Ensuring Safe and Reliable Underground Natural Gas Storage

Final Report of the Interagency Task Force on Natural Gas Storage Safety

October 2016

About the Cover:

Relief well at the SoCalGas Aliso Canyon Gas Storage Facility well Standard Sesnon 25 (SS-25) (February 2016)

Message from the Secretary of Energy

Earlier this year, Congress and the Administration worked together to establish a Federal Task Force to analyze California's Aliso Canyon natural gas leak and make recommendations on how to reduce the likelihood of future leaks from underground natural gas storage facilities across the country. While these incidents are rare, the leak at Aliso Canyon is a reminder that failures at aging natural gas storage facilities can have damaging effects on communities, the environment, and the reliability of our energy supplies.

At the same time, the Nation's 400+ natural gas storage facilities provide essential services. They deliver gas at times of high demand to heat our homes and businesses, to power American industry, and increasingly, to provide fuel for electricity generation.

The Task Force identified three principal research areas associated with natural gas storage facilities: minimizing the risk of well failures; reducing health and environmental impacts of major leak incidents; and understanding energy reliability implications. Across these areas, the Task Force has made more than 40 recommendations that identify the need for additional actions at our Nation's natural gas storage facilities to ensure their long-term safety and reliable operation.

Key recommendations of the Task Force include:

- Gas storage operators should begin a rigorous evaluation program to baseline the status of their wells, establish risk management planning and, in most cases, phase-out old wells with single-point-of-failure designs.
- Advance preparation for possible natural gas leaks and coordinated emergency response in the case of a leak can help manage and mitigate potential health and environmental impacts of leaks when they do occur.
- Power system planners and operators need to better understand the risks that potential gas storage disruptions create for the electric system.

No community should have to go through something like the Aliso Canyon leak again. The recommendations in this report outline the steps we can take to prevent such an incident in the future. Now, it is up to industry to implement these recommendations in a timely fashion, while State and Federal officials develop regulations that enhance the safety of underground storage facilities in the United States.

Ernest J. Moniz

Secretary of Energy

Message from Task Force Co-Chairs

In April, as a part of the Administration's ongoing commitment to support State and industry efforts to ensure the safe storage of natural gas, and with the support of Congress, the Department of Energy (DOE) and the Department of Transportation's (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA) announced the formation of an Interagency Task Force on Underground Natural Gas Storage Safety.

Two months earlier, along with the Secretary of Energy, we visited the Aliso Canyon site to review efforts to control the leak and to learn from experts and local officials about the impacts of the leak on the environment and community.

The Task Force includes premier scientists, engineers and technical experts from across the DOE complex, including five National Labs, DOT, the Environmental Protection Agency (EPA), the Department of Health and Human Services (HHS), the Department of Commerce (DOC), the Department of the Interior (DOI), the Federal Energy Regulatory Commission (FERC), and the Executive Office of the President. As a Task Force, we have held three national-level workshops and met with community members, industry representatives, environmental organizations, and State officials.

The Task Force established three working groups for research and analysis: (1) the physical integrity of wells at gas storage facilities, (2) the reliability of natural gas supplies from gas storage facilities, and (3) the public health and environmental impacts associated with the Aliso Canyon leak.

The "Well Integrity" working group was led by DOE's Office of Fossil Energy, with important contributions from four DOE National Labs—the National Energy Technology Laboratory, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, Sandia National Laboratories, and PHMSA.

The "Reliability" working group was led by the Department of Energy's Office of Electricity Delivery and Energy Reliability with important contributions by DOE's Argonne National Laboratory, DOE's Energy Information Administration, and FERC.

The "Health and Environment" working group was led by the EPA and HHS's Centers for Disease Control and Prevention. DOC's National Oceanographic and Atmospheric Administration and PHMSA also contributed.

This final report is a synthesis of the three working group reports, which will be made available as separate technical appendices to the report.

PHMSA plans to initiate regulatory actions to help ensure the safety of natural gas storage facilities across the country, beginning with an Interim Final Rule due out by the end of this year. Moving forward, PHMSA will consider the recommendations of this Task Force in developing future regulation and safety standards as required by the PIPES Act of 2016 (P.L. 114-183).

Natural gas provides heat to millions of American homes and is expected to provide a third of our Nation's total electric power generation this year. As co-chairs of this Task Force, we have made it a priority to support States, industry and the American public to ensure that our infrastructure is safe. The Task Force's efforts are an important step forward as we continue to work toward protecting public health and safety and making progress in reducing greenhouse gas emissions. We offer our recognition and gratitude to all those whose hard work and thoughtful analysis are assembled here.

Franklin Orr

Under Secretary for Science and Energy

Marie Therese Dominguez

Administrator, Pipeline and Hazardous Materials Safety Administration

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Errata: This document was originally published on October 18, 2016. An update to the document was published on October 24, 2016, incorporating changes to recommendations that were accidentally omitted and correcting minor typographical errors.

Executive Summary

On October 23, 2015, the largest methane leak from a natural gas storage facility in United States history was discovered by the Southern California Gas Company (SoCalGas) at well SS-25 in its Aliso Canyon Storage Field in Los Angeles County. The leak continued for nearly four months until it was permanently sealed on February 17, 2016. In the interim, residents of nearby neighborhoods experienced health symptoms consistent with exposures to odorants added to the natural gas; thousands of households were displaced; and the Governor of California declared a state of emergency for the area. Approximately 90,000 metric tons of methane was released from the well, although estimates vary and the State of California is continuing its analysis. The incident also created serious energy supply challenges for the region and prompted broader public concerns about the safety of natural gas storage facilities.

Motivated by the events at Aliso Canyon, Federal officials, including many concerned members of Congress, sought to better understand and identify opportunities to improve the overall safety and environmental impacts of our Nation's natural gas storage infrastructure. To support these efforts, the Federal Government in April 2016 formed an Interagency Task Force on Natural Gas Storage Safety. Congress codified the Task Force through the Securing America's Future Energy: Protecting our Infrastructure of Pipelines and Enhancing Safety Act of 2016 (PIPES Act). Congress directed the Task Force to perform an analysis of the Aliso Canyon events and make recommendations to reduce the occurrence of similar incidents in the future. To do so, the Task Force examined three key areas: integrity of natural gas wells at storage facilities; public health and environmental effects from natural gas leaks; and vulnerability to reduced energy reliability in the case of future leaks.

Natural gas currently meets nearly 30% of U.S. energy needs, and natural gas storage facilities are essential to the functioning of a highly seasonal natural gas market. They provide quick access to large volumes of natural gas for end users during periods of high demand, such as during a cold spell in the winter or during periods of high electricity demand in the summer. The Aliso Canyon leak illustrated how the loss of a large gas storage facility can disrupt enough gas delivery service to cause major energy reliability concerns, including potential electricity blackouts. Gas storage facilities are key components of a large and complex natural gas delivery infrastructure that serve homes, offices, power plants, and industrial facilities. Smooth functioning of that infrastructure is vital to our economy, our quality of life, and our national security. Major leaks or functional disruptions elsewhere in the gas infrastructure (i.e., at pipelines, compressor stations, gas processing plants, and liquefied natural gas terminals) could have impacts similar to those of the Aliso Canyon incident, and perhaps on an even larger scale. Further, the electric power and natural gas industries have become much more interdependent in recent years, and their interdependence is expected to grow over the next decade as the U.S. becomes more reliant on gas-fired electric generation capacity.

Approximately 80% of wells in the Nation's natural gas storage fields were completed in the 1970s or earlier. They have been exposed to decades of physical and mechanical stresses and pre-date many current materials and technology standards. In addition, many of these wells were converted to gas storage from oil production and may not have piping designed for the higher overall operating pressures of natural gas. Although rare, large natural gas storage leakage events can have negative impacts on human health and communities.

In June 2016, as part of the PIPES Act, Congress mandated that the Pipeline and Hazardous Materials Safety Administration (PHMSA) issue minimum Federal standards for all underground gas storage facilities. In response, PHMSA has stated that it plans to issue interim regulations in 2016.

This final report is organized into three chapters. Chapter 1 provides an overview of underground natural gas storage uses, locations, and regulations. Chapter 2 describes the Aliso Canyon incident, the responses by SoCalGas and various State, local, and Federal agencies to the leak, and an analysis of the impacts of the incident on gas and electric system prices and reliability. Chapter 3 records the Task Force's observations and recommendations to improve the safety and reliability of underground natural gas storage across the Nation. Those recommendations are summarized below. The appendix to the report contains a glossary of terms.

Preventing incidents like the one at Aliso Canyon in the future will require improving how operators manage the integrity of wells at storage facilities. Except under limited circumstances, natural gas storage operators should phase out single-point-of-failure well designs. In addition, they should develop risk management plans (RMP) that include several key components: analysis of risks associated with factors such as the condition of wells and their proximity to population centers; well records relevant to mechanical integrity; risk management plans that include testing programs and plans for remediating substandard wells; continuous monitoring plans; and emergency operation plans in the event of a significant integrity breach. Operators should create plans that lay out timelines to remediate substandard wells and determine how risks can be adequately monitored during periods of transition. Regulators should consider the impacts of such measures on ratepayers and reliability. Once the RMPs have been developed, operators should periodically review and update them. Along with RMPs, operators should improve and publish data on the integrity of wells within a gas storage field. This information and additional research in safety technologies will progressively improve the safety of natural gas storage fields.

Advance preparation and early coordination by the appropriate Federal, State, and local agencies would help manage and mitigate potential health and environmental impacts should another leak at a natural gas storage facility occur. A "unified command" should be formed early in response to a natural gas release when human health and environmental threats are present and multiple jurisdictions are involved in the response effort. State and local air monitoring agencies in jurisdictions where natural gas storage facilities are present should have the capacity to establish robust air quality monitoring in order to adequately characterize the public health impacts of a release. State and local air monitoring agencies should also consider developing emergency air monitoring plans to expeditiously deploy ambient air monitoring networks to assess possible health risks if a leak should occur. A quickly deployed monitoring framework and improved measurement techniques and technologies will assist State and local agencies to better measure greenhouse gas emissions in the event of a similar leak. States with underground natural gas storage should review their legal authorities to require greenhouse gas measurement and mitigation of fugitive emissions from underground natural gas storage facilities. Future decisionmaking would also benefit from further research to determine the short- and long-term effects of exposures to natural gas odorants.

Industry and government officials need to better understand the implications and risks associated with the growing interdependence of electricity and gas markets. The Task Force analysis has identified a small number of underground gas storage facilities other than Aliso Canyon that have the potential to affect energy reliability. More detailed analysis is required to better delineate whether disruptions at these underground storage (UGS) facilities could result in energy reliability concerns. Power system planners and operators, working with their natural gas counterparts, should study and understand the electric reliability impacts of prolonged disruptions of large-scale natural gas infrastructure (e.g., storage facilities, processing plants, key pipeline segments and compressor stations, and liquefied natural gas (LNG) terminals). They should share their analyses with State and Federal officials to ensure that policymakers fully understand the risks to electric reliability and can develop appropriate mitigation policies and strategies. Finally, greater availability of backup options, such as dual-fuel capabilities, energy storage options, and maintaining alternative sources of natural gas, may help electricity operators handle uncertain gas availability during extreme events while maintaining a reliable source of operable capacity available to meet seasonal peak demands.

In summary, the Task Force concludes that while incidents at U.S. underground natural gas storage facilities are rare, the potential consequences of those incidents can be significant and require additional actions to ensure safe and reliable operation over the long term.

Legislative Requirement

This report responds to legislative language set forth in Section 31 of the Protecting our Infrastructure of Pipelines and Enhancing Safety Act of 2016 (P.L. 114-183) which was signed by President Obama on June 22, 2016. Section 31 states that no later than 180 days after the day of enactment, a Task Force established by the Secretary of Energy shall submit a final report to Congress that contains analysis and conclusions regarding the cause and contributing factors of the Aliso Canyon natural gas leak; an analysis of measures taken to stop the natural gas leak, with an immediate focus on other, more effective measures that could have been taken; an assessment of the impacts of the natural gas leak on health, safety, and the environment, wholesale and retail electricity prices, and the reliability of the bulk-power system; and an analysis of how Federal, State, and local agencies responded to the natural gas leak; recommendations on how to improve the response to future leaks in order to lessen the negative impacts of leaks from underground natural gas storage facilities; recommendations on how to improve coordination among all appropriate Federal, State, and local agencies in the response to the Aliso Canyon natural gas leak and future natural gas leaks; an analysis of the potential for similar occurrences of natural gas leaks at other underground natural storage facilities in the United States; recommendations on how to prevent any future natural gas leaks; recommendations regarding Aliso Canyon and other underground natural gas storage facilities located in close proximity to residential populations; any recommendations on information that is not currently collected but that would be in the public interest to collect and distribute to agencies and institutions for the continued study and monitoring of natural gas storage infrastructure in the United States; and other recommendations as appropriate.

Chapter 1. Gas Storage Primer

Natural Gas Storage Basics

Why is natural gas stored underground?

Natural gas is an important commodity in the United States and the world, particularly for heating and for power generation. Underground natural gas storage is used in the transportation and delivery of gas by pipeline to end users. For example, the facilities can provide quick access to large volumes of gas for end users during periods of high demand, such as during a cold spell in the winter or a period of high electricity demand in the summer.[1]

How is natural gas stored?

Natural gas is injected down the wellbore and into a subsurface geological formation. As gas is injected, pressure builds within the formation. Higher reservoir pressures allow higher gas flow volume during the extraction (withdrawal) part of the storage cycle to help ensure suitable production gas flow rates.[2] Typically, vertical wells are used to inject and withdraw the gas, although horizontal wells are becoming more common.

A significant portion of the gas that is injected initially will remain in the subsurface and will not be extracted during a typical withdrawal cycle. This gas is commonly known as "base gas" or "cushion gas." It is a permanent inventory in a storage reservoir that is needed to maintain adequate pressure, minimize water being produced with the gas, and maintain delivery rates throughout the withdrawal season.

More about how natural gas storage fields work can be found in the Niska Gas Storage Industry Primer (2010) and from the Energy Information Administration's (EIA) *Basics of Underground Natural Gas Storage*.

Where is natural gas being stored?

Underground natural gas storage is found in three main types of storage formations: depleted oil and gas fields, aquifers, and salt caverns. These storage facilities can be found across the United States in 415 facilities, including approximately 400 active facilities, in more than 30 States (as shown in Figure 1). Most (~80%) of the existing natural gas storage in the United States is in depleted natural gas or oil fields that are located close to consumption centers.

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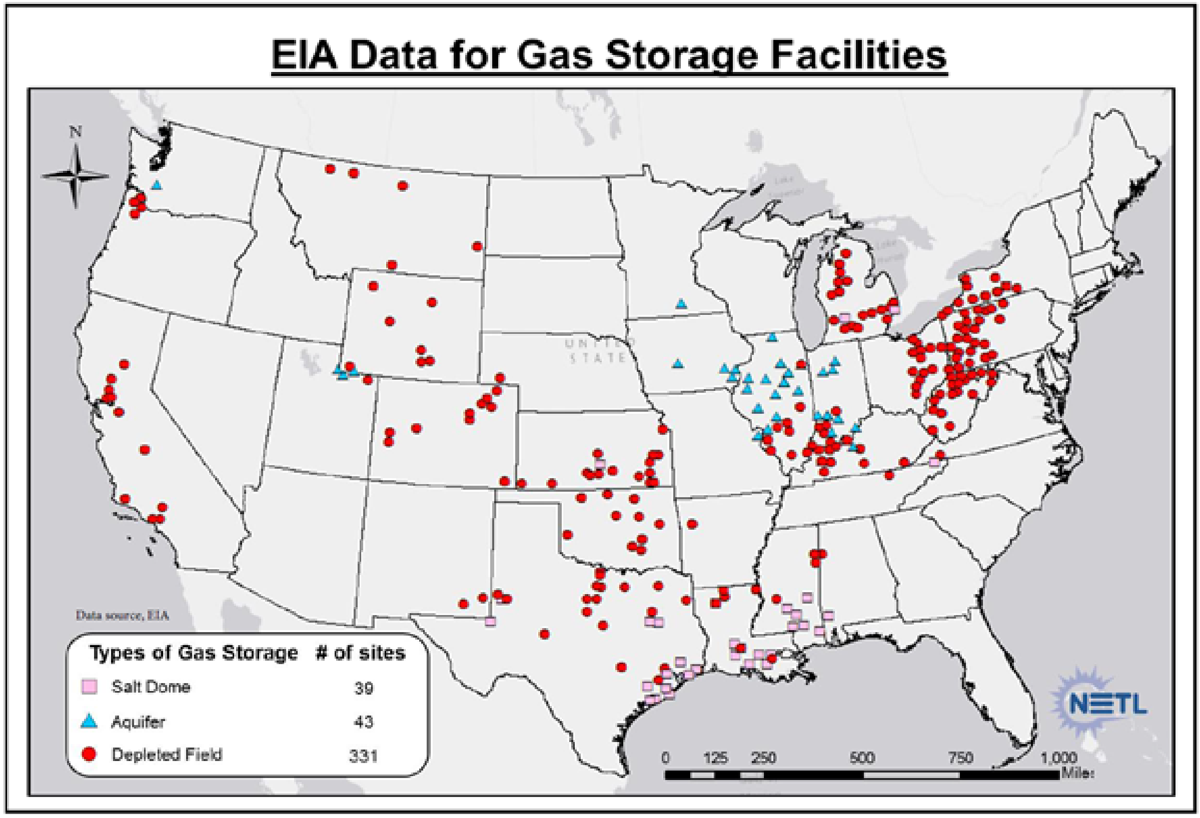
[1]U.S. EIA [Online], *The Basics of Underground Natural Gas Storage*, released November 16, 2015, September 2016, www.eia.gov/naturalgas/storage/basics/.

[2]Niska Gas Storage [Online], 2010, *Gas Storage Industry Primer*, September 2016, www.niskapartners.com/wp-content/uploads/2010/04/GasStorageIndustryPrimer.pdf.

Figure 1. Types and count of underground gas storage facilities in the United States



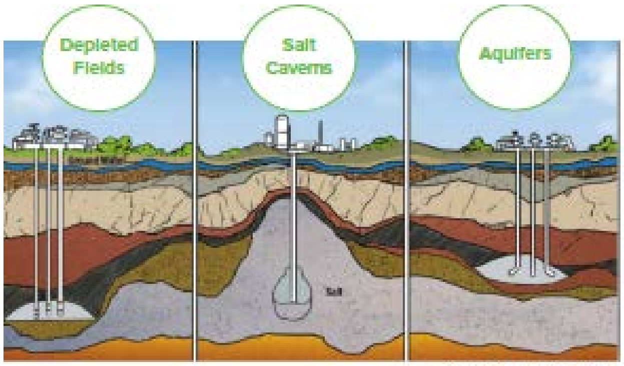
Why do we care about natural gas leaks from UGS facilities?

A gas storage field experiencing failures can be a health and safety hazard. Natural gas is flammable and can cause considerable damage if leaks are ignited. Natural gas may contain hydrogen sulfide (H_2S), other sulfur compounds, benzene, and natural gas odorants, which cause health concerns. Methane (the main constituent of natural gas) is a potent greenhouse gas. Releases of methane, such as the recent Aliso Canyon incident in California, contribute to climate change. A gas leak also causes the loss of a valuable commodity. In addition, a large UGS failure may disrupt enough gas delivery service to cause energy reliability concerns, including potential electricity blackouts.

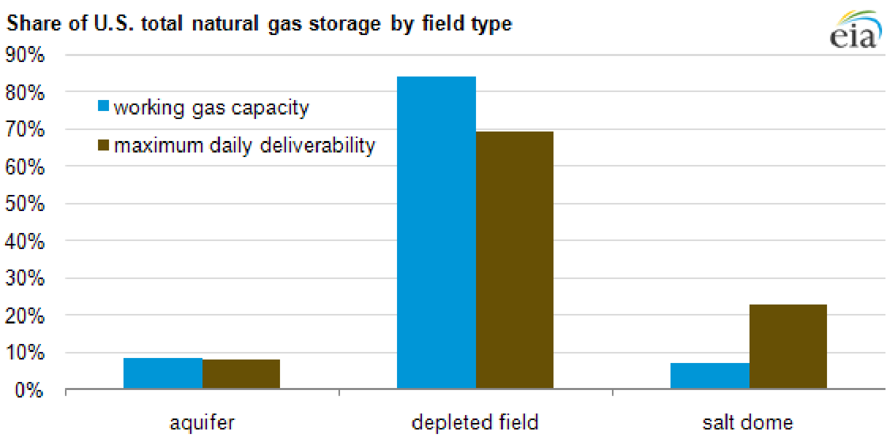
Gas storage facilities are key components of a large and complex natural gas delivery infrastructure that serve homes, offices, power plants, and industrial facilities. Smooth functioning of that infrastructure is vital to our economy, our quality of life, and our national security.

Underground Storage Types

Natural gas is stored in three principal types of underground geologic formations, including two types of naturally occurring structures: (1) aquifers, (2) depleted oil and gas reservoirs, and (3) man-made salt caverns.



Source: API Energy 2016



Depleted oil and gas fields are the most common type of underground natural gas storage field. These fields typically have been relatively well characterized (measured and mapped) during oil and gas activities and have demonstrated an ability to contain hydrocarbons over geologic time. They also typically already contain some "cushion gas" from the production phase.

Aquifers account for about 10% of the UGS fields. They are similar to the oil and gas fields in the way they function, as porous permeable formations capable of holding and releasing fluids. Although aquifers are often more expensive to develop than depleted oil and gas fields, they are more widely distributed across the United States than are oil and gas fields, and they can be found in locations that are useful for underground gas storage (e.g., near population centers with high demand).

Salt caverns differ significantly from the two other types of storage formations. They are formed in salt domes or salt beds, and they are usually mined by injecting fresh water, dissolving the salt, and producing the saturated brine in order to enlarge the cavern.

Salt caverns provide very high withdrawal and injection rates relative to their working gas capacity. Cushion gas requirements are relatively low. Most salt cavern storage facilities have been developed in salt dome formations located in the Gulf Coast States. Cavern construction is more costly than depleted field conversions when measured on the basis of dollars per thousand cubic feet of working gas capacity, but the ability to perform several withdrawal and injection cycles each year reduces the per-unit cost of gas injected and withdrawn.

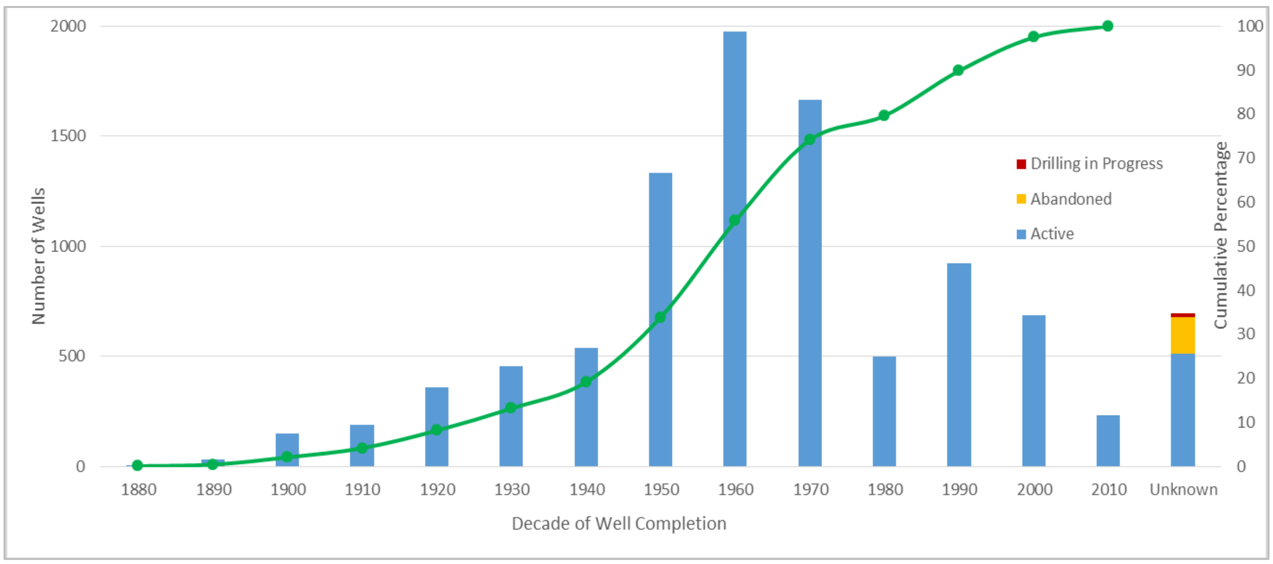
Gas Storage Wells in the United States: Data and Analysis

Analysis of Gas Storage Well Completions

Many wellbores presently in use for natural gas storage were initially designed and installed for other uses. Permitting and registration of such wellbores vary, depending on the years in which they were drilled and the States in which they are located.[3] The structural integrity of a wellbore is at least partially related to its age and past production type. Older wells are less likely to have been constructed with redundant barriers, and they are more likely to have degradation related to age (such as internal or external corrosion) or pressure cycle.[4] Nevertheless, a first-order analysis of wellbore records either drilled as—or converted to—natural gas storage wells, can assist with risk management planning and can inform the need for more detailed investigation of specific regions or wells. Wells that were originally designed for oil production and have subsequently been converted to natural gas storage may not have piping designed for the higher overall operating pressures of natural gas.

Figure 2 displays temporal trends in gas storage well records. About 80% of wellbores characterized as natural gas storage wells with known completion years were drilled before 1980. Although no firm cutoff can be stated for what constitutes an "old" well based on its completion year, wellbore construction materials and practices for all wells will be vestigial to the years in which they were drilled. Hence, the vast majority of the natural gas storage wells presently in use predate current materials and technology standards and have experienced physical and mechanical stresses from injection and withdrawal of natural gas across multiple decades.

Figure 2. Natural gas storage wells by completion date



The geographic distribution of natural gas storage wells is shown in Figure 3 and Figure 4. Ohio has the largest number of wells classified as gas storage wells (1,772), followed by Pennsylvania (1,327) and New York (964).

[3]D. Glosser, K. Rose, and J.R. Bauer, "Spatio-Temporal Analysis to Constrain Uncertainty in Wellbore Datasets : An Adaptable Analytical Approach in Support of Science-Based Decision Making," pp. 1–19, 2016.
[4]R.M. Dilmore, J.I. Sams, D. Glosser, K.M. Carter, and D.J. Bain, "Spatial and Temporal Characteristics of Historical Oil and Gas Wells in Pennsylvania: Implications for New Shale Gas Resources," *Environ. Sci. Technol.*, vol. 49, no. 20, pp. 12015–23, 2015.

Figure 3. Number and drilling status of natural gas storage wells in each State

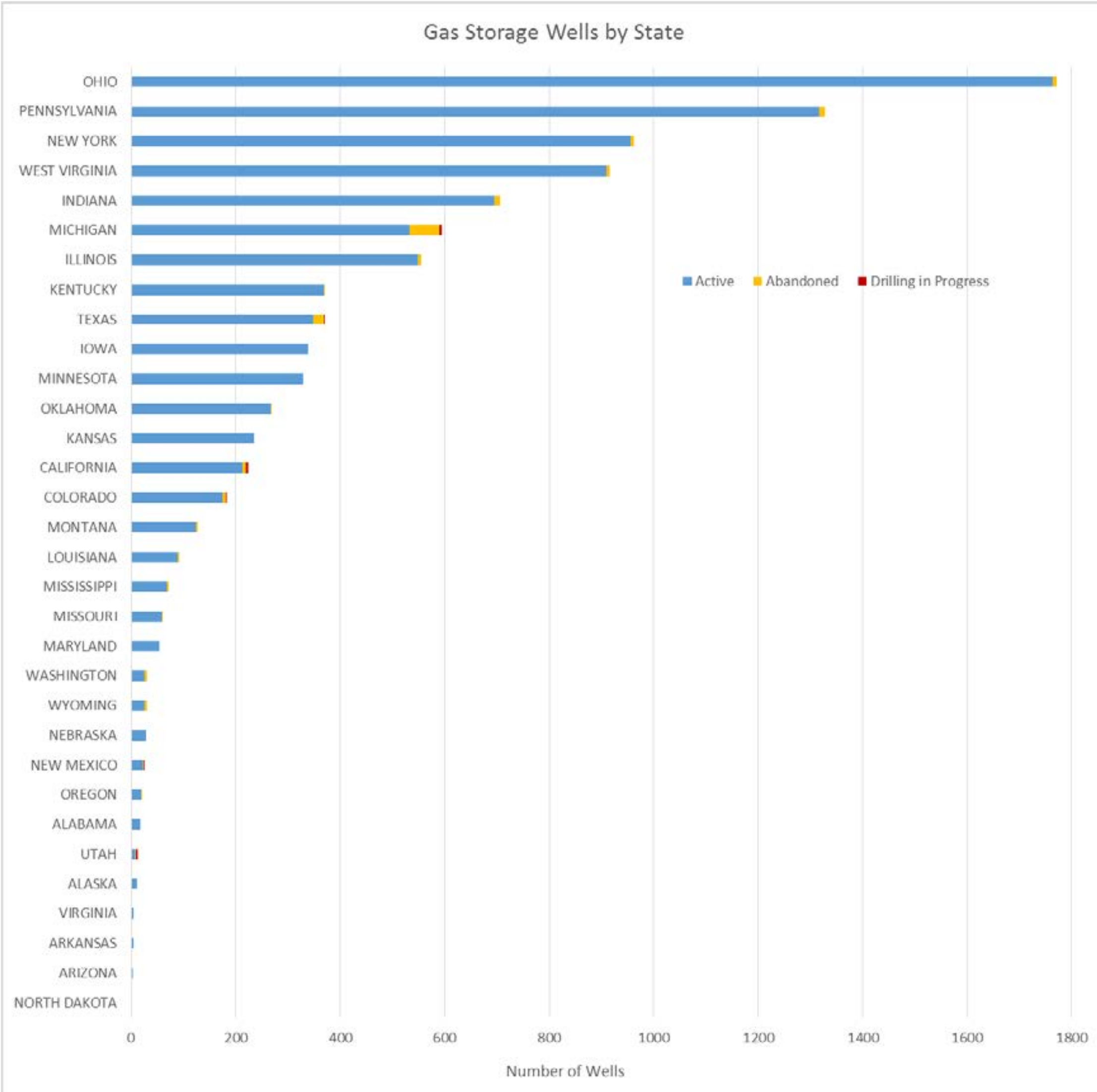
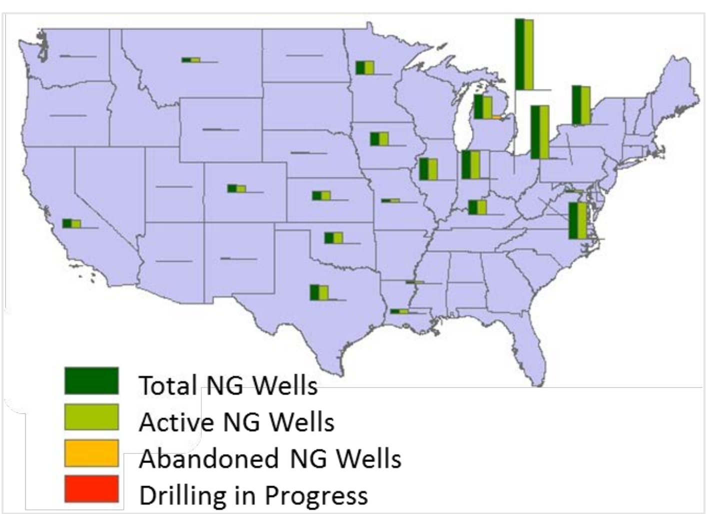


Figure 4. Geographic distribution of natural gas storage wells



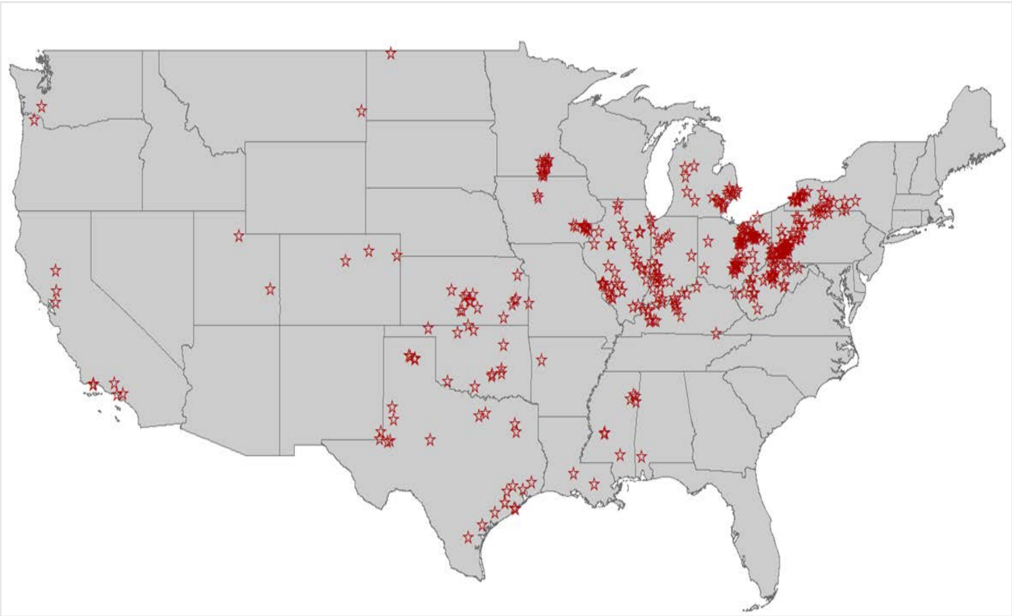
Adapting legacy energy infrastructures (such as those constructed with older oil and gas exploration and engineering practices) to contemporary use requires careful consideration of the original designs and construction practices and the operational risks that flow from those practices. Construction, inspection and monitoring, and management practices can then be put in place to mitigate those risks. Legacy uses of natural energy resources cross jurisdictional and geographic boundaries in the United States.

Natural Gas Storage and Population Centers

Although they are rare, large natural gas storage leakage events can have negative impacts on human health and communities. The proximity of human population centers to natural gas storage infrastructure clearly influences the extent and severity of the risk to human health consequent to such events. Natural gas moves relatively slowly through pipeline networks (at about 10 to 25 miles per hour), and hence storage facilities are often most valuable when they are located relatively close to the power plants and residential and commercial users that depend on the gas. Use of any gas storage facility must balance the need for storage to support reliability of heating, electric power generation, and industrial uses with safety, health, and potential environmental impacts.

Currently, 370 population centers identified as "Census Designated Places" in the 2010 U.S. census are within 5 kilometers of an active natural gas storage well (Figure 5).[5] In other regions, separation distances are much larger. Given this distribution, a graded approach to gas storage regulations may be warranted.

Figure 5. Population centers within 5 kilometers of an active natural gas storage well



[5]"United States Census." [Online]. Available: http://www.census.gov/geo/reference/gtc/gtc_place.html.

Regulation of Natural Gas Storage Facilities

Overview of Jurisdiction to Regulate Natural Gas Storage Facilities

Just as natural gas storage and transmission are essential for ensuring reliability of domestic energy supplies, appropriate regulations are essential for ensuring the safety of such systems. Regulation of natural gas pipelines bringing gas in and out of UGS facilities falls under Federal jurisdiction under the Natural Gas Pipeline Safety Act (NGPSA), codified at 49 U.S.C. § 60101, et seq., and the Natural Gas Act (NGA), 15 U.S.C. § 717f(c), et seq.

The Pipeline Hazardous Materials Safety Administration (PHMSA) has been regulating gas pipelines for decades in partnership with the States, including the surface piping at UGS facilities up to the wellhead. Until recently, PHMSA has not chosen to exercise its regulatory authority over the underground gas storage facilities, which include wells and related “downhole” infrastructure. PHMSA has recently notified the public of its intent to exercise its Federal rulemaking authority in the domain of UGS facilities from the wellhead and extending downhole, to include wellbore tubing and casing, later this year. Several States have issued and enforced rules related to their intrastate facilities.[6, 7]

Interstate versus Intrastate Regulation

Regulatory responsibility for permitting and inspection of wells and facilities receiving or storing gas currently differs for interstate and intrastate gas storage infrastructure. UGS facilities that link multiple States are considered to be “interstate” facilities and are subject to the permitting authority of the Federal Energy Regulatory Commission (FERC). Intrastate UGS facilities are facilities that exist solely within the boundaries of a State and receive natural gas from an intrastate pipeline. State public utility commissions and State oil and gas boards currently establish their own regulatory frameworks for these intrastate facilities. Approximately half of the Nation’s 415 UGS facilities are interstate facilities, and half are intrastate facilities.

Past Challenges to State Jurisdiction to Regulate Natural Gas Storage Facilities

Understanding potential jurisdictional limits on State regulatory oversight can inform the development of future regulations aimed at improving natural gas storage safety. A 2010 challenge to State regulation over interstate natural gas storage facilities in Kansas provides insight into potential limitations on State rulemaking and enforcement. In 2001, the Kansas Legislature vested jurisdiction for the safety of underground porosity and salt storage of natural gas in Kansas in the Kansas Corporation Commission and Kansas Department of Health and Environment. This regulatory action occurred following a 2001 natural gas storage leakage incident in Hutchinson, Kansas, that caused two fatalities. A series of Kansas State regulations were adopted and codified in the following years. However, a Federal court blocked Kansas from applying those regulations to a gas storage facility operated by Colorado Interstate Gas, on the ground that Congress had conveyed exclusive power to regulate interstate gas storage facilities to FERC and PHMSA.[8]

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[6] *General Rules and Regulations for the Conservation of Crude Oil and Natural Gas,* State Corporation Commission of the State of Kansas.

[7] *Underground Storage of Gas in Productive or Depleted Reservoirs*. Rule §3.96, Texas Administrative Code.

[8] *Colorado Interstate v. Wright*, 707 F.Supp.2d 1169.

Industry Develops Consensus-Based Recommended Practices with State and Federal Authorities

In August 2011, PHMSA published an Advance Notice of Proposed Rulemaking (ANPRM) in the *Federal Register*, which among other things requested comments as to whether new regulations were needed for UGS facilities.[9] Subsequently, the Interstate Natural Gas Association of America (INGAA) and the American Gas Association (AGA) created a joint task team with participation from PHMSA and State agencies. The American Petroleum Institute (API) acted as the American National Standards Institute (ANSI)-approved Secretariat of the task group's final product: consensus-based standards developed under an ANSI-approved process, published as API Recommended Practices (RPs). The task teams met over the next several years and in September 2015 produced API RP 1170, "Design and Operation of Solution-mined Salt Caverns Used for Natural Gas Storage," and API RP 1171, "Functional Integrity of Natural Gas Storage in Depleted Hydrocarbon Reservoirs and Aquifer Reservoirs." The development of those national RPs brought together expertise from industry and both State and Federal governments. The U.S. Congress, in addressing the concerns for the integrity of UGS facilities under Section 60141(b) of the 2016 PIPES Act, required PHMSA to consider consensus standards, such as API RPs 1170 and 1171, in adopting minimum standards for the operation, environmental protection, and integrity management of underground natural gas storage facilities.

Congress Mandates Minimum Federal Standards

With passage of the PIPES Act of 2016, the U.S. Congress mandated that the Pipeline Safety Act authority encompassing interstate and intrastate underground gas storage facilities served by pipeline be exercised, and required the issuance of minimum Federal standards. PHMSA anticipates that State requirements for intrastate facilities in turn will be based on adoption of those Federal standards once they are in place. Notably, the PIPES Act provides that the State authorities may adopt additional or more stringent safety regulations for intrastate UGS facilities as long as they are compatible with the Federal minimum standards.

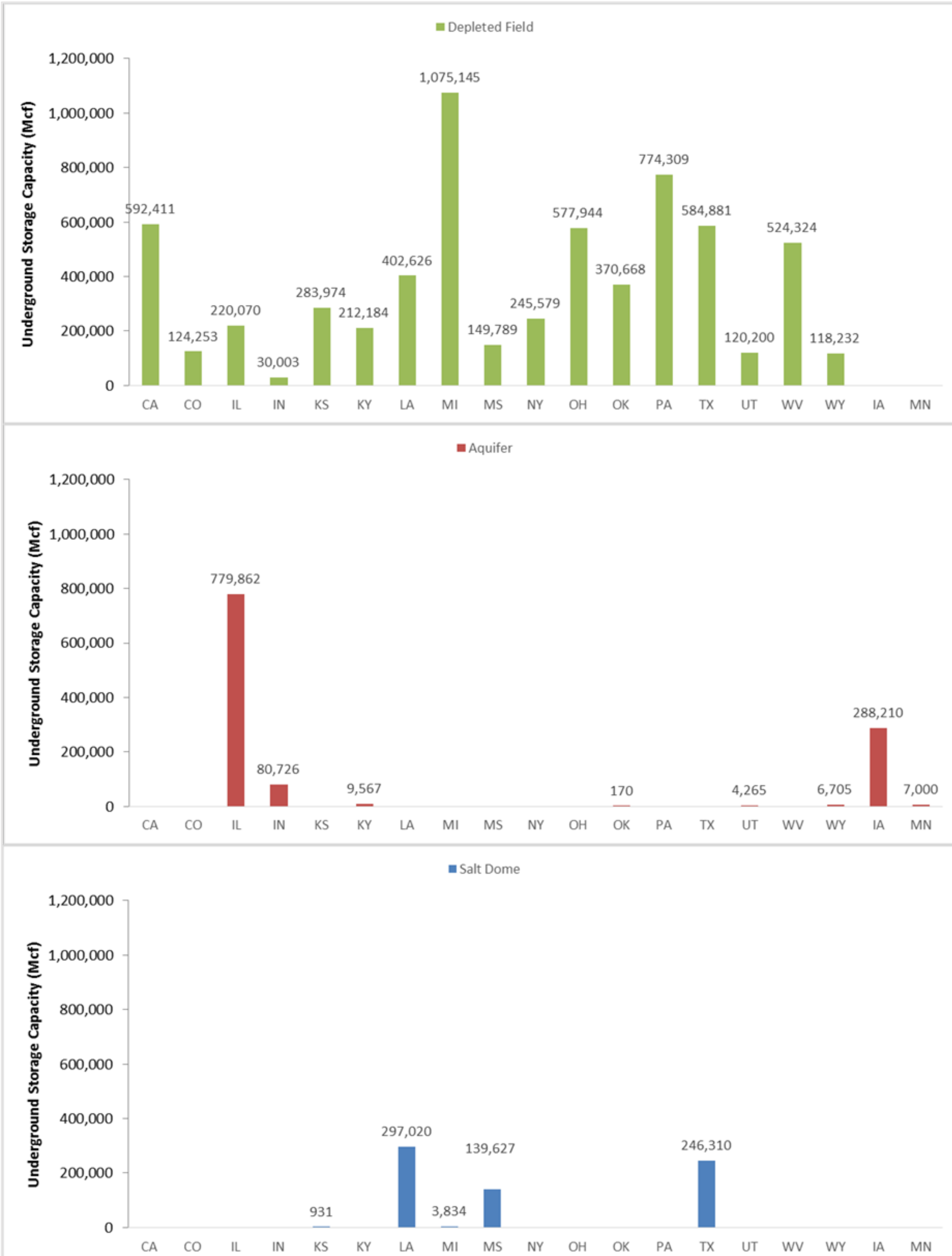
In 2016 PHMSA issued an advisory bulletin regarding safe operations of UGS facilities for natural gas. As of the writing of this report, PHMSA has stated publicly that it intends to issue interim regulations in 2016.

State-Level Regulations by Reservoir Type

Many States have enacted rules covering intrastate natural gas storage facilities within their borders. Nineteen States with natural gas storage fields were selected for an analysis of State-level natural gas storage regulations; 90% of all active natural gas storage wells are located in their jurisdictions. Of the 19 States, 11 have regulations of some type that specifically address surface or subsurface infrastructure within such facilities. Four of the 11 States have regulations addressing underground natural gas storage in all three reservoir types: depleted fields, aquifers, and salt caverns. Details of annual gas storage capacity by reservoir type are shown in Figure 6.[10]

[9] https://www.federalregister.gov/documents/2011/08/25/2011-21753/pipeline-safety-safety-of-gas-transmission-pipelines.
[10] U.S. EIA, "Gas Storage Capacity." [Online]. Available: https://www.eia.gov/dnav/ng/NG_STOR_CAP_A_EPG0_SA6_MMCF_A.htm.

Figure 6. 2012 State-level natural gas storage capacity (Mcf) by reservoir type



State Regulations Related to Natural Gas Storage Wellbore Integrity

Wellbores are the primary engineered pathway linking the subsurface and surface. Maintaining the integrity of the wells across the three stages of their lifespans—initial design and construction, use, and final plugging and abandonment—is of critical importance for mitigating risk of leakage. Several, but not all, States with natural gas storage facilities have implemented regulations that address wellbore integrity at these stages (Table 1).

Table 1. States with regulations regarding natural gas storage well construction, maintenance, and plugging and abandonment as of August 2016[11, 12, 13]

	Well Constructio	Well Maintenance	Plugging and Abandonment
CA	X	X	X
CO			
IL	X		X
IN			
KS	X	X	X
KY			
LA			
MI	X	X	
MS	X		
NY			
OH	X		X
OK			
PA	X	X	X
TX		X	
UT			
WV			
WY			
IA	X	X	X
MN			

Note: The California regulations are interim emergency regulations.

Only California, Kansas, and Pennsylvania have regulations addressing well integrity at all three stages. At the design and construction phase, Kansas regulation requires a drilling and completion plan to be signed by a professional engineer or geologist. At the operations and maintenance phase, Kansas has requirements for pressure testing, leak detection, and the presence of a safety plan. Finally, Kansas requires specific plugging and completion procedures for all natural gas storage wells.[14] In Pennsylvania, there are several gas storage well design and construction rules: specific casing and cementing procedures,

[11] G. P. Council, “Summary of Gas Storage Regulations from 17 State Oil and Gas Agencies, Ground Water Protection Council, April, 2016.” 2016.

[12] *2015 Minnesota Statutes*.

[13] *Iowa Administrative Code*.

[14] T.S.C. COMMISSION and O.T.S.O. KANSAS, *General Rules And Regulations For the Conservation of Crude Oil and Natural Gas*. 2006.

blowout prevention equipment rules, and storage well construction requirements are all prescribed by the State.[15] At the operation stage, Pennsylvania requires mechanical integrity testing every 5 years, including geophysical logging and pressure testing, and leak and corrosion inspections. Finally, Pennsylvania requires bridge plugs above and below the gas storage reservoir during the plugging and abandonment of natural gas storage wells.

The California proposed rulemaking that is underway for natural gas storage wells at the design and construction phase requires primary and secondary well barrier construction (including production casing to the surface); and tubing and packer. At the operations stage, California's interim emergency regulations and draft rules require mechanical integrity testing (temperature and noise log, and casing thickness inspections), as well as monitoring and inspections for leaks. The interim emergency regulations do not have specific requirements for plugging and abandonment protocols; however, the Division of Oil, Gas and Geothermal Resources ("DOGGR") remains vested with the authority to oversee the plugging and abandonment of the wellbores.[16] In some cases, States have developed regulations particular to ensuring the integrity of injection wells but have specifically excluded gas storage wells from those regulations.

[15]Pennsylvania, *Oil and Gas Wells*. 2012.

[16]California, *Onshore Well Regulations*. 2016.

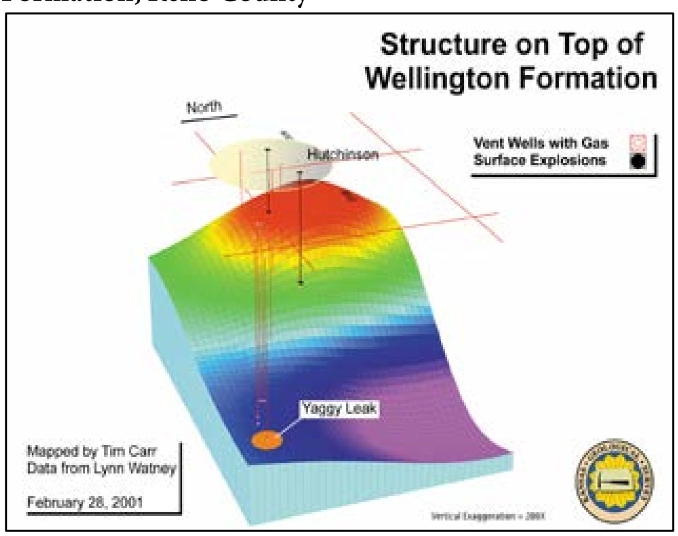
Notable Gas Storage Failures

The Yaggy Incident

On January 17 and 18, 2001, an accident occurred at the Yaggy underground natural gas storage field operated by Kansas Gas Service. Natural gas stored in underground salt caverns escaped and migrated laterally more than 8 kilometers through a porous underground geologic formation, where it came into contact with several abandoned wellbores used long before as brine wells. The gas escaped through the wellbores and caused two separate explosions in Hutchinson, Kansas. Two people were killed, and several businesses were destroyed in the explosions. Approximately 143 million cubic feet of natural gas leaked from the storage field.

Figure 7. Photo of downtown Hutchinson, KS, after explosion from an underground storage field at Yaggy

Figure 8. Structure contours on top of the Wellington Formation, Reno County



The Yaggy incident highlights the critical role of wellbores (particularly older, improperly abandoned, and structurally unsound wellbores) as a conduit for fluid flow, as well as the need to address wellbore integrity to reduce future risks related to natural gas storage. The Kansas Geological Survey investigated the incident and determined that the leak was a result of damaged casing in one of the older wellbores. The casing damage was determined to have occurred from the re-drilling of an old, cemented wellbore when the Yaggy field was reopened and converted from propane storage to natural gas storage.[17]

The Moss Bluff Incident

On August 19, 2004, the Market Hub Partners Moss Bluff storage facility, located in Liberty County, Texas, had an accident in which a wellhead fire and explosion occurred, releasing 6 billion cubic feet of natural gas.

[17]http://www.kgs.ku.edu/Hydro/Hutch/GasStorage/apr_19_97.pdf.

Prior to the explosion , the storage cavern was operating in “de-brining” mode, wherein brine is extracted as natural gas is injected. The cause of the explosion was determined to be a separation of the production casing (well string) inside the cavern. When the brine reached the separation point in the casing, pressurized gas entered the string, where it was brought to the surface through brine piping at the wellhead. Although the wellhead assembly closed properly when the pressure change was detected, the mechanical force produced by the rapid change in flow rate caused a breach in the pipe, which was already weakened from wall loss due to internal corrosion. The pipe was only 4 years old at the time of the event.

On August 26, 2004, the fire eventually self-extinguished, and installation of a blowout prevention valve was completed, effectively placing the well back under control. Most of the methane released in the leak was combusted in an explosion and subsequent fire and therefore was emitted to the atmosphere as carbon dioxide (not as methane).

Figure 9. Uncontrolled gas release and fire at storage Cavern #1

Figure 10. Local fire department response to Moss Bluff

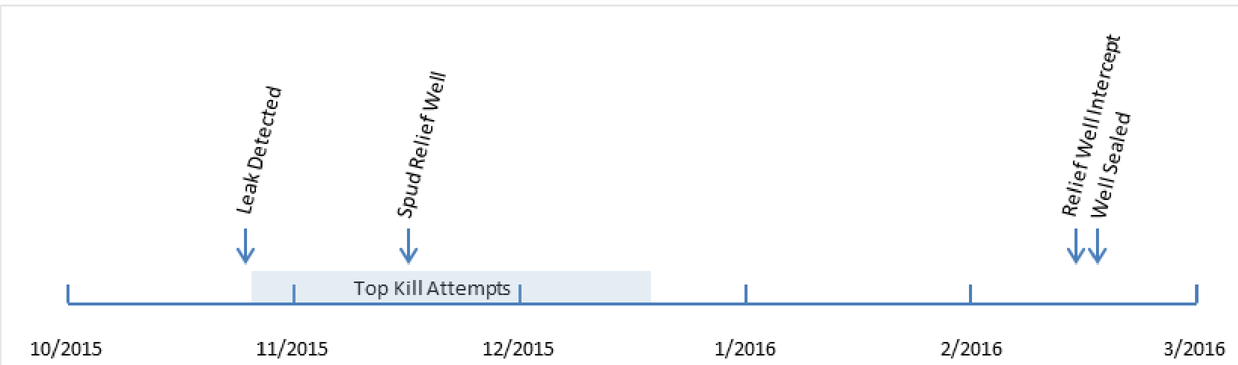
Chapter 2. The Aliso Canyon Incident

Well History and October 2015 Well Failure Analysis

On October 23, 2015, the largest methane leak[18] from a natural gas storage facility in United States history was discovered by the Southern California Gas Company (SoCalGas) at well SS-25 within its Aliso Canyon Storage Field in Los Angeles County. SoCalGas, a subsidiary of Sempra Utilities, is the owner and operator of the Aliso Canyon facility. The leak initially released approximately 53 metric tons of methane per hour, or a total of approximately 1,300 metric tons of methane per day.

The leak was exacerbated by repeated (eight) top kill attempts over the course of the first two months of the event. A relief well, which was drilled beginning in late November, was used eventually to kill the well. Relief well intercept occurred on February 12, 2016, and gas flow was stopped immediately. The well was subsequently cemented and sealed on February 17, 2016. An overview timeline of the events at Aliso Canyon is provided in Figure 11.

Figure 11. Timeline of Aliso Canyon events



SS-25 Well History

The Aliso Canyon Facility consists of 115 storage injection wells with spud ages ranging from 1939 to 2014.[19] The Aliso Canyon facility has a total storage capacity of 86 billion cubic feet (bcf) of natural gas, making it one of the largest natural gas storage facilities in the United States. Natural gas is injected into the old sandstone reservoir formation at approximately 8,500 feet below ground surface for storage and withdrawn for transmission and sale in response to market conditions.

Drilling of the SS-25 started on October 1, 1953, and the well was completed in April 1954. During drilling, the original borehole was abandoned due to an unrecoverable drill string and tool set that were lost in the hole. The main hole was sidetracked at a depth of approximately 3,900 feet, and then drilled to full completion depth of 8,749 feet.

In May 1973, a reworking of SS-25 to convert it to a gas storage well was started. As a gas storage well, it was operated by injection and withdrawal through both tubing and casing; thus, the long casing string functioned as a single barrier to the environment.

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[18]A large release of natural gas occurred from a storage facility in Moss Bluff, TX. in 2004, but most of the methane was combusted due to an explosion and subsequent fire, and therefore emitted as carbon dioxide (not methane) to the atmosphere.
[19]A "spud" is the process of beginning to drill a well. After a surface hole is completed, the main drill bit is inserted, which performs the task of drilling to the total depth; this is referred to as "spudding in."

In general, it appears that downhole safety valves (DHSVs) were installed in many of the original wells, including SS-25, when the field was converted to a gas storage facility in the 1970s. DHSVs, commonly used in the offshore environment, are devices designed to shut off flow to the surface under off-normal conditions, such as during loss of pressure control. These systems differ from the subsurface sliding sleeve valves (SSVs) that provide connections between the tubing and casing. SSVs are used during normal well operations to facilitate maintenance operations, permitting fluid circulation between the tubing and the tubing-casing annulus.

At Aliso Canyon, many DHSVs were then removed and not replaced during later well workover operations. In some cases, SSVs replaced the DHSVs. Wells drilled since approximately 1980 have not had any DHSVs installed at any time. Table 3 shows a summary of the use of DHSVs and packer and tubing well completions for the Aliso Canyon gas storage facility, based on review of the publicly available well history files maintained by the California Division of Oil, Gas, & Geothermal Resources (DOGGR). Both DHSVs and SSVs were used at various times in many of the wells, and there are some inaccuracies noted in the records, which reflect the lack of standardized terms and acronyms used to refer to various types of downhole devices. Wells were considered to be capable of casing production if the tubing was configured for gas flow to the casing using SSVs, or if there was no production tubing.

Table 3. Summary of Aliso Canyon Gas Storage Facility Well Configurations

Parameter	Well count
Total number of wells	115
Wells with a DHSV at some point in their history	54
Wells with no indication of a DHSV installation	60
Wells using packer and tubing production	102
Wells configured for casing production (includes wells with SSVs permitting tubing to casing flow)	80

Top Kill Attempts in Response to the 2015/2016 Leak

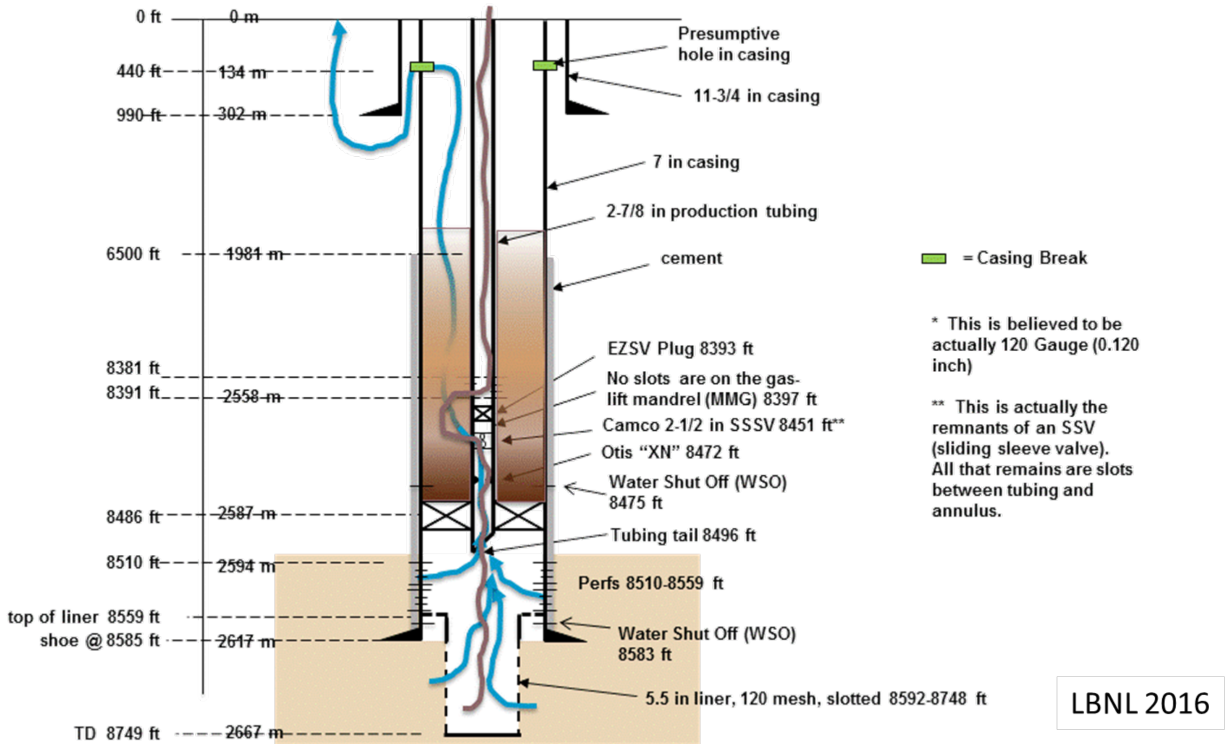
Starting on October 24, 2015, one day after the leak was discovered, and continuing until December 22, SoCalGas conducted eight separate “top kill” operations to stop the leak. “Top kill” operations involve pumping heavy drilling muds, fluids, and other material (together known as “kill fluids”) into the leaking well in an attempt to plug the well from above. After the first well kill attempt failed on October 24, SoCalGas on October 25, 2015, retained the services of Boots & Coots, a wholly owned subsidiary of Halliburton, for assistance. Boots and Coots is a company recognized as expert in well control services. After the leak was recognized at the surface on October 23, 2015, top kill attempts were made on October 24, November 6, 13, 15, 18, 24, and 25, and December 22, 2015. Heavy barite mud and calcium chloride solutions were systematically pumped with lost circulation materials. Over time, as successive top kill attempts caused erosion and expansion of the vent, the vent eroded to include the wellhead (Figure 12). During the later top kill attempts, the wellhead experienced severe vibrations and movement. In an effort to protect the wellhead and the casing couplings, the operator secured it with strapping (which failed during a top kill attempt). The wellhead was eventually secured with a bridge structure as shown in Figure 12. The final vent reached a dimension of approximately 40 feet by 60 feet and a depth of more than 20 feet, with an estimated maximum gas flow rate of 25 to 60 million cubic feet per day (MMcfd). None of the top kill operations was successful.

Figure 12. Vent crater caused by expulsion of top kill attempt materials

In at least one top kill attempt, significant volumes of kill fluids were expelled from the borehole by the escaping gas. Because the Aliso Canyon storage facility uses abandoned petroleum-bearing formations, the escaping gas also caused residual petroleum from the formations to be expelled from the well, resulting in the deposition of an oily residue on many Porter Ranch residences, vehicles, and outside areas. It is believed that these unsuccessful top kill attempts partially aerosolized some kill fluid constituents, such as barium, and that the aerosolized products, in the form of an oily mist, were in turn carried in the air and deposited in the interior of some Porter Ranch residences. To mitigate this problem, starting on January 3, 2016, SoCalGas installed a series of metal screens (called "coalescing trays") over SS-25 in an attempt to contain the oily mist.

Lawrence Berkeley National Laboratory (LBNL) simulated the top kills based on information provided by SoCalGas. The modeling showed that the high gas flow rates and the geometry of the lower section of the well severely inhibited the effectiveness of the top kill attempts. During the top kill attempts, fluids pumped down the tubing had to exit the perforations above the plug and then re-enter the tubing through the original valve at 8,451 feet in order to enter the gas-producing area of the well. The gas flowing up the well was able to entrain the kill fluids exiting the tubing, and gas flowing out from the tubing inhibited the kill fluids from re-entering the tubing. Exacerbating this issue were kill operation limitations caused by concerns for the structure of the wellhead, as shown schematically in Figure 13, where the kill fluid (brown) has to build up in the casing and overcome the methane gas (blue) flowing out of the SSV slots. In the lower section of the cased interval gas and liquid were mixed, and the upward velocity of the escaping methane was sufficient to force the liquid/gas mixture up the well and out the leak.

Figure 13. SS-25 top kill failure scenario



Bottom Kill Attempts in Response to the Leak

In early November, SoCalGas also began planning for the drilling of a relief well for a "bottom kill" operation, if needed. "Bottom kill" operations involve drilling a relief well to intercept the leaking well at depth and pumping drilling muds and cement through the relief well into the leaking well to seal the well.

SoCalGas began withdrawing natural gas from the Aliso Canyon facility in early November 2015, in an effort to reduce pressure around SS-25, and on November 25, 2015, began drilling a relief well in order to conduct a bottom kill operation. SoCalGas also started preparing for a second relief well, should it become necessary. The first relief well was ultimately successful in plugging SS-25, and no other relief wells were drilled. Relief well intercept occurred on February 12, 2016, and gas flow was stopped immediately thereafter.

Monitoring and Leak Detection History at Aliso Canyon

The gas storage industry generally has relied on subsurface measurements to detect subsurface leaks. Noise logs, listening for noise irregularities (perhaps indicative of a leak), and temperature logs, looking for thermal anomalies indicative of subsurface flow, are commonly used by the industry. For both of these technologies, historical records are of great value for comparative purposes.

Early logging of wells at Aliso Canyon (in the 1950s) was primarily for formation characterization. In the 1970s, as part of the field's conversion to storage, a small fraction (about one-fourth) of the wells were logged, focusing on cement bond and neutron logs. In recent years there has been much more well logging; however, before the 2015 leak event, the vast majority of the wells remained unevaluated for cement integrity along the production casing.

- Noise and temperature logs have been obtained for all wells in the field in 2016, as required by the California Division of Oil, Gas, and Geothermal Resources (DOGGR).
- In the preceding 5 years (2010-2015), most wells were surveyed annually for temperature.
- In the years 2006-2010, most wells were surveyed every other year.
- In the years 1990-2005, most wells were surveyed at time intervals longer than every other year.
- In the years from the 1970s conversion date to 1990, surveying was sporadic.
- There are infrequent additional geophysical log data for the storage wells, but nothing recent or systematic that could possibly have been used to assess well integrity.

Observations regarding SS-25's Failure

A formal root cause analysis of the leak at SS-25 has been initiated by the California Public Utilities Commission (CPUC) through a third-party contractor. The analysis will include detailed work at the leak site, but it is not yet known when the analysis will be completed. While the Federal Government is not part of this investigation, a review of publicly available information about SS-25[20] allows the following observations:

- SS-25 was constructed under ordinary circumstances consistent with the rest of the Aliso Canyon field. It began as a production well and then was converted to use in natural gas storage.
- The data indicate that SS-25 was operated in natural gas storage pressure cycling through both casing (uncemented in the uppermost critical sections) and tubing, providing only a single barrier. This was common practice at the storage field.
- SS-25 was monitored for gas leaks in a similar manner to other wells at the field, annually in recent years, and ranging from sporadic to biannually in earlier years.
- Logs that could be used to assess the risk of the well system (e.g., metal loss in the casing) were not located.
- Complex subsurface flow paths may have impeded the delivery of kill fluids required to suppress gas flow.

While investigation of the failure remains ongoing, there are preliminary indications that the practices for monitoring and assessing leaks (temperature and noise) and leak potential (cement bond, metal thickness, and pressure testing) at the Aliso Canyon facility were inadequate to maintain safe field operating pressures.

As a result of the Aliso Canyon incident, PHMSA in 2016 issued an advisory bulletin[21] regarding safe operations of UGS facilities for natural gas. Because Aliso Canyon is an intrastate facility, the CPUC and DOGGR have primary regulatory responsibility, and they have issued numerous orders to the operator imposing various operating restrictions and mandating remedial actions. PHMSA and DOE are providing extensive technical support to those agencies. The actions taken PHMSA, DOE, and other Federal and State regulatory agencies are described in greater detail later in this report.

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[20] http://www.conservation.ca.gov/dog/Pages/AlisoCanyon.aspx.

[21] ADB–2016–02.

Health and Environmental Effects and Responses

Ambient Air Pollutant Monitoring and Public Health Risk Assessment

State and local air pollution control agencies have the primary responsibility for conducting ambient air monitoring within their jurisdictions, including monitoring for emergency response. EPA provides funding and oversight to enable these agencies to accomplish these objectives. The two air pollution control agencies that conducted emergency ambient air monitoring in response to the Aliso Canyon natural gas leak were the South Coast Air Quality Management District (SCAQMD) and the California Air Resources Board (CARB). SoCalGas and the Los Angeles Unified School District (LAUSD) also collected ambient air samples on facility property and in the Porter Ranch community. Later during the response, and on its own initiative, the University of California at Los Angeles (UCLA) conducted ambient air monitoring.

Discrete Sampling

A series of discrete sampling efforts was conducted beginning on October 26, 2015. The first samples were taken by SCAQMD in direct response to the first community complaints received on October 24, 2015, the day after the leak was detected. Following this initial sampling, numerous other samples were taken for a wide variety of pollutants. In addition to the discrete sampling, continuous monitoring was established for a small set of pollutants at fixed monitoring sites, which is described in the next section (see Figure 14 for a map of SCAQMD and CARB sampling and monitoring locations).

The monitoring objectives for the ambient air monitoring of pollutants were generally threefold: (1) to assess potential exposure to various pollutants determined to be of concern, (2) to evaluate the extent of the emissions transport into the surrounding area, and (3) to provide information to Porter Ranch community members. One study monitored air quality at twenty schools in the area near the leak to assess students' exposure to pollutants of concern associated with the leak. Most of the sampling was done in and around the Aliso Canyon Facility, but monitoring was also conducted in a separate area in order to re-verify potential pollutants of concern within the community compared to a background location.[22] Finally, indoor air was also sampled for radon to determine whether levels exceeded EPA's action level, due to concerns about the potential presence of radon in the released natural gas.

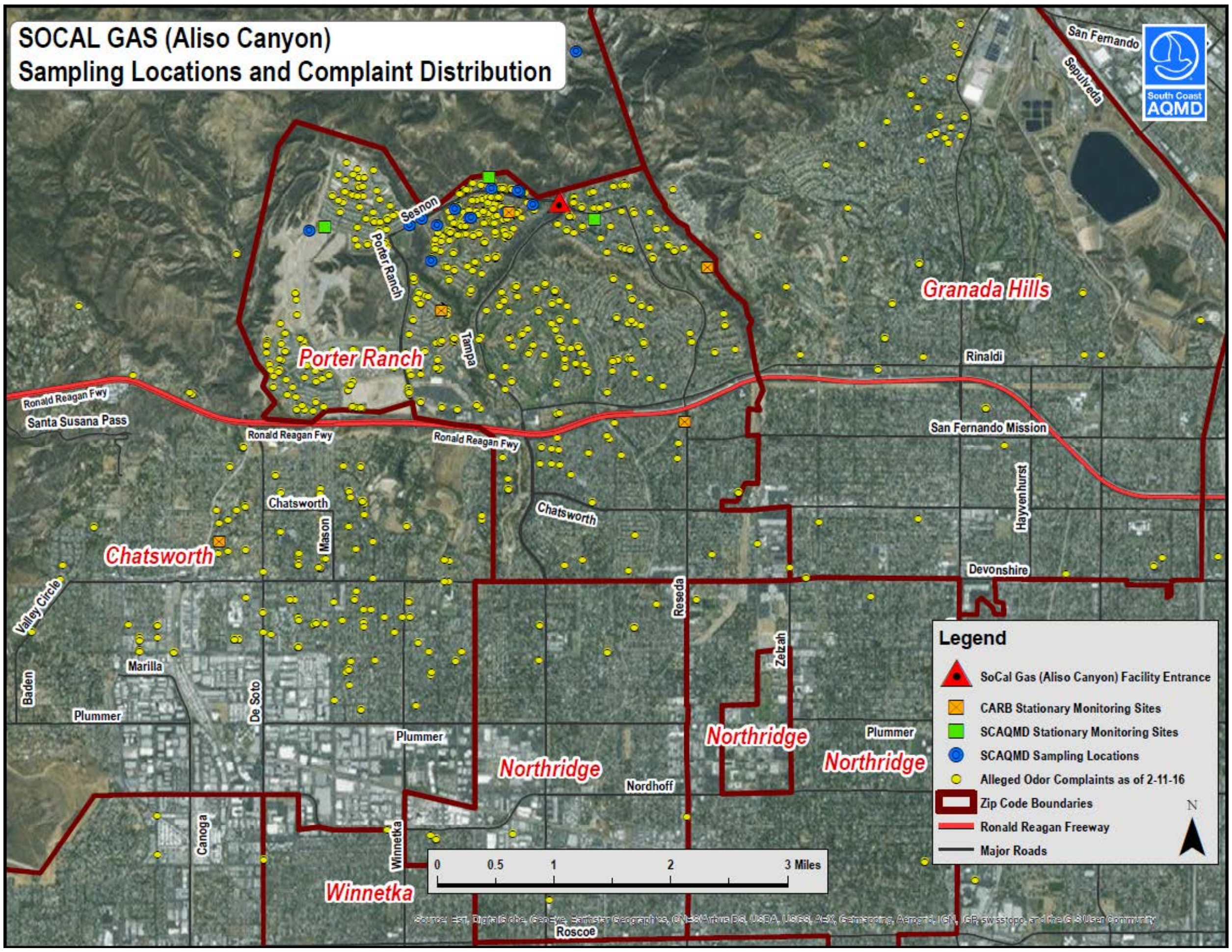
The discrete monitoring methods included:

- Instantaneous grab samples[23] and 12- and 24-hour canister samples that can collect over 50 volatile organic compounds (VOC), semivolatile organic compounds (SVOCs), metals, carbon monoxide, carbon dioxide, methane, ethane, polycyclic aromatic hydrocarbons (PAHs), and non-methane non-ethane organic carbon and sulfur species.
- Liquid scintillation activated charcoal canisters, which can be used to measure radon.

[22] https://www.alisoupdates.com/1443738525764/Facility-Supplemental-Sampling-Summary__02_15.pdf.

[23] Also referred to as short-term air samples, instantaneous grab samples are typically 10-minute samples used to assess air quality at a particular point in time, thus giving a very time resolved understanding of the ambient air, which then can be used to address specific community complaints or concerns.

Figure 14. SCAQMD and CARB sampling/monitoring locations



Each monitoring entity was responsible for reporting its own data. All agencies were committed to providing results to the public quickly and in a transparent and understandable way. Results from the SCAQMD samples were posted on its website as soon as the laboratory analysis was complete, within two to four days after sampling.[24] The results from SoCalGas sampling were summarized on the SoCalGas website under "air sample summary," which included detailed lab reports for each sample. The results for samples collected by LAUSD were posted on the LAUSD website.[25, 26]

Fixed Continuous Monitoring Sites

In December 2015, SCAQMD and CARB began to deploy a network of eight fixed ambient air monitoring sites throughout the Porter Ranch community to continuously measure methane, hydrogen sulfide (H_2S), total sulfur, and benzene (Figure 15)[27] in order to develop a baseline for various measurements and track the trends of pollutants throughout the leak event. The fixed locations allowed the agencies to collect reliable continuous measurements that provided a useful supplement to the discrete

[24]http://www.aqmd.gov/home/regulations/compliance/aliso-canyon-update/air-sampling/laboratory-results---air-sampling-data.
[25]http://achieve.lausd.net/Page/4244.
[26]http://achieve.lausd.net/cms/lib08/CA01000043/Centricity/Domain/135/LAUSD_Radon_Testing_Report_MD.pdf.
[27]Slide 21, Federal Task Force – Aliso Canyon Presentation – June 9, 2016. Presented by Mohsen Nazemi, P.E., Deputy Executive Officer, Engineering and Compliance, SCAQMD to the Public Health and Environment Workgroup on June 9, 2016.

samples, which occurred at different locations throughout the community and provided only a snapshot of air quality during a particular sampling period. Methane and meteorological measurements were also collected at the SCAQMD's Reseda State and Local Air Monitoring Station (SLAMS)[28] monitoring site, located 3.5 miles to the south. Results from the continuous monitors were posted on the SCAQMD and CARB websites in near-real time.

All the CARB sites were located at residential properties in the community. The SCAQMD sites were located at the Porter Ranch Community School (Site #3), Highlands Community Pool (Site #4), and the Castlebay Lane Charter School (Site #6).

To ensure that the data collected during the SoCalGas natural gas leak were accurate and of robust quality, both CARB and SCAQMD implemented quality assurance and quality control checks throughout the monitoring network on a regular basis and performed on-site visits for routine maintenance of the instruments.

Mobile Methane Monitoring

In addition to the eight fixed monitoring sites, SCAQMD operated a mobile monitoring platform measuring methane concentrations[29] in order to better characterize methane concentrations and track emissions transport within the community and surrounding area. While methane itself is not harmful unless it is present in such high concentrations that it displaces the oxygen needed to breathe (generally only in confined spaces), methane measurements throughout the community served as markers for areas with high emissions that could potentially include other pollutants. Mobile methane measurements beginning on December 21, 2015, were performed during different times of the day under varying meteorological conditions. Methane emissions were also observed qualitatively with a Forward Looking Infrared (FLIR) thermal camera, which allowed SCAQMD and CARB to identify the plume of fugitive emissions in areas near SS-25 and to observe the eventual leak closure.

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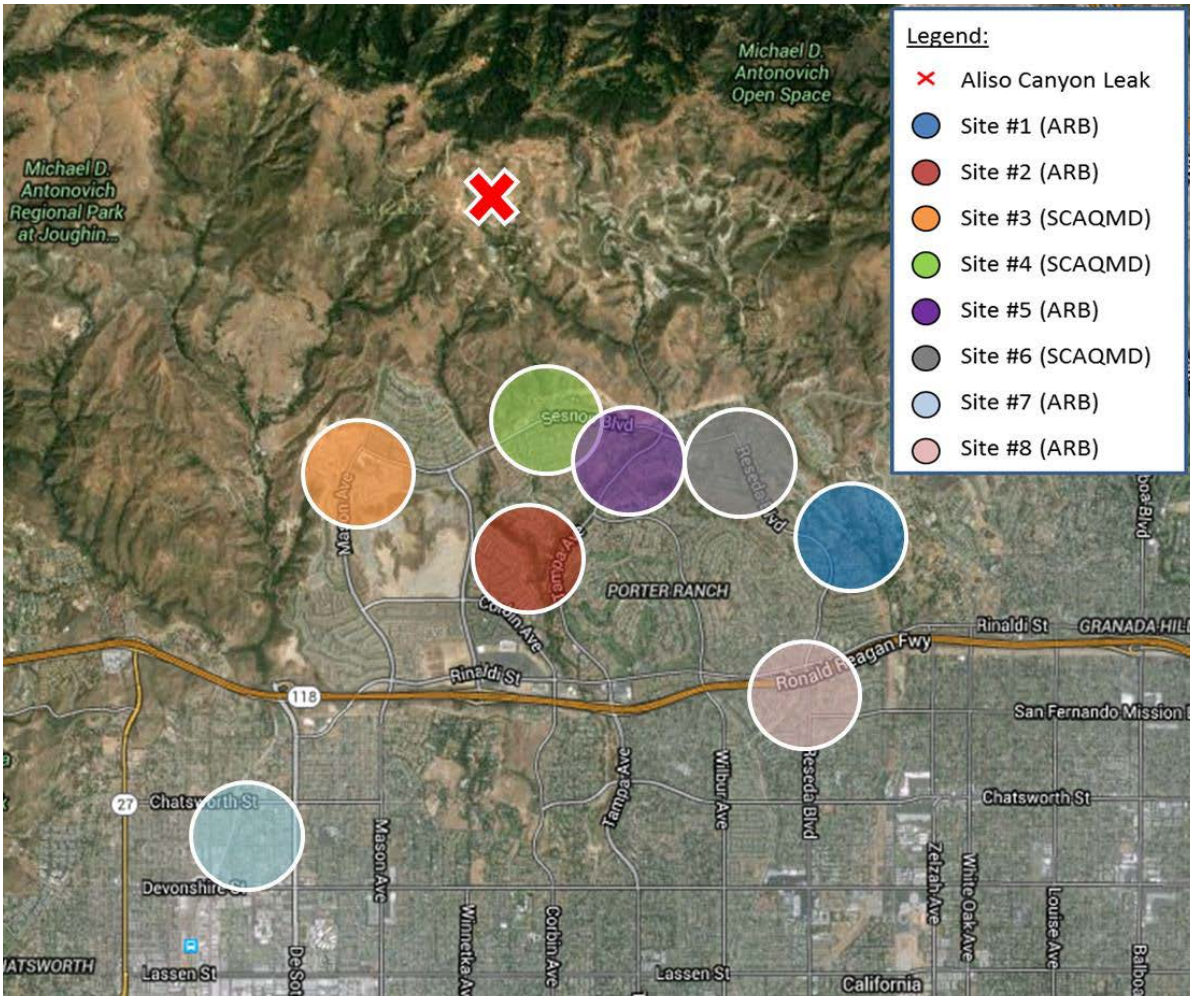
[28]SLAMS monitoring sites are part of the national ambient air monitoring network that typically measure the six criteria pollutant (Particulate matter, lead, ozone, nitrogen oxides, sulfur oxides, and carbon monoxide) in accordance with federal regulations contained in 40 CFR Part 50 and 58.
[29]LI-COR 7700 open path instrument and a Global Positioning System (GPS) mounted on a hybrid vehicle.

Figure 15. Map of fixed monitoring locations



Summary of Results of Ambient Air Pollutant Monitoring

Although final reports from the various ambient air monitoring studies have not yet been released, some preliminary results are available from SCAQMD[30] and the California Office of Environmental Health Hazard Assessment (OEHHA).[31] The collective studies found higher levels of certain air pollutants in some instantaneous samples in the Porter Ranch community. The same air pollutants were identified in a sample taken about 10 feet from SS-25.

The VOC concentrations did not exceed any available acute Reference Exposure Levels (RELs), which are concentrations of chemicals in the air that the general public can be exposed to without experiencing health problems.[32] Of the VOCs, benzene levels tended to be highest and most closely approached the

[30]http://www.aqmd.gov/home/regulations/compliance/aliso-canyon-update/health-impacts-estimates.
[31]http://oehha.ca.gov/air/general-info/aliso-canyon-underground-storage-field-los-angeles-county.
[32]RELs do not include consideration of cancer, which is evaluated using other methods. Exposure to a concentration that is higher than its REL does not necessarily cause health problems, because the RELs are based on several substantial uncertainty factors. A list of OEHHA Acute, 8-hour and Chronic RELs can be found here: http://oehha.ca.gov/air/general-info/oehha-acute-8-hour-and-chronic-reference-exposure-level-rel-summary.

corresponding acute REL. The sample with the highest levels of benzene (3.0 ppb) and other air toxics measured by SCAQMD, out of more than 70 instantaneous community samples, was collected on October 26, 2015, in Porter Ranch. Using the concentrations from that sample, SCAQMD calculated the acute health risk as approximately one-third of the REL. Out of more than 1,000 instantaneous grab samples collected by SoCalGas through February 13, 2016, the highest benzene levels (5.55 ppb) were reported on November 10, 2015. SCAQMD and OEHHA both found the estimate of acute health risk for that sample to be approximately two-thirds of the acute REL—still below the levels at which adverse health effects might begin to be observed.

SoCalGas also measured hydrogen sulfide in instantaneous samples in the Porter Ranch community. The majority of the samples had concentrations that were too low to be measured, but six community samples had detectable levels of hydrogen sulfide.[33] Among those six samples, five had concentrations well below the acute REL of 30 ppb, and only one instantaneous grab sample (collected on November 12, 2015) exceeded the acute REL, at 183 ppb. The only other sulfur-containing compound detected to date in the Porter Ranch neighborhood was a sulfur dioxide level of 54 ppb at the same location on the same day. While detectable, this was still below the sulfur dioxide acute REL of 250 ppb and below the EPA's 75 ppb 1-hour National Ambient Air Quality Standard for sulfur dioxide. These elevated levels of hydrogen sulfide and sulfur dioxide were not detected in other samples.

The majority of hourly methane levels measured at the fixed monitoring sites operated by CARB and SCAQMD were below 30 ppm. The highest hourly methane level measured at one of the sites was 96 ppm, observed on February 11, 2016, just prior to final well kill operations. While the levels are elevated, SCAQMD and CARB do not consider them to be a health concern.[34, 35]

In summary, agencies including LADPH, OEHHA, and SCAQMD reviewed the SCAQMD and SoCalGas data to determine whether there were public health risks associated with exposures to the measured air pollutants. The measured concentrations of air pollutants were below relevant thresholds of concern, except where noted above. More detailed information on the Aliso Canyon health risk assessments are provided in the following section.

Health Risk Assessment and Air Quality Criteria

On October 28, 2015, five days after the leak was discovered, LADPH was asked by the LA County Office of Emergency Management to assess whether the leak could be adversely affecting the health of nearby residents. On November 19, 2015, LADPH issued a Public Health Directive to SoCalGas, along with its first Preliminary Environmental Health Assessment based on its review of available environmental and health data at the time.[36] The directive ordered the gas company to continue the abatement process, eliminate odorous emissions, and provide free temporary relocation to residents who chose to relocate. The preliminary health assessment advised that "methane gas itself poses little direct health threat upon

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[33]The sample detection limit (SDL) is equal to the Detection Limit (1.58 ppbV) x Canister Dilution Factor X Analysis Dilution Factor. For most samples the SDL is approximately 3–4 ppb.

[34]There are no specific exposure limits for methane. Methane is a simple asphyxiant. Its primary health effects relate to its flammability as well as its ability to displace oxygen in certain situations within enclosed structures. The levels found in the community were far below the concentrations that would cause oxygen displacement. Levels of methane found in the community were substantially lower than flammable limits (50,000 ppm).

[35]http://www.aqmd.gov/home/regulations/compliance/aliso-canyon-update/air-quality-criteria.

[36]http://publichealth.lacounty.gov/eh/docs/AlisoCanyon.pdf.

inhalation in an outdoor space. Mercaptans, however, do pose a health threat to the community, including short-term neurological, gastrointestinal, and respiratory symptoms that may result from inhalation." The assessment went on to state that exposures to these pollutants would not constitute an immediate danger to life, and that permanent or long-term health effects were not expected. After the publication of that preliminary health assessment, LADPH went on to publish a number of reports summarizing the results of the SoCalGas monitoring data.[37]

OEHHA also convened an independent panel of scientific and medical experts to review public health concerns stemming from the gas leak, and to evaluate whether additional measures beyond those already put in place were needed to protect public health.

In conducting its assessment, OEHHA compared the measured peak concentrations to acute RELs in order to evaluate potential effects due to short-term exposures.[38] OEHHA also compared longer-term average benzene exposures to chronic RELs, although chronic RELs typically are used to evaluate exposures that last for at least 8 years.

One of OEHHA's earliest health risk assessments, from January 14, 2016,[39] concluded:

- Overall, the available air sample data did not indicate that an acute toxicity health hazard existed in the Porter Ranch neighborhood as a result of the Aliso Canyon natural gas leak.
- This did not mean that the adverse physical symptoms reported by many Porter Ranch neighborhood residents were not real. The natural gas odorants tert-butyl mercaptan and tetrahydrothiophene have strong odors that can be perceived at concentrations below the levels that can be detected in air samples. These odors can evoke physiological responses (e.g., nausea, headaches) without inducing more serious or longer-lasting health effects, such as eye or respiratory system damage.

The SoCalGas air samples measured levels of certain volatile organic compounds (VOCs) and sulfur-containing compounds, including benzene, hydrogen sulfide, and sulfur dioxide, all of which are pollutants that can be harmful to human health if levels are high enough. Key findings from OEHHA's review of the data included:

- Of the sampled VOCs, none was found to be above levels expected to result in adverse health effects.
- Benzene, a VOC, tended to have the highest levels, although they still were below levels expected to result in adverse health effects. (The highest sampled benzene concentration measured by SoCalGas, observed on November 10, 2015, in the Porter Ranch Community, was 5.55 ppb, which is approximately 70% of the acute health benchmark[40]).
- The level of sulfur-containing compounds (hydrogen sulfide and sulfur dioxide) sampled in the area were generally below detection limits and below levels expected to result in adverse health impacts,

[37]http://www.publichealth.lacounty.gov/media/gasleak/reportpress.htm.

[38]The assessment could only be conducted on pollutants for which a Reference Exposure Level (REL) exists. RELs are concentrations of chemicals in the air that the general public can be exposed to without experiencing health problems. RELs do not cover cancer, which is evaluated using other methods. Exposure to a concentration that is higher than its REL does not automatically cause health problems, because the RELs are based on several substantial uncertainty factors. A list of OEHHA Acute, 8-hour and Chronic RELs can be found here: http://oehha.ca.gov/air/general-info/oehha-acute-8-hour-and-chronic-reference-exposure-level-rel-summary.

[39]http://oehha.ca.gov/media/downloads/air/general-info/oehhaalisocanyonbackground01142016.pdf.

[40]Collected with 12-hour canister sample.

with one exception. On November 12, 2015, one instantaneous grab sample of hydrogen sulfide was above the acute health benchmark (183 ppb, which exceeds the acute health benchmark of 30 ppb). This elevated concentration was not repeated in other samples and was considered to be anomalous.

Subsequent updates to OEHHA's health assessments did not fundamentally change as new sampling data were collected. Evaluations of potential health impacts to the Porter Ranch community were also published by SCAQMD and the LADPH, and both agencies reached similar conclusions to those found by OEHHA.[41, 42]

OEHHA also convened an independent panel of scientific and medical experts to review public health concerns stemming from the gas leak and evaluate whether additional measures were needed to protect public health beyond those already put in place.[43], [44]

SCAQMD and CARB jointly developed a document titled "Criteria for Determining when Air Quality in the Porter Ranch and Surrounding Communities Has Returned to Typical (Pre-SS-25 Leak) Levels".[45] The criteria were developed to determine when air quality in Porter Ranch and the surrounding community returned to levels consistent with those that were typical prior to the leaking well at the Aliso Canyon natural gas storage facility.

Since February 11, 2016, when these criteria were first applied to the collected air data (after well closure), all laboratory samples and continuous monitoring data have met their respective criteria for mercaptans, benzene, and hydrogen sulfide. The only samples that have not met their criteria are a number of 12-hour methane samples collected by SoCalGas that were greater than the 3 ppm criterion for methane. According to the SCAQMD website:

> "It is possible that continued off-gassing of residual methane in the soil near SS-25 is causing higher measurements near the facility fence line. However, the reason for the slightly higher than criteria levels of methane at community sites located further south is unclear. ARB and SCAQMD are investigating to determine the cause, including reviewing potential sources and quality assurance between laboratories."

The methane criteria were set primarily to make sure that the SS-25 well had not resumed leaking. SCAQMD and CARB do not consider these levels to be a health concern, because health effects from methane exposure occur at levels far above the criteria level of 3 ppm.[46]

CARB staff also researched filtration technologies for portable indoor air cleaning devices and in-duct filters and identified those that were most likely to be effective in removing sulfur compounds and other chemicals likely to be in the plume. They communicated their recommendations to SoCalGas staff. In December 2015 and January 2016, guidance for selecting and maintaining an air cleaner, and a list of

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[41] http://www.aqmd.gov/home/regulations/compliance/aliso-canyon-update/health-impacts-estimates.
[42] The reports can be found on the LADPH website: http://www.publichealth.lacounty.gov/media/gasleak/reportpress.htm.
[43] http://oehha.ca.gov/media/downloads/air/document/alisocanyonadvisorypanel01152016.pdf.
[44] http://oehha.ca.gov/media/downloads/air/document/alisocynsummaryexpertadvisors02122016n.pdf.
[45] http://www.arb.ca.gov/research/aliso_canyon/aliso-canyon-criteria-description.pdf.
[46] Methane is a simple asphyxiant. Its primary health effects relate to its flammability as well as its ability to displace oxygen in certain situations within enclosed structures. The levels found in the community were far below the concentrations that would cause oxygen displacement. Levels of methane found in the community were substantially lower than flammable limits (50,000 ppm).

available air cleaners that appeared to be most effective for homes in the plume, were posted on a website developed specifically for the Aliso Canyon residents.[47]

Greenhouse Gas Emissions

Significant ambient air monitoring was conducted at and around the vicinity of the Aliso Canyon release, as discussed above. In addition to the methane data collection by CARB, a number of additional measurement resources were deployed by SCAQMD, LAUSD, SoCalGas, and others to quantify the methane emissions from the leak site by a variety of State, local, and Federal agencies in collaboration with several independent research teams. They included measurements near the ground at the well site, at tall monitoring network towers, and from airplanes and satellites. The efforts were intended to calculate the direct emission rates in order to help estimate the total methane emissions associated with the leak.

Aircraft Studies

Based on four airborne samples collected over the first 6 weeks of the release, the average leak rate was estimated to be 53 metric tons of methane per hour. The leak rate showed a decreasing trend after the initial 6 weeks, likely due to a deliberate effort, beginning on November 11, 2015, to withdraw natural gas to reduce the pressure in the subterranean reservoir. The estimates collected between November 7, 2015, and February 4, 2016, were interpolated over time to arrive at a total estimate of methane emitted from the event. In a February 2016 journal article, Conley et al. estimated the total mass of methane released at 97,100 metric tons over the 112-day duration of the leak.[48, 49]

On February 13, 2016, CARB publicly released its preliminary estimate of cumulative methane emissions from the Aliso Canyon natural gas leak, based on flights and updated estimates of hourly methane emissions. The February 2016 CARB preliminary estimate was 94,500 metric tons of methane.[50]

In January and February 2016, several flights funded by the National Aeronautics and Space Administration (NASA) were made for rapid response airborne surveys over Aliso Canyon with two Jet Propulsion Laboratory (JPL) imaging spectrometers. The results are being validated against measurements of methane mixing ratios from other aircraft and surface vehicles, surface observations of wind direction and speed, and up-looking thermal plume imaging. Results will be published in 2016 or early 2017.

Tracer flux from instrumented vans

Under contract with SoCalGas, Aerodyne conducted a study to estimate methane emissions by using nitrous oxide as a “tracer” in the released gas. From December 21, 2015, to March 8, 2016, Aerodyne released a known concentration of nitrous oxide near the well, then measured the nitrous oxide and methane concentrations downwind of the site. Because the concentration of nitrous oxide released at the well is known, and can be compared to the measured nitrous oxide concentration downwind, that information together with co-located measured methane concentrations can be used to estimate the

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[47]http://www.arb.ca.gov/research/indoor/aircleaners/air_cleaners_gas_leak.htm.

[48]While several data sources discussed here provide uncertainty ranges on certain components of their data (e.g. estimate for an individual day or flight), uncertainty ranges were not available from the sources for the estimates of the total methane released by the leak.

[49]Methane emissions from the 2015 Aliso Canyon blowout in Los Angeles, CA; *Science*, 18 March 2016.

[50]Aliso Canyon Natural Gas Leak Preliminary Estimate of Greenhouse Gas Emissions; CARB, as of April 5, 2016.

concentration of methane released from the well. This process is referred to as the "tracer flux ratio" method. Although the study has not yet been published, the Aerodyne estimate of the release is understood to be 86,000 metric tons of methane.[51]

Stored Gas Inventory Analysis

Stored gas inventory analysis is an industry standard method used to determine the quantity of natural gas in an UGS reservoir. The basic data used for inventory analysis are well pressures and measured volumes of gas metered into and out of the field (injection and withdrawal).[52] SoCalGas conducts periodic pressure checks of the reservoir, which require a complete multi-day shutdown of the reservoir field to let the pressure equalize throughout the reservoir. These events are referred to as "shut-ins." SoCalGas used the most recent data from "shut-in" events, which were gathered in the spring and fall of 2014 and again in late February 2016 to estimate emissions. The February 2016 shut-in inventory was done between February 19 and 29, after SS-25 was sealed. These pressure data were used to calculate total natural gas volumes and to calculate the leaked methane by accounting for total injections and withdrawals. This approach yielded a total leak estimate of 4.62 bcf of natural gas, which translates to emissions of approximately 84,200 metric tons of methane. The leak at Aliso Canyon was the largest release of methane to the atmosphere from a UGS facility in U.S. history. The 2004 UGS leak at Moss Bluff, TX, was burned as it was released, converting the methane to carbon dioxide and resulting in a lower climate change impact.

CARB Final Estimates of Methane from Aliso Canyon

CARB will issue a revised estimate of the leak from Aliso Canyon after reviewing data available from numerous monitoring methods. Consideration of multiple measurement methods should provide for a more robust assessment of methane emission rates and result in an improved quantification of emissions compared to the preliminary assessment. The final State calculation of total methane emitted, based on the full set of data, is anticipated to be released by CARB in 2016.

Environmental Impacts

This methane release is likely the largest of its kind ever in the United States, exceeding methane emissions from other known gas release incidents, such as those occurring at storage facilities in Moss Bluff, TX, in 2004 and Hutchinson, KS, in 2001. For context, the radiative forcing of about 90,000 metric tons of methane over the next 100 years is equivalent to the atmospheric release of more than 2 million metric tons of carbon dioxide—using 100-year methane global warming potential (GWP)[53]—or the greenhouse gas emissions of around 500,000 passenger cars driven for 1 year.[54, 55] CARB, in its mitigation

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[51] *Airborne Estimate of surface emissions*, slide presentation by Dr. Stephen Conley and Ian Faloona, presented at CARB's Methane Symposium on June 6, 2016; http://www.arb.ca.gov/cc/oil-gas/Conley_Presentation_ARB%20(1).pdf, accessed August 3, 2016.

[52] Aliso Canyon Underground Gas Storage Facility - Methane Emission Estimates, SoCalGas, June 14, 2016.

[53] Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (AR5), Synthesis Report, Box 3.2. The 100-year GWP of methane is 28 in AR5, and is 25 in AR4. EPA's Inventory of Greenhouse Gas Emissions and Sinks notes that methane emissions from the energy sector totaled 328 million metric tons of CO2 equivalent in 2014.

[54] USEPA Greenhouse Gas Equivalency Calculator, https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator; accessed June 13, 2016.

[55] The concept of the Global Warming Potential (GWP) was developed to allow comparisons of the global warming impacts of different gases. The U.S. primarily uses the 100-year GWP as a measure of the relative impact of different greenhouse gases (GHGs). However, the scientific community has developed a number of other metrics that could be used for comparing one GHG to another. These metrics may differ based on timeframe, the climate endpoint measured, or the method of calculation.

program, uses a 20-year methane GWP resulting in methane emissions equivalent to about 8 million metric tons of carbon dioxide.

Post-Well Closure Indoor Air and Source Sampling/CASPER Health Assessment

Following the closure of SS-25 in mid-February, residents began returning to their homes from temporary housing. From late February into March, LADPH began receiving a large number of health complaints from the Porter Ranch community. The complaints included reports of headache, nasal congestion, sore throat, respiratory problems, nausea, dizziness and skin rash. Symptoms ceased when residents returned to temporary housing located outside of the area affected by the gas leak.

On March 23, 2016, LADPH announced a protocol developed in conjunction with EPA Region 9, UCLA, CARB, SCAQMD, and others for sampling the interior of homes for residual contamination from the release. The protocol was intended to address volatile contaminants that had been measured in ambient air during the release, as well as semi-volatiles and metals that may have been present in the geological formation or in the material used during the top kill attempts and released into the air.

In an effort parallel to the indoor sampling, LADPH, with the help of the California Department of Public Health (DPH), began a Community Assessment for Public Health Emergency Response (CASPER) health assessment on March 10-12, 2016. Initial results of the assessment indicated that there were health issues reported that could be related to the gas leak or other emission sources near the storage facility.[56]

On April 20, 2016, LADPH collected six soil samples in the vicinity of SS-25 to address a data gap in the environmental sampling. Some soils near SS-25 were visibly impacted by non-volatile constituents of the release. While the soil data could have been biased by chemical breakdown, volatilization, and other weathering, it was judged as the best indicator of chemical signatures of the release that might persist in the community. These samples indicated elevated levels of chemicals including hydrocarbons up to C_{40}, barium, and naphthalene.

On May 13, 2016, LADPH released its public health assessment report, titled *Environmental Conditions and Health Concerns in Proximity to Aliso Canyon Following Permanent Closure of Well SS-25*.[57] The report presented the results of both the indoor exposure evaluation and the CASPER health effects evaluation.[58]

Indoor Exposure Evaluation

LADPH relied on testing and analysis protocols used in other environmental incidents. Using a list of 200 chemicals potentially associated with both natural gas leaks and well closure attempts at Aliso Canyon (including drilling material components), LADPH selected for analysis metals, semi-volatile organic compounds (SVOC), volatile organic compounds (VOC), and petroleum hydrocarbons. A subset of this group was identified as priority chemicals of potential concern: sulfur compounds, benzene and other volatile organic compounds, barium, petroleum hydrocarbons, and polycyclic aromatic hydrocarbons. Because reported symptoms occurred after residents returned to their homes, LADPH considered that symptoms could be the result of exposure to indoor air or from surfaces in homes, and tested for chemical

[56] http://publichealth.lacounty.gov/media/docs/assessment.pdf.
[57] http://www.publichealth.lacounty.gov/media/docs/PublicHealthAssessment.pdf.
[58] Results are presented in Appendix A of the following report: http://www.publichealth.lacounty.gov/media/docs/SummaryFieldSamplingReport.pdf.

contaminants in both indoor air and household surface dust in 114 homes and two schools. Eleven of the homes, located 6 miles from SS-25, were used as a comparison group.

Surface wipe sample analysis showed a pattern of barium plus other metals in Porter Ranch homes not observed in comparison homes. This pattern is consistent with the composition of barium sulfate drilling fluids used in well kill attempts. Indoor air analysis showed that levels of chemicals detected were similar between Porter Ranch homes and comparison homes, and were consistent with expected background levels in home environments.

CASPER Health Effects Evaluation

LADPH developed two survey tools to collect information on health symptoms experienced by residents in the Porter Ranch community. The first survey tool used was a Community Assessment for Public Health Emergency Response, or CASPER, to collect information from a representative sample of 210 homes within a 3-mile radius of SS-25. The CASPER survey was conducted March 10-12, 2016. The second survey tool was a modification of the CASPER survey directed to the approximately 100 households participating in the indoor exposure evaluation to assess the health symptoms experienced by residents.

The majority of households experienced health symptoms in the month following well seal. Households closer to the well were more likely to report health symptoms or oily residue. There was no difference in reports of gas odor in relation to well proximity. The majority of households reported using air cleaners or purifiers.

Home Cleaning Activities

On May 13, 2016, LADPH issued a Directive to SoCalGas to offer comprehensive cleaning to all homes in Porter Ranch, all homes of relocated residents, and all homes within 5 miles where residents experienced symptoms.[59] This directive was followed by a May 20, 2016, ruling from the Los Angeles Superior Court that ordered SoCalGas to pay for cleaning the homes of those households participating in the SoCalGas relocation program. According to SoCalGas, all residents who had been relocated at the time of the ruling have returned home after the completion of interior home cleaning.[60]

Additional Sampling Activities

On June 22, 2016, June 23, 2016, and July 9, 2016, LADPH collected samples from community pools in three Porter Ranch neighborhoods. Samples were analyzed for petroleum hydrocarbons (EPA Method 8015B), metals (EPA Method 6010B), and mercury (EPA Method 7470A). Petroleum hydrocarbons and mercury were not detected in any of the samples. Several metals were detected, including barium ranging from 0.085 to 0.422 milligrams per liter (mg/L), which is below the Federal maximum contaminant level (MCL) for drinking water of 1 mg/L.[61] According to LADPH, the purpose of this sampling was to provide guidance regarding the collection and analysis of water from the selected community swimming pools. The resulting data will be used to assess potential public health impacts of the gas leak event on water quality in pools, though no public health statements have yet been issued.

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[59] http://www.publichealth.lacounty.gov/media/docs/LACHODirectivetoSCG(w%20Atts).pdf.

[60] https://www.alisoupdates.com/our-commitments.

[61] The protocol and report are available at:
http://publichealth.lacounty.gov/media/docs/CommunityPoolWaterSamplingProtocol.pdf.

Greenhouse Gas Mitigation Plan

Mitigation of the greenhouse gas impacts from the Aliso Canyon natural gas leak is not required under California regulations, nor are fugitive emissions capped by California's economy-wide greenhouse gas cap and trade program. On December 7, 2015, the City of Los Angeles filed a civil lawsuit in California Superior Court in Los Angeles against SoCalGas in connection with the Aliso Canyon leak. In early 2016, CARB joined the suit. The lawsuit includes claims alleging that methane emissions from the leak have created a nuisance and have impaired and polluted the environment. The complaint seeks relief related to the leak's climate impacts.

On December 18, 2015, SoCalGas sent a letter to Governor Brown confirming the company's commitment to "mitigate environmental impacts from the actual natural gas released from the leak" and "work with State officials to develop a framework that will help us achieve this goal." On March 31, 2016, CARB recommended a program to achieve full mitigation of the climate impacts of the Aliso Canyon natural gas leak. CARB's development process included consultation with other State agencies and two rounds of public comment. CARB recommends that the emission reduction offsetting component should focus on reducing methane emissions from California agriculture (including dairies) and waste (including landfills and wastewater) that would allow for a direct ton-for-ton comparison between leaked emissions and emissions reductions from mitigation projects. CARB notes the pending litigation and its potential effect on any mitigation program.

Southern California Gas and Electric System Reliability Analysis

Role of Aliso Canyon in SoCalGas and Electric Reliability

SoCalGas owns and operates an integrated natural gas pipeline system consisting of intrastate pipeline and four storage facilities. The SoCalGas system has the capacity to accept up to 3.875 billion cubic feet per day (Bcfd) of natural gas supply, primarily from the southwestern United States, the Rocky Mountain region, Canada, and California, but system supplies generally do not exceed 3.0 Bcfd. The SoCalGas system uses natural gas from storage and pipeline supplies to meet customer demand. As a result, storage fields are essential operating assets in the SoCalGas system for delivering natural gas and maintaining pipeline pressure while serving all demand for natural gas and allowing for operating flexibility.

The four SoCalGas storage fields have a combined capacity of 136.1 billion cubic feet (Bcf), with the ability to inject up to 850 MMcfd and withdraw up to 3.68 Bcfd. Aliso Canyon is the largest storage field, with storage capacity of 86.2 Bcf, withdrawal capacity of 1.9 Bcfd, and injection capacity of 0.4 Bcfd. During the leak, California State agencies ordered SoCalGas to withdraw natural gas from Aliso Canyon in order to reduce the rate of the gas leak by reducing the pressure at the field. The field was drawn down to 15 Bcf, all of which remained available as of October 2016 in storage at Aliso Canyon to meet peak day demands and maintain system pressure. SoCalGas will need CPUC approval to begin any injections at Aliso Canyon, although it can withdraw from storage the remaining 15 Bcf if needed.

The absence of Aliso Canyon's full storage capabilities especially affects SoCalGas's Los Angeles local gas pipeline system, the L.A. Loop. The L.A. Loop is a low-pressure local pipeline system that serves a number of customers, including 17 power plants which, in sum, have a total generating capacity of about 9,400 megawatts (MW).[62] Given Aliso Canyon's size, it is important to maintaining pressure on that part of the SoCalGas system. For example, if pipeline pressure on the L.A. Loop drops too low, SoCalGas may be forced to curtail natural gas deliveries to the power plants. The three other SoCalGas storage facilities (Honor Rancho, La Goleta, and Playa del Rey) are smaller and less capable of providing natural gas to the L.A. Loop.

The amount of natural gas-fired generation on the L.A. Loop makes maintaining pipeline pressures more difficult. The power produced by the natural gas-fired generation on the L.A. Loop fluctuates continuously, because it provides ramping supply to accommodate the variability of renewable generation. The most extreme daily ramp occurs during the afternoon, when solar generation declines due to the changing angle of the sun and natural gas-fired generation must increase to meet increased load.

The increase in net electric load (load minus variable renewable generation) from daily minimum to maximum load in the afternoon to evening coincides with the increase in locally located renewable generation. While the significant growth in wind and solar generation over the past few years has reduced the net electric load served by all conventional generation, it has also increased the need to ramp up large amounts of natural gas-fired generation each afternoon to make up for the decline in solar output that occurs during the afternoon peak in electricity demand.

Gas-fired generation is typically used to meet this increase in demand for conventional generation because of its ability to respond to changes in demand quickly and efficiently, as compared with other conventional generation. This results in increased demand for natural gas pipeline deliveries and storage withdrawals. The loss of Aliso Canyon has greatly reduced the ability of storage to help meet the surge in gas demand required to support the daily ramping requirement and evening peak load in Southern California.

In prior summer periods, SoCalGas used Aliso Canyon primarily to maintain pipeline pressure, and also to assist in meeting peak demand. On average, SoCalGas withdrew natural gas from Aliso Canyon approximately 10 days per month during the summer. Between April and October, SoCalGas normally injected gas into Aliso Canyon, refilling it by the end of October so that it could be used to meet winter peak gas demand.

In prior winter periods (November-March), SoCalGas demand peaked at 5.1 Bcfd, of which 1.0 Bcfd (about 20%) was demand from electricity generation facilities. Because SoCalGas pipeline capacity for imports into Southern California is only 3.875 Bcfd, Aliso Canyon has been used to make up the difference on peak days. Toward the end of winter, SoCalGas typically has begun refilling the field to support summer needs. Concerns for winter 2016/2017 are discussed below.

Gas Balancing

In general, the largest potential cause of gas curtailments in the summer occurs when the natural gas nominated for delivery on the SoCalGas system is significantly less than gas demand, or when demand

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[62]The 17 power plants connected to the L.A. Loop, with a combined capacity of 9,388 MW, include: Los Angeles Water and Power (LADWP) Haynes, LADWP Scattergood, LADWP Valley, LADWP Harbor, Southern California Edison (SCE) Alamitos Toll, SCE Huntington Beach, SCE Redondo Beach, SCE Barre Peaker, SCE Center Peaker; El Segundo Energy Center, Long Beach Generation, City of Glendale, City of Burbank, City of Pasadena, City of Anaheim-Canyon Power, City of Vernon-Malburg, and Southern California Public Power Authority-Magnolia.

exceeds the short-term delivery capability of the gas system, creating an imbalance. Large imbalances reduce pipeline operating pressure. If pressure drops enough, reliability of gas service to gas-fired generators and other customers is jeopardized. This is of particular concern during periods of high demand for electricity generation during the summer, when natural gas is used by generators to serve electricity demand. Other challenges occur during periods when predicting demand (and thus generator dispatch) becomes especially difficult, such as periods of monsoon cloud cover.[63] In addition, large changes in electricity generation (which, in practice, translate to large changes in demand for natural gas) within short periods push the limits of the gas system's ability to keep up without the nearby supplies formerly stored in Aliso Canyon. The electricity generators in the SoCalGas L.A. Loop have limited access to additional gas during the day to meet unanticipated shortages in gas supply. Gas that is available at connecting interstate pipelines at the Arizona-California border cannot be delivered in real time to electricity generators in the L.A. Loop, because gas moves through the transmission system at approximately 25 miles per hour.

If demand for natural gas approaches any of the gas system's constraints, SoCalGas can issue an Operational Flow Order (OFO) in order to maintain gas system pressure. During an OFO, customers must keep actual gas demand close to their nominated amounts on the SoCalGas system or face penalties. If an OFO fails to improve the match of flowing gas to use, SoCalGas can order curtailments of gas supply to non-core customers, which include electricity generators. The loss of a curtailed generator can be mitigated by redispatch of the electric system, but the amount of generation available for re-dispatch is limited. In 2016, to mitigate the impacts of the limited operation of Aliso Canyon, SoCalGas issued OFOs identifying the need to keep gas flows and usage within a 5-percent tolerance to maintain pipeline pressures during certain conditions.

Compounding Concurrent Events

Potential curtailments of natural gas supply can occur as a result of concurrent events on the gas or electricity systems. Such events may place additional constraints or exhaust any operating margin on the gas system, which will limit the rate at which gas can flow. Events may include:

- Scheduled maintenance and testing of natural gas pipeline systems that may remove facilities from service or reduce the capacity of those facilities (work on the gas pipeline typically is performed during non-winter months to prepare the natural gas system to meet winter peak demands for heating)
- Forced outages due to equipment failures on the SoCalGas system
- Lack of supply into the SoCalGas system from upstream pipeline interruptions
- Deviation in actual demand from forecasts of both core (residential and commercial) and non-core (electric and industrial) natural gas customers during periods of rapidly changing weather
- Temperatures higher or lower than expected that translate into unexpected demand for electricity.

Implications for Summer Operations

During the summer of 2016, the loss of Aliso Canyon increased the likelihood of curtailments of natural gas deliveries to generators because of a lack of supply or problems maintaining sufficient pipeline pressure, which subsequently increased the likelihood of regional electricity generation shortages. The

[63]Monsoon rain storms typically develop in hot summer afternoons which result in significant cloud cover and rain which block the sun, which lowers solar electric production.

analysis performed in the Joint California Agencies April 2016 Aliso Canyon Risk Assessment Technical Report[64] estimated, in a worst case scenario, that there would be up to 14 days of loss of load and 16 days of gas curtailments during the summer of 2016. The determination of the number of loss of load and gas curtailment events assumed concurrent events, ineffective mitigation measures, and/or no gas withdrawals from Aliso Canyon.[65] As of September 2016, there were no loss of load events from curtailments of natural gas supply.

The California Independent System Operator (CAISO) and the LADWP have the ability to change their electricity generation dispatch to absorb some curtailments, depending on local and system demand. CAISO has said that it can re-dispatch about 1,500 MW out of the area affected by a curtailment; beyond that, it is at risk of being unable to serve all anticipated electric loads.[66] As of September 2016, the entities have been able to avoid electricity curtailments primarily by being attentive to the need to balance natural gas supply and demand more tightly and through the occasional use of "flex alerts," which signal electricity consumers to reduce electricity usage where possible during periods of expected high electricity use (e.g., high temperatures).

Electric Reliability Concerns for Winter 2016–2017

The *Joint California Agencies Winter Technical Analysis Report*[67] indicates that, through a series of significant mitigation measures, the L.A. Basin electric power system is expected to be able to maintain reliability for the winter 2016-2017 without interruption to electric service. This is despite the fact that winter normally brings a significant increase in natural gas demand from the residential and commercial sectors for heating needs. In a typical winter, SoCalGas meets its peak demand with a combination of pipeline gas and storage withdrawals from facilities like Aliso Canyon. Without Aliso Canyon for winter 2016-2017, the likelihood of natural gas supply curtailments, and reductions in electric power generation, increases. In addition, unforeseen events during the upcoming winter period—such as upstream supply interruptions into the SoCalGas system, gas well "freeze offs," and other equipment failures that can occur during very cold weather—may present energy reliability challenges.

However, because electricity demand throughout the U.S. Southwest is lower in the winter than in the summer, there is an ability to use spare capacity on electric transmission lines and at power plants outside the L.A. Basin to import power if SoCalGas needs to curtail gas deliveries to power plants inside the L.A. Basin. That extra capacity can be used to reduce electric reliability concerns.

Mitigation of Reliability Concerns

To mitigate the reliability risks associated with the loss of Aliso Canyon, FERC, CEC, CPUC, and SCAQMD have taken regulatory and other actions, including the following:

- FERC expedited approval of additional authority, processes, and cost recovery that CAISO claimed it needed to operate reliably.

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[64] http://www.energy.ca.gov/2016_energypolicy/documents/2016-04-08_joint_agency_workshop/Aliso_Canyon_Risk_Assessment_Technical_Report.pdf.
[65] http://www.energy.ca.gov/2016_energypolicy/documents/2016-04-08_joint_agency_workshop/Aliso_Canyon_Risk_Assessment_Technical_Report.pdf.
[66] Re-dispatching the system involves reducing generation at one or more generation plants and increasing generation at other generation plants while maintaining load-generation balance.
[67] http://docketpublic.energy.ca.gov/PublicDocuments/16-IEPR-02/TN212913_20160823T090035_Aliso_Canyon_Winter_Risk_Assessment_Technical_Report.pdf.

- The SCAQMD approved temporary variances to allow fuel switching of some of LADWP's electric generation plants in the L.A. Basin.
- The Joint California Agencies—CEC, CPUC, LADWP, and CAISO—analyzed the risks of operating without Aliso Canyon, suggested mitigation measures, and raised awareness of the issues through workshops, technical conferences and presentations at regulatory meetings to disseminate information on how each of the entities (both gas and electric) are preparing to address electric reliability issues.
- The CPUC approved a settlement addressing SoCalGas's operational issues.

The implementation of OFO and CAISO stakeholder processes has helped to raise awareness of the operational problems created by the Aliso Canyon outage. The market changes implemented in response to the Aliso Canyon have motivated generators and other gas shippers to better balance their gas supplies with their usage. Previously, SoCalGas balanced its system on a monthly basis, which allowed customers great flexibility in either under-taking or over-taking nominated gas volumes each day, provided that the amounts evened out over each month. The outage at Aliso Canyon has all but eliminated the ability to operate with that level of flexibility. SoCalGas has frequently used OFOs to require shippers to balance natural gas supply and demand by keeping their daily natural gas demand close to their daily pipeline nominations.

Peak Reliability, the WECC reliability Coordinator, has also been involved in local and regional procedures and activities to ready regional operators for possible system issues, ranging from local calls for conservation to the delivery of capacity and energy from resources across the Western Interconnection to the L.A. Basin. Peak Reliability has also reviewed firm load shed plans and procedures in preparation for shortages.

Gas/Electric System Reliability Conclusions for Southern California

Aliso Canyon has historically been a significant storage facility on the SoCalGas system used to meet peak day demand and maintain system pressure. Preparing the gas and electric systems for the absence of Aliso Canyon, by defining new gas balancing parameters, training personnel, and addressing barriers to sharing information on gas and electric deliveries into the southern California region has played and will continue to play a key role in avoiding electric load curtailments since the Aliso Canyon leak.

During 2016 summer operations planning, day-ahead scheduling, and real-time operations, the information flow between gas and electric operation planners enhanced existing processes. This led to the adjustment and coordination of gas and electric maintenance schedules in order to avoid overlapping outages that could lead to gas curtailments of electricity generation, which in turn could lead to blackouts. The information flow to both gas and electric operations and market personnel in the day-ahead gas and electric scheduling processes permitted the adjustment of gas and electric energy schedules to help balance both systems to minimize OFOs and avoid gas curtailments.

This winter, additional preparation and coordination are required in order to avoid gas and electric curtailments.

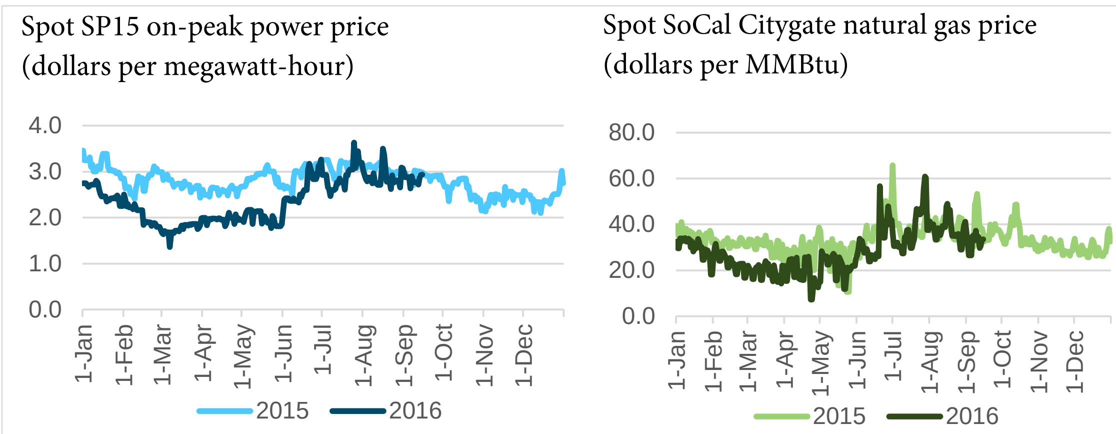
Gas/Electric Price Analysis

Summary

Through mid-September 2016, Southern California natural gas and electric prices have continued to trade within ranges set during 2015, despite restrictions on the use of the Southern California Gas Company's

(SoCalGas) Aliso Canyon natural gas storage field at Porter Ranch in Los Angeles County (Figure 16). However, the spread between the price of forward contracts for natural gas delivery in winter 2016-17 in Southern California and those for delivery at Louisiana's Henry Hub, the most important trading center for natural gas in the United States, have widened substantially from year-ago levels (Figure 17). The wider current spread is consistent with an anticipated lower level of natural gas storage deliverability from the SoCalGas system compared to expectations prior to the leak at the Aliso Canyon facility that began in October 2015 and was plugged in February 2016.

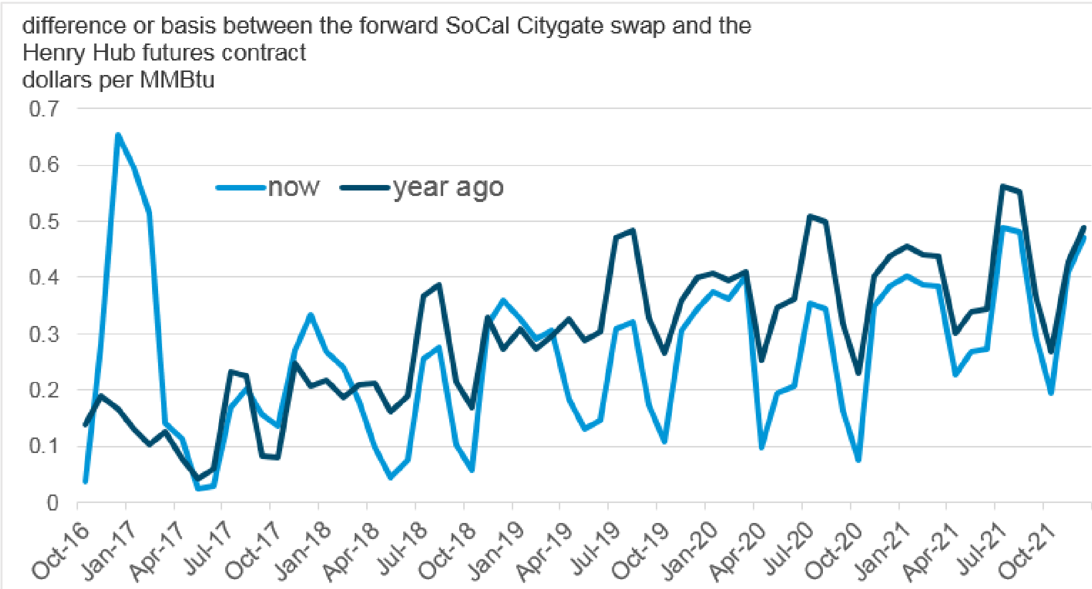
Figure 16. Southern California spot electricity prices and spot natural gas prices down slightly in 2016 compared to 2015



Note: Covers January 1, 2015-September 15, 2016.
Source: SNL Energy.

Retail energy prices are different from wholesale prices. Retail prices are determined through regulatory processes that incorporate average wholesale prices with other energy delivery expenses. Because of regulatory decisionmaking, retail prices can vary significantly by customer class and energy usage. Recent changes in retail natural gas costs are most directly linked to changes in wholesale natural gas prices.

Figure 17. Forward basis swaps for natural gas are much higher during winter 2016-17 due to lower Southern California natural gas inventories, but this effect moderates over time



Source: Bloomberg, L.P. Data reported as of September 9, 2016.

Additional Discussion

The Aliso Canyon facility plays a key role in helping to balance natural gas supply with the needs of natural gas customers, including electricity generators, in the Los Angeles basin. During the summer months, natural gas withdrawn from Aliso Canyon supports electricity generation at in-region gas-fired plants when peak or near-peak levels of in-region electricity generation are required to meet electricity demand. The electricity produced by gas-fired plants in the Los Angeles basin augments other electricity supplies. These additional supplies include:

- electricity generated from gas-fired power plants in Southern California but outside of the L.A. basin
- electricity generated by fuels other than natural gas
- electricity imported from outside Southern California.

Understanding the effects of Aliso Canyon's operating status on regional wholesale and retail electricity and natural gas prices is difficult, because the power and natural gas markets in Southern California have many moving parts. However, key findings on the effects of Aliso Canyon's status on energy prices in Southern California since last October show that:

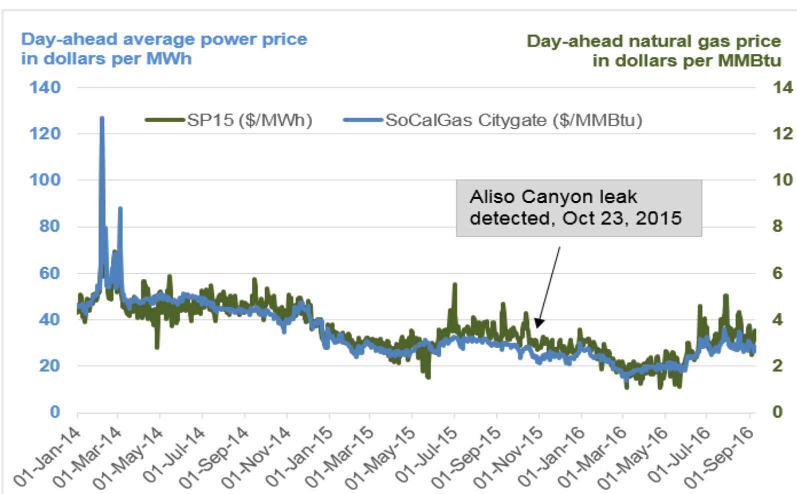
- A combination of factors have influenced trends in spot natural gas and electricity prices since the detection of the leak at the Aliso Canyon storage facility: SoCalGas storage use limitations; the fall and rise in Henry Hub natural gas prices; higher levels of electricity imports, in-State hydroelectric availability, and solar generation; and moderate load conditions.
- Wholesale, next-day, or spot natural gas prices have been generally lower but more variable during the summer of 2016 compared to the summer of 2015. For example, during several heat waves this summer the differential in the spot prices of natural gas between Southern California trading points and the Henry Hub reached winter levels; operating restrictions at Aliso Canyon likely contributed to these higher basis differentials.

- Despite changes in the regional capacity generating mix, natural gas is often the fuel that helps determine the price of electricity in Southern California.
- Wholesale electricity prices at the SP15 trading hub in Southern California in mid-September 2016 were about 8% lower than SP15 prices a year ago, despite the restrictions on Aliso Canyon.
- Higher retail prices for natural gas in Southern California starting in April 2016 probably coincided with the general rise in natural gas prices at the Henry Hub.
- The retail price of electricity in Los Angeles, Riverside, and Orange counties in July 2016 (latest data available) was about 21 cents per kilowatthour, or about the same as the retail electricity price in September 2015, according to the Bureau of Labor Statistics.

Southern California electricity fundamentals. Overall, Southern California electricity load is up by about 2% this summer (April 1 – September 12) compared with the same period in 2015, which reflects little change in cooling degree days (CDDs) in Los Angeles through summer 2016. Because of the high level of precipitation in California last winter, in-State hydroelectric generation has nearly doubled so far in 2016 compared to the same period in 2015, up by almost 1,200 megawatts (MW). Generation from renewables, including solar and wind, is up by 18%, and overall electricity imports are up by 2%. As a result, thermal generation reported by the CAISO, which covers a majority of electricity sales in California, mostly from natural gas, is down by 20% year-to-date.

Thermal generation, nearly all gas-fired in California, is often the marginal source of electricity in the power market in California. Consequently, Southern California power prices tend to move in fairly close coordination with natural gas prices; however, other factors occasionally drive them apart (Figure 18).

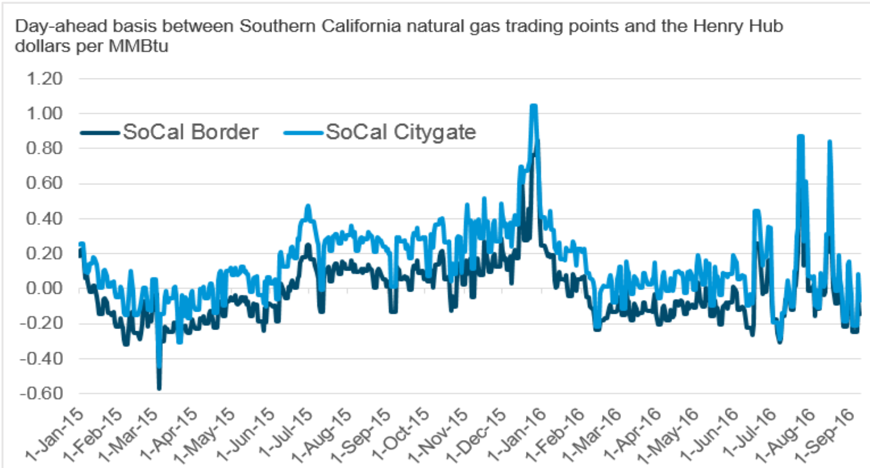
Figure 18. Southern California power prices continue to move with natural gas prices after Aliso Canyon use restrictions



Source: SNL Energy. Data provided for January 1, 2014–September 8, 2016.

Southern California natural gas fundamentals. On average, the natural gas load met by SoCalGas to date in 2016 is similar to the load in the same period for 2015. The increase in the price of natural gas in Southern California since April is attributable, in part, to rising prices across the United States. Before more volatile summer electric generation demands began to affect regional natural gas prices, 2016 Southern California natural gas prices were actually slightly closer to prices at the Henry Hub, the key benchmark for pricing natural gas throughout the United States (Figure 19).

Figure 19. Price differences or basis between Southern California natural gas trading hubs and the benchmark price of natural gas at the Henry Hub have been more volatile during summer 2016



Note: “Basis” is the difference between natural gas priced at the Henry Hub and natural gas priced at another geographic location such as the Southern California Border or the SoCal Citygate.
Source: Bloomberg, L.P. Data provided for Jan 1, 2015-Sept 8, 2016.

The pace of net national natural gas storage injections slowed this summer. Record natural gas inventories at the end of winter—due to a warm winter, slowing production, and rising demand—contributed to lower net average storage injections this summer and boosted expectations for natural gas prices.

Despite the slower-than-normal pace of injections during the 2016 refill season so far, U.S. working gas stocks were 7% above the 5-year average (2011-15) as of September 30, 2016. However, working gas stocks in the Pacific region were down by 25 Bcf, or 7% below the 5-year average for this time of year, mostly because of the injection limitations at the Aliso Canyon storage facility.

The October bidweek prices (or the price established during the last 3-5 business days of each month when buyers and sellers may transact for natural gas for the upcoming month) for wholesale natural gas at key trading points in Southern California settled between $2.80 and $2.95 per million British thermal units (MMBtu). As of October 11, 2016, the price of spot natural gas at the Southern California border was about $3.00/MMBtu. By contrast, Southern California spot natural gas prices were about $2.35/MMBtu when the Aliso Canyon leak was detected on October 23, 2015.

Prospects for wholesale Southern California energy prices this winter. Forward basis values in Southern California are expected to be higher this winter. The forward basis markets for natural gas in Southern California indicate higher price expectations for the 2016-17 winter, at least in part because of an anticipated lower level of natural gas storage deliverability from the SoCalGas system. Basis, in this context, indicates the future value of relative price differences between two market locations—in this case natural gas delivered to the SoCal Citygate and the price of natural gas established at the Henry Hub based on the Nymex futures contract. Significant changes in basis can indicate constraints in the natural gas system. Figure 19 shows higher expected basis values for the winter of 2016-17 (the light blue line) compared with what was expected a year ago at this time (the dark blue line). Before the leak at Aliso Canyon, the basis value expectations for the winter of 2016-17 were less than $0.20/MMBtu and only modestly higher until late 2018. Recent winter 2016-17 expectations for this difference recently traded as high as about $0.65/MMBtu for December 2016, suggesting concerns about meeting peak winter demands with given pipeline supplies, the level of natural gas inventories, and the restrictions on the use of the Aliso Canyon storage facility. Lower basis values are likely a key driver of the significant change in pricing, which does not persist beyond the upcoming winter.

In addition, the forward price for natural gas priced at the SoCal Citygate is considerably higher than the forward price of natural gas priced at the SoCal Border. The higher price premium at SoCal Citygate indicates that natural gas deliveries into the Los Angeles Basin will likely be influenced more by the reductions in gas inventories and deliverability than the market at the California border, at least through the 2016-17 winter.

Retail Southern California energy prices. Retail energy prices are different from wholesale prices. Retail prices are determined through regulatory processes that incorporate average wholesale prices with other energy delivery expenses.

Because of regulatory decisionmaking, the resulting prices can vary by customer class and energy usage. Recent changes in retail energy costs relate most directly to rising wholesale natural gas prices. For example, the SoCalGas residential retail natural gas rates were between $10 and $12/MMBtu in August 2016, up by about $2/MMBtu since October 2015.

Nationwide Gas/Electric System Reliability Analysis

The Task Force commissioned DOE's Argonne National Laboratory (ANL) to analyze the potential impacts of an abrupt and protracted loss of natural gas deliverability due to some disabling event at each of the Nation's other UGS facilities. The method ANL used in this analysis[68] required the estimation of two major variables for each of the Nation's 400+ UGS facilities: the probability of a major failure, and the consequences of such a failure. ("Failure" was defined as the total loss of function from the facility for a period of at least a month's duration, at the time of peak gas demand upon the facility.) Because the 400+ facilities are owned by three types of owners (local distribution companies, interstate natural gas pipelines, and third-party independent operators), and because these three types of owners use UGS facilities in somewhat different ways to serve downstream customers, three separate models were devised to estimate the impacts of the loss of a given UGS facility.

Estimated Likelihood of UGS Failure

The availability of systematic data concerning the histories of the wells at individual UGS sites, the failure rates for different categories of wells, and major incidents at UGS facilities (i.e., incidents resulting in injury, fatality, property damage, site evacuation, or uncontrolled leaks) is limited.

Consequently, a simplified approach was used to estimate the likelihood of failure. Based on available data concerning 137 incidents, the frequency of an incident at a UGS facility was estimated to range between 8.4×10^{-4} and 6.0×10^{-3} per site-year, or once every 167 to 1,190 years of UGS site operation. Assuming that there are 400 UGS facilities currently in the United States, this equates to a major incident every 4 months to 3 years in the United States, for an average of 1.4 incidents per year. Note, however, that many of the reported incidents did not result in a "failure" of the UGS facility as defined above (i.e., total outage of the affected UGS site for a month or more at time of peak demand).

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[68]See *U.S. Natural Gas Storage Risk-based Ranking Methodology and Results*, Steve Folga et al., Argonne National Laboratory, forthcoming (2016).

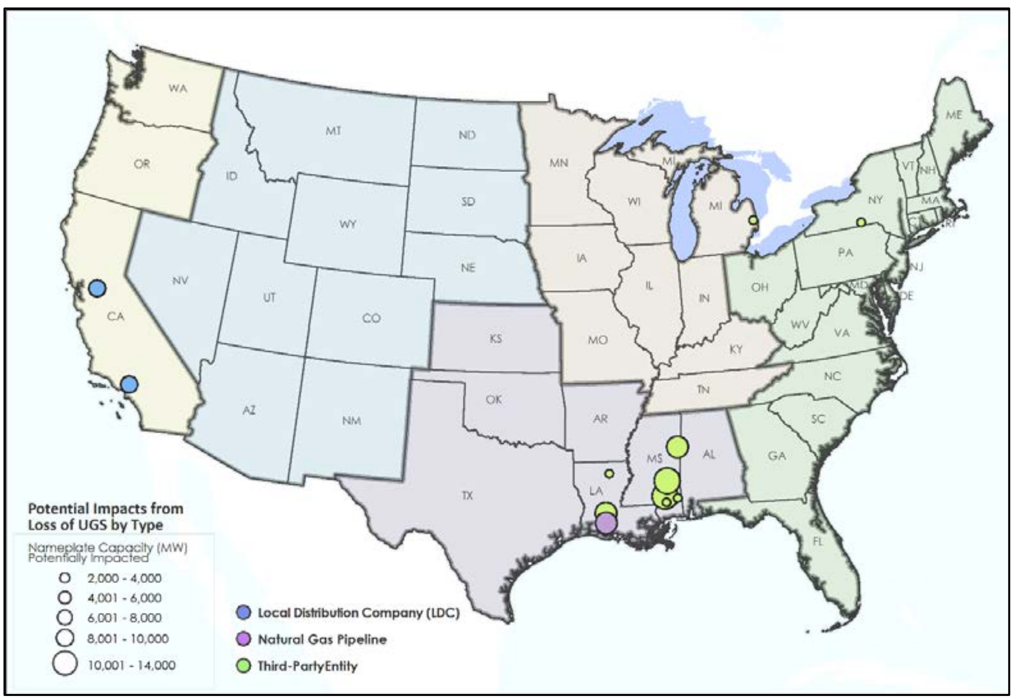
Estimated Consequences of UGS Failure

The consequence of a UGS failure was expressed in terms of the number of customers affected per sector and the amount of gas flow lost. For the purposes of this study, customers in the electric sector are of particular interest because of the interdependency that exists between the electric and gas systems, and the principal impacts in the electric sector are expressed in terms of megawatts (MW) assumed to have been forced out of service by lack of fuel.

Potential Electric Sector Impacts

Aliso Canyon is not unique as a UGS facility providing generation fuel that is, or may be, essential to maintaining electric reliability in “downstream” communities. An unexpected loss of generation capacity usually does not affect electric reliability unless the loss is relatively large (2 GW or more). ANL’s screening analysis found that a total of 12 UGS facilities appear to have the potential to affect 2 GW or more available generation capacity. Note, however, that these figures are preliminary, because the operators of the affected power plants may or may not have dual-fuel capability (i.e., diesel or equivalent liquid fuels, with access at short notice to sufficient inventories of alternative sources of natural gas) or access to alternative generation via transmission. The general locations of these UGS facilities are shown in Figure 20. Two are located in California (one of which is Aliso Canyon). Five are in Mississippi, three are in Louisiana, one is in Michigan, and one is in New York.

Figure 20. Locations of 12 UGS Facilities, Disruption of Which Could Potentially Affect 2 GW or More of Generation Capacity



This analysis indicates that the greatest impact on natural gas-fired electricity-generating plants could occur from the hypothetical loss of a high-deliverability UGS facility owned by a third-party independent storage service provider. This finding is consistent with the current evolution of the natural gas sector, in which the deregulation of underground storage combined with other factors such as the growth in the number of natural gas-fired electricity generating plants has placed a premium on high-deliverability storage facilities. Nine of the top twelve UGS facilities (in terms of potential impacts on natural gas-fired electricity generating plants) are owned by independent storage service providers.

Further, the impacts of the Aliso Canyon outage tell us that we need to estimate the likelihood and consequences of a long outage of all of the important components of our natural gas infrastructure, whether singly or in combination, and devise appropriate plans to address unacceptable risks. Given the increasing reliance on gas-fired generation in meeting our electricity requirements, maintaining electric reliability during such outages is particularly important.

The Aliso Canyon experience has also highlighted the need to address more fully the operational challenges associated with the timely provision of fuel to gas-fired generation capacity needed to ensure electric reliability. When a large gas-fired generator is dispatched to serve electricity needs, the abrupt incremental draw on the gas delivery system can be large enough to reduce pipeline pressures and the system's ability to meet other customers' needs. While some gas-fired generators have contracted for firm pipeline capacity and gas supplies, others, especially peaking generators, have relied on interruptible capacity and spot market purchases. During periods of peak gas demand, there may be little or no interruptible pipeline capacity available to serve generators that have not contracted for firm supplies, threatening electric reliability.[69] There is continuing debate among the affected companies and regulators over whether electricity generation companies should be relying to a greater extent on firm supply contracts, and if so, how best to distribute the additional costs associated with such contracts.

The Aliso Canyon experience has also led to efforts to ease some of the strains associated with abrupt reductions in gas deliverability by making changes to gas tariffs.[70] On June 11, 2015, the California Public Utilities Commission authorized SoCalGas to revise its tariff to implement new low Operational Flow Order (OFO) and Emergency Flow Order (EFO) requirements. On June 23, 2016, the Commission reaffirmed and augmented those requirements. The low OFO and EFO requirements, which will be in effect year-round, replace winter balancing rules that were in place since the early 1990s with a unified, State-wide approach.

On the electricity side, the CAISO formed a group to look at potential reliability risks to both gas and electricity markets in Southern California due to the limited operation of the Aliso Canyon gas storage facility. Through an expedited stakeholder process, the group created a proposal for tariff changes that address gas balancing, electricity and gas scheduling misalignment, and market-based mitigation measures. CAISO's proposal identifies ways to mitigate risks that impact the electric system when rapid ramping could exceed the dynamic capability of the gas system.[71]

These changes imply that the current tariff structure used in other States and regions for wholesale gas purchases by utilities may need to be examined to promote generator bids that reflect gas system limitations, to reduce the chance that Independent System Operators (ISOs) or Regional Transmission Operators (RTOs) will dispatch generators in a way that harms gas system reliability, and to permit

[69]American Gas Association (AGA), 2016. "Gas-Electric Coordination," available at https://www.aga.org/federal-regulatory-issues-and-advocacy/gas-electric-coordination, accessed September 20, 2016.
[70]Marelli, G., 2016. Application of Southern California Gas Company (U 904 G) and San Diego Gas & Electric Company (U 902 G) for Authority to Revise their Curtailment Procedures, available at https://www.socalgas.com/regulatory/documents/a-15-06-020/Ch%201%20Curtailment%20Testimony%20-%20Marelli.pdf, accessed September 20, 2016.
[71]California ISO, 2016. *Aliso Canyon Gas-Electric Coordination Straw Proposal*, available at http://www.caiso.com/Documents/StrawProposal_AlisoCanyonGas_ElectricCoordination.pdf, accessed September 20, 2016.

ISOs/RTOs to reserve sufficient internal electric transmission transfer capability to react to changes in the gas system.

The challenges that have arisen in California over the past year have highlighted concerns that have become more acute over the past decade, including gas system dependency on storage to maintain operating pressure, and insufficient appreciation of the operational characteristics of natural gas systems and their potential implications for the operations of bulk power systems. Improved coordination between electric and gas industry entities will be critical to mitigating risks and minimizing their impact. For example, the timeframe for nominating natural gas transportation service is generally not synchronized with the timeframe during which electric generators receive confirmation of their bids in the ISO/RTO day-ahead market. The North American Electric Reliability Corporation (NERC) has suggested two potentially constructive measures that merit consideration: tightening the gas balancing rules; and giving generators dispatch information as early as practicable, so that they can procure gas more accurately.[72]

Potential Impacts on All Sectors

The loss of an underground gas storage facility would in most cases affect many kinds of customers, not just electricity generators. Figure 21 provides the estimated impacts per UGS facility across all customer classes (including the electric sector), converted to an expected equivalent number of residential customer outages (loss of gas service) per year. The largest estimated impact is approximately 32,000 customer outages per year, with most UGS facilities having a predicted impact of less than 1,000 expected equivalent residential customer outages per year.[73]

The results in Figure 21 agree with indications that the loss of gas service to a large number of customers is a relatively rare occurrence. For example, in the past 35 years in the Chicago Metropolitan Area, the largest number of customers losing gas service at any one time has been on the order of 4,500.[74] Similarly, the Southwest cold weather event of February 1–5, 2011, led to extensive curtailments of gas service to more than 50,000 customers in New Mexico, Arizona, and Texas.[75] When compared with customers affected by electric power outages (which can be in excess of 100,000 at any one time), the estimated number of annual customer outages in Figure 21 appears relatively small.

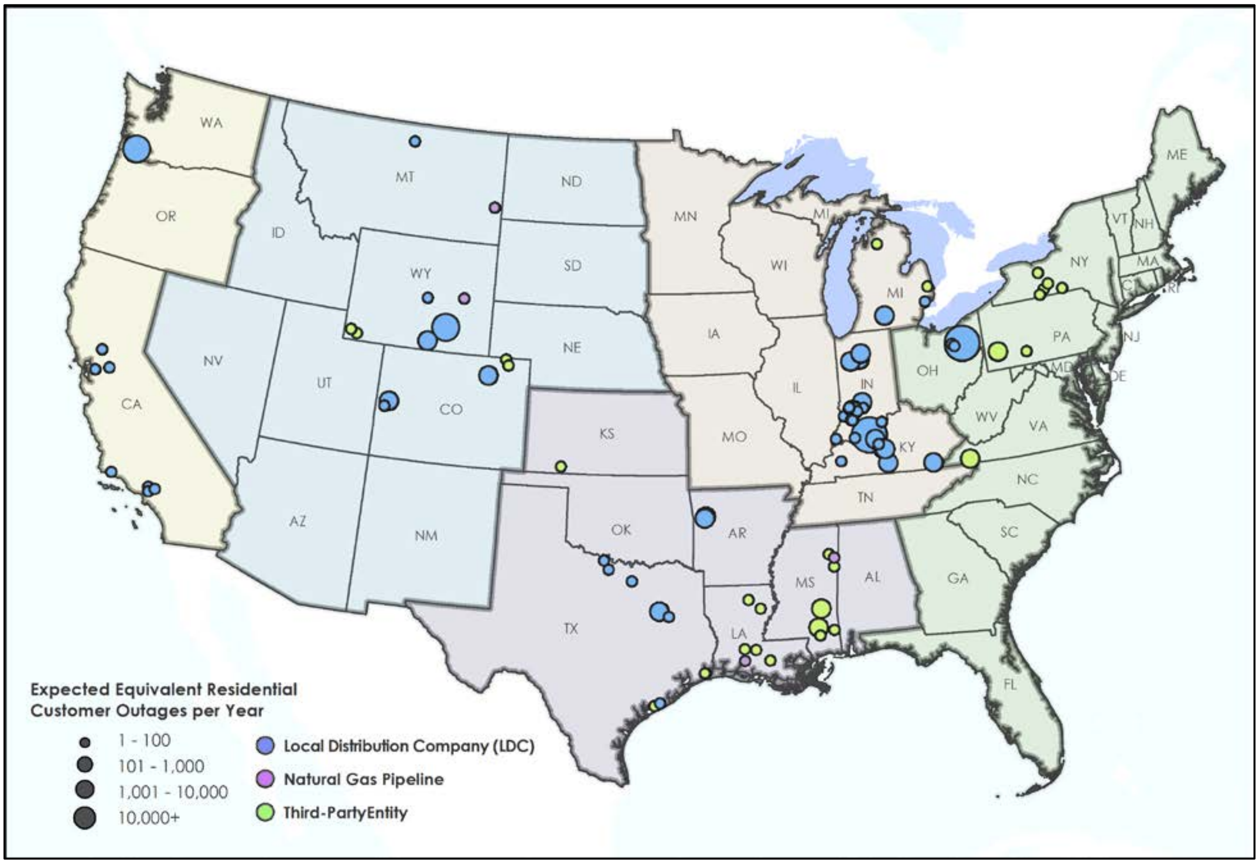
[72]North American Electric Reliability Corporation (NERC), *Short-Term Special Assessment - Operational Risk Assessment with High Penetration of Natural Gas-Fired Generation*, available at http://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC%20Short-Term%20Special%20Assessment%20Gas%20Electric_Final.pdf, accessed September 20, 2016.

[73]See *U.S. Natural Gas Storage Risk-based Ranking Methodology and Results*, Steve Folga et al., Argonne National Laboratory (forthcoming 2016) for details on these calculations.

[74]http://www.ipd.anl.gov/anlpubs/2003/02/45798.pdf.

[75]http://www.ferc.gov/legal/staff-reports/08-16-11-report.pdf.

Figure 21. Locations of underground gas storage facilities with non-zero potential impact values



Government Agency Responses to the Aliso Canyon Incident

Multiple actions were taken by SoCalGas and Federal, State, and local agencies to address the leak and associated health concerns before the leak was fully controlled on February 17, 2016.

Porter Ranch, a residential community of approximately 30,000 people, is located near the Aliso Canyon facility. The Porter Ranch properties nearest to SS-25 are located approximately 1 mile away and 1,200 feet below the leaking wellhead. Immediately after discovery of the leak, many residents began reporting odor complaints (related to mercaptans, the familiar sulfur-smelling odorant added to natural gas for safety) to various local and State agencies, including 911. The Los Angeles County Fire Department responded to the complaints and sent personnel to the scene. However, the responding personnel were informed of non-emergency circumstances of the incident at the gate of the facility by SoCalGas and departed. SoCalGas placed a call to the Los Angeles County Fire Department on October 24, 2015, and reported that the incident should be resolved by 6:00 PM PST.

Many Porter Ranch community members experienced adverse health impacts in the days following the leak. On November 19, 2015, the Los Angeles County Department of Public Health (LADPH) determined that emissions from SS-25 had caused health symptoms in some Porter Ranch residents and ordered SoCalGas to provide temporary relocation to residents who desired to move.[76]

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[76]http://publichealth.lacounty.gov/eh/docs/AlisoCanyon.pdf.

Initial Monitoring and Regulatory Actions

The SCAQMD started receiving odor complaints from Porter Ranch residents on October 24, 2015, and began ambient air quality monitoring soon thereafter. SoCalGas began its own air sampling effort on October 30, 2015. On November 5, 2015, SCAQMD issued a "Notice to Comply" that required SoCalGas to take specific steps to abate the natural gas leak, monitor the leaking gas, and reduce the impacts of nuisance odors on the local community.[77]

On November 7, 2015, CEC sponsored the first airborne methane sampling collection. Flights continued through February 2016. The National Aeronautics and Space Administration/Jet Propulsion Laboratory (NASA/JPL) conducted an onsite field survey of the Aliso Canyon facility on November 10, 2015, and began satellite imaging of methane plumes on November 13, 2015.

The California Natural Resources Agency/Department of Conservation/DOGGR and CPUC had the most direct operational oversight at the Aliso Canyon facility. In early November, DOGGR convened a panel of technical experts from the Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, and Sandia National Laboratory to provide independent expertise to assist the Division in monitoring and evaluating SoCalGas actions.

DOGGR issued two orders to SoCalGas, one on November 18, 2015, and a second one on December 10, 2015.[78] The November 18 order required SoCalGas to provide information on SS-25; the December 10 order required SoCalGas to develop plans to expeditiously capture the escaping gas, stop the leak, and communicate with State and local regulators. The December 10 order also required SoCalGas to provide access to the SS-25 site and information to a group of experts from the DOE National Laboratories who were assisting DOGGR in evaluating the SoCalGas plans for stopping the leak. In addition, the order required SoCalGas not to inject any additional gas into the Aliso Canyon reservoir without approval from DOGGR. Furthermore, it required SoCalGas to maximize the rate of withdrawal from the reservoir to reduce reservoir pressure. Gas was withdrawn from the reservoir at 0.75 to 1.5 BCF a day.

The CPUC also provided directives to SoCalGas regarding its response to the incident via a series of letters issued between December 2015 and February 2016. The information collected by CPUC from SoCalGas informed the steps that were taken by State regulatory agencies to address the gas leak, investigate its root causes, and model how an interruption in the operation of the Aliso Canyon facility might impact the availability and reliability of power generation in the Los Angeles Basin in 2016 and 2017.

The Los Angeles County Fire Department had an active operational presence with SoCalGas starting in November. They deployed a "short Incident Management Team" to work with the SoCalGas Operation and Planning Sections, preparing Incident Action Plans and other documents, and reviewing operations. The State Office of Emergency Services was also present from the first weeks of the incident.

[77]South Coast Air Quality Management District Notice to Comply E-26893, http://www.aqmd.gov/docs/default-source/compliance/aliso-cyn/so-cal-gas-aliso-canyon---notice-to-comply-e26893.pdf?sfvrsn=2.

[78]Emergency Order No. 1104; November 18, 2015, Provide Data Re: Aliso Canyon Storage Facility; Emergency Order No. 1106; December 10, 2015, Provide Data and Take Specified Actions Re: Aliso Canyon Storage Facility.

Initial Federal Actions

On December 4, 2015, PHMSA's Office of Pipeline Safety began to provide technical assistance to the California Public Utilities Commission on the leaking well at Aliso Canyon. On December 20, 2015, PHMSA and other Federal agencies began to participate in daily Incident Command calls led by SoCalGas. PHMSA conducted a site visit at Aliso Canyon on December 22, 2015.

The U.S. EPA became actively involved in the Aliso Canyon incident in early December at the request of the California Office of Emergency Services and entered into an informal Federal multi-agency coordinating group with PHMSA and DOE. On December 16, 2015, two EPA Federal On-Scene Coordinators (FOSCs) conducted a site visit at the Aliso Canyon facility with LA County Fire/HazMat. The EPA FOSCs' assessment concluded that SoCalGas appeared to have well-control experts with the appropriate knowledge in charge of the site operations. From early December 2015 to the cessation of on-site activities in February 2016, the EPA participated in multiple daily calls, briefings, and updates with Federal, State, and local partners. Federal agencies included DOE, PHMSA, Department of Interior/Bureau of Safety and Environmental Enforcement (DOI/BSEE), and NOAA.

In early December the FAA issued a Notice to Airmen (NOTAM) restricting pilots from flying aircraft within a half-mile radius of the Aliso Canyon storage facility. The restriction extended up to 2,000 feet above the surface. The flight restriction expired on March 8, 2016.

Operations to Plug SS-25

Starting on October 24, 2015, and continuing until December 22, 2015, SoCalGas conducted eight separate "top kill" operations to stop the leak. SoCalGas also began planning for the drilling of a relief well for a "bottom kill" operation, if needed. In response to the December 10, 2015, order from DOGGR to develop plans for capturing the methane at the surface, SoCalGas submitted a permit application to the SCAQMD on January 4, 2016, to obtain approval for construction and operation of temporary equipment to capture and control natural gas from the leaking well. SoCalGas ultimately abandoned this effort, after several weeks of investigation and design work, due to significant safety concerns raised by LA County Fire and by the company's well-control experts regarding the feasibility of constructing, installing, and operating a gas capture system in a methane-rich environment.

On January 6, 2016, California Governor Jerry Brown issued a proclamation declaring a State of Emergency in Los Angeles County as a result of the natural gas leak at the Aliso Canyon facility. The Governor's emergency proclamation provided for "all State agencies to use personnel, equipment and facilities to ensure a thorough and continuous response to the incident, as directed by the Governor's Office of Emergency Services and the State Emergency Plan."[79] The emergency proclamation contained requirements for a number of State agencies, including the CPUC, CEC, CARB, Office of Environmental Health Hazard Assessment (OEHHA), CAISO, and DOGGR regarding stopping the leak, protecting public safety, ensuring accountability, and strengthening oversight of gas storage facilities.

Further Federal Action

On January 4, 2016, PHMSA and EPA met to discuss the convening of a National Response Team (NRT) to coordinate the Federal agency response to the incident. The NRT is a component of the National

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[79]Proclamation of a State of Emergency, January 6, 2016, by Governor Edmund G. Brown for the County of Los Angeles due to the natural gas leak.

Response System (NRS) that consists of 15 Federal agencies specified in Section 300.175(b) of the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) and is responsible for carrying out national response and preparedness planning, coordinating regional planning, and providing policy guidance and support to incident-specific Regional Response Teams (RRTs).[80, 81] On January 7, 2016, the EPA activated its Regional Response Team 9 (RRT9).

The full NRT convened on January 11, 2016, to discuss the Aliso Canyon incident where RRT9 briefed the NRT on the incident. RRT9 requested that the NRT convene a Federal interagency panel of well-control experts to advise and consult on the safety and operation of the gas capture and disposition system being proposed by SoCalGas, which would have captured the leaking natural gas at the surface of SS-25. The gas capture system was essentially a giant, inverted funnel and flare system that would capture the gas escaping at the surface, direct it away from the wellhead through pipes, and incinerate it. As noted above, this proposal to capture and incinerate the leaking gas was ultimately abandoned due to significant safety concerns.

PHMSA leadership met with the CEOs of the American Petroleum Institute, American Gas Association, and Interstate Natural Gas Association on January 15, 2016, to discuss the industry's response efforts and encourage its support to SoCalGas with technical assistance and to ensure that the industry was reviewing UGS safety across the country.

Starting on January 20, 2016, PHMSA's Office of Pipeline Safety, Emergency Support and Security Division, began leading an ad-hoc Federal Government information exchange group. The group included representatives from the EPA (HQ and Region), DOE, BSEE, and PHMSA. The group met on a weekly basis until it was confirmed that the well was permanently sealed.

On February 5, 2016, PHMSA published an advisory bulletin entitled "Safe Operations of UGS Facilities for Natural Gas." The bulletin reminded all owners and operators of UGS facilities used for the storage of natural gas (as defined in 49 CFR Part 192) to consider the overall integrity of the facilities to ensure the safety of the public and operating personnel, and to protect the environment.

Public Meeting with State Leadership

On January 15, 2016, the State of California convened a public meeting in Porter Ranch. In attendance were a number of State leaders, representatives of EPA Region 9, and approximately 1,200 community members. The State leaders gave an overview of their agencies and authorities, and described the actions their agencies had taken thus far in the response to the gas leak at Aliso Canyon. Several other meetings took place between community members and agency leads during the leak, in an ongoing effort to communicate with the impacted community.

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[80] 40 CFR Part 300. The NCP, which is authorized by the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), the Clean Water Act § 311, and the Oil Pollution Act of 1990 (OPA), provides, among other authorities, an organizational structure and procedures, known as the National Response.

[81] The NRS is an organized network of agencies, programs, and resources with authorities and responsibilities in oil and hazardous materials preparedness and response at the local, state, tribal, territorial, insular area, and Federal levels. The RRTs and NRT include representatives from 13 additional Federal agencies that provide oil and hazardous materials expertise and support, and some have specific responsibilities for natural resource protection. (40 CFR § 300.115).

Formation of Unified Command and Bottom Kill Planning

By November 2, 2015, SoCalGas had established an Incident Command with daily briefings about the leak at SS-25. The Incident Commander designation revolved between several senior officials from SoCalGas. It was not until January 22, 2016, that the SoCalGas incident command transitioned into a Unified Command (UC) with LA County Fire and the LADPH. As a component of the Incident Command System (ICS), the UC is a structure that brings together the individual Incident Commanders of all major organizations involved in the incident to coordinate an effective response, while at the same time carrying out their own jurisdictional responsibilities. The UC links the organizations responding to the incident and provides a forum for these agencies to make consensus decisions. This was a significant organizational change that provided the local agencies with much greater control over on-site actions and improved communication to the public. PHMSA and the EPA participated in daily briefings with the Unified Command. CPUC ordered SoCalGas on January 21, 2016, to continue withdrawing gas from the Aliso Canyon storage field until it reached 15 Bcf of working gas. The withdrawal of natural gas from the Aliso Canyon storage field was intended to reduce the pressure at the field and therefore minimize the rate of the gas leak. The remaining 15 Bcf of working gas was to ensure energy reliability on high-demand days. On January 23, 2016, SoCalGas had all wells shut off from withdrawal.

On February 2, 2016, the Los Angeles County District Attorney filed a criminal lawsuit against SoCalGas, alleging misdemeanor violations for neglecting to report the release of hazardous materials and releasing air contaminants.

On February 8, 2016, the EPA participated in a Federal interagency call with PHMSA, DOE, and DOI. The EPA solicited technical help from well-drilling experts in DOI's Bureau of Safety and Environmental Enforcement to evaluate the drilling and bottom kill plans for SS-25.

On February 16, Secretary of Energy Ernest Moniz, Under Secretary for Science and Energy Franklin Orr, and PHMSA Administrator Marie Therese Dominguez visited the Aliso Canyon site and participated in a roundtable with key Federal, State, and local agencies involved in the response to the leak at Aliso Canyon.

On February 18, 2016, DOGGR issued a determination that SS-25 had been permanently sealed on February 17. This determination was preceded by a "soft touch" encounter between the relief well and SS-25 on February 10, wireline logging and testing to make sure that the relief well was properly oriented to conduct the bottom kill operation, a milling operation to establish communication between the relief well and the target well, and pumping in mud and cement to seal the well. The Unified Command for the Aliso Canyon incident stood down on February 19, 2016, when the CPUC began its lead role in the investigation phase of the incident. On September 13, 2016, SoCalGas agreed to pay $4 million to settle criminal charges filed by the Los Angeles County District Attorney alleging misdemeanor violations for neglecting to report releases of hazardous materials and air contaminants.

Federal Task Force

Motivated by the incident at Aliso Canyon, Federal officials, including many concerned members of Congress, sought to better understand the overall safety of our Nation's natural gas storage infrastructure. To support these efforts, in April 2016, the Federal Government formed an Interagency Task Force on Natural Gas Storage Safety. DOE and DOT's PHMSA co-chair the Task Force. Congress codified the Task Force through the PIPES Act of 2016, which was signed into law by President Obama on June 22, 2016.

The legislation created a Task Force established by the Secretary of Energy and consisting of representatives from the DOT, EPA, FERC, and DOI and tasked the group with performing an analysis of the Aliso Canyon event and making recommendations to reduce the occurrence of similar incidents in the future. The PIPES Act also required that PHMSA promulgate minimum safety standards for UGS that would take effect within two years.

The Task Force established three primary areas of study and chartered working groups for each: well integrity of natural gas wells at the storage facilities, vulnerability to energy reliability in the case of future leaks, and public health and environmental effects from natural gas leaks.

The Well Integrity Working Group is led by DOE's Office of Fossil Energy (FE), with technical leadership and coordination from a team of scientists and engineers from the DOE National Labs, including the National Energy Technology Laboratory (NETL), Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories (SNL), and Lawrence Berkeley National Laboratory (LBNL). DOE tasked these labs to review the state of well integrity in natural gas storage in the United States. The group's objective is to review, gather, analyze, catalog, and disseminate information and recommendations that can lead to improved natural gas storage safety and security and thus reduce the risk of future events. The DOE National Lab team is an expansion of the original "Lab Team" comprising scientists and engineers from SNL, LLNL, and LBNL which was formed to support the State of California's response to the Aliso Canyon incident and operated under the Governor of California's Aliso Canyon Emergency Order (January 6, 2016). The Lab Team played a key role in advising DOGGR in its oversight of SoCalGas during and after the incident.

The Reliability Working Group is led by DOE's Office of Electricity Delivery and Energy Reliability (OE) with technical leadership and coordination by scientists and engineers from Argonne National Laboratory, the U.S. Energy Information Administration (EIA), and FERC. The working group developed methodology and models to assess the risk to energy delivery from the potential loss of natural gas storage facilities located within the United States. The models estimated the impacts of a failure of each of the more than 400 underground storage (UGS) facilities on their owners/operators, including (1) LDCs, (2) directly-connected transporting pipelines and thus customers in downstream States, and (3) third-party entities and thus contracted customers expecting gas shipments. The working group also assessed impacts of the Aliso Canyon incident on energy reliability and energy prices.

The Health and Environment Working Group is led by scientists at EPA and the Centers for Disease Control (CDC), with support from NOAA and PHMSA. The Working Group has been in close contact with State and local officials to summarize and analyze the actions taken to address the impacts to public health and the environment from the Aliso Canyon leak. The multiple agency responses to address health and environmental concerns, both during the leak and after the well was sealed, included air quality monitoring, health risk assessments, and consideration of health symptoms reported by the public. The Working Group also addressed efforts taken to measure the volume of greenhouse gases emitted during the Aliso Canyon leak, and California's plan to mitigate those greenhouse gas effects.

During summer 2016, the Task Force held three workshops. In June, DOE's Office of Energy Policy and Systems Analysis convened a Technical Workshop on the Implications of Increasing Electric Sector Natural Gas Demand. The workshop convened stakeholders from the gas and electricity sectors for an in-depth discussion on natural gas and electricity modeling and planning. An important element of that conversation was the role of underground gas storage facilities in ensuring reliability of electric power generation and heating during periods of high demand.

In July, the Well Integrity Working Group convened a technical workshop on Well Integrity for Natural Gas Storage in Depleted Reservoirs and Aquifers in Broomfield, CO, assembling approximately 200 people, including a mix of operators, regulators, and trade industry, academic, and National Laboratory personnel. Opening remarks were provided by the Task Force co-chairs, DOE Undersecretary for Science and Energy Franklin Orr, and DOT/PHMSA Administrator Marie-Therese Dominquez. The two-day forum consisted of presentations on wellbore integrity risks, operational and wellbore construction practices, monitoring and testing of subsurface storage integrity, accident management (e.g., controlling leakage and blowouts), gaps in knowledge about wellbore integrity, and ways to improve the state of knowledge to address those gaps. There were also three panel/expert-led discussions addressing regulatory issues, performance of downhole safety valves, and a general recap of open issues to conclude the meeting.

Also in July, PHMSA convened a public workshop on Underground Natural Gas Storage Safety Regulation in Broomfield, CO. As part of its effort to initiate regulatory actions to help ensure the safety of natural gas storage facilities, PHMSA brought together stakeholders—including Federal and State agencies, industry, and the public—to discuss the response, investigation, and impact of the Aliso Canyon incident, well integrity, safe UGS operating practices, and Federal and State safety regulations for UGS. The one-day forum consisted of presentations by Federal and State regulators, the LA County Fire Department and Department of Public Health, Environmental Defense Fund, Porter Ranch Neighborhood Council, industry groups, and industry service providers.

Between April and September 2016, the National Economic Council and the Domestic Policy Council convened the Task Force at the White House on five occasions. The research results of the Task Force, including knowledge learned at the workshops, contributed to this final report of the Task Force.

Chapter 3. Task Force Observations and Recommendations

The following recommendations are based on extensive research and analysis by Task Force experts, including extensive engagement with industry representatives, State regulators, environmental groups, and other stakeholders. These recommendations will advise UGS operators on how to address well integrity, energy reliability, and health and environment risks. They will also serve as a guide to State and Federal regulators on future regulatory developments. The working groups produced reports that contain additional background on the three sets of recommendations and will be released later this year.

Well Integrity

UGS facilities are an essential component in the efficient and consistent delivery of natural gas to consumers by pipeline. These facilities provide a consistent source of energy during periods of peak consumer demand. Across the Nation, UGS facilities include wells that range in age from less than 5 years to more than 125 years old. Well completion technology has changed significantly over that time period, which means that many wells are outdated and may be in similar condition to the one at Aliso Canyon. In response to the leak at Aliso Canyon, DOE commissioned a review of the issues related to well integrity at UGS facilities. The review included an examination of issues related to regulating natural gas storage facilities, an analysis of the data that is available on natural gas storage wells across the country, and expert review of wellbore integrity risks, operational and wellbore construction practices, monitoring and testing of subsurface storage integrity, and accident management.

The Task Force recognizes that the assessment of maintenance and integrity of UGS facilities involves complex engineering concepts and methodologies. Owners and operators of UGS facilities are responsible for ensuring proper maintenance and integrity of their systems, while regulators provide oversight to determine operators' compliance with the established regulatory requirements.

Based on its review and analysis, the Task Force provides the following observations and recommendations related to well integrity, risk management, and additional research and data needs.

Topic I: Ensuring Well Integrity

1. **Operators should phase out wells with single point of failure designs.**

   Observation: SS-25 was operated with gas flowing through both production tubing and well casing, leaving the well casing as a single point of failure for a gas leak. Producing through casing as well as tubing was a common practice at Aliso Canyon and is a common practice at other gas fields, particularly those with older wells. While the failure investigation remains ongoing, preliminary indications are that the inspection program, monitoring, and risk management plan for SS-25 were inadequate to ensure safety. If a second barrier had been in place at SS-25, the uncontrolled leak would likely have been avoided.

   Discussion: About 80% of natural gas storage wells with known completion years were drilled before 1980, and many predate modern materials and technology standards. These wells have been subject to environmental processes and mechanical stresses from injection and withdrawal of natural gas across multiple decades. These stresses may be particularly acute for wells in depleted oil fields that may have been designed for lower pressures than they must now contain. Modern design practices dictate that new wells must be designed with two complete barriers. Tubing and packer installed within a properly engineered casing string with fluid in the casing-tubing annulus provides one method for achieving a double barrier system. However, many different well designs can achieve the same purpose, such as through the use of multiple strings of casing. The most appropriate design will often be site-specific and must include design safety factors to determine maximum and minimum operating pressures. It should be noted for this discussion that a casing string and cement are considered a single barrier system that does not provide independent double-barrier protection against failure.

Recommendation: Given harsh subsurface conditions and engineered components that may become unreliable due to lack of adequate metallurgy or corrosion coatings and cathodic protection, underground gas storage wells should be designed so that a single point of failure cannot lead to leakage and uncontrolled flow. New wells can readily be designed to have double barriers. Operators who have existing wells with single-point-of-failure designs should have a risk management plan to maintain safe well operating pressure that includes a rigorous monitoring program, well integrity evaluation, leakage surveys, mechanical integrity tests, conservative assessment intervals, and in most cases a plan to phase out these designs. An operator seeking to continue utilizing a single-barrier well design should prepare and make available for regulatory review during inspections a rigorous and fully documented engineering analysis of the design that considers the potential impacts and consequences of a leak at any point for each well without benefit of a double barrier. For single-barrier wells, the operator should demonstrate that a failure will not lead to pressure that can exceed the fracture gradient of the surrounding formation, and that the design protects water resources. The operator's technical justification for continued use of a single barrier should also include analysis as to why a double barrier is not practicable. While a transition plan to a double-barrier system is being developed and implemented, integrity management procedures with robust safety factors should be implemented to maintain safe maximum well operating pressures. Well integrity evaluation, risk management plans, and transition plans are discussed further below.

2. **Operators should undertake rigorous well integrity evaluation programs.**

   Observation: The incident at the Aliso Canyon storage field has highlighted the issues of aging natural gas infrastructure, inadequate integrity procedures to maintain safe operating pressures, and inadequate monitoring practices for UGS wells. Federal officials have raised concerns about how many other wells in natural gas storage fields could fail and cause similar events with serious economic implications, environmental implications, or even loss of life.

   Discussion: The natural gas storage industry faces the challenge of improving the safety of storage infrastructure while continuing to provide reliable and cost-effective service. Infrastructure maintenance and upgrade plans must therefore be prioritized, based on relative risk. Risk-based planning, in turn, requires a complete understanding of the baseline conditions of all wells within a gas storage field, whether they are active, idle, or abandoned. Without an adequate baseline, high-risk and low-risk wells cannot be identified with confidence.

   Recommendation: All operators should undertake a rigorous evaluation of the current state of their well inventories. This is consistent with PHMSA's Advisory Bulletin ADB-2016-02, which recommended that all operators of UGS facilities begin a systematic evaluation of their wells and implement voluntary consensus standards (API RP 1170 and API RP 1171). Evaluations should include: (1) a compilation and standardization of all available well records relevant to mechanical integrity; (2) an integrity testing program that includes usage of leakage surveys and cement bond and corrosion logs to establish that all wells are currently performing as expected; (3) documentation of a risk management plan to guide future monitoring, maintenance, and upgrades; (4) establishment of design standards for new well casing and tubing; and (5) establishment of safe operating pressures for existing casing and tubing. Many operators already apply these risk management practices in their operations. These approaches should be applied industry-wide.

3. **Operators should prioritize integrity tests that provide hard data on well performance.**

Observation: Maintaining well integrity is of critical importance for mitigating risk of leakage. Several, but not all, States with UGS facilities have already implemented regulations that address wellbore integrity across a well's lifespan. For example, Pennsylvania requires mechanical integrity testing at least every 5 years.

At Aliso Canyon, logging of SS-25 was performed only as a means to detect the presence of leaks. Since 1979, there are no records of logs performed for the purpose of evaluating the condition of the casing that could be used to assess the risk of a leak. For example, no logs were located that could indicate metal loss in the production casing, which is the primary barrier to the surrounding environment.

Discussion: There are considerable uncertainties in predicting the long-term behavior of wells. Operators have indicated that some very old wells perform fine—despite not conforming to modern design practices—while some newer wells need frequent maintenance. This is one of the basic tenets of risk management, i.e., that each operator's system is unique and must be continuously monitored for changing risks and modified accordingly. Given intrinsic variation in site conditions and individual well performance, frequent monitoring, logging, and mechanical integrity testing are useful tools to reduce risks to well integrity. If carried out properly, these tests provide hard information about the performance of a well and can help identify problematic situations before they become crises. However, concerns have been raised that excessively frequent logging and other well work can actually increase the overall risk when personnel risk and other operational risks are considered. Risk management plans (see Topic II) should balance these risks.

Recommendations:

a. **Monitoring, logging, and mechanical integrity testing must be top priorities for lowering risk to well integrity, as they provide hard data on well performance.** Noise and temperature logs should be run to detect leaks annually unless other methods (such as continuously monitoring casing-tubing annulus pressure) are in place to monitor for leaks—or a risk management program is in place to evaluate threats with assessment intervals based on maintaining safe operating pressures until the next re-assessment interval. As soon as possible, operators should also perform integrity assessments for casing wall thickness (corrosion) inspections on all wells for which recent data are unavailable to assess the current state of corrosion and other casing damage, and to determine the maximum safe operating pressure. Using data from this baseline assessment, the frequency of subsequent casing thickness inspections and pressure testing can be determined, based on the risk of loss of integrity for individual wells and a rational balancing of other operational risks—e.g., potential well damage during workovers, personnel safety concerns, etc. Lower risk wells (such as wells with lower operating pressure, storage volumes, and flow capacity) should receive less frequent attention in order to focus available resources on the pool of higher-risk wells. Operators should maintain detailed integrity and maintenance records and well diagrams of piping and other equipment on the well, and should review the records in aggregate periodically to estimate typical corrosion rates and other field-wide trends in well performance. These aggregate trends should be used to inform the frequency of logging and mechanical integrity testing.

b. **Well integrity testing should be executed with the goal of minimizing total risk, which includes risks to storage integrity associated with the testing, risks to personnel, etc.** To address concerns that frequent logging and other well work might increase risk, note that many types of well work can be coordinated so that the number of well interventions is reduced. Good safety procedures and safety training can be instituted to protect personnel, and appropriate well control measures can be used when a well is taken outside normal operations. Specifically, the risks associated with downhole measurements and other interventions (e.g., damage to well, injury to personnel) should be weighed against the benefits. To that end, well integrity testing should use a tiered approach, with less invasive, routine testing performed more frequently and comprehensive testing performed less frequently and as needed.

c. **Well integrity testing should use multiple methods and not rely on a single diagnostic.** Relying on a single diagnostic tool to assess well integrity can result in overlooking adverse well integrity conditions and incipient or impending failures. Temperature and noise logs are used ubiquitously in UGS to identify leaks, but the sensitivity of the measurements is limited, and the data provide no hint of impending problems. Casing corrosion logs and cement bond logs can identify integrity defects, and a time-progression of casing diagnostics can identify where well integrity is deteriorating. However, casing diagnostic logs provide no information concerning whether a leak is ongoing. A pressure test can identify a casing leak below the sensitivity of temperature and noise logs, but that test alone provides no spatial information as to where the leak is occurring. An ideal well integrity testing program will incorporate multiple methods that recognize the benefits, limitations, and complementary nature of data from each diagnostic test. The optimal diagnostic program will be site-specific and may change over time as data are collected and evaluated.

4. **Operators should deploy continuous monitoring for wells and critical gas handling infrastructure.**

Observation: To a great extent, the gas storage industry has relied on subsurface measurements to detect subsurface leaks. Noise logs, used to listen for noise irregularities (perhaps indicative of a leak), and temperature logs, used to detect thermal anomalies (perhaps indicative of subsurface flow), are commonplace in the industry.

SS-25 was monitored for gas leaks in a similar manner to other wells at the Aliso Canyon field, annually in recent time, bi-annually in less recent time, and ranging to sporadic monitoring in historic time. Logs that could be used to assess the risk of the well system (e.g., metal loss in the casing) were not located. While the failure investigation remains ongoing, there are preliminary indications that the practices for monitoring and assessing leaks and leak potential at the Aliso Canyon facility were inadequate to maintain safe operations.

Discussion: New sensors and monitoring systems, along with advanced communication technologies, are available to monitor, measure, diagnose, notify, and respond to suspected changes in gas storage field conditions. These technologies are increasingly less expensive and easy to use. They can allow a gas storage field to be operated as remotely as desired, similar to other high-hazard industrial facilities, and any necessary engineering, safety, or emergency responses can be immediate. It must be noted, however, that automated control and management systems have potential cyber vulnerabilities that pose security risks for these vital national assets.

Recommendation: Gas storage operators should deploy continuous monitoring systems at the ground surface and through the multiple casing strings for wells and critical gas handling infrastructure. This includes monitoring of annular and tubing pressure, as well as surface leak detection. Potential cyber security risks should be addressed as part of an operator's risk assessment, especially if the monitoring network is tied to a real-time control system.

Topic II. Risk Management Recommendations

1. Risk Management Plans should be comprehensive and reviewed periodically.

Observation: Some operators have comprehensive and systematic approaches to subsurface risk management. Others lack a formal approach or plan. Risk management practices vary across the gas storage industry, ranging from simple leak response to electronic data management systems that make use of statistics on failure rates. During DOE's July 2016 Workshop on Well Integrity for Natural Gas Storage in Depleted Reservoirs and Aquifers, one gas storage operator described a state-of-the-art web-based integrity management planning system for gas storage wells that was implemented when the operator was required to recertify several hundred wells. The gas storage community is making significant progress in developing and implementing processes that manage risk. This progress can be attributed to contributions from operators, regulators, trade associations, and other experts.

Discussion: Risk management planning is an ongoing process for identifying, assessing, and addressing potential threats that have adverse consequences and a finite probability of occurring. PHMSA's Integrity Management (IM)[82] regulations for pipeline systems have been in place for more than 12 years, resulting in thousands of defects being removed from pipeline systems before the defects could possibly cause a failure. IM programs also involve a cycle of continuous learning with a management of change process that applies lessons learned to the program. The pipeline industry has robust IM programs that may serve as a basis for applying the methodology to UGS facilities. Recent industry UGS standards, such as API RP 1170 and 1171, present key elements that should be included in a UGS risk management plan.[83] The European ISO/TS 16530-2:2014 standard discusses risk management but focuses more narrowly on well integrity management, which is one of several key elements in a broader risk management plan. Emergency response planning was identified during the workshop as a required element in every risk management plan. Discussions at the PHMSA workshop

[82]PHMSA's IM regulations are a type of risk management regime in 49 CFR Part 192 that requires gas pipeline operators to (1) identify riskier "High Consequence Areas" (HCAs) along the route of their pipelines that warrant extra safeguards; (2) determine and prioritize the potential threats facing each pipeline segment that could affect an HCA; (3) conduct baseline assessments of these segments, using methods tailored to those specific threats; (4) remediate any anomalies or conditions that could pose integrity threats; (5) take extra preventative and mitigative measures aimed at avoiding future problems; and (6) continually reassess the effectiveness of their IM programs and make needed improvements. A similar process is outlined in API RPs 1170/71 for UGS facilities.

[83]Use of the phrase "Risk Management Planning" throughout this report is unrelated to EPA's Clean Air Act Section 112(r)(7) risk management planning regulations for chemical accident prevention under 40 CFR Part 68. Risk management planning is a standard concept in the oil and gas industry and is discussed in industry documents, including those published by the American Petroleum Institute (API) and the International Organization for Standards (ISO).

held on July 14, 2016, identified the need to bring key stakeholders into the emergency response planning process.

Risk assessments have inherent limitations in that they cannot account for unknown threats, and they often rely on assumptions and/or estimates. Effective risk management relies on continuous improvement to ensure that decisions are based on current information and the most relevant methods. Having a risk management plan in place, and particularly one that is backed with data kept in an accessible records management system, will allow a company to apply its resources to higher-risk systems and to assure regulators and the public that it is committed to maintaining a high level of safety.

Recommendation: UGS operators should develop comprehensive risk management plans that address risks based on their potential severity and probability of occurrence. Gas storage operators should implement formal risk management plans that document their risk management strategy, identify risks, define responsibilities among stakeholders, assess risks, and provide appropriate responses. A risk management plan should include preventative and mitigation measures. As risk management will be needed for the life of a project, the plan should include a methodology by which its effectiveness can be tracked and reported, and by which the plan can be periodically reviewed and updated. Operators should develop risk management plans, and regulators should review those plans as part of the standard inspection and oversight process. The inspection and oversight process should prioritize and adjust inspection frequency based on level of risk. The inspection and oversight process should also include a periodic review cycle to adjust methods, based on data collected through the inspection and enforcement process and other means.

2. **Operators should institute more complete and standardized records management systems.**

   Observation: Records management practices vary across the gas storage industry. Guidance documents, such as API RP 1170 and 1171, indicate the need for records management, but there is not a recognized industry practice or standard.

   Discussion: Having an effective records management system allows an operator to know that all important information is current, approved as appropriate, and accessible. In addition, such a system allows operators to track information that is indicative of failures and successes within their field. Collecting data that can be analyzed and used to generate statistics on the wells in their fields will help them to manage their fields more efficiently and cost-effectively.

   Recommendations: Operators should institute records management processes within their risk management plans. These processes should ensure that documentation of essential information is created, maintained, protected, and retrievable when needed. Essential information consists of all records related to evidence of compliance with statutory and regulatory requirements. Operator data should include detailed well-completion diagrams, including casing and tubing strength, wall thickness, and coupling type schedules, maximum and minimum allowable operating pressures, safety valve locations and testing results, maximum withdrawal and injection rates, reservoir depth, well maintenance records, and incidents of failure. The latter may be particularly useful for power-sector risk management planning, as discussed in the reliability section of this report, especially if incident reports include impacts on deliverability to customers. Well records should also include how the well is used (injection, withdrawal, observation) and some volumetric flow or capacity data, so that reliability planning can assess the significance of given wells. The UGS field working and base gas capacities should also be reported and updated periodically, as they are likely to change slowly over time as field deliverability changes.

Critical information that should be preserved for the life of a facility includes findings of conditions adverse to the integrity of a well, whether or not the condition led to a release or required mitigation. Records should include information about the factors that contributed to the adverse condition and, in the event of a leak, the failure mechanisms, the size and duration of the leak, the conditions under which the leak occurred, the age and condition of the well, and its maintenance schedule. Such data can be aggregated across a field, as well as industry-wide, to provide help in understanding the relationships among completion, monitoring, and maintenance practices and well failures.

The records management processes should allow an operator to track records throughout their entire information life cycle, so that it is clear at all times where a record exists, which is the most current version of the record, and the history of change or modification of the record. The processes should ensure appropriate identification and description of records, including information such as title, date, author, reference number, etc., when records are created or modified. Record change control (version control) processes should be established to ensure that records are changed in a controlled and coordinated manner.

3. **Operators should develop and implement risk management transition plans within one year from the date when new minimum Federal standards are issued to compliance.**

   Observation: The activities required for operators to comply with new well integrity requirements will compete for resources with other risk mitigation investments, such as updating pipelines or gathering systems. Operators must contend with gaps that may exist for their operations relative to newly developed requirements and guidelines.

   Discussion: Operators will need time to become compliant with new guidelines and regulations for well integrity practices. Should risk assessments carried out by the operator identify an unacceptable level of risk, storage fields may have to curtail operations and limit availability. Well remediation will reduce the availability of storage fields to serve consumers. Discussions between operators and regulators about timelines for compliance must take into account energy reliability concerns.

   Recommendation: Operators should develop and begin implementation of transition plans within one year of the date of adoption of new regulations/standards. The transition plans should describe planned activities and a schedule that will be followed to reach compliance. Regulators should consider impacts to ratepayers and reliability through cost-benefit analyses. The transition plans should address how activities are prioritized in order to mitigate overall risk, and they may include enhanced monitoring measures that operators can use during transition to mitigate risks. Regulators should inspect operators' records during routine inspections in an effort to ensure that the transition plans have been properly implemented.

4. **Operators and regulators should account for a broad range of risk factors.**

   Observation: New industry guidelines and regulations should enhance the capability to detect/anticipate scenarios that resemble historical events (e.g., Aliso Canyon) but should also be flexible enough to address vulnerabilities that have not yet led to failure events. This is best achieved through rigorous implementation of an objective risk assessment that accounts for uncertainties rather than simply applying reactive protocols to address specific scenarios. This includes geologic and engineering factors, as well as the potential for human error, geographically relevant weather-related disruptions, geologic factors, or complications to emergency response.

Discussion: API RP 1170 and 1171 mention the use of procedures and training as mitigation measures for controlling risk. They also mention that procedures and training can embed human and organizational competence (human factors) in the management of storage facilities. Human factors are an important consideration in avoiding errors that can lead to accidents. API RPs 1170 and 1171 do not provide guidance or recommendations related to human factors; they provide only very general guidance for developing relevant procedures and training. One of the workshop presenters indicated that human factors is one of the "future directions" that the API RP Committee has discussed. There is an existing body of work that has examined human factors (or similarly, human performance, safety culture, etc.) in many contexts.

In some parts of the country, severe weather events, such as hurricanes, tornados, and floods, also can pose risks to gas storage wells and fields; and in some locations, seismic activity or landslides can pose risks. For example, at the Aliso Canyon field, there is a geologic fault that runs through the field, and the wells in the field were drilled across that fault. Although the fault has not had any seismic activity since those wells were drilled, sections of the fault that are within 50 miles of the storage field have shown seismic slip within the past 30 years.

Recommendations:

- **a.** New regulations and voluntary industry guidelines should both anticipate future events and address past events, including geologic factors, changes in the proximity of human population centers relative to gas storage facilities, and weather-related complications to field operations and emergency response.
- **b.** Risk management and emergency response plans should consider human factors in procedures and training.
- **c.** Industry should create a guidance document that discusses human factors principles in mitigating risk in underground gas storage facilities.

Topic III. Research and Data Gathering Recommendations

1. DOE and DOT should conduct a joint study of downhole safety valves.

Observation: The value of downhole safety valves (DHSVs) for natural gas storage is a source of significant controversy.

Discussion: DHSVs can provide a direct safeguard for preventing many uncontrolled flow scenarios, but their reliability and impact on production capacity raise concerns among operators. While DHSVs have seen widespread use in the offshore oil and gas industry and in European natural gas storage, it remains unclear whether DHSVs should be more widely deployed in U.S. storage facilities.

Recommendation: A quantitative study to evaluate key uncertainties related to the costs and benefits of DHSVs for the U.S. natural gas storage industry should be carried out by DOE and DOT, subject to appropriations. The study should include: (a) malfunction and failure rates of modern DHSV designs; (b) the cost and frequency of additional well work associated with their deployment; (c) the frequency of well failures for which a DHSV would provide a sufficient safeguard; (d) alternative emergency valve designs that could provide similar protection; (e) the impact of widespread DHSV deployment on UGS delivery and cost; and (f) optimal placement in wells for mitigation of well integrity failures.

2. **DOE and DOT should conduct a joint study of casing-wall thickness assessment tools.**

   Observation: Identifying deterioration in well casing is a critical component of maintaining well integrity.

   Discussion: Several casing wall thickness logging tools—e.g., various electromagnetic and ultrasonic tools—are now commonly used by natural gas storage operators to support well integrity assessments. Industry continues to improve the capabilities of wireline tools, and products with higher spatial resolution and the ability to assess multiple casing strings simultaneously are being marketed. Improving knowledge about the relative sensitivity, accuracy, and overall effectiveness of these tools will aid in developing optimal well integrity management practices and assessing residual risk.

   Recommendation: A systematic assessment of casing wall thickness assessment tools should be carried out by the DOE and DOT, subject to appropriations, with multiple tool types used to test manufactured articles and one or more reference wells with well-characterized corrosion issues. The goal should be to rigorously test and compare the ability of these techniques to identify, locate, and characterize corroded casings. Such a study could also inform better log interpretation practices.

3. **Industry and other stakeholders should review and evaluate wellbore simulation tools.**

   Observation: The Aliso Canyon event highlighted potential limitations of existing tools and analytical methods for simulating complex well processes, such as the processes associated with well kill events.

   Discussion: The SS-25 top kills were hindered by the tortuous fluid pathways governed by both tubing exits and re-entrances. The initial simulations used to support the Boots and Coots top kill efforts lacked sufficient detail to correctly predict that the well kill attempts would fail. Incorporating "real world" conditions in a wellbore simulation, such as complex fluid pathways or high-density non-Newtonian fluids, is a challenging task to conduct during a rapidly evolving crisis, particularly with the inherent limitations in knowledge of the boundary conditions and the exact configuration of a damaged well. This is also important because poorly executed top kills can have a detrimental effect on the well condition and on future kill attempts.

   Recommendation: A review of existing well simulation codes that can be, or currently are, applied for analyzing adverse well events should be undertaken by DOE (subject to appropriations), industry, and other stakeholders. The assumptions underlying each code, as well as code adaptability for a variety of geologic and reservoir settings, should be carefully considered. Working with industry providers, universities, and national laboratories, DOE, industry, and other stakeholders can develop a set of benchmark problems and well failure scenarios to exercise the codes and to compare results. Similar code comparison studies have been used in the past to support critical national programs (e.g., radioactive waste isolation). Based on the review of existing analytical capabilities, the identification of knowledge gaps and limitations can then be used to improve the toolkit of software to assist in response to future loss of well control events. Learnings from such a review should be disseminated at forums, as they are seen as broadly applicable throughout the oil and gas industry. Ultimately these tools, used by knowledgeable engineers, should be applied to the development of well integrity plans that identify weaknesses in a given design and consider failure modes that could lead to a loss of pressure control.

4. **Data gathering gaps should be addressed.**

   Observation: There is limited data available to regulators and the public on well locations and other characteristics. Collecting and aggregating this information can help stakeholders understand risks related to individual facilities and regional risks that could be posed by loss of availability at multiple facilities.

   Discussion: The records for wellbores that were drilled decades, or more than a century, ago may be inaccurate or irrecoverable. The well record for SS-25, for example, contained ambiguous and likely incorrect information regarding key aspects of the tubing-to-casing connections. There are also a number of instances, such as Aliso Canyon, where wells and fields that were originally far from population centers are now quite close to significant numbers of people.

   Recommendations:

   a. State and/or Federal agencies should consider undertaking a phased-data gathering project to identify the locations of unknown wells at or near UGS facilities, particularly in areas where known exploration and production activities have occurred in the past. This data gathering and recordkeeping may include site-scale geophysical or ground truth surveys, as well as collection and integration of data from multiple historical sources, such as maps, property records, leases, or aerial photography.

   b. State and/or Federal agencies or other stakeholders should collect and analyze data on the proximity of UGS facilities to population centers to help better quantify some of the risk factors. Best management practices and policies should take into account projected changes to land use, infrastructure, and human population centers relative to UGS facilities.

   c. State regulators and PHMSA should collaborate to collect and make data (e.g., data on fires, leaks, or other hazardous incidents) publicly available in a format that allows easy aggregation to provide better understanding of individual and system risks. It is particularly important to work with States that already collect and/or publish limited data.

Topic IV. Immediate Regulatory Actions

1. **Existing industry recommended practices should be incorporated into applicable regulatory codes.**

   Findings: Currently, the Federal gas pipeline safety regulations in 49 CFR Part 192 do not include any regulatory requirements for storage wells and wellbore tubing located at underground gas storage facilities. The Part 192 regulations apply only to the surface piping up to the wellhead at these facilities. As a result, there are no safety regulations at all for the thousands of storage wells located at the approximately 200 interstate facilities in the U.S. In addition, there is no uniform "floor" of minimum regulations for those States that already exercise limited jurisdiction over existing intrastate facilities.

   Discussion: A broad group of stakeholders, including industry and regulators, recently developed two new consensus-based standards for underground gas storage. They were developed under an ANSI-approved process and published in September 2015 as the following API Recommended Practices (RPs): API RP 1170, "Design and Operation of Solution-mined Salt Caverns Used for Natural Gas Storage," and API RP 1171, "Functional Integrity of Natural Gas Storage in Depleted Hydrocarbon

Reservoirs and Aquifer Reservoirs." Both API RPs 1170 and 1171 recommend that operators of underground natural gas storage facilities implement a wide range of current recommended practices, including operating, maintenance, risk management, qualification and training, and emergency response preparedness activities.

The incorporation of API RP 1170 and 1171 into the Part 192 regulations will be an important step in improving the safety and reliability of underground gas storage facilities. It will impose minimum requirements for all UGS operators to assess the operational safety of their underground natural gas storage facilities, and it will ensure that operators document the implementation of identified safety solutions. PHMSA will be able to enforce API RP 1170 and 1171 directly at interstate facilities. Because certified State agencies will eventually adopt the latest version of Part 192 as part of their annual certifications under 49 U.S.C. 60105, these State authorities will also be able to enforce API RP 1170 and 1171 at intrastate facilities. These State agencies will also be able to continue issuing and enforcing additional or more stringent State regulations for their intrastate facilities. PHMSA and its State partners will monitor operators' implementation of API RP 1170 and 1171 and begin inspecting facilities for compliance. PHMSA plans to build on its minimum regulations as necessary in order to ensure that operators fully address the safety issues presented by underground natural gas storage.

Recommendation: PHMSA should consider incorporating existing industry-recommended practices API RP 1170 and 1171 into the Part 192 regulations, and they should be adopted in a manner that can be enforced. They should be supplemented with reporting and recordkeeping requirements as necessary. Experience with inspections and oversight of the written plans called for in API RP 1170 and 1171 and their implementation, along with the recommendations and studies discussed elsewhere in this report, should inform additional requirements in the future.

Health and Environment

The EPA, CDC, PHMSA, and NOAA assessed the public health and environmental impacts associated with the leak at Aliso Canyon. To support their assessment, they summarized the actions taken by local, State, and Federal agencies to monitor and mitigate impacts on public health and the environment, and they have reported the best estimates of those impacts. Based on their work, the Task Force recommends the following actions to be taken by local, State, and Federal agencies in order to be prepared in the event of a future from a natural gas storage facility.

Topic I: Agency Responses to Address Gas Leak Health Concerns

1. Unified Command

Observation: During the initial leak period, a number of regulatory agencies and emergency response providers were involved in addressing various aspects of the leak, including public health and environmental impacts, well-control operations, community involvement, media communications, and public outreach. However, SoCalGas was acting as the single incident commander during this period.

Discussion: For 92 days, from discovery of the leak at SS-25 until January 22, 2016, SoCalGas acted as the incident commander. On January 22, 2016, SoCalGas, LA County Fire/HazMat, and LADPH formally entered into a Unified Command (UC). Entering into a UC earlier might have improved the response in terms of environmental and public health messaging and communication with external parties.

Recommendation: When human health and environmental threats are present and multiple jurisdictions are involved in the response effort, a Unified Command should be formed early in response to a UGS release. The jurisdictions involved could be represented by geographical boundaries, government levels (e.g., Federal, State, local, tribal), functional responsibilities (e.g., fire, oil spill, emergency medical services), statutory responsibilities (e.g., Federal Land Managers, Responsible Party), or some combination thereof. The Unified Command should identify a liaison to the affected communities to ensure direct communication with affected residents.

2. **Expert Advisory Group**

Observation: SoCalGas mobilized crews and equipment immediately upon discovery of the leak and, within 24 hours, determined that its standard procedures to abate leaks were not working and called in additional experts. Within 48 hours, SoCalGas had well-control experts on-site.

Discussion: The issues under consideration during the Aliso Canyon incident were complex and wide-ranging. They included subjects such as well-control techniques, public health effects of exposure to mercaptans or other chemicals, environmental impacts of a greenhouse-gas release of this magnitude, public communication, and regulatory oversight. It is essential that decisionmakers have access to accurate and complete information to make well-informed decisions. A readily accessible group of subject matter experts might have improved the decisionmaking process—especially for the complex engineering and health and safety issues associated with top kill attempts and surface gas collection.

Recommendation: In jurisdictions with significant natural gas storage, facility operators, regulatory agencies, and other responding agencies should consider compiling and maintaining a roster of potential subject matter expert advisors. The Unified Command could consult the roster to quickly convene a group that would be able to provide decisionmakers with advice on complex technical issues. Such an advisory group would be separate from the technical experts that are a normal component of the typical Incident Command System.

3. **Regulator Coordination and Regulatory Authority Review**

Observation: In the Aliso Canyon incident, local and State agencies in California had an existing regulatory framework and adequate authority and expertise to respond effectively to the incident. Federal agencies provided additional expertise and support for the State response efforts. However, this is not true across the country or for interstate gas storage facilities. This lack of uniformity prompted Congress, PHMSA, the gas storage industry, and State regulators (generally oil and gas boards) to examine the need for Federal and State regulators to work together more closely to produce a more effective and seamless set of safety standards and regulations.

Discussion: Federal agencies such as the EPA and the PHMSA have assessed their respective regulatory and injunctive authorities. It was determined that, in this case, State and local authorities were fully engaged, had adequate authority, and were ordering relief that was similar to what Federal authorities would have pursued.

However, in the event of a release from an interstate facility or facilities in other States, there is currently no set of mandatory safety standards that can be enforced uniformly across the country. Under PHMSA's State certification program for intrastate gas pipelines, States voluntarily file annual certifications with PHMSA, representing that they have the adequate authority and resources to effectively inspect intrastate pipelines and enforce the applicable requirements. Under this State certification program, which currently is in place in 48 States, PHMSA monitors State programs and provides Federal funding. To the extent that State oil and gas agencies other than the State pipeline safety agency will be responsible for the wells and downhole facilities, these agencies may also need to become certified. In June 2016, Congress directed PHMSA to move forward expeditiously with the adoption of minimum safety standards for underground storage. That process is currently underway. In addition, other Federal agencies may need to fill gaps and order additional relief to ensure that public health and the environment are protected.

Recommendation: Regulatory agencies at Federal, State, and, as appropriate, local levels should review their existing authorities and regulations related to natural gas storage facilities to identify potential gaps and address them in a collaborative manner that builds upon the existing State certification program for intrastate gas pipelines.

Topic II: Ambient Air Pollutant Monitoring During the Incident and Public Health Risk Assessment

1. **Monitoring Network**

Observation: The network of ambient air monitors deployed in the community and facility property was appropriate for the objective.

Discussion: Generally, the monitoring network that California state and local agencies established after the leak was discovered provided a detailed and robust characterization of ambient air quality in the vicinity of the SoCalGas natural gas leak and the surrounding community of Porter Ranch. Jurisdictions throughout the United States may not have ready access to similar resources.

Recommendation: State and local monitoring agencies with natural gas storage facilities within their jurisdictions should have the ability to establish a robust ambient air monitoring network in the surrounding communities, in order to adequately characterize the potential health impacts associated with natural gas leaks if resources are available. This includes access to real-time monitoring equipment for sulfur additive compounds, VOCs (hydrocarbons and aromatic compounds), SVOCs (e.g., naphthalene), methane, $PM_{2.5}$, H_2S, metals, and any other chemicals of concern identified by source data, as well as capability for instantaneous grab and 24-hour integrated samples.

2. **Timeliness and Data Availability**

Observation: Ambient air monitoring was deployed quickly in response to community concerns. Posting of ambient air samples in near-real time helped keep the community and public health agencies well informed.

Discussion: SCAQMD was able to initiate the collection of instantaneous grab samples on October 26, 2015—three days after the leak was discovered—in direct response to community complaints, providing a timely response to the community's concerns. Additional data were collected by SoCalGas, CARB, and LAUSD in the days that followed. All entities that collected ambient air quality data on facility property or within the surrounding communities posted the results on publicly accessible websites. CARB and SCAQMD specifically posted results from both instantaneous grab and 24-hour integrated samples, as well as near-real-time data from continuous monitors at the eight fixed locations within the community. Efforts were made to synthesize the data so that community members could understand the results.

Recommendation: State and local monitoring agencies should have an emergency air monitoring plan established for expeditious deployment of an ambient air monitoring network if a similar leak were to occur. Having data early in the process would enable agencies to reach timely decisions most consistent with public health protection (such as a decision to relocate residents). State and local monitoring agencies should also post their collected ambient air quality data in a prompt, easily accessible, and easy-to-understand manner.

3. **Pollutants of Concern**

Observation: Pollutants of concern were not identified prior to the leak event, and the composition of the kill fluids was unknown.

Discussion: It is common practice in the petrochemical industry to "fingerprint" each oil refinery's oil. [84] This type of analysis could be conducted periodically for each natural gas storage facility, in order to develop an understanding of what chemical compounds constitute the gas in each well or facility. This process could also be undertaken for any of the kill attempt fluids in order to better understand the chemical composition of the material used and its potential impact on public health. Having these analyses available would further enable health agencies and air quality agencies to develop comprehensive environmental sampling plans that could be used in the event of a leak. The analyses would also aid in determining the scope of monitoring, sampling, and analyses required, ultimately saving valuable resources and time.

Recommendation: State and local monitoring agencies in jurisdictions with natural gas storage facilities should consider collaboration with those facilities to develop facility-specific chemical fingerprints of the natural gas. If kill attempts are considered for sealing a leaking well, the kill fluid should also be analyzed for metals and other potential pollutants of concern. Once the chemical fingerprints are known, targeted monitoring plans should be developed in order to facilitate a quick and targeted response to a leak event. Such a plan should prioritize the sampling of pollutants of greatest health concern, which could include benzene, toluene, ethyl benzene and xylenes (BTEX), $PM_{2.5}$, and hydrogen sulfide.

4. **Background Concentrations of Pollutants**

Observation: Background concentrations of methane and other pollutants of concern were not specifically known for the areas surrounding the SoCalGas facility and SS-25.

Discussion: While SCAQMD, CARB, LAUSD, and SoCalGas performed extensive monitoring throughout the community and on the facility's property during the leak, there were no prior measurements for methane, benzene, mercaptans, hydrogen sulfide, or other compounds in the immediate area that would have established local background levels for those pollutants in the affected communities. Without local background levels, it is inherently difficult to interpret monitoring results accurately during the life cycle of the leak event.

Recommendation: State and local monitoring agencies should consider collaborating with stakeholders to determine local background levels of methane and other pollutants of concern.

[84]This analysis is typically done by GC/MSD or other GC detectors using either EPA Method TO-14, Method TO-15, EPA Method EPA-18, or Method TO-3.

5. Health Effects

Observation: The full range of health risks from exposures to air pollutants released from the leaking well is not known, including health risks that may manifest over the long term.

Discussion: OEHHA and SCAQMD investigated the acute health risks from exposures to pollutants for which REL values existed. Chronic risks were also evaluated, although the exposure period during the well leak was much shorter than typical chronic exposures. OEHHA searched for REL-equivalent values for the natural gas odorants (t-butyl mercaptan and tetrahydrothiophene) but found that there are insufficient studies available to establish an REL and to determine the long-term effects of exposure to these odorizing additives.

SCAQMD's independent Hearing Board approved a legal order that requires SoCalGas to fund a study (to be completed by a third party) of the potential health effects of exposure to the gas leak.[85] According to the order, the study will include exposure to the odorants added to natural gas, for which there are currently no established RELs or cancer toxicity values. The status of this study is pending.

Recommendation: Further research is needed to determine the acute and chronic effects of exposure to natural gas odorants (t-butyl mercaptan and tetrahydrothiophene). Relevant agencies should review the results of the SoCalGas-funded study ordered by the SCAQMD Hearing Board and consider any relevant findings or recommendations. Monitoring and analysis by State and local agencies should continue, and risk data should be updated if conditions change.

6. Coordination and Expertise

Observation: A breadth of local and State expertise, along with frequent interagency coordination, aided in the assessment of air pollution-related health risks to the community.

Discussion: Beginning in November 2015, twice-weekly calls were held to discuss air monitoring activities, sampling results, and health risk assessment with experts in those fields. Participating agencies included SCAQMD, OEHHA, CARB, LA DPH, LA County Fire/HazMat, LAUSD, SoCalGas, and others.

Recommendation: In the event of a future well leak, responding agencies should include health-related expertise in the response. Responding agencies should consider establishing a network of health and risk assessment professionals prior to a leak event. After a leak has been identified, the network should be convened regularly to assess collected air sampling data and the potential for health impacts from related pollutant exposures.

7. Detection Methods

Observation: The analytical methods used to detect sulfur compounds were not able to identify the ambient concentrations experienced by the community and workers at the site, because detection was limited by the sampling method.

Discussion: Methods ASTM D5504-12 and SCAQMD 307-91 were used to test for sulfur compounds in ambient air. As a result, the parts-per-billion level detection limits of these methods were above the

[85] http://www.aqmd.gov/docs/default-source/compliance/aliso-cyn/findings-and-decision-(complete).pdf?sfvrsn=4.

odor threshold for some of the sulfur-based odorants. Methods have been developed to sample and analyze sulfur compounds in ambient air at parts-per-trillion levels, which are more similar to levels detected by the human nose.

There are published methods for low-level sulfur compound testing that have been used in research studies. However, laboratories would need time and resources to prepare for analyses at the lower detection limits. In conjunction with methane sampling, these methods could aid in detecting leaks from natural gas infrastructure at lower concentrations and could reliably discern leaks that otherwise would not be detected due to background methane concentrations.

Recommendation: Natural gas facilities and local and State agencies should consider identifying laboratories with the capability to measure sulfur compounds at lower detection limits. If feasible, analytical methods to detect odorants at concentrations below odor thresholds should be available and should be used during incidents.

8. **Source Testing and Characterization**

   Observation: Source testing of emissions from SS-25 was not comprehensive.

   Discussion: Emissions from SS-25 were not characterized for the full range of compounds released. It would have been informative if, immediately after the release occurred, emissions of all chemical constituents had been evaluated, followed by continuous monitoring of some chemical constituents and periodic measurement of others. SCAQMD and SoCalGas collected a limited number of speciated air samples near SS-25 during the release. Characterization of the source was limited due to safety concerns.

   Recommendation: State and local air monitoring agencies should consider developing systems to collect source samples safely during a release and also should consider conducting robust source testing/characterization. Information collected on the chemical constituents of sources could be used in conjunction with air dispersion and deposition modeling to help inform decisions.

Topic III: Greenhouse Gas Emissions

1. **Baseline Data**

   Observation: The Aliso Canyon release occurred in a heavily populated region with several pre-existing ambient air monitoring stations measuring methane, and with robust State and local agency capacity to respond to threats to air quality.

   Discussion: Baseline monitoring data on methane concentrations in areas with storage facilities would greatly improve detection and quantification of leaks.

   Recommendation: State and local air monitoring agencies should consider having a methane monitoring framework. Baseline methane measurements would improve understanding of the magnitude of a leak. The framework and measurements should build on data already reported to Federal, State, and/or local agencies.

2. **Release Uncertainty and Multiple Measurements**

   Observation: Multiple measurement techniques were employed at Aliso Canyon to estimate the total quantity of methane released; however, uncertainties remain.

Discussion: Data from a wide variety of monitoring and measurement methods are available to quantify emissions from the leak, including information collected through grab samples, aircraft studies, mobile tracer flux ratio studies, satellite data, and inventory methods. Several groups quantified emissions using various sets of these data. Studies using different measurement and quantification methods converge around an estimate of roughly 90,000 metric tons of methane for the total quantity of methane emitted. The State's final methane emission estimate, which will consider all available data, is anticipated to be released by the end of 2016.

Other natural gas storage facilities would not typically be covered by multiple existing monitoring networks, and they also might not have access to multiple measurement technologies that are rapidly deployable to the site.

Despite multiple measurements, there are two overarching uncertainties that affect most of the measurement techniques. First, for a 15-day period between the leak's discovery on October 23, 2015, and the initial methane sampling flight on November 7, 2015, only limited data were available to estimate the rate of methane emissions. Second, it is unclear whether or to what extent any of the methane measurement efforts collected data during the eight "top kill" attempts. The "top kill" attempts may have affected the rate of natural gas release by altering the subsurface flow paths of the leaking natural gas.

Recommendation: State and local air agencies should begin methane monitoring as soon as possible following the initial detection of a leak. All monitoring should be coordinated with attempts to stop the leak, in order to determine whether those attempts decrease, increase, or stop fugitive methane emissions. When possible, future leaks from natural gas storage facilities should be measured with multiple methods to confirm measurements. State and local air agencies should consider coordination with existing measurement and quantification efforts, such as those by universities and Federal and State agencies active in methane and other air emissions monitoring efforts. These entities may have data or experience with monitoring in the area that could be of use.

3. Measurement Technology

Observation: Rapid deployment of measurement technologies following the release helped agencies understand the scale of the leak. Recent advancements in methane monitoring technologies may offer less costly, more portable, and more precise measurements.

Discussion: Scientific Aviation, a company that operates aircraft modified for atmospheric research, collected its first round of samples on November 7. (Initial safety concerns expressed by SoCalGas prevented earlier aircraft sampling.) It was fortunate that the State had an existing contract in place with the University of California, Davis, which allowed it to move quickly to initiate aircraft-based data collection. The data collected were used by the State to keep the public informed as work to stop the leak was ongoing.

Entities such as DOE's Advanced Projects Research Agency-Energy (ARPA-E) are seeking to spur development of other advanced methane leak detection technologies that could, within 10 years, detect a broad range of leak sizes. The Environmental Defense Fund (EDF) is also seeking to speed deployment of technologies to monitor for leaks on a continuous basis.[86] On July 18, 2016, the EPA

[86] https://www.edf.org/energy/natural-gas-policy/methane-detectors-challenge.

published a Request for Information inviting oil and gas owners and operators, along with States, nongovernmental organizations, academic experts, and others, to provide information on innovative strategies to locate, measure, and mitigate methane emissions accurately and cost-effectively.[87] The response period will end on November 15, 2016.

Recommendation: In advance of a leak, State emergency management agencies should determine whether they have access to aircraft and/or other mobile measurement technologies that can be deployed rapidly. Safety should be a consideration when aircraft are flying in zones with high methane concentrations. Air agencies should also consider formalizing pilot projects, involving State/local agencies, facility operators, and Federal agencies, to deploy and evaluate some of the evolving methane measurement methods.

4. **Inventory Tracking**

Observation: EPA tracks greenhouse gas emissions over time using the Inventory of U.S. Greenhouse Gas Emissions and Sinks. Many States track greenhouse gas emissions over time using State-level inventories.

Discussion: Emissions estimates from leak events like Aliso Canyon can be incorporated into emissions inventories if data are available. The EPA noted in the most recent Greenhouse Gas Inventory that it plans to include the Aliso Canyon event in its estimates of 2015 and 2016 emissions, which are to be published in 2017 and 2018, respectively.

Recommendation: Studies of natural gas releases should quantify emissions in such a way that they can be included in inventories. An emissions estimate of the total mass of gas emitted by an event can be included directly in an inventory, whereas methane concentration estimates at a given time cannot be included in an inventory without other information.

Topic IV: Post Well Closure Indoor Air and Source Sampling/CASPER Health Assessment

1. **Contaminant Identification**

Observation: A substantial effort was made to identify potential contaminants associated with the Aliso Canyon gas leak in the homes of Porter Ranch residents.

Discussion: In at least one of the top kill attempts, a significant volume of kill fluid was expelled; it was hypothesized to be part of an oily coating found on and within many homes in the Porter Ranch community. The results of a comprehensive effort to collect indoor air, surface wipe, and soil samples informed the response to citizen complaints, which culminated in a comprehensive cleaning effort by SoCalGas.

Indoor air sampling results were similar to those found in comparison homes and were within normal ranges for home indoor air. However, wipe sampling results found that a group of metals—barium, manganese, vanadium, aluminum, and iron—appeared together consistently, suggesting a common source. Soil sampling indicated elevated levels of chemicals, including hydrocarbons up to C_{40}, barium, and naphthalene.

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[87] Oil and Natural Gas Sector; Request for Information; Emerging Technologies, 81 FR 46670, July 18, 2016.

Recommendation: Given the evidence that materials used in well-kill fluids may be re-expelled and may contaminate the surrounding area, facility operators and emergency responders should use caution when determining the composition of well-kill fluids and should consider the possible health risks that might result from exposure to toxic substances present in the fluids. Knowing the composition of the fluids would also facilitate environmental testing in the event of an accidental release. If a situation should occur in which a large volume of kill fluid or other material was expelled along with natural gas, the appropriate State or local agency should test exposed homes for the presence of potential or known constituents before residents returned. Soil samples taken at or near the source should be collected and analyzed for contaminants associated with the release, especially if residues resulting from a leak were found on or within structures at the facility, or in a community, and it was thought that the contaminants could pose a potential ingestion or inhalation risk. If enough information was known about the source and the expelled contaminants, dispersion modeling could be used to help make decisions regarding additional soil, surface water, and indoor sampling within the affected community.

2. Source-Receptor Evaluation

Observation: From the perspective of making a connection between the source of emissions (SS-25) and the locations affected by those emissions (the "receptors," e.g., residences, schools, and other locations downwind from SS-25, and ultimately the people in those locations), the conditions of the Aliso Canyon leak were relatively straightforward. The conditions aided the LADPH's evaluation of the relationships between source and receptors. The LADPH Public Health Assessment analysis also relied on the common occurrence of metals in the source and receptor samples to indicate the connection between source and receptor. The analytical methods used to evaluate trace metal content of residues from residences and schools were limited to total elemental levels.

Discussion: The conditions that allowed for a straightforward demonstration of the connections between the source and receptors included a single, large-volume emissions source, relatively consistent weather patterns, and fairly well-defined trace element composition of the source. More complex situations are possible in future incidents, which could result in an inability to demonstrate adequately the connections between the source and receptors. A lower emissions rate relative to similar surrounding sources (which might be the case with a slower leak from a storage site located in an operational oil and gas production area), greater variability in weather conditions, or more complex terrain could result in substantially less confidence in the ability to connect an emissions source to health and environmental impacts than was possible with the Aliso Canyon leak.

The metals identified as suggestive of a single source due to their common occurrence in source and receptor samples are not unique to the sources. While it is likely that the common occurrence of aluminum, barium, iron, manganese, and vanadium in both source and receptor samples provides adequate evidence of SS-25 as the source of residential and school contamination in this case, in a more complex situation it might be more appropriate to evaluate the ratios of various tracer species in multiple sources and receptor sites. The metals of interest here are present in numerous sources, from crustal dust to building materials, and the ratios of those trace elements will be different for different sources.

Recommendation: Collection and analysis of source and ambient samples should be conducted to enable evaluations of links between receptors (such as ambient monitors and residential surface samples), emissions from the leak, and emissions from other emission sources nearby and to support evaluations of health risks associated with exposure to the mix of constituents emitted. A more in-depth analysis of multiple relevant source trace element ratios, the ratios of samples from receptor sites, and use of sequential extraction would be appropriate in more complex leak situations like those noted above.

3. **Post-Incident Sample Collection**

Observation: The process of post-incident indoor testing was responsive to ongoing health symptoms, but it was time consuming because information regarding potential contaminants was lacking.

Discussion: When ongoing health complaints from the public and the initial evaluation of the CASPER survey provided evidence of potential indoor exposures, an indoor testing protocol needed to be developed and implemented expeditiously. The process of preparing and conducting the sampling, performing the laboratory analysis, and interpreting the data resulted in an effort that took several months to complete before conclusions could be developed and shared with the community.

Recommendation: Responding agencies should develop a plan for post-incident sample collection and analysis and should integrate the plan into the initial incident response, in order to mitigate post-incident exposures and compress post-incident timelines.

4. **Home Cleaning**

Observation: Indoor cleaning activities were completed in an inconsistent manner.

Discussion: SoCalGas used its environmental mitigation contractor to implement cleaning activities. Many of the cleaning subcontractors did not have experience with the type of cleaning required to mitigate residences and schools. LADPH provided significant oversight of cleaning and was able to determine that much of the cleaning conducted was inadequate.

Recommendation: In-home pollutant mitigation and cleaning activities should only be performed by certified professionals under adequate supervision.

Public Health Hazard Assessment

Observation: The LADPH Public Health Assessment notes the possibility of metals, particularly barium, in household dust as causing symptoms observed in the CASPER survey.

Discussion: As LADPH summarized in its Public Health Assessment, barium was the most frequently detected metal, found in 19% of the Porter Ranch homes with concentrations ranging from 0.05 to 1.0 $\mu g/cm^2$. Along with barium, four other metals (manganese, vanadium, aluminum and iron) consistently appeared together in the Porter Ranch home samples. LADPH noted that barium and the other metal contaminants can cause respiratory and skin irritation, and their presence could have contributed to the reported symptoms.

Although barium was the metal most commonly identified at sampling locations within the Porter Ranch community, there are no surface wipe reference standards for barium for either occupational or residential exposure. The absence of methods to extrapolate from surface wipe samples to air concentrations makes it difficult to draw conclusions about human exposures to indoor concentrations of air pollutants. Similarly, the absence of human studies or reports that correlate a particular surface wipe concentration of metals to any health effects or outcomes makes it difficult to draw conclusions about health impacts from those exposures.

Recommendation: State and local health and environmental agencies should consider developing standardized approaches for collecting health information and linking it with environmental monitoring data for use in public health hazard assessment in the event of similar leaks at other well sites.

Topic V: Greenhouse Gas Mitigation Plan

1. Mitigating Releases of Short-lived Climate Forcers

Observation: There are no Federal or State requirements to mitigate the environmental (i.e., climate) impacts of methane leaks from underground natural gas storage facilities, nor are there established standards to guide voluntary mitigation of the climate impacts of fugitive releases of a short-lived climate forcer such as methane.[88]

Discussion: There are no Federal or State mitigation requirements for the fugitive greenhouse gases released from the Aliso Canyon leak. Nonetheless, during the release, SoCalGas publicly acknowledged the impacts it was having on the environment and voluntarily committed to mitigating its climate impacts. Shortly after the SoCalGas commitment, Governor Brown ordered CARB to develop a plan for full mitigation of the leak's methane emissions. The combination of corporate leadership and public agency guidance is noteworthy. However, due to the litigation, it remains uncertain whether the leak will be "fully" mitigated per Governor Brown's proclamation, and mitigation is likely to be affected by the court decision.

CARB's March 31, 2016, Mitigation Program for Aliso Canyon discusses complexities associated with mitigation and differing stakeholder opinions on approaches. For example, methane's lifetime in the atmosphere is much shorter than that of carbon dioxide, but methane is more efficient than carbon dioxide at trapping radiation. Using the metric of "global warming potential" (GWP), pound for pound, the comparative impact of methane on climate change is approximately 28 to 36 times the impact of carbon dioxide over a 100-year period and approximately 84 to 87 times the impact of carbon dioxide over a 20-year period.[89]

In the context of the Aliso Canyon incident, with approximately 90,000 metric tons of methane released, full mitigation could be considered as ranging between about 2 million and 8 million metric tons of carbon dioxide equivalent, depending on whether a 100-year or 20-year time horizon is considered.

CARB's plan includes offsetting an amount of methane equivalent to the amount of methane leaked from Aliso Canyon or, if the emissions of a different greenhouse gas are reduced, to calculate equivalence using the 20-year GWP of methane. CARB ultimately decided on a 20-year time period for conversion into carbon dioxide equivalents, in order to "…properly incorporate current scientific knowledge, underscore the influence of SLCPs [short lived climate pollutants] as immediate climate-forcing agents and emphasize the need for immediate action on climate change." SoCalGas, in

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[88]The term "short lived climate forcer" is generally used to denote a class of climate pollutants, including methane, that have relatively shorter atmospheric lifespans and relatively stronger climate impacts compared to carbon dioxide.

[89]Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (AR5), Synthesis Report, Box 3.2.

comments on CARB's approach stated, "…using the 20-year GWP in this situation is inappropriate as well as contrary to California and Federal law. Therefore, we do not intend to use a 20-year GWP as we evaluate mitigation projects."[90]

Recommendation: States with underground natural gas storage should review their legal authorities to require greenhouse gas mitigation of fugitive emissions from underground natural gas storage facilities. States interested in mitigation should review California's approach as outlined in its Mitigation Plan.

Reliability

The DOE commissioned an analysis of the impacts of a failure at each of the 400+ UGS facilities in the United States on their customers, quantified in terms of natural gas-fired electricity generation capacity potentially affected from the loss of a UGS facility. The methodology and models developed to assess the impacts are summarized below. All models and analyses are based on publicly available data. Based on the analysis, the Task Force presents observations and recommendations in terms of the need to improve gas/electric industry coordination for electric and gas reliability, the need for further analyses, the need for data for additional gas/electric reliability studies, and changes to regulatory requirements and standards. A supplementary Technical Report, which will be released by the end of the year, provides more details and extends the analysis. The analysis also assessed the impact of the Aliso Canyon incident on energy reliability and energy prices.

Topic I: Ensuring Electric Reliability and Managing Gas-Electric Interdependency Risks

1. Aliso Canyon Event Has Implications Beyond Management of UGS Facilities

Observation: The Aliso Canyon event was a wake-up call, alerting us to the need for better understand of the implications and risks associated with growing interdependence between the electric and natural gas industries, and the need to take appropriate actions to mitigate such risks.

Discussion: Aliso Canyon is not a unique UGS facility in terms of its potential, if disrupted, to have adverse impacts on electric reliability in the affected area. A total of 12 UGS facilities appear to have the potential to affect 2 GW or more of available generation capacity. Note, however, that these figures are preliminary, because the operators of the affected power plants may or may not have dual-fuel capability (i.e., diesel or equivalent liquid fuels, with sufficient inventories), access at short notice to alternative sources of natural gas, or access to alternative generation via transmission.

Recommendations:

a. Power system planners and operators, working with their natural gas counterparts, should study and understand the electric reliability impacts of prolonged disruptions of large-scale natural gas infrastructure (e.g., storage facilities, processing plants, key pipeline segments and compressor stations, LNG terminals).

b. Power system planners and operators should communicate and share the results of their analyses with State and Federal officials to ensure that policymakers fully understand the risks to electric reliability and can develop appropriate mitigation policies and strategies.

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[90]Letter from SoCalGas to CARB chair Mary Nichols re: Aliso Canyon Methane Leak, Climate Impacts Mitigation Program (Draft), dated March 14, 2016.

c. Regulators, electric and gas operators, and other market participants should strive to disseminate planning and operational information to all facets of the electric and gas industries, so that key operating parameters, such as those pertaining to gas balancing, are defined, solutions can be developed, and coordination achieved. By sharing information, entities can develop and train on new operating/market procedures, increase situational awareness, prepare to implement procedures to maintain the operation of the electric and gas systems under constrained conditions, and avoid gas and electric curtailments.

2. Backup Strategies Can Reduce Risks

Observation: The availability and use of a backup fuel source for electricity generation (or some functional equivalent) can enable a generation facility to operate in isolation from a potential natural gas infrastructure disruption.

Discussion: Greater reliance on such measures as dual-fuel capabilities (i.e., diesel or equivalent liquid fuels, with sufficient inventories), energy storage options, and maintaining alternative sources of natural gas may help electricity operators bridge the gap between the uncertainties of gas availability during extreme events and maintaining a reliable source of operable capacity available to meet seasonal peak demands. This approach could include natural gas storage at or near electricity generation plants, if feasible and affordable.

Recommendation: NERC, generators, and Federal and state agencies should consider broader usage of back-up strategies, including dual-fuel capabilities, energy storage options, and alternate sources of natural gas supply, to reduce reliability risks associated with the possible abrupt loss of a major source of natural gas for electricity generation.

3. Joint Gas/Electric Planning and Coordination Should be Strengthened

Observation: Opportunities exist for DOE, FERC, NERC, and the electric and gas trade associations to strengthen joint gas-electric planning and coordination, with the objectives of seeing the electric and natural gas systems as interdependent critical infrastructures and minimizing risks (including physical and cyber security) to both sectors and their customers.

Discussion: Enhanced operational coordination between the gas and electric industries would decrease the impacts of widespread outages. As an example, joint actions could be taken to optimize real-time gas flows across regional and local systems.[91]

Recommendation: Federal and State agencies should work with NERC and the electric and gas trade associations to develop reliability guidelines, as well as identifying best practices for improved procedures, practices, and market designs to reduce and manage the impacts of gas curtailment events and related electricity contingencies.

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[91] http://western.wp.naruc.org/wp-content/uploads/sites/2/2016/06/GasSafety-All.pdf.

Topic II: Further Analyses and Tools Required

1. **Analyze a Broader Range of UGS-Related Contingencies**

   Observation: The Task Force's current analysis of the potential loss of UGS facilities considered only the loss of one such facility at a time. A wider range of regionally relevant contingencies is plausible and merits review by electric system planners.

   Discussion: Earthquakes or other disasters could disable multiple UGS facilities in an affected area, or they could take out combinations of UGS facilities and other important gas supply infrastructure. Further, planning to make gas/electric infrastructure more resilient against such events should take into account the need to ensure the availability of adequate "black start" capability in appropriate locations. (In the event of a regional-scale blackout, it is important to have some generation units in the affected area that can be restarted without electricity from an external source. Once running, these black-start-capable units can be used to help reactivate the broader network.)

   Recommendation: DOE should work with the Department of Homeland Security (DHS) and other organizations to leverage the capabilities of DHS's National Infrastructure Simulation and Analysis Center (as defined in 6 USC 321) to review a variety of UGS disruption scenarios.

2. **Special Reliability Assessment by NERC**

   Observation: The current Task Force analysis of the impacts of losing service from a given UGS facility relied on publicly available information on UGS characteristics and operations. The accuracy and confidence of the analytic results could be improved through the use of additional but proprietary or restricted-access information on UGS and their relationship to pipeline operations, which is available from sources such as EIA (Form 191, "Monthly Underground Gas Storage Report") and FERC (Form 567, "System Flow Diagrams").

   Discussion: While ensuring appropriate protections for proprietary information, DOE intends to determine how these additional data can be re-analyzed to determine the potential consequences of the disruption of UGS operations—with particular attention to the 12 UGS sites of interest noted above. DOE also plans to work with NERC on its Special Reliability Assessment on Single Points of Disruption to Natural Gas Infrastructure, which will examine transmission-level reliability impacts on the bulk power system in the event of disruptions of service from key UGS facilities.

   Recommendation: DOE, NERC, and appropriate National Laboratories should proceed with the proposed analysis (subject to appropriations, as necessary) and give particular attention to those UGS facilities that, if disrupted, appear in the current analysis to have significant potential to create electric reliability problems in affected communities.

3. **Need for Combined Gas/Electric Models to Analyze Short-Term Dynamics**

   Observation: As delivery systems, the existing pipeline and storage networks must cope with short-term changes in operating conditions that affect the deliverability of gas to wholesale customers—particularly, gas-fired generators whose gas requirements are highly changeable from hour to hour. As the interdependence between the industries increases, the need to understand and cope with such rapid changes in both gas demand and gas deliverability becomes more acute.

   Discussion: Combined gas/electric models are needed to determine in near-real-time the dynamic capability and adequacy of the combined regional systems. Such models would enable planners and operators to identify constraints and potential sources of disruption (e.g., storage facilities, key pipeline segments and compressor stations, LNG terminals), so as to operate both systems reliably. The models could be used to determine what facilities should be added, define adequate operating parameters (such as balancing on the gas system or ramping on the electric system), or estimate the impacts of facility outages, additions, or retirements. The models should include all planning periods (future years) and operations (current year and real-time) so that resource adequacy, steady-state, and dynamic analysis can be performed on both gas and electric systems. This work could include using the pipeline simulation models that interstate pipeline companies use when providing support for their applications to FERC to construct and operate pipeline facilities. In addition, development of pipeline simulation models by local gas distribution companies could be considered.

Recommendation: Power and gas system planners and operators should jointly develop, validate, and apply combined models to improve the capability and ensure the adequacy of the combined infrastructure.

4. **Tools for Analysis of Short-Term Gas Deliverability**

Observation: The electric industry needs the capability to produce quick-response analyses of rapidly changing conditions affecting the short-term deliverability of natural gas for electricity generation.

Discussion: During a July 2016 DOE workshop in Washington, DC, on resilient electric distribution systems, electric industry participants identified a need for a real-time tool that would access natural gas system operations data, starting with the existing gas electronic bulletin board (EBB) data. Once developed, this tool or capability could be used to perform quick-response contingency analyses related to the deliverability of natural gas for electricity generation.

Recommendation: DOE (subject to appropriations), in coordination with NERC, the ISOs, and others should consider performing a scoping study to examine the quality and relevance of EBB data and data from other sources for assessing real-time reliability risks, determine the costs of developing and testing a computer-based analytic tool capability for this purpose, examine who would pay to maintain the tool on a long-term basis, and consider whether user fees would be an effective way to fund its maintenance.

Topic III: Data Needed for Additional Gas/Electric Reliability Studies

1. **Collect Additional Information on EIA surveys**

Observation: EIA's Form 860 could be modified immediately to collect additional information on connections between individual gas-fired power plants and the natural gas supply system. In addition, currently withheld information on the availability of backup fuel oil at gas-fired power plants could be made public information.

Discussion: Making this information more readily available would aid analysts in determining the potential implications of any future disruptions to natural gas supply for regional or local electric reliability.

Recommendation: EIA should consider modifying Form EIA-923 and Form EIA-860 to include additional data that would be useful for analysis of issues related to maintaining the reliability of existing gas-fired electric generation capacity. This information might include, for example, information on the capacity of the pipelines connecting to power plants and data on a plant's reliance on firm and non-firm natural gas transportation.

Topic IV: Regulatory Requirements and Standards

1. Reduce Likelihood and Impacts of Gas Curtailments

Observation: Actions may be taken to reduce the likelihood of natural gas curtailments, but curtailments may occur nonetheless due to changes in market conditions, weather, equipment failures, natural disasters, physical attacks, cyber intrusion, etc. The growing interdependence between the gas and electric industries calls for greater preparedness by and among the affected companies to avert potential curtailments and reduce the impacts of those that occur.

Discussion: Natural gas service is generally available to electricity generators, subject to the regulatory and physical constraints of the natural gas system, although "firm" (non-interruptible) service typically costs considerably more than "interruptible" service. Regulators and policymakers need to understand the broad terms of the contractual arrangements for supplying gas to generators in areas under their jurisdictions, and to understand the physical limitations of the natural gas infrastructure for serving the needs of electric generators. Increased coordination between natural gas and power industry regulating agencies could help ensure improved cross-capture of information as the role of natural gas as a fuel source for power generation continues to grow.

Recommendations:

a. State PUCs or other relevant agencies should consider requiring natural gas LDCs and electric utilities under their jurisdiction to collaborate in the joint development of specific and clear procedures for managing future natural gas curtailments to minimize impacts, and to submit the procedures for regulatory approval.

b. State PUCs should consider whether to make changes in current LDC tariffs to establish more specific provisions concerning the allocation of gas among electric generators in advance of curtailment of service from an LDC-owned UGS facility. This review should also address the States' end-use curtailment rules, which may include *force majeure* policies under which service to natural gas-fired power plants with firm contracts could be curtailed.

2. Managing Short-term Variability of Generators' Demand for Gas

Observation: Natural gas-fired generators often demand fuel in large quantities at short notice that may strain pipelines' ability to deliver. Many older pipeline systems are not designed to accommodate this pattern of withdrawal behavior on a large scale. However, rising dependence in many areas on natural gas for electricity generation suggests that this strain will become more acute.

Discussion: Tariffs for wholesale gas purchases by utilities that would promote generator bids and reflect gas system limitations are needed, with the aims of reducing the chance that ISOs/RTOs will dispatch generators in a way that harms gas system reliability and permitting ISOs/RTOs to reserve sufficient internal electric transmission transfer capability to react to changes in the gas system.

Recommendation: Federal and State regulators should consider the operational demand characteristics of natural gas-fired generation when developing or reviewing the regulatory framework for planning, building, and operating the natural gas delivery system.

3. Avoiding Mismatches Between Nominated Gas Flows and Actual Gas Demand

Observation: The timing of the nomination processes for the electric and gas markets do not coincide, and this increases the risk of a mismatch between nominated gas flow and actual gas demand.

Discussion: If sufficient gas for electricity generation is not procured in advance, the result may be may be gas procurement, including from UGS facilities, during more illiquid periods and lead to higher costs for electric generation and increased reliability risk.[92]

Recommendation: Both gas and electric industries should continue to review and improve existing processes and the timing of information flows pertaining to energy bidding and/or gas nominations processes so that both systems are balanced and can operate within their respective reliability parameters. Similarly, the two industries should work together to develop flexible pipeline services to accommodate the changing needs of the electricity industry.

[92]http://western.wp.naruc.org/wp-content/uploads/sites/2/2016/06/GasSafety-All.pdf; and https://www.caiso.com/Documents/Agenda_Presentation_AlisoCanyonGasElectricCoordination.pdf.

Glossary

Blowout prevention

One or more valves installed at the wellhead to prevent the uncontrolled escape of fluids from the well, particularly during drilling and completion operations. A variety of blowout preventers (BOPs) can be used to cover casing, tubing, and even an open hole. BOPs are a critical component to keep workers safe in the event of a loss of well control event.

Bridge plugs

Downhole tools that are located and set to isolate the lower part of the well. Bridge plugs may be permanent or retrievable, enabling the lower portion of a well to be permanently sealed from production or temporary isolated from a treatment conducted on an upper zone.

Casing thickness inspections

A test that measures the thickness of the casing, looking for changes that could be due to deformation, physical wear, or corrosion. A number of different downhole logs, including fingered calipers, magnetic field, and acoustic tests can be used to perform or contribute to a casing thickness inspection. If the inspection reveals thinning of the casing, the casing strength is calculated to ensure that it can safely withstand authorized operating pressures for the well.

Cementing procedures

Cement is used to hold casing in place and to prevent fluid migration between subsurface formations. Cement plugs also prevent fluid migration within the well's casing, and are often put in place during abandonment procedures. Cementing is the process of mixing unhydrated cement, cement additives and water and pumping the cement slurry down casing to critical points in the annulus around the casing or in the open hole below the casing string. The three principal purposes of cementing are to: 1) restrict fluid movement between the formations, 2) bond and support the casing, and 3) restrict fluid movement between casings and within the well.

Corrosion inspections

Physical inspection of a metallic structure (e.g., casing and tubing strings) to locate damage by means of corrosion in a structure, as well as gaining insight to the amount and severity of that damage.

Gas well "freeze offs"

Freeze offs occur when the ambient temperature drops below freezing, and water or other liquids freeze in the wellhead and block the flow of gas, thereby stopping or significantly limiting production. Such freeze offs can be prevented by protecting the wellhead from cold temperatures.

Geophysical logging (also known as "borehole geophysics")

The practice of recording and analyzing measurements of physical properties made in wells by lowering equipment via wire line into the wellbore. State-of-the-art logging systems collect multiple logs with one pass of the tool and can measure properties of casing, cement, and subsurface rock and fluid, and can be performed in open hole or cased wells.

Kill the well

To stop a well from flowing or having the ability to flow into the wellbore. Kill procedures typically involve circulating reservoir fluids out of the wellbore or pumping higher density fluid into the wellbore, or both, and are typically used during normal well maintenance operations or after a loss of well control.

Lost circulation material

The collective term for substances added to drilling fluids when drilling fluids are being lost to a formations downhole. Commonly used lost circulation materials are fibrous (cedar bark, shredded cane stalks, mineral fiber and hair), flaky (mica flakes and pieces of plastic or cellophane sheeting) or granular (ground and sized limestone or marble, wood, nut hulls, Formica, corncobs and cotton hulls). Less conventional materials include ball sealers, steel balls, golf balls, and junk.

Mechanical integrity testing

Mechanical integrity testing (MIT) is a set of tests used to ensure that a well systems conforms to its design specifications and that there are no significant leaks in the casing, tubing, or packer system or vertically around the outside of the casing-cement system. Several different types of tests have been used to demonstrate mechanical integrity, including an annulus pressure test or radioactive tracer surveys. Cement bond logs, casing inspection logs, temperature logs, and noise logs have also been used for MIT.

Noise log

A highly sensitive acoustic sensor capable of detecting the sound of gas flowing will be lowered down the length of the well above the gas reservoir. This sensor detect the source of any gas escaping from or around the well bore. If the well has a leak, gas will bubble up from the well bore causing a sound that can be detected by the sensor.

Packer

A packer or "mechanical seal" is a device lowered into a well to produce a liquid-tight seal to hydrologically separate two or more sections of a well. These seals can be set in place near the bottom of the well, within the portion of the well surrounded by cement. This method is an industry standard practice for isolating a well from reservoir gases or fluids and will further protect the casing from internal gas pressure.

Plugging and abandonment

This procedure is used to prepare a well to be closed permanently, usually after it is deemed no longer cost-effective to operate. Different regulatory bodies have their own requirements for plugging operations. Most require that cement plugs be placed and tested across any open hydrocarbon-bearing formations, across all casing shoes, across freshwater aquifers, and perhaps several other areas near the surface, including the top 20 to 50 feet [6 to 15 meters] of the wellbore. The well designer may choose to set bridge plugs in conjunction with cement slurries to ensure that higher density cement sets at the desired interval. In that case, the bridge plug would be set and cement pumped on top of the plug.

Pressure testing

A pressure test is a deliberate modification to the pressure within the interior of the well and the measurement of subsequent pressure changes, for example in the annular space between the production tubing and the well's intermediate casing, to determine the well's ability to withstand expected operating pressures. Pressure testing can also evaluate the integrity of packers that seal the annular space between the tubing and casing.

Primary and secondary well barrier construction

In a system with two barriers in place, there shall be always one barrier that acts as a first level of protection and one as a second level of protection. The primary barrier's function is to prevent unintentional flow to the environment or other formations. The secondary barrier is to prevent unintentional flow if the primary barrier fails. To function effectively as two different barriers, they must be able to be independently tested for failure.

Production casing

Production casing refers to the deepest section of casing that is above the producing reservoir. It may penetrate into the reservoir or a liner may be hung off it to penetrate the reservoir. It isolates the gas formation from other subsurface formations.

Relief well

A relief well is a well drilled to intersect an oil or gas well that has experienced a blowout. Specialized liquid, such as heavy (dense) drilling mud followed by cement, can then be pumped down the relief well in order to stop the flow from the reservoir in the damaged well.

Surface leak detection

In addition to a mechanical integrity test (described above), monitoring and inspection for leaks includes surface, near surface, atmospheric, and remote sensing monitoring to detect leaks to the atmosphere or the shallow subsurface. Such monitoring can include soil gas sensors, eddy flux towers, LIDAR, or gas flux monitors.

Temperature log

A sensor can be lowered down the depth of the well to measure the temperature within the well at different depths (usually continuously or at high resolution intervals). If the casing in the well is not intact, Joule-Thompson cooling of the escaping gas will appear as a reduced temperature anomaly.

Top kill

In this method dense fluids are pumped from the surface into the well and against the upward flowing gas to cease its flow.

Tubing

Injection tubing is a smaller diameter uncemented casing string hung inside the other casing strings and used to convey fluids between the surface and subsurface formations. Tubing is often used during injection or production activities, as subsurface fluids can be corrosive to steel casing, and the tubing can be more easily pulled and replaced than cemented casing strings.

http://energy.gov/downloads/report-ensuring-safe-and-reliable-underground-natural-gas-storage