CALIFORNIA
AIR RESOURCES BOARD

Evaluation of Methane as a Surrogate to Identify Leaks and Associated Toxic Emissions from Crude Oil and Natural Gas Production Wells and Facilities

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Table of Contents

I. Executive Summary 1
A. Background 1
B. Key Findings 1
C. Key Conclusions, Recommendations, and Next Steps 2
II. Introduction & Background 2
III. Objective 4
IV. Literature Review 4
A. Atmospheric Methane 4
B. Emissions of Methane and Non-Methane Volatile Organic Compounds from Upstream Oil and Gas Activities 6
C. Toxic Air Contaminant Emissions from Oil and Gas Activities 13
V. Conclusions and Recommendations for Using Methane as a Surrogate for Leaks and Toxic Compound Exposure 30
VI. References 31
VII. Appendices 38

List of Tables

Table 1: Crude oil types by API gravity range and sulfur content. 11
Table 2: Representative list of TACs found near oil and gas facilities. 15
Table 3: Methane and benzene ratios by oil and gas production source. 20
Table 4: Toxics Identified in Available Source Profiles. 27
Table 5: Summary of weighted health risks from U.S. EPA SPECIATE database of California oil and gas equipment. 29

List of Figures

Figure 1: Air toxics commonly found at upstream oil and gas facilities. 8

Figure 2: Summary of U.S. refinery inputs by API gravity. 11

Figure 3: Comparison of California crude oil to other U.S. regions.* 12

Figure 4: Map of California crude oil and natural gas basins. 12

Figure 5: Select source categories of CARB emission inventory data for upstream oil and gas fugitive emissions. 17

Figure 6: Phase 1 VOC Speciation from CARB Produced Water Evaporation Study. 18

Figure 7: Representative plot of select oil and gas facility equipment from the U.S. EPA SPECIATE Database. 21

Figure 8: Representative composite California gas wells, oil tanks, and oil separator from the U.S. EPA SPECIATE database. 22

Figure 9: Composite average speciation from gas wells in California from USGS database. 23

Figure 10: Representative weighted fraction of health risks from California oil and gas production facility equipment from the U.S. EPA SPECIATE Database. 28

List of Appendices

Appendices are available in separate Microsoft Excel files.

Appendix 1: Source profiles for oil and gas emissions downloaded from the CARB speciation profiles used in CARB modeling (November 19, 2024).

Appendix 2: All source category and emission profiles for 'Oil and Gas' downloaded from the U.S. EPA SPECIATE database (February 19, 2025).

Acronyms

§ – Section
AQPSD – CARB Air Quality Planning and Science Division
ASTM – American Society for Testing and Materials
BTEX – Benzene/Toluene/Ethylbenzene/Xylenes
COGMR – California Oil and Gas Methane Regulation
CalGEM – Geologic Energy Management Division in the California Department of Conservation
CARB – California Air Resources Board
CEC – California Energy Commission
CFR – Code of Federal Regulations

CH_4 – Methane

EIA – U.S. Energy Information Administration

H_2S – Hydrogen sulfide

HAP – Hazardous Air Pollutant

HPZ – Health Protection Zone

LDRP – Leak Detection and Response Plans

NMHC – Non-methane Hydrocarbons

NMVOC – Non-Methane Volatile Organic Compound(s)

OEHHA – California Office of Environmental Health Hazard Assessment

ONG – Oil and Natural Gas

PADD – Petroleum Administration for Defense Districts

PAH – Polycyclic Aromatic Hydrocarbons

REL – Reference Exposure Level

SB 1137 – Senate Bill 1137, Enacted in 2022/2023 session

SNAPS – Study of Neighborhood Air near Petroleum Sources

TAC – Toxic Air Contaminant

U.S. – United States of America

U.S. EPA – United States Environmental Protection Agency

USGS – United States Geological Survey

VOC – Volatile Organic Compound(s)

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I. Executive Summary

A. Background

California Senate Bill 1137 (SB 1137) establishes a 3,200-foot health protection zone (HPZ) between sensitive receptors and upstream oil and gas production facilities or wellheads[a] in California. This legislation requires operators with an oil and/or natural gas production facility or well with a wellhead within an HPZ to develop and implement leak detection and response plans (LDRP). LDRPs are required to identify key chemical constituents and potential toxics of concern and to include a continuously operating emission detection system to detect these chemical constituents so that leaks can be identified and repaired before emissions impact the surrounding communities. SB 1137 states that “methane may serve as a surrogate for chemical constituents that cannot be continuously monitored but are identified in the leak detection and response plan.” Methane (CH_4) is already being used by monitoring programs governed by other state and federal statutes as a surrogate indicator for fugitive emissions that cannot be continuously monitored due to logistical or cost constraints. This document provides an evaluation by California Air Resources Board (CARB) staff of the effectiveness of CH_4 as a surrogate for detecting fugitive emissions[b] and air toxics as well as potential limitations, based on a comprehensive literature review of oil and gas emissions and speciation data.

B. Key Findings

- Methane and non-methane volatile organic compounds (NMVOC) are co-emitted from upstream oil and gas operations, including production, maintenance (vented leaks), and fugitive emission events. Fugitive emissions are unintentional leaks that occur during oil and natural gas production and processing. NMVOCs consist of a wide range of compounds, including benzene, toluene, ethylbenzene, xylenes (BTEX), polycyclic aromatic hydrocarbons (PAHs), light and heavy alkanes, and sulfur compounds such as hydrogen sulfide.
- Many of the NMVOCs released are classified by CARB as toxic air contaminants (TAC) and have been shown to cause negative health impacts to humans.
- Methane is found at all upstream oil and gas facilities and the composition of NMVOCs and ratios to methane vary significantly across oil and gas fields, facility production equipment, and operational processes. Methane monitoring is widely used as a tool for

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[a] Upstream facilities include production wells and production facilities, compared to midstream facilities such as pipeline networks, and downstream facilities such as refineries.

[b] The terms “leak” and “fugitive emissions” are used interchangeably in this document to describe the unintentional release of emissions.

detecting upstream oil and gas facility leaks because methane is present at some proportion at all upstream oil and gas facilities.

- Temporal and spatial variability in emissions composition complicates methane's role as a universal surrogate for NMVOCs and TACs, and methane-to-TAC ratios vary significantly across different facility production equipment.

C. Key Conclusions, Recommendations, and Next Steps

- Methane can serve as an effective tool to detect fugitive emissions at upstream oil and gas production facilities under certain conditions, but not at all due to variable ratios with TACs from differing equipment.
- Existing speciation data suggest the primary air toxic of concern at the majority of oil and gas production facilities will be benzene. Benzene was found to dominate acute, chronic, and cancer risk factors for existing emission speciation inventories. This report focuses on short term, acute metrics to be consistent with early notification requirements of SB 1137 even though benzene is the dominate risk factors for chronic and cancer.
- Any leak detection system correlating methane concentrations with toxic pollutant concentrations should ideally include site-specific chemical speciation, including TACs and methane, of on-site equipment.
- CARB staff will provide companion reports that evaluate options for performance standards for emissions detection systems and species composition sampling that build on these conclusions and recommendations. These reports will be available at CARB's webpage, Senate Bill 1137: Meetings, Workshops, Technical Reports, and Draft Rulemaking Documents[c].

II. Introduction & Background

California Senate Bill 1137 (SB 1137) sets requirements for protecting public health by creating a minimum health and safety distance of 3,200 feet between sensitive receptors, which include residences, schools, childcare facilities, playgrounds, hospitals, or nursing homes, and an oil and gas production well or facility[d]. These areas are designated health protection zones (HPZ). An estimated 3 million, or approximately 1 in 12 (~8%) California residents live within 3,200 feet of at least one active-producing oil and/or gas well (active oil

[c] Senate Bill 1137: Meetings, Workshops, Technical Reports, and Draft Rulemaking Documents.

[d] Senate Bill 1137 (Gonzalez, Stats. of 2022, Ch. 365; adding Public Resources Code Article 4.6 (commencing with Section 3280 to Chapter 1 of Division 3)). Legislative Counsel's Digest. Approved by the Governor: September 16, 2022. Filed with the Secretary of State: September 16, 2022. Published by the California Legislative Information: September 19, 2022. Accessed: January 22, 2025.

and gas development)(Shonkoff, et al., 2024; Ferrar, 2022). Compared to the overall California population, Hispanic, non-Hispanic Black, and non-Hispanic Asian communities, as well as populations of lower socioeconomic status, are more likely to live within 3,200 feet of at least one active-producing oil and/or gas well and live in areas with the highest density of oil and gas wells(Shonkoff, et al., 2024; Ferrar, 2022).

SB 1137 requires all operators with a production facility or wellhead within HPZ to develop and submit a leak detection and response plan (LDRP) to the Geologic Energy Management Division in the California Department of Conservation (CalGEM) by July 1, 2028, for review and approval by CalGEM and the California Air Resources Board (CARB). Within the LDRP, the operators must identify the chemical constituents and the potential toxics of highest concern in the region that will be detection targets for a continuously operating emissions detection system. SB 1137 requires the LDRP to include the identification of a continuously operating emissions detection system, selected by the owner or operator, designed to provide for rapid detection of target chemical constituents to identify leaks before emissions impact the surrounding communities. SB 1137 directs CARB to set performance standards by regulation for the emission detection systems to be selected and placed into use by the operators. The statute does not mandate the use of specific monitoring technology or detection methods. SB 1137 allows the emission detection systems to use methane as a surrogate for identified chemical constituents that cannot be continuously monitored(Gonzalez and Limón, 2022).

The use of surrogate measurements is a common practice in cases where directly measuring a compound or a suite of compounds is logistically infeasible or cost prohibitive. For example, continuous storage tank pressure measurements are used in CARB's vapor recovery program for gasoline marketing operations to estimate pressure driven fugitive emissions rather than a direct emissions measurement(CARB., 2003). Methane (CH_4) is commonly utilized as a surrogate for oil and gas facility leaks across the world and in California. For example, the San Joaquin Valley Air Pollution Control District (SJVAPCD)[e] sets absolute methane concentration value thresholds as a surrogate for fugitive or leak-based VOC emissions (SJVAPCD Rule 4409).

This document provides a literature review discussing the use of methane as a surrogate for other chemical constituents that pose a risk to human health that may be present in fugitive emissions from an upstream oil and gas facility. This document will also provide CARB staff's draft recommendations to provide guidance for the development of performance standards for the emissions detection systems required by SB 1137.

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[e] Components at Light Crude Oil Production Facilities, Natural Gas Production Facilities, and Natural Gas Processing Facilities (Adopted April 20, 2005; Amended June 15, 2023), Rule 4409 (SJVAPCD Rule 4409).

III. Objective

Provide a literature review and present CARB staff's recommendations for using methane as a surrogate for detecting volatile organic compounds (VOC) and toxic air contaminants (TAC) in fugitive emissions from upstream oil and gas facilities by answering the following specific questions:

1. Which VOCs and TACs are found in fugitive emissions from upstream oil and gas facilities?
2. Is methane a reliable surrogate for indicating leaks that contain these VOCs and TACs?
3. Can methane be used as a surrogate for VOCs and TACs in quantitative assessments of leaks from those facilities, e.g., assessments to estimate toxic compound concentration?

IV. Literature Review

A. Atmospheric Methane

Methane is the simplest hydrocarbon, consisting of one carbon atom and four hydrogen atoms. It is an odorless, colorless, and highly flammable gas with a variety of atmospheric sources. Methane is also a potent greenhouse gas with global warming potential significantly higher than carbon dioxide over shorter timeframes.

Atmospheric methane originates from three primary sources: biogenic, thermogenic, and pyrogenic processes.

- Biogenic methane is produced by microbial activity in anaerobic environments and can be released from permafrost thawing, rice paddies, livestock operations, landfills, wetlands, and wastewater treatment processes(Schulze, et al., 2023; Townsend-Small, et al., 2016; Kirschke, et al., 2013; Schuur, et al., 2015). These sources are becoming increasingly important contributors to the global methane budget due to expanding agricultural activities(Schaefer, et al., 2016).
- Thermogenic methane is generated deep within the Earth's crust under high heat and pressure. It enters the atmosphere through natural seeps, mud volcanoes, and fossil fuel extraction activities, including coal mining, oil and gas production, processing, and distribution(Kirschke, et al., 2013; Schaefer, et al., 2016). In California, thermogenic methane emissions are primarily associated with oil and gas operations.
- Pyrogenic methane is released from the incomplete combustion of fossil fuels and biomass, occurring during wildfires and combustion processes in transportation and industry(Kirschke, et al., 2013).

California has a complex mixture of biogenic, thermogenic, and pyrogenic methane sources, with their relative contributions varying by location and season(Schulze, et al., 2023). While biogenic sources dominate statewide methane emissions, thermogenic and pyrogenic contributions are significant in certain regions(Schulze, et al., 2023; Marklein, et al., 2021; Lebel, et al., 2022). Thermogenic methane sources in California include oil and gas exploration, extraction, processing, maintenance, and distribution(Kirschke, et al., 2013; Schaefer, et al., 2016; Garcia-Gonzales, et al., 2019). This document focuses on thermogenic methane emissions, specifically from upstream oil and gas facility fugitive emissions.

Methane itself does not pose a direct toxicological risk and is therefore not classified as a TAC in California, nor is it listed under California Proposition 65 or regulated as a Hazardous Air Pollutant (HAP) by the United States Environmental Protection Agency (U.S. EPA).

- Under California law, a TAC is defined as an air pollutant that may cause or contribute to increased mortality, serious illness, or potential health hazards (California Health and Safety Code § 39655[f]). CARB has identified TACs under Title 17, California Code of Regulations § 93000. CARB establishes Air Toxics Control Measures (ATCM) outlining the need and degree to regulate pollutants once they are identified as a TAC[g].
- The U.S. EPA designates HAPs under Section 112(b) of the Clean Air Act (42 U.S.C. § 7412(b)) as pollutants that pose significant health risks, including cancer and other serious health effects.
- In 1993, CARB adopted federal HAPs as TACs[h], identifying 189 HAPs as regulated TACs, with the current CARB TAC list exceeding 200 substances[i].
- In 1987, California adopted the Safe Drinking Water and Toxic Enforcement Act, also known as Proposition 65, to provide the public with warnings about exposure to chemicals with harmful effects. Currently, this list is over 900 chemicals and many of these compounds are also listed as HAPS or TACs[j].
- The California Office of Environmental Health Hazard Assessment (OEHHA) defines the Reference Exposure Level (REL) as the level of airborne TAC concentration chemical that is not expected to cause adverse health effects over specified exposure time periods at or below the specified amount (e.g., 1-hour, 8-hour)[k].

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[f] Assembly Bill 1807 (AB 1807) (Stats. 1983, Ch. 1047; Health and Safety Code § 39650 et seq., Food and Agriculture Code § 14021 et seq.), enacted in September 1983, set forth a procedure for the identification and control of TACs in California. CARB is responsible for the identification and control of TACs, and prepares identification reports on candidate substances under consideration for listing as TACs.

[g] See CARB's description of health risk assessment.

[h] More information can be found on the U.S. Environmental Protection Agency's Hazardous Air Pollutants.

[i] See CARB's TAC identification reports for descriptions and summaries of each listed substance.

[j] State of California Office of Environmental Health Hazard Assessment Proposition 65.

[k] Office of Environmental Health Hazard Assessment Reference Exposure Limits.

VOCs are carbon-containing compounds that readily evaporate under ambient conditions. Reactions of VOCs with nitrogen oxides in sunlight contribute to the formation of ground-level ozone, a key component of smog and a known respiratory irritant[l].

- VOCs are broadly classified under federal regulation (40 CFR 51.100(s)), excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate.
- While some TACs are classified as VOCs, not all VOCs are considered TACs.
- Methane is explicitly excluded from the federal VOC definition because it has negligible photochemical reactivity and does not significantly contribute to ozone formation.
- As a result of the above considerations, emissions of methane and non-methane VOCs (NMVOCs) are often analyzed separately in atmospheric studies and regulatory frameworks.

Methane is a major component of natural gas and crude oil. Methane can be released intentionally during routine oil and gas production operations ("vented" emissions) or unintentionally leaked ("fugitive" emissions), alongside a wide range of NMVOCs and air toxics (HAPs and TACs)(Garcia-Gonzales, et al., 2019; Schade and Heienickle, 2023; Cardoso-Saldaña, et al., 2021; Paulik, et al., 2018; Roest and Schade, 2017; Brantley, et al., 2014; Hecobian, et al., 2019; Tzompa-Sosa, et al., 2019; Rossabi, et al., 2021; McKenzie, et al., 2018; DiGiulio, et al., 2023; Rich and Orimoloye, 2016; Halliday, et al., 2016; Lebel, et al., 2020). The Legislature has made an allowance for methane to be utilized as a surrogate for NMVOC emissions detection purposes as part of SB 1137 text[m]. The next section of this document will discuss methane and NMVOC emissions from upstream oil and gas operations and their potential use in emission detection and exposure assessment.

B. Emissions of Methane and Non-Methane Volatile Organic Compounds from Upstream Oil and Gas Activities

1. Upstream Emissions Overview

Upstream oil and gas activities emit methane, NMVOCs, and other gases during normal operations, maintenance activities, and fugitive emission events(Garcia-Gonzales, et al., 2019; CARB., 2024a; Rowland, et al., 2025). NMVOC and other constituents from upstream facilities are composed primarily of light and heavy alkanes, nitrogen, hydrogen, carbon monoxide, carbon dioxide, small aromatics, larger polycyclic aromatic hydrocarbons (PAHs),

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[l] CARB Ozone and Health.

[m] Senate Bill 1137 (Gonzalez, Stats. of 2022, Ch. 365; adding Public Resources Code Article 4.6 (commencing with Section 3280 to Chapter 1 of Division 3)). Legislative Counsel's Digest. Approved by the Governor: September 16, 2022. Filed with the Secretary of State: September 16, 2022. Published by the California Legislative Information: September 19, 2022. Accessed: January 22, 2025.

and sulfur compounds, including hydrogen sulfide(Shonkoff, et al., 2024; Garcia-Gonzales, et al., 2019; Roest and Schade, 2017; Censullo, 1991; Marrero, et al., 2016; Cardoso-Saldaña, et al., 2019). Studies characterizing NMVOC emissions have identified hundreds of individual species emitted from upstream oil and gas facilities, though many are not classified as HAPs or TACs(Garcia-Gonzales, et al., 2019).

The presence and distribution of hydrogen sulfide, NMVOCs, and specific TACs depend on the original products at the upstream facility — whether from natural gas, high- or low-viscosity crude oil, high-sulfur crude oil, or specific extraction methods(Lebel, et al., 2022; Garcia-Gonzales, et al., 2019; Cardoso-Saldaña and Allen, 2020; Robertson, et al., 2017; Helmig, et al., 2014). It is important to note that limited NMVOC speciation data is available for California oil and gas sites, and much of the current understanding is inferred from studies conducted in Texas, Colorado, Utah, Pennsylvania, Wyoming, and Oklahoma(Rowland, et al., 2025). This document focuses on TACs directly emitted from upstream oil and gas facilities and evaluates the potential use of methane as a surrogate for these emissions.

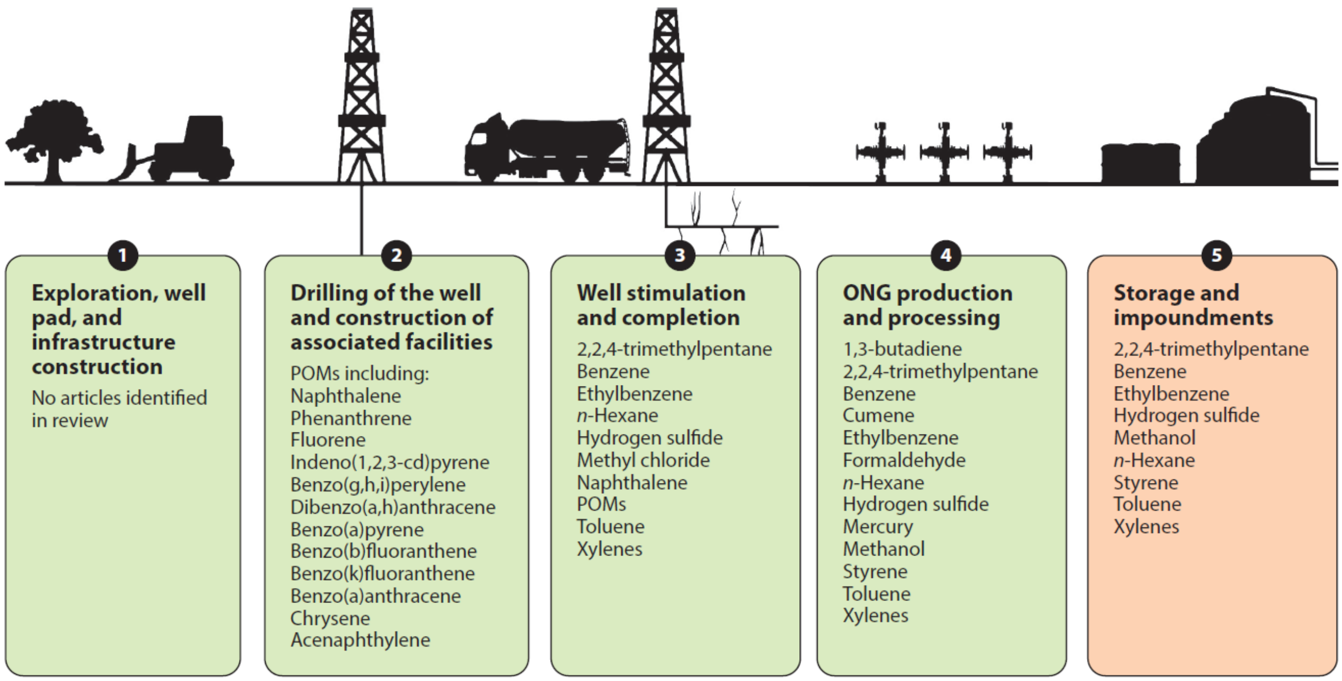
Multiple mechanical and chemical transformations alter the composition of emitted pollutants throughout the oil and gas production process and impact the chemical speciation of fugitive emissions (Shonkoff, et al., 2024; Garcia-Gonzales, et al., 2019; Schade and Heienickle, 2023; Cardoso-Saldaña, et al., 2021; Brantley, et al., 2014; Hecobian, et al., 2019; Tzompa-Sosa, et al., 2019; Rich and Orimoloye, 2016; Halliday, et al., 2016; Censullo, 1991; Marrero, et al., 2016; Ghosh, 2018; Rella, et al., 2015; Kang, et al., 2023; Michanowicz, et al., 2022; Macey, et al., 2014; CARB., 2020). These processes are common to all upstream oil and gas facilities and occur throughout California, depending on facility location and operational conditions(Shonkoff, et al., 2024) and include:

- Well drilling and maintenance
- Compressor and separator operations
- Produced water evaporation
- Storage tank flash emissions
- Transportation of crude oil and natural gas between production equipment

Figure 1 summarizes commonly identified toxic compounds found in upstream oil and gas emissions based on a detailed literature review by Garcia-Gonzales and others (2019)(Garcia-Gonzales, et al., 2019). Additional speciation data and identification of air toxics are discussed later in this document.

Figure 1: Air toxics commonly found at upstream oil and gas facilities.

(Source: Garcia-Gonzales et al., 2019)(Garcia-Gonzales, et al., 2019)



2. Temporal Distribution of Oil and Gas Emissions

Emissions from upstream oil and gas facilities are often not continuous and can vary over time based on the production equipment-specific emission source(Brantley, et al., 2014; Marrero, et al., 2016; Rella, et al., 2015; Perry, 2016). Methane emissions from oil and gas infrastructure can result from both intentional releases (i.e., "vented" emissions) and unintentional leaks (i.e., "fugitive" emissions). Intentional releases may happen due to system design (such as using natural gas to operate pneumatic devices), safety or maintenance needs, or the absence of feasible control or disposal methods (where permitted). Unintentional leaks can arise from issues like wear and defects in valves, seals, and connections, as well as process disruptions, equipment failures, or human mistakes. Some leaks can be unpredictable and challenging to prevent(Shonkoff, et al., 2024; Alvarez, et al., 2018). Emissions are dependent on operationally defined variables like maintenance, operational design, and leaks and will vary based on location and site-specific protocols. For example, evaporation of VOCs into the atmosphere from produced water ponds can be a source of methane, NMVOCs, and TACs(CARB., 2020).

Multiple mobile laboratory studies investigating emissions leaving oil and gas facilities have found elevated emissions during some study periods and not others, often on the same day(Brantley, et al., 2014; Rella, et al., 2015; Perry, 2016; Mellqvist, et al., 2022). In all of these studies, methane was found to be a co-emitted pollutant from oil and gas facilities, with emissions generally tracking NMVOCs, including some air toxics. Additionally, these studies found emissions may not originate consistently from the same equipment on the field. For example, in 2015, the South Coast Air Quality Management District contracted Kassay Field Services to investigate emissions from a variety of VOC point sources using mobile open path spectroscopic methods(Perry, 2016). This study investigated both NMHC and methane from 17 gas stations, 16 oil wells, and 2 cattle ranches. The study found that emissions were not consistent over time, with quantifiable emission events followed by periods of no detectable emissions. Methane was also found to be present at concentrations proportional to NMHC emissions (e.g., alkanes with 1–12 carbons, BTEX) at all facilities.

3. Spatial Distribution of Oil and Gas Emissions: Crude Oil and Natural Gas Composition by Region

Crude oil reserves are often classified by American Petroleum Institute (API) gravity, a standardized industry metric for comparing the density of crude oil and natural gas relative to water. API gravity is widely used alongside sulfur content to categorize oil reservoirs and products(Geary, 2017). Higher API gravity values indicate lower-density (lighter) crude oil, while lower values indicate heavier crude oil. Crude oil with an API gravity above 38° is classified as light, whereas oil with an API gravity below 20° is considered heavy[n,(EIA.)]. Regulations, like the United States Code and the California Oil and Gas Methane Regulation (COGMR), both define heavy oil as having an API gravity below 20. (26 U.S.C. 613A(c)(6); 17 C.C.R. 95667(c)(2).

API gravity varies significantly by region, depending on the geological origin of the crude oil. API gravity is also used in combination with sulfur content to classify crude oil as "sour" or "sweet." Crude oil with sulfur content at or above 1.1% is categorized as sour(EIA., 2019). Rocky Mountain crude oil is generally light, with API gravity ranging from 30° to 40°, while California crude oil is predominantly heavy, with API gravity typically below 30° and is sour with a sulfur content greater than 1.1% (Figure 2)(EIA., 2019; 2024), distinguishing it from crude oil produced in other U.S. regions (Table 1)(EIA., 2015).

The composition of crude oil and natural gas significantly influences fugitive emissions(Lebel, et al., 2022; DiGiulio, et al., 2023; Censullo, 1991) and affects refining and processing operations(EIA., 2024). A key compositional factor is sulfur content, as not all oil and gas formations contain sulfur compounds at levels that require specialized processing(EIA., 2024). California crude oil has a significantly higher sulfur content than the U.S. average, with an average sulfur concentration of 1.64% in 2018 (Figure 3)(EIA., 2019; CEC, 2020). Many California oil and gas formations were derived from ancient marine

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[n] California Oil and Gas Methane Regulation, April 2024.

organic material and have undergone significant biodegradation(Lillis and Magoon, 2007). This biodegradation process, driven by anaerobic microbial activity, reduces API gravity and increases sulfur content, as microbes consume hydrocarbons, including methane, for survival(Lillis and Magoon, 2007; Bian, et al., 2015).

California’s largest oil and natural gas production fields are located in the San Joaquin Basin, Los Angeles Basin, Santa Maria Basin, Ventura Basin, and several offshore areas in Southern California. These regions are dominated by the Monterey Formation, a major geological formation containing significantly biodegraded oil and natural gas reserves (Figure 4)(Beckwith, 2013; EIA., 2023). Crude oil from the Monterey Formation has a higher sulfur content than most U.S. reserves, with concentrations reaching up to 8% in some areas(CEC, 2020; Piper and Isaacs, 1995). The large production volumes and high-sulfur content of Monterey Formation crude oil contribute to California’s overall higher average sulfur content. However, high-sulfur crude oil and natural gas are not uniformly distributed across the state.

Studies conducted by the United States Geological Survey have found that oil and gas fields within the Monterey Formation generally contain higher sulfur content than those outside of it, even within the same basin. In contrast, some oil and gas fields located outside the Monterey Formation exhibit no measurable sulfur content(Lillis and Magoon, 2007; Piper and Isaacs, 1995). Sulfur-containing compounds, such as hydrogen sulfide, are present in many California oil and gas formations, but they are not ubiquitous. Methane and NMVOCs are however, consistently present at all oil and natural gas production facilities, though their proportions vary by location and operational processes.

Figure 2: Summary of U.S. refinery inputs by API gravity.

(Source: U.S. Energy Information Administration, 2019)(EIA., 2019)

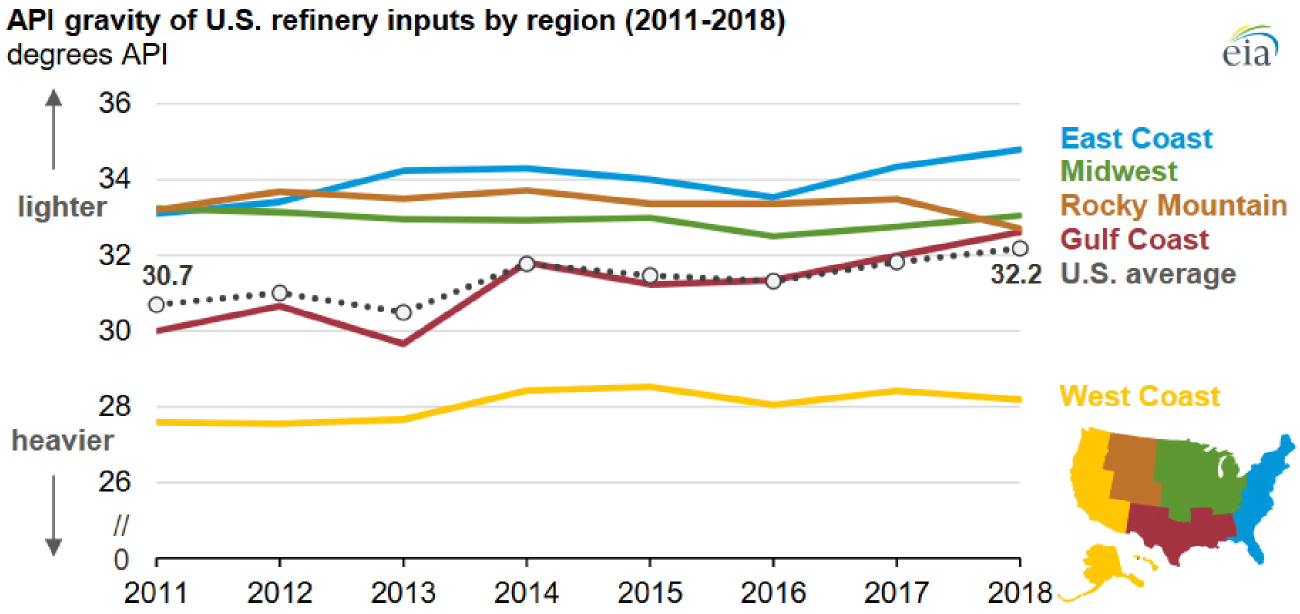


Table 1: Crude oil types by API gravity range and sulfur content.

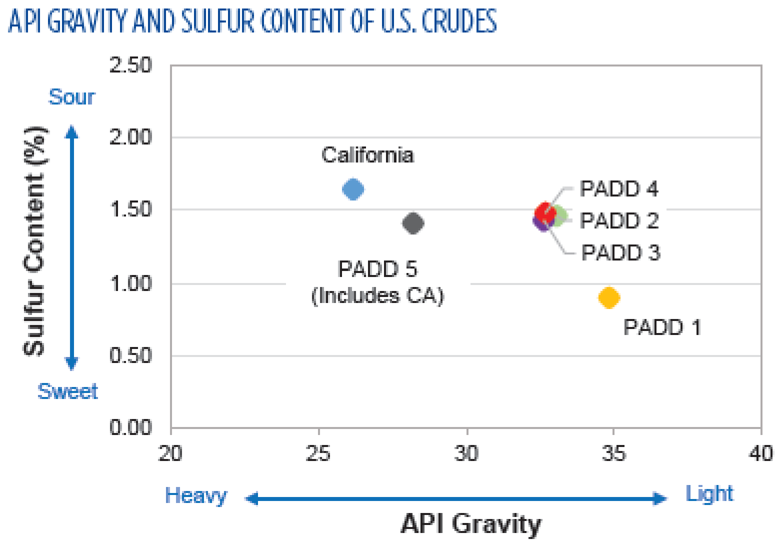
(Source: U.S. Energy Information Administration, 2015[o])(EIA., 2015)

Crude Type	API Gravity	Sulfur Content (%)	Classification
API 50+ sweet	API ≥ 50	< 0.5	Light Sweet
API 45-50 sweet	45 ≤ API < 50	< 0.5	Light Sweet
API 40-45 sweet	40≤ API < 45	< 0.5	Light Sweet
API 35-40 sweet	35≤ API < 40	< 0.5	Light Sweet
API 35+ sour	35≤ API < 40	< 0.5	Light Sour
API 27-35 med-sour	27≤ API < 35	< 1.1	Medium – Medium Sour
API 27-35 sour	API < 27	≥ 1.1	Medium Sour
California	API < 27	1.1-2.6	Medium – Heavy Sour
API <27 sweet	API < 27	< 1.1	Heavy Sweet
API <27 sour	API < 27	≥ 1.1	Heavy Sour

[o] Adopted from U.S. Energy Information Administration for this document.

Figure 3: Comparison of California crude oil to other U.S. regions.*

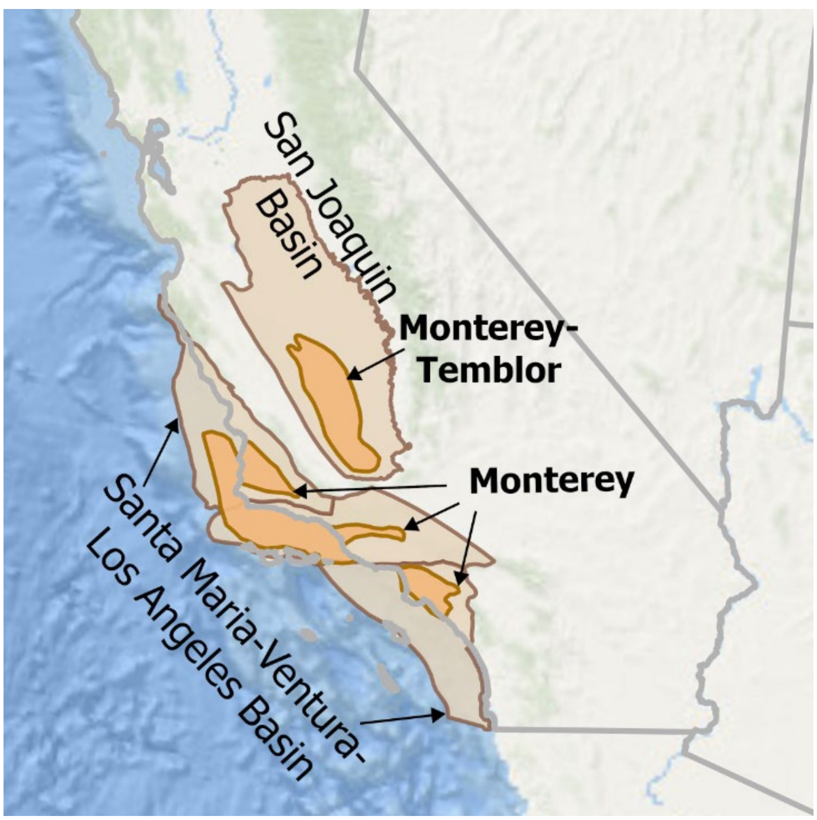
(Source: California Energy Commission, 2020)(CEC, 2020)



*PADD = Petroleum Administration for Defense Districts

Figure 4: Map of California crude oil and natural gas basins.

(Source: U.S. Energy Information Administration, 2023)(EIA., 2023)



C. Toxic Air Contaminant Emissions from Oil and Gas Activities

Methane and NMVOCs are released from various oil field equipment in different proportions. In this section, we will discuss the current information on the distribution and speciation of air toxics known to be emitted from oil and gas activities in the State of California.

1. Ambient Air Monitoring and Emission Studies

Direct compositional analysis of California oil and gas emissions remains limited, with most existing studies lacking a specific focus on TACs(Shonkoff, et al., 2024; Rowland, et al., 2025). This section highlights the publicly available data characterizing the speciation of emissions from upstream oil and gas facilities in California.

In contrast, numerous ambient monitoring studies have quantified methane and NMVOC concentrations near oil and gas facilities. In 2024, the California Oil and Gas Public Health Rulemaking Scientific Advisory Panel ("Panel") submitted a comprehensive summary on upstream oil and gas development to CalGEM to inform future rulemaking(Shonkoff, et al., 2024). The Panel's findings identified multiple cases in which NMVOCs – including TACs – emitted from upstream oil and gas operations had measurable impacts in nearby communities(Shonkoff, et al., 2024). CARB's Study of Neighborhood Air near Petroleum Sources (SNAPS) program in Lost Hills, CA, was designed to characterize air quality in communities near oil and gas production facilities and found that thermogenic methane and NMVOCs from nearby upstream oil and gas activities were detectable in the local community(CARB., 2024b).

Quantifying the relationship between methane and NMVOC from oil and gas facilities in ambient air is challenging due to the presence of multiple methane and NMVOC sources (e.g., diesel combustion, landfills, agriculture). Consequently, direct emissions data – such as those discussed later in this section – are essential for accurately assessing impacts to the community(Shonkoff, et al., 2024; Rowland, et al., 2025). Speciation data for all operational equipment identified in a leak detection response plan is necessary to quantitatively assess health risks from leaks at a given production facility.

2. VOC Emission Summary

Upstream oil and gas facilities emit methane alongside a broad spectrum of VOCs, with emission profiles varying by region, facility production equipment, and operational processes. TACs represent a critical subset of the hundreds of NMVOCs that may be released from oil and gas operations due to their potential human health risks.

TAC emissions occur at multiple stages of production, across various facility production equipment, and in diverse geographic regions(Garcia-Gonzales, et al., 2019; Brantley, et al., 2014; Marrero, et al., 2016). Table 2 summarizes select TACs or compounds associated with adverse health impacts commonly detected in air emissions near upstream oil and gas operations, based on data from recent literature and emission inventories(Shonkoff, et al., 2024; Garcia-Gonzales, et al., 2019; Brantley, et al., 2014; Rowland, et al., 2025; Censullo, 1991; Marrero, et al., 2016; Brennan, et al., 2021; CARB., 1978; 1985). This list, while not exhaustive, identifies common pollutants that are identified as toxic air contaminants and have a documented presence in fugitive emissions near upstream oil and gas facilities.

In the following sections, we examine the state of available data on the relationship between NMVOCs, TACs, and methane, with a focus on specific oil and gas production equipment and emission sources.

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Table 2: Representative list of TACs found near oil and gas facilities.

Species	CARB TAC?	OEHHA Acute REL ($\mu g/m^3$) [b]	OEHHA Cancer Inhalation Unit Risk Factor ($1/(\mu g/m^3)$) [b]
1,3-butadiene	Yes	6.60E+02	1.70E-04
acenaphthylene	Yes	2.70E+01	N/A
acetaldehyde	Yes	4.70E+02	2.70E-06
acrolein	Yes	2.50E+00	N/A
benzene	Yes	2.70E+01	2.90E-05
benz(a)anthracene	Yes	N/A	1.10E-04
benzo(a)pyrene	Yes	N/A	1.10E-03
benzo(b)fluoranthene	Yes	N/A	1.10E-04
carbonyl sulfide	Yes	6.60E+03	N/A
chrysene	Yes	N/A	1.10E-05
cumene	Yes	N/A	N/A
dibenzo(a,h)anthracene	Yes	N/A	1.20E-03
ethylbenzene	Yes	N/A	N/A
ethylene oxide	Yes	3.0E+01[c]	8.8E-05
formaldehyde	Yes	5.50E+01	6.00E-06
hydrogen cyanide	Yes	3.40E+02	N/A
hydrogen fluoride	Yes	2.40E+02	N/A
hydrogen sulfide	No	4.20E+01	N/A
indeno(1,2,3-cd)pyrene	Yes	N/A	1.10E-04
methanol	Yes	2.80E+04	N/A
methane	No	N/A	N/A
naphthalene	Yes	N/A	3.40E-05
n-hexane	Yes	7.00E+03	N/A
PAHs Bulk[a]	Yes	N/A	1.10E-03
phenanthrene	Yes	N/A	N/A
Styrene	Yes	2.10E+04	N/A
sulfur dioxide	No	6.60E+02	N/A
Toluene	Yes	5.50E+03	N/A
vinyl chloride	Yes	1.80E+05	7.80E-04
xylenes (all isomers)	Yes	2.20E+04	N/A

Table 2 Notes:

[a] PAHs Bulk defined by U.S. EPA and CARB as "4 - Includes organic compounds with more than one benzene ring, and which have a boiling point greater than or equal to 100 °C."

[b] Acute Reference Exposure Level values from Office of Environmental Health Hazard Assessment (OEHHA).

[c] Ethylene oxide risk factor expressed as Chronic Inhalation.

3. CARB Emissions Data and Inventories

CARB maintains emission inventories and funds emission studies for a variety of pollutant sources in California, including oil and gas operations. The CARB oil and gas emissions inventory quantifies the weight percentage of select pollutants found at oil and gas facilities and links these compounds to specific oil and gas production equipment. Data in this inventory are derived from CARB-funded contracts designed to establish and refine these emissions estimates(CARB., 1978; 1985; 2025a). Data shown here are taken from studies where emissions are estimated using source speciation profiles applied to reported criteria pollutant data. Other data available in the CARB emissions inventory also contains emissions data collected and reported by local air districts across the State. Please refer to the CARB Consolidated List for Speciation Profiles online repository(CARB., 2025b) for additional details on these emission sources.

For the purposes of this document, we focus on available emission inventory source category data applicable to upstream oil and gas facilities, specifically:

- Crude Oil Evaporation (Organic Speciation Profile 297)
- Oil and Gas Production Fugitives – Liquid Service (Organic Speciation Profile 756)
- Oil and Gas Production Fugitives – Gas Service (Organic Speciation Profile 757)
- Oil and Gas Production Fugitives – Unspecified Valves (Organic Speciation Profile 758)

Figure 5 presents speciation information for these four inventory classifications. Methane is the dominant species in oil and gas production fugitive liquid service (37.6%), gas service (61.3%), and unspecified valves (45.8%); however, methane is a small portion (8.8%) in crude oil evaporation. Specifically, benzene represents 2.4% of total emissions from crude oil evaporation and 0.1% of total emissions in the three fugitive emissions categories, with methane-to-benzene ratios ranging from 3.7:1 to 613:1 (Table 3). These values were derived from source emission factors and calculated emission rates. While the original authors noted considerable uncertainty (estimates between 20 to 30%), the relationship between methane and benzene provide a useful comparison metric. Given these findings, any leak detection system intended to correlate methane concentrations with toxic pollutant exposure should account for equipment-specific emissions at each site. A complete list of the speciation profiles referenced above is provided in Appendix 1, which is provided in a Microsoft Excel worksheet.

Produced water is a liquid by-product from some oil and gas production operations. Produced water can contain dissolved solids or dissolved VOCs that make the water unfit for use as drinking water or irrigation(CARB., 2020). This water can be disposed of via the removal of residual oil followed by evaporation in lined pits, called production water ponds, or stored in tanks for further remediation. CARB funded a study in 2016 to investigate the VOC speciation from the evaporation of open produced water ponds(CARB., 2020). This study quantified over 60 NMVOCs (including many TACs), methane, and carbon dioxide in over 100 samples(CARB., 2020). The initial phase of the study screened produced water ponds across California and locations were selected as those close to populations, from different operators, and from different regions of the State. Figure 6 shows the combined speciation results from the U.S. EPA TO-14 method analysis for sampling sites. TACs were found and quantified in all sites, with the ratio of methane to these toxics varying significantly across sample locations (Figure 6).

Figure 5: Select source categories of CARB emission inventory data for upstream oil and gas fugitive emissions.

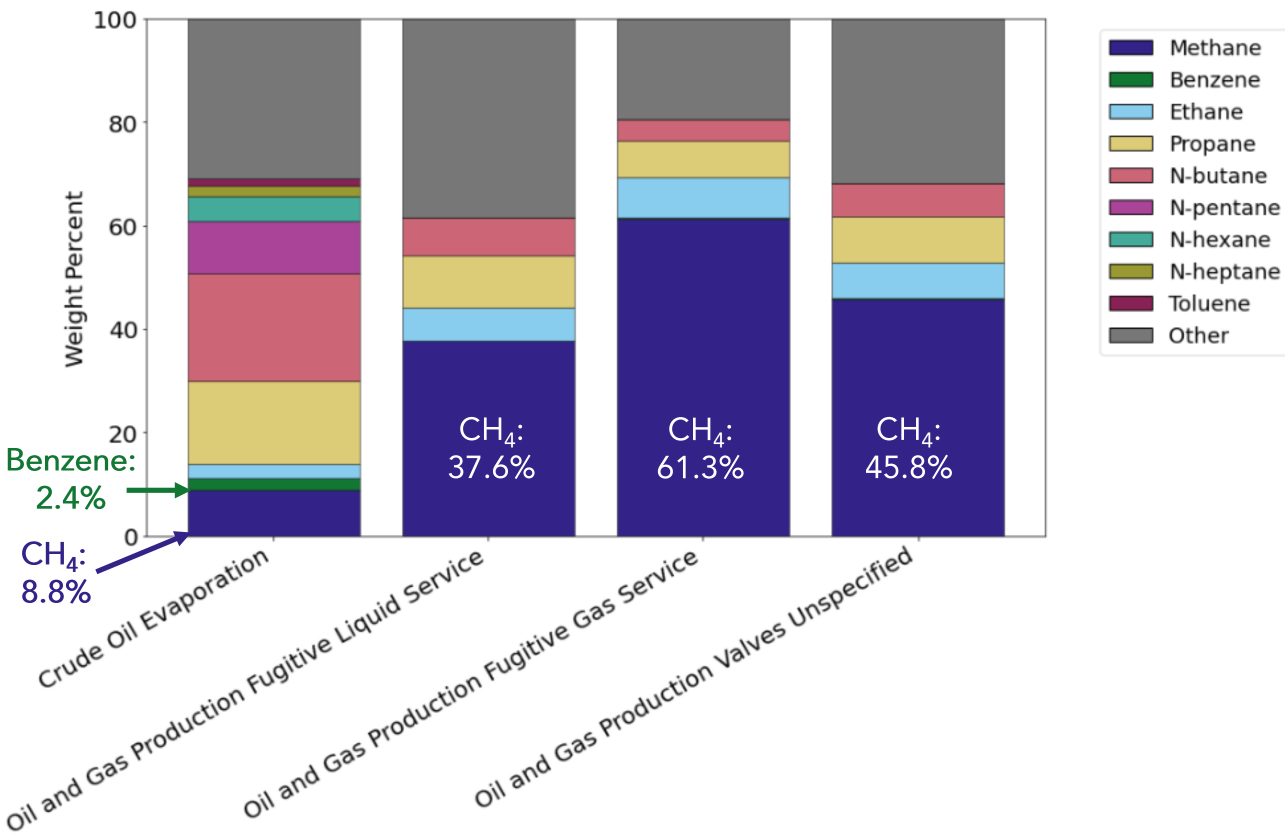
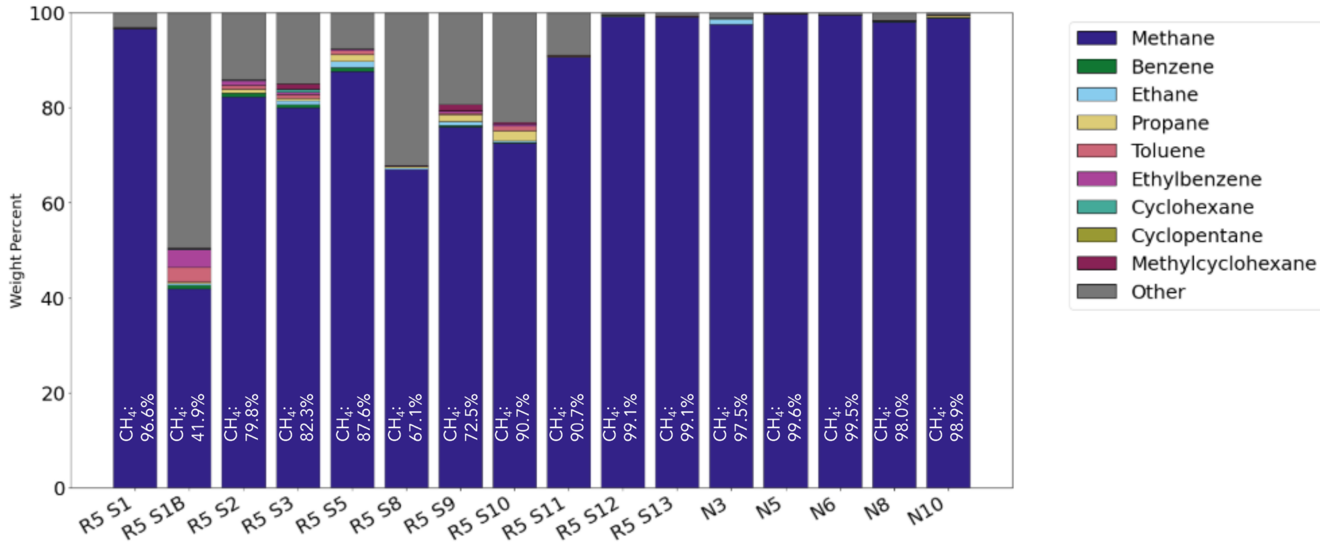


Figure 6: Phase 1 VOC Speciation from CARB Produced Water Evaporation Study.



4. U.S. EPA SPECIATE Database

The U.S. EPA operates and maintains SPECIATE, an online database of organic gas and particulate matter profiles applicable nationwide. This database consolidates emission rates, chemical speciation, and process data into individual emission source profiles for a wide range of sources. As of this writing, the SPECIATE version 5.3 database contains 6,895 unique source profiles of particulate matter and organic gases(USEPA., 2025a; b).

CARB staff used the SPECIATE database access tool to select all "Oil and Gas" source categories under Category Level 2 to evaluate the relationship between methane and NMVOCs from upstream oil and gas emissions. This search returned 180 unique source categories representing 105 distinct organic gaseous pollutants from nationwide sources(USEPA., 2025b). These categories include crude oil and natural gas sources from California, Colorado, Wyoming, Pennsylvania, Montana, North Dakota, and Texas. The database includes emissions data from a broad range of crude oil and natural gas production equipment, including wells, flash gas from condensate and oil tanks, glycol dehydrators, natural gas flares, separators, and vapor recovery equipment. Data obtained from the SPECIATE database is presented in Appendix 2, which is provided in a Microsoft Excel worksheet(USEPA., 2025b).

The dataset was further filtered to include only California-specific source profiles to refine the evaluation of methane as a surrogate for NMVOCs in California oil and gas facilities. This resulted in 21 source profiles containing more than 30 unique NMVOCs, including TACs. California-specific data within these profiles were obtained through a CARB-funded research contract focused on developing speciation profiles for select organic emission sources(Censullo, 1991) and supplemented by several external academic studies(Scheirer, 2007; Lyman, et al., 2018). These datasets represent the most comprehensive summary of California oil and gas production facility emissions currently available, although with limited sample sizes.

For this analysis, we present available California data along with representative figures from other states to illustrate broad NMVOC speciation patterns for crude oil and natural gas production equipment (see Appendix 2). Figures 7 and 8 provide select representative datasets illustrating direct speciation of oil and gas equipment across the United States and California, derived from the SPECIATE database. The SPECIATE dataset contains composite profiles for multiple individual equipment and studies(Lillis and Magoon, 2007; USEPA., 2025a; b; Lillis, et al., 2007). Methane composition varies significantly across different oil and gas field equipment (Table 3) similar to data in the CARB emission inventory. For example, the reported 'Composite Gas Well' in California is reported as 96.3% methane, while a 'Composite Oil Well' is reported as 48.5% methane (Figure 8). These trends hold true in other areas where a Wyoming gas well composition is reported as 51.1% methane, while oil wells in the same Wyoming county reported 41.3% methane (Figure 7). These speciation results may be valuable for estimating emissions at oil and gas production equipment.

These findings align with prior studies and support existing reports indicating that methane is associated with NMVOC emissions at oil and gas production facilities and is a reliable indicator of leaks that include NMVOC emissions. However, methane alone may not be a reliable surrogate in quantitative assessments of NMVOCs or specific TACs, such as benzene, leaving an oil and gas facility due to variability in production equipment speciation (Table 3)(Shonkoff, et al., 2024).

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Table 3: Methane and benzene ratios by oil and gas production source.

Source	Category	Source Code or Speciation Profile	Methane Weight %	Benzene Weight %
US EPA SPECIATE	Composite Profile – Raw Gas, Gas Well, Campbell County, Wyoming	95476	51.1	0.138
US EPA SPECIATE	Composite Profile – Raw Gas, Oil Well, Campbell County, Wyoming	95477	41.3	0.0656
US EPA SPECIATE	Composite Profile – Condensate Tank, Sweetwater County, Wyoming	95496	23.2	0.468
US EPA SPECIATE	Composite Profile – Glycol Dehydrator, Uinta/Piceance Basin	95420/ PNCDH [b]	37.4	6.40
US EPA SPECIATE	Flash Gas Composition from Tanks at Oil Wells – Williston Basin North Dakota	WIL02	5.11	0.148
US EPA SPECIATE	Oil Field - Compressor – Vapor Recovery California	8960	37.7	0.0912
US EPA SPECIATE	Composite Profile – Gas Wells California	95403	96.3	0.0113
US EPA SPECIATE	Composite Profile – Oil Field – Tanks California	95400	48.5	0.231
US EPA SPECIATE	Composite Profile – Oil Field – Separators California	95401	30.7	0.145
US EPA SPECIATE	Composite Profile - Oil and Gas Separators	95405	84.8	0.00879
US EPA SPECIATE	Composite Profile - Gas and Oil Condensate Wells	95408	64.6	0.0456
US EPA SPECIATE	Composite Profile - Oil Field – Wells	95404 / 95399 [b]	52.1	0.183
US EPA SPECIATE	Composite Profile - Oil Field - Vapor Recovery	95402	32.5	0.287
CARB Inventory [a]	Crude Oil Evaporation	297	8.8	2.4
CARB Inventory [a]	Oil and Gas Production Liquid Service	756	37.6	0.1
CARB Inventory [a]	Oil and Gas Production Gas Service	757	61.3	0.1
CARB Inventory [a]	Oil and Gas Production Valves Unspecified	758	45.8	0.1

Table 3 Notes:

[a] All CARB Inventory data is reported to maximum 0.1% resolution(CARB., 2025b).

[b] Methane and benzene values are averages between profiles listed in these cells.

Figure 7: Representative plot of select oil and gas facility equipment from the U.S. EPA SPECIATE Database.

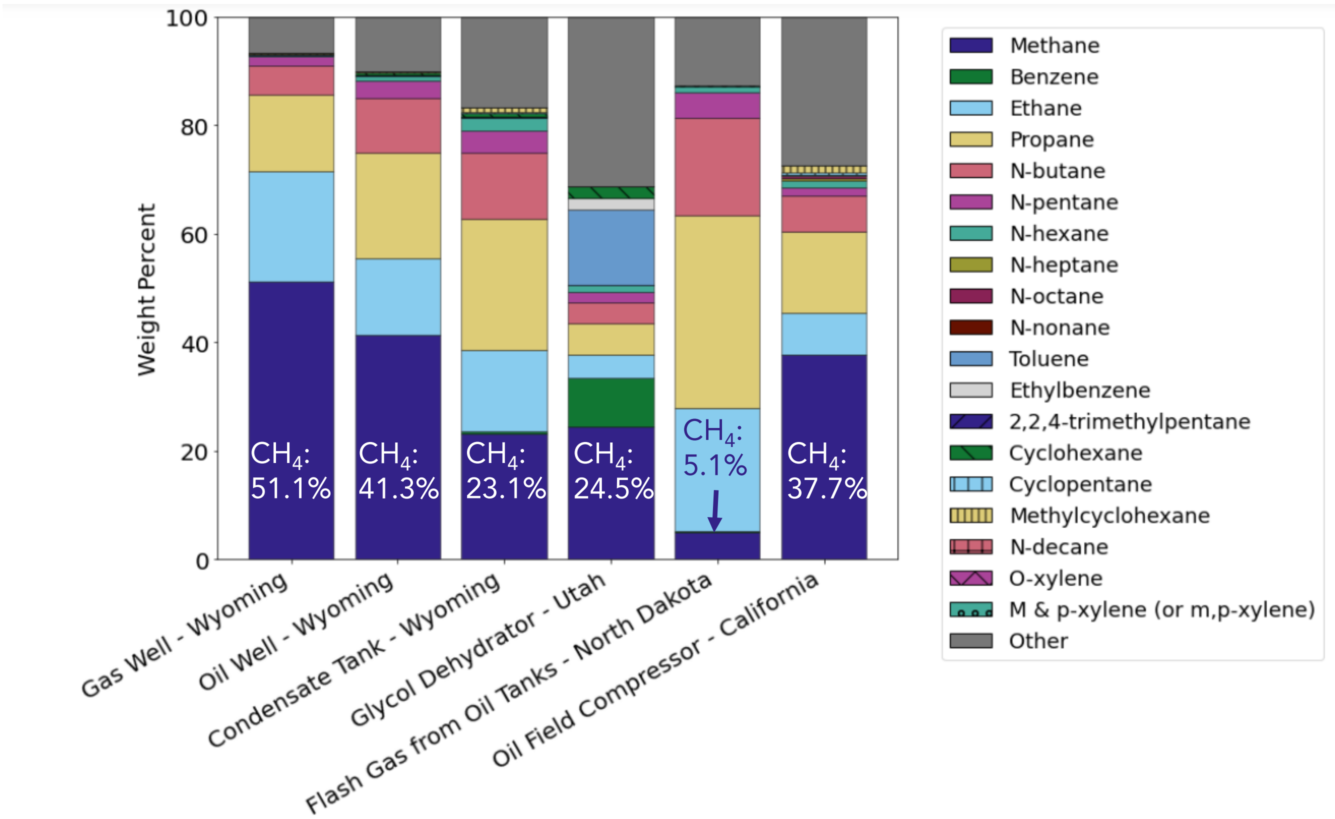

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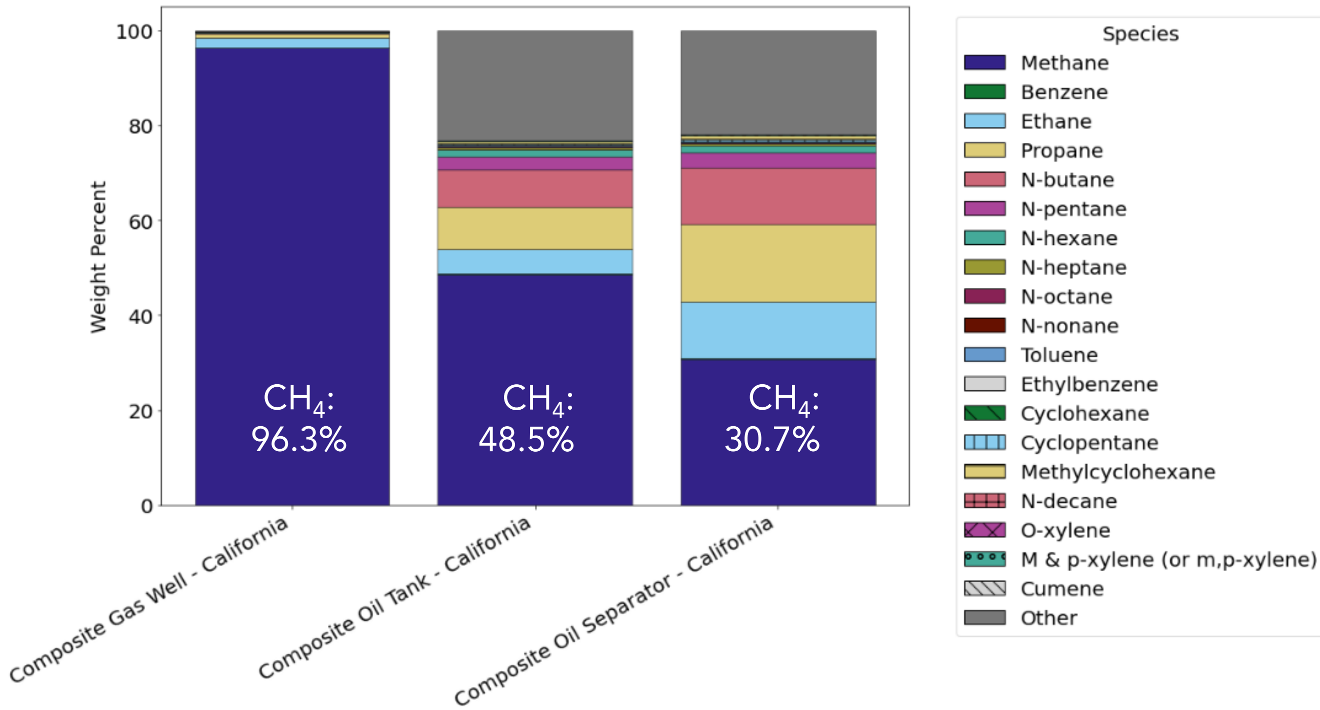
Figure 8: Representative composite California gas wells, oil tanks, and oil separator from the U.S. EPA SPECIATE database.

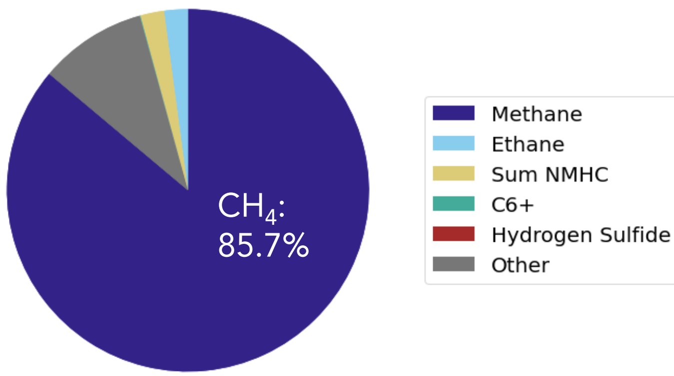


5. United States Geological Survey Database

The United States Geological Survey (USGS) has generated a compositional analysis database for gas wells across the United States, covering operations from 1917 to 2021(Brennan, et al., 2021). This database provides nationwide gas well speciation for broad pollutant classes and smaller hydrocarbons, offering valuable insights into the composition of natural gas emissions.

The dataset includes speciation for C1–C5 alkanes (methane, ethane, propane, butane, and pentanes), alkanes with more than six carbon atoms (C6+), hydrogen sulfide, oxygen, nitrogen, helium, and carbon dioxide(Brennan, et al., 2021). This dataset supports existing findings from the CARB emission inventory and the U.S. EPA SPECIATE database that methane is the dominant component of gas well emissions, even though it does not provide detailed NMVOC speciation. Figure 9 presents the composite average composition of these species for California natural gas wells based on the USGS dataset.

Figure 9: Composite average speciation from gas wells in California from USGS database.



6. Data Uncertainties

Direct compositional analysis from oil and natural gas field production equipment helps to reduce significant uncertainties caused from other sources present in the area not directly related to oil and gas equipment. There are numerous sources outside of oil and gas facilities that emit similar compounds; for example, benzene is emitted from mobile source tailpipe emissions and methane can be released from agricultural operations. These confounding sources can alter methane-to-benzene ratios measured at and near a facility relative to ratios in production processes, making it difficult to attribute emissions directly to oil and gas operations without the collection of sufficient background data and data specific to a facility's equipment. Thus, assuming oil and gas emission composition remains consistent(Rowland, et al., 2025), direct source analysis of VOC composition from oil and gas facility production equipment emissions will reduce uncertainty associated with potential impacts of increased TAC concentrations.

Atmospheric physical and chemical processes can affect the lifetime of TACs and methane in the atmosphere(Monod, et al., 2001; Liu, et al., 2025) and can introduce uncertainty in the use of methane as a surrogate for TACs. Any processes that disproportionately reduce TAC or methane concentrations can lead to uncertainty in health risk estimations. Physical processes such as wind, precipitation, temperature, and relationship to topography can affect dispersion of pollutants over short distances(Liu, et al., 2025). Different dispersion rates can result for pollutants whose density is heavier than air(USEPA., 2018). However, the U.S. EPA has found that under typical conditions most air toxics, including benzene, do not exhibit significant separation based only on molecular weight and simple Gaussian models can describe their behavior(USEPA., 2018). Chemical processes in the atmosphere include direct photodegradation or reactions with other species that result in the destruction of a compound. For example, atmospheric benzene and xylene removal processes are typically dominated by reactions with the hydroxyl radicals(Shonkoff, et al., 2024; Lebel, et al., 2022; Liu, et al., 2025). Xylene lifetimes have been found to be on the range of 10 - 20 hours(Liu, et al., 2025), whereas benzene lifetimes[p] have been found to be 9.5 days(Lebel, et al., 2022; Liu, et al., 2025). Methane does not exhibit significant hydroxyl radical degradation relative to benzene and xylenes, as the reaction rates are approximately 187 times slower(Atkinson and Arey, 2003). These chemical uncertainties will, in most cases, result in small reductions of TACs, and negligible degradation of methane under most atmospheric conditions(Liu, et al., 2025; Atkinson and Arey, 2003) on the applicable time scales for SB 1137 health protection zones unless significant atmospheric stagnation events occur. For example, under calm wind conditions (0.5 meters per second) any pollutant emissions will leave a defined HPZ (3,200 feet in size) in approximately 33 minutes. Under typical atmospheric hydroxyl radical concentration (1×10^6 cm^{-3})(Monod, et al., 2001; Liu, et al., 2025) less than 1% of benzene will have reacted during this time[q].

Further uncertainty arises from the limited number of California-specific studies on oil and gas emission speciation. Recent work characterized the uncertainty associated with methane-to-toxic ratios at oil fields across the United States; however, there was insufficient data for oil and gas facilities in California(Rowland, et al., 2025). Additionally, some of the studies referenced in the CARB emission inventory and the U.S. EPA SPECIATE database are over 30 years old and may have data uncertainties associated with less sensitive analysis methods, (e.g., lower method detection limits and expanded analyte lists) or not sampling from modern oil and gas operations (e.g., equipment equipped with vapor recovery systems)(Censullo, 1991; CARB., 1978; 1985).

The public availability of recent direct compositional data for TACs from upstream oil and gas operations is limited, particularly for California facilities. Historically, conducting these studies is logistically and financially challenging, as direct sampling from oil and gas equipment requires specialized access to facilities and resources(Shonkoff, et al., 2024; CARB., 2024c). Specifically, this sampling requires access to production equipment on a wide array of oil and gas facilities as well as access to analytical laboratories for testing. These challenges can be reduced through direct sampling done directly through operator agreements that would allow researchers or contractors site access, improved sampling methods(DiGiulio, et al., 2023), and lower costs when large numbers of samples are collected.

CARB is funding a research contract to better characterize emissions from California oil and gas facilities to help address these data uncertainties. CARB has selected a qualified contractor to collect and speciate gaseous samples directly from active upstream oil and gas wells and production equipment. This contractor will use established sampling and

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[p] Lifetimes were calculated following pseudo first-order kinetics with benzene rate constant of 1.2×10^{-12} cm^3 mol^{-1} s^{-1} and hydroxyl radical concentration of 1×10^6 cm^{-3} as defined in Monod et al. 2001.

[q] Using benzene rate constant of 1.2×10^{-12} cm^3 mol^{-1} s^{-1} from Atkinson and Arey, 2003.

testing methods to characterize emissions of methane, NMVOCs, hydrogen sulfide, and TACs from different equipment at various facilities across the state. The goal of this study is to improve understanding of how speciation profiles for oil and gas emissions vary within and between facilities, specifically focus on the variation in the ratios between methane and air toxics. Emission composition can vary significantly by region, facility, and equipment, and this new information will supplement methane monitoring, which would result in more representative health impact assessments for NMVOCs and TACs from fugitive emissions. The results of this study will not be included in the current rulemaking process due to statutory timelines. Results will be made public by CARB and will be considered in future rulemaking.

7. Identification of Air Toxics of Highest Concern

The U.S. EPA SPECIATE oil and gas emissions inventory lists over 100 unique gaseous pollutants (Section IV.C.4). Within the upstream categories analyzed (Table 3), 50 distinct non-methane volatile organic compounds (NMVOCs) were identified (Appendix 2)(USEPA., 2025b). These compounds represent detection targets for emissions detection systems. Under SB 1137, CARB and local air districts must identify air toxics of highest concern as primary targets for monitoring[r]. This section focuses on toxics identified through direct speciation of oil and gas production equipment.

Section IV.C.1 summarizes ambient air monitoring studies near oil and gas production facilities and highlights associated air toxics (Table 2). These data often include pollutants from multiple sources (e.g., diesel combustion), and while informative for assessing regional air quality and health risks in an air basin containing oil and gas facilities, it is difficult to attribute ambient concentrations directly to production equipment or process leaks(Shonkoff, et al., 2024). Therefore, the identification of priority toxics should focus on those that can be directly emitted from oil and gas equipment through leaks.

California specific direct emission speciation inventories were cross-referenced with U.S. EPA HAPs[s] and California TACs[t]. Inventories from outside California contain additional potential toxics; however, due to the unique nature of California oil and gas productions, these are not considered here (Section IV.B for more information). However, CARB staff do recommend that any future speciation measurements screen all potential toxics (Section IV.C.6). The analysis in this report focuses on acute (1-hour) risks due to the transient, or short-lived, nature of leaks. Although many toxics have chronic and cancer risk factors per

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[r] Senate Bill 1137 (Gonzalez, Stats. of 2022, Ch. 365; adding Public Resources Code Article 4.6 (commencing with Section 3280 to Chapter 1 of Division 3)). Legislative Counsel's Digest. Approved by the Governor: September 16, 2022. Filed with the Secretary of State: September 16, 2022. Published by the California Legislative Information: September 19, 2022. Accessed: January 22, 2025.

[s] More information can be found on the U.S. Environmental Protection Agency Hazardous Air Pollutants.

[t] See CARB's TAC identification reports for descriptions and summaries of each listed substance.

OEHHA, these values are better utilized for longer-term exposure analysis. Risk factors at 1-hour best represent the potential health risks in these scenarios and accounting for shorter time interval risks should in-turn help reduce health risks associated with longer exposure – chronic and cancer risks(Maji, et al., 2023; Busch, et al., 2024; Kloog, et al., 2013).

50 compounds were identified during California based speciation measurements(USEPA., 2025a; b) and 8 are classified as acute TACs (Table 4). These compounds were benzene, n-hexane, ethylbenzene, cumene, xylenes (all isomers), and toluene (Table 4). In this analysis, cumene was identified as present near oil and gas operations (Table 2) and in direct speciation measurements, but there is no current acute REL defined by OEHHA. Thus, cumene is not included in this risk factor analysis. There is no current acute REL defined by OEHHA for ethylbenzene; therefore, ethylbenzene is only considered in the chronic and cancer analysis in the following calculations. These calculations are based on the CAPCOA Facility Prioritization Guidelines for California Assembly Bill AB 2588 (AB 2588) assuming no specific sensitive receptor or source location[u].

$$RF(acute) = \frac{Species\ Mass\ Percentage\ (\%)}{Inhalation\ Reference\ Expsoure\ Level\ (\mu g\ m^{-3})} \qquad [1]$$

Where RF (acute or chronic) is the species-specific risk factor, the pollutant mass percentage is the measured mass percentage of each pollutant from U.S. EPA SPECIATE database, and the Inhalation Reference Exposure Level is the OEHHA determined inhalation risk factor for acute or chronic exposure[v].

$$RF\ (cancer) = \ Pollutant\ Mass\ Percentage\ (\%)\ \times Chronic\ Inhalation\ Factor\ (\frac{1}{\mu g\ m^{-3}}) \qquad [2]$$

Where RF (cancer) is the species-specific risk factor, the pollutant weight percentage is the measured weight percentage of each pollutant from U.S. EPA SPECIATE database, and the inhalation Reference Exposure Level is the OEHHA determined inhalation risk factor for acute or chronic exposure.

$$Weighted\ Risk\ Contribution\ (\%) = \frac{RF}{\sum All\ Species\ RF} \times 100\% \qquad [3]$$

CARB staff found that benzene contributes over 90% of the acute, cancer, and chronic risk across all equipment types and locations (Figure 10 and Table 5). Ethylbenzene, n-hexane, toluene, and xylenes contributed to the remaining risk (Figure 10 and Table 5). These results

[u] See CARB's "Hot Spots."

[v] Reference Exposure Level values from Office of Environmental Health Hazard Assessment (OEHHA).

correlate with databases from United States oil and gas facilities outside of California(Rowland, et al., 2025). Thus, based on the available speciation profiles and production equipment inventory information, CARB staff conclude benzene is the toxic of greatest concern for potential fugitive emissions across California oil and gas equipment.

Table 4: Toxics Identified in Available Source Profiles.

Species [a]	TAC?	Measurement Source [b]
Benzene	Yes	U.S. EPA/CARB
N-hexane	Yes	U.S. EPA/CARB
Ethylbenzene	Yes	U.S. EPA
M-xylene	Yes	U.S. EPA
O-xylene	Yes	U.S. EPA
P-xylene	Yes	U.S. EPA
Toluene	Yes	U.S. EPA/CARB

[a] Species shown here are unique pollutants identified from California based speciation measurements.

[b] Sources are U.S. EPA SPECIATE database(USEPA., 2025a; b) and CARB Emission Inventory(CARB., 2025a; b).

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Figure 10: Representative weighted fraction of health risks from California oil and gas production facility equipment from the U.S. EPA SPECIATE Database.

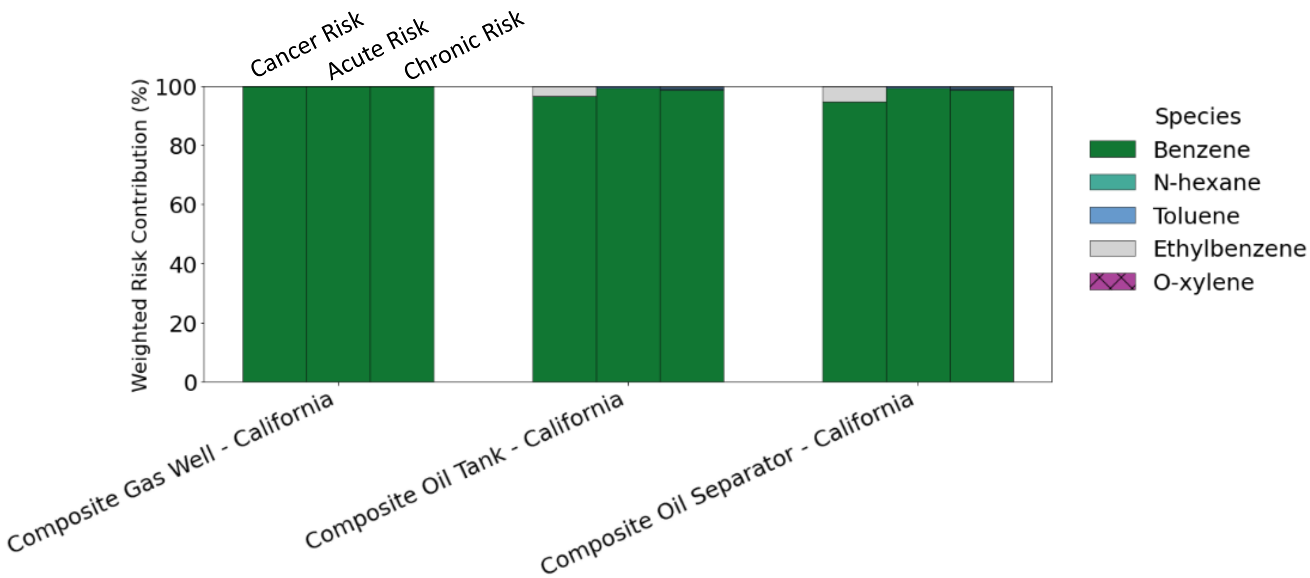

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Table 5: Summary of weighted health risks from U.S. EPA SPECIATE database of California oil and gas equipment. [a]

(Table 5 data is visualized in Figure 10)

Source	Risk Category	Benzene	n-hexane	Toluene	Ethylbenzene	o-xylene
Composite Gas Well California	Cancer	100.0%	0.0%	N/A	N/A	N/A
Composite Gas Well California	Acute	100.0%	0.0%	N/A	N/A	N/A
Composite Gas Well California	Chronic	99.9%	0.1%	N/A	N/A	N/A
Composite Oil Separator California	Cancer	96.5%	N/A	0.0%	3.5%	0.0%
Composite Oil Separator California	Acute	99.4%	N/A	0.5%	N/A	0.0%
Composite Oil Separator California	Chronic	98.7%	0.4%	0.7%	N/A	N/A
Composite Oil Tank California – Cancer	Cancer	94.7%	N/A	0.0%	5.3%	N/A
Composite Oil Tank California	Acute	99.4%	N/A	0.5%	N/A	0.0%
Composite Oil Tank California	Chronic	98.7%	0.2%	0.6%	N/A	N/A

Table 5 Notes:

[a] Sources are U.S. EPA SPECIATE database(USEPA., 2025a; b) and CARB Emission Inventory (CARB., 2025a).

V. Conclusions and Recommendations for Using Methane as a Surrogate for Leaks and Toxic Compound Exposure

NMVOC and TAC emissions from upstream oil and gas operations are often accompanied by methane emissions. This association suggests that methane monitoring could serve as a proxy for detecting other harmful emissions in certain contexts(Schade and Heienickle, 2023; Hecobian, et al., 2019; Rich and Orimoloye, 2016; Halliday, et al., 2016; Censullo, 1991; Marrero, et al., 2016; Rella, et al., 2015; Perry, 2016).

Methane is a useful marker for fugitive (leak-based) emissions (Figures 8 and 9) as methane was found to be emitted to some degree from all operational equipment evaluated in this literature review.

The implementation of rapid methane leak detection and control measures would also control TAC emissions associated with methane emissions in specific situations. However, the use of methane as a surrogate for toxic compounds cannot be applied uniformly and requires further emission compositional analysis. This is because the composition of NMVOCs and their ratios with methane vary significantly between natural gas and crude oil production facilities within an oil field, as well as between individual pieces of equipment at the same facility. Setting a fixed methane concentration threshold for fugitive emissions may fail to identify impacts to the communities and direct TAC measurements may be necessary in cases where methane constitutes only a small fraction of total VOC emissions. Overall, while methane concentration or emission can be a useful indicator of leaks, methane alone may not be directly related to toxic air contaminants due to variable emission ratios.

CARB staff recommend that continuously operating emission detection systems that target methane as a surrogate for other compounds, like benzene, be supplemented with for direct speciation data of VOCs and TACs from process equipment within a facility. These speciation data are necessary to support fugitive emissions modeling at each production facility. The establishment of site-specific TAC speciation profiles is necessary to bridge the gap between using methane as a proxy for leak detection and using it as a surrogate for TACs during leak events at a production facility. Existing speciation data suggest that benzene is the pollutant driving health risks; however, these data are limited in scope and additional toxics may be present. Thus, future facility-specific composition analysis should identify other toxics that may be a concern with respect to potential health impacts. Analysis methods can include U.S. EPA Methods TO-15A and TO-13 for VOCs[w], as well as ASTM methods D5504 and D1946/2650 for sulfur compounds and methane, respectively[x]. Once speciation profiles for a facility's production equipment are established, methane concentrations can be used to estimate impacts for nearby sensitive receptors within and around the health-protection zone.

CARB staff will provide companion reports that evaluate options for performance standards for emissions detection systems and species composition sampling that build on these conclusions and recommendations. These reports will be available at CARB's webpage: Senate Bill 1137: Meetings, Workshops, Technical Reports, and Draft Rulemaking Documents[y].

VI. References

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VII. Appendices

Appendices are available in separate Microsoft Excel files.

Appendix 1: Source profiles for oil and gas emissions downloaded from the CARB speciation profiles used in CARB modeling (November 19, 2024).

Appendix 2: All source category and emission profiles for 'Oil and Gas' downloaded from the U.S. EPA SPECIATE database (February 19, 2025).