Research Report 232, *Measuring and Modeling Air Pollution and Noise Exposure Near Unconventional Oil and Gas Development in Colorado*, by J.L. Collett Jr. et al.

INTRODUCTION

The scale and rate of onshore oil and natural gas development in the United States since the early 2000s differ markedly from earlier periods, driven by technological changes involving increased use of hydraulic fracturing and horizontal drilling. Although hydraulic fracturing has captured much public attention, the process itself is not new. Neither is horizontal drilling nor the extraction of oil and gas from unconventional formations, such as tight (i.e., low permeability) sandstone and shale. What is new is the use of high-volume (millions of gallons of water per well) multistage hydraulic fracturing combined with horizontal drilling (thousands of feet in length).

Unconventional oil and natural gas development (UOGD*) has been associated with a wide range of potential exposures to chemical and nonchemical agents. The rapid expansion of this development has given rise to concerns about potential effects on human health, and there exist knowledge gaps about these exposures that must be addressed to better understand these potential impacts.

In August 2020, HEI Energy issued a Request for Applications (RFA) *E20-1*: Community Exposures Associated with Unconventional Oil and Natural Gas Development. The goal of the RFA was to better understand the nature, extent, and frequency of potential exposures related to UOGD impacts on air quality and noise (see Preface). HEI sought to fund studies that would apply a combination of approaches to quantify the spatial and temporal variability in population exposures to UOGD in outdoor air and to noise.

Dr. Collett was one of three investigators funded under this RFA. He and his colleagues at Colorado State University and the Colorado School of Public Health proposed to improve the characterization of air quality changes associated with UOGD-related emissions with fixed-site and mobile monitoring of noise and air quality over the well pad development life cycle in the Denver-Julesburg Basin in Colorado. The team would examine relationships between air quality monitoring data and UOGD operational data provided by well pad operators to understand linkages between specific UOGD processes and effects on air quality, and they planned to develop an emissions model to predict volatile organic compound (VOC) concentrations in ambient air. Together, the resulting monitoring data and model results were expected to contribute to an improved understanding of potential exposures for those living and working near well pads. The HEI Energy Research Committee recommended the study for funding because it had several strong features. The Committee valued the meticulous examination of air emissions across the life cycle of a well pad at fine temporal and spatial scales. Moreover, the team's demonstrated ability to gain operator cooperation enabled them to achieve a primary RFA objective of better understanding associations between emissions and specific UOGD operations. The Committee also thought that Collett had assembled a highly qualified team with demonstrated air quality measurement expertise and appreciated the inclusion of A- and C-weighted noise measurements to address both audible and low-frequency noise concerns.

This Commentary provides the HEI Energy Review Panel's evaluation of the study. It is intended to aid the sponsors of HEI and the public by highlighting the study's strengths and limitations and placing the results presented in the Investigators' Report in a broader scientific and regulatory context.

SCIENTIFIC AND REGULATORY BACKGROUND

UOGD OVERVIEW

UOGD refers to the development and production of oil and natural gas through multistage hydraulic fracturing in horizontal wells. UOGD processes occur on and off the well pad and include the following:

- **Field development**: Exploration, pad preparation, vertical and horizontal drilling, well completion (casing and cementing, perforating, acidizing, hydraulic fracturing, millout, flowback, and well testing) in preparation for production, and management of wastes
- **Production operations**: Extraction, gathering, processing, and field compression of gas; extraction and processing of oil and natural gas condensates; management of produced water and wastes; and construction and operation of field production facilities
- **Postproduction**: Well closure and land reclamation

Dr. Jeffrey L. Collett Jr.'s 2-year study, "Measuring and Modeling Air Pollution and Noise Exposure Near Unconventional Oil and Gas Development in Colorado," began in February 2022. Total expenditures were $1,375,427. The draft Investigators' Report from Collett and colleagues was received for review in December 2024 and accepted by the HEI Energy Review Committee in March 2025. During the review process, the HEI Energy Review Committee and the investigators had the opportunity to exchange comments and clarify issues in both the Investigators' Report and the Review Committee's Commentary.

This Commentary has not been reviewed by public or private party institutions, including those that support HEI Energy, and may not reflect the views of these parties; thus, no endorsements by them should be inferred.

*A list of abbreviations and other terms appears at the end of this report.

Some UOGD operations are regulated at the federal level under the Clean Air Act, the Clean Water Act, and the Safe Drinking Water Act, while state authorities play a major role in governing UOGD more generally. The rules vary among the US states, with some defining minimum setback distances between UOGD and specific land uses, such as residences and schools, to protect local populations.

UOGD PROCESSES

Different UOGD processes give rise to chemical and nonchemical releases to the environment (e.g., ambient air, soil, surface water, and groundwater) that are complex and highly variable. Such releases and resulting human exposures are a function of numerous process-related factors, including variation in operator practices and regulatory requirements. Releases can also happen because of accidental spills and leaks. In addition, the level of UOGD activity can vary widely between and across regions and over time in response to fluctuating market conditions.

The well pad preparation phase involves land clearing and other activities similar to many types of construction activities. Various chemicals are used to drill and complete the well. The completion step often includes the process of hydraulic fracturing. Following hydraulic fracturing, pressure is released and the injected fluids, along with natural brines in the source rock, flow back to the surface during a period referred to as flow back.[1] Once a well is completed, it enters the production phase during which fluids continue to flow to the surface with the composition of the fluids increasingly dominated by natural brines over time. This fluid is commonly referred to as produced water, and must be managed properly along with flowback, drilling muds and drill cuttings, and other wastes.

During the development of a well or production, exposures can be associated with vehicle exhaust and emissions from various types of equipment (e.g., drill rig engines, drill mud recycling equipment, flowback equipment, hydraulic fracturing engines, compressors, and pneumatic devices). Pneumatic controllers are used to operate valves that control liquid level, pressure, and other process variables, while pneumatic pumps use gas pressure to drive a fluid by raising or reducing the pressure of the fluid.

UOGD EMISSIONS AND TRANSPORT PATHWAYS

UOGD processes can release methane, VOCs, and other pollutants of concern to human health. UOGD emissions can occur on or off well pads, originating from equipment (e.g., drill rigs, shakers, frac engines, separators) and other point and mobile sources or resulting from releases (e.g., leaks, venting from storage tanks, equipment maintenance, or volatilization from surface spills). These emissions can vary significantly in composition and quantity depending on the specific processes and equipment used. Liquid unloading can be an important source of emissions; this process involves clearing liquids (i.e., water and liquid hydrocarbons) that have accumulated in mature gas wells and that can slow or even halt gas production. The flaring of natural gas is an important source of emissions in some oil-producing regions where gas is produced along with oil, but insufficient infrastructure is available to transport and sell the gas. For this reason and others (e.g., safety), natural gas is sometimes burned (i.e., flared).

After emission into the environment, chemicals are dispersed and can react in the atmosphere, leading to widely varying concentrations and potential exposures at local and regional scales.[2-6] A few studies have used air quality monitoring data or modeling to address regulatory needs, such as assessing setback distances between UOGD and residences.[7-10]

UOGD EXPOSURE

A growing body of scientific literature exists about human exposures to a range of potential exposures to chemical agents (e.g., radioactive material, indicators of produced water, and odorous compounds) and nonchemical agents (e.g., noise, light, and vibration) that can be associated with UOGD.[11-13] While many of these studies provide valuable information for understanding population exposures, only a small group of studies have been conducted with the direct aim of estimating potential air pollution and noise exposures to UOGD.[14-18] Knowledge gaps remain about these exposures to understand potential impacts on health.

STUDY OBJECTIVES

The Collett research team sought to assess population exposure to chemical emissions and noise associated with UOGD in the Northern Front Range region of Colorado, which is located within the Denver-Julesburg Basin. Colorado's changing regulatory environment has driven innovation to better protect human health and the environment, making the study location valuable for comparisons with previous observations to assess whether new operational practices have reduced effects on air quality, and by extension, exposures in surrounding communities.

The investigators developed the following three aims:

Aim 1: Identify complete exposure pathways that connect hazardous air pollutants (HAPs) and other emissions from UOGD to nearby populations on the Colorado North Front Range.

Aim 2: Characterize the range of exposure to A- and C-weighted noise from UOGD operations, focusing on distances relevant to Colorado regulatory requirements.

Aim 3: Contextualize air pollution measurement and modeling results at health-relevant temporal (i.e., acute and chronic) and spatial (i.e., potential setback distances) scales. Develop a stakeholder-friendly model to characterize air emissions and their impacts from new well development.

Briefly, to address Aim 1, Collett and colleagues monitored emissions from UOGD well pads at fine spatial and temporal scales over the life cycle of well development and early production using fixed-site and mobile monitoring methods. The team conducted a specific study of emissions from the use of synthetic drilling muds, which have been used to reduce odors associated with conventional, petroleum-based drilling muds.

For Aim 2, the team deployed a noise monitoring platform to simultaneously measure A- and C-weighted noise along with octave band measurements and noise level-based triggered recording at two locations at distances from UOGD activities that are relevant to Colorado regulations.

For Aim 3, the team compared observed concentrations of benzene and other HAPs to established health-based guidelines to assess risk for those living near UOGD operations. They examined how UOGD emissions have changed in the study location because of evolving operational practices. They also developed and tested a new emissions model designed to be a practical, user-friendly tool to predict the effect of UOGD preproduction activities on air quality.

SUMMARY OF METHODS AND STUDY DESIGN

AIM 1: IDENTIFY COMPLETE EXPOSURE PATHWAYS CONNECTING UOGD EMISSIONS TO NEARBY POPULATIONS ON THE COLORADO NORTH FRONT RANGE

Collett and colleagues sought to improve understanding of air quality and noise exposures near UOGD by monitoring four large UOGD well pads overseen by three major Denver-Julesburg Basin operators at three locations in the Colorado North Front Range. The sites were selected to characterize preproduction phases using modern practices (i.e., electrified and grid-powered drilling operations, low-odor drilling muds, and operational modifications to minimize flowback emissions) and because the well pad operators committed to providing on-pad activity data. Monitoring took place from October 2022 to August 2024.

Fixed-Site and Mobile Monitoring

Previously, few studies characterized HAP emissions from preproduction processes. The team addressed this knowledge gap in studies they conducted between 2013 and 2022, but questions remained about how evolving UOGD practices and some less-studied processes (e.g., coiled tubing/millout, use of synthetic, low-odor drilling muds, use of closed-loop, tankless fluid-handling systems) influence emissions. In the current study, the team aimed to address these questions by monitoring the well-development life cycle, specifically during drilling, hydraulic fracturing, coil tubing/millout operations, flowback, and early production. The team monitored methane and speciated VOC concentrations near the well pads as well as background locations and used UOGD operator-provided timelines of on-pad activities to link specific processes to monitoring results. One operator provided drilling mud samples, which allowed the team to examine how emissions differed between older and newer formulations.

Collett and colleagues conducted fixed-site and mobile monitoring primarily of methane and VOCs, some of which are HAPs, and to a lesser extent, particulate matter ≤2.5 µm in aerodynamic diameter ($PM_{2.5}$) and nitrogen oxides (NO_x). Fixed-site monitoring was conducted using the Colorado Air Monitoring Mobile Lab (CAMML) at a 1-hour time resolution necessary to capture acute exposures. To provide additional spatial coverage to further detect transient plumes that might be associated with elevated acute exposures, the team used photo-ionization detector sensors (SPODs) with triggered canisters deployed around each well pad, typically within 1,500 feet. When the SPOD response exceeded a prespecified threshold, a canister was triggered to take a 1-minute sample. The team periodically conducted mobile monitoring to locate and identify source plumes, and once identified, collect a 1-minute air sample. To understand longer-term exposures, the team deployed evacuated canisters at two locations near each well pad to quantify weekly average concentrations at the well pad and at one regional background location corresponding to the well pad.

The team reported monitoring results by well pad and operational phase, commonly grouping analytes as follows: ethane, C8–C10 alkanes, benzene, BTEX (benzene, toluene, ethylbenzene, xylenes), the sum of 20 VOCs measured by the CAMML, and the sum of 49 VOCs measured by the canisters. Ethane and other alkanes are useful for identifying UOGD sources, while BTEX and n-nonane are of particular concern for human health. Wind direction data collected by SPODs were used to exclude transient plume samples that were likely to be affected by sources other than the well pad. One-minute VOC concentrations collected in plume-triggered canisters were extrapolated to 1-hour concentration estimates.

Synthetic Drilling Mud Outgassing Experiment

The research team supplemented its monitoring with an experiment to measure outgassing from a relatively new type of synthetic drilling mud that is used by many operators in the Denver-Julesburg Basin to avoid the odor complaints associated with petroleum-based drilling muds. In a previous study of drilling mud outgassing conducted by members of the research team,[19] they observed differences in outgassing from the two types of drilling mud. In the current study, they conducted laboratory headspace analyses with drilling mud samples from a well pad operator to better characterize the origin and composition of emissions observed with the air monitoring program and to test the influence of temperature on emissions. The team was also permitted to collect air samples on a well pad during horizontal drilling operations at key locations where drilling muds and drill cuttings were handled.

AIM 2: CHARACTERIZE AUDIBLE AND LOW-FREQUENCY NOISE FROM UOGD OPERATIONS

Because UOGD operations have been the subject of noise complaints,[20,21] the research team supplemented its monitoring of atmospheric VOC concentrations at two study sites with monitoring of A- and C-weighted noise levels at multiple locations near the well pads. Studied pads had sound walls designed to minimize noise beyond the well pad footprint. The research team listened to audio recordings for triggered events to distinguish sounds from UOGD and other noise sources, such as birds, train whistles, thunder, and automobiles, and they excluded noises from these other sources from the dataset.

AIM 3: ESTIMATE EXPOSURES AT TIMES AND LOCATIONS RELEVANT TO POPULATION HEALTH AND DEVELOP A USER-FRIENDLY MODEL TO PREDICT EXPOSURES FROM NEW WELL DEVELOPMENT

Significance of HAPs Concentrations for Human Health

The research team estimated chronic and acute health hazards for nearby residents potentially exposed to HAPs emissions from UOGD operations to assess the significance of HAPs monitoring data for health. The team focused on selected HAPs and compared the concentrations to their corresponding acute and chronic health guidelines to assess the potential for noncancer health effects. The research team did not estimate cancer risk given the relatively short durations of the operations.

Significance of Noise Levels for Human Health

Colorado's Energy & Carbon Management Commission (ECMC) specifies minimum and maximum compliance points of 350 feet and 1,975 feet, respectively, which are distances from well pad centers where compliance with ECMC's noise requirements is assessed. The research team used equations from ECMC regulations to estimate noise levels at these two distances and compared them to regulatory and health-based noise thresholds established by ECMC, the US Environmental Protection Agency (EPA), the European Environmental Agency (EEA), and the World Health Organization (WHO) (see Investigators' Report Table 4).

Assessment of Colorado's UOGD Setback Distance for Sensitive Land Uses

Colorado requires a 2,000-foot setback between new wells and sensitive land uses, such as schools and homes, although the rule allows for some specific exceptions. To assess whether this setback distance is protective of human health, the research team combined its air monitoring observations with the AERMOD dispersion model to predict HAPs concentrations at various distances from a well pad.

TRACER Preproduction Model

The research team used findings from this study and its earlier UOGD emissions research in the region to construct the TRACER (TRAcking Community Exposures and Releases) preproduction model. The model predicts the effects of various UOGD preproduction activities on VOC emission timelines and on air quality as a function of distance from well pad operations. Model users are able to explore how different preproduction management practices and changes in meteorology affect emissions and potential air toxics exposure. They constructed the model using emissions data gathered in previous research and subsequently evaluated the model using data from the current study. This approach allowed field observations from this study to be used independently to test the TRACER model predictions.

The research team was uniquely positioned to develop the tool, given its history of collecting UOGD-related emissions data around a variety of operations over the last decade or so, and they used these data to construct and evaluate the model. They also compared model predictions with those from the EPA 2020 Nonpoint Oil and Gas Emission Estimation Tool (hereafter, EPA Emission Tool).

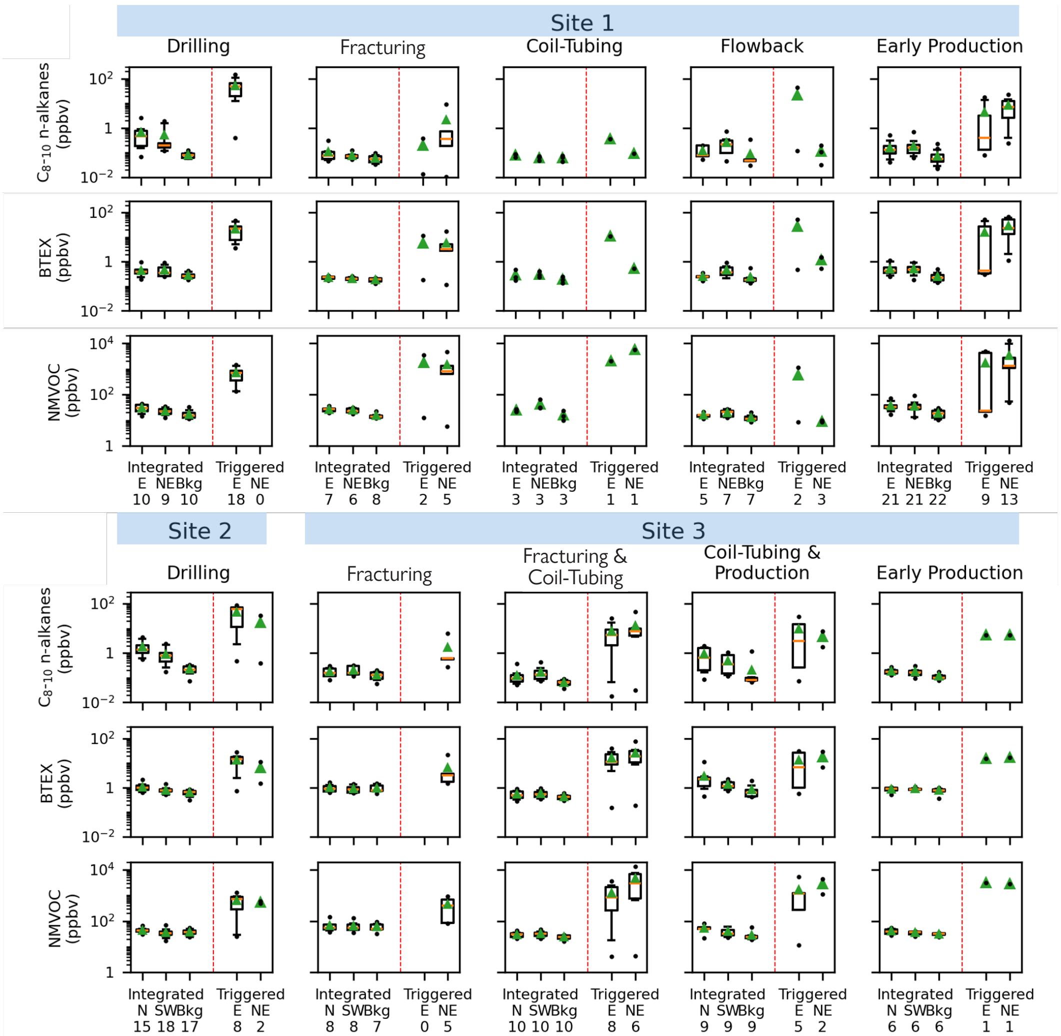
SUMMARY OF KEY RESULTS

IDENTIFY COMPLETE EXPOSURE PATHWAYS CONNECTING UOGD EMISSIONS TO NEARBY POPULATIONS ON THE COLORADO NORTH FRONT RANGE

Assessing Links Between Specific Operations and Atmospheric Concentrations of HAPs

The research team linked weekly and triggered canister periods and activities using time stamps for each sample and activity logs provided by well pad operators that describe the corresponding UOGD operations underway (**Commentary Figure 1**). Observed concentrations vary considerably among UOGD operations. Modest concentration increases of many VOCs were evident around the well pads during preproduction activities, but much higher concentrations were observed in PID-triggered canister samples associated with intermittent plumes.

The research team previously reported VOC field measurements from UOGD operations in the Piceance and Denver-Julesburg basins, where they quantified large emission rates of benzene and other VOCs during well flowback operations.[22] As part of the current project, the team inverted VOC concentration fields obtained through a separately sponsored UOGD air monitoring campaign in Broomfield, Colorado, to determine emissions associated with current operational practices in the Denver-Julesburg Basin, including use of



Commentary Figure 1. Concentrations of selected VOCs at the three study sites that were linked to various UOGD operations. Results are presented for the background location and two near-pad monitoring locations at each study site. Weekly average concentrations ("Integrated") and background ("Bkg") are shown on the left of each panel, and two plume canister samples ("Triggered") on the right. Wind directions indicate the position of the sampling locations from the well center. The box and whisker plots depict the median (line), 25th and 75th (box), 5th and 95th (whiskers) percentiles of the measured concentrations along with individual points that fall outside these values. Beneath the sample locations are the number of samples. Data points and mean values are presented directly if the sample size is smaller than 5. Source: Investigators' Report Figure 2.

grid-powered, electrified drill rigs and synthetic drilling muds and closed-loop, tankless fluid-handling systems. By comparison, results from the current study indicate that the use of "closed-loop, tankless fluid-handling systems can reduce flowback emissions of benzene by more than 98% relative to other, recent green completion operations" reported by Hecobian and colleagues. These analyses also provide new estimates of speciated VOC emissions from conventional, petroleum-based, and synthetic drilling muds and provide the first estimate of speciated VOC emission rates from coiled tubing/millout operations.

Synthetic Drilling Mud Outgassing Experiment

In its experimental headspace analyses, the research team identified 14 VOCs that were strongly associated with drilling mud outgassing, with large fractional contributions represented by n-octane, n-nonane, n-decane, and methylcyclohexane. They noted minimal variability in composition across replicates or with changing temperature, found similar emission profiles in VOC emissions captured in plumes emitted during drilling operations, and concluded that the composition "fingerprint" provides a tool for identifying the influence of emissions from Neoflo, a popular synthetic drilling mud.

AUDIBLE AND LOW-FREQUENCY NOISE FROM UOGD OPERATIONS AT DISTANCES RELEVANT TO COLORADO REGULATORY REQUIREMENTS

The research team compared noise parameters for A- and C-weighted noise to the Colorado ECMC thresholds for chronic noise at ECMC minimum and maximum compliance points from the well pad center during all monitored UOGD activities. At the minimum compliance point of 350 feet, both A- and C-weighted noise consistently exceeded ECMC thresholds for chronic noise. At the maximum compliance point of 1,975 feet, C-weighted noise consistently exceeded ECMC chronic thresholds during drilling and hydraulic fracturing and intermittently during coiled tubing/millout operations.

However, A-weighted noise at the maximum compliance point did not exceed ECMC chronic thresholds except intermittently during hydraulic fracturing.

COMBINING AIR POLLUTION MEASUREMENT AND MODELING TO ASSESS HEALTH RISK AND DEVELOPING A USER-FRIENDLY MODEL TO CHARACTERIZE POTENTIAL IMPACTS FROM NEW WELL DEVELOPMENT

Significance of Potential Population Exposures to UOGD

The research team assessed the significance of HAPs monitoring data for health by estimating screening-level noncancer hazards for nearby residents potentially exposed to HAPs emissions from UOGD operations. As noted earlier, the research team did not estimate cancer risk given the relatively short durations of the operations studied. The noncancer hazard calculations included seven HAPs: benzene, n-hexane, n-nonane, m,p-xylenes, o-xylene, toluene, and ethylbenzene. Weekly (and mean activity duration) and 1-hour average concentrations of each HAP were divided by their chronic and acute HGVs for inhalation exposure, respectively, to quantify noncancer hazard quotients (HQs) (**Commentary Figure 2**).

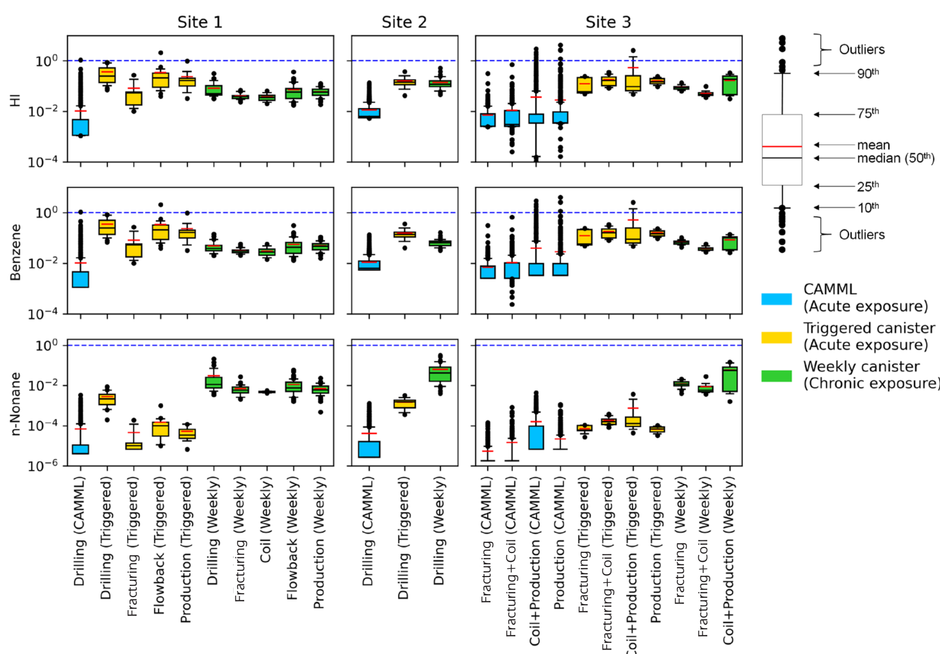
To estimate the noncancer hazard associated with cumulative exposure to the seven HAPs, the research team added the individual HQs to estimate a hazard index (HI). As shown in Commentary Figure 2, the chronic HIs (green bars) for benzene alone and in combination with the six other HAPs are all less than one, suggesting that no adverse health effects are expected. For acute noncancer HIs (blue and yellow bars), a few exceed one across most operation categories except hydraulic fracturing.

The research team collected data over time and spatial scales that are relevant to understanding exposures to air pollution and noise that could be experienced by nearby populations. They assessed the significance of noise monitoring data for health by comparing the results to applicable health thresholds from the US EPA, EEA, and WHO. No A- or C-weighted noise parameters exceeded the US EPA's 70 dBA auditory guideline for tinnitus. However, both parameters consistently exceeded WHO and EEA health guidelines at Colorado's minimum compliance point of 350 feet from the center of the well. At Colorado's maximum compliance point of 1,975 feet, the levels consistently exceeded the EEA health guideline for hypertension and the WHO guidelines for sleep disturbance.

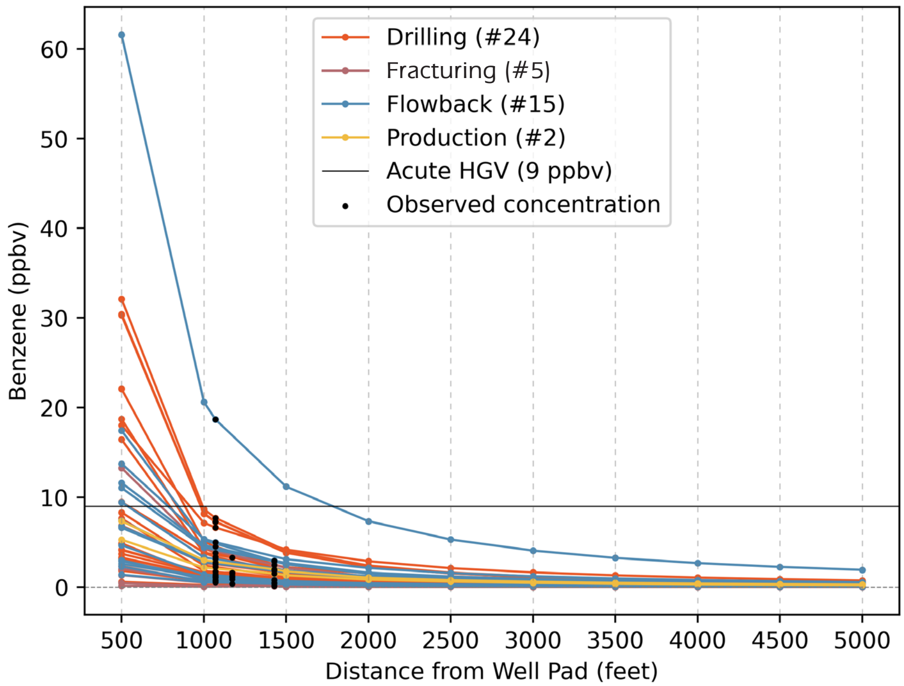
Protectiveness of Colorado's UOGD Setback Distance

Given that some acute HIs exceeded 1 at site measurement locations, the research team set out to determine whether Colorado's 2,000-foot setback requirement would protect against the potential for noncancer health effects among members of nearby populations. Because benzene dominated HI calculations, they used benzene concentration observations to constrain benzene emissions in an AERMOD dispersion model simulation to predict benzene concentrations at various distances from two studied well pads (**Commentary Figure 3**). The results suggest that the 2,000-foot setback requirement is protective for all UOGD operations at the two study well pads. Higher benzene concentrations are expected at closer distances and in operations where emissions are not as tightly controlled as they were at the well pads included in this study.

TRACER UOGD Preproduction Emission Model



Commentary Figure 2. Distributions of hourly (acute) and weekly (chronic) HIs associated with benzene alone (bottom panels) and combined with six additional HAPs (top panels) for various UOGD operations at the three study sites. HIs were calculated by dividing results from monitoring with the CAMML, triggered canisters, and weekly canisters by acute and chronic health guideline values recommended by the State of Colorado. The blue dashed line indicates an HI of one, above which adverse health cannot be ruled out. Source: Modified from Investigator Report Figure 8.



Commentary Figure 3. Predicted hourly benzene concentrations as a function of distance from the well pad during 46 hours of plume-triggered canister collection at study sites 1 and 2. Results are shown by operation type. Concentrations are simulated using AERMOD at 500-foot intervals, along the plume centerline, with benzene emission rates constrained so that simulated and observed (black dots) concentrations match. A horizontal line is plotted at 9 parts per billion by volume (ppbv) of benzene, the acute health guideline value (HGV). Source: Investigator Report Figure 10.

The team developed the TRACER UOGD preproduction emission model to provide a tool that can predict HAPs and other VOC emissions from UOGD operations at distances relevant to understanding local population exposures. This tool can be used to predict emissions from planned drilling and completion operations, and it can also be used to assess specific efforts or interventions to reduce UOGD effects on air quality.

They designed the model's graphical user interface as a user-friendly, stand-alone Windows application (**Commentary Figure 4**). On the left side of the interface, users choose an operation timeline and can select from a variety of UOGD preproduction activities, such as drilling and hydraulic fracturing, and adjust emission factors using data from a variety of sources. Users can also alter dispersion conditions to assess effects on modeled concentration fields. On the right side of the interface, users can view plots illustrating the model's predictions.

HEI ENERGY REVIEW COMMITTEE'S EVALUATION

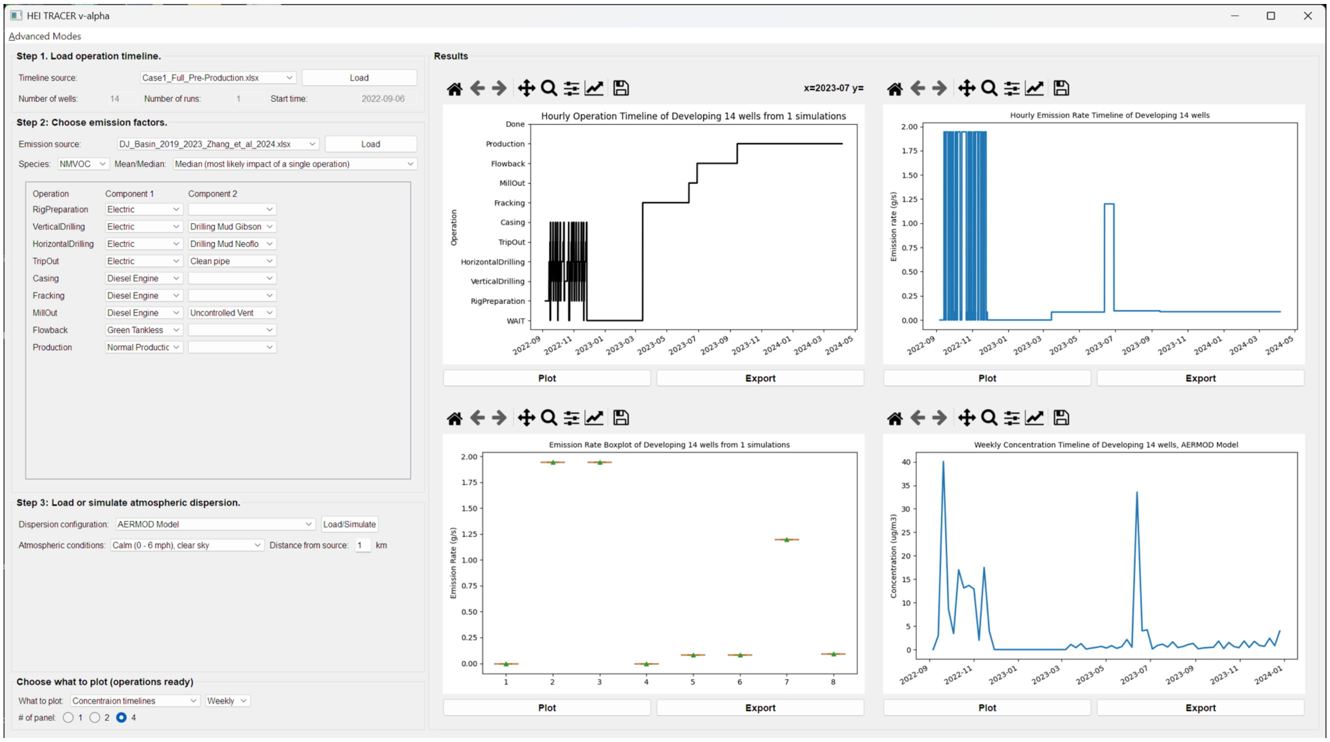
In its independent review of the study, the HEI Energy Review Committee thought the study provided novel measurements that document links between air quality and noise monitoring data with specific UOGD operations, information that is vital to address exposures of concern for surrounding populations in an important US oil and gas region.

Observed HAP concentrations varied considerably among UOGD operations, with the highest concentrations associated with intermittent plumes. The team did not identify any chronic health hazards associated with UOGD processes but noted the potential for noncancer health concerns in some instances, primarily during coil tubing/millout and other production operations that produced concentration spikes.

STRENGTHS OF THE STUDY

The Committee agreed with the overall results and noted several important strengths of the study:

- Employing a robust combination of continuous monitors and triggered canister samples enabled the research team to capture both longer-term trends and short-term peak concentrations with detailed VOC profiles.
- Meticulous examination of air emissions during various phases of UOGD operations provided valuable insights into how emissions vary across the life cycle of a well pad. The cooperation of companies in sharing daily activity information strengthens the association between emissions and specific UOGD operations.
- Measurements at background sites helped to better identify the specific contributions of UOGD activities to local air quality.
- The inclusion of both A- and C-weighted noise measurements provides a more complete understanding of the effects on local populations by addressing both audible and low-frequency noise concerns.
- The focus on a region where evolving state governance has driven changes in UOGD operations to better protect human health and the environment provides an opportunity to assess the impact of the new practices. For example, study findings illustrate the value of Colorado's relatively new 2,000-foot setback requirements under operational and environmental conditions in this study.
- The Committee concluded that the TRACER preproduction emissions model would be of broad interest and value to state and federal authorities, the oil and gas industry, research scientists, and local communities. This value is illustrated by the fact that the team has already had requests from several stakeholders to participate in beta testing.



Commentary Figure 4. Example of the graphical user interface of the TRACER preproduction model. Source: Investigator Report Figure 12.

- The focus on modern UOGD practices provides timely and relevant data for policy decisions by government and industry.

LIMITATIONS OF THE STUDY

The Committee noted a few limitations of the study. The study's generalizability is limited because it only includes data from four well pads in three locations within a single region. Although the study offers valuable insights into a state known for its leadership in UOGD governance, this uniqueness may further restrict its applicability to other regions. The Committee appreciated the research team's measurement of NO_x and $PM_{2.5}$ with the CAMML but felt that the study would be enhanced with analyses of these data.

INTERPRETATION AND RECOMMENDATIONS FOR AREAS OF FUTURE WORK

The team reported that the highest HAP concentrations were observed when sampling was triggered by intermittent plumes that occurred primarily during coil tubing/millout. Previously, the research team reported VOC field measurements from UOGD operations in the Piceance and Denver-Julesburg basins, where they quantified large emission rates of benzene and other VOCs during well flowback operations (Hecobian et al. 2019). By comparison, results from the current study indicate that the use of "closed-loop, tankless fluid-handling systems can reduce flowback emissions of benzene by more than 98% relative to other, recent green completion operations." This is important new information that would be useful to replicate in other locations.

The research team was uniquely positioned to develop the TRACER tool, given its history of collecting UOGD-related emissions data around a variety of operations. The results indicate that the TRACER model performed better than the EPA Emission Tool, especially during drilling and coiled tubing. It should be noted that the EPA Emission Tool incorporates some emission factors that have limited applicability to modern UOGD operations. For example, emission factors for drilling mud degassing are based on a decades-old US EPA report focused on offshore oil and gas operations, and it does not include coiled tubing/millout operations at all.

While the TRACER model improves the prediction of preproduction emissions, the research team describes three limitations that could be addressed with further research.

1. Emission rates for specific operations can vary substantially, and model predictions could be improved with a better understanding of the frequency and magnitude of high-emission events.
2. The model is based on observations of UOGD operations in the Denver-Julesburg Basin that may not be fully applicable to other basins with different operators and environmental conditions.
3. The observed discrepancies between observed VOC concentrations during early production and model simulations might indicate that the current study does not fully reflect recent operational changes or increased emissions from equipment failure or maintenance. The Committee agrees with these recommendations.

This study highlights the need to understand transient, or acute, exposures, which were sometimes observed to exceed relevant health guidelines (unlike chronic exposures, which did not exceed guidelines). The TRACER model currently incorporates mean emission rates for specific operations and does not capture the variability in emissions. Recognizing the research observations of substantial variability in emission rates for specific UOGD operations, the research team and the Research Committee noted the opportunity for additional investigations targeting a better understanding of the frequency and magnitude of high-emission events and the operations that give rise to these events.

Because the research team measured NO_x and $PM_{2.5}$ concentrations with the CAMML but did not have the opportunity to analyze those data, the Committee encourages the team to continue to analyze these data carefully and consider whether they might be incorporated into the TRACER model.

Finally, the Committee appreciated the screening-level assessment of noncancer hazard associated with local population exposure to HAPs emissions while recognizing the uncertainty associated with such calculations. They narrow the scope of exposures that merit further investigation under UOGD operational conditions in this study.

CONCLUSIONS

In HEI Energy's original series of research planning workshops that resulted in the RFA under which Dr. Collett was funded, state officials, industry, and other stakeholders repeatedly voiced a need for setback distances that are informed by scientific data rather than driven by arbitrary choices. This study contributes significantly to answering the underlying question about how close is too close, at least in the context of the Colorado-based UOGD operations evaluated in this study. Importantly, the study highlights UOGD operations that may be associated with acute exposures of potential concern for health. In so doing, the study not only improves understanding of potential population exposures associated with UOGD, but it also provides a data-driven assessment of Colorado's setback requirements. The TRACER preproduction emissions model provides a means to predict emissions and their effect on air quality from planned UOGD operations; the model can also be used to assess specific efforts or interventions to reduce UOGD effects on air quality.

ACKNOWLEDGMENTS

The HEI Energy Review Committee thanks the ad hoc reviewers for their help in evaluating the scientific merit of the Investigators' Report. The Committee is also grateful to Donna Vorhees for her oversight of the study, to Cloelle Danforth for assistance with review of the Investigators' Report and in preparing its Commentary, to Tara Hamilton for editing the Investigators' Report and its Commentary, and to Kristin Eckles and Hope Green for their roles in preparing this Research Report for publication.

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