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

## An Independent Review of Scientific and Technical Information

Chapter 1, Section 1.5
Quantification of greenhouse gas emissions from underground gas storage in California

Marc L. Fischer[1] and Riley Duren[2]
*[1] Energy Technologies Area, Lawrence Berkeley National Laboratory, Berkeley, CA*
*[2] Jet Propulsion Laboratory, Pasadena, 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 Long-Term Viability of Underground Natural Gas Storage in California: An Independent Review of Scientific and Technical Information

**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

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

### 1.5.1 Abstract

At the time of the Aliso Canyon incident in 2015, there was no reported quantitative operational monitoring program for ambient methane or other trace gases at Aliso Canyon (or any other UGS facility in California). A variety of methane measurement methods was deployed in the months that followed to improve confidence in the SS-25 well leak rate as it evolved in response to efforts to control the well and reduce reservoir pressure by gas withdrawal. These methods include complementary airborne surveys using low-altitude *in situ* sampling and high-altitude remote sensing, as follows: (1) total methane emissions were determined using an aircraft equipped with a Picarro *in situ* methane analyzer flying cylindrical patterns around the facility; and (2) spatially resolved emissions from individual infrastructure components were estimated using an aircraft equipped with JPL's Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG). Both airborne methods have since been applied to other UGS facilities in California: Total facility methane emissions were measured at selected facilities roughly 40 times, from June 2014 through August 2017. Local methane emissions were measured roughly 80 times from January 2016 through August 2017 with the AVIRIS-NG method. UGS facilities are also subjected to daily surveys of all wellheads with hand-held gas analyzers, offering the ability to find small concentration anomalies at wellheads. Together, these measurements provide relevant information on current UGS facility emissions, discussed below in the context of greenhouse gas (GHG) emissions as well with regards to integrity implications.

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

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

### 1.5.2 Quantification of Greenhouse Gas Emissions

This section reviews current knowledge on methane ($CH_4$) emissions from underground gas storage (UGS) facilities in California. The context for concern about methane emissions in this section is climate change owing to the fact that methane is the second largest anthropogenic greenhouse gas (GHG) emitted after carbon dioxide (CARB, 2017b; 2017d). The following four sections present results and discussion of (1) historical natural gas usage in California, (2) direct measurements of GHG emissions from UGS operations, (3) identification of significant knowledge gaps on emissions, (4) the comparison of average UGS operational emissions with the 2015-2016 Aliso Canyon blowout, and (5) the comparison of average ongoing emissions plus the Aliso Canyon blowout emissions, with California's total GHG emissions and those emissions not included under current cap and trade legislation.

#### 1.5.2.1 Background: GHG Emissions from the Natural Gas Sector

Total monthly natural gas use and stored gas expressed in mass units are show in Figure 1.5-1. As shown, both seasonal variations and longer term trends indicate that while gas usage has been relatively constant, gas storage has increased roughly 10% between 2001 to 2017 (U.S. EIA, 2017).

From the GHG perspective, total natural-gas-related emissions can be summarized by noting that the vast majority of natural gas is combusted during power production, resulting in $CO_2$ emissions. However, methane is both the dominant component of natural gas (typically ~ 90-95% by volume) and a strong GHG itself, with a mass weighted global warming potential (GWP) of 33 and 86 times that of $CO_2$ for 100- and 20-year time scales, respectively, on a mass basis in the 5$^{th}$ Intergovernmental Panel on Climate Change (IPCC) assessment, if carbon feedbacks are included (Myhre et al., 2013). Hence, the importance of methane can be put in a climate perspective relative to total $CO_2$ emissions by equating the radiative forcing of the $CO_2$ emitted with that from emitted $CH_4$. Accounting for the difference in molecular weights, and assuming natural gas is essentially pure $CH_4$, fractional

emissions of $CH_4$ at 3.2% and 9%, for 20-yr and 100-yr time scales, respectively, double the total radiative forcing arising from $CO_2$ alone (Fischer et al., 2017). This suggests that $CH_4$ emissions from the natural gas supply chain from production to combustion should be carefully controlled below ~3% if short-term climate impacts are
to be minimized, a result similar to that identified in previous work (Alvarez et al., 2012).

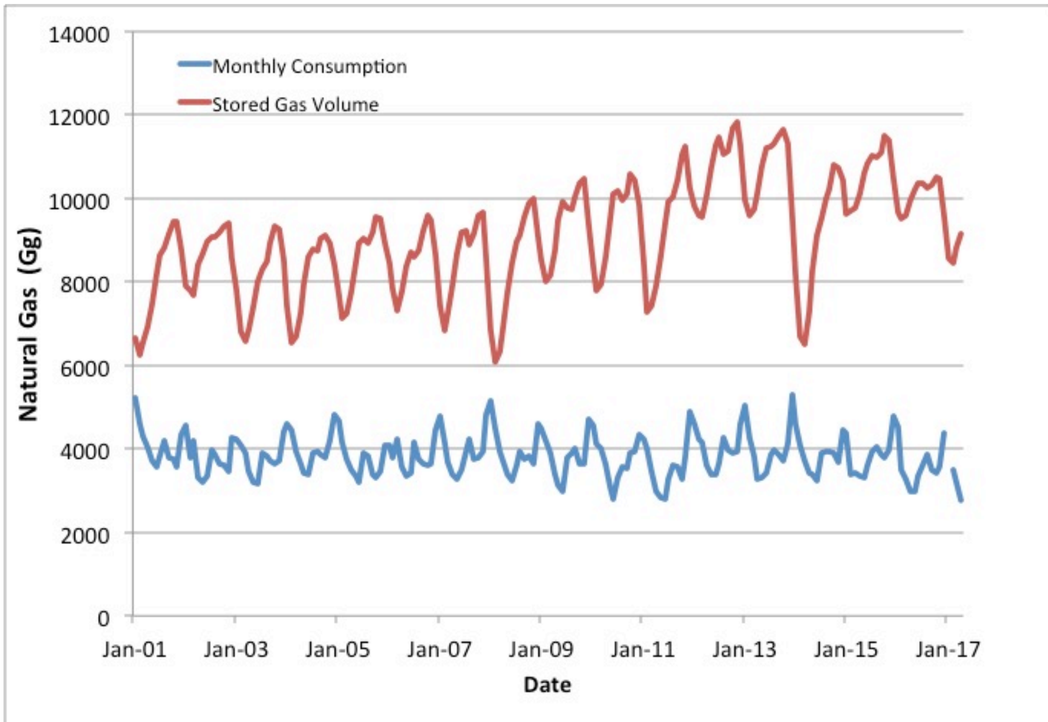


*Figure 1.5-1. Total monthly natural gas use and stored gas in California for 2001-2017. Seasonal cycles in both gas usage and stored gas are observed together with interannual variations. Note assuming natural gas is pure methane ($CH_4$), 1 Bcf = 19 Gg.*

### 1.5.2.2 Estimates of Average Ongoing Emissions for California Natural Gas Storage Facilities

#### 1.5.2.2.1 Methods

Here we describe two aircraft-based methods and results for estimating average methane emissions from California UGS facilities derived from both *in situ* and remotely sensed $CH_4$ mixing ratio measurements combined with wind measurements. Together, the two airborne systems conducted repeated surveys of the 12 active UGS facilities in the state between June 2014 and August 2017. Nine of the facilities were surveyed between 3 and 9 times, and the three top-emitting facilities—Honor Rancho, McDonald Island, and Aliso Canyon—were surveyed 25, 30, and 13 times, respectively[7].

***Airborne in situ methane imaging and mass-balance emission estimates***

To quantify facility emissions with *in situ* measurements of methane and wind velocities, cylindrical flight patterns ranging in elevation from ~150 ft (45 m) to 5,000 ft (1.5 km) above ground were employed to provide data to calculate facility emissions as approximated by the divergence of mass flux within the flight cylinder. An example flight pattern and the resulting methane anomalies are shown in Figure 1.5-2.

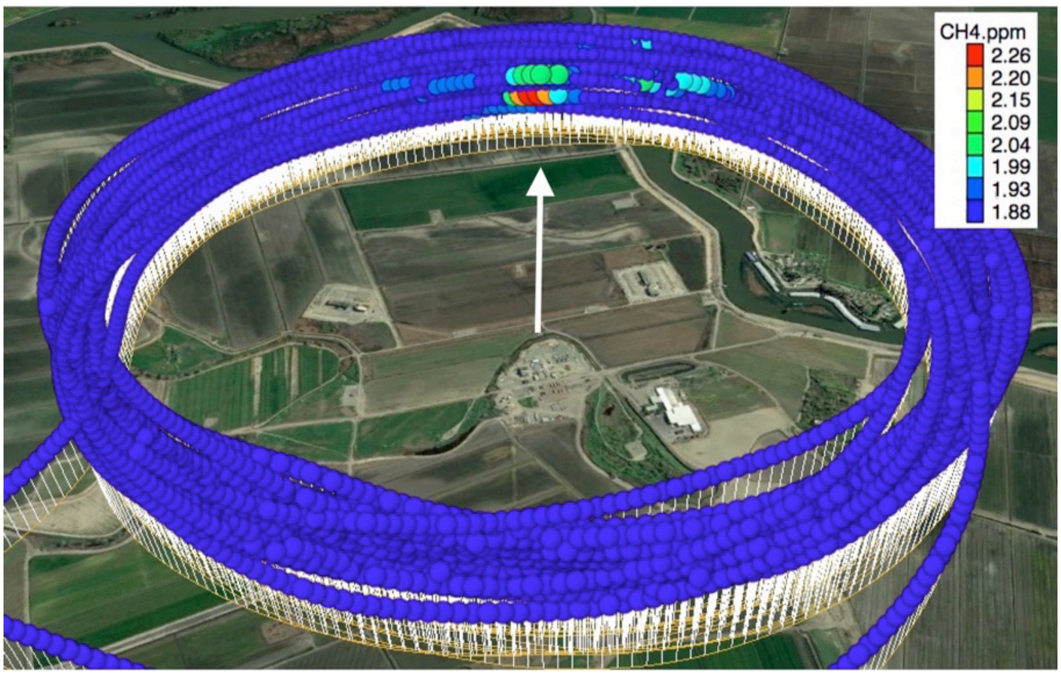


***Figure 1.5-2. Methane mixing ratios observed from an airplane flying multiple loops above the McDonald Island gas storage facility on May 13, 2015. The white arrow in the center of the figure shows the mean wind direction measured by the aircraft, with the on-site compressor facility located at the base of the arrow. Methane enhancements are clearly visible on the downwind side of the loop as compared with nearby background values (~1.9 ppb) obtained in the remainder of the loop. Note, the thin white lines indicate the height of each data point above the ground surface, in this flight ranging from 320 to 1,340 ft (98 to 406 m) above ground level.***

7. Note that the 2015 Aliso Canyon incident was not resolved until the bottom-kill on February 11, 2016, and the soil outgassing likely did not reach an e-folding level until early March 2016. The Aliso Canyon methane emission estimates (and number of surveys) cited in this section exclude data collected prior to March 2016.

Using Gauss' Theorem, Conley et al. (2017) estimate emissions from a site, E, as:

$$E = \int_{z_{min}}^{z_{max}} \oint c' \boldsymbol{u_h} \bullet \hat{\boldsymbol{n}} \, dl \, dz$$

(1)

where the outer integral represents the vertical extent of the cylindrical flight pattern, which extends from the lowest safe altitude, $z_{\text{min}}$, to the maximum flight altitude, $z_{\text{max}}$, where there is no indication of a plume crossing, and is the vector normal to the flight path. Here, the horizontal advective methane flux, $c'u_{\text{h}}$, is computed as the product of methane density variation, c', after subtracting the mean density for each loop, multiplied by $u_{\text{h}}$, the horizontal wind vector. In order to average over natural turbulent variability, the measurements are first averaged into altitude bins of ~100 m depth. The bottom altitude bin is extrapolated to the ground assuming constant concentration and winds, which was shown to be accurate to within 10-20% of estimated emissions during controlled release testing at a range of distances downwind of the source (Conley et al., 2017).

Applying the mass-balance method described above, Mehrotra et al., (2017) report methane emissions from a subset of ten gas storage facilities and nine compressor stations in California. The authors also provide an analysis of uncertainty that includes consideration of the number of loops flown, the stability of the wind velocities, and the fraction of the plume estimated below the lowest flight altitude from the controlled release experiments from Conley et al. (2017). This analysis suggests that uncertainties for the storage facility flights likely range from 10% to 30% of estimated emissions.

***Airborne infrared imaging spectroscopy and mass-balance emission estimates***

The next generation Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG) measures ground-reflected solar radiation from the visible to infrared spectral regions (350 to 2,500 nm). AVIRIS-NG provides the ability to image localized atmospheric plumes of $CH_4$, geolocate their emission sources, quantify their enhancements relative to background $CH_4$ mixing ratios, and estimate emission fluxes when combined with wind measurements (Thorpe et al., 2016). This push broom instrument has a 34° field of view and operates from aircraft, allowing for efficient mapping of large regions. Increasing flight altitude affects the ground resolution (i.e., the size of each image pixel increases) while the image swath increases. For surveys of California UGS facilities in 2016, AVIRIS-NG flew at 3 km (9,800 ft) above ground level, resulting in 3 m image pixels and a 1.8 km swath width.

AVIRIS-NG retrieval of column-averaged mixing ratios for $CH_4$ point source plumes is based on absorption spectroscopy (Figure 1.5-3) and has been used for a number of prior $CH_4$ studies, including the COMEX investigation observing Kern River, CA oil fields (Thompson et al., 2015), a campaign to Four Corners, CO and NM (Frankenberg et al., 2016), Aliso

Canyon, CA, (Thompson et al., 2016), and a study of California landfills (Krautwurst et al., 2017). Controlled-release experiments have demonstrated robust detection of $CH_4$ plumes for emission rates as low as 10 kg/hr for a range of altitudes and wind speeds (Thorpe et al., 2016).

For each plume, an Integrated Methane Enhancement (IME) in units of $kgCH_4$ is calculated by integrating over the physical area of the plume. This is done by first calculating the mass of $CH_4$ present in each image pixel as follows:

$$kg = \frac{ppm * m}{1} * \frac{1}{1E6\, ppm} * \frac{pixel\,res.\ (m) * pixel\,res.\ (m)}{1} \frac{pixel\,res.\ (m) * pixel\,res.\ (m)}{1} * \frac{1000\, L}{1\, m3} * \frac{1\, mole}{22.4\, L} * \frac{0.01604\, kg}{1\, mole}$$

(2)

The IME is then calculated by integrating over all pixels exceeding a specified threshold in a given plume.

The IME and plume length can then be combined with wind speed information to estimate point source emission rates as follows:

$$\textbf{Emission rate (kg/hr)} = \frac{IME\ (kg)}{1} * \frac{Wind\,speed\ (m)}{s} \frac{IME\ (kg)}{1} \frac{Wind\,speed\ (m)}{s} * \frac{1}{plume\,length\ (m)} * \frac{3600\, s}{1\, hr}$$

(3)

Wind-speed errors represent one of the largest sources of uncertainty in estimating emission rates with this method. For this reason, Large Eddy Simulation (LES) and Gaussian plume modeling is typically used to validate surface wind measurements for many of the UGS facilities studied here.

An example of AVIRIS-NG detection of $CH_4$ plumes at McDonald Island is provided in Figure 1.5-4.

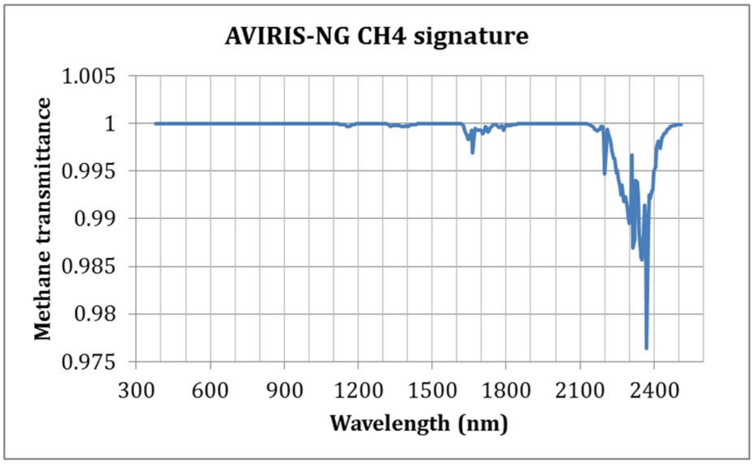


*Figure 1.5-3. $CH_4$ absorption signature (transmittance) plotted for the wavelength range measured by AVIRIS-NG. Strong absorptions are present between 2,200 and 2450 nm.*

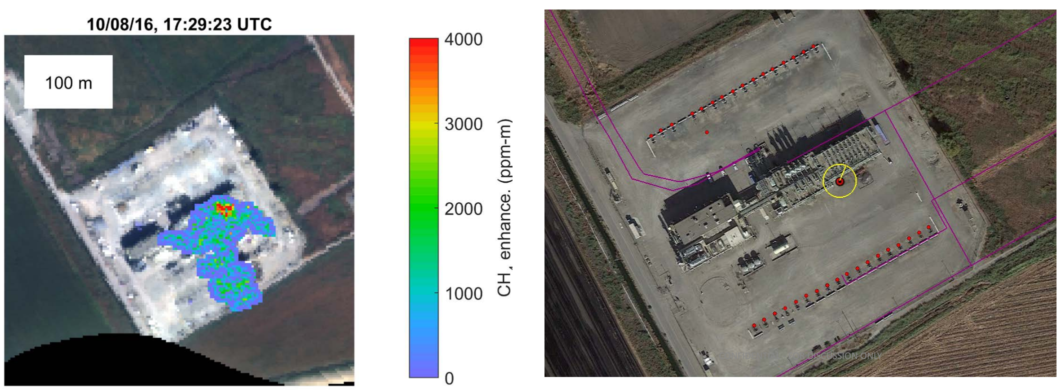


*Figure 1.5-4. Example of AVIRIS-NG detection of a $CH_4$ plume and quantification of column mixing ratios at the McDonald Island Turner Cut gas injection and recovery control station (left-hand panel). Approximate location of strongest leak location marked with yellow circle together with gas wells shown as two lines of red dots on visible image taken during the AVIRIS-NG observations (right-hand side panel).*

### 1.5.2.2.2 Industry Reporting to California Air Resources Board

Measurements of methane emissions from gas storage facilities can be compared with annual GHG reporting from industry to the California Air Resources Board (CARB reporting, 2017a; 2017b). In some cases, facilities are co-located with or near other methane-emitting activities (e.g., livestock, petroleum production) requiring care in interpreting the estimated UGS-related emissions.

#### 1.5.2.2.3 Results of Airborne Measurements of California Storage Facilities

Table 1.5-1 summarizes observations of methane emissions over the period June 2014 through August 2017 for the 12 active California natural gas storage facilities. With the exceptions of Aliso Canyon, McDonald Island, and Honor Rancho, all of the other sites were found to emit less than 100 kg/hr (<1 Gg $CH_4$/yr (<0.05 Bcf/yr)) on average and together constitute less than 25% of total storage-related GHG emissions. The spatial locations of methane emissions for the larger emitters were identified with the infrared imaging method, and emission modes are listed in Table 1.5-1. During the McDonald Island measurements, PG&E recognized the need for maintenance and began inspection and repairs of wells in the summer of 2016.

Taken together, the mean emissions of roughly 1,060 kg/hr (~9.3 Gg$CH_4$ ~0.5 Bcf annually) from the active UGS facilities in California are ~7.8% of total natural-gas-related methane emission estimated by the California Air Resources Board (CARB) and ~2.6 times the CARB estimate for gas storage-related methane emissions (CPUC, 2016).

Additionally, eight UGS facilities participated in California's GHG Reporting Program in 2015. Comparison of reported and measured emissions from those facilities indicates wide disagreement, with three significant underestimates and three overestimates. This, combined with the fact that four facilities did not report data, suggests room for improvement in UGS methane accounting.

#### 1.5.2.2.4 Uncertainties and Recommended Measurement Improvements

The focused application of the airborne methane measurement systems described here was unprecedented before the 2015 Aliso Canyon incident. Hence, there are no historical, independent measurement data available for assessing methane emissions from California UGS prior to 2015. Arguably, UGS methane emissions in California in the immediate wake of the Aliso Canyon incident are not entirely representative of long-term emissions from this sector. Additionally, the combination of the intermittent measurements reported here and the observed episodic signatures of UGS methane emissions prevent an unambiguous comparison with annual averages. To reduce the possibility of overestimating emissions, the instantaneous measurements described here were scaled by the observed frequency of methane sources at each facility, typically reducing the mean emission rate. However, intermittent sampling remains a source of uncertainty in estimates of annual mean emissions. We therefore recommend that a more frequent and robust methane measurement program be established for UGS facilities, perhaps combining persistent fence-line monitoring by UGS operators (capable of basic event detection through threshold detection methods), frequent semi-quantitative on-site inspections for leakage detections as required by the California Air Resources Board (CARB, oil and gas regulation, 2017c)[8],

8. The CARB regulations (CARB, 2017c) specify measurement of gas concentration rather than flow rate as a protocol for detection of leakage, rather than quantification of leakage of emissions.

and independent, periodic quantitative airborne measurements that would provide a more accurate estimate of annual average emissions and reduce the likelihood of leaks due to equipment malfunction or damage not being rapidly detected and repaired.

*Table 1.5-1. Summary of annual methane emissions for California gas storage facilities from a combination of airborne surveys using in-situ measurements and remote sensing from June 2014 through August 2017.*

| Facility | Observed emission modes | # obs | source detection frequency | Mean Measured CH4 Emissions, 2016 (kg/hr) | % of measured emissions | Reported CH4 emissions[1], 2015 (kg/hr) | % of California CH4 inventory for NG sector[2], 2015 | % of California inventory for UGS[3], 2015 |
|---|---|---|---|---|---|---|---|---|
| Aliso Canyon (after blow-out incident)[4] | residual soil outgassing from earlier well blowout; compressor loss | 13 | 0.73 | 166 | 16% | 152 | 1.2% | 40% |
| McDonald Island | maintenance and leading bypass valves | 30 | 0.86 | 150 | 14% | n/r | 1.1% | 36% |
| Wild Goose | episodic compressor loss | 4 | 0.47 | 35 | 3% | 88 | 0.3% | 8% |
| Honor Rancho | persistent leaking bypass valve; episodic compressor loss; blowdown event | 25 | 1.00 | 482 | 45% | 76 | 3.5% | 116% |
| Gill Ranch | episodic compressor loss | 9 | 0.77 | 88 | 8% | 242 | 0.6% | 21% |
| La Goleta | unknown | 5 | 0.17 | 36 | 3% | 86 | 0.3% | 9% |
| Los Medanos | unknown | 6 | 0.11 | 11 | 1% | 3 | 0.1% | 3% |
| Lodi | none | 5 | 0.24 | 0 | 0% | 1 | 0.0% | 0% |
| Kirby | unknown | 6 | 0.22 | 37 | 3% | 6 | 0.3% | 9% |
| Princeton | unknown | 5 | 0.43 | 43 | 4% | n/r | 0.3% | 10% |

1 Aliso Canyon observations included here cover the period after the SS-25 leak was plugged and soil out-gassing e-folding limit was reached (early March, 2016). Also note that with the exception of the first two weeks of August 2017, Aliso Canyon was in an idle state during this period.

2 CARB GHG reporting program 2015.

3 CPUC, 2016.

4 CPUC, 2016

| Facility | Observed emission modes | # obs | source detection frequency | Mean Measured CH4 Emissions, 2016 (kg/hr) | % of measured emissions | Reported CH4 emissions[1], 2015 (kg/hr) | % of California CH4 inventory for NG sector[2], 2015 | % of California inventory for UGS[3], 2015 |
|---|---|---|---|---|---|---|---|---|
| Playa Del Rey | none | 3 | 0.00 | 0 | 0% | n/r | 0.0% | 0% |
| Pleasant Creek | unknown | 6 | 0.33 | 16 | 2% | n/r | 0.1% | 4% |
| totals | | 117 | | 1064 | | 654 | 7.8% | 256% |

1 Aliso Canyon observations included here cover the period after the SS-25 leak was plugged and soil out-gassing e-folding limit was reached (early March, 2016). Also note that with the exception of the first two weeks of August 2017, Aliso Canyon was in an idle state during this period.

2 CARB GHG reporting program 2015.

3 CPUC, 2016.

4 CPUC, 2016

#### 1.5.2.3 Summary of Methane Emissions from the 2015 Aliso Canyon Incident as an Example of a Large Leakage Event

The large 2015 Aliso Canyon incident methane emissions during the 2015-2016 SS-25 well blowout (~100 Gg $CH_4$) reported by Conley et al. (2016) are roughly equivalent to ~10 years of the average emissions measured for California's remaining storage facilities. It is also worth noting that measurements at Aliso Canyon following the SS-25 well repair were found to be similar to that from the two other high-emitting UGS facilities (Honor Rancho and McDonald Island), suggesting that some aboveground leaks remain present at Aliso Canyon despite the reservoir being partially depressurized. This suggests the need for careful monitoring following resumption of operations at Aliso Canyon, and especially if Aliso Canyon is operated again at full pressure.

#### 1.5.2.4 Comparison of Average Ongoing Emissions with California's Natural Gas Methane, Total Methane, and Total GHG Emissions

As noted above, the observations to date suggest UGS-related methane emissions are approximately 8% of the current total natural gas-related methane emissions, which are 2.9% of total gas use (CPUC, 2016). Comparing this with total California methane, the storage emission estimate of ~10 Gg $CH_4$/yr is still only ~0.5% total California $CH_4$ emissions (~ 2Tg $CH_4$ /yr), and ~0.05% of total GHG emissions (w/ 100 yr GWP = 25 $gCO_2eq/gCH_4$) estimated by CARB (GHG Inventory, 2017a). We conclude that UGS-related methane emissions appear to be a small part of both California's methane and total GHG emission inventories. If both methane and total GHG emissions are reduced by 40% to 80% as required by 2030 and 2050, respectively, then storage-related methane emissions will become proportionately more important unless controlled. We also note that the 2015 Aliso Canyon leak would correspond to roughly 1/3 of total petroleum and natural gas-related methane, 5% of total methane, and ~0.5% of total California GHG emissions. Hence, we recommend that care should be taken to reduce the frequency and magnitude of episodic emissions observed at Honor Rancho, McDonald Island, and Aliso Canyon, whatever their cause may be, through improved leak detection and equipment repair/replacement programs (including but not limited to those required by the CARB regulations (CARB, 2017c)), as well as additional controls aimed at preventing another major leak of the magnitude that occurred at Aliso Canyon.

#### 1.5.2.5 Recommendations from GHG Emission Measurement and Analysis

**Finding:** Observed methane emissions vary by factors >10× across sites, with three sites (Honor Rancho, McDonald Island, and Aliso Canyon) dominating emissions. Within sites, variations of ~3-5× occur over time. Directly observed emissions are 2-5× higher than the average of emissions reported to CARB. Observations suggest total California UGS emissions are ~9.3 $GgCH_4$/yr (≈ 1% California total methane emissions) which is < 0.1% total California GHG emissions, with compressors and aboveground infrastructure apparently contributing the majority of the emissions.

**Conclusion:** Though there are discrepancies between directly observed greenhouse gas emissions and those reported to CARB, average methane emissions from UGS facilities are not currently a major concern from a climate perspective compared to other methane and GHG sources, such as dairies and municipal solid waste landfills. However, average methane emissions from UGS facilities are roughly equivalent to an Aliso Canyon incident every 10 years, and hence worthy of mitigation. (See Conclusion 1.11 in the Summary Report.)

**Recommendation:** An improved methane monitoring program is needed for better quantitative emissions characterization that allows for direct comparison with reported emissions. The monitoring program could benefit from a combination of persistent on-site measurements and higher accuracy, periodic independent surveys using airborne- and surface-based measurement systems. (See Recommendation 1.11a in the Summary Report.)

**Recommendation:** Average underground gas storage methane emissions should be monitored primarily for safety and reliability (see Recommendation 1.12 below), since the net GHG effect of UGS facilities is relatively small. However, most of the current GHG leakage detection measurements (e.g., of methane concentration) conducted at UGS facilities point to easily mitigatable sources for above-ground leaks, such as compressors or bypass valves. Thus, with regard to reducing GHG emissions, facilities should maintain and upgrade equipment (particularly compressors and bypass valves) over time, repair leaking equipment (e.g., following the new CARB regulations for natural gas facilities) (CARB, 2017c), and reduce leakage and releases (blowdowns) during maintenance operations. (See Recommendation 1.11b in the Summary Report)

### 1.5.3 Atmospheric Monitoring for Integrity Assessment

This section evaluates the potential contribution of atmospheric monitoring to end-to-end assessments of the physical integrity of UGS facilities and associated risk management.

This evaluation builds on previous discussions regarding the impact of loss-of-containment incidents on air toxics (Section 1.4) and greenhouse gases (Section 1.5.2).

### 1.5.3.1 Background

In Section 1.6.5.3 we review regulatory changes being developed in California that focus on assuring the ongoing physical integrity of UGS operations, including new requirements on testing, monitoring, and inspections. That review highlights three potential issues. First, mechanical integrity testing is mandated for storage wells annually (temperature and noise logs) and bi-annually (pressure testing), raising a potential latency issue. For example, integrity problems could arise between tests. Second, adding real-time pressure monitoring for all well annuli at UGS facilities is acknowledged to be a major undertaking and involves a significant risk trade-off for aging wells, and some wells may remain unmonitored. Third, all of the above is focused on wells but not components of UGS surface infrastructure that may also be significant hazards. Additionally, the complex configuration and situation of some oil and gas fields can introduce ambiguities that cloud UGS risk assessment efforts (summarized below). Despite significant resources applied to monitoring Aliso Canyon during and following the 2015 Aliso Canyon incident, there remain unresolved questions about potential residual gas leakage there (also summarized below). These points raise the question of whether additional monitoring may be required to support robust risk management.

Natural gas at UGS facilities provides an atmospheric tracer that can enable efforts to monitor integrity of surface and subsurface infrastructure, potentially offering early warning to minimize the impact of leaks and avoid loss-of-containment and other hazardous situations for some failure modes[9]. Methane in particular is both the primary constituent of natural gas (typically about 96%) and can be measured by a variety of methods to identify, diagnose, and guide responses to integrity issues. Methane also serves as a proxy for other compounds that may be co-emitted, including air toxics such as benzene. Leak detection based on atmospheric measurements can be challenging at UGS facilities given the large quantity of components (wells, pipes, and other surface infrastructure) that are often distributed over large areas and in some cases, complex terrain. Isolating leaks to specific components and process attribution can also be complicated by other, nonstorage infrastructure within or adjacent to a UGS facility. In the following section, we present a case study of experiences with methane monitoring at Aliso Canyon and Honor Rancho, to illustrate the capabilities and limitations of different methodologies, including their potential use as complementary “tiers” in an observing system.

9. The possibility the 2015 Aliso Canyon incident might have been preceded by a smaller leak that could have been detected before the main blowout remains an open question and may not be resolvable with data from measurement systems that were in operation at that time.

### 1.5.3.2 Case Study: Monitoring System Capabilities and Limitations

Aliso Canyon has a combination of gas storage and oil production wells and surface infrastructure involving 12 operators, as well as a number of abandoned wells that are not readily accessible. These facilities and their immediate environs span nearly 20 $km^2$ of rugged mountainous terrain. Figure 1.5-5 illustrates this complexity as well as the locations of persistent “fence-line” monitoring systems established by SoCalGas and SCAQMD following the 2015 Aliso Canyon incident. The latter systems in principle can provide low-latency detection and quantification of major gas leaks; however, their utility is limited to favorable wind conditions, specifically, these systems are only sensitive to Aliso Canyon emissions when winds are from the north. Also, accurate interpretation requires sophisticated tracer-transport models that can address the complex interaction of winds and terrain in the area. We are unaware of any such modeling capability currently established for routine, operational use at Aliso Canyon or other California UGS facilities. Currently, each of the wells highlighted in blue in Figure 1.5-5 (operated by SoCal Gas) are subjected to daily surveys with hand-held gas analyzers, offering the ability to find small leaks at wellheads but offering little information about the rest of the facility. The status of monitoring protocols for the nonstorage wells and surface infrastructure in Aliso Canyon is uncertain.

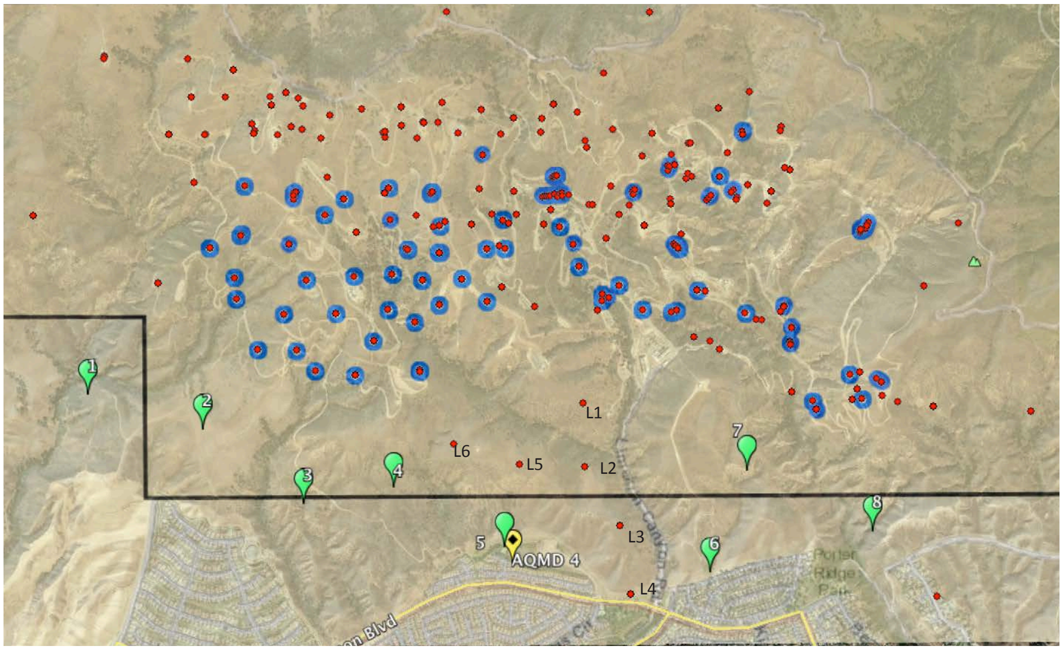


*Figure 1.5-5. Aliso Canyon shaded relief where the red dots indicate 251 known wells within the Aliso Canyon field plus several nearby wells [source: DOGGR well finder], and the blue circles indicate the 115 UGS wells operated by SoCalGas that were known to be connected to the gas reservoir at the time of the SS-25 incident (only a subset are currently connected). The remaining wells are operated by 11 other companies or reported as abandoned. Some of the older wells are not readily accessible from roads (e.g., Limekiln wells L1-3, L5-6). All of these wells and associated surface infrastructure have the potential to release methane and other compounds, which presents a challenge for some monitoring systems to identify and discriminate emission sources. The green pins indicate the locations of eight new "fenceline" infrared sensors recently installed by SoCalGas. The yellow pin indicates a persistent methane monitoring site operated by SCAQMD. These systems provide persistent and near-real-time monitoring of local methane enhancements, but are only sensitive to Aliso Canyon emissions under northerly wind conditions and require sophisticated modeling to interpret.*

At the time of the 2015 Aliso Canyon incident in Fall 2015, there was no reported quantitative monitoring program for ambient methane or other trace gases at Aliso Canyon (or any other UGS facility in California). At that time, leak detection was limited to infrequent Mechanical Integrity Testing of wells and daily on-road surveys by facility operators "sniffing" for odorized gas. The SS-25 well blowout was initially reported on October 23, 2015, based on such a survey. Several weeks passed before the first quantitative leak-rate estimates could be made. In the months that followed, a variety of methane measurement methods were deployed to improve confidence in the leak rate, as it evolved in response to efforts to regain control of the well and withdraw reservoir gas to lower reservoir pressure. Two of those methods included airborne surveys using low altitude *in situ* sampling and high altitude remote sensing, described in Section 1.5 and Conley et al. (2016) and Thompson et al. (2016). Figure 1.5-6 illustrates the unique capability of both methods to rapidly[10] assess gas emissions from complex UGS facilities: Scientific Aviation's Mooney aircraft equipped with a Picarro *in situ* methane analyzer and remote sensing by JPL's Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) on the NASA ER-2 aircraft.

10. "Rapidly" requires a caveat. Neither of the airborne systems described here are currently used for routine surveys and their ability to deploy in a rapid-response mode is limited by other research commitments. However once the aircraft is deployed, assessments of a given UGS facility in California can usually be conducted within a few hours.

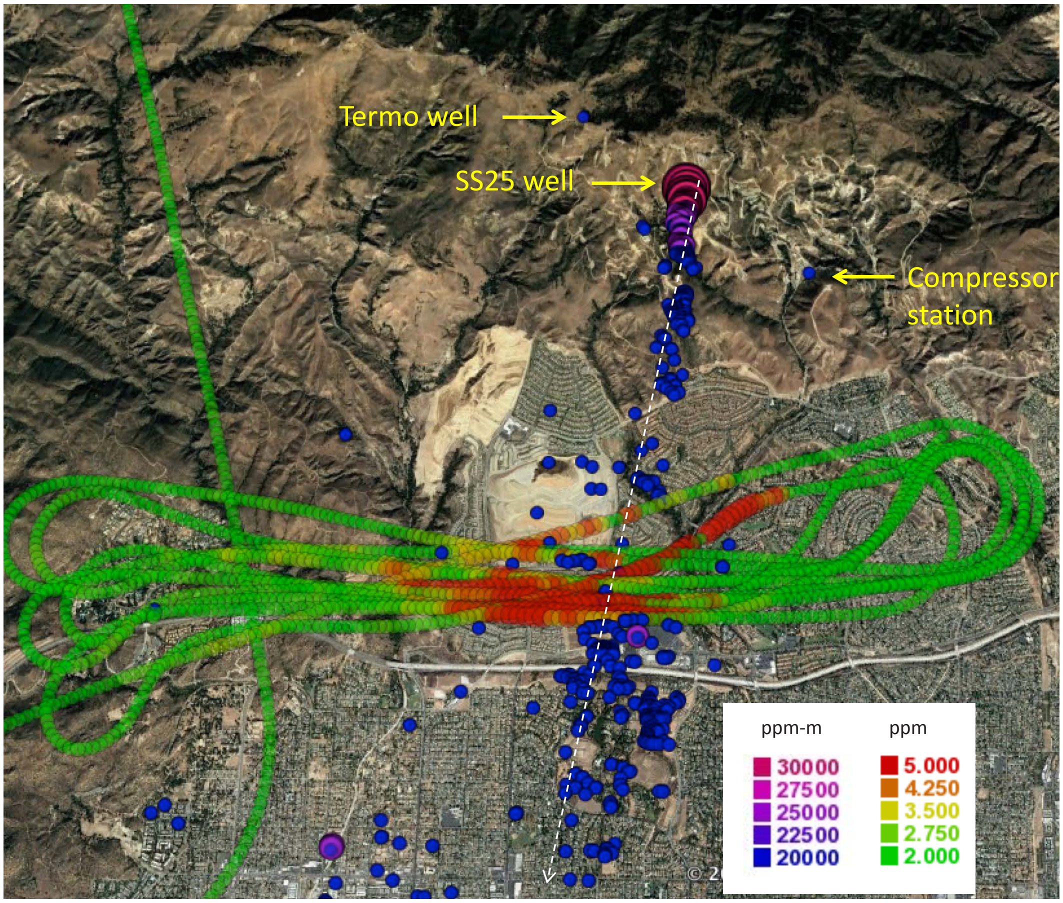


*Figure 1.5-6. Application of two airborne measurement systems to assess methane emissions from the 2015 Aliso Canyon incident over a two-hour period on January 12, 2016: Scientific Aviation's Mooney aircraft equipped with a Picarro in situ methane analyzer and JPL's AVIRIS infrared imaging spectrometer on the NASA ER-2 aircraft. The white dashed arrow indicates the NNE wind direction. The data points indicate enhancements in methane mixing ratios in the gas plume beyond ambient background levels. Scientific Aviation flew a series of "curtain" profiles approximately 5 km downwind of the SS-25 leak source to sample methane from near-surface to the top of the planetary boundary layer (red-yellow-green scale). That enabled an accurate net emission rate estimate for the facility (~20,000 kg$CH_4$/hr). AVIRIS flew nine times over the facility during this time at an altitude of 8 km each with a swath width of 5 km and 6 m pixels. AVIRIS column-averaged methane values are shown with units of ppm-m (Blue-Magenta scale with higher values indicated by larger circles; 20,000 ppm-m column averaged enhancement is equivalent to a 2.5 ppm surface enhancement). AVIRIS derived a direct estimate of the leak rate (within 10% of the Scientific Aviation number) and also identified multiple sources within the facility including the SS-25 main leak, venting from the adjacent hillsides, the compressor station, and associated gas venting from an adjacent (Termo) oil well, subsequently verified by SCAQMD surface measurement.*

The airborne *in situ* method offers a fast, highly accurate estimate of net facility methane emissions without the need for sophisticated tracer-transport models; however, it cannot resolve emissions to individual infrastructure components. Additionally, in this case the method was limited to northerly wind conditions because the steep terrain required downwind curtain flights over Porter Ranch rather than the cylindrical flight pattern normally used for other facilities (Figure 1.5-2). AVIRIS was able to pinpoint individual sources within Aliso Canyon, including two previously unreported secondary vents on the hillsides surrounding the SS-25 well, and also associated gas being vented from an oil well to the northwest, attributed to an inability to deliver gas to the shut-in Aliso Canyon storage field (Duren et al., 2017). Emission rates were directly estimated for the SS-25 leak source by scaling a Large Eddy Simulation with the AVIRIS methane retrievals, showing agreement to within 10% of the Scientific Aviation net facility estimate of 20,000 $kgCH_4$/hr (Duren et al., 2017).

Following the February 11, 2016, bottom-kill of the SS-25 leak, the Aliso Canyon facility remained in a shut-in state for nearly 18 months. During that time, periodic flights by Scientific Aviation tracked the evolution of the facility's methane emissions, which involved both the slow decay due to soil outgassing from the hillsides adjacent to SS-25 and unexpected episodic spikes[11]. Additionally, periodic on-road methane surveys through the facility by AQMD indicated several persistent methane plumes (Figure 1.5-7). While the observed worst-case methane emissions and plume enhancements during this period were orders of magnitude smaller than during the SS-25 blowout, they underscore the challenge in fully understanding leaks in complex locations like Aliso Canyon. While the sources of two of the observed methane plumes in Aliso Canyon are likely understood, the third remains a mystery. This is most likely owing to the incomplete spatial sampling of the wellhead surveys, on-road surveys, and periodic downwind airborne *in situ* measurement flights.

Figure 1.5-8 provides another example. Here, airborne remote sensing, using the next-generation AVIRIS (AVIRIS-NG) on a King Air aircraft at 3 km altitude, detected a persistent methane gas plume and identified the specific source: in this case, an emergency shutdown vent at Honor Rancho. On-road methane surveys confirmed the presence of the plume. The operator subsequently confirmed that the root-cause was a leaking bypass valve that was scheduled for repair.

Other measurement methods not described here include persistent regional scale tracer-transport inverse modeling using a network of *in situ* monitoring stations. Such systems have the potential to identify the sudden onset of a large LOC event at a UGS facility; however, they are typically unable to resolve methane fluxes below 1 km resolution, and the numerically intensive computer simulations often require weeks or months to run and

11. https://www.arb.ca.gov/research/methane/NG_Chart_All.png

verify. Another method involves tracer-release experiments (e.g., where a control gas such as $N_2O$ is intentionally released at a known emission rate near the leak source and then detected along with the methane plume from the leak by downwind measurement sites, to enable accurate emission estimates of the leak). The tracer-release method is useful in cases where a leak has already been detected and located by other means. Finally, there are a variety of hand-held infrared cameras and methane sniffers that can provide rapid identification of gas leaks at very close range (typically a few meters from a source); however, these typically only provide qualitative information. The latter methods are typically employed with the aforementioned periodic manual surveys of wellheads.

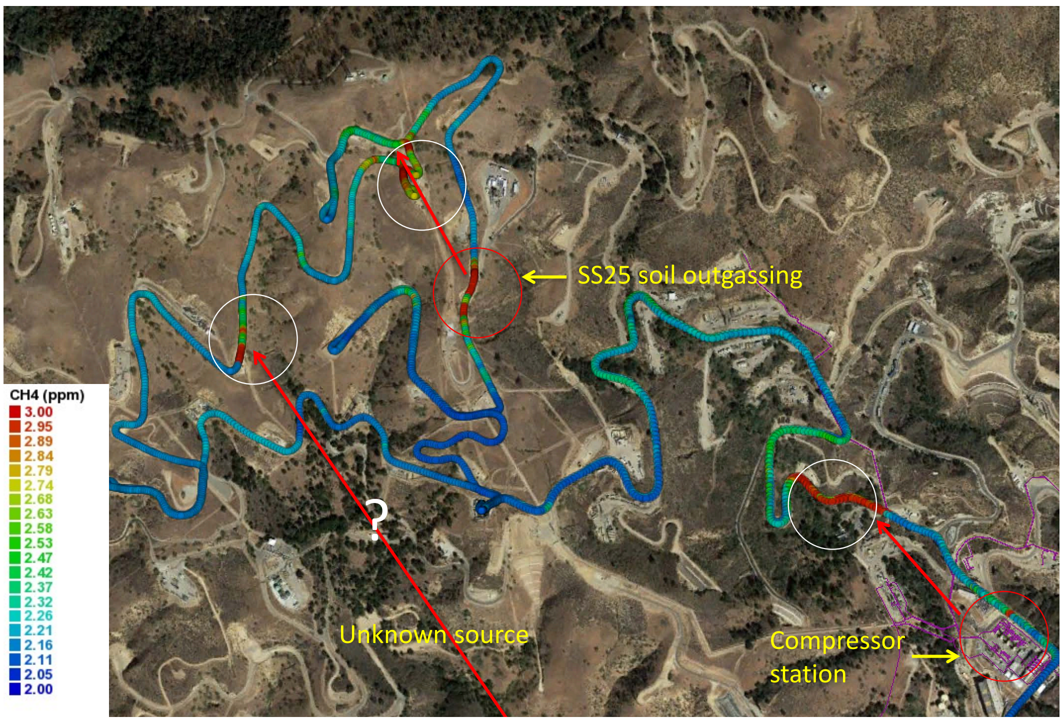


*Figure 1.5-7. Example of an on-road methane survey using an in situ methane analyzer. The color scale indicates near-surface methane mixing ratios. Data were collected on July 8, 2016, roughly five months after the SS-25 leak was plugged. The facility was in a shut-in state. The red arrows indicate prevailing wind direction. This reveals several methane hotspots that exceed normal background levels, consistent with gas plumes crossing the roads. There were two likely methane sources: residual soil outgassing from the SS-25 incident and the facility's compressor station. The former is expected given earlier measurements of soil methane levels there. The latter suggests either venting associated with maintenance or a leaking component at the compressor station. The source of the third methane hotspot observed to the west is unclear. There are multiple UGS and producing and abandoned oil wells along the red arrow that could be responsible (data courtesy SCAQMD).*

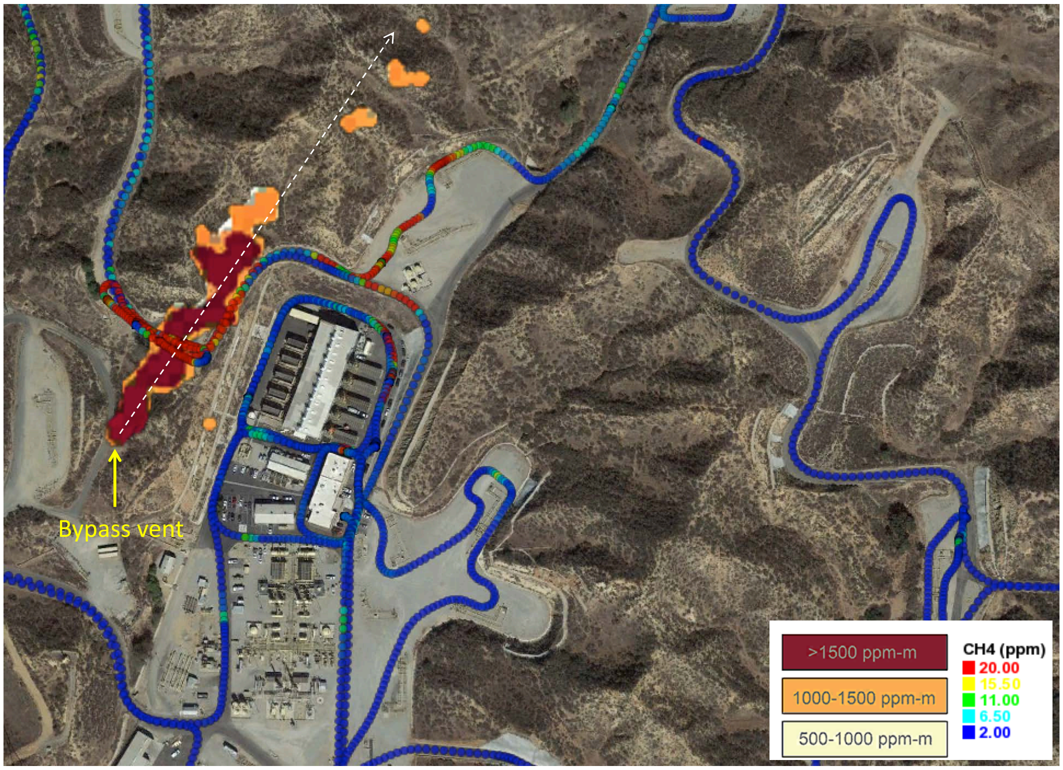


*Figure 1.5-8. Example of a persistent gas leak at Honor Rancho discovered by AVIRIS-NG imaging spectrometer during a September 2016 over-flight (tan-brown color scale). The white arrow indicates the direction of the wind and methane plume. An emergency shutdown vent was identified as the source—attributed by the operator to a leaking bypass valve. The plume was detected on another day with the same wind conditions by an SCAQMD mobile survey (blue-red color scale); however, the exact source was not identified.*

### 1.5.3.3 Recommendation for Atmospheric Monitoring for Integrity Assessment

**Finding:** Natural gas at UGS facilities provides an atmospheric tracer that can enable efforts to monitor integrity of surface and subsurface infrastructure — potentially offering early warning to minimize the impact of leaks and avoid loss-of-containment and other hazardous situations for some failure modes. Methane in particular is both the primary constituent of natural gas and can be measured by a variety of methods to identify, diagnose, and guide responses to integrity issues. Methane also serves as a proxy for other compounds that may be co-emitted, including air toxics such as benzene. There are many methane measurement methods that can be applied to UGS leak detection; however, they have differing capabilities and limitations. Several of these methods have been successfully demonstrated in operational field conditions at Aliso Canyon, Honor Rancho, and other facilities, including several examples that illustrate the potential for coordinated application of multiple synergistic observing system "tiers." As of October 1st, 2017, regulations of the California Air Resources Board (CARB) went into effect. These regulations require UGS operators to develop monitoring plans that need to be approved by CARB and also specify detailed repair requirements in case leaks have been detected. At a minimum, operators are required to continuously monitor meteorological conditions, including temperature, pressure, humidity, and wind speed and direction, monitor predominantly upwind (background) and downwind methane concentrations in air, and carry out daily gas hydrocarbon concentration measurements at each injection/withdrawal wellhead and attached pipelines (CARB, 2017c). If anomalous concentrations of hydrocarbons persist above certain thresholds for certain periods of time, notification must be made to CARB, DOGGR, and the local air district. It is important to note that the purpose of these monitoring requirements is to detect that leakage is occurring, not to quantify emissions (i.e., leakage rates). Once leaks are detected and located, they can be addressed. However, wellhead focused leak monitoring may not detect leakage coming out of the ground away froom the wellhead which may be indicative of a nascent or well-developed subsurface blowout.

**Conclusion:** Coordinated application of multiple methane emission measurement methods can address gaps in spatial coverage, sample frequency, latency, precision/uncertainty and ability to isolate leaks to individual UGS facility components in complex environments and in the presence of confounding sources. A well-designed methane emission and leakage-detection monitoring strategy can complement other integrity assessment methods—such as the mechanical integrity testing, inspections, and pressure monitoring now required by the new DOGGR regulation for storage wells (see Section 1.6) —by providing improved situational awareness of overall facility integrity. In addition to supporting proactive integrity assessments, methane emissions monitoring systems also help improve accounting of greenhouse gas emissions and timely evaluation of co-emitted toxic compounds in response to potential future incidents. (See Conclusion 1.12 in the Summary Report.)

**Recommendation:** An optimized methane emission monitoring system strategy should be devised to provide low-latency, spatially complete, and high-resolution information about methane emissions from UGS facilities and specific components of the UGS system. A program based on this strategy could benefit from a combination of persistent on-site measurements and higher accuracy, periodic independent surveys using airborne- and surface-based measurement systems. These emissions measurements would complement the concentration-based leakage-detection measurements required by CARB (CARB, 2017c). The scientific community should be engaged in helping UGS operators and regulators design such a strategy, and should be serving in an ongoing advisory capacity to ensure that best practices and new developments in monitoring technology can be implemented in the future. (See Recommendation 1.12 in the Summary Report.)

### 1.5.3.4 Recommendation for Assessment, Management, and Mitigation Actions In Case of Local Methane Leakage Observations

**Finding:** At Aliso Canyon, McDonald Island, and Honor Rancho, where total methane emissions have been measured to be above 250 kg/hr in some of the recent airborne measurement campaigns, the sources of these emissions were localized in most cases as originating from above-ground infrastructure such as compressor stations or leaking valves. This is a maintenance or repair issue but not an early warning indicator for large loss-of-containment events. (The 250 kg/hr emissions rate is a limit defined by DOGGR in its order allowing resumption of injection at the Aliso Canyon underground gas storage facility. If this limit is exceeded, the operator must continue weekly airborne emissions measurements until the leaks have been fixed, no new leaks have been found, and emissions are below 250 kg/hr.) But local methane hot spots could also be associated with wellheads or emissions from the ground near gas storage wells, in which case timely assessment and mitigation response can be essential in preventing the evolution of a small leak into a major blowout.

**Conclusion:** Periodic airborne and surface-based methane monitoring strategies provide the ability for detection of localized leaks within facilities, which in turn allow for early identification, diagnosis, and mitigation response to prevent smaller leaks from becoming a major loss-of-containment incident. (See Conclusion 1.13 in the Summary Report.)

**Recommendation:** We recommend that DOGGR or CARB develop a protocol for all facilities defining the necessary assessment, management, and mitigation actions for the cases in which periodic airborne and surface-based methane identify potential emission hotspots of concern. (See Recommendation 1.13 in the Summary Report.)

For example, if a leakage hot spot is located, the operator would be required within one week to provide to DOGGR or CARB a detailed assessment of the hot spots, with information on how large the leak is (flux or flow rate), what is leaking, where is it leaking from, etc. If the leak cannot be immediately fixed, the operator should be required to develop and present a plan within the following week of how to fix the leak. The follow-up would consist of agency staff visiting the site to observe the mitigation of the leak. We note that irrespective of leakage emission rate, the CARB regulations in place since October 1, 2017 outline a detailed time frame for fixing leaks detected on the basis of anomalous concentration, depending on concentration and duration thresholds.

### 1.5.3.5 Recommendation for Integration, Access, and Sharing of Monitoring/Testing Data

**Finding:** Since the 2015 Aliso Canyon incident, increasing institutional monitoring requirements, new regulatory monitoring/testing standards, and various measurement and data collection campaigns conducted in academic settings have provided a large amount of information on UGS facilities, in particular with regards to integrity issues and potential loss-of-containment. For example, airborne based measurements of local methane emissions can potentially offer early warning of well integrity concerns, which can then be followed up by detailed well integrity testing and mitigation. Meanwhile, persistent hotspots of gas odorants from environmental monitoring in communities might point to unknown gas leaks in nearby facilities. However, the value of these complementary data types is limited if they are not integrated and maintained in a central database and if access is only given after long delays.

**Conclusion:** We recognize the value of coordinated and integrated assessment of complementary types of data on methane emissions and other environmental monitoring to be able to act early and avoid potentially LOC incidents. However, we are concerned that there is no single data clearing house where (1) the multiple sources of data from required or voluntary reporting/monitoring are collected and maintained; and (2) these data can be easily accessed and evaluated by oversight bodies and the public. (See Conclusion 1.24 in the Summary Report.)

**Recommendation:** We recommend that these data, particularly on methane concentrations within and near the fence line of the facility and in key locations in adjacent communities, should be posted in real time, informing residents living nearby of potential airborne hazards associated with any LOC. Data that cannot be posted in real time, because more extensive quality assurance and control is required, should be released at frequent intervals without significant delay from the time of collection in a standardized digital format. (See Recommendation 1.24a in the Summary Report.)

**Recommendation:**We further recommend identifying a lead agency in California (e.g., DOGGR, CARB, CPUC) that develops and implements a strategy for the integration, access, quality control, and sharing of all data related to UGS facilities integrity and risk. (See Recommendation 1.24b in the Summary Report.)