of acute toxicity information for non-cancer health endpoints. Inhalation was the primary route of exposure assessed. To evaluate chemicals according to health hazard characteristics, regulatory and health-based values from state and federal sources were compiled and converted to same units of measurement (ug/$m^3$). When assessing toxic hazard, chemicals with observed effects at the lowest concentration pose greater hazard. For chemicals with multiple acute regulatory or health-based values, the minimum or most conservative value was chosen as the screening criterion for that chemical.

***Acute Screening Values for the Inhalation Route***

Regulatory and health-based values for acute toxicity for non-cancer effects include the following:

1. Office of Environmental Health Hazard Assessment-derived (OEHHA) acute Reference Exposure Levels (RELs)

2. Agency for Toxic Substances and Disease Registry (ATSDR) acute Minimum Risk Levels (MRLs)

Acute screening criteria included OEHHA acute reference exposure levels (RELs) and ATSDR acute minimum risk levels (MRLs). Acute RELs are airborne concentrations of a chemical that are not anticipated to result in adverse non-cancer health effects for short exposure durations in the general population, including sensitive subpopulations (OEHHA, 2016). Acute MRLs are estimates of the daily human exposure to a hazardous substance that is likely to be without appreciable risk of adverse non-cancer health effects over a short duration of exposure (1 – 14 days) (ATSDR, 2017a). To compare values, MRLs were converted to the same unit as RELs, micrograms per cubic meter (ug/$m^3$). MRLs reported as ppm were first multiplied by chemical-specific molecular weight and then divided by 24.25, taking into account standard temperature and pressure. MRLs were then multiplied by 1,000 to convert from mg/$m^3$ to ug/$m^3$.

6. For chemicals with both non-cancer and cancer toxicity weights, the highest (most conservative) toxicity weight was reflected in the Inhalation Toxicity Score. Non-cancer and cancer toxicity weights and chemical ranking specific to UGS facilities are included in Appendix 1.C, Table 1.B-2.

If multiple acute benchmarks were available, the most restrictive was chosen as the respective screening value. Chemical-specific hazard screening values for acute (non-cancer) endpoints are listed in Table 1.4-7. Methods are adapted from California Council on Science and Technology (CCST, 2015a).

#### 1.4.6.4 Results of Human-Health Hazard Assessment of Chemicals Emitted from UGS Facilities

In this section, we provide results of toxicity-based emissions ranking for chemicals reported to emissions inventories from UGS facilities.

##### 1.4.6.4.1 Chemical Hazards Associated with UGS Facility Emissions

Acute (non-cancer) screening criteria availability and chronic (non-cancer and cancer) toxicity weight availability are presented in detail in Table 1.4-5. Of the 83 compounds identified in the emissions inventories, 34 compounds (41%) had acute toxicity health benchmarks and 73 compounds (88%) had chronic (non-cancer or cancer) toxicity weights. Thirty (36%) compounds had identifiable CASRN and both available acute screening criteria and chronic toxicity weights. Six (7%) compounds with unique chemical identifiers lacked both acute screening criteria and chronic toxicity weights.

In cases where multiple acute, multiple chronic, or multiple cancer screening values were available for a particular chemical, the most restrictive one was chosen as the hazard screening criteria. Acute, chronic, and cancer screening criteria calculations are presented in Appendix 1.C, Tables 1.C-2., 1.C-3., and 1.C-4. Hazard screening criteria can be used to rank chemicals according to their human health hazard potential. For risk-based calculations and risk-ranking, original health-based criteria (e.g., REL, MRL) should be used in combination with the appropriate risk assessment exposure metrics.

*Table 1.4-5. Availability of information to characterize toxicity of chemicals reported in emissions inventories (n = 83).*

| Number of chemicals | Acute screening criteria | Chronic (non-cancer and cancer) toxicity-weights |
|---|---|---|
| 30 (36%) | Available | Available |
| 4 (5%) | Available | Unavailable |
| 43 (52%) | Unavailable | Available |
| 6 (7%) | Unavailable | Unavailable |

#### 1.4.6.4.2 Chronic Toxicity and Carcinogenicity Screening

A total of 73 compounds (88%) had Inhalation Toxicity Scores for chronic non-cancer and/or cancer hazards, including 18 PAHs, 45 nonmetals, and 10 metals. Ten compounds (12%) lacked toxicity-weights. These compounds included: 2,2,4-trimethylpetnane; carbon monoxide; diesel engine exhaust, particulate matter; diethylene glycol monobutyl ether; dipropylene glycol methyl ether; ethylene glycol monobutyl ether; nitrogen oxide; silica, crystalline; sodium hydroxide; and methylene chloride.

Toxicity-weighted emission scores accounting for chemical-specific toxicity and size of releases are reported in Table 1.4-6. Chronic toxicity weights are detailed in Appendix 1.C, Table 1.C-2. Chemicals with the highest calculated toxicity-weighted emissions from UGS facilities in California include formaldehyde, acrolein, ethylene dibromide, 1,3-butadiene, benzene, acetaldehyde, tetrachloroethane, trichloroethylene. Chronic non-cancer and cancer health effects associated with these compounds are discussed in Section 1.4.6.4.4.

#### 1.4.6.4.3 Acute Toxicity Screening

Thirty-four (34) chemicals (41%) had established acute hazard screening values, including 30 nonmetals (excluding PAHs) and 4 metals (Table 1.4-7). For chemicals with multiple acute screening values, the most restrictive (lowest) value was chosen as the chemical-specific hazard screening criteria. Acute screening values and screening criteria are detailed in Appendix 1.C, Table 1.C-3. Acute toxicity (non-cancer) screening criteria are shown in Table 1.4-7. Compounds with low health benchmarks for acute toxicity and high median annual emissions from UGS facilities are discussed in Section 1.4.6.4.4.

*Table 1.4-6. Chronic (noncancer and cancer) toxicity-weighted emissions from UGS facilities in California between 1987 and 2015. Compounds are listed by most hazardous to least hazardous based on chemical-specific median annual emissions and toxicity weights.*

| | | Inhalation Toxicity Score | | |
|---|---|---|---|---|
| **Chemical Name[1,2]** | **CASRN** | **Median annual emissions (pounds/year)** | **Toxicity Weights** | **Toxicity-weighted emissions** |
| **Formaldehyde** | 50-00-0 | 3159 | 46,000 | 145,310,537 |
| **Acrolein** | 107-02-8 | 206 | 180,000 | 37,066,065 |
| **Ethylene dibromide** | 106-93-4 | 4 | 2,100,000 | 8,428,974 |
| **1,3-Butadiene** | 106-99-0 | 57 | 110,000 | 6,236,313 |
| **Benzene** | 71-43-2 | 171 | 28,000 | 4,791,412 |
| **2-Methyl naphthalene[1]** | 91-57-6 | 6 | 710,000 | 4,433,950 |
| **Acetaldehyde** | 75-07-0 | 392 | 7,900 | 3,093,610 |
| **Phenanthrene[1]** | 85-01-8 | 2 | 710,000 | 1,388,760 |
| **Tetrachloroethane** | 79-34-5 | 4 | 210,000 | 760,790 |
| **Trichloroethylene** | 79-01-6 | 44 | 15,000 | 657,075 |
| **Phosphorus** | 7723-14-0 | 13 | 50,000 | 636,875 |
| **Acenaphthylene[1]** | 208-96-8 | 0.9 | 710,000 | 623,337 |
| **Propylene oxide** | 75-56-9 | 45 | 13,000 | 579,800 |
| **Fluorene[1]** | 86-73-7 | 0.8 | 710,000 | 579,379 |
| **Chromium[2]** | 7440-47-3 | 0.008 | 43,000,000 | 325,080 |
| **Asbestos** | 1332-21-4 | 0.002 | 165,000,000 | 324,225 |
| **Naphthalene** | 91-20-3 | 24 | 12,000 | 285,914 |
| **Ethylene dichloride** | 107-06-2 | 3 | 93,000 | 251,633 |
| **Chloroform** | 67-66-3 | 2 | 82,000 | 157,053 |
| **Pyrene[1]** | 129-00-0 | 0.2 | 710,000 | 138,969 |
| **Acenaphthene[1]** | 83-32-9 | 0.2 | 710,000 | 127,729 |
| **Fluoranthene[1]** | 206-44-0 | 0.2 | 710,000 | 113,423 |
| **Carbon tetrachloride** | 56-23-5 | 3 | 21,000 | 69,689 |
| **Chrysene[1]** | 218-01-9 | 0.09 | 710,000 | 63,190 |
| **Vinyl chloride** | 75-01-4 | 2 | 31,000 | 48,999 |
| **Perchloroethylene** | 127-18-4 | 51 | 930 | 47,695 |
| **1,2,4-Trimethylbenzene** | 95-63-6 | 69 | 580 | 39,750 |
| **Benzo[e]pyrene[1]** | 192-97-2 | 0.06 | 710,000 | 39,663 |
| **Benzo[a]anthracene[1]** | 56-55-3 | 0.06 | 710,000 | 39,612 |
| **1,3-Dichloropropene** | 542-75-6 | 2.6 | 14,000 | 36,384 |

1 Toxicity-weight for polycyclic aromatic hydrocarbon was applied as chemical-specific toxicity weight was unavailable. These values may over- or under-represent toxic potency of a specific polycyclic aromatic hydrocarbon.

2 Chromium is hexavalent; nonhexavalent chromium reported separately in emissions inventories, lacked toxicity weight information, and was therefore excluded from analysis.

| Chemical Name[1,2] | CASRN | Inhalation Toxicity Score | | |
|---|---|---|---|---|
| | | Median annual emissions (pounds/year) | Toxicity Weights | Toxicity-weighted emissions |
| **Ammonia** | 7664-41-7 | 996 | 35 | 34,874 |
| **Ethylbenzene** | 100-41-4 | 25 | 890 | 22,193 |
| **Arsenic** | 7440-38-2 | 0.001 | 15,000,000 | 17,865 |
| **Benzo[b]fluoranthene[1]** | 205-99-2 | 0.02 | 710,000 | 16,962 |
| **1,1,2-Trichloroethane** | 79-00-5 | 3 | 5,700 | 16,426 |
| **Biphenyl** | 92-52-4 | 18 | 800 | 14,271 |
| **Cadmium** | 7440-43-9 | 0.001 | 6,400,000 | 6,912 |
| **Xylene, m-** | 108-38-3 | 190 | 35 | 6,635 |
| **Nickel** | 7440-02-0 | 0.003 | 930,000 | 3,116 |
| **Xylenes** | 1330-20-7 | 72 | 35 | 2,522 |
| **1,2-Dichloropropane** | 78-87-5 | 2 | 880 | 2,145 |
| **Chlorine** | 7782-50-5 | 0.08 | 23,000 | 1,867 |
| **Hexane** | 110-54-3 | 250 | 5 | 1,252 |
| **Benzo(g,h,i)perylene** | 191-24-2 | 0.06 | 20,000 | 1,116 |
| **Beryllium[1]** | 7440-41-7 | 0.0001 | 8,600,000 | 784 |
| **Methylene chloride** | 75-09-2 | 10 | 36 | 361 |
| **1,1-Dichloroethane** | 75-34-3 | 0.6 | 570 | 328 |
| **Propylene** | 115-07-1 | 245 | 1.2 | 294 |
| **Indeno[1,2,3-cd]pyrene[1]** | 193-39-5 | 0.0004 | 710,000 | 288 |
| **Ethylene glycol** | 107-21-1 | 27 | 8.8 | 234 |
| **Lead** | 7439-92-1 | 0.01 | 23,000 | 207 |
| **Benzo(a)pyrene[1]** | 50-32-8 | 0.0003 | 710,000 | 198 |
| **Perylene[1]** | 198-55-0 | 0.0002 | 710,000 | 171 |
| **Benzo[k]fluoranthene[1]** | 207-08-9 | 0.0002 | 710,000 | 148 |
| **Toluene** | 108-88-3 | 198 | 0.7 | 139 |
| **Xylene, p-** | 106-42-3 | 2 | 35 | 78 |
| **Methanol** | 67-56-1 | 213 | 0.18 | 38 |
| **Phenol** | 108-95-2 | 2 | 18 | 36 |
| **Methyl tert-butyl ether** | 1634-04-4 | 0.4 | 93 | 35 |
| **Zinc** | 7440-66-6 | 0.3 | 100 | 26 |
| **Hydrogen sulfide** | 2148878 | 0.01 | 1,800 | 23 |
| **Manganese** | 7439-96-5 | 0.002 | 12,000 | 23 |
| **Hydrochloric acid** | 7647-01-0 | 0.09 | 180 | 17 |
| **Xylene, o-** | 95-47-6 | 0.4 | 35 | 15 |

1 Toxicity-weight for polycyclic aromatic hydrocarbon was applied as chemical-specific toxicity weight was unavailable. These values may over- or under-represent toxic potency of a specific polycyclic aromatic hydrocarbon.

2 Chromium is hexavalent; nonhexavalent chromium reported separately in emissions inventories, lacked toxicity weight information, and was therefore excluded from analysis.

| Chemical Name[1,2] | CASRN | Inhalation Toxicity Score | | |
|---|---|---|---|---|
| | | Median annual emissions (pounds/year) | Toxicity Weights | Toxicity-weighted emissions |
| **Mercury** | 7439-97-6 | 0.001 | 12,000 | 10 |
| **Styrene** | 100-42-5 | 2 | 3.5 | 5 |
| **Chlorobenzene** | 108-90-7 | 1 | 3.5 | 4 |
| **Copper** | 7440-50-8 | 0.002 | 1,500 | 3.4 |
| **1,1,1-Trichloroethane** | 71-55-6 | 1 | 0.7 | 1 |
| **Chlorodifluoromethane** | 75-45-6 | 10 | 0.07 | 1 |
| **Selenium** | 7782-49-2 | 0.001 | 180 | 0.2 |
| **Anthracene** | 120-12-7 | 0.03 | 3.3 | 0.1 |
| **Methyl ethyl ketone** | 78-93-3 | 0.02 | 0.7 | 0.01 |

1 Toxicity-weight for polycyclic aromatic hydrocarbon was applied as chemical-specific toxicity weight was unavailable. These values may over- or under-represent toxic potency of a specific polycyclic aromatic hydrocarbon.

2 Chromium is hexavalent; nonhexavalent chromium reported separately in emissions inventories, lacked toxicity weight information, and was therefore excluded from analysis.

*Table 1.4-7. Acute non-cancer benchmarks for compounds reported in emissions inventories by UGS facilities in California between 1987 and 2015.*

| Pollutant Name | CASRN | Acute (ug/m$^3$) | Acute Data Source | Acute Endpoint(s) | Median annual emissions (pounds/year) |
|---|---|---|---|---|---|
| **Nonmetals** | | | | | |
| 1,1,1-Trichloroethane | 71-55-6 | 6.80E+04 | OEHHA | Neurological | 1.1 |
| 1,3-Butadiene | 106-99-0 | 6.60E+02 | OEHHA | Developmental | 57 |
| Acetaldehyde | 75-07-0 | 4.70E+02 | OEHHA | Ocular; respiratory | 392 |
| Acrolein | 107-02-8 | 2.50E+00 | OEHHA | Ocular; respiratory | 206 |
| Ammonia | 7664-41-7 | 1.18E+03 | ATSDR | Respiratory | 996 |
| Benzene | 71-43-2 | 2.70E+01 | OEHHA | Developmental; immune; hematologic | 171 |
| Carbon monoxide | 630-08-0 | 2.30E+04 | OEHHA | Cardiovascular | 45360 |
| Carbon tetrachloride | 56-23-5 | 1.90E+03 | OEHHA | Alimentary; reproductive; developmental; neurological | 3.3 |
| Chlorine | 7782-50-5 | 2.10E+02 | OEHHA | Ocular, respiratory | 0.081 |
| Chloroform | 67-66-3 | 1.50E+02 | OEHHA | Reproductive/ developmental; respiratory; neurological | 1.92 |
| Ethylene glycol | 107-21-1 | 2.00E+03 | ATSDR | Respiratory | 27 |

| Pollutant Name | CASRN | Acute (ug/m³) | Acute Data Source | Acute Endpoint(s) | Median annual emissions (pounds/year) |
|---|---|---|---|---|---|
| Ethylene glycol monobutyl ether | 111-76-2 | 4.46E+03 | ATSDR | Hematological | 2.17 |
| Formaldehyde | 50-00-0 | 4.91E+01 | ATSDR | Respiratory | 3159 |
| Hydrogen chloride | 7647-01-0 | 2.10E+03 | OEHHA | Respiratory; ocular | 0.094 |
| Hydrogen sulfide | 7783-06-4 | 4.20E+01 | OEHHA | Neurological | 0.013 |
| m-Xylene | 108-38-3 | 2.20E+04 | OEHHA | Neurological; respiratory; ocular | 190 |
| Methanol | 67-56-1 | 2.80E+04 | OEHHA | Neurological | 213 |
| Methyl ethyl ketone | 78-93-3 | 1.30E+04 | OEHHA | Respiratory; ocular | 0.017 |
| Methyl tert-butyl ether | 1634-04-4 | 7.21E+03 | ATSDR | Neurological | 0.38 |
| Methylene chloride | 75-09-2 | 2.08E+03 | ATSDR | Neurological | 10.04 |
| o-Xylene | 95-47-6 | 2.20E+04 | OEHHA | Neurological; respiratory; ocular | 0.43 |
| p-Xylene | 106-42-3 | 2.20E+04 | OEHHA | Neurological; respiratory; ocular | 2.23 |
| Phenol | 108-95-2 | 5.80E+03 | OEHHA | Respiratory; ocular | 2.02 |
| Propylene oxide | 75-56-9 | 3.10E+03 | OEHHA | Respiratory; ocular; reproductive/ developmental | 45 |
| Sodium hydroxide | 1310-73-2 | 8.00E+00 | OEHHA | Respiratory; ocular; dermal | 4.4 |
| Styrene | 100-42-5 | 2.10E+04 | OEHHA | Respiratory; ocular; reproductive/ developmental | 1.54 |
| Perchloroethylene | 127-18-4 | 4.07E+01 | ATSDR | Neurological | 51 |
| Toluene | 108-88-3 | 7.54E+03 | ATSDR | Neurological | 198 |
| Vinyl chloride | 75-01-4 | 1.80E+05 | OEHHA | Neurological; respiratory; ocular | 1.58 |
| Xylenes | 1330-20-7 | 8.68E+03 | ATSDR | Neurological | 72 |
| **Metals** | | | | | |
| Arsenic | 7440-38-2 | 2.00E-01 | OEHHA | Developmental; cardiovascular; neurological | 0.0012 |
| Copper | 7440-50-8 | 1.00E+02 | OEHHA | Respiratory | 0.0022 |
| Mercury | 7439-97-6 | 6.00E-01 | OEHHA | Neurological; development | 0.0008 |
| Nickel | 7440-02-0 | 2.00E-01 | OEHHA | Immune | 0.003 |

#### 1.4.6.4.4 Discussion of Priority Compounds associated with UGS

Compounds with high emissions from UGS facilities are associated with acute and chronic (non-cancer and cancer) adverse health effects. Chronic toxicity-weighted emissions and acute hazard screening criteria are shown in Tables 1.4-6 and 1.4-7, respectively. Below we

discuss (1) acute toxicants with low health benchmarks and high median annual emissions, and (2) chronic toxicants and carcinogens with high toxicity-weighted emissions.

***Acute Toxicants***

Carbon monoxide (CO) is a colorless, odorless gas that can be acutely toxic. It is the highest emitted compound from UGS facilities in California, and it is health-relevant for acute exposures. High concentrations of carbon monoxide can displace oxygen and cause simple asphyxiation. While displacement of oxygen is unlikely to occur outdoors, elevated CO concentrations can adversely impact those with heart disease, especially while exercising or under stress. Acute exposures to elevated CO may reduce oxygen to the heart, which can result in chest pain (angina) (U.S. EPA, 2016a).

***Acute and Chronic Toxicants (non-cancer)***

Both ammonia and acrolein are emitted in great quantities from UGS facilities and are health-relevant pollutants regarding acute and chronic toxicity. Ammonia is a colorless gas with a sharp odor that causes irritation upon direct contact, such as with the skin, eyes, respiratory, and digestive tracts. Chronic exposure to elevated concentrations of ammonia can impair respiratory function (ATSDR, 2004). Direct exposure to low concentrations of acrolein in air may cause irritation to the eyes, nasal cavity, and respiratory tract. In animals, acrolein has been found to damage the gastrointestinal lining, with the severity of effects dose-dependent (Faroon et al., 2008). Neither acrolein nor ammonia have been identified as carcinogens.

***Chronic Toxicants (including known carcinogens)***

Ethylene dibromide is a colorless liquid with a sweet odor that is not detectable at very low concentrations (ATSDR, 2014). It is extremely toxic, but chronic effects from ethylene dibromide exposure have not been well documented in humans. Animal studies show that chronic exposure to ethylene dibromide may result in toxic effects to the liver, kidney, and the testis. Limited data on men occupationally exposed to ethylene dibromide indicate that chronic exposure to ethylene dibromide can impair reproduction by damaging sperm. U.S. EPA classifies ethylene dibromide as a Group B2 probable human carcinogen, based on evidence from animal studies at various tumor sites (U.S. EPA, 2016b).

Trichloroethylene is a clear liquid with a sweet odor and is widely used in industrial degreasing operations (U.S. EPA, 2016c). Chronic inhalation exposure to trichloroethylene can adversely impact the central nervous system, causing dizziness, facial numbness, blurred vision, and nausea. In occupational settings, trichloroethylene exposure has been associated with autoimmune disease (sclerodema) (ATSDR, 2016). Trichloroethylene is a known human carcinogen, with strong associations observed between trichloroethylene exposure and kidney cancer in humans (National Toxicology Program, 2016).

Similar to trichloroethylene, tetrachloroethane is a clear liquid with a sweet odor and is used as a solvent (ATSDR, 2008a). Chronic exposure to tetrachloroethane can cause respiratory and eye irritation, as well as impacts to the central nervous system and liver. U.S. EPA has classified tetrachloroethane as a Group C possible human carcinogen for evidence of liver tumor formation in animal studies (U.S. EPA, 2016d).

Benzene, acetaldehyde, 1,3-butadiene, and formaldehyde are recognized as acute and chronic toxicants, known carcinogens, and highly emitted compounds from UGS facilities in California. Benzene is a colorless gas with a sweet odor. Acute exposures to benzene in air (10,000-20,000 ppm) can result in death. Lower concentrations (700-3,000 ppm) can cause dizziness, headaches, confusion, and unconsciousness. Chronic exposure to lower levels can impair the ability to form healthy blood cells, particularly in bone marrow. Long-term exposure to benzene is strongly associated with hematological cancers (leukemia) and multiple myeloma, which often forms tumors in the bone barrow. Benzene is recognized as a known carcinogen by the International Agency for Research on Cancer (IARC) (ATSDR, 2007).

Acute exposure to acetaldehyde can cause irritation of the eyes, skin, and respiratory tract, and depressed respiration. Carcinogenic effects from acetaldehyde exposure have been documented in animals via nasal tumors in rats and laryngeal tumors in hamsters (U.S. EPA, 2000). 1,3-Butadiene is a colorless gas that smells like gasoline and is a product of the incomplete combustion of hydrocarbons (National Institutes of Health, 2017). Acute inhalation exposures to 1,3-butadiene can cause respiratory and eye irritation, and chronic exposure has been associated with adverse impacts to the respiratory and cardiovascular system in animals (U.S. EPA, 2016e). 1,3-butadiene is known to be a human carcinogen, based on sufficient evidence of carcinogenicity from studies in humans, and is known to cause lymphatic and hematopoietic cancers (National Toxicology Program, 2016).

Formaldehyde has the highest toxicity-weighted emissions of toxic air pollutants associated with UGS facilities in California, and is known for acute and chronic toxicity and carcinogenicity. This aligns with default emission factor information, as formaldehyde is often the highest emitted compound from gas-fired compressor stations and other infrastructure associated with UGS; and also implies that extensive formaldehyde emissions are associated with routine operations, rather than off-normal events (SCAQMD, 2014). Acute exposures to formaldehyde can cause irritation of the eyes, nasal cavity, and throat. There is a well-established relationship between chronic workplace exposure to formaldehyde and cancers of the nose and throat. Formaldehyde is a known human carcinogen classified by IARC (ATSDR, 2008b).

***Toxic substances not included in comparative hazard assessment***

A few criteria pollutants were not included in this assessment because they lacked unique chemical identifiers. However, these compounds are among the highest emitted compounds from UGS facilities in California (see Appendix 1.C, Table 1.C-1) and are known to adversely impact human health.

Nitrogen oxides ($NO_X$) and sulfur oxides ($SO_X$) are highly reactive gases that can form from combustion of hydrocarbons. Acute exposure to both $NO_X$ and $SO_X$ can cause respiratory irritation. Long-term exposure to $NO_X$ can result in respiratory diseases such as asthma; children, the elderly, and those who suffer from respiratory diseases are particularly sensitive to effects of both $NO_X$ and $SO_X$ Additionally, both $NO_X$ and $SO_X$ can react with chemicals in the air to form other health-harming air pollutants, including particulate matter.

Particulate matter (PM) is made up of microscopic solid or liquid droplets that can come directly from a source or result from complex reactions of chemicals in the atmosphere. The incredibly small size of these particles means that they can be inhaled into the respiratory tract and deep into the lungs, causing serious respiratory and cardiovascular health problems.

Ground-level ozone is formed from chemicals reaction between $NO_x$ and volatile organic compounds (VOCs) in the presence of sunlight. Exposure to ozone can cause respiratory issues, especially for children, the elderly, and those with respiratory disease. (U.S. EPA, 2017a). We did not have sufficient data to assess potential for ground-level ozone formation from ozone precursors (such as alkanes) that could result in secondary ozone. The contribution of organic gas species both from normal operation and LOCs to ground-level ozone formation is a potentially important public health question that has not been addressed to date for the 2015 Aliso Canyon incident or for any other UGS facility.

***Discussion and Data Limitations***

As mentioned previously, there is inherent uncertainty and lack of spatial and temporal detail in emissions inventory reporting, which makes it difficult to determine resulting atmospheric concentrations and quantify public health risks. As such, this assessment examines potential hazards posed by chemicals emitted from any UGS facility in California.

Quality and quantity of available data limit this assessment. Median annual emissions estimates were calculated using all publicly available data between 1987 and 2015. However, operators are only required to update emissions estimates every four years. Therefore, some emissions data are repeated for multiple years. While 75 compounds (90%) identified in emissions inventories had established values for acute toxicity and/or chronic toxicity weights, 8 (10%), compounds with unique chemical identifiers lacked any toxicity information. Finally, this assessment is limited to compounds reported in emissions inventories. While the Air Toxics Hot Spots Program requires reporting for compounds with significant health relevance, it does not include compounds particularly relevant to UGS, including mercaptans (odorants), which are discussed in detail in Section 1.4.10.

Despite these limitations, this assessment identifies priority chemicals, including criteria and toxic air pollutants, associated with UGS in California, based on annual mass emitted and chemical toxicity. These results are important when discussing chronic exposures

to nearby communities and workers from routine UGS operations, as well as acute to subchronic exposures during large LOC events.

### 1.4.7 Assessment of Nearby Populations at Increased Health Risk: Proximity Analysis and Air Dispersion Modeling

In Section 1.1, we characterized the wells at each of the 13 UGS facilities. In Section 1.2, we discussed the subsurface migration pathways through which gas in UGS facilities can be emitted to the atmosphere. In this section, we use these data to evaluate nearby populations and their demographics that are at potential risk of exposures to air pollutant emissions and potential explosions from the California UGS facilities.

This section is broken into two primary parts: (1) A proximity analysis of populations in close proximity to UGS facilities in California; and (2) an assessment of air dispersion modeling and the populations that are at highest risk given average meteorological conditions, (e.g. wind direction, wind speed, and atmospheric mixing characteristics).

#### 1.4.7.1 Proximity Analysis of UGS Facilities and Human Populations

##### 1.4.7.1.1 Approach to Analysis of UGS Facilities and Potential Risk to Human Populations

Here we provide an overview of our approach to the analysis of populations in proximity and at varying likelihoods of exposures to emissions of toxic air pollutants and potential explosions from UGS facilities (CPUC, 2010), especially during larger loss-of-containment events (see Section 1.4.10). In particular, we analyzed the proximity of infrastructure directly associated with UGS facilities, and of infrastructure with potential sub-surface connectivity to UGS infrastructure, to human populations and sensitive receptors including schools, daycare centers, elderly care facilities, etc. For our detailed methodology, please see Appendix 1.D. Figure 1.4-2 below illustrates the general location of all California UGS facilities along with the relative scale of their working-gas capacity in Bcf. The approach we take here has similarities to what has been considered in the California Environmental Quality Act (CEQA) impact assessment process. However, a review of CEQA reports posted on the CPUC site for the subject storage facilities reveals that, with the exception of the Princeton site, the CEQA impact assessments for natural gas storage facilities focused on compliance with emissions standards for permitted releases. At all sites that have CEQA reports, these emissions are assumed to have an insignificant impact on the health of adjacent communities, because they are in compliance with California Air Resources Board (CARB) standards. This resulted in a “negative declaration,” which does not initiate the need for a proximity assessment. In the case of the Princeton site, the CEQA report included a fire and explosion risk assessment that supported a finding regarding a safe buffer distance for adjacent nonoccupational populations.

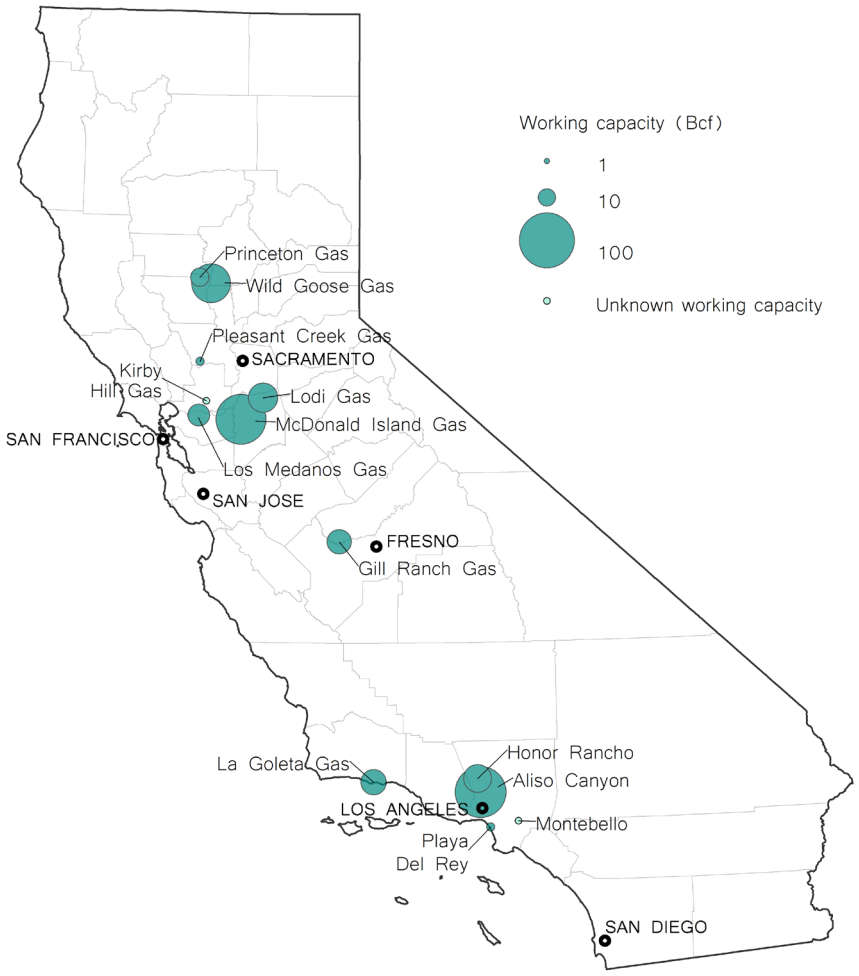


***Figure 1.4-2. California underground natural gas storage wells depicted by working capacity in Bcf. These UGS facilities include 12 working gas storage facilities and one decommissioned facility, Montebello, with data that suggest that injections and withdrawals occurred at the facility up through 2016 (see Section 1.1.3).***

We first divided wells based on their potential likelihood to serve as a conduit for gas leakage from the UGS storage facilities to the atmosphere. In making this division, we are considering the potential for leakage, which gives rise to two tiers. When we consider the potential inventory of toxic air emissions, it is also important to make a distinction between wells in depleted gas reservoirs and wells in depleted oil reservoirs, because the latter will have more trace constituents associated with oil residue (see Section 1.4.5).
For leakage potential, two tiers carried through our population proximity analysis include:

**Tier 1 Wells:** All wells located within an oil and/or gas pool used for gas storage and represents the most likely subsurface infrastructure subject to LOC to the atmosphere. We do not include wells that have been plugged.

**Tier 2 Wells:** All open (unplugged) wells located within the same *field area* as an oil and gas pool used for gas storage. The field area is a quasi-geological and administrative boundary used by DOGGR to delineate a given oil and/or gas accumulation. Field areas can represent multiple oil/gas pools. While the risk of subsurface migration of gas and other fluids from the pools used for gas storage to these wells in the greater field area is lower than the risk of emissions from Tier 1 wells (in the storage pool itself), historical data suggest that gas can certainly migrate in the subsurface over these geographical distances and across these geological strata.

UGS facilities are not always discrete facilities, and their surface administrative boundaries are not always a good predictor of where emission-prone infrastructure is located. More specifically, the administrative boundaries tend to cover a larger area than where the wells, compressors, and other infrastructure are located. Moreover, emission inventories do not provide insight into the spatial, temporal, or infrastructural distributions of emissions of air pollutants at UGS facilities. As such, it was necessary to assume that emissions could come from anywhere in the facility at any given time. In order to operationalize this assumption, we drew a contour line around the outermost wells of each facility to approximate the facility area, outside of which we would create our buffer distances for analysis.

**Well Data Description and Approach**

We obtained data for California wells from DOGGR. We intentionally used an older well dataset from 2015 (DOGGR, 2015) to reflect storage well conditions before the incident at Aliso Canyon that started in October 2015. We included all well data covering the 10-year time period up to dataset's end, which included years 2006–2015. We categorized wells as either "open" or "closed" to evaluate the likelihood of a well acting as a conduit for underground gas to reach the surface. This distinction is based on the presence or absence of an unplugged wellbore.

To examine the public health risks with a range of perspectives, we split the well dataset into two partially overlapping datasets that we labeled Tier 1 and Tier 2. The Tier 1 dataset is focused specifically on the storage pool around each underground gas storage facility, and it includes any open well that is located within a gas storage pool. The Tier 2 dataset represents a more conservative approach for public health and includes a broader set of criteria. This dataset includes all wells from Tier 1, and in addition it includes any open well that is located within the same field area as the gas storage pool.

**Proximal Population Data Description and Approach**

As a basis for understanding potential public health hazards attributable to UGS facilities, we evaluated the spatial relationships of gas storage pool and field area wells to the surrounding population, by evaluating resident counts and selecting sites considered to be "sensitive receptors." We examined the general population as well as vulnerable subgroups of the communities in proximity to underground gas storage facilities. One issue that we did not have resources to explore is that of encroachment—the historical rate of change of population proximity around a site. To assess encroachment requires detailed historical population mapping along with a chronology of when a facility was first put into operation and how its operations changed as the size and location of the population changed. Gathering this information would be time-consuming, and not particularly useful in informing the findings and recommendations of this study.

We obtained demographic information from the U.S. Census Bureau (2011) for the California general, youth, and elderly population to determine population counts for the following variables: total population, under five years of age, and 75 years and older. We also collected data for a series of point locations we are calling "sensitive receptors," which are places where vulnerable subgroups congregate. Schools and daycare centers for the youth population; residential elderly care facilities for the elderly population; and hospitals for the sick. These locations represent sites where a hazard may pose elevated risk to people, because of their vulnerability. While fetuses are in many instances among the most sensitive receptor to toxic exposures, we were unable to include this sub-population given the lack of access to a high-resolution, household-level pregnancy or birth dataset given the short timeline of this report. We do, however, recommend that questions of risks to fetuses posed by the 2015 Aliso Canyon incident be undertaken in the future.

Children and the elderly are two populations that are especially vulnerable. Children are still developing, and as such have respiratory systems that are particularly susceptible to chemical exposures (Webb et al., 2016)particulate matter . Children have much faster breathing rates than adults, thus they inhale a greater amount of air pollutants and dust in comparison to adults, resulting in proportionally higher exposures than adults in the same conditions would receive (Landrigan et al., 2004; Webb et al., 2016). Unlike adults, they have less ability to metabolize and excrete chemicals (Landrigan et al., 2004). Children have more years remaining in their lives, which increases their likelihood of chronic illnesses with long latency periods such as certain cancers (Sly and Carpenter, 2012). In addition, they have behavioral tendencies that could increase exposures, such as hand-to-mouth behavior, as well as active time outside, which not only increases exposures because of faster respiration due to activity, but in addition exposure is often higher outdoors (Landrigan et al., 2004; Webb et al., 2016).

Similar to children, elderly and sick populations generally have weaker immune systems than healthy adults (Risher et al., 2010). Pre-existing health conditions can hinder the body's ability to adapt and protect itself from potential effects of environmental exposures

(Risher et al., 2010; Hong, 2013). As part of normal aging, elderly individuals have had many more years of potential opportunities for environmental exposures, and they generally have a decreased ability to metabolize and excrete xenobiotics, including air pollutants related to gas storage (Risher et al., 2010; Hong, 2013).

**Geographic Proximity Analysis Approach: 360-Degree Assessment**

We created radial buffers at 0, 100, 200, 400, 600, 800 (~1/2 mile), 1000, 1600 (~1 mile), 2000, 5000, and 8000 (~5 miles) meters around the storage facility boundaries determined by the contour around the outermost wells, as described above.

The buffers used in this analysis are designed to encompass populations within various proximities to natural gas storage infrastructure and associated possible emissions, with the assumption that exposure to emissions will be the highest at the 0 m buffer and will continue at decreasing exposures through the remaining buffers as distance from facility increases. The 0 m buffer is the same thing as the storage facility boundary. This assumption is supported by analysis of resident complaint calls summarized by the Los Angeles County Department of Public Health (LACDPH) in response to the Aliso Canyon incident. This analysis found that the likelihood of reported health symptoms, including headache, nausea, nosebleeds, and respiratory problems, among other symptoms, was substantially greater for residents that lived ≤3 miles from the gas leak (55.8% of complaints), compared with residents that lived >5 miles from the gas leak (16.8% of complaints) (LACDPH, 2016c; see Section 1.4.10). For risk in particular of wells sustaining subsurface blowouts with breaching to surface, there is evidence that the locations of emission points to atmosphere (surface fractures or craters) typically do not exceed a distance of 600 m from the wellhead (Jordan and Benson, 2009).

For a complete description of our methods and approach to the spatial proximity analysis, please see Appendix 1.D.

#### 1.4.7.1.2 Results of Analysis of UGS Facilities and Potential Risk to Human Populations

Our assessments of population and sensitive receptor counts between the Tier 1 (UGS facility wells) and Tier 2 (wells in the field area where each UGS facility is located) analyses are very similar. The difference in total population between the Tier 1 and Tier 2 results at the 1,600 m buffer distance is less than 10 people at 11 out of 13 sites. Los Medanos Gas had a population increase of an estimated 193 people, or a 26.1% increase, but this percentage is so high only because the original population count was quite small at 740 people. Montebello is the only gas storage facility with a substantial population change between the Tier 1 and Tier 2 well datasets. The population living within 1,600 m increased 12.7%, from 41,170 to 46,399 people. Given the similarity in results between the UGS well and the greater field area well analysis (Tier 1 and Tier 2), the remainder of the results for this section will focus exclusively on the Tier 1 (UGS well) analysis results.

As noted in Table 1.4-8, across California, we estimate that 1,864,775 people live within 8,000 m (~5 miles) of a UGS facility. Population counts differ substantially across gas storage facilities, with a minimum of 116 people at Wild Goose Gas and a maximum of 734,988 people at Montebello living within the 8,000 m buffer distance.

Approximately 115,125 children under the age of five live within 8,000 m of an active UGS facility. There are an estimated 1,358 daycare centers within this distance, with 1,337 currently open and 21 pending. In addition, there are 556 schools within this distance, all currently open, which enroll 292,935 children. An estimated 103,085 adults age 75 and older also live within 8,000 m of an UGS facility. There are also 359 residential elderly care facilities within this buffer distance, with 326 of them currently open and 33 pending (Table 1.4-8). Unlike the small buffers, the 8,000 m buffers overlap for two pairs of UGS facilities, creating populations that are within the buffers of two facilities in the case of Wild Goose Gas and Princeton, and also at Aliso Canyon and Honor Rancho. Population and sensitive receptor counts in Table 1.4-9 represent the populations in relation specifically on a UGS facility-by-facility basis; therefore, the same people and sensitive receptors may be counted more than once. In Table 1.4-8, this is remedied in a sum over all UGS facilities, where each person and sensitive receptor is only counted once. This explains why a sum of counts at each UGS facility does not equal the 8,000 m buffer sum over all UGS facilities.

*Table 1.4-8. Summed population and sensitive receptor counts in proximity to underground storage sites in California, by buffer distance.*

| Distance From any UGS Well (meters) | Number of Residents | Under 5 | Age 75 and Older | Number of Open Schools | Number of Children Enrolled in School | Number of Open Daycare Centers | Number of Open Elderly Care Facilities | Number of Hospitals |
|---|---|---|---|---|---|---|---|---|
| 0 | 5,585 | 257 | 356 | 0 | 0 | 1 | 0 | 0 |
| 100 | 8,179 | 408 | 542 | 0 | 0 | 1 | 0 | 0 |
| 200 | 11,443 | 568 | 788 | 3 | 1,046 | 5 | 1 | 0 |
| 400 | 18,385 | 876 | 1,434 | 4 | 1,448 | 7 | 2 | 0 |
| 600 | 28,158 | 1,308 | 2,058 | 9 | 3,699 | 18 | 2 | 0 |
| 800 (1/2 mile) | 40,503 | 1,843 | 2,704 | 12 | 5,435 | 29 | 2 | 0 |
| 1,000 | 54,127 | 2,597 | 3,458 | 17 | 9,974 | 35 | 2 | 1 |
| 1,600 (1 mile) | 113,721 | 5,522 | 6,278 | 32 | 23,035 | 64 | 3 | 2 |
| 2,000 | 161,367 | 8,051 | 8,467 | 42 | 28,868 | 89 | 3 | 3 |
| 5,000 | 743,678 | 42,543 | 43,323 | 213 | 117,406 | 516 | 109 | 8 |
| 8,000 | 1,864,775 | 115,124 | 103,085 | 556 | 292,935 | 1,337 | 326 | 23 |

*Table 1.4-9. Population and sensitive receptor counts for the 8,000 m (~5 mile) buffer, by underground storage site; N/A = data not available.*

| Underground Storage Facility | Working capacity (Bcf) | Number of Residents | Under 5 | Age 75 and Older | Number of Open Schools | Number of Children Enrolled in School | Number of Open Daycare Facilities | Number of Open Elderly Care Facilities | Number of Hospitals |
|---|---|---|---|---|---|---|---|---|---|
| Aliso Canyon | 86 | 232,202 | 12,502 | 14,962 | 77 | 48,000 | 183 | 93 | 2 |
| Gill Ranch | 20 | 545 | 55 | 18 | 0 | 0 | 0 | 0 | 0 |
| Honor Rancho | 26 | 156,688 | 9,495 | 4,963 | 45 | 35,369 | 105 | 52 | 1 |
| Kirby Hill | N/A | 291 | 11 | 14 | 0 | 0 | 0 | 0 | 0 |
| La Goleta | 21 | 94,421 | 3,734 | 6,719 | 26 | 12,132 | 74 | 39 | 3 |
| Lodi Gas | 29 | 24,114 | 1,625 | 1,595 | 9 | 2,851 | 10 | 2 | 0 |
| Los Medanos | 16 | 139,902 | 9,981 | 6,457 | 43 | 1,551 | 112 | 60 | 2 |
| McDonald Island | 82 | 646 | 51 | 17 | 0 | 0 | 0 | 0 | 0 |
| Montebello | N/A | 734,877 | 51,768 | 42,119 | 198 | 117,402 | 437 | 17 | 10 |
| Playa del Rey | 2 | 493,459 | 26,787 | 27,065 | 158 | 65,306 | 420 | 69 | 5 |
| Pleasant Creek | 2 | 8,270 | 522 | 342 | 4 | 0 | 9 | 0 | 0 |
| Princeton | 11 | 642 | 30 | 47 | 2 | 169 | 0 | 0 | 0 |
| Wild Goose | 50 | 116 | 4 | 6 | 0 | 0 | 0 | 0 | 0 |

In our examination of the association between working gas capacity and population counts for each underground gas storage facility, we found that there is not a strong relationship between population size and facility capacity. As noted in Table 1.4-9, Aliso Canyon, McDonald Island, and Wild Goose are the three facilities with the largest working capacities, at 86, 82, and 50 Bcf, respectively. Of these, both McDonald Island and Wild Goose are located in remote, low-population-density areas with a very small number of adjacent residents. In contrast, Aliso Canyon has a substantial proximal population and ranks 3rd of the 13 underground gas storage facilities in California including Montebello when comparing population at the 8,000 m buffer distance. Playa del Rey is located in an urban area on the coast and has the 2nd highest proximal population with greater than 400,000 people living within 8,000 m of the site, and it is tied with Pleasant Creek as the lowest working gas capacity UGS facility in California (2 Bcf). Montebello is the facility with the largest proximal population; however, the working capacity of this facility is unknown. The Montebello facility represents a unique case among the California UGS facilities, in that there are discrepancies in its regulatory records indicating whether the facility is administratively considered an operating gas storage facility, as discussed in Section 1.1 of this report.

There are populations that live directly above UGS pools, and these populations are captured under our analysis of the 0 m buffer. People living within this area are at greater risk of exposures to emissions of toxic air pollutants and potential explosions from surface and subsurface UGS facility infrastructure than populations located outside of the gas storage pool boundary. As seen in Table 1.4-10, there are 5,585 people living within this 0 m buffer distance of a UGS facility, with populations at seven of the 13 UGS facilities. Out of the total population living immediately above a gas storage pool, 258 are under age 5, and an additional 356 are age 75 and older, representing two population groups that are disproportionately vulnerable to environmental hazards. While four storage facilities have fewer than 100 people living within the boundary of the gas storage pool, one site (Lodi Gas) has 242 people, and two sites (Playa del Rey and Montebello) each have over 1,000 people living within its gas storage area. There are no schools, daycare facilities, residential elderly care facilities, or hospitals indicated in the data for these areas.

*Table 1.4-10. Population counts for the 0 m buffer, by underground storage site.*

| Underground Storage Facility | Number of Residents | Under Age 5 | Age 75 and Older |
|---|---|---|---|
| Playa del Rey | 3,782 | 165 | 193 |
| Montebello | 1,470 | 75 | 149 |
| Lodi | 242 | 12 | 9 |
| La Goleta | 39 | 1 | 3 |
| Aliso Canyon | 25 | 1 | 2 |
| McDonald Island | 24 | 4 | 0 |
| Princeton | 3 | 0 | 0 |
| **TOTAL** | **5,885** | **258** | **356** |

*Population Density*

Similar to population counts, there is a wide range of population densities among the 13 (including Montebello) storage facilities in California. We calculated population densities for each combination of buffer distance (11 buffers) and UGS facility (13 facilities), providing 143 combinations. We categorized the population density values into five groupings, with category breaks chosen based on examination of residential land-cover patterns using aerial orthoimagery. The population density category breaks are as follows:

- 0 people per square kilometer ($km^2$) represents a population density of "None";
- >0 – 20 people/$km^2$ is categorized as "Very low";
- >20 – 100 people/$km^2$ is categorized as "Low";
- >100 - <1,000 people/$km^2$ is categorized as "Medium," and
- >1,000 – <5,000 people/$km^2$ is categorized as "High."

To provide context, areas categorized as "None" and "Very low" are primarily undeveloped, agricultural, industrial, or water (ocean) areas; and "High" are urban areas with a large ratio of residential land. "Low" and "Medium" areas are typically a mixture of undeveloped or agricultural land and residential areas, with expectedly lower or higher ratios of residential land, respectively.

Out of the 143 storage facility buffer combinations, 11 fall into the None, 69 in the Very Low, 20 in the Low, 19 in the Medium, and 22 in the High categories. With this categorization, 80 out of 143 storage facility buffer combinations (55.9%) have a population density of ≤100 people/$km^2$, indicating that they are located in very rural areas. Of these, 55 come from the 11 buffers of the McDonald Island, Princeton, Kirby Hill, Gill Ranch, and Wild Goose facilities, indicating that these five UGS facilities may have a lower relative

hazard compared to more population-dense areas. Population density at the Kirby Hill Gas facility is shown in Figure 1.4-3. The 15.4% in the high population density category are in very urban areas, representing all 11 buffers around both the Montebello and Playa del Rey facilities, located in the Los Angeles Basin. Population density around the Montebello facility is shown in Figure 1.4-4. The buffers around the remaining storage facilities vary in their population density, ranging from medium to no population density. La Goleta has more buffers in the medium population density range, while Honor Rancho, Aliso Canyon, Los Medanos, Lodi, and Pleasant Creek have more buffers located within the low and very low population density ranges.

There are generalizations we can make about trends in population density between the northern and southern California UGS facilities. When the facilities are ranked by population density over all buffers, the five UGS facilities in the greater Los Angeles area in southern California rank one through five, indicating the greatest population densities out of the 13 storage facilities (includes Montebello). Montebello and Playa del Rey, the two facilities located in urban areas, are located in southern California. La Goleta, Honor Rancho, and Aliso Canyon have very low to low population densities at the smallest buffers, but as buffer distance increases, population density also increases into the "medium" range, as the buffers encroach into the urban areas in the greater Los Angeles area. In contrast, all UGS facilities north of the greater Los Angeles area have lower proximal population densities: 80.6% of the buffers in northern California are categorized as "none" or "very low," indicating either an absence of people (12.5%) or a population density of less than 20 people per square km (68.2%).

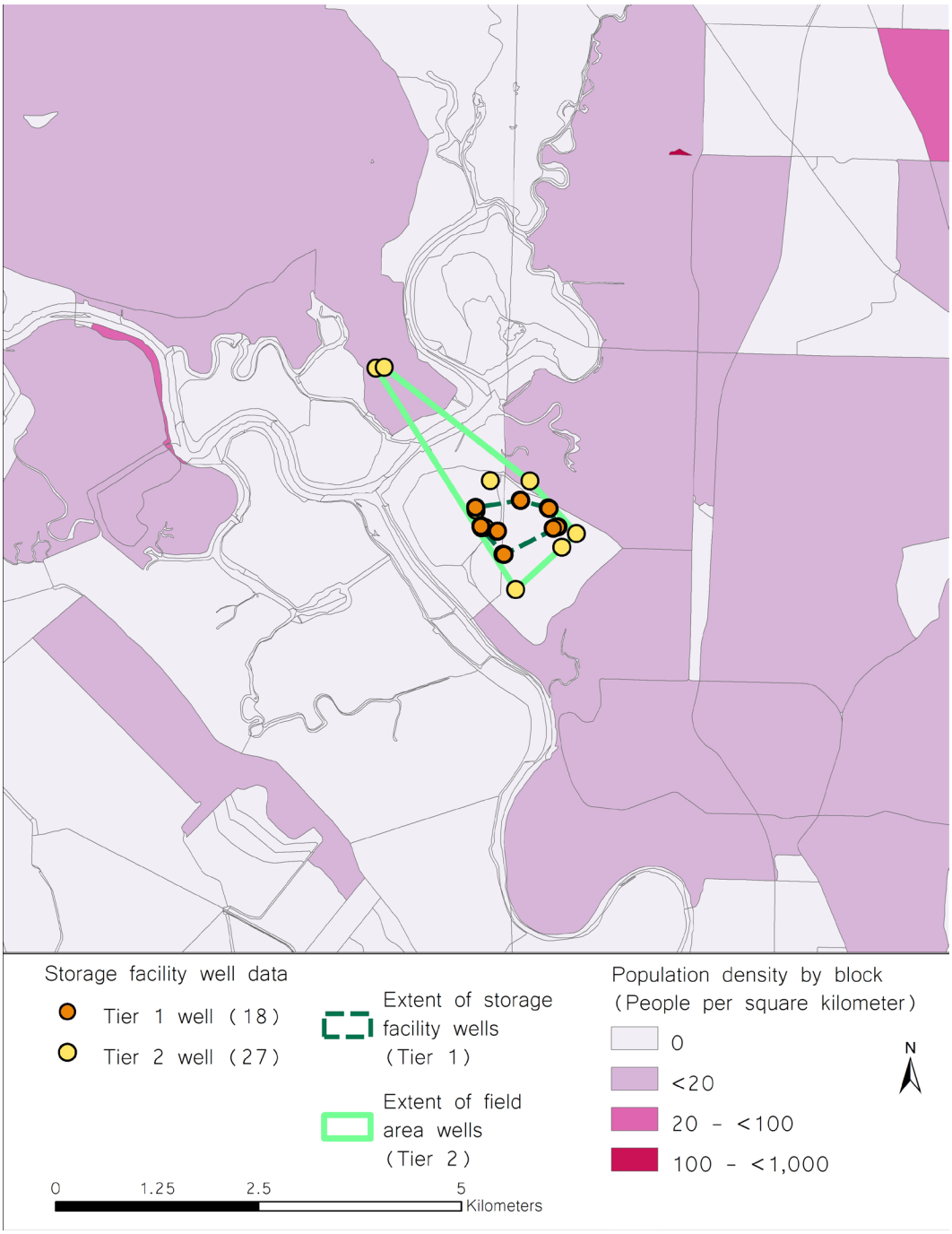


*Figure 1.4-3. Population density measured in people per square kilometer around the Kirby Hill UGS facility.*


*Figure 1.4-4. Population density measured in people per square kilometer around the Montebello UGS facility.*

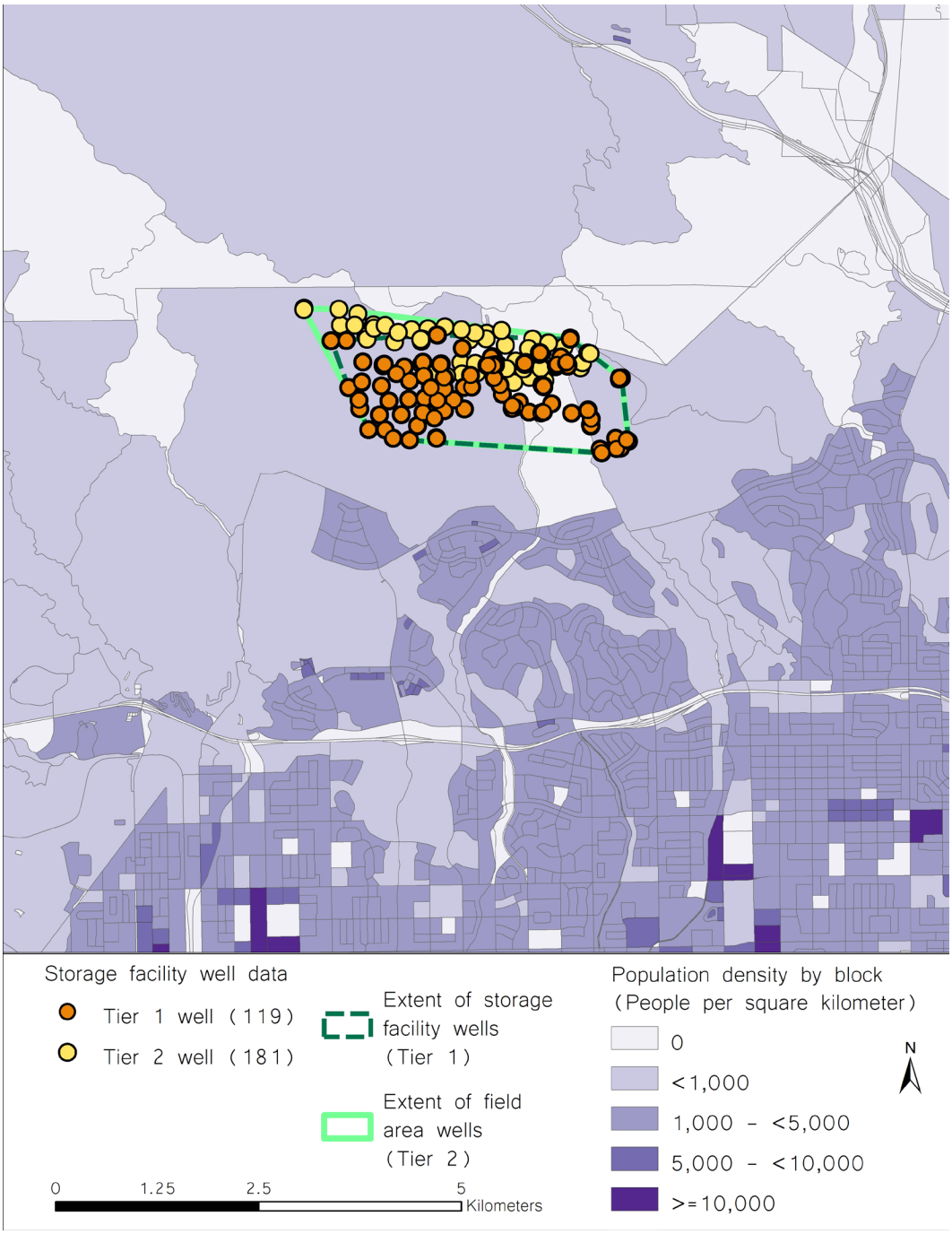


*Figure 1.4-5. Population density measured in people per square kilometer around the Aliso Canyon UGS facility.*

As a general rule, the smaller buffers, including 800 m and smaller, are more frequently located in the two lowest population density categories, indicating 100 or fewer people/km$^2$, while the likelihood of a buffer being located in a higher population density area increases as buffer size increases. Therefore, in general, populations directly adjacent to underground gas storage facilities tend to be more rural, while populations farther out (while still in the general vicinity of gas storage facilities) have a greater likelihood of being urban or suburban.

#### 1.4.7.2 Air-Dispersion Modeling for UGS Emissions Health Assessment

In order to assess the potential for community exposures, we rely on air-dispersion modeling applied to each of the storage sites. These models are useful for describing how a known emission rate translates into air concentrations as a function of distance and radial location. However, making accurate concentration estimates requires a knowledge of emissions inventories and rates, and knowledge of atmospheric conditions—including wind speed and direction and atmospheric turbulence. In the absence of reliable emissions data (as noted earlier in Section 1.4.5), we used normalized concentration/emission ratios to determine the relative dilution of toxic air pollutants emitted by the UGS facilities into the atmosphere and transported by wind to nearby communities. We follow the approach to air-dispersion modeling that is introduced in Section 1.2 and described in more detail in Appendix 1.B.

Because we have very limited information on the quantities and chemical composition of emissions at UGS sites, we rely on bottom-up approaches that employ empirical emission factors to estimate emission inventories. These approaches do not provide the spatially and temporally varying emission inventory data that are critical for estimating downwind consequences of leaks from individual UGS sites. For instance—as described earlier in this section on the emission inventories—emissions reporting to air districts and CARB are not specific as to *where* the emissions originate from in the facility, and *which infrastructure* are the sources of any given emission.

Lack of temporal and spatially varying emissions data and lack of reliable meteorological data make it difficult to accurately estimate the concentrations and dispersion of gas leakage from UGS facilities. This finding means that continuous methane monitoring technology (with trigger sampling for toxic air pollutants) should be deployed at each UGS facility to provide reliable spatially and temporally varying data for analysis. On-site weather stations should be installed at each UGS facility following National Weather Service (NWS) guidelines to provide accurate and timely information during a release event.

#### 1.4.7.3 Approach to Air-Dispersion Modeling

In this section, the methodology for estimating downwind concentrations due to a leak from a UGS facility is described. We present the air-dispersion results in terms of the ratio of downwind concentration (C) divided by the leakage flow rate (Q). This is because the concentrations depend on the emissions rate, and the emission rate is not known *a priori*.

The ratio of downwind concentration and the emission rate is commonly referred to as the C/Q ratio in the atmospheric dispersion literature. Dimensions of C/Q are $L^{-3}$ t with common units $m^{-3}$ s.

Meteorological data were collected over a period of one year (August 15, 2015–August 15, 2016) for each of the 13 UGS facilities in California (discussed in detail in Appendix 1.B). A unit emission rate was assumed at each well of the storage facility and was assumed constant in time for the entire period. The emission rates were combined with meteorological data (including wind speed, wind direction, shortwave incoming radiation, cloud cover) to estimate the downwind concentration, using the Gaussian Plume air dispersion model. The downwind concentrations were computed over a 10 km radius centered on the source, with a spatial resolution of 100 m. To account for the spatial distribution of the source, all the active wells within a storage facility were considered as point sources. The resulting concentration field was then normalized by the total emission rate from the facility to obtain the C/Q ratio.

The C/Q ratio can be used to compute the downwind concentration by multiplying an emission rate from the UGS facility with the C/Q ratio. For example, if the emission rate was 16 kilograms/second (kg/s) and the C/Q ratio was $44 \times 10^{-9}$ $m^{-3}$ s, then the downwind concentration would be computed as 16 kg/s $\times$ $44 \times 10^{-9}$ $m^{-3}$ s = 704 ug/$m^3$.

Table 1.4-11 shows the 13 underground storage facilities (including Montebello) considered in this work, along with the location, capacity, reservoir type, area, and number of active wells.

*Table 1.4-11. Characterization of Underground Gas Storage Facility location, capacity, type and other attributes in California.*

| Storage Facility | Latitude, Longitude | Capacity (Bcf) | Reservoir type | Field Area ($km^2$) | Active Wells | County |
|---|---|---|---|---|---|---|
| Aliso Canyon | 34.313, -118.558 | 86.2 | Oil | 13.75 | 141 | Los Angeles |
| Gill Ranch Gas | 36.793, -120.250 | 20.0 | Gas | 25.90 | 26 | Madera |
| Honor Rancho | 34.456, -118.598 | 27.0 | Oil | 9.27 | 51 | Los Angeles |
| Kirby Hill Gas | 38.169, -121.918 | 15.0 | Gas | 17.15 | 23 | Solano |
| La Goleta Gas | 34.421, -119.826 | 19.7 | Gas | 4.95 | 19 | Santa Barbara |
| Lodi Gas | 38.201, -121.208 | 17.0 | Gas | 19.50 | 24 | San Joaquin |
| Los Medanos Gas | 38.027, -122.021 | 17.95 | Gas | 18.18 | 23 | Contra Costa |
| McDonald Island Gas | 37.994, -121.480 | 82.0 | Gas | 46.75 | 88 | San Joaquin |
| Montebello | 34.025, -118.094 | --- | Oil | 15.07 | 211 | Los Angeles |
| Playa del Rey | 33.970, -118.446 | 2.4 | Oil | 7.46 | 49 | Los Angeles |
| Pleasant Creek Gas | 38.553, -122.000 | 2.25 | Gas | 11.91 | 7 | Yolo |
| Princeton Gas | 39.390, -122.020 | 11.0 | Gas | 9.97 | 13 | Colusa |
| Wild Goose Gas | 39.323, -121.890 | 75.0 | Gas | 6.53 | 21 | Butte |

#### 1.4.7.4 Meteorological Data and Approach

As described in Section 1.2.7, we used meteorological data, UGS locations, and the NOAA real-time High-Resolution Rapid Refresh (HRRR) model to assess emissions dispersion.

With the HRRR data, we developed a wind rose dataset for each UGS site. For illustration, we provide in Figure 1.4-6 and Figure 1.4-7 the wind roses for the Aliso Canyon and McDonald Island facilities. These figures show the annual wind roses for each storage facility obtained from the HRRR model data for a one-year period at four different times of the day; 00-06 (night), 06-12 (morning), 12-18 (afternoon), 18-00 (evening) PST to understand the dominant or primary wind directions (and speed). For Aliso Canyon, the main wind directions are N-NNE, with high frequency of strong winds for most of the day. However, during the afternoon, winds come from SSW with considerably lower wind speeds. McDonald Island Gas presents winds persistently from W-NW through the day, with some rare events from S-E mostly during nights and mornings. Winds are generally weak with the exception of the afternoons, when the winds tend to be stronger.

More details on how we compared the results from different meteorological datasets, along with the presentation and evaluation of wind roses for each UGS site, are provided in Appendix 1.B.

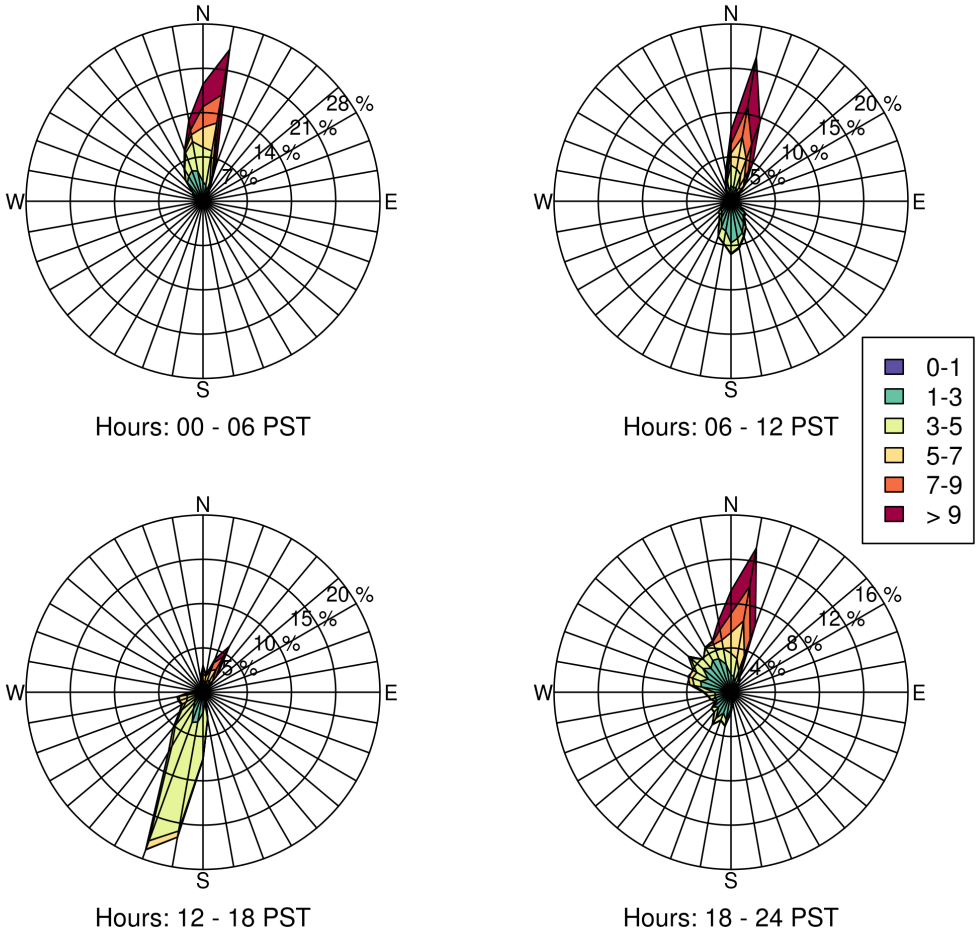


*Figure 1.4-6. Wind roses at the Aliso Canyon UGS facility obtained from HRRR data.*

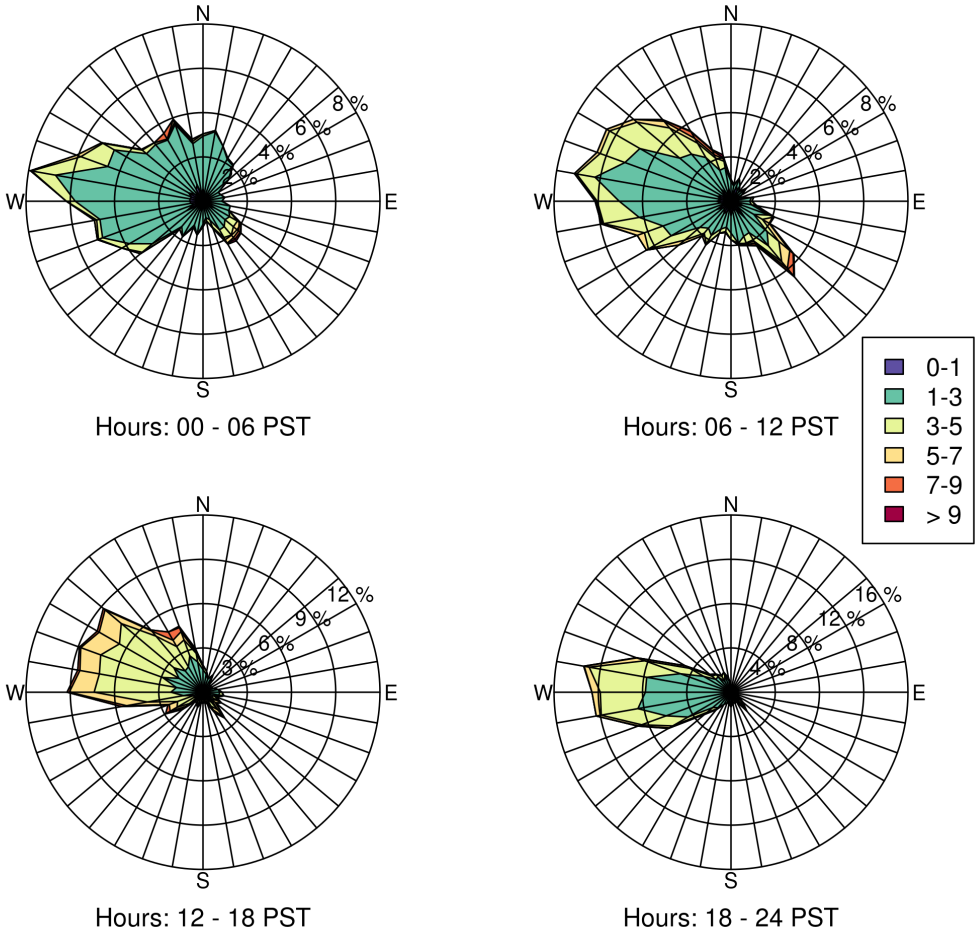


*Figure 1.4-7. Wind roses at the McDonald Island UGS facility obtained from HRRR data.*

### 1.4.7.5 Exposure Climatology

Figures 1.4-8–1.4-11 provide example contour plots for the annual mean tracer concentration/flux ratio (C/Q) (sometimes referred to as the "concentration over flux" ratio, even though Q is formally a flow rate) for Aliso Canyon, Gill Ranch, Honor Rancho, and Kirby Hill UGS facilities. Contour plots for all sites are provided in Appendix 1.B. The flooded contour plots show the spatial distribution of the C/Q ratio superimposed on a Google Earth image of the facility. The + symbols on the contour plots indicate the locations of the wells, the * symbol shows the centroid of the facility, and the black contours show the boundary of the storage facility. Red colors on the flooded contours indicate high values

of C/Q ratio, while the blue colors indicate low values of C/Q ratio. This implies that for a given emission rate, the concentration field decays exponentially with distance from the storage facility.

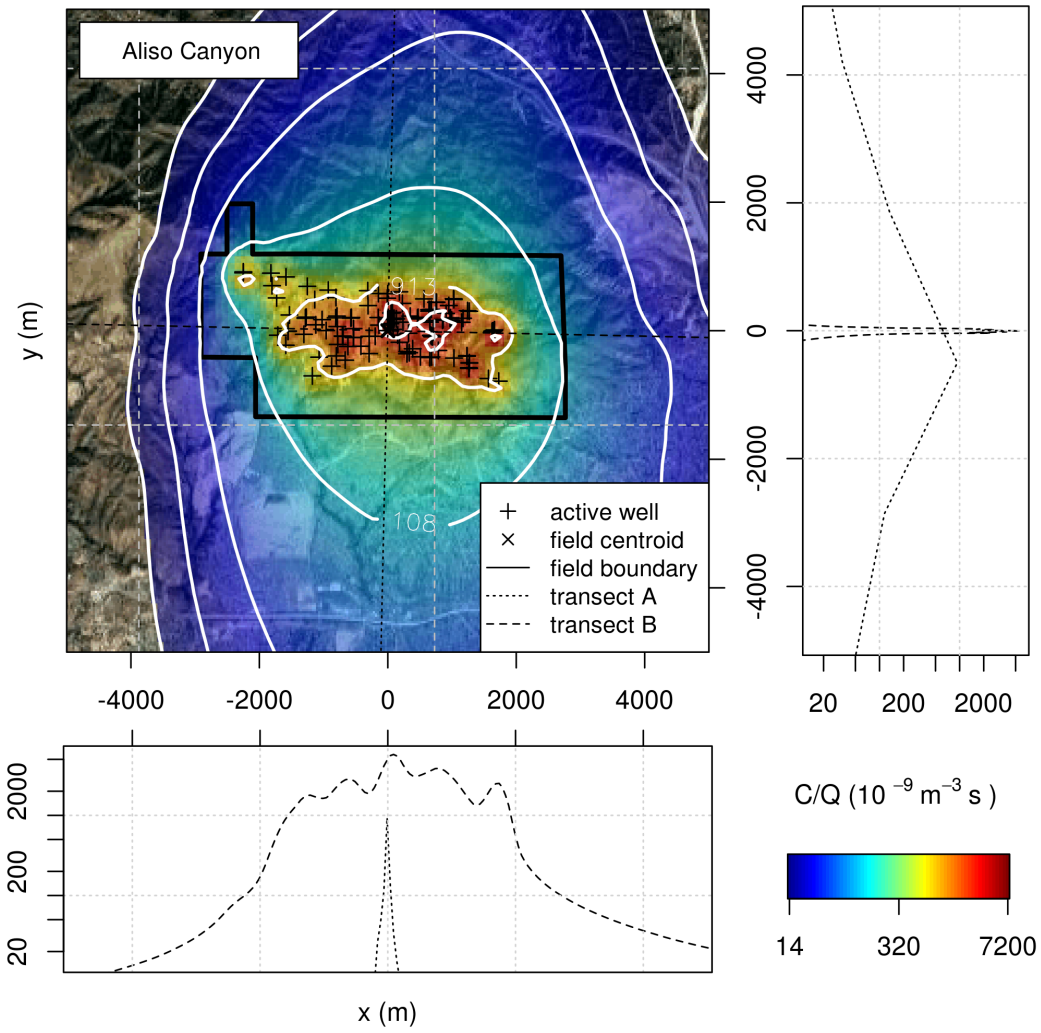


*Figure 1.4-8. Annual mean tracer concentration/flux ratio (C/Q) for Aliso Canyon). Side panels are the concentration profiles along the transects marked on the map.*

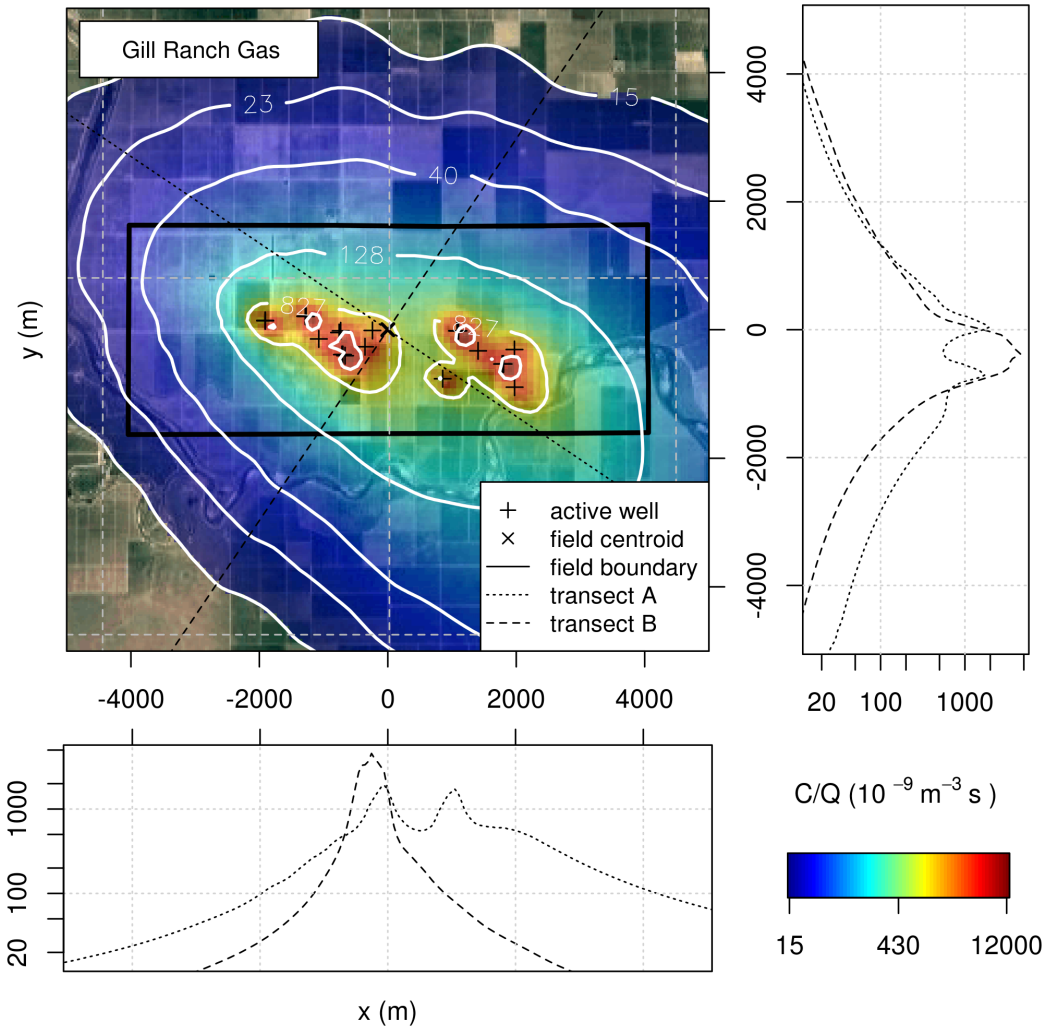


*Figure 1.4-9. Annual mean tracer concentration/flux ratio (C/Q) for Gill Ranch. Side panels are the concentration profiles along the transects marked on the map.*

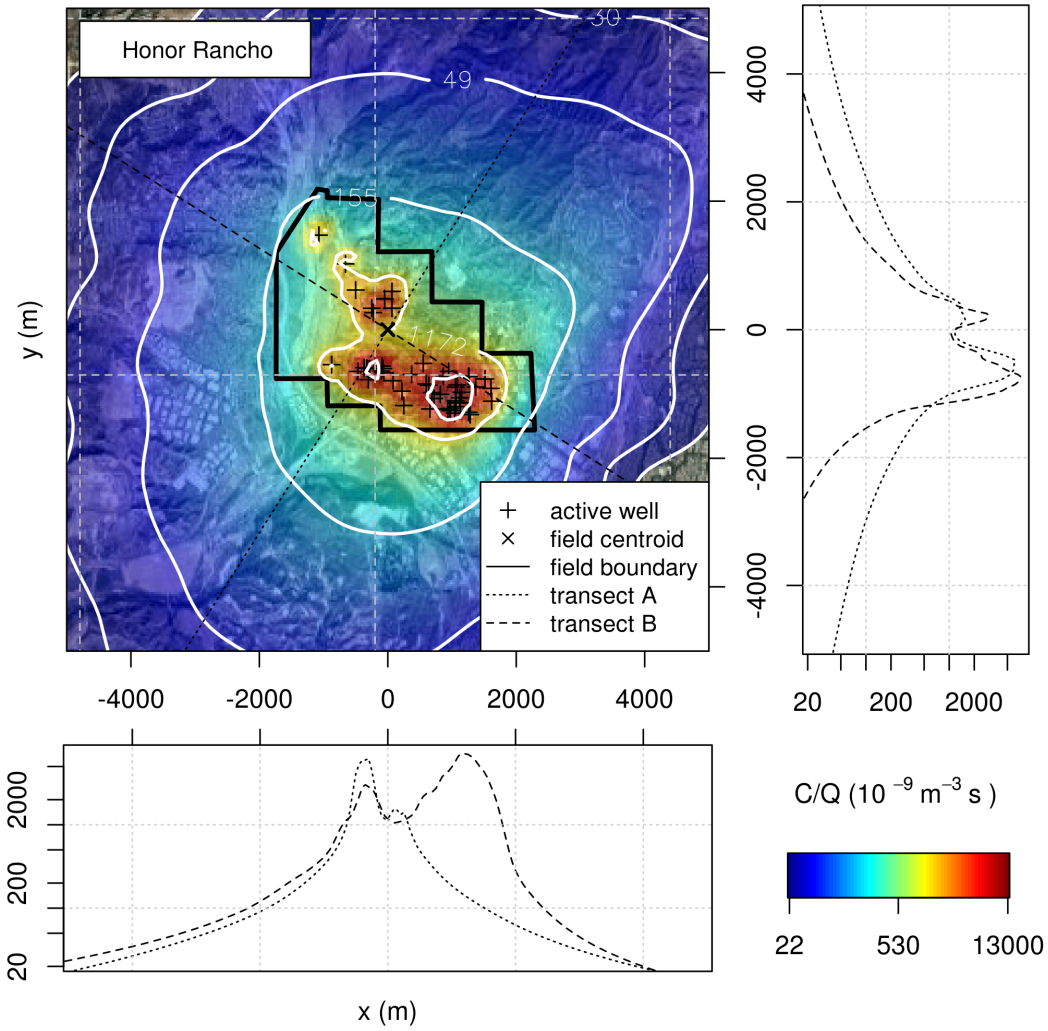


*Figure 1.4-10. Annual mean tracer concentration/flux ratio (C/Q) for Honor Rancho. Side panels are the concentration profiles along the transects marked on the map.*

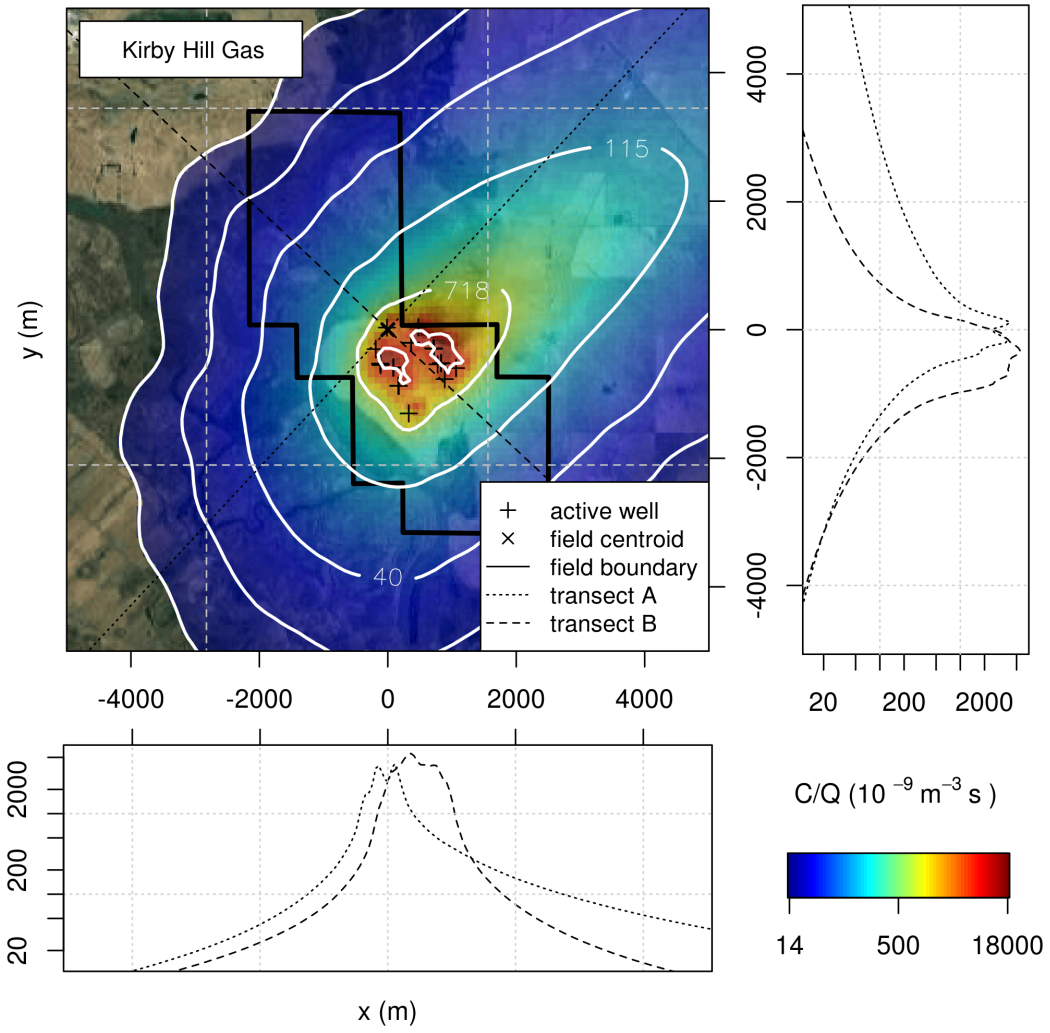


*Figure 1.4-11. Annual mean tracer concentration/flux ratio (C/Q) for Kirby Hill. Side panels are the concentration profiles along the transects marked on the map.*

The contour plots (Figures 1.4-8–1.4-11) also show white contour lines representing the 65%, 75%, 85%, 95%, 99%, and 99.9% quantile level. The quantile levels were computed from the cumulative distribution of all the pixel values in the computational domain. Each quantile level corresponds to a unique C/Q value for each storage facility. Figure 1.4-12 shows the C/Q ratio for each storage facility for each quantile level. For example, the 99% quantile level for Aliso Canyon corresponds to a C/Q value of ~ $1000 \times 10^{-9}$ $m^{-3}$ s (See Figure 1.4-12). A 99% quantile level for Aliso Canyon implies that 99% of all the C/Q values for that UGS facility were smaller than the C/Q value of $1000 \times 10^{-9}$ $m^{-3}$ s. Similarly, the 66% quantile level for Aliso Canyon implies that 66% of the C/Q values were smaller than $20 \times 10^{-9}$ $m^{-3}$ s.

The air dispersion modeling accounts for seasonal effects, boundary layer conditions, and temperature inversions through the boundary layer stability parameters. For example, the stability conditions could be very different during the day (sunny or cloudy day) than during the night. The dispersion model and the role of stability parameters are discussed in detail in Appendix 1.B.

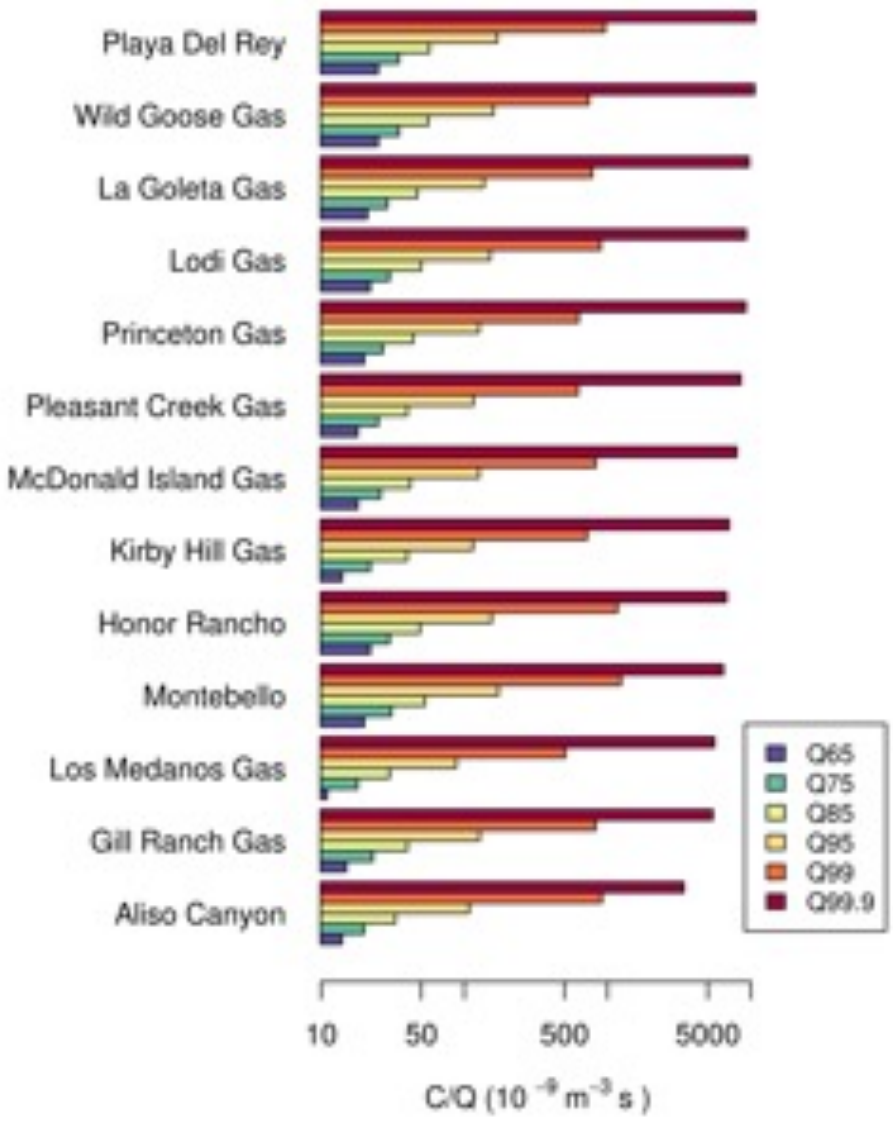


*Figure 1.4-12. Percentiles calculated for the annual mean tracer concentration/flux ratio for each storage facility.*

Different storage facilities will have different C/Q values corresponding to a certain quantile level. The 99% quantile level for Aliso Canyon has a C/Q value of $1000 \times 10^{-9}$ $m^{-3}$ s, while the 99% quantile level for Los Medanos is approximately $500 \times 10^{-9}$ $m^{-3}$ s. This is due to differences in meteorological conditions at the two facilities. It should be noted that the contour corresponding to the 99% quantile level for Aliso Canyon and Los Medanos roughly covers a similar area. Figure 1.4-12 also clearly shows the decaying values of the percentiles, indicating the distribution is very skewed.

The contour plots (Figures 1.4.10 & 1.4.11) also show the location of two perpendicular transects (dashed lines) crossing at the centroid of the field. The x-y plots to the bottom of the contour plot show the variability of the C/Q ratio (plotted on the Y axis) as a function of distance (measured along the X axis). Similarly, the x-y plots to the right of the contour plot shows the variability of the C/Q ratio (plotted on the X axis) as a function of the distance (measured along the Y axis).

P99.9 values ranged from 3,400 to 10,800 $\times 10^{-9}$ $m^{-3}$ s, for Aliso Canyon and Playa del Rey, respectively (see Figure 1.4-12). A big drop in the values is noticeable by looking at the P99, which ranged from 508 to 1,240 $\times 10^{-9}$ $m^{-3}$ s, for Los Medanos Gas and Montebello, respectively. P95 ranged from 88 to 173 $\times 10^{-9}$ $m^{-3}$ s, coincidently for Los Medanos and Montebello, respectively. P85 was 30 to 57 $\times 10^{-9}$ $m^{-3}$ s for Los Medanos and Playa del Rey, respectively, while P75 was 18 to 35 $\times 10^{-9}$ $m^{-3}$ s, for Los Medanos and Wild Goose Gas. Last, P65 ranged from 11 to 25 $\times 10^{-9}$ $m^{-3}$ s, for Los Medanos and Wild Goose Gas.

These values imply that the average C/Q ratio of fugitive but persistent emissions from underground storage facilities decays dramatically with the distance from the source. Overall, large values are only found in the first 0.5 $km^2$ surrounding the source, while in the first 5 $km^2$ the ratio gets reduced by 5–15 times and in the first 25 $km^2$ by 35-75 times.

Consistently, Los Medanos shows the smallest values for the percentiles, with the exception of P99.9, which is smallest for Aliso Canyon. The largest values for the percentiles are more equivocal between Playa del Rey, Montebello, and Wild Goose Gas.

Table 1.4-12 shows the annual mean C/Q ratio for the defined quantiles for each storage facility at four different times of the day; 12:00 a.m. to 6:00 a.m. (night), 6:00 a.m. to 12:00 p.m. (morning), 12:00pm to 6:00pm (afternoon), 6:00pm to 12:00am (evening) Pacific Standard Time (PST).

Larger C/Q ratios are always found during nights and evenings, as expected. This is due to the increased atmospheric stability and generally calmer winds during nights. Overall, night-afternoon differences are on the order of 2–12 times, depending on the contour level and facility, with a mean of 3.7 times. Playa del Rey exhibits the largest differences, while Los Medanos exhibits the smallest difference between night-afternoon hours.

*Table 1.4-12. Annual mean tracer concentration/flux ratio ($m^{-3}s$) scaled by $10^9$ for the quantiles (Q65, Q75,Q85, Q95, Q99, Q99.9) for each storage facility at four different times of the day; 00-06 (night), 06-12 (morning), 12-18 (afternoon), 18-00 (evening) PST.*

| Underground Storage Facilities | Hours (PST) | Q65 | Q75 | Q85 | Q95 | Q99 | Q99.9 |
|---|---|---|---|---|---|---|---|
| Playa del Rey | 00-06 | 38 | 58 | 96 | 279 | 1580 | 18413 |
| Playa del Rey | 06-12 | 10 | 15 | 26 | 88 | 479 | 3642 |
| Playa del Rey | 12-18 | 3 | 6 | 18 | 68 | 374 | 3181 |
| Playa del Rey | 18-24 | 36 | 53 | 87 | 254 | 1425 | 17309 |
| Montebello | 00-06 | 36 | 53 | 88 | 279 | 2061 | 10625 |
| Montebello | 06-12 | 10 | 15 | 26 | 95 | 596 | 2158 |
| Montebello | 12-18 | 4 | 7 | 19 | 76 | 494 | 2349 |
| Montebello | 18-24 | 30 | 45 | 79 | 246 | 1827 | 10278 |
| Aliso Canyon | 00-06 | 11 | 21 | 42 | 136 | 1130 | 4589 |
| Aliso Canyon | 06-12 | 6 | 9 | 17 | 63 | 422 | 1216 |
| Aliso Canyon | 12-18 | 5 | 9 | 17 | 62 | 405 | 1314 |
| Aliso Canyon | 18-24 | 25 | 35 | 57 | 180 | 1689 | 6727 |
| Honor Rancho | 00-06 | 34 | 47 | 76 | 234 | 1826 | 11112 |
| Honor Rancho | 06-12 | 8 | 12 | 21 | 76 | 539 | 2285 |
| Honor Rancho | 12-18 | 5 | 9 | 18 | 61 | 349 | 1688 |
| Honor Rancho | 18-24 | 37 | 51 | 82 | 255 | 1882 | 12196 |
| La Goleta Gas | 00-06 | 33 | 45 | 71 | 203 | 1155 | 15748 |
| La Goleta Gas | 06-12 | 10 | 14 | 25 | 79 | 452 | 3211 |
| La Goleta Gas | 12-18 | 7 | 11 | 20 | 64 | 363 | 3708 |
| La Goleta Gas | 18-24 | 33 | 46 | 74 | 207 | 1132 | 16781 |
| Gill Ranch Gas | 00-06 | 23 | 35 | 59 | 182 | 1229 | 8779 |
| Gill Ranch Gas | 06-12 | 9 | 14 | 25 | 89 | 532 | 2397 |
| Gill Ranch Gas | 12-18 | 8 | 13 | 26 | 88 | 526 | 2861 |
| Gill Ranch Gas | 18-24 | 17 | 27 | 50 | 158 | 1038 | 7487 |
| McDonald Island Gas | 00-06 | 31 | 43 | 69 | 201 | 1382 | 14645 |
| McDonald Island Gas | 06-12 | 10 | 14 | 25 | 81 | 492 | 3400 |
| McDonald Island Gas | 12-18 | 9 | 12 | 21 | 66 | 406 | 3330 |
| McDonald Island Gas | 18-24 | 18 | 30 | 56 | 166 | 1075 | 9427 |
| Lodi Gas | 00-06 | 33 | 49 | 82 | 245 | 1440 | 16101 |
| Lodi Gas | 06-12 | 11 | 16 | 28 | 92 | 507 | 3368 |
| Lodi Gas | 12-18 | 9 | 14 | 23 | 75 | 422 | 3469 |
| Lodi Gas | 18-24 | 30 | 42 | 68 | 204 | 1223 | 14011 |
| Los Medanos Gas | 00-06 | 11 | 21 | 42 | 123 | 704 | 7545 |
| Los Medanos Gas | 06-12 | 7 | 11 | 18 | 59 | 331 | 2561 |
| Los Medanos Gas | 12-18 | 7 | 10 | 18 | 55 | 312 | 2747 |
| Los Medanos Gas | 18-24 | 14 | 25 | 43 | 123 | 716 | 8953 |
| Wild Goose Gas | 00-06 | 41 | 56 | 89 | 245 | 1144 | 15177 |
| Wild Goose Gas | 06-12 | 13 | 18 | 31 | 97 | 459 | 5288 |

| Underground Storage Facilities | Hours (PST) | Q65 | Q75 | Q85 | Q95 | Q99 | Q99.9 |
|---|---|---|---|---|---|---|---|
| Wild Goose Gas | 12-18 | 12 | 17 | 29 | 88 | 412 | 4685 |
| Wild Goose Gas | 18-24 | 36 | 49 | 78 | 213 | 994 | 13308 |
| Princeton Gas | 00-06 | 32 | 44 | 70 | 194 | 956 | 15574 |
| Princeton Gas | 06-12 | 10 | 14 | 25 | 78 | 396 | 4256 |
| Princeton Gas | 12-18 | 10 | 14 | 24 | 74 | 392 | 3964 |
| Princeton Gas | 18-24 | 27 | 37 | 59 | 165 | 804 | 13947 |
| Kirby Hill Gas | 00-06 | 20 | 32 | 60 | 172 | 1103 | 11336 |
| Kirby Hill Gas | 06-12 | 9 | 14 | 24 | 77 | 450 | 3157 |
| Kirby Hill Gas | 12-18 | 8 | 12 | 21 | 64 | 377 | 3134 |
| Kirby Hill Gas | 18-24 | 17 | 28 | 53 | 155 | 973 | 10236 |
| Pleasant Creek Gas | 00-06 | 28 | 38 | 61 | 173 | 945 | 14671 |
| Pleasant Creek Gas | 06-12 | 11 | 16 | 26 | 81 | 412 | 3519 |
| Pleasant Creek Gas | 12-18 | 9 | 13 | 22 | 68 | 358 | 3848 |
| Pleasant Creek Gas | 18-24 | 21 | 33 | 54 | 153 | 850 | 13136 |

### 1.4.7.6 Refined Proximal Population Assessment Using Air Dispersion Modeling

Above in this section, we estimated populations and sensitive receptors in proximity to UGS facilities using distance alone, given that at any time of routine or off-normal releases of gas to the atmosphere, the wind may not blow in the annual average direction. In Table 1.4-13, we provide the results of our assessment of population counts for each quantile level for each UGS facility. Analysis covers all the quantile levels discussed in the previous section and has also been extended to the 50% quantile level.

*Table 1.4-13. Total population counts for each wind rose contour quantile level by UGS facility. Facilities are in descending order from high population to low population.*

| Underground Storage Facility | 99.9 Quantile Level | 99% Quantile Level | 95% Quantile Level | 85% Quantile Level | 75% Quantile Level | 65% Quantile Level | 50% Quantile Level |
|---|---|---|---|---|---|---|---|
| Montebello | 133 | 3,038 | 30,779 | 178,963 | 313,758 | 422,241 | 607,185 |
| Playa del Rey | 263 | 6,613 | 36,590 | 106,209 | 161,038 | 223,529 | 343,059 |
| Aliso Canyon | 0 | 38 | 6,910 | 37,027 | 88,854 | 144,290 | 219,991 |
| La Goleta Gas | 26 | 695 | 14,542 | 57,823 | 75,858 | 89,830 | 99,546 |
| Honor Rancho | 0 | 256 | 8,248 | 23,776 | 41,099 | 61,410 | 90,520 |
| Los Medanos Gas | 0 | 10 | 2,326 | 14,237 | 24,188 | 44,382 | 90,444 |
| Lodi Gas | 18 | 218 | 1,056 | 3,243 | 5,520 | 7,010 | 13,634 |
| Pleasant Creek Gas | 0 | 2 | 28 | 6,123 | 7,413 | 7,704 | 8,103 |
| McDonald Island Gas | 3 | 25 | 95 | 222 | 309 | 3,767 | 6,223 |
| Princeton Gas | 3 | 15 | 35 | 309 | 427 | 472 | 569 |
| Gill Ranch Gas | 0 | 0 | 4 | 60 | 168 | 279 | 492 |
| Kirby Hill Gas | 0 | 4 | 21 | 129 | 180 | 218 | 272 |
| Wild Goose Gas | 0 | 2 | 4 | 16 | 31 | 53 | 97 |

We also calculated population densities for each combination of quantile level (6 levels) and underground gas storage facility (13 facilities), providing 78 values. Similar to the Tier 1 results, we categorized each quantile level and underground gas storage facility combination as "None," "Very low," "Low," "Medium," and "High" population density. With the Tier 1 population counts, 55.9% of the buffer gas storage facility results are located in very low or no population density areas, while 28.7% are located in medium or high population density areas. In contrast, with the wind rose population counts, 47.4% of the quantile level gas storage facility results are located in very low or no population density areas, while 38.5% are located in medium or high population density areas. This demonstrates that when wind direction is considered, more densely populated areas will be affected than if radial buffers are considered alone. These results show the importance of incorporating wind direction data into an evaluation quantifying proximal populations that could potentially be at risk. For illustrative purposes, in Figures 1.4-13–1.4-15, we show the relationship between the location of Aliso Canyon, La Goleta, and Montebello UGS facilities, the air dispersion model results, and population density.

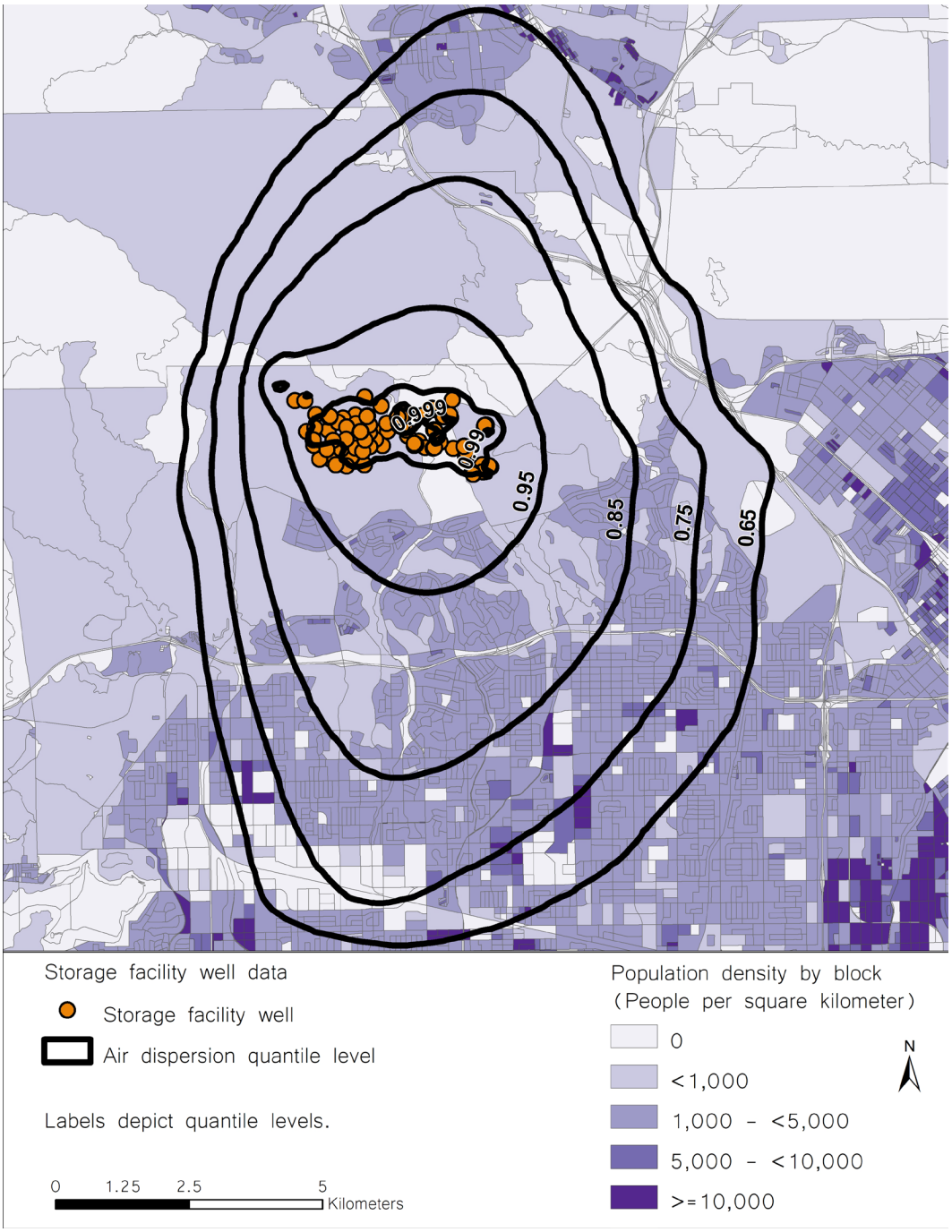


*Figure 1.4-13. Air dispersion quantiles and population density at the Aliso Canyon UGS facility.*

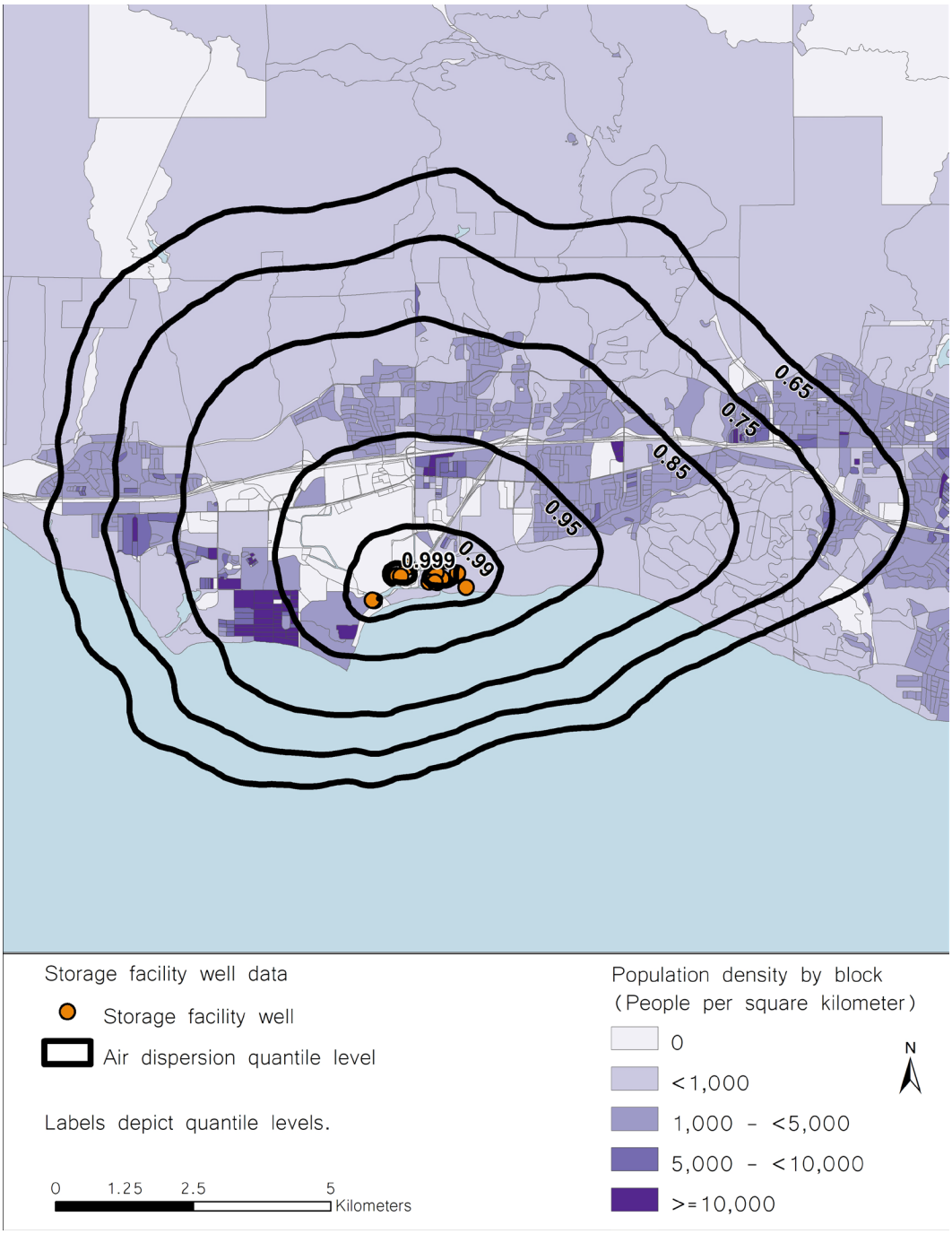


*Figure 1.4-14. Air dispersion quantiles and population density at the La Goleta UGS facility.*


*Figure 1.4-15. Air dispersion quantiles and population density at the Montebello UGS facility.*

The wind dispersion modeling indicated that air pollutants emitted by UGS facilities could travel out to beyond 8,000 m (~5 miles) at the 0.50 quantile level, depending on the geographic location of each UGS facility, especially during a larger loss-of-containment event such as the one that occurred at Aliso Canyon. To incorporate this information, we created a final radial buffer that we call the QL50 buffer to indicate the maximum distance per storage facility from the outermost extent of the UGS well boundary to the 0.50 quantile level boundary. This distance varies between sites, ranging from 7,977 m at Lodi Gas to 12,037 m at Montebello, depending on and constrained by prevailing wind patterns, with a mean distance of 9,427 m.

Calculating population counts under the 0.50 quantile level distances is important, because available self-reported health symptoms data collected by LACDPH (2016c) during and after the 2015 Aliso Canyon incident extended out to similar distances. In fact, the majority of the reported symptoms potentially attributable to the 2015 Aliso Canyon incident were reported up to 16,090 meters (10 miles) from the facility (see Section 1.4.10). Consideration of distances greater than 10,000 m from a UGS facility, according to our air dispersion model, seemed not to be justified, because the C/Q values of UGS facilities began to level off around the 50$^{th}$ percentile.

The results of our QL50 population and sensitive receptor count assessment can be found in Table 1.4-14 below. We estimate that in total, 3,127,434 Californians live within the QL50 buffer area. Of these, 204,772 are under the age of five and 165,313 are age 75 or older. There are also substantial sensitive receptors within this area: there are 967 schools (966 open and 1 pending), 2,121 daycares (2,094 open and 27 pending), 519 residential elderly care facilities (470 open and 1 pending), and 46 hospitals.

Even with the variance in buffer distance, the facilities rank very similarly to the 8,000 m radial buffer with population count magnitudes. Montebello continues to have the highest population, with over 1.5 million people living within the QL50 area, while Wild Goose Gas has the lowest population, with a minimal 195 people. Six facilities have greater than 100,000 people within this area, and two facilities have greater than 500,000 people.

*Table 1.4-14. Population and sensitive receptor counts for the QL50 buffer, by underground storage site; N/A = data not available.*

| Underground Storage Facility | Buffer Distance | Number of Residents | Under 5 | Age 75 and Older | Number of Open Schools | Number of Children Enrolled in School | Number of Open Daycare Facilities | Number of Open Elderly Care Facilities | Number of Hospitals |
|---|---|---|---|---|---|---|---|---|---|
| Aliso Canyon | 9,116 m | 325,330 | 18,711 | 19,269 | 102 | 60,241 | 244 | 130 | 4 |
| Gill Ranch | 9,124 m | 909 | 82 | 29 | 0 | 0 | 0 | 0 | 0 |
| Honor Rancho | 8,998 m | 180,359 | 11,139 | 5,807 | 54 | 38,631 | 121 | 61 | 1 |
| Kirby Hill | 9,813 m | 401 | 17 | 18 | 0 | 0 | 0 | 0 | 0 |
| La Goleta | 8,608 m | 101,371 | 4,040 | 7,611 | 32 | 13,991 | 77 | 41 | 3 |
| Lodi Gas | 7,977 m | 23,771 | 1,600 | 1,576 | 9 | 2,851 | 10 | 2 | 0 |
| Los Medanos | 9,743 m | 223,069 | 15,640 | 10,407 | 63 | 29,169 | 176 | 92 | 3 |
| McDonald Island | 9,282 m | 6,473 | 388 | 244 | 0 | 0 | 2 | 0 | 0 |
| Montebello | 12,037 m | 1,594,128 | 113,206 | 81,789 | 482 | 273,453 | 877 | 59 | 26 |
| Playa del Rey | 9,506 m | 691,757 | 39,352 | 38,121 | 218 | 93,325 | 577 | 85 | 9 |
| Pleasant Creek | 9,553 m | 8,821 | 545 | 373 | 4 | 0 | 9 | 0 | 0 |
| Princeton | 9,686 m | 848 | 41 | 59 | 2 | 169 | 0 | 0 | 0 |
| Wild Goose | 9,102 m | 195 | 9 | 11 | 0 | 0 | 0 | 0 | 0 |

### 1.4.8 Explosion and Fire Hazards of Loss-of-containment Events

The accidental release of natural gas stored under high pressure at a UGS facility can pose a significant threat to people and property in the vicinity of the failure location. Based on the history of explosions and fires in the natural gas industry (e.g., from pipelines), it is important to consider these risks involving large volumes of gas, such as those stored in UGS facilities (CPUC, 2010). Among the significant hazards associated with such a release is thermal radiation from sustained fire and collapse of buildings from an explosion inside or in a partially confined area enclosed by buildings. Decompression cooling can cause small pipeline leaks to turn into large leaks.

The area of hazard associated with the damage will depend on the mode of failure, time to ignition, environmental conditions at the failure point, and meteorological variables. For example, ignited releases can produce pool fires, jet flames, vapor cloud fires, or fireballs, all of which behave differently and exhibit markedly different radiation characteristics. The thermal radiation hazards from hydrocarbon pool fires depend on a number of parameters, including the composition of the hydrocarbon, the size and shape of the pool, the duration of the fire, its proximity to the object at risk, and the thermal characteristics of the object exposed to the fire (Smith et al., 2011; Jo and Ahn, 2002).

Accidental release of hydrocarbon vapors or intentional disposal of unwanted gas can result in large turbulent diffusion flames and flares (Dryer et al., 2007; Montiel et al., 1996; Sklavaounos, 2006). Thermal radiation from flares and turbulent flames can represent

substantial hazard to personnel, equipment, and the environment. The base diameter of a flare stack, height of the stack, and composition of the burning substance are important variables in determining the radiation from turbulent jet flames. Horizontal jet dispersion models that characterize the concentration profile and fire models that characterize the radiative heat flux can estimate the ground area (hazard zone) affected by credible failure scenarios. Leak rates and meteorological data can be combined with flammability/explosion-limit estimates to delineate the extent of the hazard zone (Benjamin et al., 2016; SFPE, 2008).

For many UGS facilities, the size of fire and explosion hazard zones can be larger than the infrastructure footprint, especially for facilities with gas processing and compressor equipment. The impacts of loss-of-containment (LOC) failure to UGS infrastructure are potentially very large (SFPE, 2008). Hazard zones should be delineated for each UGS facility to focus risk mitigation on elimination of leakage and ignition sources (loss prevention) and safer site-use planning. In this section, a method to estimate the size of the hazard zone based on atmospheric dispersion of the leaked gas is described.

As is the case for air dispersion modeling described above and in Section 1.2, meteorological data were collected from stations that are part of NOAA's Integrated Surface Database (ISD) and located closest to the various underground storage facilities. The High-Resolution Rapid Refresh (HRRR) also provided annual averaged values of meteorological data for each storage facility for four different times of the day; 00-06 (night), 06-12 (morning), 12-18 (afternoon), 18-24 (evening) PST. The averaged wind speed and wind direction data were subsequently combined with plume dispersion models to compute the methane concentrations downwind of the storage facility. Furthermore, since the leak rate (referred to frequently as the flux) from the storage facility is not known, a unit flow rate was assumed. Appendix 1.B provides detailed contour plots that show the average downwind concentration per unit flux for each storage facility.

The downwind concentrations per unit flow rate are particularly useful, since the contour levels can be multiplied by the actual leak rate to obtain the average concentrations downwind of the UGS facility. If the leak rates are very large, then downwind concentrations can be large as well; the concentrations in the model decay with distance from the leak in an exponential manner. When the leak rates are small, the downwind concentrations close to the leak site will be relatively small.

Under high leak rates, the downwind concentrations can be larger than the flammability or explosions limits. Flammability limits refer to the range of compositions, for fixed temperature and pressure, within which exothermic chemical reactions are possible. Flammability limits are given in terms of fuel concentration (by volume) at a specified pressure and volume. The lower flammability limit for pure methane is 4.4% (percent volume of air), while the upper flammability limit is 16.4%. For comparison, the lower and upper flammability limits of pure ethane are 3% and 12.4%, respectively.

If the leak rates are very high, then the downwind concentrations can be larger than the lower flammability limits. Results of the detailed air dispersion calculations provided in Appendix 1.B show that the C/Q contours extend well beyond the boundary of the storage facility. This implies that the size of the hazard zone can be much larger than the infrastructure footprint and the LOC hazard can be potentially very large.

This analysis points to the need for clearly establishing the extent of the hazard zone around each of the 13 UGS facilities in California. Establishing the extent of the hazard zone would focus the mitigation efforts on eliminating leakage and ignition sources as well as safer site-use planning.

#### 1.4.8.1 Minimum Flux Required to Reach Flammability Limits

In this section, we present the minimum leak rate required to reach the lower flammability limit in the vicinity of each storage facility. The minimum methane volume fraction required in a gas mixture to reach flammability is 0.044; this limit is referred to as the lower flammability limit (LFL) (SFPE, 2008). The approach used to compute the flammability limits (discussed in this section) is fundamentally different from that used to understand health effects (described earlier in this section). In case of health effects, the average values (long-term effects) were presented. On the other hand, in this section we are interested in the worst-case scenario for flammability and explosion limits.

To estimate the flammability risk under possible catastrophic leak events of an underground storage facility, it was assumed that any single well could leak at any time through the year. It is also assumed that the leak rate is constant in time. More complex computational fluid dynamics (CFD) tools can account for leak rates that vary with time. For a storage facility, the plume concentrations were computed hourly for each active well independently (concentration fields do not add up) during the period of interest. For this analysis, the hourly meteorological fields were assumed for a one-year period, as described in earlier sections. Subsequently, the maximum concentration through the year generated by any of the plumes was selected as the peak concentration for each point (pixel) of the computation domain. This approach enables us to compute the maximum possible hourly concentration for any known flux at any point in the domain of interest downwind of the storage facility. We next computed the minimum leak rate required to reach the lower flammability limit for methane at each point in the computational domain. The analysis and results presented in this section do not account for the vertical momentum-dominated jet that will occur during a high-pressure blowout scenario, nor does the analysis account for the thermal effects of a burning cloud or fire ball. These effects can be approximated to some extent through the concept of stack height. Multiphase flows involving a mixture of oil and gas and orientation of the leak can also influence the results presented in this section.

Figures 1.4-16 through 1.4-20 show the contours for minimum leak rate required to reach a flammable Leak Rate for Flammability (LRF) mixture for each storage facility. The top panel of Figure 1.4-16 shows the results for the Aliso Canyon natural gas storage facility. The contour plot shows the spatial distribution of the minimum estimated leak rate to reach a flammable mixture superimposed on a Google Earth image of the facility. The + symbols on the contour plot indicate the location of the wells, the * symbol shows the centroid of the facility, and the black contour shows the boundary of the storage facility. Blue color on the flooded contour plot indicates that the flammability limit was reached for higher values of leak rate, while red color indicates that the flammability was reached for lower values of leak rates. Due to the exponential decay in the concentration field, lower values of leak rate to achieve flammability were found closer to the wells, while higher values were found away from the wells.

The contour plot also shows white contour lines representing the 15%, 5%, 1%, and 0.1% quantile levels. Each quantile level corresponds to a unique leak rate for each storage facility. The minimum leak rate required for flammability corresponding to the various quantile levels is shown in Table 1.4-15. The quantile levels were computed from the cumulative distribution of all the pixel values of leak rate in the computational domain. For example, the 15% quantile level for Aliso Canyon corresponds to a leak rate of 9,141 t/hour, while the 15% quantile level for Los Medanos corresponds to a leak rate of 13,251 t/hr. A 15% quantile level would imply that 15% of the values are inside the contour level. This implies that for Aliso Canyon, 15% of the values of leak rate to reach flammability were less than 9,141 t/hour. The 15% quantile level is the outermost level (farthest away from the storage facility/wells), while the 0.1% quantile is located closest to the wells. Leak rates corresponding to the 15% quantile levels are quite large as expected, and the rate gets smaller for smaller quantile levels.

Each contour plot also shows the location of two perpendicular transects (dashed lines) crossing at the centroid of the field. The x-y plots to the bottom of the contour plot show the variability of the minimum leak rate required to reach flammability (plotted on the Y axis) as a function of distance (measured along the X axis). Similarly, the x-y plots to the right of the contour plot show the variability of the minimum leak rate required to reach flammability (plotted on the X axis) as a function of distance (measured along the Y axis).

In addition, a reference contour (red) representing a leak rate of 50 tonnes/hr was added on the contour plot. This leak rate of 50 tonnes/hour was the peak leak rate measured at Aliso Canyon during the November 2015 period (Conley et al., 2016). The red contour shows the maximum possible extent of the flammable zone or hazard zone if a leak comparable to the Aliso Canyon leak occurred at any of the facilities.

Overall, the estimated leak rate to reach flammability increases significantly as we move away from the wells. This is due to the dispersion of the leaked gas, where the concentration decays exponentially with distance from the leak source. The 50 tonnes/hour contour (red) for Aliso Canyon in Figure 1.4-16 (top left panel) was contained within the boundary of the

facility. If the leak rate at the Aliso Canyon facility was significantly larger, then the region outside the facility would also fall into the hazard zone. The required leak rate to expose the outside of the fields to flammability risk increases to approximately 2,300 tonnes/hour.

Results for Gill Ranch Gas (Figure 1.4-16, top right panel) shows that the 50 t/hr contour (red) is not continuous as for Aliso Canyon, but exhibits hazard regions around each well. Similar features are observed at Honor Rancho and Kirby Hill (Figure 1.4-16). This analysis indicates that facilities where the well pads are located at the boundary of the facility (as for Honor Rancho, Kirby Hill, La Goleta, Los Medanos, and Playa del Rey) would result in potential hazard zones that extend outside the facility. The analysis also indicates that the flammable zone (hazard zone) can extend beyond the facility for very large leak cases (much larger than that for the Aliso Canyon Incident).

Wild Goose (Figure 1.4-20) is a very interesting case, because it shows a circular pattern around the source. This is the case of a point source. The circular pattern results from the fact that, through the year, there is at least one hour of meteorological conditions yielding to the largest values for every direction. This result allows us to say that for point sources, a worst-case scenario estimation may very well be drawn with a simpler one-dimensional plume model.

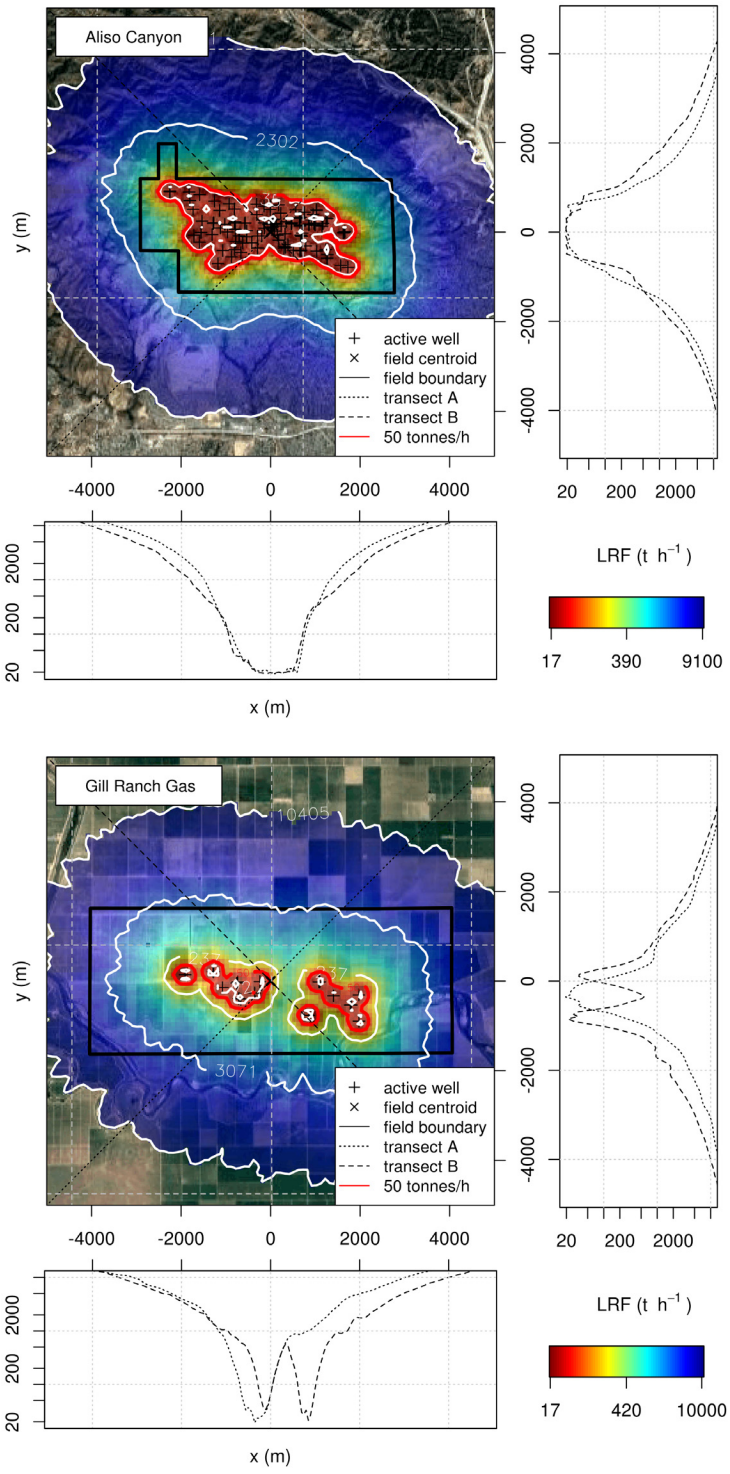


*Figure 1.4-16. Contours of minimum leak rate required to reach lower flammability limit (LRF) for Aliso Canyon (top) and Gill Ranch (bottom) underground gas storage facilities.*

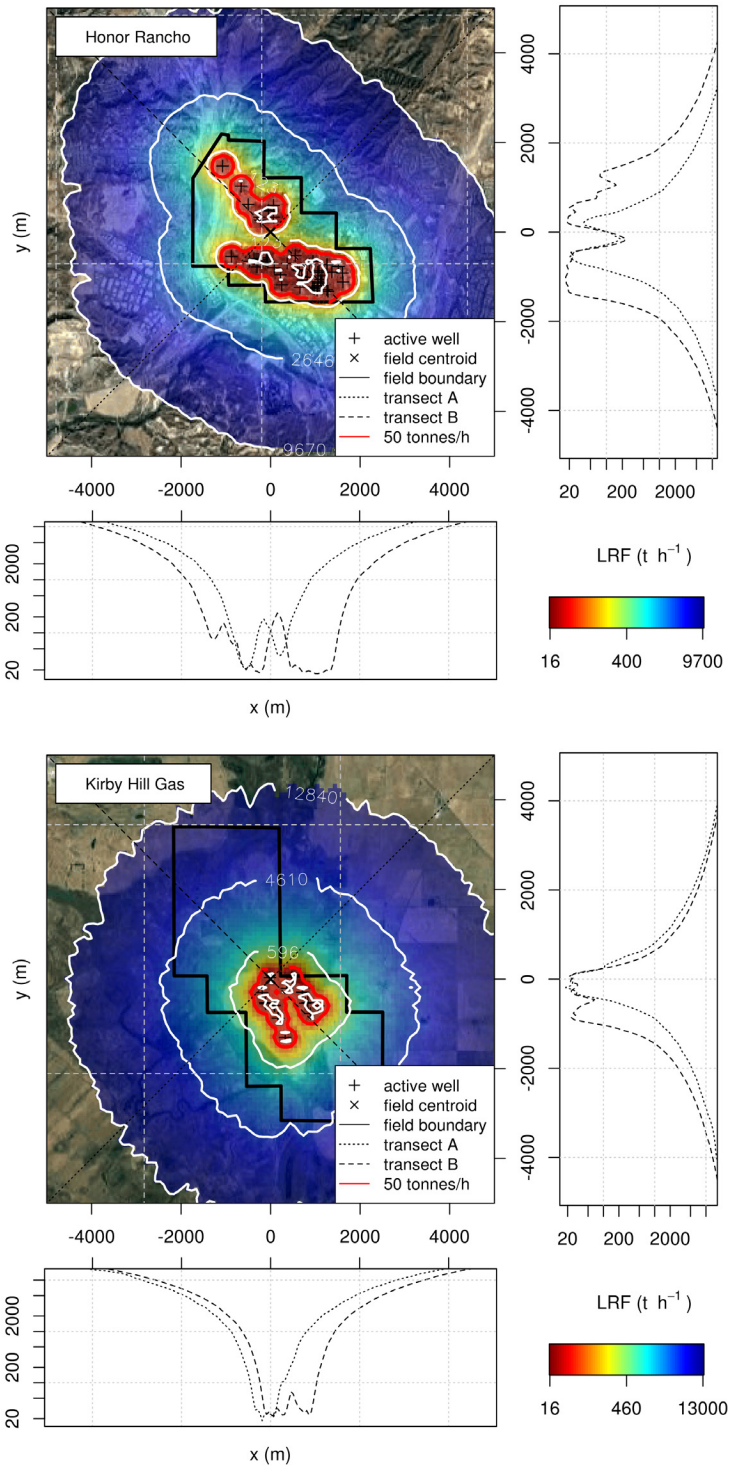


*Figure 1.4-17. Contours of minimum leak rate required to reach lower flammability limit (LRF) for Honor Rancho (top) and Kirby Hill (bottom) underground gas storage facilities.*

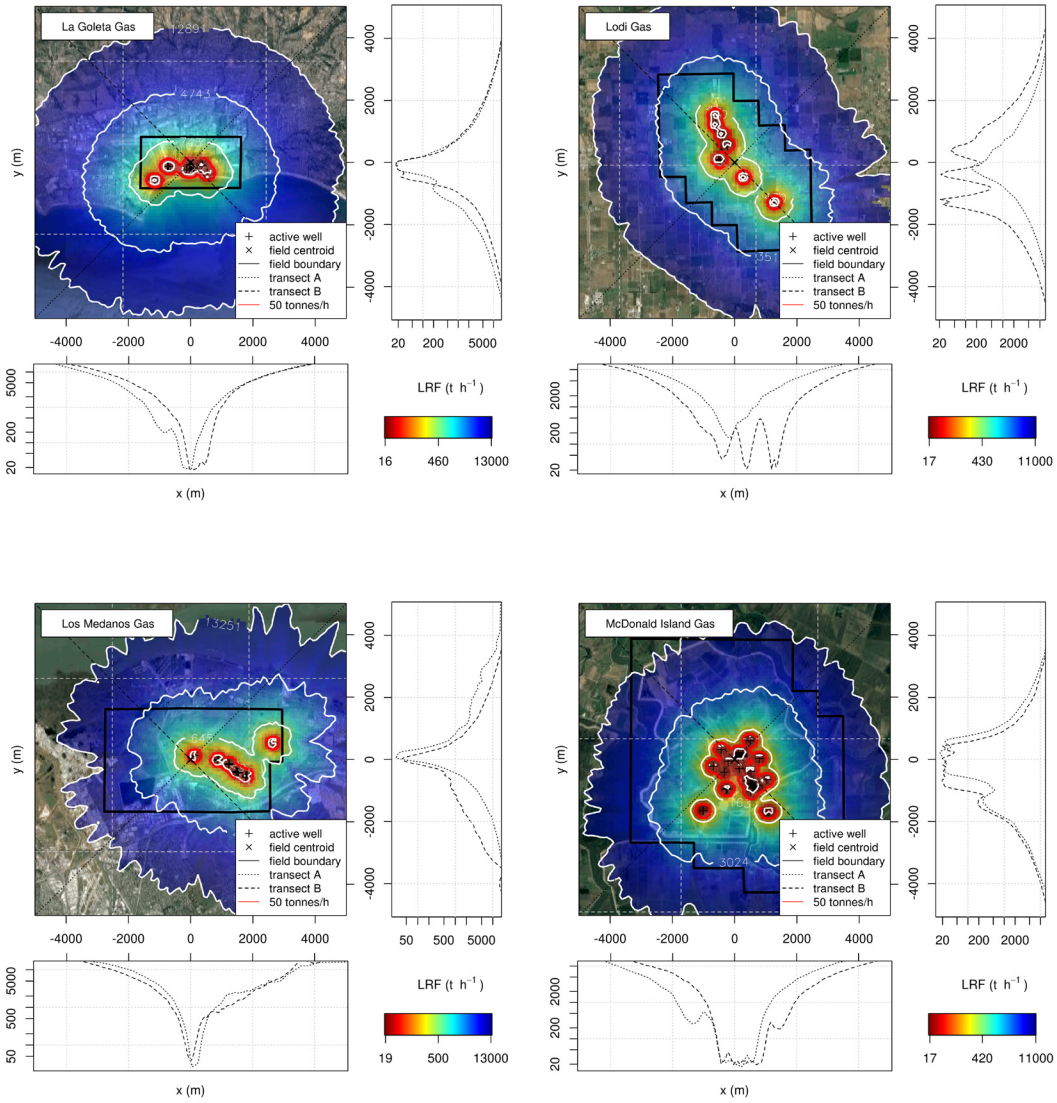


*Figure 1.4-18. Contours of minimum leak rate required to reach lower flammability limit (LRF) for La Goleta Gas, Lodi Gas, Los Medanos Gas, and McDonald Island underground gas storage facilities.*

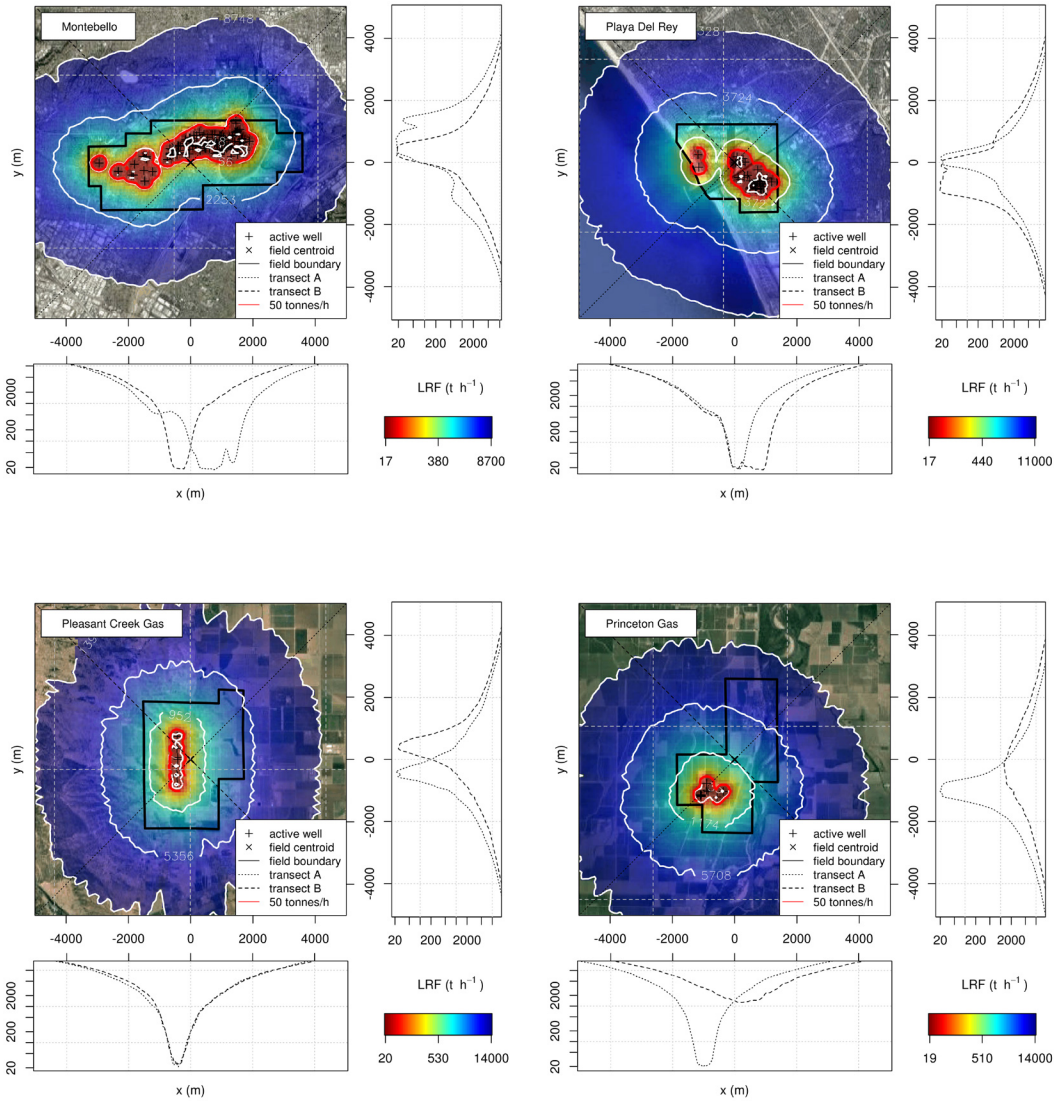


*Figure 1.4-19. Contours of minimum leak rate required to reach lower flammability limit (LRF) for Montebello, Playa del Rey, Pleasant Creek, and Princeton underground gas storage facilities.*

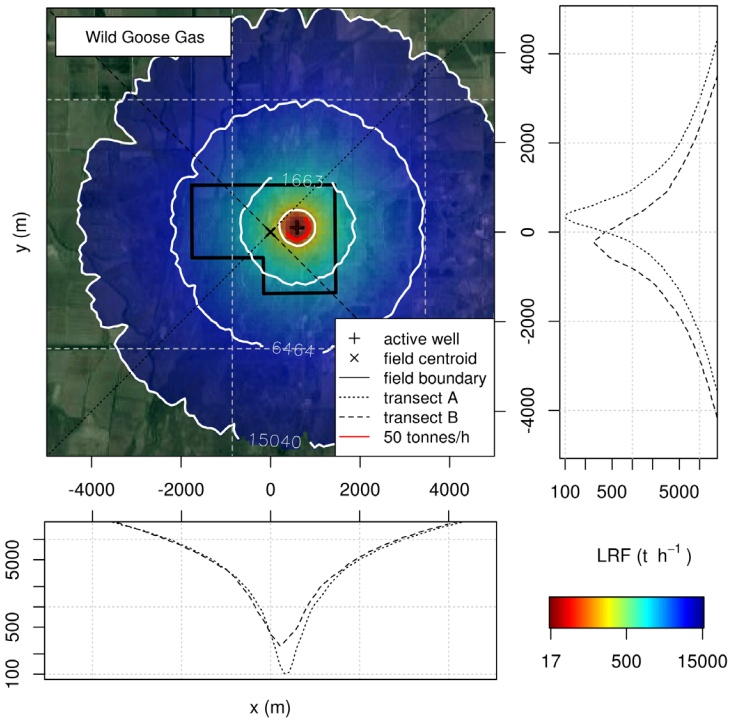


*Figure 1.4-20. Contours of minimum leak rate required to reach lower flammability limit (LRF) for Wild Goose underground gas storage facilities.*

*Table 1.4-15. Estimated minimum leak rate (t / hour) for flammability corresponding to the 15%, 5%, 1%, and 0.1% quantile levels.*

| Storage Facility | q15 | q05 | q01 | q00.1 |
|---|---|---|---|---|
| Playa del Rey | 11328 | 3724 | 372 | 19 |
| Montebello | 8748 | 2253 | 66 | 18 |
| Aliso Canyon | 9141 | 2302 | 35 | 18 |
| La Goleta Gas | 12891 | 4743 | 743 | 22 |
| Gill Ranch Gas | 10405 | 3071 | 237 | 22 |
| Honor Rancho | 9670 | 2646 | 123 | 18 |
| McDonald Island Gas | 10619 | 3024 | 163 | 20 |
| Lodi Gas | 10998 | 3519 | 430 | 23 |
| Los Medanos Gas | 13251 | 4549 | 645 | 29 |
| Wild Goose Gas | 15040 | 6464 | 1663 | 143 |
| Princeton Gas | 14160 | 5708 | 1174 | 35 |
| Kirby Hill Gas | 12840 | 4610 | 596 | 21 |
| Pleasant Creek Gas | 13960 | 5356 | 952 | 27 |

### 1.4.9 Public Health Hazards Arising from Potential UGS Impacts on Underground Sources of Drinking Water (USDW)

As discussed in Section 1.2, there are historical cases of stray gas migration in the subsurface from a loss of zonal isolation of gas into Underground Sources of Drinking Water (USDW) in California. Contamination of USDW with methane and other associated compounds introduces routes of exposure via drinking water, bathing, and other human water uses. To date, there are limited available data to assess the risk of USDW contamination from stray gas and other fluid migration from UGS facilities; however, such events can expose populations that rely on these aquifers for domestic consumption to a variety of chemical constituents. Monitoring should be carried out to detect and prevent or mitigate gas and other fluid migration from UGS storage facilities (surface and subsurface) into USDW.

The only publicly available assessment of impacts to water resources to date following the SS-25 well LOC event at the Aliso Canyon UGS Facility was sampling of *surface* water, conducted by Geosyntec Consultants (Geotracker, 2017). Geosyntec Consultants was contracted by SoCalGas in response to a 13267 order by the California State Water Resources Control Board following the SS-25 event (Geotracker, 2017). This assessment focused only on contamination of surface water with respect to deposited "work-over fluids" used in the SS-25 well kill attempts and did not find evidence of contamination (Geosyntec, 2017). However, aside from the highly narrow chemical scope of the study which fails to account for many of the known substances that would be appropriate to test for – as previously discussed in this chapter – this approach suffers from other shortcomings including that sampling did not take place until after a number of precipitation events. This delay introduces significant uncertainty given that chemicals that may have been deposited could have either eroded or been washed away prior to sampling. It is also worth stating, again, that it is more likely that groundwater would be impacted from such an event compared with surface water. Geosyntec Consultants is to perform a subsurface water study near SS-25 (Geotracker, 2017), but to date this report has not been released and there are questions as to whether data collection has yet commenced.

### 1.4.10 Large UGS Loss-of-containment Events and Public Health: The Case of the 2015 Aliso Canyon Incident

As noted in Sections 1.2 and 1.5 of this report, the blowout of the SS-25 well at the Aliso Canyon UGS Facility (Aliso Canyon) resulted in the largest atmospheric emission of methane from a single source in UGS history in the United States (Conley et al., 2016). The 2015 Aliso Canyon incident side bar in Section 1.2 describes what is known so far about the SS-25 well and the challenges to bring this loss-of-containment (LOC) event under control. The incident resulted in thousands of households being temporarily relocated and impacted the health of tens of thousands of people. While this report as a whole concerns underground gas storage facilities in California in general, the 2015 Aliso Canyon incident provides an important case study to assess the human health hazards, risks, and impacts of a large UGS disaster. The Aliso Canyon case is also important to assess from a public

health perspective, given that it is the only UGS facility to be subjected to substantial air and environmental quality monitoring.

While the mass of methane emitted from the SS-25 blowout is well characterized (Conley et al., 2016; CARB 2016a), the mass of toxic air pollutant emissions and their resultant atmospheric concentrations and exposures to human populations are more uncertain.

As is the case for any large-scale emission—UGS or otherwise—in order to understand the environmental public health hazards, risks, and impacts - data must be available for a variety of factors, including but not limited to:

1. The composition of the substances emitted to the atmosphere
2. The rate and magnitude of emissions
3. The acute and chronic toxicity of the emitted substances
4. The extent of exposure to human populations.

Our team made formal attempts to gain access to data on the chemical composition of gas that is stored in UGS facilities, including gas stored at the Aliso Canyon UGS facility. The documentation and summary of these unsuccessful efforts are detailed in Appendix 1.D. The lack of motivation and effort on the part of operators to provide detailed chemical composition analyses may arise because operators take measurements to meet the tariffed standards for pipeline quality. These types of measurements are not sufficient for us to conduct a full assessment of air pollutant emissions and associated health effects. There may also be other reasons that operators failed to share these data with our study team.

What was shared with us was often the percentage breakdown of typical constituents of natural gas, with limits of reporting often at 1% or more. However, 1% of a substance in natural gas is 10,000 parts per million (ppm) or 10 parts per thousand (ppt). Even with substantial dilution of gases in the atmosphere, some harmful substances pose risks at ppt or parts per billion (ppb) levels in gas. CalEPA Reference Exposure Levels (RELs) are pollutant concentrations at or below which adverse health effects are not likely to occur (U.S. EPA, 2015). For instance, given that the REL for an 8-hour exposure to benzene is 3 ug/$m^3$ or 1 ppb, ppt levels in stored gas would easily reach this level in the diluting atmosphere. While it is not likely that 1% of gas withdrawn from the Aliso Canyon UGS facility is an air toxic such as benzene, this does suggest that it is critical to have access to these data to be able to estimate exposure of facility workers and nearby populations.

Based on the limits of on-site and nearby air dilution, we have determined that reporting values should be at least as low as one tenth of the relevant exposure reference values. The practice of making measurements for tariff standards needs to be modified to support health impact assessments. Lack of trace chemical detection precision may not matter at a

measuring and metering station out along the transmission pipeline. However, it can matter at UGS sites, because a UGS site concentrates more gas in one place, allowing for higher potential
leak quantities—suggesting the need for more precise composition measurement standards.

Given that we were not able to obtain the chemical composition of gas stored in Aliso Canyon at the level of detail needed, we are unable to determine the rate and magnitude of emissions of air pollutants that were emitted during the SS-25 and other events at the Aliso Canyon facility. Further, as mentioned earlier in this Section 1.4.5 and 1.4.6, the lack of spatial, temporal, and infrastructure-source specificity in reporting of toxic and criteria air pollutant releases renders it difficult to effectively estimate these health-damaging air-pollutant emissions during the SS-25 event.

With respect to the acute and chronic toxicity of the pollutants emitted from Aliso Canyon in general, the reported emissions inventories are generally helpful. For a full description of the substances reported as being emitted from Aliso Canyon, please see Section 1.4.5, where we analyze the emissions inventories.

There are three primary ways to assess the ambient concentrations of and potential exposures to toxic air pollutants enhanced by emissions from the 2015 Aliso Canyon incident, and the associated exposure of human populations both at the facility (occupational exposures) and in the Porter Ranch and other communities (community exposures). The best, but most difficult, approach is to conduct personal sampling on workers and community members. The second approach is to conduct *in situ* air quality monitoring during the event to empirically observe the changes in air quality over time. The third approach is to model atmospheric transport of the substances being emitted—that is, their emission rate and their dispersion patterns, based upon meteorological variables (e.g., Gaussian plume modeling) to determine concentrations and estimate exposures and associated risk to human health across geographic space and demographic groups.

As discussed previously, there is substantial uncertainty inherent in any approach that relies upon modeling of emissions data without access to data on the composition of stored gas. However, during the course of the SS-25 blowout at Aliso Canyon, there was a large amount of *in situ* air quality monitoring data collected. Despite the significant shortcomings of these monitoring networks – which are discussed below - these datasets help to elucidate concentrations of the health-damaging air pollutants monitored over time, and to a certain extent, across geographic space. Below, we provide a summary of key events during the SS-25 blowout and then describe the air quality monitoring efforts undertaken during the SS-25 well blowout and in the time after the blowout was successfully stopped.

#### 1.4.10.1 Summary of Key Events During the Aliso Canyon SS-25 Well Blowout

Below, in Figure 1.4-21, we summarize many of the key events from the commencement of the SS-25 blowout to the successful killing of the well. This figure provides a chronological guide for reading this case study.

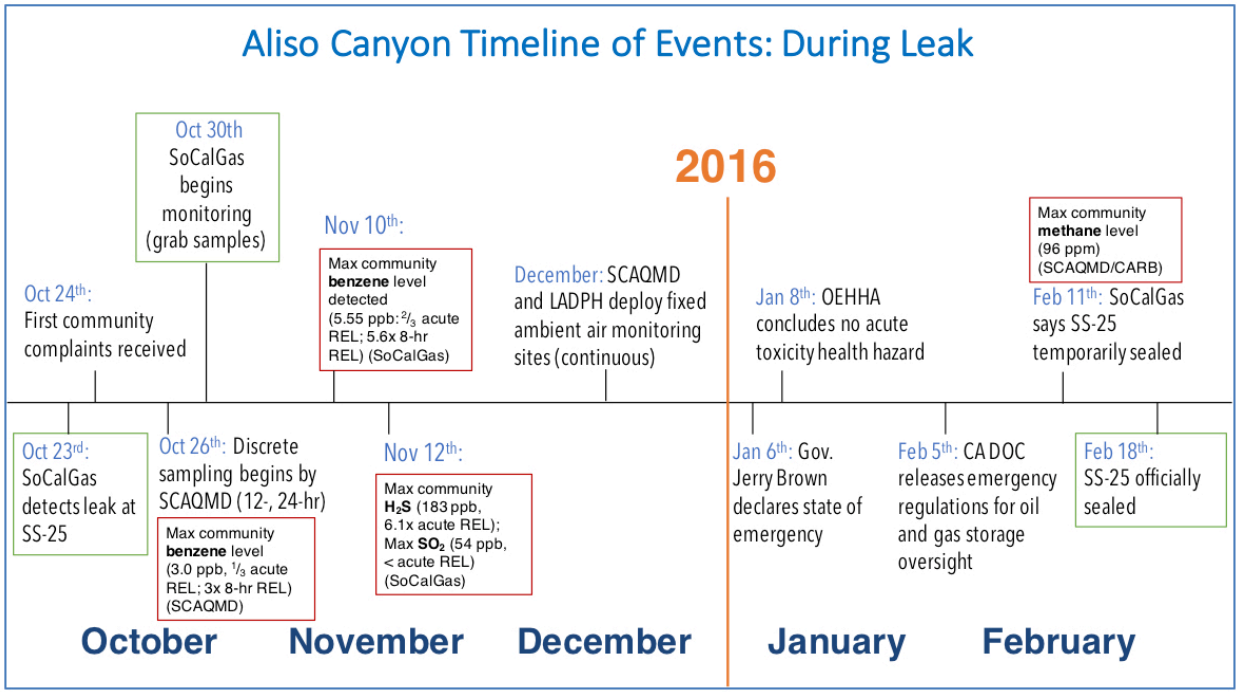


***Figure 1.4-21. Aliso Canyon SS-25 Well Blowout Timeline of key events, monitoring moments, and regulatory determinations.***

### 1.4.10.2 Air and Environmental Monitoring Data Collected in Response to the SS-25 Well Blowout

In response to the SS-25 well blowout, several entities carried out two primary categories of environmental monitoring: (1) outdoor air quality monitoring, and (2) indoor air and dust monitoring. Human exposures to toxic air pollutants by an outdoor emission source are not necessarily restricted to the outdoor environment, or even just to inhalation pathways.

We first describe the outdoor ambient air quality monitoring during and after the SS-25 blowout. This assessment includes discussion of:

1. The air pollution and other environmental monitoring conducted during and after the SS-25 blowout

2. The results of studies that assess the health symptoms of people in the Porter Ranch, CA, community during and after the SS-25 well blowout

3. Gaps in our understanding of the human health dimensions of this event

### 1.4.10.3 Air Quality Monitoring During and After the SS-25 Blowout

The blowout of the SS-25 well at Aliso Canyon set off a large number of air quality monitoring efforts headed by the gas storage operator, Southern California Gas Company (SoCalGas), by state agencies, universities, private citizens, law firms, and beyond. Table 1.4-16 lists the range of entities involved in the collection of ambient air pollutant concentration data during and after the 2015 Aliso Canyon incident, as well as the array of monitoring approaches and analytes of focus. It is important to note that there were more monitoring efforts focused on methane, which are excluded from this list but explained in detail in Section 1.5 of this report. For example, UC Davis, NASA, and CARB focused on the collection of methane emissions and atmospheric concentrations. Again, it is important to note that if we had access to the composition of Aliso Canyon UGS stored gas down to the parts per billion by volume concentration, we would be able to exploit the correlation of methane with concentrations of specific compounds in the gas of concern (e.g., benzene) to make inferences about the concentration of specific toxic air pollutants when only methane measurements were available. Unfortunately, without these composition data it is not possible to make these interferences with any certainty.

*Table 1.4-16. Entities monitoring for air quality (excluding methane) during and after the SS-25 blowout.*

| | Agency[1] | Start Date | End Date | Analyte(s)[2] | Sample Type | # Sites | Location |
|---|---|---|---|---|---|---|---|
| During Active Blowout | SoCalGas | 10/30/15 | 3/11/16 | 17 compounds | Grab | 38 | Porter Ranch/SS-25 |
| | SCAQMD/CARB | 12/16/15 | TBD | 64 compounds | Trigger/Grab | 2 | Porter Ranch |
| | SCAQMD/CARB | 12/21/15 | 12/26/16 | 56 compounds | 24-hr | 4 | Porter Ranch/Reseda |
| | UCLA/Jerrett | 1/13/16 | 2/25/16 | $NO_x$, $CO_2$, tVOC, PM | Continuous | 6 | Porter Ranch/Northridge |
| | UCLA/Jerrett | 1/13/16 | 2/12/16 | 25 VOCs | Passive Sampler | 24 | Porter Ranch/Northridge |
| | CARB | 1/14/16 | 7/21/16 | Benzene | Hourly | 1 | Site 5 (34.294993, -118.558115) |
| | SoCalGas | 1/11/16 | 2/3/16 | 17 compounds | 12-hr | 13 | Porter Ranch/SS-25 |
| | SCAQMD | 2/2/16 | 7/19/16 | Benzene | Hourly | 1 | Site 7 (34.26140, -118.594) |
| Post-Active Blowout | SCAQMD/CARB | 2/26/16 | 2/24/17 | $H_2S$ | Hourly | 1 | Site 3 (34.293563, -118.580401) |
| | LACDPH | 3/25/16 | 4/6/16 | 250 compounds | 24-hr (summa) | 210 | Porter Ranch/Northridge |
| | LACDPH | 3/25/16 | 4/8/16 | 86 compounds | Wipe | 210 | Porter Ranch/Northridge |
| | LACDPH | 4/20/16 | 4/20/16 | 187 compounds | Soil | 5 | SS-25 |

1 SCAQMD – South Coast Air Quality Management District; CARB – California Air Resources Board; UCLA/Jerrett – University of California, Los Angeles – Michael Jerrett; LACDPH – Los Angeles County Department of Public Health

2 $NO_x$ – nitrogen oxides; $CO_2$ – carbon dioxide, tVOC – total volatile organic compounds, PM – particulate matter; VOC – volatile organic compounds; $H_2S$ – hydrogen sulfide

The SS-25 well blowout began on October 23, 2015. Unfortunately, there was no air quality monitoring of this event by any entity until October 30, 2015—seven days after the gas leak commenced—when the SoCalGas began to collect short-term air quality "grab samples" of ambient air with summa canisters at a number of sites at the facility and in the nearby community of Porter Ranch, CA, every 12 to 24 hours (Table 1.4-16).

Below, we assess two datasets that are the most salient to the characterization of air quality during and following this loss-of-containment event: (1) the SoCalGas short-term air quality "grab" sampling (SoCalGas, 2016a), and (2) the South Coast Air Quality Management District (SCAQMD) trigger sampling (SCAQMD, 2017a).

The SoCalGas short-term "grab" air-sampling data contains air pollutant measurements conducted by SoCalGas from October 30, 2015, to January 23, 2016. While we have not been able to confirm the time duration that each "grab" sample was collected, multiple sources indicate that it was not longer than a period of 10 minutes (Interagency Task Force on Natural Gas Storage Safety, 2016; PEHSU, 2016). We focus on this dataset and time period specifically for many reasons. The short-term grab samples collected by SoCalGas are the most temporally relevant attempt to characterize air quality during the ramp-up to the peak emission rate from the SS-25 well and also represent the only air pollution monitoring during the decline in emission rates. Other ambient air pollution monitoring datasets that focus on later time periods may not be reliably calibrated to this time period, due to increased uncertainty in source, meteorology, and other factors. The primary focus of this assessment is the health hazards posed by toxic air pollutants of the most significant temporal period of the SS-25 blowout and the data gaps that remain.

The SCAQMD "trigger" sampling dataset is also important in that it contains two critical approaches and insights: (1) continuous methane monitoring and (2) a "triggered" grab sample when methane concentrations surpass 4 ppm ambient concentrations considered in the normal range in the South Coast Air Quality Management District (SCAQMD) jurisdiction. As such, it minimizes the possibility that high concentrations of compounds emitted from the Aliso Canyon facility were missed, with the assumption that methane can be an indicator of the emission of other toxic air pollutants; and also ensures that nonmethane VOCs will be speciated at times of high concentrations of atmospheric methane, to evaluate their contents, concentrations, and related hazards. However, as noted in Table 1.4-16, the trigger sampling did not commence until approximately two months after the LOC event began.

#### 1.4.10.4 Background on the Rate of Emissions from SS-25

According to the California Air Resources Board (CARB, 2016a; 2016b), due to the depressurization of the gas storage facility as gas is emitted, the rate of flow of methane decreased substantially from when the acute blowout began on October 23, 2015, to when it peaked in late November 2015 (Figure 1.4-22). The range of methane leak rates over time is estimated to be from 58,000 to 20,000 kilograms/hour (kg/hr). Based on the rate of methane emitted as a proxy for the rate of emission of other associated air pollutants as scaled down by their individual concentrations, it is likely that the continuous monitoring that commenced later in the leak after December 2015 or January 2016 has limited utility for assessing atmospheric concentrations and human exposures to toxic air pollutants during the period of highest-rate leakage.

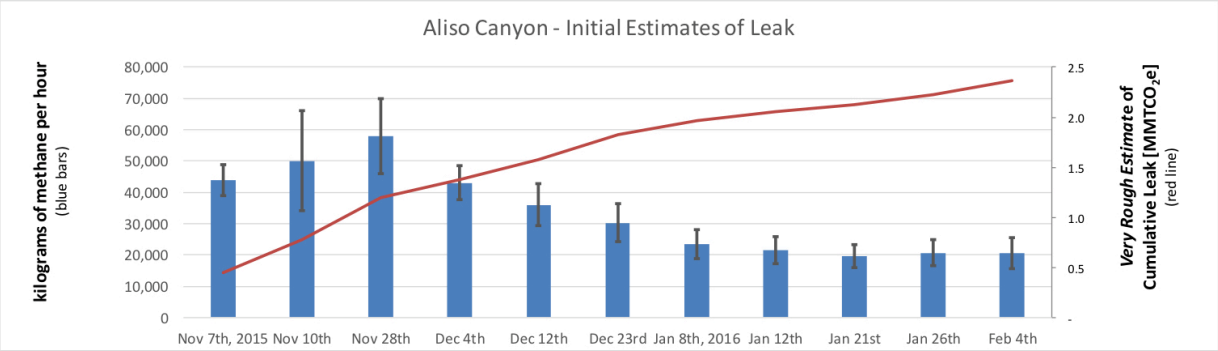


*Figure 1.4-22. Rate and cumulative mass of methane emitted from the Aliso Canyon facility from November 7, 2015 to January 26, 2016. (CARB, 2016b).*

### 1.4.10.5 Assessment of SoCalGas Short-Term Air Quality Monitoring Dataset

#### 1.4.10.5.1 Approach to Assessment of SoCalGas Short-Term Air Quality Monitoring Data:

SoCalGas monitored 17 unique air pollutants in their short-term air sampling during the SS-25 blowout (methane, benzene, ethylbenzene, toluene, m&p-xylenes, o-xylene, carbon disulfide, carbonyl sulfide, dimethyl sulfide, hydrogen sulfide, ethyl mercaptan, isopropyl mercaptan, methyl mercaptan, propyl mercaptan, t-butyl mercaptan, sulfur dioxide, tetrahydro-thiophene). It should be noted that nearly half of these compounds are sulfur odorants. To make the decision as to which pollutants to focus on in this assessment, we used the following screening criteria:

1. **Reference Exposure Level Screen:** We screened each pollutant for its California Environmental Protection Agency (CalEPA) reference exposure level (REL). CalEPA RELs are pollutant concentrations at or below which adverse health effects are not likely to occur (U.S. EPA, 2015). For a full list of CalEPA RELs, please refer to OEHHA (2014). We included pollutants in this assessment if reporting in the SoCalGas short-term monitoring dataset indicated that the pollutant concentrations exceeded at least one half of the published CalEPA REL or air pollutant monitoring limits of detection were above the CalEPA RELs. From this screen, benzene and hydrogen sulfide ($H_2S$) came out as relevant. Benzene concentrations exceeded at least 50% of the CalEPA 8-hr and chronic REL (1 ppb, 3 ug/$m^3$) 112 times over the course of 74 days. It should be noted here that benzene emissions are likely associated with gas leaks from storage formations that have liquid hydrocarbons present, such as depleted oil wells as is the case in the Aliso Canyon UGS facility. Hydrogen sulfide, on the other hand, only exceeded 50% of the CalEPA REL (Acute REL: 30 ppb, 42 ug/$m^3$; Chronic REL: 8 ppb, 10 ug/$m^3$) twice between November 1, 2015 and January 12, 2016, but one of the times it reached a level of 185 ppb at a Porter Ranch community monitor, which is more than 600% of the acute REL.

2. **Commonly Reported Symptom Screen:** The most common symptoms that residents of Porter Ranch and surrounding areas have reported since the Aliso Canyon gas leak commenced are dizziness, headaches, general weakness, respiratory irritation, nausea, vomiting, abdominal discomfort, and epistaxis (nosebleeds) (LACDPH, 2016a). Most of these symptoms are consistent with—but not exclusive to—exposures to mercaptans and sulfur odorants (Behbod et al., 2014) with the exception of epistaxis. Based on this symptoms-based screen, we examine all mercaptans monitored for during the Aliso Canyon gas leak.

While some of the other compounds monitored were elevated above baseline or what is expected in Los Angeles, none reached the criteria above. It should be noted, however, that the emission of multiple air pollutant species at once or in close succession can introduce synergistic and additive effects beyond the influence of any one pollutant (U.S. EPA, 1986). Additionally, exposures to multiple sulfur compounds (e.g., hydrogen sulfide, sulfur dioxide, and the sulfur odorants (mercaptans), simultaneously or in close succession, may exacerbate and compound health impacts. Of course, emission of these air pollutants from the Aliso Canyon UGS Facility also entered the atmosphere with other air pollutants from other sources, potentially further compounding potential air-pollutant interactions and corresponding human health hazards.

***Assessment of Benzene Monitoring Data***

The Office of Environmental Health Hazard Assessment (OEHHA) under the California Environmental Protection Agency (CalEPA) has established benzene RELs for noncarcinogenic effects (reproductive/development, immune system, hematologic system, and nervous system) as:

- Acute (1-hour): 8 ppb (27 ug/$m^3$)
- 8-hour: 1 ppb (3 ug/$m^3$)
- Chronic: 1 ppb (3 ug/$m^3$).

Benzene is also identified as a carcinogen by OEHHA, IARC (the International Agency for Research on Cancer), and the World Health Organization (WHO). There is no level at which benzene exposure can be considered to be safe, although there are exposure levels for benzene that reflect de minimus risk (such as 1 in 100,000 lifetime added cancer risk). Even short-term exposures to benzene can be relevant for the development of childhood leukemias and other childhood cancers that may be initiated in-utero (Filippini et al., 2015; Zhou et al., 2014).

***During the Active SS-25 LOC Event***

The most elevated benzene concentrations in the community (not at the facility) found by the SoCalGas air monitoring data during the monitoring period were at the Highlands

Group (5.6 ppb) and the Porter Ranch Estates Group (3.68 ppb) monitors. Because all of the readings on the SoCalGas monitors are from grab samples—meaning only at one point in time—there is considerable uncertainty with respect to the duration of time for which these air pollution levels remain high or low. As such, the duration of time that benzene concentrations may have been elevated and contributed to acute (or chronic) exposures is not entirely clear. For instance, benzene concentrations at any concentration found using grab samples could mean that the concentration was steady for 60 seconds while the sample was being taken, or for 8 to 12 hours or more until the next sample was taken at the site, or a variety of other possible trajectories. Further, given the episodic nature of grab sampling, it is a possibility that samples taken during the day may not be representative of peak nighttime concentrations (Gifford, 1968) or vice versa.

SoCalGas air monitoring data indicate that benzene concentrations exceeded atmospheric concentrations for the 8-hour and chronic REL (1 ppb, 3 ug/m$^3$) 112 times at various monitoring sites during this short-term grab sampling. Measured exceedances of the 8-hour and chronic REL appear to be limited, with the majority of these exceedances in the community occurring before December 2016 (Figure 1.4-23). Of these 112 exceedances of the 8-hour and chronic RELs (measured concentrations ranged from 1.05 ppb to 5.6 ppb), 15 (13.4%) occurred in the Porter Ranch community, near homes and other places where people live, work, and play. The other 97 benzene REL exceedances were found at monitors on the property of the Aliso Canyon facility, reaching as high as 30.6 ppb, with a concurrent methane concentration of 1,747 ppm.

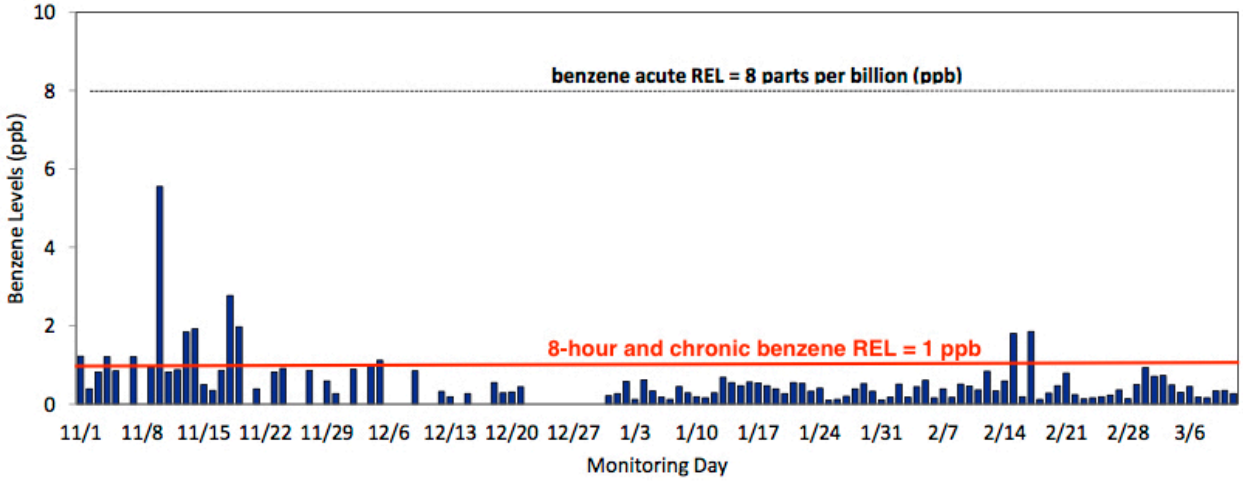


***Figure 1.4-23. Highest benzene concentrations per day reported in the SoCalGas short-term sample dataset from November 1, 2015 to March 6, 2016. Please note that this figure only contains community benzene concentration measurements and not those at the facility. Source: Modified from OEHHA (2016).***

The data presented in Figure 1.4-23 suggest that benzene concentrations are not high enough to warrant concern about acute exposures, and are not consistently elevated above 1 ppb to warrant concern over 8 hr and chronic exposures to the general population. However, while atmospheric concentrations of benzene in the community (not at the facility) may not have been elevated above the REL with significant frequency, there are a number of reasons why there is uncertainty in drawing a conclusion of limited health impact attributable to benzene:

1. From the commencement of community monitoring of the SS-25 gas blowout through January 11, 2016, benzene concentration data were collected using short-term grab sampling methods. As noted above, this type of sampling introduces uncertainty as to the duration for which these concentrations persisted in the atmosphere.

2. The use of inappropriately high limits of detection—or limits of detection above the REL—for many samples during benzene monitoring as discussed in the section below does not enable researchers to be able to determine with confidence that benzene concentrations were in fact low.

3. Air samples may have been diluted because of high concentrations of other air pollutants, in which case benzene could have been elevated or the other pollutants may have interfered with the ability to detect benzene (i.e., a matrix effect).

4. The "oily mist" emitted from the Aliso Canyon UGS facility discussed below induced a highly abnormal air-pollution monitoring environment and could have interfered with the ability of air pollution monitoring equipment to detect hydrogen sulfide and other pollutants.

***High Limits of Detection for Benzene Introduce Uncertainty to Exposure***

In addition to an assessment of reported benzene concentrations, it is important to take a close look at the limits of detection of the air monitoring equipment used to detect benzene in the air. If a limit of detection is above the concentration at which a pollutant is suspected to cause harm to human health in the general population, it is not possible to determine if the air pollutant in question is at a level where it does or does not pose a hazard to human health.

Of the 2,451 benzene concentration measurements taken by SoCalGas between October 30, 2015 and January 23, 2016, 467 (19%) of the samples used a limit of detection higher than the 1-hour and Cal/EPA 8-hour REL of 1 ppb (3 ug/$m^3$). Of these 467 samples, 259 (55.4%) were samples from the Porter Ranch community, where people live, work, and play, and not from the facility area. The limits of detection of SoCalGas air monitoring equipment that was above 1 ppb ranged from 1.1 ppb to 20 ppb.

Early on in the air-quality monitoring, there were 11 samples (0.4% of all samples with limits of detection above 1 ppb), which had a limit of detection of 20 ppb, more than 20 times the Cal/EPA REL. Of these 11 samples, two of them were in the Porter Ranch community at the Holleigh Bernson Park location, and the other nine samples were taken at the facility. These samples were collected on October 30, 2015, and October 31, 2015. It is not likely that benzene concentrations in the Porter Ranch community approached 20 ppb given the other data available, but the actual air-pollutant concentrations remain unknown during these early days of the leak, when emission rates were high.

In sum, from a limit-of-detection point of view, the scientific and regulatory communities as well as the public do not have sufficient information to know whether the benzene concentrations were below the acute, 8-hour, and chronic RELs early in the 2015 Aliso Canyon incident, and whether there were locations where benzene exposure could have risen to levels that could cause health effects.

***Comparing Benzene Concentrations to the South Coast Air Quality Management District Annual Averages***

To understand if there has been an increase in benzene concentrations in air resulting from the 2015 Aliso Canyon incident, it would be helpful to compare the current reported concentrations in the Porter Ranch area to baseline concentrations before the leak started. The best data for this comparison would be data collected prior to the leak in the same Porter Ranch locations where air monitoring was conducted after the leak. Unfortunately, this location-specific information (e.g., Porter Ranch benzene concentrations in air) is not available. However, there is another baseline dataset that can be used to shed light on benzene concentrations, namely the South Coast Air Quality Management District (SCAQMD) annual average concentration of benzene, reported through the Multiple Air Toxics Exposure Study (MATES). As discussed above and shown in Figure 1.4-23, higher benzene concentrations (>1 ppb) were reported at SoCalGas air monitoring sites in Porter Ranch following the SS-25 blowout relative to the <0.5 ppb MATES IV average reported benzene concentrations (see Figure 1.4-24; SCAQMD, 2015). If we assume the ambient Porter Ranch benzene concentrations to be similar to those at the Burbank MATES site, it is apparent from comparison of Figures 1.4-23 and 1.4-24 that benzene was elevated above average concentrations at Porter Ranch during the SS-25 well blowout. Note further that the MATES datasets reveal a significant reduction in ambient benzene concentrations between 2000 (MATES II) and 2015 (MATES IV), attributable to the reduction of benzene in gasoline.

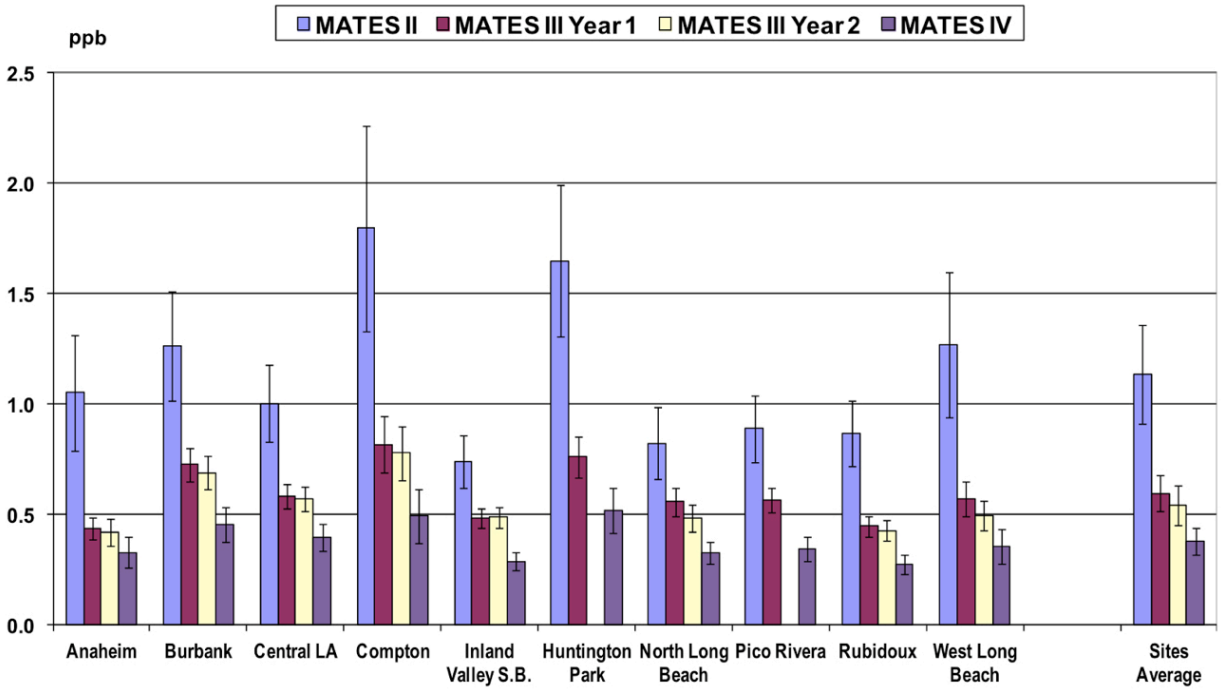


*Figure 1.4-24. Average Benzene Concentrations in the Los Angeles Basin (SCAQMD, 2015).*

### 1.4.10.5.2 Assessment of Hydrogen Sulfide Monitoring Data

The CalEPA RELs for hydrogen sulfide are reported as the following:

- Acute REL: 42 ug/$m^3$ (30 ppb)
- Chronic REL: 10ug/$m^3$ (8 ppb).

As described above in the case of benzene monitoring, because all of the hydrogen sulfide data are from grab samples—meaning only at one point in time—it is difficult to conclude with certainty the duration for which hydrogen sulfide levels are high or low, as the air pollutant concentration reported from the grab samples could have been the concentration for 60 seconds or up to 12 hours until the next sample is taken.

There are a few very elevated concentrations of hydrogen sulfide ($H_2S$) found at monitors operated by SoCalGas. However, there was one reading at a monitor at the Porter Ranch Estates Group that reported 183 ppb (more than 6 times the acute REL), a level that creates highly elevated acute toxicity risk to those exposed. Other noteworthy readings were at the Highlands Group and Porter Ranch School monitors at 16 ppb and 10.4 ppb, respectively.

The Porter Ranch School monitor's reading of 10.4 ppb $H_2S$ occurred on Wednesday, November 17, 2015, likely while children were present. However, with the exception of the 183 ppb concentration noted at the Porter Ranch Estates Group monitor, none of the other grab samples reported concentrations that exceeded the acute REL (30 ppb).

***Limits of Detection Issues for Hydrogen Sulfide***

On the first three days of monitoring, across 36 samples (1.5% of all $H_2S$ samples), SoCalGas used a limit of detection for $H_2S$ of 50 ppb, or 1.7-times higher than the acute REL (30 ppb), and all samples came out as nondetects. Of these 36 samples, 14 were at the facility and 22 were in the community of Porter Ranch. Given that all but two grab sample readings following these days were below the acute REL (exceptions are the 183 ppb reading in Porter Ranch Estates Group and 29.1 ppb at the facility), it is unlikely that the concentration of $H_2S$ was above the acute REL on these days, but it is very difficult, if not impossible to confirm.

***Limits of Detection and Odor***

It is important to note that not all of the concern regarding health effects from exposures to compounds can be determined by an exceedance of a REL. There is a heterogeneity and variation within and among populations that make some more susceptible to having physiological reactions to exposures than others. One form of physiological response is that to odor and in this way, the SoCalGas limits of detection for $H_2S$ are not sufficient.

Hydrogen sulfide has a strong "rotten egg" odor that is often considered unpleasant and noxious. The odor threshold (the minimum concentration of a pollutant that the human nose can smell) of $H_2S$ is 0.5 ppb, but the lowest limit of detection used by SoCalGas was 1.58 ppb, and most limits of detection used were 5 ppb and above. Thus, if the limit of detection is 5 ppb, people can be exposed to concentrations of $H_2S$ up to 10 times the odor threshold while the monitor will report a "non-detect." Much like exposures to other sulfur compounds such as the mercaptans and other odorants added to gas (described below), people can respond very differently from one another to these smells. It is entirely possible that the nausea, headaches, vomiting, and other often-reported symptoms among those in proximity to the gas leak are reactions to elevated atmospheric concentrations of hydrogen sulfide.

***Summary of Hydrogen Sulfide Monitoring Data***

The monitoring data indicates that $H_2S$ concentrations were elevated, in some cases significantly above the acute 8-hour REL, posing human health risks to populations that may have been exposed. Nevertheless, available data suggest that $H_2S$ concentrations have not been regularly elevated above the acute REL (30 ppb) at the monitoring sites and there is little indication that $H_2S$ concentrations were sustained above the chronic REL (8 ppb). As discussed above, the sampling design and equipment employed to monitor $H_2S$

concentrations prior to the commencement of the 12-hour and 24-hour sampling are unable to provide conclusive evidence that $H_2S$ concentrations were above or below RELs with the exception of the moments that grab samples were collected.

#### 1.4.10.5.3 Assessment of Sulfur Odorants (Mercaptans) Monitoring Data

Unlike benzene and hydrogen sulfide, mercaptans only have *occupational* exposure limits and do not have CalEPA-recommended community RELs. For instance, the NIOSH REL of 0.5 ppm (500 ppb) for most methyl mercaptans is the ceiling concentration determined in any 15-minute sampling period (OSHA, 2016). Outside of acute exposures in occupational settings—which are clearly inappropriate from a community exposure perspective—there is little guidance on safe levels of exposure.

The sulfur compounds, and in particular the odorants, are a likely cause of a number of the health complaints of residents living in proximity of the Aliso Canyon facility following the leaking of gas from well SS-25. The mercaptans in particular are known to elicit dizziness, headaches, general weakness, respiratory irritation, nausea, abdominal discomfort, and vomiting (Behbod et al., 2014).

There is only one study to date in the peer-reviewed scientific literature on potential community health effects of exposure to tert-butyl-mercaptan (TBM) (Behbod et al., 2014). The authors found statistically significant evidence that there are more self-reported health complaints closer to rather than further away from a mercaptan spill. Behbod and colleagues (2014) concluded that some of the factors that explain the health symptoms were likely due to the odor and the different sensitivities across the exposed population, and not necessarily attributable to actual physiological irritation caused by the mercaptans. While Behbod et al. (2014) assert that there are no long-term health implications of TBM exposure (at concentrations more elevated than at Porter Ranch), there are no longitudinal epidemiological data to support this claim.

The researchers made the following recommendations for future incidents when populations are exposed to elevated concentrations of mercaptans:

1. Health departments should prepare public health communication messages in advance to include strategies to minimize exposures (e.g., limit outdoor activity and keep windows closed in the evening and overnight hours).

2. Advise those with chronic respiratory and cardiovascular conditions to have their medications readily available.

***Assessment of the SoCalGas Air Monitoring Data for Mercaptans***

The odor threshold (the minimum concentration of a pollutant that the human nose can begin to smell) of tert-butyl mercaptan is 0.1 ppb, but the air monitoring equipment employed by SoCalGas had limits of detection well above this and up to 9.3 ppb (only one

air sample used a limit of detection of 9.3 ppb), or 93 times the concentration at which the human nose is able to start to smell the skunk/rotten egg scent of mercaptans. Most of the limits of detection were not this high above the odor threshold, but 998 (43%) of all samples (2332) taken used a limit of detection at or above 5 ppb—at least 50 times the odor threshold. Of the grab samples that used limits of detection that were at or above 5 ppb, 493 (47%) were at monitors in the Porter Ranch Community, representing 20% of all TBM air samples taken.

***Suggested Health Effects Evidence from Potential Increase in Epistaxis (Nosebleeds) Incidence***

Anecdotally, there was an increased incidence of epistaxis in Porter Ranch and other areas near the Aliso Canyon facility during the 2015 Aliso Canyon incident. If there was truly an increase in incidence of epistaxis in these areas, it is probable that some other compound than the mercaptans was driving this trend. Of the compounds monitored for, hydrogen sulfide is a candidate (Mousa, 2015), but it could also be something else that is or is not currently being measured. Formaldehyde is also a candidate compound that may have been elevated in the atmosphere, given that methane can oxidize in the atmosphere and produce formaldehyde (Cicerone and Oremland, 1988). However, formaldehyde was not monitored in the ambient air during the SS-25 blowout.

### 1.4.10.6 Assessment of SCAQMD Trigger Sample Dataset

***Description of SCAQMD Monitoring Approach***

The South Coast Air Quality Management District (SCAQMD) collected air quality data via trigger samples beginning on December 16, 2015 through November 14, 2016 (SCAQMD, 2017). These trigger samples were taken by continually monitoring for methane; when the concentration of methane exceeded a certain threshold, it would "trigger" a canister sample that could be sent to the laboratory for chemical speciation. The analyses of the trigger samples focused on 64 chemical compounds.

***Notable Results and Assessment of the Trigger Sample Dataset***

The majority of the trigger samples did not find concentrations in exceedance of CalEPA RELs. However, a large proportion of the samples taken measured analytes at concentrations that exceeded normal ambient concentrations by an order of magnitude or more.

Also noteworthy is that a number of trigger samples had measured concentrations of benzene that were elevated substantially above the CalEPA REL. For instance, at the Highlands Pool monitor, seven out of the 92 VOC samples taken (7.6%) were above the REL, with the highest concentration measured at 13 ppb, which is 13 times the 8-hr REL (1 ppb, 3 ug/$m^3$) and 1.6 times the acute REL (8 ppb, 27 ug/$m^3$). Given that these are grab samples, it is highly uncertain how fast the concentrations of benzene returned back to normal

ambient concentrations (0.1 ppb to 0.5 ppb). It is also noteworthy that the highest benzene concentrations found in the SCAQMD trigger sample dataset were measured after the SS-25 well was sealed, suggesting that the source of the benzene emissions was either from other infrastructure at the Aliso Canyon site, or from another source unassociated with the Aliso Canyon UGS facility.

The trigger sample laboratory analysis also included a metric called non-methane volatile organic compounds (NMVOCs). NMVOC is a coarse measure of organic compounds excluding methane in the air by weight. NMVOCs also include precursors for the atmospheric formation of tropospheric ozone, a strong respiratory irritant. While a high NMVOC value does not necessarily confirm that air is unhealthy or out of attainment from a regulatory perspective, it can be compared to the typical ambient air concentrations as an indicator of poor air quality. During the active SS-25 blowout, the NMVOC ambient concentrations during times that trigger samples were taken exceeded the normal ambient concentration range (100-700 ppb) in eight out of nine samples (89%) at the Porter Ranch Community School site; in 62/98 samples (63%) at the Highlands Community Pool site; and five out of ten samples (50%) at the Castlebay site. While it is likely that ethane, a relatively toxicologically inert compound prevalent in natural gas, may be one of the primary drivers for these atmospheric enhancements of NMVOCs observed in these samples, values that exceed normal ranges of NMVOCs in the atmosphere can be a proxy for other VOCs that potentially were not monitored, such as formaldehyde.

The trigger samples do not test for a number of important chemical compounds that are known to be associated with UGS and Aliso Canyon in particular. It is notable that these trigger samples do not include an assessment of sulfur odorants (e.g., mercaptans during the active SS-25 blowout phase). Also, given the small number of detections but very high observed concentrations of $H_2S$ during the short-term air quality monitoring conducted by SoCalGas, it would have been helpful if this data collection effort had included $H_2S$.

Finally, formaldehyde associated with UGS is an intermediate in both the oxidation and combustion of methane. When produced in the atmosphere by the action of sunlight and oxygen on atmospheric methane and other hydrocarbons, its concentration in the atmosphere increases. According to reporting to the SCAQMD emissions inventory, Aliso Canyon is the largest single source of formaldehyde emissions in the SCAQMD during normal operations. While formaldehyde is likely emitted disproportionately by the operation of gas-powered compressor stations, the large amount of stored natural gas emitted into a relatively dense urban area could also contribute to the formation of locally elevated concentrations of formaldehyde in the area.

Also noteworthy is that following the sealing of the SS-25 well, 25 out of the 40 trigger samples (62.5%) were taken in the morning between the hours of 6:00 a.m. and 8:30 a.m. There are two potential factors that could explain why the majority of elevated methane concentrations were observed during this 2.5-hour period in the morning:

1. Meteorological: air pollutants tend to settle in the lower atmosphere, closer to ground level in the mornings and the evenings (Gifford, 1968).

2. Withdrawal of stored gas or other operations associated with emissions may be planned or often occur in the morning: the concurrence of elevated toxic air contaminant concentrations with elevated methane concentrations may signify that withdrawals or other activities that are associated with emissions to the atmosphere are occurring at the Aliso Canyon UGS facility at regular intervals.

If the reasons that methane concentrations were increasing were meteorological, then it would make sense that methane concentrations would also be elevated in the evenings. However, there is only one trigger sample in the SCAQMD dataset taken after the sealing of the SS-25 well that was in the evening (10:00 p.m. on July 10, 2016). As such, the temporal patterns of these data suggest that emissions may be occurring regularly in the mornings between 6:00 a.m. and 8:30 a.m. at the Aliso Canyon UGS facility. In order to confirm that this is indeed occurring, detailed information on scheduled stored gas withdrawals or activities involving emissions would need to be reported by the operator and made available for analysis.

If scheduled releases are indeed occurring, this may have implications for air pollutant concentrations on an intermittent basis for populations in proximity to UGS facilities statewide where these practices also may occur. Of course, Aliso Canyon is monitored far more extensively than any other UGS facility in the state, and so it is not yet possible to know whether episodic spikes in concentrations of methane and associated compounds in other communities near UGS facilities are actually occurring.

***Limitations of Using Methane Concentrations as a Surrogate of other VOCs***

The SCAQMD trigger samples rely on methane concentrations in the atmosphere to trigger further analysis of non-methane VOCs. The limitation of this approach is that it likely underestimates emissions of VOCs that are not co-emitted with methane. For instance, air pollution attributable to loss-of-containment of solvents, odorants, or other constituents stored in tanks will not be captured by this monitoring approach.

### 1.4.10.7 Review of Health Complaints in the Context of the Aliso Canyon Facility

***Health Symptoms Survey Results***

The first community complaint of symptoms was made on October 24, 2015, the day after the acute blowout at the SS-25 well commenced. The LACDPH conducted surveys of symptoms in the population surrounding the SS-25 blowout and after SS-25 was sealed. During the acute blowout, 81% of households surveyed reported symptoms (LACDPH, 2016a). The results of their follow-up survey after the SS-25 well was sealed indicated that 63% of sampled households continued to report health symptoms that they attributed to the

Aliso Canyon facility (LACDPH, 2016b). If this post-leak proportion is extrapolated across the population, it would mean that 4,800 households in the surrounding communities may have been experiencing symptoms after the well was sealed, at the time the study was undertaken in April 2016. The LACDPH also reported that several weeks after sealing well SS-25, the majority of households in the community had at least one household member that was still experiencing symptoms.

LACDPH found spatial trends in the distribution of symptoms and health impact survey results. As can be seen in Figure 1.4-25, which is a visual representation of health complaints per unit area, while positive symptom reporting was distributed throughout Porter Ranch and to a lesser degree in neighboring communities, positive symptom findings were concentrated closer to the Aliso Canyon UGS facility.

While self-reporting may over- or underestimate the true prevalence of health symptoms, these health symptom data were assessed in the context of other data that enable a more reliable understanding of the prevalence of these health symptoms in the populations. Of note is that symptom complaints during the SS-25 well blowout and after the plugging of the well were reported beyond 10 km from the SS-25 well (Figure 1.4-26) (LACDPH, 2016c).

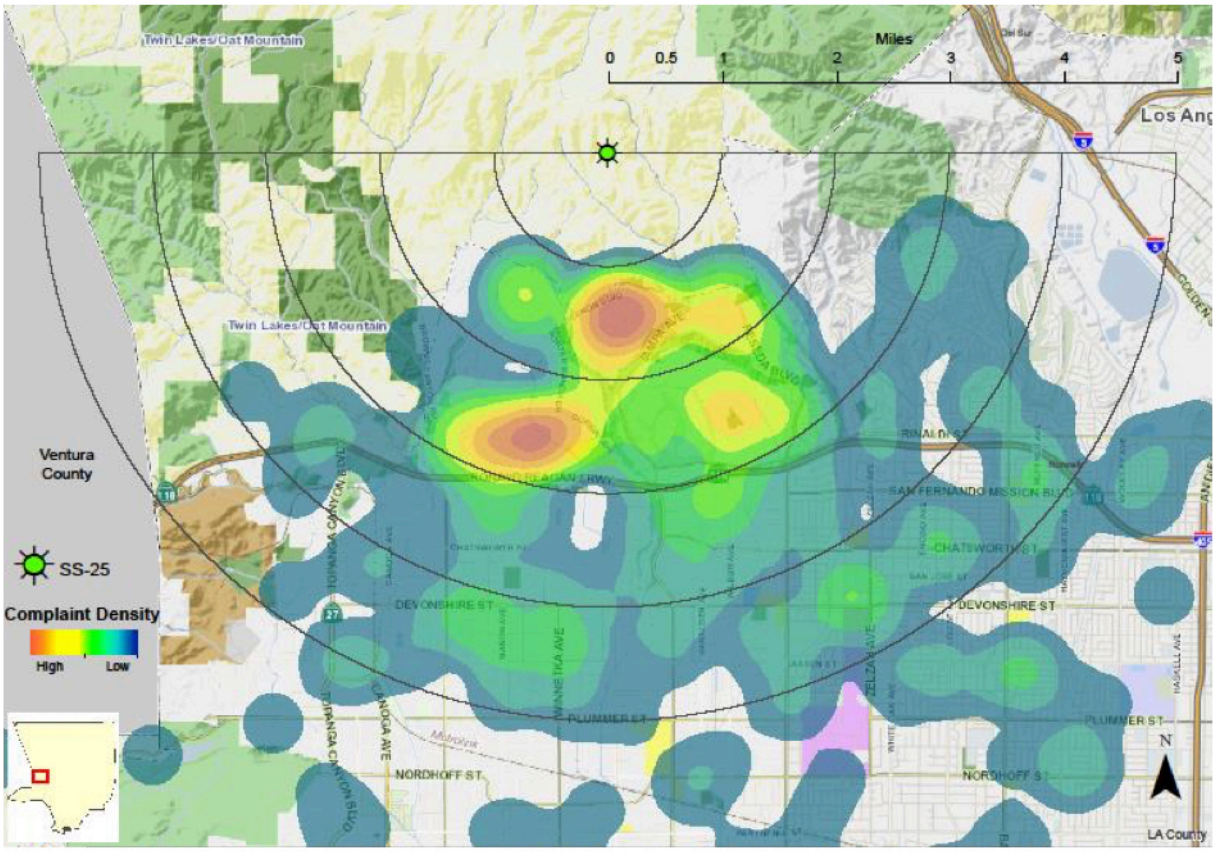


*Figure 1.4-25. Aliso Canyon symptoms by respondent's address: complaint density. Created by the Office of Health Assessment and Epidemiology, Epidemiology Unit. 02/03/16. Map shows the density of symptoms by respondent's addresses. 511 of 687 addresses were located (the rest were excluded due to incorrect or missing addresses). (LACDPH, 2016c).*

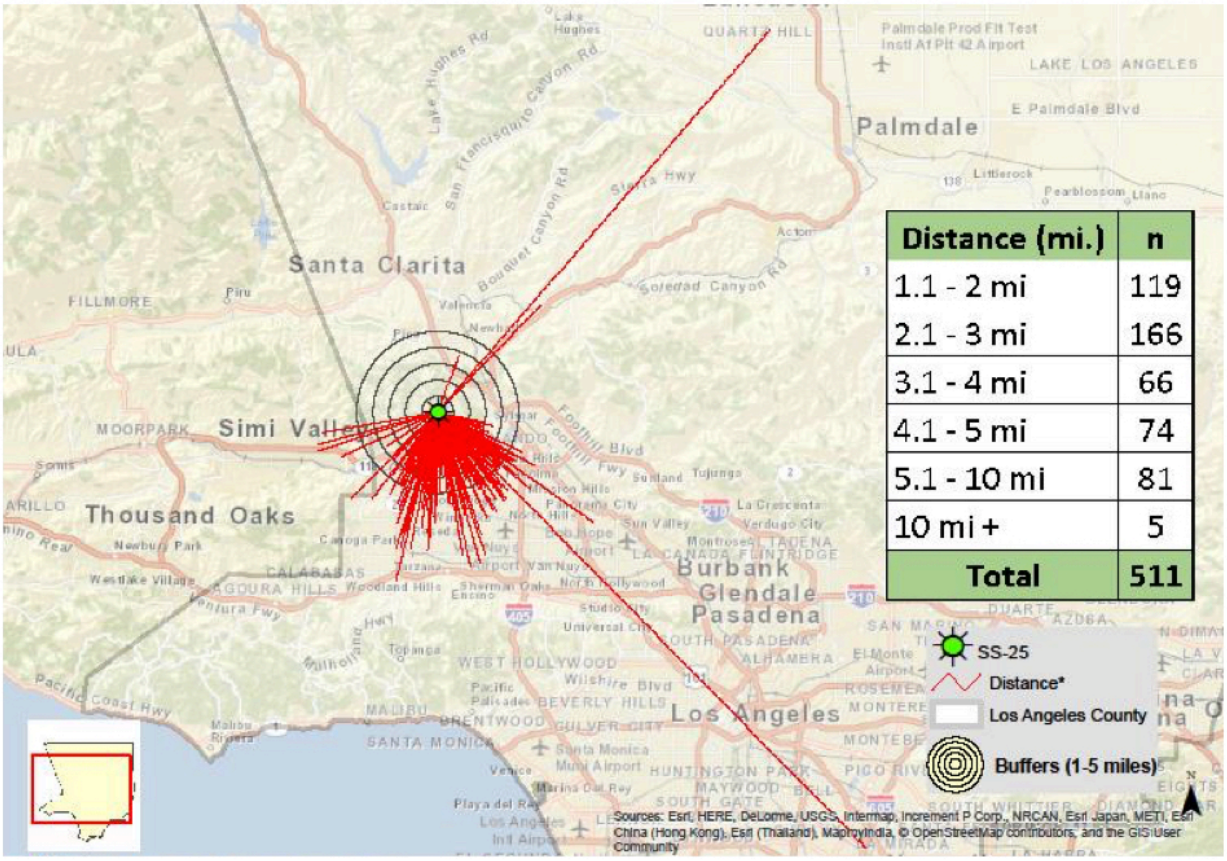


***Figure 1.4-26. Aliso Canyon symptoms by respondent's address: Euclidean distance from the SS-25 well. Created by: Office of Health Assessment and Epidemiology, Epidemiology Unit. 02/03/16. Map shows the density of symptoms by respondent's addresses. 511 of 687 addresses were located (the rest were excluded due to incorrect or missing addresses). (LACDPH, 2016c).***

LACDPH (2016e) conducted multiple health symptom surveys of households in proximity to the Aliso Canyon UGS facility during the SS-25 blowout and after the well was successfully plugged. The survey results during and after SS-25 LOC event can be found in Table 1.4-17. Also, as seen in Table 1.4-17, during the active SS-25 well LOC event, a projected 6,278 households, or 81% of the total household population in Porter Ranch and Granada Hills, likely were suffering from at least one health symptom attributable to the Aliso Canyon facility (LACDPH, 2016e). After the LOC event at SS-25 was stopped, LACDPH estimated that 4,801 households, or 63% of the total household population in Porter Ranch and Granada Hills, likely were still suffering from at least one health symptom attributable to the Aliso Canyon facility (LACDPH, 2016e).

***Table 1.4-17. Households reporting that any member of the household experienced any of the following health symptoms believed to be related to the 2015 SS-25 well blowout weighted to the entire sampling frame, Porter Ranch and Granada Hills, CA, March 2016 (LACDPH, 2016e).***

| | During active gas leak | | | After well was sealed | | |
|---|---|---|---|---|---|---|
| | Number of households (n=210) | Projected number of households (n=7,755) | Weighted % of households (95% CI) | Number of households (n=210) | Projected number of households (n=7,755) | Weighted % of households (95% CI) |
| **Any symptom(s)** | 170 | 6,278 | 81.3 (75.5 – 87.2) | 130 | 4,801 | 62.5 (56.3 – 68.7) |
| Eye, nose and/or throat irritation | 153 | 5,650 | 73.9 (67.2 – 80.6) | 123 | 4,542 | 59.1 (52.6 – 65.7) |
| Headache/migraine | 148 | 5,465 | 71.8 (65.3 – 78.4) | 108 | 3,988 | 51.9 (45.0 – 58.9) |
| Respiratory complaint* | 138 | 5,096 | 67.0 (60.6 – 73.3) | 105 | 3,878 | 50.7 (44.1 – 57.4) |
| Stress | 123 | 4,542 | 60.0 (52.4 – 67.6) | 88 | 3,250 | 42.9 (36.1 – 49.8) |
| Dizziness/light headedness | 121 | 4,468 | 59.9 (53.1 – 66.7) | 81 | 2,991 | 39.9 (33.5 – 46.3) |
| Nausea/vomiting | 112 | 4,136 | 54.4 (48.2 – 60.5) | 83 | 3,065 | 40.7 (34.3 – 47.0) |
| Nosebleed(s) | 97 | 3,582 | 46.9 (40.2 – 53.6) | 64 | 2,363 | 30.9 (24.4 – 37.4) |
| Skin rash/irritated skin | 95 | 3,508 | 46.1 (38.6 – 53.6) | 76 | 2,807 | 37.3 (31.0 – 43.5) |
| Diarrhea | 55 | 2,031 | 27.0 (21.1 – 32.8) | 44 | 1,625 | 21.7 (15.5 – 27.8) |
| Fever | 32 | 1,182 | 16.0 (10.7 – 21.3) | 26 | 960 | 12.9 (8.7 – 17.1) |

*Note: Excluded missing during gas leak: any symptom (n = 1); eye, nose and/or throat irritation (n = 1); headache/ migraine (n = 1); respiratory (n = 1); stress (n = 1); dizziness (n = 2); nausea/vomiting (n = 2); nosebleeds (n = 1); diarrhea (n = 2); fever (n = 3) and don't know: eye, nose and/or throat irritation (n = 2); headache/migraine (n = 3); respiratory (n = 3); stress (n = 4); dizziness (n = 6); nausea/vomiting (n = 2); nosebleeds (n = 2); skin (n = 3); diarrhea (n = 4); fever (n = 7). Excluded missing after leak: nausea/vomiting (n = 1); and don't know: any symptom (n = 2); eye, nose and/or throat irritation (n = 2); headache/migraine (n = 2); respiratory (n = 3); stress (n = 5); dizziness (n = 7); nausea/vomiting (n = 5); nosebleeds (n = 3); skin (n = 6); diarrhea (n = 8); fever (n = 8). (LACDPH, 2016e).*

These health symptoms reported to the LACDPH during the leak event, as well as after the SS-25 well was sealed, are consistent with exposures to mercaptans used as odorants. There are, however, exceptions to this, including – as noted above - the high reporting of epistaxis (nosebleeds), as mercaptans are not associated with increased incidence of nosebleeds in populations. For example, a symptom survey in one of the largest population exposures to tert-butyl mercaptans - one of the four mercaptans added to natural gas in the Aliso Canyon facility - during a spill in Alabama did not find that nosebleeds were being reported with any frequency, even though levels of this mercaptan were much higher than during the 2015 Aliso Canyon incident (Behbod et al., 2014).

The LACDPH conducted a health symptoms survey of households in Porter Ranch, CA, in the month after the SS-25 well was sealed. The results of this survey and the widespread prevalence of health symptoms that residents attributed to the leak are noteworthy given that outdoor ambient concentrations of methane, the primary constituent of natural gas, had come down considerably towards baseline, and the acute, high-rate emissions from the SS-25 well were determined to be low again.

***Reported Community Health Symptoms and Visuals of "Black Oily Substance" Guide Environmental Monitoring to the Indoor Residential Environment***

After the SS-25 well was sealed, the majority of households near the Aliso Canyon UGS facility reported experiencing health symptoms (LACDPH, 2016e). The LACDPH (2016d) reports that these symptoms are likely related to the 2015 Aliso Canyon incident and/or other emission sources from the Aliso Canyon UGS facility (LACDPH, 2016e). Given the ongoing health symptoms and their temporal and geographic association with the Aliso Canyon facility and the SS-25 blowout in particular, the LACDPH launched an indoor-environment testing investigation. The high-level conclusions of this investigation are summarized below, with our further assessment of the data and results listed below that.

***After the SS-25 Well is Sealed: LACDPH Conclusions of Resident Symptoms Reporting and Indoor Environment Testing***

LACDPH conducted an indoor assessment of contaminants related to natural gas and oil emissions, and a comprehensive investigation of reported symptoms after the gas leak was sealed. The results of this LACDPH (2016d) assessment are quoted below:

1. The majority of households near the Aliso Canyon Storage Facility experienced health symptoms after the well was sealed, and these symptoms were likely related to the gas leak and/or other emission sources from the Aliso Canyon UGS facility.

2. Barium and several other metal contaminants found in household dust are common additives in the drilling and well-kill fluids used at the Aliso Canyon UGS facility. The findings suggest that metals were emitted during the leak and may have been distributed into the surrounding area and into the homes of residents. Metals in household dusts can cause respiratory and skin irritation, and could be contributing to reported symptoms.

3. Overall, the indoor air testing did not detect chemicals at levels that present an elevated health risk. The occurrence of indoor air contaminants within the study area was found to be generally consistent with both the comparison area and with published background data on air contaminants in residential settings.

4. Adequate ventilation of homes to flush out residual contaminants, deep cleaning of surfaces, regular change-out of HVAC filters, and proper maintenance of air purifiers will minimize the potential for exposure that may produce symptoms. Such cleaning will also remove routine dust, pollens, and molds that may have accumulated during the period when people were not residing in their homes and practicing normal house cleaning.

5. It is possible that other contaminants from the leak site and/or other sources are present in the homes and the ambient air. For example, the Aliso Canyon UGS facility is the largest single emitter of formaldehyde in the South Coast Air Quality Management District, releasing ~14,054 pounds per year. SCAQMD reported that formaldehyde was not found at elevated concentrations in the community during the gas leak; however, DPH will continue to consult with experts to monitor this issue.

6. Ongoing monitoring by CARB and SCAQMD indicates that methane levels in the area around the Aliso Canyon UGS facility continue to be higher than expected and may indicate some additional source of methane in the area. Although these methane levels are not as high as during the leak periods, the elevated levels do indicate the need for continued monitoring. DPH will continue to work with its partners to understand why methane levels continue to be above normal at times.

As noted above by LACDPH, even after the successful sealing of the SS-25 well when the rate of gas emissions from this site dropped dramatically (Figure 1.4-17), the LACDPH Community Assessment for Public Health Emergency Response (CASPER) study reported that health symptoms among residents moving back to their homes were still very prevalent. This finding led the LACDPH to consider other environmental pathways and routes of exposure, and specifically to consider the possibility that the insides of residences might hold sources of health-damaging exposures, or at least exposures that were causing deleterious health symptoms in residents.

Other key signs that the indoor environment might contain exposures sourced from the Aliso Canyon facility potentially responsible for the health effects reported by residents was visible black oily substances deposited both on private property outdoors (on cars, walkways, windows, pools) as well as indoors on countertops and elsewhere. This black substance on the homes of people in Porter Ranch demonstrates substances from the Aliso Canyon facility were atmospherically transported and deposited on and into places where people live, work, and play.

***Composition of the Black Substance Deposited on Porter Ranch Residential Properties Including Inside of Homes***

It is highly likely that this "black" substance originated from the SS-25 well site at the Aliso Canyon UGS facility. The substance includes, but is not identical to, the heavy drilling muds used in the multiple attempts to kill the SS-25 well to stop the leak (see discussion of kill attempts in Sections 1.1 and 1.2 of this report). Shortly after complaints that this substance was being deposited on and inside of homes, cars, and other areas, SoCal Gas set up nets to capture this black substance by agglomeration as it was being emitted through craters adjacent to the well. Below are some considerations that are important to consider with respect to the composition and potential human exposures
to this substance.

While this substance has been referred to as "crude oil" and "heavy drilling muds" in some news media accounts, it is not entirely clear what this substance actually consists of. It is very likely that crude oil (which in itself is a mix of sometimes hundreds of petroleum hydrocarbons and other solid, liquid, and volatile constituents) is a component, given the fact that the Aliso Canyon facility is a depleted oil field, and oil is still produced from shallower reservoirs above the gas storage reservoir (see Section 1.1 of this report). However, it is unclear what the full chemical profile of this substance is and where its constituent compounds, naturally occurring or otherwise, may have originated. Given that the substance was emitted from Aliso Canyon, possible sources of other compounds that are likely to have been intermingled with this oily mist include:

- **Naturally occurring chemical constituents that are not crude oil**: Crude oil and associated fluids contain naturally mobilized chemical constituents including heavy metals, volatile organic compounds (VOCs), naturally occurring radioactive materials (NORMs), salts, and other compounds that are well known to be present, sometimes in elevated concentrations.

- **Chemical additives related to historic and recent well stimulation and other oil and gas development and maintenance**: Prior to the use of Sesnon-Frew reservoir at Aliso Canyon for natural gas storage, it was a productive oil field. Many chemical constituents are used routinely to maintain and clean out wells, and these same chemicals may also be used to stimulate and enhance oil and gas production (Stringfellow et al., 2017). Some of these chemicals remain in the subsurface and can be emitted during a blowout such as the 2015 Aliso Canyon incident. More than half of the wells put into operation in the Aliso Canyon UGS reservoir in the last 20 years have been hydraulically fractured (CCST, 2015b). The relatively small sand mass or fluid volume used in each of these operations, as reported in the record available for each well, suggests they were "frac packs," the purpose of which was likely to increase the peak gas delivery rate.

- **Synergistic Chemical Constituents**: Chemical additives that are added to wells can co-mingle with compounds that are naturally occurring in the formation. Under elevated temperature and pressure, some of these compounds can undergo reactions and create new compounds with unknown human health and environmental profiles. To date, there are no data available on these synergistic chemical constituents or clear evidence that they are in the black substance that has been deposited in the Porter Ranch community as a result of the SS-25 well blowout.

Other toxicological and exposure considerations of this oily black substance that remain unknown to date include:

***Aerosolized Particle-Size Considerations***

It would be helpful to know the range of particle sizes of the aerosolized "oily mist" when it was suspended in and transported through the atmosphere. Particle size is important, because respiratory exposures and their health consequences are more elevated when people are exposed to particles less than 10 micrometers (μm) in aerodynamic diameter ($<PM_{10}$). Particle size matters because particles larger than $PM_{10}$ tend not to pass beyond the nose, while those between $PM_{2.5}$ and $PM_{10}$ penetrate to the upper respiratory tract (nose, throat, bronchi), while particles smaller than 2.5 μm in aerodynamic diameter are able to penetrate deeper into the lung to the alveoli (U.S. EPA, 2017a).

***Environmental Degradation Considerations***

As noted, total petroleum hydrocarbons (TPHs) can represent hundreds of chemical compounds, and many of them degrade relatively rapidly in the environment. As such, it would be helpful to know the duration of time between the deposition of these droplets on people's property and when the samples of these droplets were tested in the laboratory.

Below, we describe an indoor environmental quality investigation undertaken by the LACDPH and researchers at UCLA and UC Berkeley to answer some of these questions. The investigation included taking "swab samples" of indoor dust on countertops and other surfaces to determine the presence of potentially health-damaging and symptom-inducing compounds that could explain the ongoing symptoms reported by residents upon returning to their homes.

***Implications of Indoor Metal Testing Findings in Swab Sampling***

In this study, LACDPH sampled and evaluated dust wipes from 114 homes and two schools. Thirteen of the 16 metals tested for in the surface-wipe samples of household dust were detected in Porter Ranch homes, while only four of the 16 metals were found in the control homes outside of the Porter Ranch area. The most frequently detected metal in the samples was barium, which was found in 19% of the Porter Ranch homes in concentrations from 0.05 to 1.0 ug/$cm^2$, levels higher than in the control homes. Other metals identified in the study (aluminum, cobalt, iron, manganese, nickel, strontium, and vanadium) were also higher in Porter Ranch homes than in the group of control homes (Figure 1.4-27). These results act as a sort of "fingerprint" of substances that entered the indoor environment in Porter Ranch.

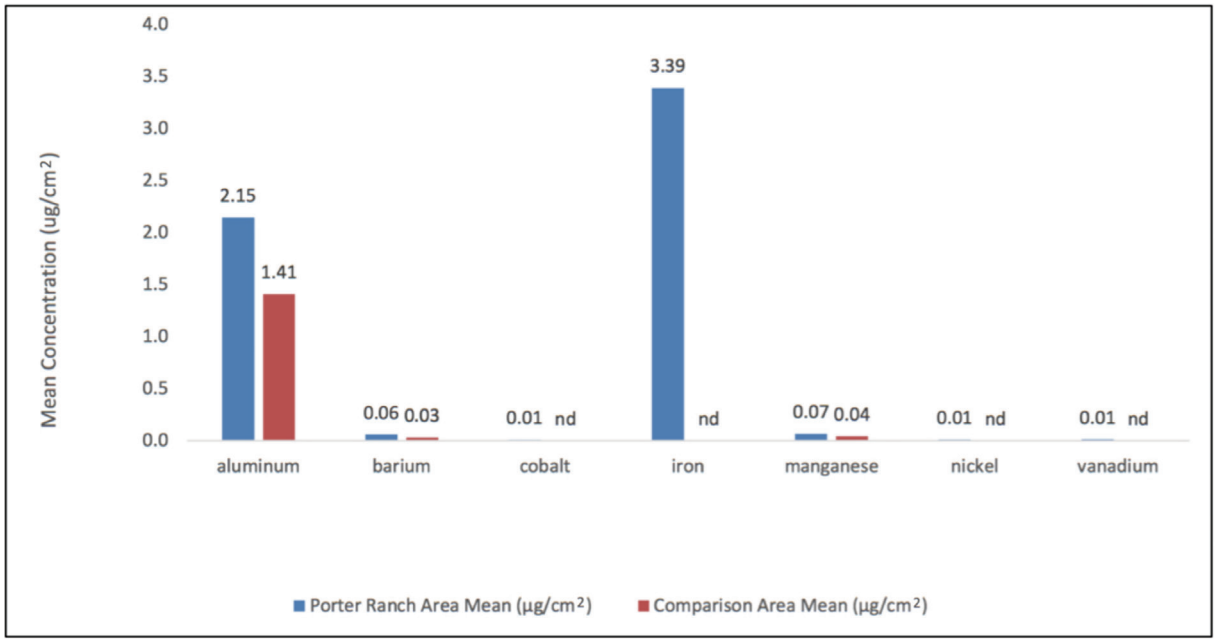


***Figure 1.4-27. Average metal concentrations in surface wipe samples (ug/cm²)—Porter Ranch area homes and schools, and comparison area. (Source: Beckerman and Jerrett, 2016).***

Additionally, further analyses conducted by UCLA researchers indicate that there is a very high correlation between the presence of these metals in homes in Porter Ranch compared with the control (Beckerman and Jerrett, 2016). Further, given that barium sulfate was known to be used in the drilling muds that were used in the attempt to kill the SS-25 well blowout, the high correlation between metals, oily residues, and barium sulfate in Porter Ranch homes compared to the control homes outside of Porter Ranch provides strong evidence that contaminants and other materials sourced from the Aliso Canyon facility penetrated the inside of homes.

In summary, the findings above build upon one another to provide important information about potential health risks from exposure:

**Source Attribution:** As noted above, findings from this indoor environment study indicate that there was a clear environmental pathway through which contaminants—originating from the 2015 SS-25 blowout—could enter the indoor environment of homes downwind of the facility. These contaminants include compounds in stored gas from the facility and compounds used to kill the well, indicating that methods used and overall ability to stop a leak must be taken into account when considering potential health risks to nearby populations.

**Uncertainties about Chemicals of Concern:** There is strong evidence that metals from the Aliso Canyon facility penetrated the indoor environment of the Porter Ranch homes downwind of the SS-25 well, but there remains uncertainty as to whether other *unmonitored contaminants* could have penetrated the indoor environment as well. The LACDPH identified the following as priority chemicals of potential concern based on "available information": sulfur compounds, benzene, and other VOCs, barium, petroleum hydrocarbons, and polycyclic aromatic hydrocarbons" (LACDPH, 2016c) Given the widespread historical and current chemical usage during activities in oil and gas wells—and by default in depleted oil reservoirs used for natural gas storage—this list of chemical constituents may be overly narrow, especially given the extent of the reported health symptoms in the Porter Ranch community. *To address this concern, it would be helpful for SoCalGas to disclose chemicals used in the Aliso Canyon field—and in what mass and frequency—to the LACDPH and the research community in order to better set priorities for monitoring.*

***Table 1.4-18. Summary of chemicals of concern that LACDPH used for monitoring of indoor Porter Ranch environments after the SS-25 well was sealed (LACDPH, 2016c).***

| Compound(s) | Potential Source | Data Supporting Compound as a Potential Source |
|---|---|---|
| Sulfur compounds | Odorants & Reservoir | Soil near SS-25, air downwind of SS-25, ambient air |
| Benzene, toluene, ethylbenzene and xylenes (BTEX) | Reservoir | Soil near SS-25, air downwind of SS-25, ambient air |
| Barium | Well kill mud | Material safety data sheets, Soil near SS-25, air downwind of SS-25 |
| Petroleum Hydrocarbons | Reservoir & Well kill solutions | Material safety data sheets, Soil near SS-25, air downwind of SS-25 |
| Polycyclic Aromatic Hydrocarbons (PAHs) | Reservoir | Soil near SS-25, air downwind of SS-25 |
| 1,2,4 Trimethylbenzene | Reservoir | Soil near SS-25, air downwind of SS-25 |
| Crystalline Silica | Well kill solids | Material Safety Data Sheets |

***Other potential sources of toxic compounds: Chemicals used by UGS facilities***

While chemicals used in oil and gas production during routine activities (e.g., drilling, routine maintenance, completions, well cleanouts) and well stimulation (e.g., hydraulic fracturing and acid stimulation) are reported for all other wells in the South Coast Air Quality Management District (SCAQMD, 2013, rule 1148.2; Stringfellow et al., 2017), no such disclosures are made for UGS wells. This is true for UGS facilities statewide. UGS operators disclose chemical information to the California Environmental Reporting System (CERS) for chemicals stored on-site; however, this information is not publicly available for all facilities, does not include what the chemicals are used for, or the mass or frequency of use on-site, and often lists product names without unique chemical identifiers (SoCalGas,

2015). As such, it is likely that on-site chemical use occurs, but the composition of those chemicals, the purpose, mass, and frequency of their use, and their associated human health risks during normal and off-normal events at UGS facilities remain unknown.

#### 1.4.10.8 Aliso Canyon Monitoring and Emissions Inventory Reporting for UGS Facilities

As discussed in Section 1.4.5, UGS facilities report annual emissions for criteria and toxic air pollutants through the Air Toxics Hot Spots Program. While many pollutants emitted by UGS facilities were monitored for during or after the 2015 Aliso Canyon incident (Table 1.4-16), there are notable exceptions. Of all chemicals with unique chemical identifiers – or Chemical Abstract Service Registry Numbers (CASRN) – (i.e., excluding broad chemical groupings such as particulate matter) reported in the emissions inventory for Aliso Canyon (n=58), 18 (31%) were monitored for in air during or shortly after the SS-25 blowout. These compounds are listed in Appendix 1.C, Table 1.C-4. However, the majority of compounds historically reported as emitted from the Aliso Canyon UGS facility with CASRNs (69%) were not monitored for in air during or after the Aliso Canyon SS-25 blowout.

A few of these unmonitored compounds are particularly relevant due to the large estimated amount emitted and chemical-specific toxicity. Ammonia was not monitored for during or after the SS-25 blowout, but was consistently ranked in the top three emitted pollutants across all years of reported data (data not shown). Ammonia is associated with acute and chronic respiratory health impacts. Compounds emitted from Aliso Canyon with higher median annual emissions (<175 pounds/year) include acrolein (associated with eye and respiratory irritation) and methanol (associated with adverse effects on the nervous system and development), both of which were not monitored for during the Aliso Canyon blowout (Appendix 1.C, Table 1.C-4).

Facility-specific emissions inventories can be used to inform air and other environmental monitoring efforts near UGS facilities during routine operations as well as during and after large LOC events. Notably, many broad chemical groupings (excluded from unique chemical analysis above) are reported to emissions inventories but were not monitored for during and after the SS-25 blowout. For example, particulate matter (PM) and other secondary air pollutants are known to be directly emitted from UGS facilities and indirectly formed through atmospheric transformation processes and are associated with adverse health outcomes (Section 1.4.6.4.4).

There are also a few notable compounds that are not included in the emissions inventories, but that are particularly relevant when discussing health-relevant compounds associated with underground gas storage in California. Mercaptans are compounds added to odorize methane so that leaks and exposures can easily be detected. Mercaptans are not included on the list of substances required for reporting through the Air Toxics Hot Spots Program. Additionally, mercaptans do not have Cal/EPA community RELs, and only have occupational exposure limits. Outside of acute exposures in occupational settings, which are clearly inappropriate from a community health perspective, there is little guidance on

safe levels of exposure. The sulfur compounds and in particular, the odorants are a strongly suspected cause of a number of the health complaints of residents living in proximity of the Aliso Canyon facility since the leak from well SS-25 began in October 2015 (see Section 1.4.10 below). Mercaptans in particular are known to elicit dizziness, headaches, general weakness, respiratory irritation, nausea, abdominal discomfort, and vomiting (Behbod et al., 2014).

#### 1.4.10.9 Emerging Health Datasets and Reports Regarding the 2015 Aliso Canyon SS-25 LOC Event

There have been recent efforts by community members and others to conduct sampling of human hair, blood, and urine and environmental media to evaluate exposure and environmental contamination from the 2015 Aliso Canyon incident. A presentation by Dr. Jeffrey Nordella (2017) has reported some of these results but future work needs to be done to contextualize these results and to date there is not yet a written document to assess and the raw data are not publicly available. Future work should evaluate these data. New reports and publications related to the 2015 Aliso Canyon incident are expected in the coming months from LACDPH and UCLA (Personal Communication, Katherine Butler, LACDPH).

#### 1.4.10.10 Aliso Canyon and Public Health: Discussion and Conclusions

The 2015 Aliso Canyon incident involving nearly four months of surface blowout of the SS-25 well, and all of the environmental monitoring that ensued provides an opportunity to evaluate the public health dimensions of this kind of large-scale disaster at a California UGS facility. The confluence of multiple datasets, including (1) air pollution and indoor environment samples, (2) the prevalence and geographic distribution of health complaints reported by the surrounding population, and (3) time-activity information on symptoms reporting strongly suggest that the cause of many of the health effects and symptoms reported by the nearby population were related to the Aliso Canyon UGS facility. However, as noted, the exact mechanisms that induce a number of these health effects and symptoms remain uncertain. It is highly likely that many of the symptoms experienced by the nearby population were induced by exposures to sulfur odorants (mercaptans). However, mercaptan exposures do not explain the high reporting of epistaxis (nosebleeds). Moreover, mercaptans also do not explain why the majority of households returning to their homes near the Aliso Canyon facility after the sealing of the SS-25 well complained of health symptoms.

The uncertainty with respect to which contaminants were the culprit of health symptoms reported by residents could be driven by multiple factors, including but not limited to:

1. The fact that air monitoring only focused on 24 of the 98 contaminants reported as emitted by UGS facilities statewide.

2. The possible use of hazardous chemicals in wells and associated infrastructure (e.g., for maintenance, well work-overs, well killing, and other purposes) that has not been disclosed and which could have been entrained in the gas, leading to human exposures. All oil and gas wells in the SCAQMD are required to disclose their chemicals use except for UGS wells pursuant to SCAQMD Rule 1148.2.

3. A chemical or groups of chemicals were released intermittently during the first part of the leak when only short-term grab samples were being collected and the presence of these compounds were missed by more continuous and thorough monitoring later on.

4. The possibility that interactions between multiple pollutants from the facility and possibly from other sources created a mixture of contaminants that induced health effects and symptoms in the population, but no one chemical was responsible for all symptoms.

5. The emissions of the compounds from the facility atmospherically transformed to other chemical species or particles that were not monitored for. Data collected on secondary formation of particles downwind of the Aliso facility during and after the leak by a team of researchers from UCLA and UC Berkeley (Jerrett and Garcia-Gonzales) may shed light on a part of this issue; however, their results have not been published as of the writing of this report.

Of course, many of the non-acute symptoms and health effects that take time to clinically manifest that are now being alleged will require retrospective and prospective public health and medical surveillance approaches to ascertain their association with the Aliso Canyon facility.

### 1.4.11 Occupational Health Dimensions of UGS in California

This section evaluates health and safety hazards relevant to on-site workers at UGS facilities in California, including employees and contracted or temporary workers. The assessment considers health and safety hazards associated with routine and off-normal emissions scenarios (e.g., the 2015 Aliso Canyon incident), and includes potential exposures to toxic air pollutants, fire, and explosions. The lack of data involving emissions, gas composition, and occupational air monitoring at California UGS facilities limited the scope and detail of this assessment. However, information was gathered from UGS site visits, operators, and

state agencies. The protection of workers from these hazards would inherently provide better protection for the community, as workers are on the front line for most incidents.

#### 1.4.11.1 Characterization of workers associated with UGS facility operations

UGS workers include both employees of the operating gas storage companies (e.g., SoCalGas and PG&E), and those provided by staffing agencies (i.e., "temporary workers") who are engaged in construction, routine operations, and non-routine operations. Temporary workers or contractors are especially at risk because they are often not covered by company health and safety plans; their exposures are usually not monitored; their numbers at any given time on site may not be known with precision; their presence on-site is often intermittent (but may include living on-site for days to weeks at a time); and they are sometimes called upon to perform highly specialized and high-risk tasks (e.g., killing a well blowout) as companies tend to contract out jobs associated with the highest exposures. The Occupational Safety and Health Administration (OSHA) and National Institute for Occupational Safety and Health (NIOSH) published recommendations on the necessity of protecting *all* workers:

> *"Whether temporary or permanent, all workers always have a right to a safe and healthy workplace. The staffing agency and the staffing agency's client (the host employer) are joint employers of temporary workers and, therefore, both are responsible for providing and maintaining a safe work environment for those workers. The staffing agency and the host employer must work together to ensure that the Occupational Safety and Health Act of 1970 (the OSH Act) requirements are fully met" (OSHA & NIOSH, 2014).*

During a site visit by our research team to the McDonald Island Underground Gas Storage Facility (see side bar below), we observed that the contracted or "temporary" workers were responsible for much of the above-ground well maintenance and monitoring operations. Along with the employees of UGS facilities, temporary workers should be included as much as possible in all evaluations of occupational human health and safety risks associated with UGS. As such, throughout this section, the term "workers" refers to both employees and contracted or temporary workers.

## Side bar: McDonald Island Underground Gas Storage Facility Site Visit

In June 2017, CCST staff and the authors of this and other chapters in this report visited the McDonald Island Underground Gas Storage Facility, a Pacific Gas and Electric (PG&E) operated underground gas storage facility in Northern California. Prior to the visit, authors of this chapter gathered a list of questions specific to risks associated with UGS activities. The site visit included the following: (1) an overview of activities at McDonald Island and other PG&E operated gas storage facilities in Northern California; (2) a guided tour around the facility; and (3) opportunities to ask further questions. While questions specific to health and safety aspects associated with UGS were posed during the visit, many of these questions went unanswered. To our knowledge, PG&E staff did not follow-up with answers to questions that were documented in written form prior to the visit or questions asked verbally during the visit.

Although UGS facilities can cover relatively large geographic areas, we understand that relatively few workers are needed for the normal operations at these facilities and that employees include at least two system operators on each shift and numerous maintenance workers. During our site visit to the McDonald Island UGS Faciltiy, PG&E staff stated that there are typically four mechanics, six technicians, two assistants, two to four engineers, one full-time environmental specialist, and approximately 20 others on-site. From conversations with state agencies, we understand that SoCalGas has approximately 200 employees in total at their four UGS sites (Aliso Canyon, Playa del Rey, La Goleta, and Honor Rancho). However, the number of contractors on site is unknown and could equal or exceed the number of employees. Some contractors temporarily live on-site in travel trailers, and may be exposed during work and also during residence.

During our site visit to McDonald Island UGS Facility, we observed several contractor trailer residences on-site. Occupational exposure limit (OEL) standards are intended to protect workers from eight hours of exposure per day, with 16 hours away from exposure during which the body can recover and some materials can be metabolized and eliminated from the body (AIHA, 2017). For temporary workers living on site, OELs are therefore not applicable, and other exposure limit recommendations may be more appropriate. Furthermore, the OELs should be reconsidered carefully for those who work longer than eight-hour shifts, during which time recovery or elimination may not occur.

#### 1.4.11.2 Review of Processes and Potential for Occupational Exposures

Routine exposures can occur from specific job tasks and from the continuous emissions from leaks (e.g., fugitive losses from valves, flanges, and other fittings). Because workers are in close proximity to leak sources, they can be exposed to much higher chemical concentrations than the community. Dispersion models indicate that near-field (worker) exposures can be several orders of magnitude higher than community exposures (Benarie, 1980). Specific job tasks may also produce brief releases of gases or other chemicals. These can occur during gas sample extraction for analysis, during daily pressure readings at each well, and during ongoing inspections of pipelines, compressors, storage tanks, scrubbers, and other equipment. In addition to exposures to natural gas and contaminants from the storage wells, workers are also exposed to process materials that are stored on-site in above-ground storage tanks.

***Potential for chemical exposures***

As described previously, natural gas – predominantly methane – is injected and stored under pressure in underground depleted oil and gas reservoirs. Given that methane can act as a solvent while underground, the injected gas admixes with chemicals present in the storage reservoirs, and the composition of the contaminants likely varies between facilities given the geology and historical and sometimes still current oil and gas production activities (see Section 1.2). When gas is withdrawn from the storage reservoir it must be processed

before it is re-introduced into the pipeline system. Processing includes cleaning to remove sand, dirt and other gases and non-methane VOCs using scrubbers, purifiers, or additional chemicals; adding methanol to prevent formation of hydrates; dehydrating the gas to remove water; and re-introducing odorants before the gas re-enters the pipeline (Personal Communication, McDonald Island UGS Facility Visit, 2017).

Thus, in addition to methane itself, several other chemicals used in on-site operations present possible hazards to workers. The origins of these chemicals are various, and include:

1. Natural contaminants from the underground storage reservoirs (e.g., benzene, toluene, xylenes, ammonia, acetaldehyde, hydrogen sulfide);

2. Formaldehyde, a known human carcinogen, formed predominantly at gas-fired compressors due primarily to combustion during normal operations;

3. Chemicals used to clean and treat the gas (e.g., glycols, methanol);

4. Odorants, typically mercaptans.

5. Possibly other chemicals used down-hole during routine well maintenance and other activities.

On-site materials we were able to identify during our site visit to McDonald Island include: mercaptans (odorants), triethylene glycol (for dehydration) and methanol (to prevent the formation of hydrates). Methanol is reported as emitted from UGS facilities in California (see Section 1.4.6). These compounds are typically stored in above-ground tanks, which have the potential both for fugitive emissions or larger uncontrolled leaks.

Hydrogen sulfide (H2S) presents both a toxic and a flammability hazard at the worksite after it is separated from the gas. Hydrogen sulfide is a flammable, colorless gas that is toxic at extremely low concentrations. Denser than air, hydrogen sulfide can accumulate in low-lying areas and smells like “rotten eggs.” The odor is easily recognizable and can cause anosmia, or loss of smell (OSHA, 2017a). At high concentrations, sense of smell can be lost immediately (olfactory paralysis) (OSHA, 2017b). High concentrations of hydrogen sulfide (above 500 ppm) can lead to unconsciousness, cessation of breathing, and death, while concentrations of 100-1000 ppm can adversely impact the respiratory, nervous, and cardiovascular systems (OSHA, 2017b).

Recommended exposure limits from the American Conference of Government Industrial Hygienists (ACGIH) and Agency for Toxic Substances and Disease Registry (ATSDR) are shown in Table 1.4-19. Note that in this section we use concentration units of ppm and ppb with the understanding that all concentrations are volumetric, often denoted ppmv or ppbv.

*Table 1.4-19. Hydrogen sulfide and corresponding exposure limits as specified by the 1) ACGIH (2017) and 2) ATSDR (2017b).*

| Exposure period | Description | Limit |
|---|---|---|
| Short-term exposure limit (STEL) [1] | Short periods, 15-minutes | 5 ppm |
| Threshold limit value (TLV) [1] | 8-hour average | 1 ppm |
| Time-weighted average (TWA) [1] | 8-hour time-weighted average | 1 ppm |
| Acute Minimum Risk Level (MRL) [2] | 1 - 14 days | < 70 ppb |
| Chronic Minimum Risk Level (MRL) [2] | 15 - 364 days | < 30 ppb |

Removal of hydrogen sulfide, if present, is necessary to prevent corrosion of the pipelines and containment systems. Hydrogen sulfide can be removed by an absorbing agent such as diethanolamine (a possible human carcinogen) (IARC, 2000), by activated charcoal, or by high temperature catalytic hydrogenation followed by zinc oxide treatment. However, the removal process presents serious risk related to exposure to workers and is cited as a major concern by those responsible for worker health and safety. The extent of the hydrogen sulfide contamination likely varies considerably among the facilities, but where it is present several precautions are necessary. Because hydrogen sulfide is so toxic, direct-reading instruments are commonly used to measure hydrogen sulfide concentrations continuously in areas where it might be present, and workers wear continuous hydrogen sulfide monitors. Potential hydrogen sulfide exposures may occur from minor leaks encountered in maintenance and during manual sampling, which in refinery operations could result in concentrations above 300 ppm that are immediately hazardous to life or health (Burgess, 1995). While this information is reported for refinery operations, it may also be relevant when discussing UGS operations where hydrogen sulfide is present.

Despite requests to operators and regulators, we were unable to obtain any monitoring data from UGS facilities, although we understand that monitoring occurs where hydrogen sulfide is present in the gas. Notably, during the 2015 Aliso Canyon incident the concentration of hydrogen sulfide reached 185 ppb at a Porter Ranch community monitor (see Section 1.4.10), which is a remarkably high concentration given both toxicity and distance from the source. On-site concentrations must have been much higher and may have exceeded the short-term exposure level (STEL) and the threshold limit value (TLV) (Table 1.4-19).

Because of the toxic potency of hydrogen sulfide, instrumentation that can monitor hydrogen sulfide continuously and at the low concentrations should be installed where hydrogen sulfide may be present; furthermore, workers should wear instruments which can detect hydrogen sulfide below health-relevant concentrations and sound warnings when those concentrations are exceeded. We understand that hydrogen sulfide is a chemical of sufficient concern and UGS facilities should monitor it routinely when it is present in the gas; however, we were not able to obtain any of this monitoring data despite several requests.

*Physical safety hazards: fires and explosions*

On-site workers are especially at risk if an accidental release leads to fire and/or explosion. Such hazards are acknowledged by the requirements that each facility have an incident commander trained to the "first responder" operation level. During the 2015 Aliso Canyon UGS Facility SS-25 well LOC event, the incident commander was not sufficiently trained, and this failure led CalOSHA to cite SoCalGas for a serious violation (CalOSHA, 2017a; see Section 1.4.11.3). UGS facilities are also required to have an emergency plan that is well understood by all workers. OSHA requires preventing or minimizing the consequences of catastrophic releases of toxic, reactive, flammable, or explosive chemicals, which may result in toxic, fire, or explosion hazards (OSHA, 1992).

OSHA Process Safety Management of Highly Hazardous Chemicals standard contains requirements for the management of hazards associated with processes using highly hazardous chemicals and establishes a comprehensive management program that integrates technologies, procedures, and management practices (OSHA, 2017c). While these regulations articulate good practices, there is an exception to **process safety management (**PSM) for hydrocarbons used only as fuels, and so these regulations do not apply to UGS. We recommend that California should eliminate this exemption in the interest of occupational health risk reduction.

### 1.4.11.3 Occupational Aspects of the 2015 Aliso Canyon UGS Facility SS-25 LOC Event and Regulatory Oversight

There is a current legal dispute about which regulatory agency has jurisdiction over the health and safety of workers. The federal Occupational Safety and Health (OSH) Act covers most private sector employers and their workers. OSH also provides for states to develop their own programs that must be approved by OSHA. The California State Plan (approved by OSHA and administered through CalOSHA) covers all private sector places within the state with some exceptions; however, UGS facilities are not among the exemptions listed (OSHA, 2017d).

In June 2016, the California Division of Occupational Safety and Health (DOSH, or CalOSHA) cited SoCalGas concerning the 2015 Aliso Canyon SS-25 well LOC event for three serious and three general violations. The serious citations allege violations of:

- Petroleum Safety Orders (PSO) §6851 for allegedly failing to make "reasonable efforts" by inspection and maintenance to prevent the possible occurrence of leaks from piping consisting of casing and tubing of the wells;

- PSO §6845 for allegedly failing to ensure that well inspection complied with relevant American Petroleum Institute standards;

- General Industry Safety Orders §5192(q) for allegedly failing to make sure that the site incident commander was trained at the first-responder operations level and failure to certify that the commander knew how to implement the SoCalGas incident command system.

SoCalGas is challenging the legality of these citations and states that the "citation is preempted by the Federal Natural Gas Pipeline Safety Act" and that the Pipeline Safety Act (PSA) "expressly preempts all state and local safety standards for natural gas pipeline facilities and precludes state and local authorities from imposing or enforcing safety standards on natural gas pipelines except as permitted under federal law." These authorities, SoCalGas contends, must first obtain annual certification under the PSA, the firm asserts, and, it says, neither CalOSHA nor Los Angeles County have done so. "The only California authority certified to impose or enforce safety standards for SoCalGas natural gas pipelines and underground storage facilities is the California Public Utilities Commission," the complaint says (CalOSHA, 2017a; SoCalGas, 2017b).

Federal preemption claimed by SoCalGas may apply to safety of the pipelines, but not to the health and safety of workers. Similarly, it appears that CPUC is concerned with safety in the context of the integrity of the wells and pipelines and the quality of the gas, but not explicitly with worker health and safety (e.g., slips and falls, monitoring benzene exposure, etc.). Clearly safety as it relates to pipe and well hardware is important for worker safety, but there are other hazards workers face that do not directly compromise the natural gas supply. After searching the OSHA databases for inspection reports and chemical monitoring data, reading the CalOSHA inspector's notes and citations from the 2015 Aliso Canyon incident, reading the CalOSHA citations and the SoCalGas appeal of those citations and the lawsuit SoCalGas filed, and conducting or attempting to conduct interviews with CPUC, CalOSHA, SoCalGas and PG&E, we conclude it is unlikely that any regulatory agency is monitoring the health and safety of workers at California UGS facilities. Further, it is unlikely the companies are monitoring chemicals to which workers are exposed, except for hydrogen sulfide. Even the exception may prove this rule, as we were unable to obtain any reports of hydrogen sulfide exposures; it may well be that this chemical is monitored with an alarm to indicate life-threatening exposures, but that the values below this threshold are neither recorded nor reported.

#### 1.4.11.4 Attempts to gather information about occupational health and safety risks

We contacted the following organizations in an attempt to obtain information about worker exposures to airborne contaminants and to fire and explosive hazards associated with UGS:

- National Institute for Occupational Safety and Health (NIOSH)
- NIOSH Western States Division
- Occupational Safety and Health Administration (OSHA)

- CalOSHA
- California Public Utilities Commission (CPUC)
- United Steel Workers Union, Health, Safety and Environment Office
- International Brotherhood of Electrical Workers (IBEW) 1245
- Current and past industrial hygienists at SoCalGas and PG&E
- Health and safety officers at McDonald Island facility

Most of the information that we were provided with came from the CalOSHA investigation, citations from the Aliso Canyon incident, the CPUC, conversations with an industrial hygienist who had worked at one of the major companies, and communications from a site visit to the McDonald Island UGS facility. The latter site visit provided some good insights about operations and staffing. We asked several questions related to occupational health and safety, but few of these were answered, and none of the data we requested (e.g., airborne measurements) were provided (see side bar above).

#### 1.4.11.5 Occupational Health Summary

On-site workers are those most likely to be exposed to the highest concentrations of both routine and off-normal emissions, and dispersion models indicate worker exposures could be several orders of magnitude higher as compared to community exposures (Benarie, 1980). On-site workers are also most at risk from injury due to fire and explosion. As noted previously and in Section 1.5, most emissions likely originate from above-ground infrastructure, and hence the highest exposures will be experienced by those on-site, before significant dispersion mitigates the hazard. In Appendix 1.G, we provide a brief summary of some of the best practices that could be deployed to help to reduce occupational health risks. While well-intentioned agencies seek to mandate health and safety protections for all workers, employees and temporary workers associated with UGS activities may not be adequately protected and protective measures may not be effectively enforced.

### 1.4.12 Health and Safety Risks and Impacts of UGS in California: Findings, Conclusions, and Recommendations

In this section, we described and analyzed the human health and safety hazards, risks, and impacts of UGS facilities in California. The human health hazards and risks of underground gas storage (UGS) facilities depend on the following:

1. the composition of stored, withdrawn, and stripped and compressed gases
2. the reservoir type (e.g., dry gas vs. oil)

3. the age and mechanical integrity of the subsurface and surface infrastructure
4. the type and number of gas compressors
5. the long-term expected emissions rate of chemical constituents from the wells
6. the magnitude and duration of emissions during containment failures
7. atmospheric dispersion conditions during the period of release
8. the number and density of gas storage, oil and gas production, and other wells in the vicinity of a loss of zonal isolation in the subsurface collection of UGS infrastructure
9. the activities and locations of on-site workers and contractors
10. the location and density of downwind populations
11. the location of sensitive populations as reflected by the very young, the elderly, women of childbearing age, schools, child care facilities, hospitals, and elderly care facilities
12. the prevalence of groundwater aquifers proximal to UGS facilities

Effective risk management requires that information on each of these 12 categories is available to regulators, decision-makers, site managers, and local emergency managers, so that decisions can be well informed. Risk management plans for addressing public health should include a process that provides site managers and first responders with the following information:

- A list of the chemical composition of the downhole stored gas (down to the parts per billion concentration), withdrawn gas (immediately after withdrawal), and stripped gas delivered into the pipeline. This information should contain toxicological information on each chemical constituent.
- A comprehensive list of chemicals stored on site, e.g., odorants and glycols including information on their mass and use.
- Tools for continuous air-quality monitoring.
- On-site weather stations to provide real-time information on the likely direction and concentration of off-site emission transport.
- Access to real-time air dispersion modeling tools.

- Geospatial locations of residents, workers, and sensitive populations.
- Communications channels with local first-responders.

Below, we provide the major findings, conclusions, and recommendations from our assessment of the human health dimensions of UGS facilities in California.

#### 1.4.12.1 Emissions Inventory Information Gaps and Uncertainty

**Finding:** There are a number of human health hazards associated with UGS in California that can be predominantly attributable to exposure to toxic air pollutants. These toxic compounds emitted during routine and off-normal emissions scenarios include but are not limited to odorants, compressor combustion emissions, benzene, toluene, and other potentially toxic chemicals extracted from residual oil in depleted oil reservoirs. Given the limited number of compounds monitored for during the 2015 Aliso Canyon incident compared to the number of compounds reported to the California Air Resources Board as emitted from UGS facilities, there is significant uncertainty as to the human health risks and impacts of this large LOC event both over the short- and long-term. Our repeated attempts to acquire useful information about gas composition at each UGS facility in California were unsuccessful. Working with the CPUC, we made formal requests to all operators seeking information on the chemical composition of the stored gas. All responded, but none could provide the detailed information we needed (See Appendix 1.D).

**Conclusion:** Because emissions inventories for UGS facilities lack temporal, spatial, and technology-specific detail as well as verifiability of emission types and rates, currently available emissions inventories cannot support quantitative human exposure or health risk assessments. There is a need to identify the chemical composition of the gas that is stored, withdrawn, stripped, and delivered to the pipeline, so that associated hazards during routine and off-normal emission scenarios can be assessed. (See Conclusion 1.5 in the Summary Report.)

**Recommendation:** Agencies with jurisdiction should require that UGS facility operators provide detailed gas composition information at appropriate time intervals. Additionally, these agencies should require the development of a comprehensive chemical inventory of all chemicals stored and used on-site, and the chemical composition of stored, withdrawn, stripped and compressed gas for each UGS facility. These data should be used to prioritize chemicals to enable site operators and local first responders to set health-based goals for monitoring and risk assessment actions. (See Recommendation 1.5 in the Summary Report.)

#### 1.4.12.2 Health Symptoms in Communities Near the 2015 Aliso Canyon Incident Were Attributable to the Aliso Canyon UGS Facility

**Finding:** The majority of households near the Aliso Canyon UGS facility experienced health symptoms during the SS-25 blowout and after the well was sealed, and these symptoms

were likely related to the gas leak and/or other emission sources from the Aliso Canyon UGS facility. While many of the symptoms reported by residents match the symptom profile of exposure to mercaptans (gas odorants), other symptoms such as nosebleeds do not, suggesting that air pollutant and other environmental monitoring was not sufficiently inclusive of potential health-damaging pollutants.

**Conclusion:** Emissions from the 2015 Aliso Canyon incident were likely responsible for widespread health symptoms in the nearby Porter Ranch population. These types of population health impacts should be expected from any large-scale natural gas releases from any UGS facility, especially those located near areas of high population density. However, many of the specific exposures that caused these symptoms remain uncertain due to incomplete information about the composition of the air pollutant emissions and their downwind concentrations. (See Conclusion 1.6a in the Summary Report.)

**Recommendation:** Community health risks should be a primary component of risk management plans and best management practices for emission reductions, and measures to avoid (normal and off-normal) gas releases should be immediately implemented at existing UGS facilities. In addition, options for public health surveillance should be considered both during and following major loss-of-containment events to identify adverse health effects in communities. (See Recommendation 1.6a in the Summary Report.)

#### 1.4.12.3 Population Exposures to Toxic Air Pollutants Increase with Higher Emissions, Closer Community Proximity and Higher Population Density

**Finding:** Approximately 1.85 million residents live within five miles of UGS facilities in the State of California. In the absence of reliable information on emissions inventories and expected release rates, potential health hazards can be evaluated using normalized source-receptor relationships obtained from atmospheric transport models and best estimates of population distance and density. Both concentration/source and population-intake/source ratios (intake fraction) provide helpful tools to assess the variability of potential exposures and risks among different UGS facilities.

**Conclusion:** UGS facilities pose more elevated health risks when located in areas of high population density, such as the Los Angeles Basin, because of the larger numbers of people nearby that can be exposed to toxic air pollutants. Emissions from UGS facilities, especially during large loss-of-containment events, can present health hazards to nearby communities in California. Many of the compounds potentially emitted by underground gas storage facilities can damage health and place disproportionate risks on sensitive populations, including children, pregnant women, the elderly, and those with pre-existing respiratory and cardiovascular conditions. (See Conclusion 1.7 in the Summary Report.)

**Recommendation:** Regulators need to ensure that the risk management plans required as part of the new DOGGR regulations take into account the population density near and proximity to UGS facilities. One mitigating approach to reduce risks to nearby population centers could be to define minimum health-based and fire-safety-based surface setback

distances between facilities and human populations, informed by available science and results from facility-specific risk assessment studies. This may be most feasible for future zoning decisions and new facility or community construction projects. Such setbacks would ensure that people located in and around various classes of buildings such as residences, schools, hospitals, and senior care facilities are located at a safe distance from UGS facilities during normal and off-normal emission events. (See Recommendation 1.7 in the Summary Report.)

#### 1.4.12.4 Occupational Health and Safety Considerations

**Finding:** Based on toxic chemicals known to be present on-site, and publicly available emission reporting to air regulators under the Air Toxics Hot Spots Program, we have identified toxic chemicals used at and emitted from UGS facilities. These chemicals include, but are not limited to, hydrogen sulfide, benzene, acrolein, formaldehyde, and 1,3-butadiene. Currently we have found no available quantitative exposure measurements.

**Conclusion:** Workers at UGS facilities are likely exposed to toxic chemicals, but the actual extent of those exposures is not known. Without quantitative emission and exposure measurements, we cannot assess the impact of these exposures on workers' health. (See Conclusion 1.8 in the Summary Report.)

**Recommendation:** UGS facilities should make quantitative data on emissions of, and worker exposures to, toxic chemicals from UGS facility operations available to the public and to agencies of jurisdiction (e.g., CalOSHA, CPUC) to enable robust risk assessments. It may be advisable to require that UGS facilities be subject to the Process Safety Management of Highly Hazardous Chemicals Standard (29 CFR 1910.119), which contains requirements for the management of hazards associated with processes using highly hazardous chemicals. (See Recommendation 1.8a in the Summary Report.)

**Recommendation:** Require that UGS workplaces conform to requirements of CalOSHA and federal OSHA, and impose additional requirements to protect the health and safety of on-site workers (employees, temporary workers and contractors), whether or not they are legally bound to comply (SoCalGas, 2017b). These requirements include that (1) all training and preparation for incidents and releases be fully concordant with best practices (see Appendix 1.G); (2) all safety equipment be fully operational and up to date, readily available, and all workers trained in equipment location and proper use; (3) all incident commanders be provided with sufficient, current training; (4) all health and safety standards be observed for all workers on site; and (5) air sampling of workers' exposures be required during routine and off-normal operations to ensure that exposures are within the most health-protective occupational exposure limits. (See Recommendation 1.8b in the Summary Report.)

The exact chemicals to be monitored should be evaluated when more data are available about potential exposures, but some important ones include hydrogen sulfide where it is present, benzene, formaldehyde, the odorants in use at the facility (e.g., mercaptans), methanol, triethylene glycol, and other dehydrants.

### 1.4.12.5 Continuous Facility Air-Quality Monitoring

**Finding:** Many UGS facilities emit multiple health-damaging air pollutants during routine operations. Available emissions inventories suggest that the most commonly emitted air pollutants associated with UGS by mass include nitrogen oxides, carbon monoxide, particulate matter, ammonia, and formaldehyde. For instance, Aliso Canyon is the single largest emitter of formaldehyde in the South Coast Air Quality Management District. Gas-powered (as compared to electric-powered) compressor stations are associated with the highest continuous emissions of formaldehyde. CARB regulations (CARB, 2017c) for underground gas storage facilities in place since October 1, 2017 require continuous methane concentration monitoring at facility upwind and downwind locations (at least one pair of upwind and downwind locations) but without air sampling.

**Conclusion:** There is a need to track, and, if necessary, reduce emissions of toxic air pollutants from UGS facilities during routine operations. (See Conclusion 1.9 in the Summary Report.)

**Recommendation:** Agencies with jurisdiction should require actions to reduce exposure of on-site workers and nearby populations to toxic air pollutants, other health-damaging air pollutants emitted from UGS facilities during routine operations, and ground level ozone, nitrogen oxides, and other ozone precursors. These steps could include (1) the implementation of air monitors within the facilities and at the fence line or other appropriate locations—preferably with continuous methane monitoring with trigger sampling to quickly deploy appropriate off-site air quality monitoring networks during incidents; (2) the increased application and enforcement of emission control technologies to limit air pollutant emissions; (3) the replacement of gas-powered compressors with electric-powered compressors to decrease emissions of formaldehyde; and (4) the implementation of health protective minimum-surface setbacks between UGS facilities and human populations. (See Recommendation 1.9 in the Summary Report.)

### 1.4.12.6 Community Symptom-based Environmental Monitoring for High Priority Chemicals

**Finding:** Symptom reporting and environmental monitoring in Porter Ranch, CA, during and after the 2015 Aliso Canyon incident indicate that chemicals and materials sourced from the SS-25 well entered residences, demonstrating clear indoor and outdoor exposure pathways. However, air pollutant exposures during the SS-25 event are significantly uncertain with respect to characterizing health-relevant exposures, because (1) detection limits for air pollutants such as benzene, mercaptans, and other toxic air pollutants during the SS-25 blowout were often above health and/or odor thresholds; (2) air and other environmental monitoring during much of the time of the SS-25 blowout was non-continuous; and (3) only a small fraction of pollutants known to be associated with UGS facilities was included in the monitoring.

Many of the health symptoms most commonly reported by residents of Porter Ranch, CA, during and after the SS-25 blowout are consistent with exposures to mercaptans. However, reporting of epistaxis (bloody noses) suggests that there could have been exposures to hydrogen sulfide, hexane, or other substances from the Aliso Canyon UGS facility that were not monitored for during and after the blowout. Environmental and air sampling inside Porter Ranch homes during and following the SS-25 blowout indicate that chemical constituents and other materials sourced from the Aliso Canyon UGS facility entered residences, demonstrating clear indoor and outdoor exposure pathways. Monitoring during and after the SS-25 blowout was limited by detection limits above health-relevant and/or odor thresholds and non-continuous sampling. Health risk management requires quick and coordinated deployment of indoor and outdoor environmental sampling for high priority chemicals, using health-relevant limits of detection.

**Conclusion:** Effective health risk management requires continuous, rapid, reliable, and sensitive (low-detection limit) environmental monitoring of chemicals of concern in both ambient and indoor environments. (See Conclusion 1.6b in the Summary Report.)

**Recommendation:** To support a more detailed exposure assessment to communities located near UGS facilities, procedures need to be in place to be able to: (1) rapidly deploy a network of continuous, reliable, and sensitive indoor and outdoor sensors for high priority chemicals, capable of detecting emissions at levels below thresholds for minimum risk levels; and (2) employ real-time atmospheric dispersion modeling to provide information about the dispersion and fate of a large release of stored natural gas to the environment. (See Recommendation 1.6b in the Summary Report.)

#### 1.4.12.7 Chemical Disclosure for Storage Wells and Associated Aboveground Operations

**Finding:** While chemicals used in oil and gas production during routine activities (e.g., drilling, routine maintenance, completions, well cleanouts) and well stimulation (e.g., hydraulic fracturing and acid stimulation) are reported for all other wells in the South Coast Air Quality Management District (SCAQMD rule 1148.2; Stringfellow et al., 2017), no such disclosures are made for UGS wells. And this is true for UGS facilities statewide. UGS operators disclose chemical information to the California Environmental Reporting System (CERS) for chemicals stored on-site; however, this information is not publicly available for all facilities, does not include what the chemicals are used for, or the mass or frequency of use on-site, and often lists product names without unique chemical identifiers (SoCalGas, 2015). As such, it is likely that on-site chemical use occurs, but the composition of those chemicals, the purpose, mass, and frequency of their use, and their associated human health risks during normal and off-normal events at UGS facilities, remain unknown.

**Conclusion:** To be able to conduct comprehensive hazard and risk assessment of UGS facilities, risk managers, regulators, and researchers need access to detailed information for all chemicals used in storage wells and in associated infrastructure and operations. (See Conclusion 1.22 in the Summary Report.)

**Recommendation:** Require operators to disclose information on all chemicals used during both normal operations and off-normal events. Each chemical used downhole and on UGS facilities should be publicly disclosed, along with the unique Chemical Abstract Service Registry Number (CASRN), the mass, the purpose and the location of use. Studies of the community and occupational health risks associated with this chemical use during normal and off-normal events should be undertaken. (See Recommendation 1.22 in the Summary Report.)

#### 1.4.12.8 Explosion and Flammability Considerations

**Finding:** During large LOC events, downwind methane concentrations can be higher than flammability or explosion limits. This poses a significant threat to people and property due to sustained fires and collapse of buildings and infrastructure from explosions. For risk assessment purposes, this study compared predicted concentrations from atmospheric dispersion models with methane concentration flammability limits. There are air dispersion conditions and failure scenarios that can present risks of severe harm to workers and nearby communities if a release of flammable gas is ignited due to exposure to high temperatures and associated radiation from a blast. Based on our modeling, the methane concentrations in the close vicinity of the leakage points may exceed the lower flammability limits for typical "off-normal" leakage fluxes. Flammable zones are typically not expected to extend beyond UGS facility boundaries, unless the leak rates are extremely large, i.e., larger than the fluxes experienced in the 2015 Aliso Canyon incident.

**Conclusion:** Each UGS facility needs an assessment of emitted natural gas combustion potential, and a mapping of the flame and the thermal dispersion associated with this combustion. (See Conclusion 1.10 in the Summary Report.)

**Recommendation:** Regulators and decision-makers should require the implementation and enforcement of best practices to reduce the likelihood of ignition of flammable gases in and near UGS facilities. Occupational and community hazard zones should be delineated for each UGS facility (possibly based on bounding simulations conducted with atmospheric dispersion models) to focus risk mitigation on elimination of leakage and ignition sources (loss prevention) and safer site-use planning. (See Recommendation 1.10 in the Summary Report.)