March 6, 2023

EPA-SAB-23-005

The Honorable Michael S. Regan
Administrator
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, N.W.
Washington, D.C. 20460

Subject: Science Advisory Board Report on the Scientific and Technical Basis of the Proposed Rule Titled "Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review" RIN: 2060-AV16

Dear Administrator Regan,

The Science Advisory Board (SAB) is submitting the attached report on the scientific and technical basis of the proposed rule titled "Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review" RIN: 2060-AV16, published in the Federal Register on November 15, 2021. The Agency subsequently published a supplemental proposal on December 6, 2022. The SAB reviewed the proposed revisions to regulations implementing the Clean Air Act section 111 to be included in 40 CFR Part 60 subparts 0000b and 0000c.

The Environmental Protection Agency (EPA) has proposed a rule intended to reduce air pollution from the domestic oil and gas industry. The proposed rule would reduce the emission of greenhouse gases, in particular methane, with additional benefits expected via reduction of emitted volatile organic compounds, other co-emitted pollutants and secondarily formed air pollution such as tropospheric ozone.

In conducting this review, the SAB followed the engagement process for review of science supporting EPA decisions outlined in the memo of February 28, 2022, signed by the Associate Administrator in the Office of Policy, the Deputy Assistant Administrator for Science Policy in the Office of Research and Development, and the Director of the Science Advisory Board Staff Office.

The SAB met by video conference on May 31, 2022, and June 2, 2022, and elected to review the scientific and technical basis of the proposed rule. The SAB discussed providing advice on the proposed rule and future regulatory actions the Agency would consider. The SAB's Science Supporting Decisions workgroup received the supplemental rule material on August 26, 2022, to consider with the rule material. A subset of SAB members was assembled to review the proposed rule and supplemental material. This group of SAB members developed and responded to charge questions on several topics of interest in the proposed rule including a new super-emitter source category, the use of advanced measurement technologies, the scope of the rule, emissions reporting, costs, benefits, and environmental justice considerations and submitted a report to the full SAB. The full SAB discussed and approved the report with revisions in a public meeting held on January 20, 2023. Revisions were incorporated into the final report. The SAB's advice and comments on the science supporting the proposed rule are provided in the enclosed regulatory review report.

The SAB commends the Agency on this significant action and recognizes the innovative nature of provisions including the program for detection and response to large emission events (super-emitters), the advanced measurement certification program, and methods for promoting scientific engagement of communities. The Board supports the innovative approaches proposed by the Agency, as described in the attached report, but recognizes that these innovative strategies can and should evolve over time. Therefore, the Board recommends that the Agency continue to receive scientific advice from a diverse group of outside experts on issues including the super-emitter program, the advanced measurement certification program, the inclusion of data from diverse sources, capacity building, and the integration of the rule with other methane emission efforts within the Agency. The SAB is available to support and will continue to monitor these activities through its climate science committee.

The SAB appreciates the opportunity to provide comments on the science supporting the proposed rule. We look forward to receiving the Agency's response.

Sincerely,

/s/

Alison C. Cullen, Sc.D.
Chair
EPA Science Advisory Board

Enclosure

NOTICE

This report has been written as part of the activities of the EPA Science Advisory Board, a public advisory committee providing extramural scientific information and advice to the Administrator and other officials of the Environmental Protection Agency. The Board is structured to provide balanced, expert assessment of scientific matters related to problems facing the Agency. This report has not been reviewed for approval by the Agency and, hence, the contents of this report do not represent the views and policies of the Environmental Protection Agency, nor of other agencies in the Executive Branch of the Federal government, nor does mention of trade names or commercial products constitute a recommendation for use. Reports of the EPA Science Advisory Board are posted on the EPA website at https://sab.epa.gov.

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Science Advisory Board Review of the Scientific and Technical Basis of the Proposed Rule: Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review RIN: 2060-AV16

TABLE OF CONTENTS

ACRONYMS AND ABBREVIATIONS

AMEL	alternate means of emissions limitation
ANSI	American National Standards Institute
APA	Administrative Procedures Act
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
AVO	audio, visual, and olfactory
AWP	alternative work practice
BMP	best management practices
boe	barrels of oil equivalents
BSER	best system of emission reduction
Btu/scf	British thermal unit per standard cubic foot
°C	degrees Centigrade
CAA	Clean Air Act
CBI	Confidential Business Information
CCR	Code of Colorado Regulations
CDX	EPA's Central Data Exchange
CEDRI	Compliance and Emissions Data Reporting Interface
CFR	Code of Federal Regulations
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
CO_2 Eq.	carbon dioxide equivalent
CRA	Congressional Review Act
CVS	closed vent systems
CWA	Clean Water Act
D.C. Circuit	U.S. Court of Appeals for the District of Columbia Circuit
DOE	Department of Energy
EAV	equivalent annual value
EDF	Environmental Defense Fund
EG	emission guidelines
EIA	U.S. Energy Information Administration
EJ	environmental justice
EO	Executive Order
EPA	Environmental Protection Agency
ESD	emergency shutdown devices
°F	degrees Fahrenheit
FEAST	Fugitive Emissions Abatement Simulation Toolkit
FRFA	final regulatory flexibility analysis
g/hr	grams per hour
GHG	greenhouse gas
GHGI	Inventory of U.S. Greenhouse Gas Emissions and Sinks
GHGRP	Greenhouse Gas Reporting Program
GOSAT	Greenhouse Gases Observing Satellite
HAP	hazardous air pollutant(s)

ICR	information collection request
IRFA	initial regulatory flexibility analysis
IWG	Interagency Working Group on the Social Cost of Greenhouse Gases
kg	kilograms
low-e	low emission
LDAR	leak detection and repair
Mcf	thousand cubic feet
Mcfd	thousand cubic feet per day
MCM	thousand cubic meter (1MCM = 35.3Mcf)
MERP	Model Emission Rates for Precursors
METEC	Methane Emissions Technology Evaluation Center
MW	megawatt
NAAQS	National Ambient Air Quality Standards
NAICS	North American Industry Classification System
NDE	no detectable emissions
NESHAP	National Emissions Standards for Hazardous Air Pollutants
NGO	non-governmental organization
NHV	net heating value
NOx	nitrogen oxides
NSPS	new source performance standards
NTTAA	National Technology Transfer and Advancement Act
OAQPS	Office of Air Quality Planning and Standards
OGI	optical gas imaging
OMB	Office of Management and Budget
$PM_{2.5}$	particulate matter with a diameter of 2.5 micrometers or less
ppm	parts per million
PRA	Paperwork Reduction Act
PTE	potential to emit
PV	present value
REC	reduced emissions completion
RFA	Regulatory Flexibility Act
RIA	regulatory impact analysis
RULOF	remaining useful life and other factors
SBAR	Small Business Advocacy Review
SC-CH_4	social cost of methane
SC-GHG	social cost of greenhouse gases
scf	standard cubic feet
scfh	standard cubic feet per hour
scfm	standard cubic feet per minute
SIP	state implementation plan
SO_2	sulfur dioxide
SPeCS	State Planning Electronic Collaborative System
tpy	tons per year
the court	U.S. Court of Appeals for the District of Columbia Circuit
TAR	Tribal Authority Rule
TIP	tribal implementation plan
TROPOMI	TROPOspheric Monitoring Instrument
TSD	technical support document
UMRA	Unfunded Mandates Reform Act

U.S.	United States
VCS	Voluntary Consensus Standards
VOC	volatile organic compounds
VRU	vapor recovery unit

PREAMBLE

The Science Advisory Board (SAB) reviewed the proposed rule and supplemental rule text, regulatory support documents, and regulatory agenda information for the EPA's proposed rule, **Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review** RIN: 2060-AV16 (the "Oil and Gas Rule" for purposes of this document). These proposals were published in the *Federal Register* on November 15, 2021, and December 6, 2022.

The SAB commends EPA on this significant action and recognizes the innovative nature of several provisions. The proposed rule would take direct action to reduce greenhouse gas emissions and contribute to significant attempts to meet U.S. pledges for international agreements addressing Global Climate Change.

The SAB supports the innovative approaches proposed by the Agency and is making multiple recommendations on this proposed rule and recommends revisiting the rule requirements periodically and methodically as new science and technology emerge. In particular, the SAB recommends EPA engage with multiple stakeholders with expertise in the rapidly evolving science and technology that supports the proposed rule.

The SAB looks forward to continuing as a constructive partner in the Agency's efforts to discern and apply the best science in a transparent manner inclusive of all stakeholders for implementing the law to protect human health and the environment.

1. INTRODUCTION

As part of its statutory duties, the EPA Science Advisory Board (SAB) may provide advice and comments on the scientific and technical basis of planned EPA actions pursuant to the Environmental Research, Development, and Demonstration Authorization Act of 1978 (ERDDAA). ERDDAA requires the EPA to make available to the SAB proposed criteria documents, standards, limitations, or regulations, together with the relevant scientific and technical information on which the proposed action is based. Based on this information, the SAB may provide advice and comments. Thus, the SAB has reviewed the scientific and technical basis of the proposed rule titled **Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review** RIN: 2060-AV16 (86 FR 63110) and the supplemental proposal for this rule (87 FR 74702).

EPA proposed the rule to establish comprehensive New Source Performance Standards (NSPS) for methane and volatile organic compounds (VOC) emissions from the exploration and production, transmission, processing, and storage segments of the domestic crude oil and natural gas industry and establish Emissions Guidelines (EG) for existing sources of methane emissions from the same industry segments. In the supplemental rule material, in response to public comments, EPA proposes to reduce emissions from the source category more comprehensively by adding proposed standards for certain sources that were not addressed in the November 2021 proposal, revising the proposed requirements for fugitive emissions monitoring and repair, and establishing a super-emitter response program. The EPA also is proposing revisions to the alternative standards for fugitive emissions monitoring and repair. EPA's proposal is aiming to encourage the deployment of innovative technologies and techniques for detecting and reducing methane emissions and provide additional options and incentives for the use of advanced and emerging monitoring technologies, techniques and analysis.

The SAB met by video conference on May 31, 2022, and June 2, 2022, and elected to review the scientific and technical basis of the proposed rule. The SAB discussed providing advice on the proposed rule and future regulatory actions the agency would consider. A workgroup of the SAB took the lead in reviewing the proposed rule and considering topics of interest raised by the SAB including the new super-emitter source category, the use of advanced measurement technologies, the scope of the rule, emissions reporting, costs, benefits, and environmental justice considerations. The workgroup's draft report on the proposed rule was discussed by the full SAB at a virtual public meeting held on January 20, 2023 and approved with revisions.

In conducting this review, the SAB followed the engagement process for review of science supporting EPA decisions outlined in the February 28, 2022, memo, signed by the Associate Administrator in the Office of Policy, the Deputy Assistant Administrator for Science Policy in the Office of Research and Development, and the Director of the Science Advisory Board Staff Office. All materials and comments related to this document are available at: https://sab.epa.gov.

2. SAB ADVICE AND COMMENTS ON THE PROPOSED RULE

2.1 Super Emitter Category Designation.

2.1.1 Charge Question 1: Comment on the definition of a separate emission category of "super-emitters," using a threshold of a detected methane emission rate of 100 kg/hr. Is treatment of a separate super emitter category likely to result in a significant climate benefit, and is the choice of 100 kg/hr a reasonable threshold for identifying super emitters?

Methane emissions from the oil and natural gas sectors frequently include sources with high emission rates. These super-emitting sources represent only a small fraction of oil and natural gas sector sources, but they can constitute a much larger, though varying, proportion of emissions from oil and gas production regions and facilities. To address these emission sources, the EPA is proposing to define a "super-emitter emissions event as quantified emissions of 100 kg/hr or greater of methane" (87 FR 74747).

Super-emitter emission events are characterized by both continuous and intermittent methane emissions and result from a wide variety of causes, including routine operating conditions, abnormal operating conditions, and malfunctions (Zavala-Araiza et al., 2017). Super-emitters have been found both at onshore (Robertson et al., 2020) and offshore facilities (Gorchov et al., 2020; Chen et al., 2022) and across all segments of the oil and gas supply chain (Robertson et al., 2020; Weller et al., 2020; National Academy of Sciences, Engineering and Medicine, 2018).

Super-emitter frequencies and magnitudes have been difficult to quantify because commonly used statistical distributions of emissions consistently under-estimate the contribution of super-emitters to total emissions from a region (Brandt et al., 2016). Using a probabilistic method that combined process modeling with measured data, Omara et al. (2018) simulated natural gas emissions from individual sites and found that a small fraction (less than 5%) of natural gas sites producing less than 390 thousand cubic feet per day (Mcfd) would emit above 100 kilograms per hour (kg/hr), and that 0-10% of sites producing more than 390 Mcfd would emit at a rate of more than 100 kg/hr. These estimates vary widely by production basin. For example, for three different oil and gas production basins, all in the State of Texas, super-emitter contributions to total emissions range from negligible to a large fraction of total emissions. In measurements at production sites in the dry gas production region in East Texas, Tullos et al. (2021) found no sources with emission rates >100 kg/hr. For the Barnett Shale region in north-central Texas, Zavala-Araiza et al. (2017) found that 20% of emissions were from sites with emission rates above 100 kg/hr, and that this percentage was much greater than that estimated from a process-based model alone. In the Permian Basin of west Texas, multiple studies have found higher fractions of emissions accounted for by super-emitters. Stokes et al. (2022) found that at tank battery sites in the Permian Basin 30-50% of emissions were due to sources with emission rates greater than 100 kg/hr, rates that were much greater than emissions estimated from process models. Examining a much larger number of sites in the same basin, Cusworth et al. (2021) reported high emission rates at more than 1000 sites. Many of these sites had emission rates greater than 100 kg/h, with some emission rates as high as 5000 kg/h. Collectively, these events represented a third to half of the total emissions in the Permian Basin, taking the total emissions as those measured by satellite (Zhang, et al., 2020).

Justification for defining a super-emitter as a source with an observed, instantaneous emission rate that is greater than 100 kg/hr does not appear in the Supplemental Proposal, however, the Preamble to the Supplemental Proposal described two principles that guide this threshold definition: identification of the largest, most harmful emission events; and a release rate that is not expected and therefore likely to be unintentional. The proposed boundary of 100 kg/hr captures only the highest category of emission events or sites and is high enough that a detected event will lie above almost all expected routine emissions, even when measurement uncertainties are included, once the other proposed emission reduction measures are implemented.

Defining a super-emission event as a measurement of an emission rate greater than 100 kg/hr would have little effect on the smallest production facilities, based on observations reported by Omara, et al. (2018), which found that sites with gas production less than 200 Mcfd had not been observed to emit more than 100 kg/hr. While these sites may have a greater fraction of the gas product escape as emissions, compared with larger sites, in general the baseline production is too low for releases to reach the super-emitter threshold. The SAB supports the use of an absolute emission rate, not the relative fraction of product emitted, in the super-emitter definition.

The SAB concludes that using a rate-based definition of a super-emitter is appropriate and that the super-emitter threshold of 100 kg/hr is a reasonable boundary that captures the largest events that constitute an important source of emissions in many regions. An instantaneous, rate-based threshold is appropriate, rather than a threshold based on total mass emitted by an event, since many emission measurement technologies are short duration measurements and might not capture an entire emission event. The rate-based threshold of 100 kg/hr will lead to a varying level of super-emitter detections across regions, however, these large release events are an important national-scale source of methane emissions and warrant special attention. Despite the uncertainties in super-emitter frequencies, magnitudes and spatial distributions, there is extensive evidence (National Academies of Science, Engineering and Medicine, 2018) that super-emitters contribute significantly to methane emissions and that addressing them is integral to a methane emission reduction strategy. As an initial attempt to introduce a regulation of poorly characterized and intermittent sources, the SAB finds EPA's careful approach to be warranted.

The EPA should revisit the super-emitter threshold periodically. As routine operations that result in short-duration high emission rate events are reduced or eliminated as a result of other provisions in the proposed rule, it is expected that super-emitters will be due almost exclusively to malfunctions or unintended operations. This shift, as well as rapidly improving detection technology, can be expected to make it possible to lower the super-emitter threshold over time.

The SAB supports the designation of a super-emitting source category at the threshold proposed by the Agency and recommends periodically re-evaluating the threshold.

> *2.1.2 Charge Question 2: Comment on the super-emitter response program. What challenges are likely to arise in detection of emissions at the 100kg/hr rate using emerging measurement technologies?*

The EPA is proposing a super-emitter response program that "would allow the use of reliable and demonstrated remote sensing technology deployed by experienced, certified entities or regulatory authorities to find these large emissions sources" (87 FR 74747). The EPA is proposing "a pathway by which an EPA-approved entity or regulatory authority may provide credible, well-documented identification of a super-emitter emissions event using one of several permitted technologies and approaches, and then notify the responsible owner or operator. Once notified of the event, owners and operators would be required to perform a root-cause analysis and take corrective actions to address the emissions source at their individual well sites, centralized production facilities, and compressor stations" (87 FR 74747).

Establishing action levels and required responses to detection of super-emitter events will enable powerful emerging technologies to be used in identifying and possibly mitigating large methane emission sources, however, establishing action levels will be challenging. One of the challenges will be the variable precision and accuracy of emerging emission rate measurements. Another challenge will be the duration of super-emission events. A growing body of evidence (Stokes et al., 2022; Cusworth et al., 2021; Wang et al., 2022) indicates that a large fraction of the super-emission events may be less than a few days in duration, and consequently response times of more than a few days may make determining the root causes of many events difficult.

2.1.2.1 Precision and accuracy of emission rate measurements

Most technologies currently employed in estimating methane emissions rely on some level of modeling (plume dynamics, inversions, spectral absorptions to concentrations) to convert a measurement of atmospheric concentrations or spectral properties of a column of air to emission rates. For example, some measurements determine optical path concentrations of methane and then use local wind speeds to estimate emission rates. Other measurements use point measurements of methane concentrations and meteorological data to estimate emissions. Similarly, some sensing systems that are able to visualize and quantify concentrations in an entire plume need to make assumptions about the structure and meteorological conditions in the plume to estimate emissions.

A variety of testing approaches for methane emission quantification technologies exist. Some of the tests have involved assessing responses to controlled releases, either as point releases (Sherwan et al., 2022; Johnson, et al., 2021; Crosson, et al., 2017; Corbett, et al., 2022) or as releases from full scale mock-ups of oil and gas facilities at a Methane Emission Technology Evaluation Center (METEC)[1], established by the Department of Energy at Colorado State University. Other tests have involved controlled releases or technology intercomparisons at operating facilities (Tullos et al., 2021; Stokes et al., 2022), sometimes with controlled releases that are added to routine facility emissions. The general findings emerging from this testing are that individual uncertainties in emission estimates can be as high as a factor of two or more, although multiple repeat measurements decrease uncertainties (Karion et al., 2015). The uncertainty can often be attributed to the models and assumptions used in converting an atmospheric measurement of methane to emission rate measurements, but spatio-temporal variation is also a key factor.

Many of the testing approaches for emission quantification technologies routinely operate at emission rates that are less than the 100 kg/hr super-emitter emission threshold. Satellite based measurements are a rapidly expanding set of technologies for systematic monitoring of super emitters, with a large spatial coverage and frequent repeat measurements. However, limited testing approaches exist at emission rates that are above the proposed super-emitter threshold and that are currently detectable by satellites. Because satellites measurements are evolving rapidly

[1] https://energy.colostate.edu/metec/

and because their use in routine regulatory monitoring has been limited, they will pose new scientific and technical challenges for the EPA in implementing the proposed rule. A review of satellite missions with potential for methane monitoring is provided in Jacob et al. (2022). Methane satellites can be grouped as area flux mappers and point source imagers. This classification responds mostly to trade-offs in spatio-temporal sampling and retrieval precision.

Area flux mappers provide accurate measurements globally with a spatial resolution of several kilometers. These missions are typically used to quantify methane emissions on regional to global scales. The European Sentinel-5P/TROPOspheric Monitoring Instrument (**TROPOMI**) mission (~5.5 x 7 km^2 pixel size, daily global coverage) is the main representative of this category, especially because of its continuous global coverage and high data rate. The satellites from the Greenhouse Gases Observing Satellite (GOSAT) family (GOSAT, GOSAT-2 and GOSAT-Gasses and Water Cycle (GW)) can also be considered area flux mappers. GOSAT and GOSAT-2 have high spectral resolution, but their spatial sampling is sparse, whereas the upcoming GOSAT-GW has similar characteristics to TROPOMI. Despite TROPOMI's coarse spatial sampling and the subsequently high detection limits, the mission has still been used to detect super-emission events around the world and to monitor them over time (Lavaux et al., 2022; Pandey et al., 2019).

Point source imagers enable the detection and quantification of large methane plumes as well as the attribution of these plumes to individual point sources, thanks to their fine spatial sampling (20-50 m pixel size). Their main drawback is poor spatial coverage. Within the group of point source imagers are both imaging spectrometers (also known as hyperspectral imagers) and multispectral imagers. Imaging spectrometers (e.g., GHGSat and the Italian Space Agency's PRecursore IperSpettrale della Missione Applicativa (PRISMA)) offer a high sensitivity to methane through a dense spectral sampling of methane absorption features in the shortwave infrared part of the spectrum, but they only acquire data over selected sites after tasking by the mission operators (Varon et al., 2020; Guanter et al., 2021; Jervis et al., 2021). On the other hand, multispectral missions (e.g., Sentinel-2 and Landsat-8 and 9) offer a global and frequent coverage, but their detection limits of methane are much higher than those of hyperspectral instruments because of the substantially poorer spectral information (1-2 spectral channels sensitive to methane absorption). This makes the use of multispectral imagers to be mostly restricted to bright and homogeneous surfaces, such as oil and gas extraction basins in the Middle East (Varon et al., 2021; Irakulis-Loitxate et al., 2022). GHGSat constellation, a private sector mission, is the only point source imager mission currently operating which was developed for methane mapping. Another private sector mission is WorldView-3, which can provide very low detection thresholds due to a combination of relatively high sensitivity to methane combined with higher spatial resolution than the other missions (3.7 m) (Sánchez-García et al., 2022). The Carbon Mapper mission is envisioned to consist of a constellation of hyperspectral imagers with a high sensitivity to methane. The initial Carbon Mapper satellite(s) are expected to start providing data in 2024.

Finally, the observational gap between area flux mappers and point source imagers will be covered by the MethaneSAT mission, which combines a sub-kilometer spatial sampling, a broad swath, a short revisit time and a high retrieval precision. MethaneSAT will have detection limits comparable to most current point source imagers and will offer the possibility of attributing individual plumes to specific sources thanks to its 100x400 meters (m) spatial sampling. At the same time, its high spatio-temporal coverage and retrieval precision will allow the sampling of diffuse emission sources and the accurate estimation of regional fluxes, which can complement (and often improve) the measurements by area flux mappers.

Details on the observational characteristics of most of those satellite missions capable of detecting point source super emitters are listed in Table 1. The detection limits in the Table reflect ideal observing conditions (bright and spatially homogeneous areas, i.e., arid regions, as well as wind conditions under which a distinct plume develops) and thus can be highly variable depending on *in situ* conditions. Table 1 is based on data from Guanter et al. (2021), Irakulis-Loitxate et al. (2022), Jacob et al. (2022), Jervis et al. (2022), Lauvaux et al. (2022), Pandey et al. (2019), Sánchez-García et al. (2022), Sherwin et al. (2022), Varon et al. (2020), and Varon et al. (2021).

Table 1. The ecosystem of methane-measuring satellites is highly heterogeneous with respect to measurement approach, spatio-temporal sampling and detection limits.

Spatial coverage	**Satellite**	**Agency**	**Data Available**	**Pixel Size**	**Revisit Frequency**	**Data availability**	**Point Source detection limit (kg/h)**
Global	GOSAT/ GOSAT-2	JAXA	2009— /2018—	10 x 10 km	3 days each satellite	Free	7000 / 4000
Global and regional	TROPOM I	ESA	2017—	7 x 5.5 km	1 day	Free	4000
Global and regional	Sentinel-5	ESA	Expected 2024	7.5 x 5.5 km	1 day	Free	4000
Regional	MethaneS AT	EDF	Expected 2024	130 x 400 m	3-4 days	Free	1000
Individual point-sources	Landsat 8 and 9	NASA	2013 - / 2021 -	30 x 30 m	16 days each satellite	Free	900
Individual point-sources	Sentinel-2 (A+B)	ESA/EU	2015 -	20 x 20 m	5 days	Free	900
Individual point-sources	PRISMA	ASI	2019 -	30 x 30 m	4 days	Free	500
Individual point-sources	EnMAP	DLR	2022 -	30 x 30 m	4 days	Free	500
Individual point-sources	EMIT	NASA	2022 -	60 x 60 m	3 days	Free	500
Individual point-sources	WorldVie w-3	MAXAR	2014 -	3.7 x 3.7 m	<1 days	payment	<100
Individual point-sources	GHGSat	GHGSat, Inc.	2016 -	25 x 25 m	1-7 days	payment	200
Individual point-sources	Carbon Mapper	Carbon Mapper and Planet	Expected 2024	30 x 30 m	1-7 days	TBD	100

For the particular case of point source detection as it relates to the application of the super emitter concept contained in the proposed rule, satellite missions and processing methods are already in place to detect sources greater than 500-1000 kg/hr, which can be further improved to 200-300 kg/h with GHGSat mission data. The estimation of emission rates from data provided by those satellites can be effective for the purposes required in the proposed regulations, under ideal observation conditions of bright and homogeneous surfaces and clear skies, as shown by the controlled release experiment described in Sherwin et al. (2022). Detection limits can increase substantially for those sites where and when conditions are not ideal, which would be the case for vegetated and urban surfaces, leading to data artifacts and noise which increases the difficulty of confidently detecting methane plumes and thus the detection threshold. The more sensitive hyperspectral missions (GHGSat, PRISMA, EnMAP) operate using a tasking approach, in which acquisitions must be programmed in advance. This means that acquisitions of data from all potential super-emitter sites is not routine, limiting the ability to detect transient emissions and to characterize the sources' temporal dynamics. Frequent and comprehensive observations are available from the Sentinel-2 and Landsat multispectral systems, but with a much higher detection limit.

The field of methane super-emitter detection from space has advanced rapidly. Currently available satellite systems can provide good coverage for semi-arid regions and emissions above 300 kg/h, whereas observations are more constrained for other types of regions (vegetated, snow-covered, frequently cloudy) and for smaller emission rates. Carbon Mapper and MethaneSAT are expected to improve the current observational scenario for super-emitters, both by decreasing detection limits (Carbon Mapper for point sources, MethaneSAT for area and regional emissions that comprise the bulk of emissions in most basins) and by increasing the frequency of higher precision observations. Integration of all this emergent information, evaluating detection limits in a variety of regions and under a variety of conditions, and establishing consistent methods for converting satellite observations into emission estimates will be challenging. Nevertheless data obtained from satellites, as well as other multi-scale advanced measurement technologies, will be important data resources for the EPA.

Establishing action levels for methane emissions detected by multiple emerging technologies should be a high priority for the EPA. The action level may be based on an inferred emission rate, but the assessments of the action level should include transparent methods for converting concentration measurements to emission rate estimates. Detection limits and the accuracy and precision of advanced measurement methods are evolving rapidly, so rapid certification systems for new technologies could lead to rapid improvements in emission identification and quantification.

The SAB supports EPA's proposed use of advanced measurement technologies in the detection of super-emitters and other methane emissions from oil and natural gas sector sources. The advanced measurement technologies should be certified by the EPA and the Agency should partner with other federal agencies and external organizations to develop robust testing and certification platforms.

The SAB encourages development of emissions testing capabilities by the EPA in collaboration with other standard setting organizations in the U.S. and internationally to

ensure that the time between development and certification of measurement technologies keeps pace with the rapid evolution in methane emission measurement technology.

2.1.2.2 Short duration events

Recent scientific literature has documented that methane emissions at oil and gas sector facilities can result from short events, often significantly less than a day in duration. This presents challenges in replicating emissions measurements. For example, in measuring emissions from more than a thousand high emitting sources in the Permian Basin over several months, Cusworth et al. (2021) found that when sites were revisited multiple times, high emissions were observed in only about a quarter of observations at individual sites that were visited multiple times, with a wide range in the persistence factor. Stokes et al. (2022) found that only about half of high emitting tank batteries in the Permian Basin still had high levels of emissions when observed a few days later. Wang et al. (2022), measuring emissions in multiple production basins, reported emission event durations that were frequently less than a day.

The short duration of many events presents a challenge to identifying the root causes for many large emission events. For example, over-pressurization of a storage vessel may cause a pressure release valve to allow venting, but once the over-pressurization ends and the valve re-seats, *post hoc,* it may be difficult to identify the root cause of the emissions. When root cause follow-up, even within a day or two, finds that high emitting conditions are not present at the time of the follow-up, doubt may be cast on the accuracy of emerging technologies.

Because of the short duration of many super-emission events, the EPA should evaluate methods for considering persistence in defining responses to super-emitter detections. Multiple approaches are possible and could include placing a priority on repeat sampling of high emitting sources and prioritizing differentiated responses across super-emitters with differing characteristics, while retaining reporting for all super-emitter detections. Other organizations are developing response mechanisms for super-emitter detection that may help inform EPA's approach. For example, the International Methane Emissions Observatory (IMEO),[2] an initiative supported by the U.S. government and the European Commission, has launched the Methane Alert and Response System (MARS), a satellite-based system established to detect, attribute, and notify stakeholders on very large methane emission events that are at least an order of magnitude higher than the definition included in EPA's supplemental proposal. The intention is to lower the notification threshold as globally available technology improves. After detection and notification takes place, this initiative includes a strong engagement and mitigation strategy.

If the EPA does include a measure of super-emitter persistence in defining required responses, the Agency should revisit the persistence measure periodically. As experience is gained in understanding root-causes of super-emitter events, more confidence can be placed in a single detection and a required response based on a single detection.

The SAB supports requiring responses to super-emitter detections by certified measurement technologies, but recommends that a measure of emission persistence, based on the characteristics of the observed emissions, be included in defining required responses. The persistence measure should be periodically re-evaluated.

[2] https://www.unep.org/explore-topics/energy/what-we-do/methane/imeo-action/methane-alert-and-response-system-mars

2.2 Evaluating and Certifying Advanced Emission Measurement and Monitoring Technologies.

Charge Question 3: Comment on the evaluation frameworks used for evaluating whether advanced measurement and monitoring technologies could replace existing leak detection and repair (LDAR) programs.

The EPA's Supplemental Proposal introduces a method of evaluating advanced measurement and monitoring technologies that was developed using the Fugitive Emissions Abatement Simulation Toolkit (FEAST) modeling framework. Estimates of the effectiveness for alternative methods are compared to the estimated methane emission reduction effectiveness of periodic Optical Gas Imaging (OGI) surveys for LDAR. This framework is demonstrated in the proposal by comparing the use of periodic aircraft overflights, with two different measurement methods, to periodic OGI surveys.

The framework used by the EPA in evaluating alternative emission measurement methods is described in Appendix D of the Regulatory Impact Analysis (RIA) in the EPA's Supplemental Proposal. The steps involved are:

1. create model site(s);
2. establish an emission time series for leaks and large-emitting sources (super-emitters);
3. determine detections and time to mitigation;
4. repeat multiple times with different assumptions concerning onset of leaks and onset, size, and duration of large-emitting sources.

The result of applying this framework is a matrix of approaches that lead to equivalent emission reductions. The elements of the matrix include a variety of assumptions about measurement detection limits and frequencies of sampling for the over-flight technologies.

This analytical framework could also be applied to other advanced measurement methods or combinations of advanced technologies. For example, at other points in the Supplemental Proposal, the EPA describes detailed requirements for continuous monitoring systems, yet continuous emissions monitoring systems can be evaluated using the same framework as employed for other alternative emission measurements. Model sites with geolocated emission sources, similar to those described in the RIA (Appendix D), could be used to evaluate continuous monitoring networks. Dispersion models could be used to determine emission detection efficiencies and times to emission detection, similar to the detection efficiencies used in the EPA's analysis framework for other measurement technologies. Methods for determining these detection efficiencies have recently been described in Chen, et al. (2022). This can then be followed by the types of Monte Carlo analyses used in the current analysis framework. This type of assessment of continuous monitoring networks, and other measurement technologies, could then be incorporated into a matrix of equivalent approaches, similar to the matrix in the existing proposal.

Similarly, combinations of alternative technologies, such as satellite measurements coupled with measurements made in aircraft overflights, may prove to be effective monitoring combinations

(Cardoso-Saldana, 2022). A consistent analytical framework for evaluating emission reduction effectiveness would allow for effective mixing of technologies operating at multiple scales and with multiple sampling frequencies. The use of a consistent framework for evaluating alternative technologies would also foster the development of infrastructures for method testing and would help accelerate the adoption of new measurement and monitoring technologies.

The SAB recommends that the EPA develop and periodically update a framework for evaluating alternative emissions measurement and monitoring technologies including the use of data from emission testing systems.

2.3 Scope of Covered Facilities.

Charge Question 4: Comment on the inclusion of all oil and gas facilities in the proposed rule.

The EPA proposes that LDAR surveys be required across all sites. The type of inspection (optical gas imaging (OGI) and/or Audio, Visual, and Olfactory (AVO)) and frequency depends on site complexity and equipment present onsite. For example, well sites and centralized production facilities with failure-prone equipment are required to perform quarterly OGI and AVO every two months.

In contrast with the November 2021 proposal, the exemption for well sites with estimated emissions below three tons/yr has been removed in the 2022 Supplemental Proposal. Consequently, regular inspections would be required at all sites, including wellhead only sites (where only AVO is required) and sites without leak-prone equipment. This change is important for the effectiveness of the regulation, as a large proportion of emissions come from smaller sources, particularly low-production well sites, though the proportion varies across geographies and operational practices. For example, Omara et al. (2022) found that in the U.S., low production well sites account for roughly one-half of total methane emissions from all U.S. oil and gas well sites (37-75%). These well sites, with average site-level production <15 barrels of oil equivalent per day, represent 80% of the total population of active well sites and account for only 6% of the total production in 2019.

If the large number of well sites with limited equipment are covered by the rule, the definitions of a facility and what constitutes monitoring at a facility will become important in the deployment of advanced measurement technologies. When emissions monitoring involves an operator periodically visiting a site and making measurements directly at the source, the definition of a facility is relatively straightforward. For remote sensing technologies, where the spatial resolution of a measurement may be a kilometer or more, or a single long path length sensing system may cover an area >10 km^2, the definitions become more complex. In parts of many oil and gas production regions, well site densities are >2-10 per km^2 and operators may choose to maximize the efficiency of their monitoring by simultaneously monitoring multiple sites. As part of its frameworks for evaluating advanced measurement technologies, the EPA should consider defining a variety of model sites, such as multiple nearby well sites and tank batteries and the nearby well sites that supply them.

In some regions, flaring, including malfunctioning unlit flares, may be a particularly significant source of emissions from low production rate sites. In the Permian Basin, both lit and unlit flares contribute over 10% of total methane emissions (Cusworth et al., 2021; Irakulis-Loitxate et al., 2021). Plant et al. (2022) measured flaring efficiency across several U.S. production basins, finding that unlit flares and incomplete combustion have a similar contribution to an estimated methane destruction efficiency of 91%, illustrating the relevance of inefficient flaring as a major source of emissions for both high and low production rate facilities. Aerial OGI surveys in the Permian Basin found that about 5% of flares are unlit and another 5% have visible incomplete combustion (Lyon et al., 2021); surveys indicate an even higher failure rate for low production wells. In the current rules the EPA maintains a 95% destruction efficiency requirement which is complemented by additional measures to ensure flares are lit and not malfunctioning, as well as rules to reduce the use of flaring in favor of productive uses.

The SAB supports the inclusion of all facilities in the proposed rule and recommends that the EPA provide guidance on defining model geographies of varying sizes for effective deployment of remote sensing technologies to simultaneously monitor emissions from a diversity of types of facilities. The SAB further supports the measures that reduce emissions from flaring.

2.4 Emission Reporting

> *Charge Question 5: Comment on the integration of the proposed rule with emission reporting frameworks.*

The proposed rule could promote the collection of extensive new high-quality measurements of methane emissions from oil and gas supply chains. These new data could lead to new actionable insights into emissions patterns and could be used to improve emissions reporting as required under the Inflation Reduction Act (IRA). Coordinating emission reporting used in the IRA with the technology development and data collection that will be driven by the proposed rule will be important to ensure there is an integrated understanding of where and how much methane is being emitted. For example, the Inflation Reduction Act's Methane Emission Reduction Program (MERP) requires EPA to update Subpart W of the Greenhouse Gas Reporting Program[3] (GHGRP) to ensure empirically based and accurate reporting within two years. In 2025, operators would begin paying a fee based on annual reported emissions (starting with 2024 emissions). The EPA potentially could use data collected through the proposed rule to periodically update methods used in calculating emissions reported through Subpart W.

The development of measurement-based emission inventories will be essential to ensuring alignment across the increasing number of uses for such data. The current framework for operator reported methane emissions in the GHGRP is a bottom-up estimation approach, based on detailed accounting of equipment and operations, coupled with average emission rate estimates (emission factors). Emissions reported on an annual basis take time to reflect shifts in operating practices, including those that result from the proposed rule. While emissions data that are likely to expand under the proposed rule are often short duration measurements, when combined with the data needed to meet the MERP requirement for an accurate empirically-based GHGRP, they should more accurately reflect spatial and temporal differences in emissions. With the greatly improved measurement capacity that is currently, or soon to be, available, it is reasonable to expect that the temporal mismatch that has historically proved difficult to

[3] 40 CFR Part 98

overcome is possible. Data collected on annual, semi-annual, quarterly, monthly, weekly, or daily repeat cycles can be integrated to provide a consistent and resolved understanding of emission patterns. To develop measurement-informed annual emission estimates, these diverse observational data could be integrated into accurate annual emission estimates. Given the multiple data sources coming online it will be important for data integration methods be transparent and based on the best current scientific understanding.

The EPA should promote the development of consistent and transparent mechanisms for developing measurement-informed emission inventories. Multiple approaches are possible, for example, the EPA could consider an approach based on independent measurement-based regional estimates (i.e., at basin or sub-basin scale) integrated with empirically based estimates from statistically representative site-level measurements. Recent studies have demonstrated how the integration of multi-scale data can inform accuracy and completeness of inventories, and guide improvements to source-level reporting (Alvarez et al., 2018; Rutherford et al., 2021).

To implement this type of approach, the EPA could coordinate the collection and analysis of site-level and regional-level data. Reconciliation between statistically aggregated site-level data and regional estimates would provide accurate and empirically-based emission factors to assess the fee under MERP and provide an effective approach to understanding the efficacy of the proposed regulations.

The SAB recommends that the EPA develop and periodically update consistent and transparent mechanisms for using high quality, empirical emission measurement data, including those collected in response to this rulemaking, to create measurement-informed emission inventories.

2.5 Capacity Needs.

> *Charge Question 6: Comment on the needs for new human and institutional capacity introduced by novel elements of this rule.*

The SAB finds the proposed rule and supplemental rule notable in their definition of new categories of emissions, in the use of independent certified emission measurement methods, and in their use of rapidly emerging measurement technologies.

As is common in an emerging field, the proposed rule may contain elements of operation, communication, and management that are unfamiliar in standard practice. These elements include quality control procedures, judicious use of uncertainties, and interpretation of intermittent observations. The SAB recognizes the need for development in human and institutional capacity and possible implementation gaps including educational and training programs. Practical interpretation and troubleshooting in emergent fields may not lend themselves to rapid knowledge transfer through the scientific literature, documents, and manuals. The coordinated efforts of implementers, community representatives, government workers, and researchers may be effective for tackling some of the challenges of using these emerging technologies.

The SAB recommends that the EPA encourage, and participate in developing, coordinated efforts of multiple stakeholders supporting emission measurement and reduction. This coordination should include education for community-based organizations that may wish to participate in emission detection, but lack expertise in doing so.

2.6 Benefit Analyses.

> *Charge Question 7: Are the technical analyses of the benefits of the proposed rule scientifically sound, following best practices, and applying state of the art scientific understandings?*

The quantitative assessment of benefits of the proposed rule relied on the Social Cost of Carbon and the SAB notes that the EPA recently added the "External Review Draft of Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances" as Supplemental Material for the Oil and Gas rule. The draft states that the revised estimates of social costs "…reflect recent advances in the scientific literature on climate change and its economic impacts and incorporate recommendations made by the National Academies of Science, Engineering, and Medicine" in 2017. These social costs are based upon revised and expanded methods for evaluating climate damage attributable to greenhouse gas emissions, including three separate evaluations of the damage function from recent studies. The EPA report released as part of the rulemaking the SAB is reviewing here is also currently undergoing an EPA contracted, external peer review. Given the importance, and far-reaching implications of this scientifically developing material, the SAB commends the Agency for soliciting a peer review of the report and reserves any recommendations on SAB review at this time, pending Agency follow through and action on the peer review currently underway.

Climate benefits are the only benefits quantified in the proposed rule, and do not account for health effects of ozone exposure from methane emissions. There is no reason given for the exclusion of the health effects of ozone exposure from methane emissions.

Ozone health effects are discussed in Section C of the Executive Summary of the proposed rule "Costs and Benefits" (p. 63122 in the November 2021 proposal) and again in section XVI, "Impacts of This Proposed Rule" (p. 63257) both of which describe the effects of VOCs on ozone, pointing out that "Calculating ozone impacts from VOC emissions changes requires information about the spatial patterns in those emissions changes." The analysis does not characterize the spatial distribution of VOC changes. It is noted that the impact of those changes on ozone can only be approximated and, although an illustrative screen analysis is included in Appendix B of the RIA, the results of this analysis is not included in the estimate of benefits and net benefits projected from this proposal."

Although that logic holds for the ozone response to VOC emissions, it does not hold for the ozone response to methane emissions, the primary focus of these regulations. The ozone response to methane emissions has very little dependence on the location of the methane emissions owing to the relatively long (decadal) residence time of methane in the atmosphere (e.g., Fiore et al., 2008). Hence, the continental to global scale ozone benefits of methane reductions can be quantified analogously to the quantification of the social cost of methane, as the change in response to a marginal change in methane emissions. This has been done by multiple research teams, including scientists from the EPA. While there are uncertainties associated with factors such as the assumed income elasticity around the world, the background composition of the atmosphere in a given future year, and the discount rate, similar uncertainties arise with the social cost of methane that is included in the benefit analysis.

The SAB therefore recommends that the EPA include an estimate of the monetized value of the ozone health benefits attributable to methane emissions changes based on published literature (West et al., 2012; Shindell et al., 2015; Melvin et al., 2016; Sarofim et al., 2017; UNEP, 2021; Vandyck et al., 2022). These studies all show that the monetized value of this ozone-attributable health response is comparable to the climate-related social cost of methane, so that leaving out this impact leads to a large underestimate of the total benefits. The SAB notes that although uncertainties lead to a substantial range in the valuation of the ozone-attributable health response to methane emissions, this value does not encompass zero impact. Therefore, lack of monetization (a zero value) does not fall within the range of uncertainty.

The SAB recommends that the EPA include an estimate of the monetized value of the ozone health benefits attributable to methane emissions reductions.

Methane sources are often emitters of other compounds, typically referred to as co-emissions. These can include substances that adversely affect human health or their precursors, such as fine particulate matter ($PM_{2.5}$), ozone and hazardous air pollutants (HAPs). These co-emissions are acknowledged in the proposed rule. For instance, in Section XVI, "Impacts of This Proposed Rule," it is pointed out that in addition to the methane emissions directly targeted by this rule, reductions of co-emissions "will improve air quality and are likely to improve health and welfare associated with exposure to ozone, $PM_{2.5}$, and HAP."

The RIA assessed cancer risks from hazardous air pollutant (HAP) emissions from the oil and natural gas sector using AERMOD with 4 km and 9 km grid resolutions and the 2017 National Emissions Inventory nonpoint HAP emissions. The EPA found that present-day HAP emissions led to about 2 million people with an elevated cancer risk above one in 1 million, EPA's level of concern. These risk estimates are for the entire oil and gas industry, not just sources affected by the proposed regulation. The Agency estimated that many of the sources of cancer risk would not be altered by the proposed regulation but acknowledged that the analysis was conducted for screening only. Health benefits of HAP reductions remained unmonetized in the RIA. Regardless of the fractional reduction achievable by the proposed rule, its benefits are underestimated because of this exclusion.

The SAB encourages the EPA to move toward quantifying HAP-related health benefits of future rules, not just the baseline.

Such analyses are needed to support estimates of how benefit is distributed in addition to cost-benefit assessments of the overall rule.

2.7 Environmental Justice.

Charge Question 8: Please comment upon the analysis in the RIA and supporting documents regarding the extent to which the proposed rule may reduce impact, and environmental disparities of impacts, upon historically disadvantaged groups or communities. Include *consideration of recent developments in treatment of environmental justice, uncertainties, and cumulative impacts.*

Emissions from oil and gas operations have been found to pose a risk to nearby communities and may disproportionately affect disadvantaged populations (Proville et.al., 2022). Section 4.2 of the Proposed Supplemental Rule's RIA includes environmental justice (EJ) analyses focusing on climate impacts, ozone from VOC emissions, air toxics impacts, demographics of oil and natural gas workers and communities, and household energy expenditures. Disparities in environmental impacts result from differing spatial distributions of pollutant concentrations. Before discussing environmental justice, we first review the factors that govern spatially distributed impact.

2.7.1 Considerations affecting spatial distribution.

The spatial distribution of environmental impact, and its influence on distributed environmental burdens, depends on characteristics of both the pollutant and the environmental system. First, the concentration of any contaminant is greatest near the emission source, and those elevated concentrations may induce health effects. Second, pollutant reactivity after emission, or formation after emission (secondary formation), affect spatial gradients of concentrations. Highly reactive pollutants like NO_2 are more concentrated near sources. Slowly reacting pollutants like methane are well-mixed outside of the immediate plume and do not have strong differential effects near sources, and secondary formation generates pollutants with regional, rather than solely near-source, impacts. Pollutants that are well-mixed throughout the atmosphere, like greenhouse gases, may cause impacts whose spatial distribution is governed by the environmental system, rather than the location of emissions. Table 2 compares some characteristics of pollutants emitted from oil and gas operations and the resulting spatial distribution of impact.

Table 2. Some pollutants emitted from industrial operations and the characteristics that affect spatial distribution of impact.

Pollutant	**Effect**	**Lifetime of Effect**	**Health effects at plume levels?**	**Spatial distribution for analysis**
CO_2	Climate change	Long	No	Climate system
CH_4	Climate change	Long	No	Climate system
O_3 from VOCs	Health	Moderate	No	Regional ozone
O_3 from CH_4	Health	Long	No	Background ozone
NO_x	Health	Moderate		Regional air pollution
NO_2	Health	Short	Yes	Plume
$PM_{2.5}$	Health	Moderate	Yes	Plume; regional air pollution
Hazardous Air Pollutants (HAPs)	Health	Short to Long	Yes	Plume and deposition in surrounding area

2.7.2 Climate impacts.

In terms of climate impacts, the RIA rightly notes that some population sub-groups are disproportionately impacted by climate change, including individuals who are low income, identify as a racial or ethnic minority, are without high school diploma, and are 65 years and older. The impacts of climate change on these communities occur regardless of where methane was emitted, due to the relatively long atmospheric lifetime of methane; the spatial distribution of emissions does not matter. Damages and benefits from changes in methane are quantified in the EPA's RIAs using the Social Cost of Greenhouse Gas (SC-GHG) metric which does not consider disproportionate risks to different populations.

2.7.3 Ozone produced by methane.

The impact of methane on ozone is relatively insensitive to emission location and can be estimated without a separate analysis of spatial or short-term (less than one year) temporal distribution.

2.7.4 Ozone from VOCs.

Unlike the climate impacts from methane emissions, air pollution impacts from reactive oil and gas sector emissions are dependent on location (as well as the amount and mixture of co-emitted pollutants), with greater risks to the communities surrounding these operations. The Proposed Supplemental Rule RIA analyzed a recent pre-control baseline air quality scenario comparing ozone formed from VOC emissions from the oil and gas sector across race/ethnicities, ages, and sexes. It found that "Native American populations on average may be exposed to higher concentrations of ozone from oil and natural gas VOC emissions than White populations, who in turn may on average be exposed to a higher concentration than the overall reference group." In addition, it found that "African American or Black populations and Asian populations may on average be exposed to lower concentrations than White populations and the overall reference group." The differences between these population subgroups are relatively small, ranging from approximately 0.08 parts per billion (ppb) to 0.10 ppb. While the analysis was limited in spatial resolution of the concentration estimates, based on atmospheric chemistry and transport governing ozone levels in the atmosphere, the SAB does not anticipate that further refining the analytical approach and higher resolution chemical transport modeling would yield substantially different results for this exposure pathway.

2.7.5 Hazardous Air Pollutants and NO_2.

As opposed to the ozone impacts from methane, air toxic concentrations are highly sensitive to emission location. As these substances can have large local impacts, they play a role in environmental disparities, since oil and gas infrastructure is often located near historically marginalized communities. The RIA analysis of HAP exposure and cancer risk estimated the demographic breakdown of people living in areas with potentially elevated risk levels (Table 4-7, Supplemental Rule RIA). Around 30% of those individuals were of minority status, with most of those being of Hispanic or Latino ethnicity. Because only the baseline situation was analyzed, the effect of the proposed rule on environmental disparities was not determined. In addition, flaring activities are expected to be curtailed by the proposed rule, and flaring emissions have a disproportionate effect on Hispanic communities (Johnston et al., 2020). The benefit of reducing flaring emissions was not analyzed in the RIA.

The SAB commends the Agency for including a separate section on EJ impacts and considering the multiple pathways by which this proposed rule would affect environmental health risks for disadvantaged communities. The SAB finds that many of the analyses required to assess improvements in environmental disparities are presented within the RIA, i.e., impacts on climate change and regional distributions of ozone. However, the influence of the proposed rule on spatial distributions of pollutants that affect communities near emission sources was incompletely quantified.

The SAB recommends that future environmental justice analyses include the influence of rulemaking on exposures and health in near-source communities.

Such analyses would support the goal of evaluating environmental health disparities.

In addition, the SAB acknowledges that climate change may affect vulnerable populations in ways that are desirable to reduce, yet which are not accounted for in the social cost of greenhouse gas emissions.

The SAB encourages EPA to consider how the valuation of distributed effects of climate change might be communicated, including within collaborative discussions on the social cost of carbon.

Policy-specific air quality scenarios for future years were not evaluated in the RIA, so many of the analyses relating to environmental disparities are qualitative, or they quantitatively assess risks for the baseline scenario only. The effect of the rule on greenhouse-gas emissions and climate impacts is captured with the social cost of carbon. However, the current social cost of greenhouse gas (SC-GHG) metric does not place a value on disproportionate risks to different populations caused by climate change. One possibility for future analysis would be valuing the disproportionate impacts of climate change on disadvantaged groups within the SC-GHG framework.

The present-day influence of co-emitted air toxics was evaluated, but not for potential reductions in the future. The SAB recommends that future regulatory impact analyses expand to include changes from the present-day situation. Assessments of the specific groups that benefit from federal rules are becoming more commonplace, being driven by initiatives such as the present Administration's Justice40 initiative.[4]

Finally, the effect of the rule on potential future installations beyond present-day facilities has not been discussed. Considerations of climate alone might suggest that oil and gas facilities are not expected to increase in number, but other societal factors may drive growth, including the choice of methane as a lower-carbon fuel. The proposed rule sets criteria for performance in incoming installations, preventing introduction of poorly performing technology that may later require retrofit to protect human health and climate. History suggests that these potential new installations might also have disproportionate effects on disadvantaged populations.

The SAB acknowledges that these issues of Environmental Justice have not been commonly addressed in regulatory impact analyses, and that the RIA accompanying the proposed rule has adequately addressed the current state-of-the-art.

The SAB recommends that future regulatory impact analyses evolve to include future benefits of emissions reductions and their spatial distributions, in addition to characterizing present conditions.

Such analyses are required to reduce environmental impacts and should also address environmental disparities.

Environmental justice, broadly defined, encompasses several forms (EPA Science Advisory Board, 2022). Among these are retributive justice (punishments for allowing harm and injustice); distributive justice (the fair allocation of burdens and benefits); procedural justice (allowing individuals and communities to bring forward claims); recognition justice (recognizing all stakeholders in the decision process); and restorative justice (improving relationships among those who impose burdens and those who bear them). The SAB notes that the proposed rule is primarily framed in terms of retributive justice and begins to address procedural justice. It does not yet address distributive justice nor restorative justice.

Distributive justice includes consideration of communities' cumulative burden. The term "cumulative impacts" refers to the total burden from chemical and non-chemical stressors and their interactions that affect the health, well-being, and quality of life of an individual, community, or population at a given point in time or over a period of time. Communities near oil and gas installations are candidates for consideration as "Environmental Justice" communities as they have high exposure to air toxics, are subject to exposure through other media (Adgate et al., 2014; Johnston et al., 2019; Proville et al., 2022) and are at risk for psychological and social

[4] https://www.whitehouse.gov/environmentaljustice/justice40/

stress from extractive industries (Malin, 2020). Communities disproportionately affected by oil and gas operations include a wide range, from high-poverty and largely white, to low-poverty and high ethnic diversity, to high ethnic diversity with a variety of income levels (Clough, 2018).

The RIA does not address the disproportionate impact of air toxic releases on communities that have been cumulatively burdened by environmental hazards from the same or different installations. The SAB recognizes that procedures for assessing cumulative impacts are emerging, yet also notes that the ability to conduct such assessments is a current priority for the Agency and necessary to move toward distributive justice.

The SAB recommends that a strategy for systematic and quantitative assessment of justice impacts be implemented for future Regulatory Impact Assessments; such strategies should take initial steps toward incorporating evaluations of mixed stressors and cumulative impacts.

This recommendation aligns with a similar recommendation in the SAB review the EPA's Proposed Heavy-Duty Engine and Vehicle Rule (U.S. EPA Science Advisory Board, 2022), although the sources and distribution of oil and gas emission sources differ from the urban sources in the Heavy-Duty Engine and Vehicle Rule.

3. SUMMARY OF RECOMMENDATIONS

The SAB has developed recommendations on the super-emitter program, the use of advanced measurement technologies, the scope of the proposed regulation, the use of data collected in implementing this rule in emissions reporting, capacity building, the evaluation of benefits and the consideration of Environmental Justice.

On the super-emitter program and the use of advanced measurement technologies:

- **The SAB supports the designation of a super-emitting source category at the threshold proposed by the Agency and recommends periodically re-evaluating the threshold.**

- **The SAB supports the EPA's proposed use of advanced measurement technologies in the detection of super-emitters and other methane emissions from oil and natural gas sector sources. The advanced measurement technologies should be certified by the EPA and the Agency should partner with other federal agencies and external organizations to develop robust testing and certification platforms.**

- **The SAB encourages development of emissions testing capabilities by the EPA in collaboration with other standard setting organizations in the U.S. and internationally to ensure that the time between development and certification of measurement technologies keeps pace with the rapid evolution in methane emission measurement technology.**

- **The SAB supports requiring responses to super-emitter detections by certified measurement technologies, but recommends that a measure of emission persistence,**

based on the characteristics of the observed emissions, be included in defining required responses. The persistence measure should be periodically re-evaluated.

- **The SAB recommends that the EPA develop and periodically update a framework for evaluating alternative emissions measurement and monitoring technologies including the use of data from emission testing systems.**

On the scope of the proposed rule:

- **The SAB supports the inclusion of all facilities in the proposed rule and recommends that the EPA provide guidance on defining model geographies of varying sizes for effective deployment of remote sensing technologies to simultaneously monitor emissions from a diversity of types of facilities. The SAB further supports the measures that reduce emissions from flaring.**

On the use of data collected in implementing this rule in emissions reporting:

- **The SAB recommends that the EPA develop and periodically update consistent and transparent mechanisms for using high quality, empirical emission measurement data, including those collected in response to this rulemaking, to create measurement informed emission inventories**.

On capacity building:

- **The SAB recommends that the EPA encourage, and participate in developing, coordinated efforts of multiple stakeholders supporting emission measurement and reduction. This coordination should include education for community-based organizations that may wish to participate in emission detection, but that lack expertise in doing so.**

On benefits estimation:

- **The SAB recommends that the EPA include an estimate of the monetized value of the ozone health benefits attributable to methane emissions reductions.**

- **The SAB encourages the EPA to move toward quantifying HAP-related health benefits of future rules, not just the baseline.**

On Environmental Justice:

- **The SAB recommends that future environmental justice analyses include the influence of rulemaking on exposures and health in near-source communities.**

- **The SAB encourages EPA to consider how the valuation of distributed effects of climate change might be communicated, including within collaborative discussions on the social cost of carbon.**

- **The SAB recommends that future regulatory impact analyses evolve to include future benefits of emissions reductions and their spatial distributions, in addition to characterizing present conditions.**

- **The SAB recommends that a strategy for systematic and quantitative assessment of justice impacts be implemented for future Regulatory Impact Assessments; such strategies should take initial steps toward incorporating evaluations of mixed stressors and cumulative impacts.**

Overall, the Board commends the Agency on this significant action and recognizes the innovative nature of provisions including: the program for detection and response to super-emitters, the advanced measurement certification program, and methods for promoting scientific engagement of communities. The Board supports the innovative approaches proposed by the Agency, as described in this report, but recognizes, as summarized in its recommendations, that these innovative strategies can and should evolve over time. Therefore:

- **The SAB recommends that** the **Agency continue to receive scientific advice from a diverse group of outside experts on issues including the super-emitter program, the advanced measurement certification program, the inclusion of data from diverse sources, capacity building, and the integration of the rule with other methane emission efforts within the Agency. The Board is available to support and will continue to monitor these activities through its climate science committee.**

The frequency of this input should keep pace with the advancement of emission measurement technologies. At current rates of scientific advancement annual or biennial reviews would be appropriate.

REFERENCES

Adgate, J.L., Goldstein, B.D., and McKenzie, L.M. 2014. Potential Public Health Hazards, Exposures and Health Effects from Unconventional Natural Gas Development. *Environmental Science & Technology* 48(2014) 8307–8320. https://doi.org/10.1021/es404621d.

Alvarez, R.A., Zavala-Araiza, D., Lyon, D.R., Allen, D.T., Barkley, Z.R., Brandt, A.R., and Davis, K.J., et al. 2018. Assessment of methane emissions from the US oil and gas supply chain. *Science* 361, no. 6398 (2018): 186-188.

Brandt, A.R., Heath, G.A., and Cooley, D. 2016. Methane Leaks from Natural Gas Systems Follow Extreme Distributions. *Environmental Science & Technology* 50 (2016) 12512–12520. https://doi.org/10.1021/acs.est.6b04303.

Cardoso-Saldana, F. 2022. Tiered Leak Detection and Repair Programs at Oil and Gas Production Facilities. *ChemRxiv* doi: 10.26434/chemrxiv-2022-f7dfv (2022)

Chen, Q., Schissel, C., Kimura, Y., McGaughey, G., McDonald-Buller, E.C. and Allen, D.T. 2022. Assessing detection efficiencies for continuous methane emission monitoring systems at oil and gas production sites. submitted to *Environmental Science & Technology* (2022).

Chen, Z., Yacovitch, T.I., Daube, C., Herndon, S.C., Wilson, D., Enoch, S., and Allen, D.T. 2022. Reconciling methane emission measurements for offshore oil and gas platforms with detailed emission inventories: Accounting for emission intermittency. *Environmental Au* (2022), https://doi.org/10.1021/acsenvironau.2c00041.

Clough, E. 2018. Environmental justice and fracking: A review. *Current Opinion in Environmental Science and Health* volume 3, 2013, 14-18. doi.org/10.1016/j.coesh.2018.02.005.

Conley, S., Faloona, I., Mehrotra, S., Suard, M., Lenschow, D.H., Sweeney, C., Herndon, S., Schwietzke, S., Pétron, G., Pifer, J., Kort, E.A., and Schnell, R. 2017. Application of Gauss's Theorem to Quantify Localized Surface Emissions from Airborne Measurements of Wind and Trace Gases. *Atmospheric Measurement Techniques 10* (9). https://doi.org/10.5194/amt-10-3345-2017.

Corbett, A., and Smith, B. 2022. A Study of a Miniature TDLAS System Onboard Two Unmanned Aircraft to Independently Quantify Methane Emissions from Oil and Gas Production Assets and Other Industrial Emitters. *Atmosphere* 2022, *13* (5). https://doi.org/10.3390/atmos13050804.

Cusworth, D.H., Duren, R.M., Thorpe, A.K., Olson-Duvall, W., Heckler, J., Chapman, J.W., Eastwood, M.L., Helmlinger, M.C., Green, R.O., Asner, G.P., Dennison, P.E, and Miller, C.E. 2021. Intermittency of Large Methane Emitters in the Permian Basin. *Environ Sci Technol Lett 8* (7), 567–573. https://doi.org/10.1021/acs.estlett.1c00173.

Fiore, A.M., West, J.J., Horowitz, L.W., Naik, V. and Schwarzkopf, M.D., 2008. Characterizing the tropospheric ozone response to methane emission controls and the benefits to climate and air quality. *Journal of Geophysical Research: Atmospheres*, *113*(D8).

Gorchov Negron, A.M., Kort, E.A., Conley, S.A., and Smith, M.L. 2020. Airborne assessment of methane emissions from offshore platforms in the US Gulf of Mexico. *Environmental science & technology* 54, no. 8 (2020): 5112-5120.

Guanter, L., Irakulis-Loitxate, I., Gorroño, J., Sánchez-García, E., Cusworth, D.H., Varon, D.J., Cogliati, S., and Colombo, R. 2021. Mapping methane point emissions with the PRISMA spaceborne imaging spectrometer. *Remote Sens. Environ.* 265, 112671, https://doi.org/10.1016/j.rse.2021.112671, 2021.

Irakulis-Loitxate, I. Guanter, L., Liu, Y-N, Varon, D.J., Maasakkers, J.D., Zhang, Y., and Chulakadabba, A., et al. 2021. Satellite-based survey of extreme methane emissions in the Permian basin. *Science Advances* 7, no. 27 (2021): eabf4507.

Irakulis-Loitxate, I., Guanter, L., Maasakkers, J.D., Zavala-Araiza, D., and Aben, I. 2022. Satellites detect abatable super-emissions in one of the world's largest methane hotspot regions, *Environ. Sci. Technol.* 56, 4, 2143–2152, https://doi.org/10.1021/acs.est.1c04873, 2022.

Jacob, D.J., Varon, D.J., Cusworth, D.H., Dennison, P.E., Frankenberg, C., Gautam, R., Guanter, L., Kelley, J., McKeever, J., Ott, L.E., Poulter, B., Qu, Z., Thorpe, A.K., Worden, J. R., and Duren, R.M. 2022. Quantifying methane emissions from the global scale down to point sources using satellite observations of atmospheric methane. *Atmos. Chem. Phys.* 22, 9617–9646, https://doi.org/10.5194/acp-22-9617-2022.

Jervis, D., McKeever, J., Durak, B.O.A., Sloan, J.J., Gains, D., Varon, D.J., Ramier, A., Strupler, M., and Tarrant, E. 2021. The GHGSat-D imaging spectrometer. *Atmos. Meas. Tech.*, 14, 2127–2140, https://doi.org/10.5194/amt-14-2127-2021.

Johnston, J.E., Lim, E., and Roh, H. 2019. Impact of upstream oil extraction and environmental public health: A review of the evidence. *Science of the Total Environment* 657 (2019) 187–199.

Johnston, J.E., Chau, K., Franklin, M., and Cushing, L. 2020. Environmental Justice Dimensions of Oil and Gas Flaring in South Texas: Disproportionate Exposure among Hispanic communities. *Environmental Science & Technology* 54 (2020) 6289–6298. https://doi.org/10.1021/acs.est.0c00410.

Johnson, M.R., Tyner, D.R., and Szekeres, A.J. 2021. Blinded Evaluation of Airborne Methane Source Detection Using Bridger Photonics LiDAR. *Remote Sensing of Environment* 2021, *259*. https://doi.org/10.1016/j.rse.2021.112418.

Karion A., C. Sweeney, E.A. Kort, P.B. Shepson, A. Brewer, M. Cambaliza, S.A. Conley, K. Davis, A. Deng, M Hardesty, S.C. Herndon, T. Lauvaux, T. Lavoie, D. Lyon, T. Newberger, G. Petron, C. Rella, M. Smith, S. Wolter, T.I. Yacovitch, and P. Tans. 2015. Aircraft-based estimate of total methane emissions from the Barnett Shale Region. *Environ. Sci. Technol.* 49, 8124–8131.

Lauvaux, T., Giron, C., Mazzolini, M., d'Aspremont, A., Duren, R., Cusworth, D., Shindell, D., and Ciais, P. 2022. Global assessment of oil and gas methane ultra-emitters. *Science* 375, 557–561, https://doi.org/10.31223/X5NS54.

Lyon, D.,R., Hmiel, B., Gautam, R., Omara, M., Roberts, K.A., Barkley, Z.R. and Davis K.J., et al.2021. Concurrent variation in oil and gas methane emissions and oil price during the COVID-19 pandemic. *Atmospheric Chemistry and Physics* 21, no. 9 (2021): 6605-6626.

Melvin, A.M., Sarofim, M.C., and Crimmins, A.R.. 2016. Climate benefits of U.S. EPA programs and policies that reduced methane emissions 1993-2013. *Environmental Science & Technology* 50 (13):6873-6881.

National Academies of Science, Engineering and Medicine (NASEM). 2018. Improving Characterization of Anthropogenic Methane Emissions in the United States. (Report of committee), National Academy Press, Washington, DC, 2018

Omara, M., Zimmerman, N., Sullivan, M.R., Li, X., Ellis, A., Cesa, R., Subramanian, R., Presto, A.A., and Robinson, A.L. 2018. Methane emissions from natural gas production sites in the United States: Data synthesis and national estimate. *Environmental Science & Technology* 52 (2018) 12915–12925.

Omara, M., Zavala-Araiza, D., Lyon, D.R., Hmiel, B., Roberts, K.A., and Steven P. Hamburg. 2022. Methane emissions from U.S. low production oil and natural gas well sites. *Nature communications* 13, no. 1 (2022): 1-10.

Pandey, S., Gautam, R., Houweling, S., Denier van der Gon, H., Sadavarte, P., Borsdorff, T., Hasekamp, O., Landgraf, J., Tol, P., van Kempen, T., Hoogeveen, R., van Hees, R., Hamburg, S. P., Maasakkers, J.D., and Aben, I. 2019. Satellite observations reveal extreme methane leakage from a natural gas well blowout. *P. Natl. Acad. Sci*. USA, 116, 23676–23681, https://doi.org/10.1073/pnas.1908712116, 2019.

Plant, G., Kort, E.A., Brandt, A.R., Chen, Y., Graham, F. Gorchov Negron, A.M., Schwietzke, S., Smith, M., and Zavala-Araiza, D. 2022. Inefficient and unlit natural gas flares both emit large quantities of methane. *Science* 377 (2022):1566-1571.

Proville, J., Roberts, K.A., and Peltz, A. et al. 2022. The demographic characteristics of populations living near oil and gas wells in the USA. *Popul Environ* 44, 1–14 (2022). https://doi.org/10.1007/s11111-022-00403-2.

Robertson, A.M., Edie, R., Field, R.A., Lyon, D., McVay, R., Omara, M., Zavala-Araiza, D. and Murphy, S.M. 2020. New Mexico Permian Basin measured well pad methane emissions are a factor of 5–9 times higher than U.S. EPA estimates. *Environmental Science & Technology* 54(21), 3926-13934.

Rutherford, J.S., Sherwin, E.D., Ravikumar, A.P., Heath, G.A., Englander, J., Cooley, D., Lyon, D., Omara, M., Langfitt, Q., and Brandt, A.R. 2021. Closing the methane gap in U.S. oil and natural gas production emissions inventories. *Nature communications* 12, no. 1 (2021): 1-12.

Sarofim, M.C., Waldhoff, S.T. and Anenberg, S.C., 2017. Valuing the ozone-related health benefits of methane emission controls. *Environmental and Resource Economics 66*(1), pp.45-63.

Sánchez-García, E., Gorroño, J., Irakulis-Loitxate, I., Varon, D.J., and Guanter, L. 2022. Mapping methane plumes at very high spatial resolution with the WorldView-3 satellite. *Atmos. Meas. Tech*. 15, 1657–1674, https://doi.org/10.5194/amt-15-1657-2022, 2022.

Sherwin, A.D., Rutherford, J.S., Chen, Y., Kort, E.A., Jackson, R.B., and Brandt, A.R. 2022. Single-blind validation of space-based point-source methane emissions detection and quantification, *EarthArXiv*, https://doi.org/10.31223/X5DH09, 2022.

Shindell, D. T. 2015. The Social Cost of Atmospheric Release, *Climatic Change* 130, 313-326, 2015.

Stokes, S., Tullos, E., Morris, L., Cardoso-Saldaña, F.J., Smith, M., Conley, S., Smith, B., Allen, D.T. 2022. Reconciling multiple methane detection and quantification systems at oil and gas tank battery sites. *Environmental Science & Technology*, doi: 10.1021/acs.est.2c02854.

Tullos, E.E., Stokes, S., Cardoso-Saldaña, F.J., Herndon, S.C., Smith, B., Allen, D.T. 2021. Use of short duration measurements to estimate methane emissions at oil and gas production sites, *Environmental Science & Technology Letters*, 8, 463–467.

United Nations Environment Programme and Climate and Clean Air Coalition. 2021. *Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions.* United Nations Environment Programme, Nairobi, Kenya, ISBN: 978-92-807-3854-4.

U.S. EPA. 2022. Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review, Federal Register, Vol. 87, No. 233, 74702-74847, Tuesday, December 6, 2022.

U.S. EPA Science Advisory Board. 2022. *Final Science Advisory Board Regulatory Review Report of Science Supporting EPA Decisions for the Proposed Rule: Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards (RIN 2060-AU41).* EPA-SAB-23-001, U.S. EPA Science Advisory Board, Washington, DC

Vandyck, T., Keramidas, K., and Tchung-Ming, S. et al. 2022. Quantifying air quality co-benefits of climate policy across sectors and regions. *Climatic Change* 163, 1501–1517 (2020). https://doi.org/10.1007/s10584-020-02685-7

Varon, D.J., Jacob, D.J., Jervis, D., and McKeever, J. 2020. Quantifying time-averaged methane emissions from individual coal mine vents with GHGSat-D satellite observations. *Environ. Sci. Technol.* 54, 10246–10253, https://doi.org/10.1021/acs.est.0c01213, 2020.

Varon, D.J., Jervis, D., McKeever, J., Spence, I., Gains, D., and Jacob, D.J. 2021. High-frequency monitoring of anomalous methane point sources with multispectral Sentinel-2 satellite observations. *Atmos. Meas. Tech.* 14, 2771–2785, https://doi.org/10.5194/amt-14-2771-2021, 2021.

Wang, J.L., Daniels, W.S., Hammerling, D.M., Harrison, M., Burmaster, K., George, F.C., Ravikumar, A.P. 2022. Multiscale Methane Measurements at Oil and Gas Facilities Reveal Necessary Frameworks for Improved Emissions Accounting. *Environ. Sci. Technol.* 2022, 56, 14743−14752

West, J.J., Fiore, A.M. and Horowitz, L.W. 2012. Scenarios of methane emission reductions to 2030: abatement costs and co-benefits to ozone air quality and human mortality. *Climatic Change* 114, 441–461 (2012). https://doi.org/10.1007/s10584-012-0426-4.

Zavala-Araiza, D., Alvarez, R.A., Lyon, D.R., Allen, D.T., Marchese, A.J., Zimmerle, D.J., and Hamburg, S.P. 2017. Super-emitters in natural gas infrastructure are caused by abnormal process conditions. *Nature Communications* 8 (2017) 14012. https://doi.org/10.1038/ncomms14012.

Zhang, Y., Gautam, R., Pandey, S., Omara, M., Maasakkers, J.D., Sadavarte, P., Lyon, D., Nesser, H., Sulprizio, M.P., Varon, D.J., Zhang, R., Houweling, S., Zavala-Araiza, D., Alvarez, R.A., Lorente, A., Hamburg, S.P., Aben, I., and Jacob, D.J. 2020. Quantifying Methane Emissions from the Largest Oil-Producing Basin in the United States from Space. *Sci. Adv.* 2020, 6, eaaz5120, doi: 10.1126/sciadv.aaz5120