CALIFORNIA AIR RESOURCES BOARD

Determination of Total Methane Emissions from the Aliso Canyon Natural Gas Leak Incident

October 21, 2016

This report documents the California Air Resources Board (ARB) staff's determination of the total methane emissions from the Aliso Canyon natural gas leak incident and the amount needed for full mitigation of the climate impacts. The mitigation is expected to be accomplished with projects funded by the Southern California Gas Company. The report summarizes the various efforts by ARB and others to measure methane emissions from the Aliso Canyon natural gas leak incident, and how they were used to estimate the total methane emitted from the incident. The total amount of methane needed to fully mitigate the climate impacts of the leak is 109,000 metric tons.

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Summary

This report documents the California Air Resources Board (ARB) staff's determination of the total methane emissions from the Aliso Canyon natural gas leak incident and the amount needed for full mitigation of the climate impacts. The leak at the Southern California Gas Company's (SoCalGas) Aliso Canyon natural gas storage facility in Los Angeles County was reported on October 23, 2015 and controlled on February 11, 2016, and has been described as the largest documented leak of methane in the United States[1]. In response to the leak, Governor Brown issued a proclamation[2] that directed ARB to prepare a program, to be funded by SoCalGas, which will "fully mitigate the leak's emissions of methane". SoCalGas has indicated that it is committed to mitigating the climate effect of the leak, and is ready to work with ARB staff to develop the appropriate programs to do so[3].

The Aliso Canyon methane release was caused by an uncontrolled breach in the natural gas storage infrastructure and occurred outside the envelope of instruments put in place to measure the flow of natural gas at the facility. The size of the leak was therefore initially unknown, and could only be evaluated qualitatively using available ambient air measurements in the vicinity of the leak. Subsequent to the leak being controlled, the scientific research community and SoCalGas have provided different methane emission estimates based on a variety of measurements including ambient measurements, remote sensing, and an inventory accounting method. ARB also provided a preliminary estimate based on downwind flights that measured flux rates at various times during the leak. The Los Angeles basin has a uniquely dense network of methane measurement efforts and instrumentation that allow for several different quantification methods to be used to estimate total amount of methane released. The additional information from this network was used to inform and corroborates ARB's final estimate. This report provides an overview of the various efforts, and describes ARB's updated approach to estimate the total methane emissions from the Aliso Canyon natural gas leak incident.

ARB's updated estimate indicates that the incident resulted in a total emission of 99,650 ± 9,300 metric tons of methane. To *fully* mitigate the leak, as directed by the

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[1] Conley, S., et al. (2016). Methane release rates from a single leak were nearly double that of the entire rest of the Los Angeles region. Science, 351 (6279), pp. 1317-1320, DOI: 10.1126/science.aaf2348

[2] Governor's Proclamation of a State of Emergency (January 6, 2016), https://www.gov.ca.gov/news.php?id=19263

[3] Letter from Mr. Dennis V. Arriola, President and Chief Executive Officer of SoCalGas to Governor Brown, (December 18, 2015), https://www.arb.ca.gov/research/aliso_canyon/sgc_letter_mitigation_12-18-2015.pdf

Governor's Proclamation, the upper bound of this estimate should be used. Hence, **the required amount of methane that needs to be mitigated is 109,000 metric tons**.

Background

On October 23, 2015, Southern California Gas (SoCalGas) informed the State of a natural gas leak at its Aliso Canyon natural gas storage facility. Natural gas is composed primarily of methane, which is a potent greenhouse gas (GHG) and classified in the category of gases called short-lived climate pollutants (SLCPs). These types of gases remain in the atmosphere for much shorter periods than longer-lived climate pollutants, such as carbon dioxide (CO_2); but when measured in terms of how they heat the atmosphere, pound for pound their impacts can be tens, hundreds, or even thousands of times greater than that of carbon dioxide[4]. Methane is 84 times more potent that CO_2 on a 20-year time scale (based on global warming potentials from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change[5]).

The leak had an extraordinary impact on the local population. The emissions were a major public nuisance, and resulted in more than 2,300 odor complaints during the leak from the nearby communities to the South Coast Air Quality Management District and the relocation of over 6,800 households and several schools. The complaints included odor, dizziness, headaches, nausea, eye, nose and throat irritation, and nose bleeds. Concerns were also expressed about exposure to other compounds found in natural gas, such as benzene, oil residue, hydrogen sulfide, and radon in the neighboring communities, although measurements did not suggests levels were sufficient to be of concern.

In addition to the leak's many effects on local residents, the methane emissions from Aliso Canyon exacerbated statewide greenhouse gas emissions which contribute to climate change, a problem California has recognized and is working to address. The estimates show that during the leak, it alone was responsible for approximately 20 percent of statewide methane emissions, which is more than double the statewide fugitive emissions from oil and gas production (Figure 1). The ability of a single source to materially affect total statewide emissions is a serious concern.

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[4] Kirschke, S., et al. (2013), Three decades of global methane sources and sinks, Nature Geoscience, 6, pp. 813–823. http://www.nature.com/ngeo/journal/v6/n10/full/ngeo1955.html?WT.ec_id=NGEO-201310

[5] IPCC (2014): Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp. https://www.ipcc.ch/report/ar5/

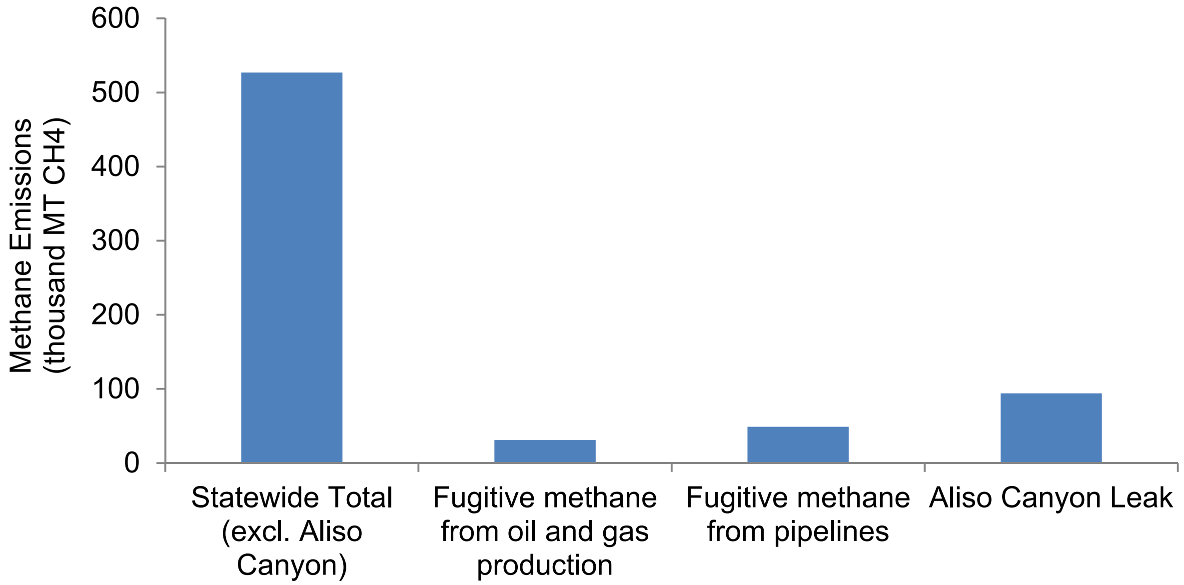

Figure 1: Statewide total methane emissions and oil and gas methane emissions during the leak compared to the Aliso Canyon leak.

California is committed to reduce the emission of methane and other SLCPs. A decade ago, the State enacted the California Global Warming Solutions Act of 2006 (Assembly Bill 32, Nunez), which requires a return to 1990 statewide greenhouse gas emission levels by 2020. The passage of Senate Bill 32 (Pavley) on September 8, 2016, sets an even more ambitious target by requiring the State to reduce GHGs to 40 percent below 1990 levels by 2030. The Legislature directly recognized the critical role that SLCPs must play in the State's climate efforts with the passage of Senate Bill 605 (Lara), which required ARB to develop a strategy to reduce SLCP emissions. The draft SLCP Strategy was released in April, 2016 and outlines plans to reduce emissions of methane by 40 percent below current levels in 2030. Subsequently Senate Bill 1383 (Lara) was passed, which requires a 40 percent reduction in methane from 2013 levels by 2030.

On December 18, 2015, with the leak still ongoing, Mr. Dennis V. Arriola, President and Chief Executive Officer of SoCalGas, wrote a letter to Governor Brown committing SoCalGas to "mitigate the environmental impact of the actual natural gas released from the leak" and "working with you and your staff to develop a framework that will help us achieve this goal."[3]

On January 6, 2016, Governor Brown issued a proclamation[2] that included direction to ARB to prepare a program, to be funded by SoCalGas, that will "fully mitigate the leak's emissions of methane", "be limited to projects in California", and "prioritize projects that reduce short-lived climate pollutants". This program, with its focus on the leak's climate impacts, represents one facet of a comprehensive response by State and local agencies to the leak and its short- and long-term effects upon the environment, and public health and safety.

In response, ARB developed and released the mitigation program on March 31, 2016[6]. The mitigation program was a product of a public process that included a presentation to the ARB Board[7], as well as two periods of public comment, the second of which followed the posting of a draft version of this program on ARB's website. Altogether, ARB received, and considered, more than 60 comments on the mitigation program from the public and other stakeholders prior to finalizing the plan.

In order to quantify the methane emissions from the Aliso Canyon gas leak, State agencies, in collaboration with scientific experts, relied on existing and new methane measurements in the Los Angeles basin, including ambient measurements around the well site, at nearby air monitoring towers, and using airplanes, as well as remote sensing and satellites. These measurements allow for an estimation of the leak's cumulative emissions and can be used to estimate a mitigation threshold that provides confidence the emissions will be fully mitigated.

This report summarizes the various efforts by ARB and other institutions including the National Aeronautics and Space Administration's Jet Propulsion Laboratory (NASA-JPL), California Institute of Technology (Caltech), Scientific Aviation, and SoCalGas to determine the total methane emissions from the Aliso Canyon natural gas leak incident, provides insight on the strengths and limitations of each of the methods, and updates ARB's preliminary estimate. The updated estimate is then compared to the other currently available estimates. The report concludes by providing the amount of methane required for full mitigation of the leak.

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[6] ARB Aliso Canyon Methane Leak Climate Impacts Mitigation Program, (March 31, 2016), https://www.arb.ca.gov/research/aliso_canyon/arb_aliso_canyon_methane_leak_climate_impacts_mitigation_program.pdf

[7] Presentation to the ARB Board: Update on Aliso Canyon Methane Leak (February 18, 2016),https://www.arb.ca.gov/board/books/2016/021816/16-2-1pres.pdf

Quantifying the Amount of Methane Emitted

The following sections compile the various methods that have been used to estimate the amount of methane leaked, discusses the quality of each of the methods, and updates ARB's preliminary estimate.

Preliminary ARB Estimate

The first estimate of the Aliso Canyon natural gas leak emissions were generated by ARB using airborne flight measurements conducted during the leak event. ARB and the California Energy Commission coordinated 11 downwind flights by Scientific Aviation during the leak, using a small airplane equipped with instruments that measure methane. The plane is able to capture both the horizontal and vertical extent of the plume by flying downwind through the plume at many different elevations. These downwind measurements were used to make a calculation of the instantaneous emission rate (the rate of emissions at the time the measurement was made) using scientifically peer reviewed methods (Figure 2). However, the measurements do not shed light on the emission rate in the periods between the flights which may have been variable, especially prior to late November 2015 due to the activity at the well pad and the many attempts to control the well.

An initial rough estimate of the leak was made by utilizing the airborne measurement data, and assuming the leak rate was constant between each flight. Using this approach, it was estimated that the Aliso Canyon incident released 5.4 billion cubic feet (Bcf) of natural gas or 94,500 metric tons (MT) of methane into the atmosphere, which is equivalent to emitting about 7.9 million metric tons of carbon dioxide equivalent (MMTCO$_2$e) (using the 20-year global warming potential for methane from the Fifth Assessment Report[5]).

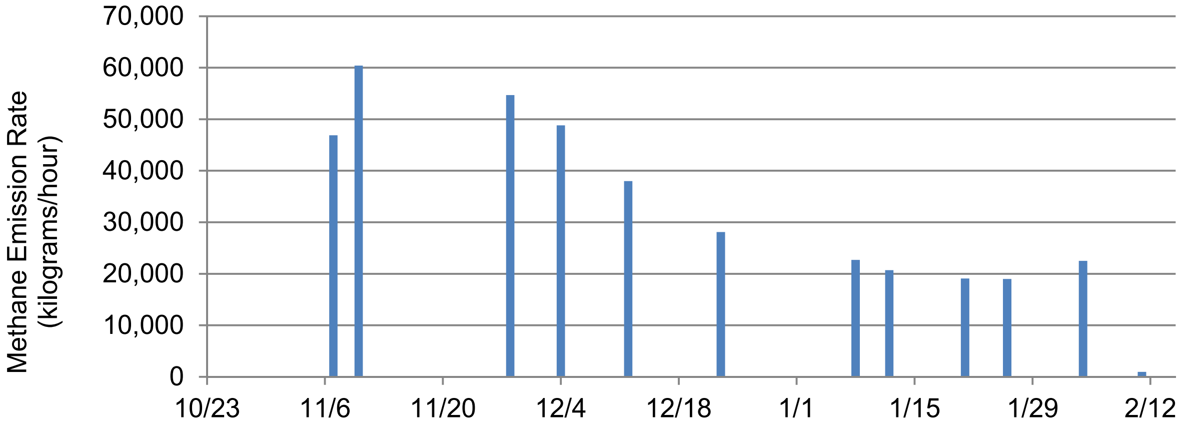

Figure 2: Updated results from the downwind flights showing hourly emission rates

Emission Estimates from Southern California Gas Company

On May 26, 2016, SoCalGas issued a press release that described their estimate of leaked methane emissions from the Aliso Canyon leak incident from October 23, 2015, until February 11, 2016, when the leaking well was controlled via the relief well[8]. SoCalGas reported estimates of the total methane emissions using two separate methodologies, which are referred to as "inventory verification" and "tracer flux ratio study (TFR)", that yielded estimates of 4.62 Bcf and 4.75 Bcf (84,200 MT and 86,000 MT), respectively. Below is a description of the methods used in each estimate.

Inventory Verification

The first estimate released by SoCalGas used a mass balance approach that utilized storage field inventory estimates prior to and after the leak and an accounting of all withdrawals and injections to infer how much methane was "missing". SoCalGas has stated the inventory method is not designed to calculate a leak rate, and has not provided an uncertainty for this estimate, which is expected to be significant considering the errors in both the inventory estimates[9] and in accounting for all withdrawals and injections. To better understand whether the result from the inventory method is inconsistent with the other estimates, an expected error, or uncertainty, of the inventory verification estimate is needed. If the uncertainty in the inventory estimate encompasses the other estimates, they would not be considered inconsistent.

Inventory estimates at the Aliso Canyon natural gas storage facility were last made in October 2014 and March 2016. Between these two estimates the reservoir has been emptied, then filled, and then emptied again (the reservoir is typically emptied during November – March and filled during April – October every year). The Aliso Canyon Natural Gas Storage reservoir has a capacity for more than 167 Bcf of natural gas, of which 86 Bcf is usable (working) gas and 81 Bcf is cushion gas. To make an inventory estimate all withdrawals and injections are stopped for several weeks, and near steady state pressure readings from wells throughout the reservoir are used to infer the amount of natural gas in the reservoir. Uncertainty in calculating the inventory based on the pressure measurements range from 3 to 10 percent[10]. Assuming the most conservative, or lowest, uncertainty of 3 percent in the inventory estimates and assuming a

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[8] SoCalGas (2016), SoCalGas Delivers on Commitment to Conduct Thorough Measurement of Emissions from Aliso Canyon Leak [Press release, May 26, 2016]. https://www.socalgas.com/1443739536978/thorough-emissions-measurement-52616.pdf

[9] Tutt, C. J., and Dereniewski, E. (1978), A Practical Regression Model of Pressure/Inventory Hysteresis in Natural Gas Storage Fields, SPE 6488, doi:10.2118/6488-PA

[10] Tek, M.R. (1991), Errors and Uncertainty in Inventory Verification in Underground Storage, SPE 23829

0.5 percent uncertainty in accounting for injections and withdrawals, the overall emissions result of 84,221 MT of methane is expected of have an uncertainty of 125 percent, or range from 0-190,000 MT. Table 1 shows the calculation of uncertainty for the inventory method as a function of the accuracy in each of the numbers required to make the estimate. The total uncertainty is provided as the square root of the sum of squares of the uncertainty for each of the terms used to calculate the 4.62 Bcf.

Table 1 – A simple model to estimate uncertainty for the storage field inventory method

Inventory Method for Calculating Leak			***Expected Uncertainty***		
		[Bcf]			Uncertainty in each term (Bcf)
			Uncertainty	Inventory	3.0%
				Withdrawals/Injections	0.5%
Amount in Reservoir October 2014		167.53			5.03
Withdrawn during winter 2014-2015	-	70			0.35
Injected summer 2015	+	70			0.35
Withdrawn during winter 2015-2016	-	70			0.35
Amount in Reservoir March 2016	-	92.91			2.79
Leaked amount		4.62	Total Uncertainty (Bcf*)		5.78
			Uncertainty as a percentage of estimate		125%

* Total uncertainty calculated as the square root of sum of squares for individual terms: $\sqrt{(5.03)^2 + 3X(0.35)^2 + (2.79)^2}$

Tracer Flux Ratio Study

The second estimate released by SoCalGas utilized a tracer release method. This technique relies on releasing a known quantity of a tracer gas under controlled conditions near the leak site, and measuring the concentration of the gas along with methane in downwind locations. The ratios of tracer to methane concentration and tracer concentration to tracer source size are then used to estimate the methane emission rate. SoCalGas contracted with Aerodyne to conduct the tracer release study by deploying a mobile measurement platform to sample in the plume downwind from the facility along Sesnon Boulevard. Aerodyne conducted 25 tracer measurements between December 21, 2015, and the end of the leak on February 11, 2016. The tracer studies consistently estimated a lower leak rate than Scientific Aviation during late December 2015 and January 2016 when both measurements were being made (Figure 3). Assuming that the TFR technique would have resulted in the same lower emission estimates compared to the flights prior to December 20, Aerodyne estimated a methane emission of 86,022 ± 8,393 MT of methane.

TFR is generally a well-practiced methodology when estimating emissions from point sources in terrain that allows for good mixing of the tracer and the point source. There are four important factors in the Aliso Canyon case that suggest the uncertainty in the estimate would be larger than indicated by SoCalGas.

1. Degree of mixing of the tracer with the plume,
2. The assumption that the leak can be treated as a point source,
3. Road access downwind of the leak to capture the full downwind plume and determine the true methane to tracer ratio.
4. Lack of TFR measurements prior to Dec 21, 2015

For the TFR method to work properly, the tracer and plume need to be well-mixed. The methane plume exited well SS-25 with considerable upward velocity in to complex terrain and wind patterns. These conditions create the potential for spatial separation of leaked methane and the tracer released near the source.

The assumption of a single point source at the wellhead is simplistic for the Aliso Canyon leak. Initially, the leak was described as coming from the entire surrounding hillside, making the leak more of an area source. After the November 6 well kill attempt, the crater around the wellhead formed, and it was assumed from then on all the gas leaked from this crater. However, several NASA-JPL overflights indicate methane was still leaking from the hillside below the wellhead to the west and east. After SS-25 had been controlled surveys with mobile platforms conducted by ARB and the South Coast Air Quality Management District found methane continuing to be emitted from the surrounding hillsides. The fraction of emissions during the leak that was emitted from the hillside vs near the well itself will likely remain unknown, but any emissions from the hillside would be missed by the TFR.

Multiple leakage points in combination with the complex terrain and wind patterns potentially resulted in complex plume behavior, degrading the ability to completely measure the plume downwind and downhill from the leak site at the ground level to establish the tracer to methane ratios as required by the TFR. The flights by Scientific Aviation suggest that the downwind plume was often bi-modal, splitting it in two as it was blown downwind, and often only one of the modes drifted over Sesnon Boulevard where the TFR measurements were made (see Figure 4). An example of this is presented in Figure 5 and complicates the determination of the tracer to methane ratios needed to calculate the emissions.

The uncertainty provided by SoCalGas with the TFR estimate appears to be based on observed variability in repeated measurements, and is therefore representative of the uncertainty in the method itself. The added steps needed to convert the measured emissions rate to an overall emissions estimate inject additional uncertainty that should be accounted for. This includes the lack of TFR measurements prior to December 21 2015 and the assumption that the TFR to flight measurement ratios would have been the same during the early period of the leak.

The uncertainty in the mixing of the tracer combined with methane leakage through the surrounding hillside, the added error associated with the assumptions on leak rates prior to December 21, 2015, and the inability to properly capture the downwind plume from Sesnon Boulevard, likely make the TFR estimate a lower bound and suggests the uncertainty was greater than what has been provided by SoCalGas.

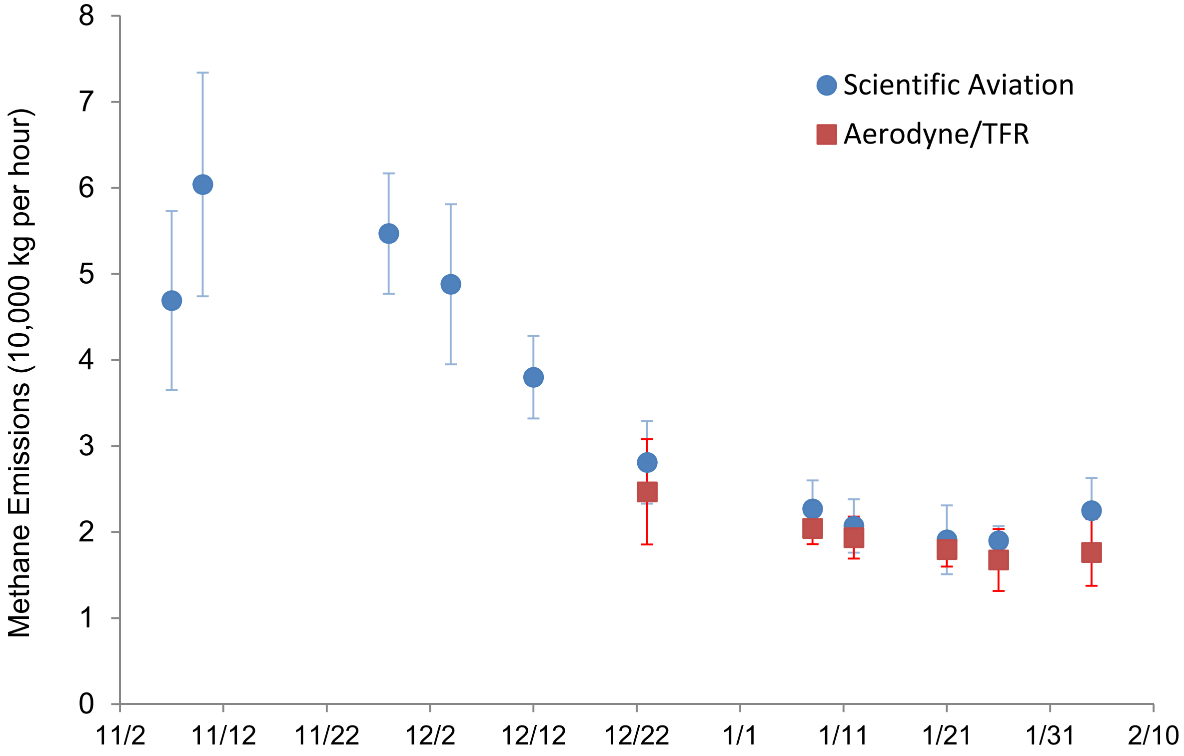

Figure 3: Relationship between SCG/Aerodyne's TFR and Scientific Aviation's emission estimates

Figure 4: The terrain at Aliso Canyon is very complex leading to highly variable winds and non-linear plume propagation patterns. The downwind measurements for the TFR method took place along Sesnon Boulevard between the two red points on the map. The plume may not always have solely passed over this stretch of Sesnon Boulevard.

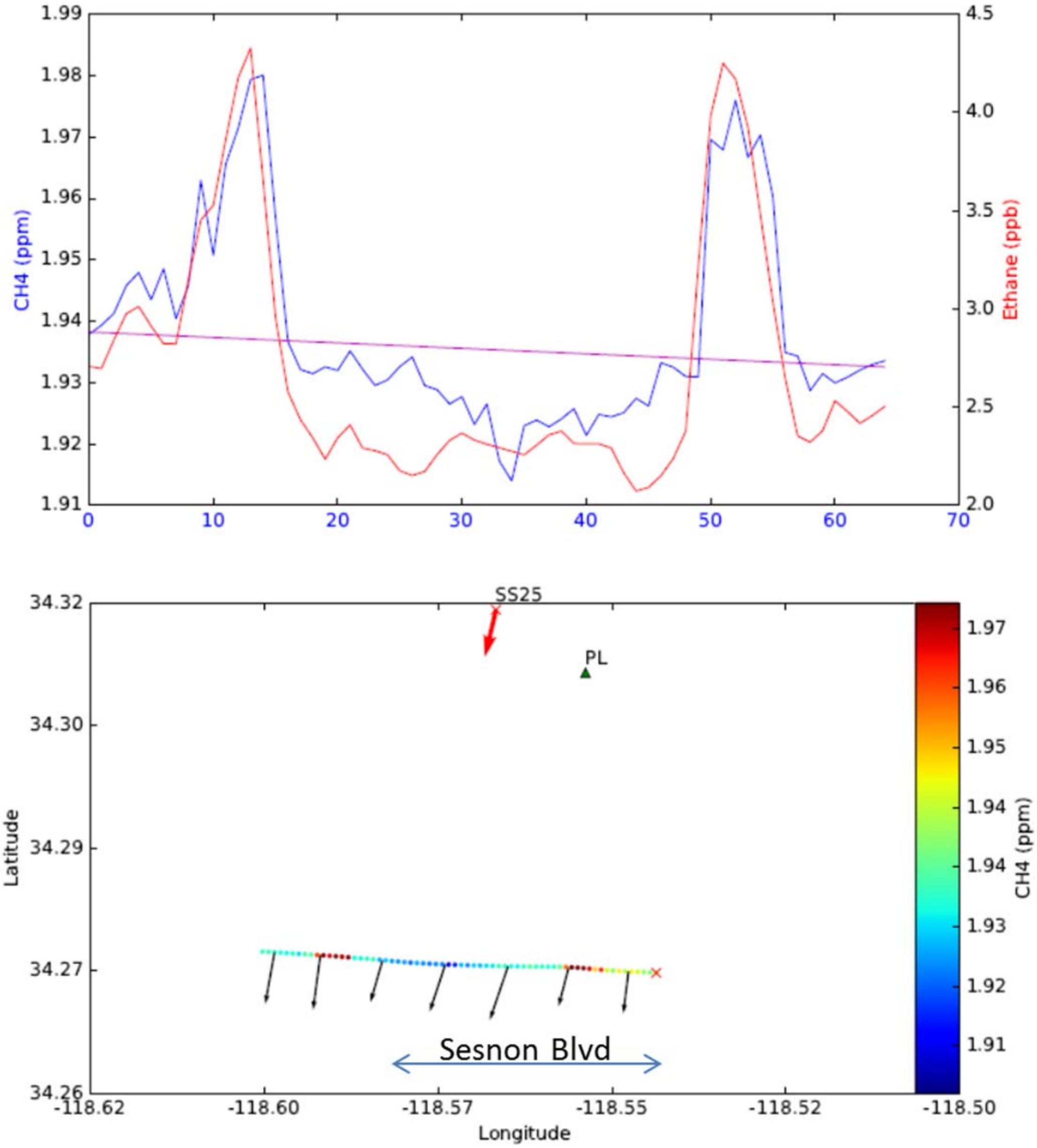

Figure 5: Example of bi-modal plume measured downwind with a small airplane (top panel). The bottom panel shows the longitudinal profile (seen as the two areas of high methane concentrations) with the east-west span of Sesnon Boulevard. The TFR method would only have measured the eastern mode.

Estimates by Research Organizations

During the leak incident, there was considerable coordination between State agencies and scientific experts to monitor, measure, and quantify the size of the leak based on ambient measurements and other monitoring efforts. In addition to an aircraft and several passenger cars equipped with methane monitors, the research teams leveraged existing monitoring resources that are in place to make routine measurement of carbon dioxide, methane, and other greenhouse gases in the Los Angeles basin. These routine measurements are made by ARB's statewide greenhouse gas monitoring network and a wider collaboration with other State agencies and the federal government through the Megacities Carbon Project, and have been effectively used in the past to inform the State's greenhouse gas inventories, confirm that emission reductions are occurring, and improve the understanding of sources and mitigation options. Additional novel tools included a satellite operated by the Japanese Space Agency, a high-altitude aircraft, advanced remote sensing devices located on Mount Wilson and in Pasadena, and flask measurements.

A short summary of the analytical methods to inform the quantification of the leak is shown in Table 2 and discussed below. Collectively, these efforts have provided a diverse data set that is being used in this report.

Table 2: Overview of other methods

Method	Project Teams	Measurement Approach	Measurement Frequency
Airborne Measurements	Scientific Aviation	Small airplanes with instruments measuring methane and other pollutants flying downwind of the leak through the plume at various elevations.	11 measurements campaigns made during the leak
Ground-Based Remote Sensing	NASA JPL, Caltech 1. TCCON, 2. CLARS	Ground based spectrometers use sunlight and its attenuation to estimate GHG concentration in the atmosphere above LA.	Continuous, operating pre-leak and afterwards
Airborne Remote Sensing	NASA, JPL, NIST [AVIRIS, HyTES]	Imaging spectrometers deployed on aircraft image the methane plume at the leak site with high resolution (meters) and spatial accuracy.	Only a few hours on select days
Satellite Remote Sensing	Hyperion EO1, GOSAT	Satellite sensors measure enhancement of methane at different locations in and around the LA basin. No emission estimate expected at this point.	Continuous, intermittent, repeated every few days, large pixels
Tower-Based Measurements and Large Eddy Simulation Modeling	Megacities Carbon Project	GHG tower network, with atmospheric transfer models and high-resolution flow-resolving models to directly simulate the methane plume at the leak site and its propagation into the atmosphere. Fitting of results to observations can be used to estimate leakage flux.	Continuous measurements, operating pre-leak and afterwards; intermittent plume identification

Below is a short summary of the specific efforts that have resulted in emission quantifications with the methods from Table 2.

- Airborne Measurements: Steve Conley, the primary investigator for Scientific Aviation, published another estimate based on the same overflights as used for the ARB estimate[1]. Conley used a slightly different integration method than the one used by ARB in the initial estimation, and arrived at a marginally higher emission estimate of 97,100 MT CH_4.
- Ground-Based Remote Sensing: A joint research team from JPL and Caltech operates the Total Carbon Column Observing Network (TCCON), which is a remote sensing technique that determines the total amount of carbon in the air column above the instrument stationed at Caltech in Pasadena. This instrument has been in use for several years, operates continually, and was able to observe the Aliso Canyon leak whenever any part of the plume reached the Caltech campus. The TCCON team published the estimate for ethane (C_2H_6) emissions from the leak based on measurements of LA basin-wide enhancement[11]. Although the researchers did not present a methane estimate in the paper, ARB staff utilized the ethane data to estimate the methane emissions by using observed methane to ethane ratios. This approach yielded a total methane emission estimate of 100,050 ± 23,562 MT CH_4 Uncertainties in the ratio estimates were compiled from different estimates of this ratio and propagated into the methane error for the TCCON result. The error for the TCCON estimate for the published C_2H_6 emission is large and the resulting error for the methane emission total is greater than 20 percent. Since the TCCON represents a basin-wide estimate and is not specifically sensitive to the Aliso Canyon leak, any uncertainty in the basin-wide enhancements observed by the sensor will lead to increased uncertainty in the emission estimate for the Aliso Canyon leak.

In addition to the above approaches, researchers are currently working on additional analyses, which are expected to produce emission estimates or inform the Aliso Canyon natural gas leak incident, as described below.

- Ground-Based Remote Sensing: NASA-JPL also operates the California Laboratory for Atmospheric Remote Sensing (CLARS) at Mount Wilson. This remote sensing instrument is able to measure the amount of methane in the Los Angeles basin and has been in continuous use for several years. This instrument is able to observe the increase in the basin-wide methane due to the leak.

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[11] Wunch et al.(2016), Quantifying the Loss of Processed Natural Gas Within California's South Coast Air Basin Using Long-term Measurements of Ethane and Methane, Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-359

Emission estimates from the JPL/CLARS team using JPL/Megacities team's inverse modeling effort are still in progress. Preliminary findings by the inverse modeling group indicate that the Aliso Canyon leak roughly doubled the LA Basin methane emissions, which is broadly consistent with other measurements.

- Airborne Remote Sensing: A research team from NASA-JPL and the National Institute of Standards and Technology (NIST) is working on analysis of data from two airborne NASA-JPL imagers (AVIRIS and HyTES) that are capable of detecting methane. These imagers flew over the leak and resulting plume repeatedly in January and February. The investigators are combining the resulting measurements of methane enhancements in the plume with a high-resolution numerical model (Large Eddy Simulation or LES with a flow resolution of 10's of meters) to arrive at independent emission estimates for the time of overflight. This approach will not yield an estimate of total emission for the leak but will rather serve as validation for the Scientific Aviation measurements during Phase II of the leak.
- Satellite Remote Sensing: Satellite-based sensors used by Hyperion/EO1 and GOSAT were able to identify methane enhancements in the region, suggesting the presence of a methane plume from space[12]. This method is not expected to produce emission estimates from the leak incident, but does provide an overall visual confirmation of the presence and flow pattern of the escaping natural gas.
- Tower-Based Measurements and Large Eddy Simulation Modeling: The Megacities Carbon Project team is currently undertaking a set of modeling efforts, which includes inverse modeling as well as Large Eddy Simulation Modeling efforts using monitoring data from GHG tower networks, in combination with advanced transport models to directly resolve the methane plume at the leak site and its propagation into the atmosphere and surrounding communities. Although these methods are only intermittently able to identify the plume on days when the meteorological conditions are conducive to transporting the plume from the leak site to the neighboring monitoring stations, it nevertheless provides a more comprehensive and continuous view of the Aliso Canyon facility from the earliest phases of the leak. The researchers are also utilizing data from concurrent airborne remote sensing campaigns (AVIRIS/ HyTES) to inform the modeling analysis.

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[12] Thompson, et al. (2016), Space-based remote imaging spectroscopy of the Aliso Canyon CH4 superemitter, Geophys. Res. Lett., 43, 6571–6578, doi: 10.1002/2016GL069079

Refinement of the Preliminary ARB Estimate

ARB evaluated the information, assumptions, and data used in the different estimation efforts to inform the refinement of the ARB preliminary estimate of total leaked methane emissions from Aliso Canyon. ARB also evaluated all available information from the leak site, including pressure data from the well and the reservoir, and notes from staff at the California Department of Conservation's Division of Oil, Gas, and Geothermal Resources (DOGGR), to inform our estimation approach. In the initial estimate produced by ARB, the emission rates between the flights were assumed to be constant. However, little was known at the time about how the leak rate varied between these flights. Using information now available, such as a better understanding of the flow of natural gas from the reservoir to the atmosphere, and the well pressure logs, it is possible to adjust the assumed emission rate between the flights and update the emissions estimate.

Well Configuration

Figure 6 shows a conceptual schematic of the leaking well, consisting of the inner well tubing, and the production and surface casings. Early well tests suggest the leak was caused by a breach in the 7-inch production casing at approximately 440 feet. The cause of the leak is the subject of a root-cause-analysis still under way, and will remain unknown until that investigation is complete. Nevertheless, the main factors that would affect the leak rate include the pressure in the reservoir (field pressure), and the configuration of the well, the size of the production casing breach, and the flow pathway through the geologic media from the base of the surface casing to the ground surface.

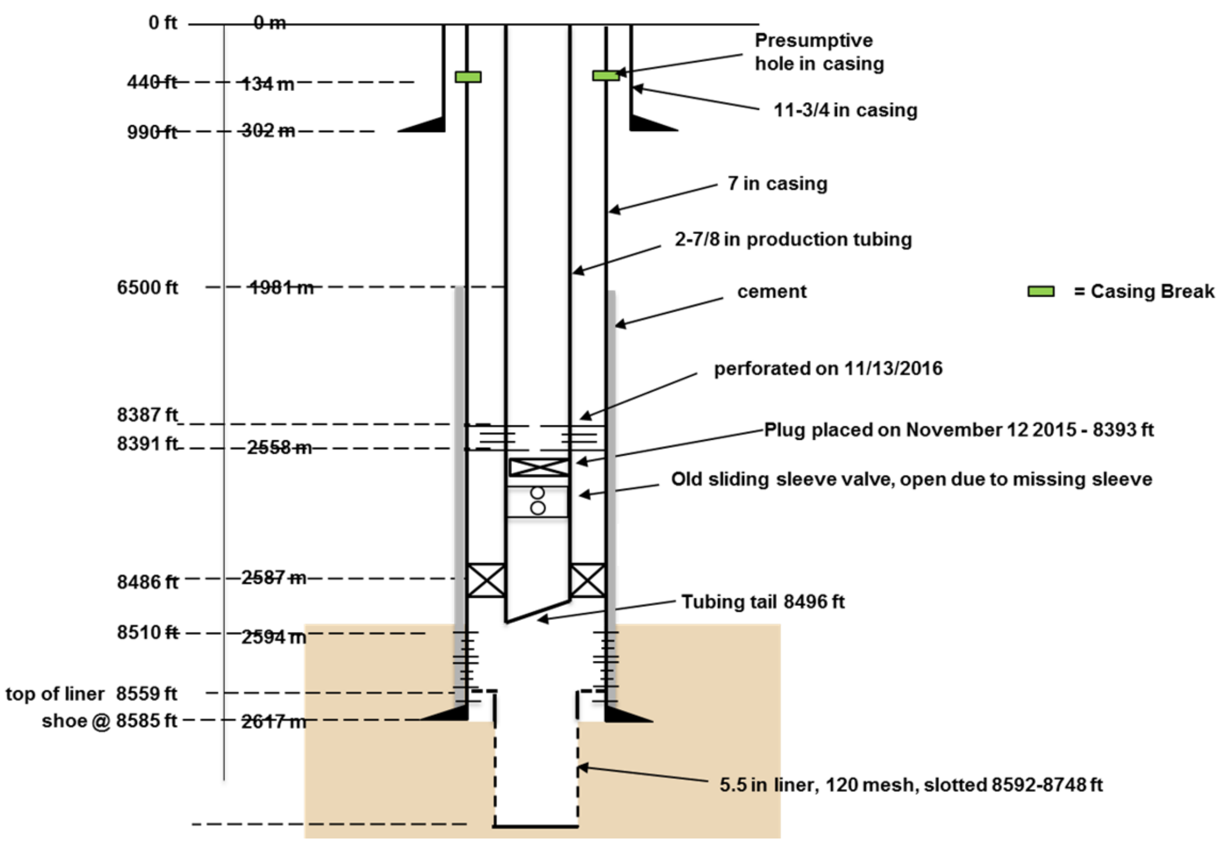

Figure 6: Conceptual schematic of the leaking well (SS25)
(image provided courtesy of Lawrence Berkeley National Laboratory)

Well Control Attempts

A well control attempt in the context of this report refers to attempts to place a column of heavy fluid into the well in order to interrupt the flow of reservoir gas through the well. This involves pumping “heavy-weight drilling mud” or “kill fluid” into the well to establish a large enough column of heavy fluid in the well that its hydrostatic pressure is sufficient to counteract the field pressure. This fluid can be pumped in through the wellhead (“top kill”), as was the case for all attempts at SS-25 except the final operation, or into the base of the well via an intersecting well built for the purpose (“relief well”), as was the case for the final operation. The operators can choose from different fluid densities to achieve a hydrostatic pressure at the base of the well deemed suitable for its geometry and the reservoir pressure.

All seven top well control attempts made at SS-25 were unsuccessful and failed to establish sufficient downward pressure from a large enough column of “kill fluid”. Instead, the kill fluid was observed exiting the ground surface around the well, like the escaping natural gas. Observations suggest the ejection of the kill fluid from the well altered the pathway through the geologic media during some of the kill attempts. In particular, the November 6 and 13 , 2015, well kill attempts are believed to have created an almost unrestricted path from the bottom of the surface casing to the crater that formed near the well head during these attempts. Subsequently, except for the field pressure, most variables important to predicting the leak rate appear to have remained mostly unchanged. The well was finally controlled by a kill through a relief well, which took months to construct.

Updating the Preliminary ARB Estimate

To improve upon the simplifying assumptions made in the initial rough estimate, ARB combined available data to conduct a detailed analysis of the emission rates from the Aliso Canyon leak. Through conversations with staff at DOGGR and researchers at NASA-JPL and Lawrence Berkeley National Laboratory (LBNL), ARB identified two major phases in the course of the leak requiring separate methods to calculate the leak rate:

1. The first phase runs from the beginning of the leak on October 23, 2015 until November 28, 2015, and is characterized by heightened well activity such as adding pressure gauges, installing and removing vertical pipes, installation of equipment to stabilize the well and reduce oil misting, multiple well control attempts and resultant changes in the geologic media surrounding the well. These activities likely resulted in variability in emission rates during this time. During this initial phase, wellhead pressures were available from pressure gauges installed on the well on October 30, 2015.

2. The second phase runs from November 29, 2015 until the well was successfully controlled on February 11, 2016. This period is characterized by less site activity, as the focus had shifted from trying to stop the leak by a top kill to doing so from a relief well under construction. Well pressure data during this phase is unfortunately not available as the gauges were accidentally knocked off at the end of November, and were not reinstalled afterwards. However, the leak rate is expected to be steadier during this time, and driven mostly by the pressure in the natural gas storage field. In addition, Scientific Aviation conducted regular downwind flights during this period, and captured the leak rates with good temporal coverage.

The following section details the relevant leak characteristics, as well as the emission estimation approaches used in the two phases.

Phase I: Initial Leak and Well Control Attempts (October 23 – November 28, 2015)

Well Control Attempts:	October 24, November 6, 13, 18, 24, 25; 2015	
Downwind flights:	November 7, 2015	46,900 ± 10,400 kg/hr CH_4
	November 10, 2015	60,400 ± 13,000 kg/hr CH_4
	November 28, 2015	54,700 ± 7,000 kg/hr CH_4

During Phase I, there was considerable activity at the well site including six top kill well control attempts, adding and removing lateral piping, adding pressure gauges, and installing equipment to stabilize the well and reduce oil misting. During this period, the State agencies were able to coordinate only three flights to measure the methane emissions from the leak. The first such measurement occurred two weeks into the leak, making the initial leak rate largely unknown. The scarcity of measurements, combined with activity at the well which allows for the possibility of highly variable emissions rates, could make simple interpolations between the airborne measurements a poor representation of the emissions.

Pressure data indicate some of the top well control attempts reduced resistance to leakage along the pathway through the geologic media. Specifically, the well control attempt on November 6 is described by DOGGR staff as “re-agitating’ the leak and the November 13 attempt resulting in a crater forming around the well and kill fluid observed being ejected from it. The pressure in the well also dropped significantly indicating the creation of a path through the geologic media that provided almost no resistance to flow.

Figure 7 shows the production casing pressure data that is available from October 30 to November 25, 2015. The reduction of this pressure on November 6 is consistent with less resistance along the path through the geologic media. There is no data indicating subsequent well kill attempts altered the flow pathway either in the geologic media or the well in a manner that changed the emission rate. Unfortunately, the pressure gauges that were installed on October 30 were knocked off by accident during the November 25 well control attempt, and were not reinstalled for the remainder of the leak. Pressures from October 23-30 and November 26-28 have been inferred based on the trends in pressures during those periods to create a continuous pressure log for Phase I.

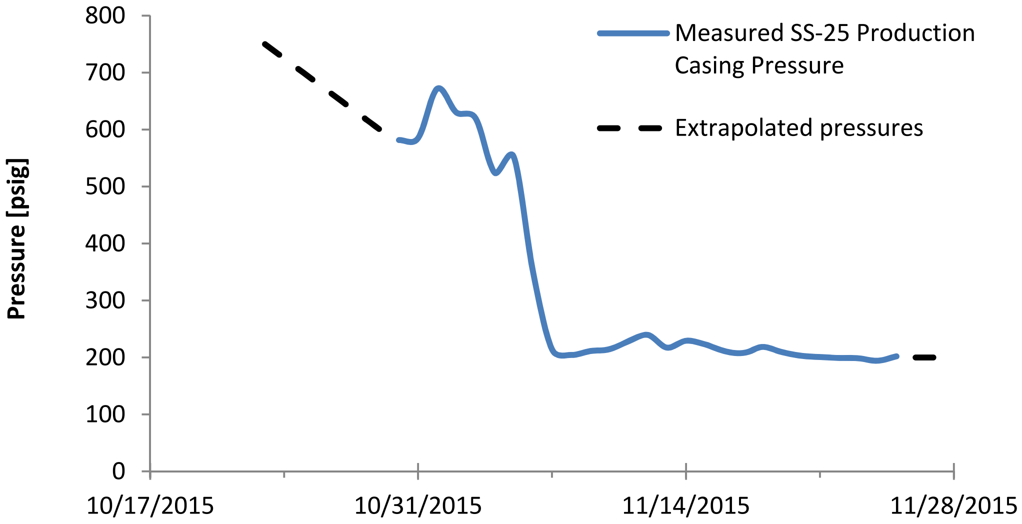

Figure 7: SS-25 Average daily production casing pressure. Pressure gauges were installed on 10/30, and accidentally knocked off on 11/25. Pressures before and after that period are extrapolations.

Using pressure differentials between points in a pipe is often used to estimate fluid flow and many equations have been developed to do so. Each equation is appropriate to a different set of conditions such as type of pipe, type of fluid, and prevailing conditions such as pressures and temperature. ARB consulted with researchers from LBNL and selected an approach to estimate the flow in SS-25 which integrates one such equation, the Weymouth equation, the pressure in the storage reservoir, as represented by a pressure data from a well near SS-25, and the pressure data from production casing, along with the rates from the downwind flights to estimate flow rates during this period.

Weymouth equation

The Weymouth Equation, presented below, is used for high-Reynolds-number flows where the Moody friction factor is merely a function of relative roughness.

$$Q = 1.1\, d^{2.67} \left[\frac{P_1^2 - P_2^2}{LSZT_1}\right]^{1/2}$$

Where:

Q = gas-flow rate, MMscf/D,
d = pipe inside diameter, in.,

P_1 = upstream pressure, psia,
P_2 = downstream pressure, psia,
L = length, ft,
T_1 = temperature of gas at inlet, °R,
S = specific gravity of gas, and
Z = compressibility factor for gas, dimensionless.

In the current application the Weymouth Equation can be rearranged as follows.

$$Q = C \times (P_1^2 - P_2^2)^{1/2}$$

Where:

Q = gas flow rate
C = a constant that includes the fluid and pipe parameters
(specific gravity, compressibility, length, diameter, and temperature)
P_1 = the pressure at the upstream end of the pipe
P_2 = the pressure at the downstream end of the pipe

The pressure at the bottom of SS-25, P_1, is assumed to be the pressure in the natural gas storage reservoir measured in a nearby well, and the pressure at the top of the well, P_2, is the production casing pressure at the breach depicted in Figure 7. Q in the Weymouth equation is the gas flow rate in the well, and therefore, the leak rate.

Rather than calculating C based on well and fluid characteristics, we use the three downwind flight measurements to find the C value that best fits all three measurements. The method draws on both the available pressure data and the Scientific Aviation flights to allow a calculation of emission rate for the entirety of Phase I. By minimizing the sum of squares of the difference between the calculated Q and the estimate from the flight results, we arrived at a C value of 23.7, which results in a total methane emission estimate from Phase I of 48,450 MT. Figure 8 shows the results, and Table 3 shows the calculation of the total emission during Phase I.

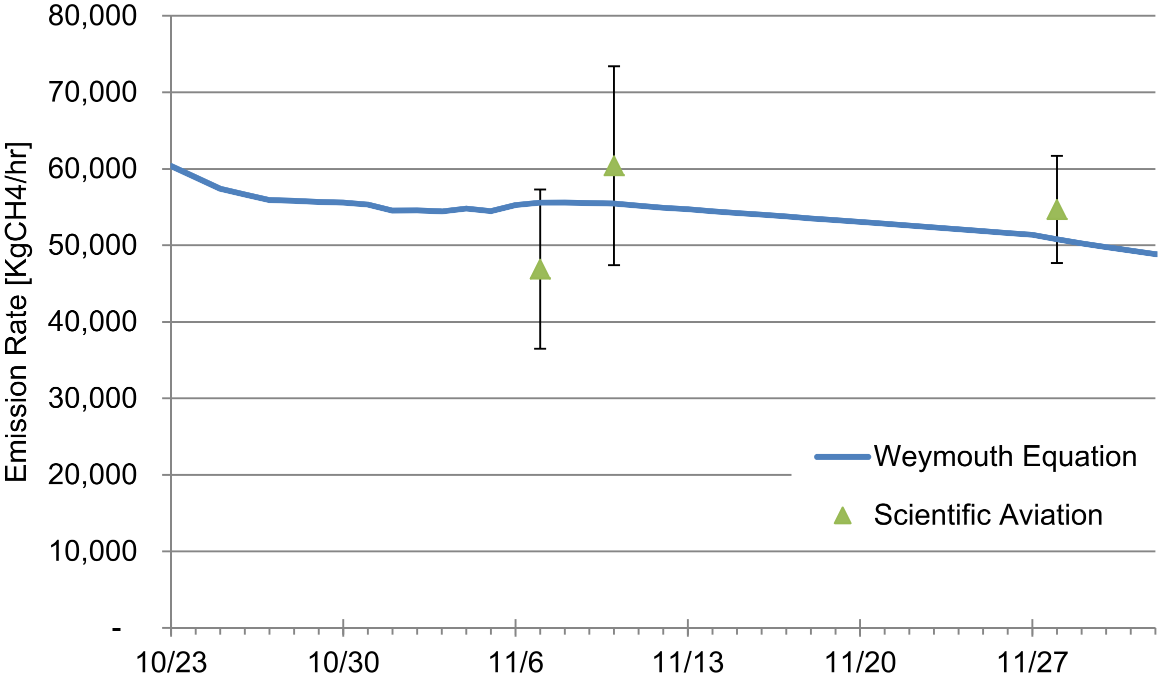

Figure 8: Emission rate during Phase I calculated using the Weymouth Equation, C=23.7, and the downwind measurements by Scientific Aviation and their uncertainties.

Table 3: Offset well and SS-25 production casing pressures and emissions calculations

	Offset Well Pressure (_P_1) [PSIG]	Offset Observation well	Average Daily Production Casing Wellhead Pressure in SS25 (_P_2) [PSIG]	Calculated Emissions Rate [KgCH_4/hr]	Daily Emissions [MT CH_4]
10/23/2015	2655	SS 5	_750**_	60,361	1,449
10/24/2015	2588	SS 5	_725**_	58,880	1,413
10/25/2015	2521	SS 5	_700**_	57,398	1,378
10/26/2015	2484	SS 5	_675**_	56,656	1,360
10/27/2015	2447	SS 5	_650**_	55,910	1,342
10/28/2015	2436	SS 5	_625**_	55,801	1,339
10/29/2015	2424	SS 5	_600**_	55,661	1,336
10/30/2015	2416	SS 5	582	55,575	1,334
10/31/2015	2407	SS 5	585	55,336	1,328
11/1/2015	2397	SS 5	672	54,532	1,309
11/2/2015	2387	SS 5	630	54,565	1,310
11/3/2015	2379	SS 5	620	54,432	1,306
11/4/2015	2371	SS 5	524	54,802	1,315
11/5/2015	2364	SS 5	552	54,477	1,307
11/6/2015	2358	SS 5	351	55,261	1,326
11/7/2015	2355	SS 5	214	55,583	1,334
11/8/2015	2354	SS 5	204	55,579	1,334
11/9/2015	2352	SS 5	211	55,517	1,332
11/10/2015	2350	SS 5	214	55,463	1,331
11/11/2015	_2340*_	SS 5	229	55,189	1,325
11/12/2015	_2330*_	SS 5	240	54,920	1,318
11/13/2015	_2319*_	SS 5	217	54,730	1,314
11/14/2015	_2309*_	SS 5	229	54,460	1,307
11/15/2015	_2299*_	SS 5	223	54,232	1,302
11/16/2015	_2289*_	SS 5	211	54,016	1,296
11/17/2015	_2279*_	SS 5	208	53,782	1,291
11/18/2015	_2269*_	SS 5	219	53,515	1,284
11/19/2015	_2258*_	SS 5	209	53,294	1,279
11/20/2015	_2248*_	SS 5	203	53,065	1,274
11/21/2015	_2238*_	SS 5	201	52,828	1,268
11/22/2015	_2228*_	SS 5	199	52,589	1,262
11/23/2015	_2218*_	SS 5	199	52,348	1,256
11/24/2015	_2208*_	SS 5	194	52,115	1,251
11/25/2015	_2197*_	SS 5	202	51,857	1,245
11/26/2015	_2187*_	SS 5	_200**_	51,619	1,239
11/27/2015	2177	SS 24	_200**_	51,377	1,233
11/28/2015	2153	SS 24	_200**_	50,805	1,219

* November 11-26 Pressures have been adjusted to account for withdrawals from SS 5

** October 23-29 and November 26-28 pressures are extrapolations

Total Emissions for Phase I → 48,445

For Phase I, the uncertainty of the emission rate for each day was calculated using error propagation for the Weymouth Equation, starting with errors for each parameter in the equation: the coefficient C has an uncertainty of ± 4.3, the maximum amount of variability in C that still puts the flow rate calculated within the uncertainty bounds of the three downwind flights, while P_1 was assigned a 1 percent uncertainty and P_2 was assigned a 6 percent uncertainty.

The 1 percent uncertainty value for P_1 is approximately ten times the variation from November 7 to November 10, a period of relative stability that provides some perspective on the measurement uncertainty. The larger value was chosen to account for the possibility of some nonlinear variation between the pressures at the offset well and the base of SS-25 for which it was used as a proxy. P_2 was assigned a 6 percent uncertainty based upon the range of the central 95 percent of production casing wellhead measurements from 9:53 to 22:41 on November 14. This period was selected because the overall trend was nearly zero (no change in pressure).

These daily errors were added to give a total uncertainty for the estimate of methane leaked during Phase I of ± 8,810 MT CH_4.

Estimate of Methane leaked during Phase I: 48,450 ± 8,810 MT

Phase II: Drawdown (November 29, 2015 – February 11, 2016)

Kill Attempts:	December 22, 2015	
Downwind flights:	December 4, 2015	48,800 ± 9,300 kg/hr CH_4
	December 12, 2015	38,000 ± 4,800 kg/hr CH_4
	December 23, 2015	28,100 ± 4,800 kg/hr CH_4
	January 8, 2016	22,700 ± 3,300 kg/hr CH_4
	January 12, 2016	20,700 ± 3,100 kg/hr CH_4
	January 21, 2016	19,100 ± 4,000 kg/hr CH_4
	January 26, 2016	19,000 ± 1,700 kg/hr CH_4
	February 4, 2016	22,500 ± 3,800 kg/hr CH_4

During Phase II there was much less activity near the well as the focus shifted to drilling the relief well, and the leak rate was mainly driven by the field pressure which was steadily reduced with the withdrawal of natural gas from the reservoir. The only kill attempt during the Phase is not expected to have affected the pathway through the geologic media, and therefore, not expected to have affected the leak rate.

The period was well sampled with 8 downwind flights. For this portion of the leak, although well pressure data are not available, non-linear changes in leak rates are not expected since there were no major well control attempts. Therefore, we used simple interpolation of the measured leak rates from the downwind flights between the sampling dates. The uncertainty for Phase 2 was calculated based on the uncertainties provided by Scientific Aviation for the downwind flights as listed above. The error was propagated by taking the square root of the sum of squares of the errors for each specific period when summing over all periods for the total emission for Phase 2.

Estimate of Methane leaked during Phase II: 51,200 ± 2,970 MT

Table 4: Methane Emission Estimates of the Aliso Canyon Natural Gas Leak

Phase	Flight Date	Leak Rate [kilogram methane per hour]	Uncertainty [kilogram methane per hour]	Assumed number of days at this leak rate	Leaked methane for this period	
					[kilogram methane]	[billion cubic feet of natural gas, bcf*]
Phase I					48,444,715	2.8
Phase II	11/28/2015	54,700	7,000	3.0	3,938,400	0.2
↓	12/4/2015	48,800	9,300	7.0	8,198,400	0.5
	12/12/2015	38,000	4,800	9.5	8,664,000	0.5
	12/23/2015	28,100	4,800	13.5	9,104,400	0.5
	1/8/2016	22,700	3,300	10.0	5,448,000	0.3
	1/12/2016	20,700	3,100	6.5	3,229,200	0.2
	1/21/2016	19,100	4,000	7.0	3,208,800	0.2
	1/26/2016	19,000	1,700	7.0	3,192,000	0.2
	2/4/2016	22,500	3,800	11.5	6,210,000	0.4
				Total	99,637,915	5.7

* Assumes natural gas from the leak is 94% methane, and methane and NG has density of 0.01858 kg/cu-ft

Total Emissions: Phase I + II (October 23, 2015 – February 11, 2016)

Finally, the total estimated methane leaked during both Phases was calculated by aggregating the emissions estimated in the two phases (Figure 9 and Table 4). The combined error was calculated by taking the square root of the sum of squares of the individual Phases.

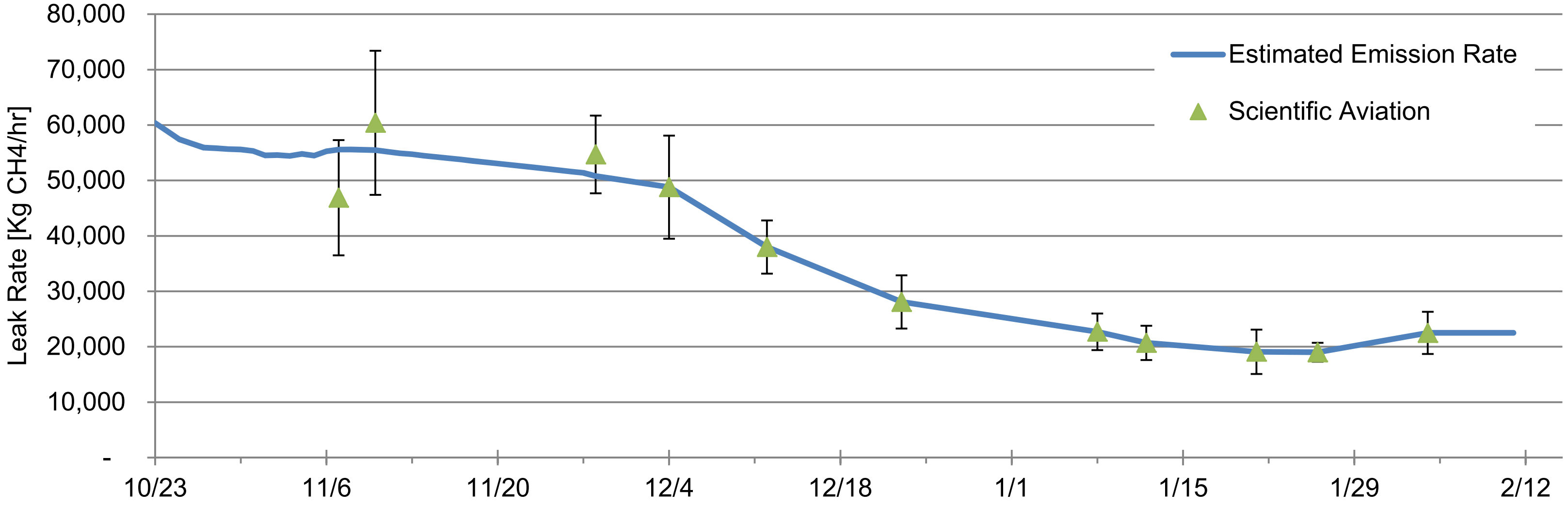

Figure 9: The leak rate over the duration of the incident and the downwind measurements.

Estimate of Methane leaked during Phases I - II = 48,450 ± 8,810 MT + 51,200 ± 2,970 MT

= 99,650 ± 9,300 MT

Final emission estimates and amount of methane that needs to be mitigated

As described in the above sections, ARB calculated the updated emission estimate of 99,650 ± 9,300 MT methane based on the best available data on the leak, including pressure data from well SS-25 and an offset well, as well as direct measurements of emissions rates made with the small instrumented airplane that flew through the methane plume.

ARB also reviewed the revised estimate in relation to all the other available estimates from SoCalGas, DOGGR, LBNL, and NASA-JPL to corroborate the data and inform the final number. ARB utilized the uncertainty range defined by expected errors in each of the numbers and calculations in order to conduct an equivalent comparison (Figure 10). The comparison chart shows that updated number is within the error bounds of all other estimates published, except for the SoCalGas tracer flux method.

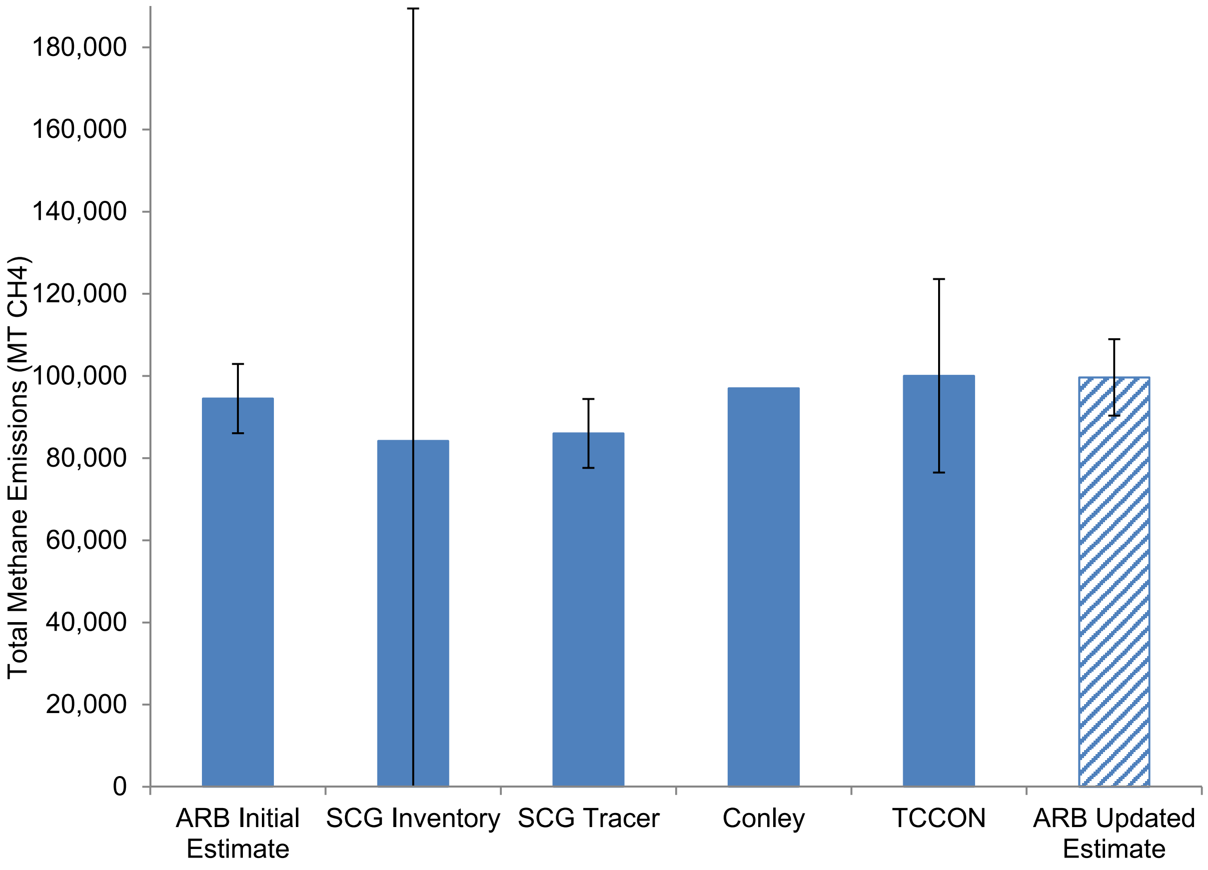

Figure 10: Overview of different emission estimates

The Governor's Proclamation directs ARB to provide a plan that *fully* mitigates the climate impacts of the methane leaked from the Aliso Canyon Natural Gas Storage Facility. The updated emissions estimate represents the most likely result with an expected uncertainty. The final number must recognize that "fully mitigating" the environmental damage, as required by the Governor's Proclamation, requires taking a conservative, or upper bound, estimate to mitigate the full potential emissions from the leak. Therefore, to ensure that the Aliso Canyon natural gas leak is fully mitigated, **the total amount of methane that needs to be mitigated is 109,000 MT**.