

# Ethylene Oxide: An Air Contaminant of Concern

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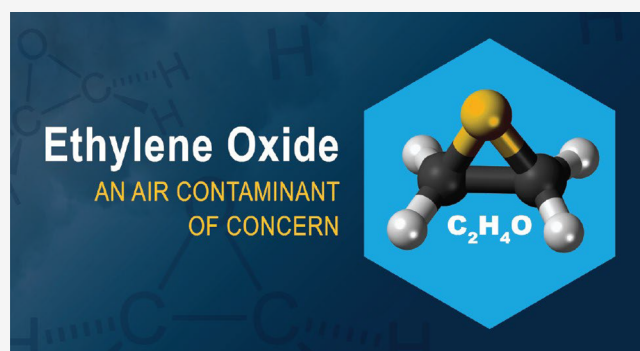
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**ABSTRACT:** Ethylene oxide (EtO) is a colorless, flammable, reactive gas commonly used for sterilization and chemical manufacturing. It has become a contaminant of concern for the United States Environmental Protection Agency (USEPA) due to an assessment of its toxicity, which found that EtO is more potent than had been previously understood and which also revised the weight-of-evidence classification of EtO from “probably carcinogenic” to “carcinogenic to humans”. With the revised toxicity assessment came findings of increased cancer risk to communities near some facilities that emit EtO to ambient air, including communities with environmental justice (EJ) concerns. To address EtO, the USEPA has conducted intensive research in recent years, centering its attention on measurement and sampling technology development, as well as monitoring of EtO in source emissions, near-source air, and atmospheric environments to further support science-based policy and regulations that reduce harmful impacts to human health. Research efforts by government, academic, and commercial institutions have resulted in the development of novel measurement and monitoring techniques, which has led to more robust characterization of EtO emissions and atmospheric levels across a wide range of concentrations, including trace levels (ppt). This Perspective covers the importance of capturing high quality, analytical measurements of EtO, what is known so far about these measurement technologies, EPA’s response to the increasing concerns of EtO contamination, what still needs to be accomplished on the air quality front, and a focus on USEPA research and development moving forward.

assessment for EtO that characterized it as carcinogenic to humans by the inhalation route of exposure and established an updated inhalation unit risk estimate (URE).<sup>4</sup> Because EtO is mutagenic (i.e., it damages DNA), an age-dependent adjustment factor is applied to the URE when assessing lifetime risks to account for childhood exposures. The age-adjusted inhalation URE for EtO is 0.005 per  $\mu\text{g}/\text{m}^3$  and is nearly 60 times higher than the California EPA (CalEPA) inhalation URE<sup>5</sup> that the USEPA was using previously for EtO air toxics risk assessments.

**KEYWORDS:** ethylene oxide, air emissions, measurements and monitoring, continuous sampling, time-integrated sampling, sampling and analysis



## BRIEF HISTORY AND CHALLENGES ASSOCIATED WITH ETHYLENE OXIDE

The United States Environmental Protection Agency (USEPA) defines ethylene oxide (EtO or EO) as a colorless, flammable, and reactive gas listed and regulated under the Clean Air Act (CAA) as a hazardous air pollutant (HAP) and listed and regulated as an antimicrobial agent under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). Due to its physical properties, EtO is predominantly transported through air. It also degrades rapidly, surviving approximately 2–5 months in ambient air, with temperature and humidity being key factors determining its lifetime.<sup>1,2</sup> Ethylene oxide is not anticipated to persist in soil or water, as it volatilizes rapidly. The World Health Organization<sup>3</sup> estimates the half-life in soil and groundwater is 10.5 and 11.9 days, respectively, and it is therefore not expected to accumulate in either. That said, there are no published data on soil or groundwater EtO accumulation, which perhaps warrants further investigation. Because EtO emissions transport and remain in ambient air for up to 5 months and due to the toxicity of EtO, inhalation is the primary human exposure pathway of concern. In 2016, the USEPA issued a toxicological

Based on the updated inhalation URE of 0.005 per  $\mu\text{g}/\text{m}^3$ , the concentration of EtO associated with an increased risk of 1 in 10000 people developing cancer over a lifetime (~70 years) of continuous exposure is 0.02  $\mu\text{g}/\text{m}^3$ , or approximately 11 parts per trillion (ppt). Since the final IRIS assessment was

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published in 2016, the USEPA has determined that EtO emissions to air can contribute to increased cancer risk for this high priority HAP. Populations working or living near facilities that manufacture or use EtO can be at a greater risk of exposure and, subsequently, increased cancer risk. EPA is therefore interested in reducing this risk in and near communities, including communities with EJ concerns.<sup>6–10</sup> Elevated risk varies based on exposure factors including emissions rate, duration, and pollutant level among other dependent variables.<sup>11</sup> Additionally, in 2019 the National Environmental Justice Advisory Council (NEJAC) expressed concerns to USEPA that communities with EJ concerns are disproportionately exposed to EtO, requesting regulations to protect public health, particularly for workers and those who are most vulnerable to EtO-related health threats.<sup>12</sup>

At the time the updated URE was determined, commercially available techniques capable of making quality EtO measurements at concentrations of less than 0.02  $\mu\text{g}/\text{m}^3$  were unavailable. Consequently, the sampling, measurement, and monitoring of EtO in source emissions, near-source air, and atmospheric environments has rapidly evolved into an important air quality research topic of broad interest. Such research aims to provide an improved understanding of potential source contributions and background concentrations of EtO and develop novel measurement and monitoring solutions to further support sound human exposure assessments, science-based policy, and regulatory strategies. The USEPA defines background EtO as any EtO “in outdoor air that is not clearly linked to a particular industrial facility, such as a chemical plant or commercial sterilizer”.<sup>13</sup> The USEPA continues to work toward a better understanding of what background concentrations of EtO are nationally. Still, further research is needed due to the challenges posed by current, available measurement methodologies (e.g., adequate sensitivity, stability of reference materials, and sampling and analytical bias).

Achieving accurate and precise measurements of EtO in air is a critical first step in understanding background concentrations of EtO, exposures, mitigation possibilities, and potential human health impacts. Additionally, quantifying source contributions, improving the confidence in dispersion model inputs, and identifying future sites for long-term monitoring will all require high-quality and accurate EtO concentration data. This perspective examines the successes and challenges in rapidly evolving EtO research investigating analytical-chemical, sampling, methodological, instrumental, and data science techniques for measuring and monitoring EtO in various air environments over relevant spatial and temporal scales. Recognizing that research and development associated with measurement of EtO in the environment is in its infancy, several fundamental challenges relevant to air quality must be addressed, including gaining a better understanding of underlying background EtO concentrations, determining the extent of EtO reactivity in the atmosphere, deciphering potential source contributions, and evaluating the technical feasibility of control and mitigation.

## ■ KNOWN ETO SOURCES AND POINTS OF RELEASE

EtO is commonly used as a sterilizing agent by the medical and food industries and as an intermediate in chemical manufacturing, yielding a broad range of products like antifreeze, solvents, textiles, plastics, and detergents.<sup>11</sup> Prior to its use, EtO requires bulk transfer and transport and may

require loading into pipelines, marine vessels, rail cars, and on-road tanker trailers. EtO is subject to accidental spills, leaks, and releases during transport. It is among the most dangerous chemicals to transport and store in bulk due to its flammability and low ignition energy.<sup>14</sup>

In 2019, approximately 116 tons of EtO were emitted into the atmosphere by stationary industrial sources.<sup>15</sup> In the U.S., commercial sterilization and chemical manufacturing industries contributed approximately 44% and 54%, respectively, of industrial EtO emissions to air, for a total of 98% of known EtO emissions from sources.<sup>16</sup> The scale of the commercial sterilization process can vary with the application (e.g., small benchtop sterilizers used in medical offices up to full-scale commercial sterilizers processing large batches of spices or medical equipment). For instance, the Center for Disease Control and Prevention (CDC) offers guidelines for the medical sterilization process, including multiple stages of preconditioning and humidification, followed by EtO gas introduction into a chamber or room, subsequent product exposure, evacuation, and air washes.<sup>17</sup> The final aeration stage for EtO desorption may take 12 or more hours, depending on the material being sterilized and the chamber volume used. For the indoor workplace, the Occupational Safety and Health Administration (OSHA) has established a permissible exposure limit of 1 ppmV EtO as the total weighted average for an 8 h shift in a 40 h work week.<sup>18</sup>

Presently, state and federal authorities, including the USEPA, have taken actions to reduce EtO emissions to air from industrial sources. The USEPA has proposed requirements, under the CAA, that would reduce EtO emissions from chemical manufacturing and commercial sterilization facilities,<sup>8,9</sup> lowering the exposure risk for people residing near those facilities. Under FIFRA,<sup>10</sup> EPA has proposed requirements for facilities using EtO as a sterilizing agent, and those requirements would reduce risks to workers and further reduce risks to people residing near commercial sterilization facilities. As part of the requirements proposed by the USEPA, facilities must perform periodic monitoring evaluations.

Other potential biogenic, pyrogenic, and anthropogenic sources of EtO are currently being investigated by the USEPA, state and local government agencies, and the scientific community. However, to date, there is scant definitive scientific evidence showing that these potential sources significantly contribute to atmospheric EtO concentrations.

## ■ AVAILABLE ETO SAMPLING, MEASUREMENT, AND MONITORING TECHNOLOGIES

Accurate EtO measurements are essential to understanding source contributions and exposures. Various sampling techniques and optical and mass spectroscopy instrumentation can now detect and quantify EtO. Table 1 provides information on select commercially available measurement technologies and instrumentation, illustrating the variety of methods currently employed for EtO measurement. The sensitivity, dynamic range, and reproducibility vary by instrument technology and the conditions under which measurements are conducted. With such variation, it is critical that method detection limits (MDL) be established to ensure data quality of specific applications, particularly when measuring EtO at trace levels in ambient air.<sup>19,20</sup> Sampling and analysis are performed by using both manual and automated techniques. Real-time, continuous EtO measurements can be performed directly in the field, while time-

Table 1. Sampling Techniques and Commercially Available Instrumentation for Quantifying EtO<sup>a</sup>

technology	sampling type (rate)	suggested application	potential limitations	potential vendors (if commercially available, model)
Fourier transform infrared (FTIR) spectroscopy	continuous	source/in-stack sampling	interference gases and water	Thermo MAX Analytical <sup>24</sup> (MAX-IR)
photoacoustic infrared (IR) spectroscopy	continuous	source/in-stack sampling	interference gases and water	Advanced Energy <sup>25,26</sup> (Innova)
mid-infrared (mid-IR) spectroscopy	continuous	near-source sampling	interference gases and water; inherent noise in signal	Aeris <sup>27,28</sup> (MIRA Ultra and Pico)
cavity ring-down spectroscopy (CRDS)	continuous	near-source and ambient sampling	interference gases and water; potential for use with front end preconcentrator or scrubber	Picarro <sup>29,30</sup> (G2920, G2910)
cavity ring-down spectroscopy (CRDS) with preconcentrator	semicontinuous	near-source and ambient sampling	not real-time measurement	Entanglement <sup>31</sup> (AromaVOC)
proton transfer reaction mass spectrometry (PTR-MS)	continuous	near-source and ambient sampling	interference gases and water	Ionicon <sup>32,33</sup> (T-6000x2)
quantum cascade or interband cascade tunable infrared laser direct absorption spectrometry (TILDAS)	continuous or time-integrated	near-source and ambient sampling	interference gases	Aerodyne <sup>34–37</sup> (TILDAS-CS and TILDAS-FD-EtO)
TO-15/TO-15A canister analysis by VOC preconcentration/gas chromatography/mass spectrometry (GC/MS)	time-integrated canister sample (passive or active sampling)	ambient and near-source	canister bias, coelution with VOCs	Entech, <sup>23,38,41</sup> (7200A)/Agilent (8890 GC-5977B MS)
modified OSHA method 1010	time-integrated sorbent tube or cartridge sample	ambient and near-source	variability in extraction recovery, coelution with VOCs	Agilent 8890 with electron capture detector <sup>25,29</sup>

<sup>a</sup>The mention of companies, trade names, or commercial products does not constitute endorsement or recommendation for use.

integrated samples are typically collected in the field and analyzed subsequently in a laboratory.

Analytical technique selection depends on the field application, expected concentration levels, required spatial and temporal resolution, overall method performance, and sample matrix, among other factors. Regarding the matrix, early evidence suggests that many compounds like methane, acetaldehyde, ethyl nitrite, trans-2-butene, and water interfere with EtO detection.<sup>21</sup> Eliminating these interferences may require the use of upstream driers, scrubbers, and preconcentration equipment. More study is required to determine the extent of these interferences and to correct additional, possible analytical, and chemical sources of interference. Table 1 shows that the use of a preconcentrator in tandem with cavity ring down spectroscopy (CRDS) may achieve as low as a 10 pptV detection limit and a dynamic range of up to 5 ppmV. An EtO concentration of 10 pptV represents a critical threshold value as it is just below the value associated with a one hundred-in-a-million-lifetime cancer risk for continuous adult exposure, as expressed above. Longer sample times of 5 to 30 min are required to achieve this sensitivity, which still allow for high temporal resolution. On-line CRDS without preconcentration is approximately an order of magnitude less sensitive (MDL < 100 ppt), sampling at 1–2 Hz with 2–10 min averaging times; these faster response times are potentially helpful for geospatial mobile mapping of EtO. USEPA Method TO-15A,<sup>22</sup> an integrated canister analysis that uses preconcentration and gas chromatography–mass spectrometry (GC-MS), can achieve detection limits of roughly 30 pptV or lower, with the USEPA research laboratories achieving detection limits of ~15 pptV.<sup>23</sup> Comparatively, TO-15A is a versatile method because it detects additional hazardous volatile organic compounds (VOCs), is standardized based on performance, is widely available, and is routinely used for regulatory purposes other than point source compliance. The disadvantages of TO-15A are that it is labor-intensive, practiced offline, and can suffer from canister reactivity, interferences, and analytical-chemical biases, which are discussed in more detail later. The USEPA is currently investigating the application of these methods and instrumentation techniques in its laboratories. Additional methods of potential interest to be investigated include Fourier-Transform infrared (FTIR) spectroscopy, photoacoustic infrared IR spectroscopy, proton transfer reaction mass spectrometry (PTR-MS), and Quantum Cascade-Tunable Infrared Laser Direct Absorption Spectrometry (QC-TILDAS). Still, many of the technologies discussed in Table 1, based on manufacturer self-reported detection capabilities and limited available literature, are less sensitive for measurement of EtO at this point, requiring further development and demonstration before being applied in the air environment to specifically characterize EtO.

## MEASUREMENT AND ANALYSIS CHALLENGES

Due to EtO's potency, it is expected that a wide measurement concentration range will be needed across a breadth of complex matrixes, including ultralow, trace-level concentrations in ambient air, concentrations at a variety of near-source and fenceline locations, and substantially higher concentrations under potentially corrosive source sampling conditions (e.g., in stacks). The practice of measuring VOCs using online, continuous, semi-continuous, and time-integrated techniques is already quite demanding, but measuring EtO introduces multiple additional challenges due to matrix interferences, an

incomplete understanding of background, source contributions, EtO emission trends, and the need to measure a wide concentration range ( $\sim 10$  pptV to 10 ppmV). These issues make it almost certain that multiple EtO measurement approaches will be needed and method selection will depend on the sampling conditions. Additionally, as advances in EtO measurement techniques push detection limits lower, extremely low concentration gas standards will be required (e.g., sub-ppbV) for instrument testing and calibration to ensure high-quality analysis and confidence in the results. That said, preparing reliable standards of reactive gases at trace concentrations is historically problematic.<sup>40</sup> Due to EtO's high volatility and reactivity, there are concerns associated with both time-integrated and real-time measurements,<sup>23</sup> and these issues may manifest themselves during either the sampling or the analysis stages. For example, the canisters used for Method TO-15A may exhibit positive canister bias.<sup>41</sup> Moreover, co-elution of EtO and other compounds is often observed in GC-MS chromatograms during TO-15A analysis.<sup>21</sup> There can also be EtO loss in sampling lines during fenceline or stack testing, depending on temperature, humidity, or the sample line materials in use.<sup>42</sup> Overcoming these challenges often requires testing and incorporating several measurement technologies on various platforms to adequately characterize EtO emissions and to be confident about data quality. For example, in the same field study, Thoma et al.<sup>43</sup> showed it is necessary to use time-integrated canister sampling at stationary sites inside a fenceline; however, for the areas outside the fenceline, TO-15A sampling and analysis are coupled with CRDS on a mobile platform.

A positive bias due to EtO growth in canisters following cleaning is among the most challenging issues with canister sampling. The USEPA is currently examining this phenomenon, but the growth is difficult to quantify due to the variability in canister linings (e.g., coating materials and thickness), type, history, age, and cleaning procedures. Preliminary results from a limited number of canisters tested in our laboratories over a 4–5 week period indicate that certain canister types may not be suitable for EtO monitoring. For example, compared with silicon-ceramic-coated canisters, electropolished stainless steel canisters show high positive bias when filled with humidified zero air.<sup>44</sup> Certain aspects of method TO-15 (e.g., blank canister certification and cleaning procedures) may not adequately identify problematic canisters. However, method TO-15A has updated procedures that include heated canister cleaning and more stringent canister cleanliness criteria in general.<sup>45</sup> Sufficient canister cleaning and certified blank checks are necessary before using canisters for EtO sampling. Because of this issue and irrespective of canister type, the USEPA recommends that the canister qualification procedures outlined in TO-15A be performed to evaluate and confirm that canisters are suitable for measurements of low-level EtO concentrations found in ambient or background air.

## ■ SAMPLE ANALYSIS AND DATA INTERPRETATION

Understanding the need, use, and purpose of EtO concentration data prior to field testing or sampling is critical to designing proper sample collection strategies and achieving sound data interpretation. For instance, obtaining continuous data to characterize EtO emissions and evaluate necessary emission control technologies is quite different from collecting data for characterizing EtO exposure risks. Modeling is typically used to evaluate exposure risk over the 70 year, 24

h lifetime exposure period. While there is currently no standard practice, attempting to estimate risk with a single sample or a small number of samples over a short period would be inappropriate, just as a single stack or fenceline sample would be inappropriate for evaluating emissions or controls. Next, we consider EtO concentration data and their use across the national air quality monitoring programs.

EtO was not previously included in the required target analytes measured in the National Air Toxics Trends Stations (NATTS) ambient air monitoring program,<sup>46</sup> but since 2019, some sites have been including EtO in the target analytes from canister analysis. EtO is listed as a quantifiable VOC by using TO-15/TO-15A, but no estimates of sensitivity or detection limits are provided. NATTS began analyzing EtO from canister samples using TO-15 in 2018. EtO monitoring also began at other non-NATTS air toxics monitoring sites (e.g., the Urban Air Toxics Monitoring Program) in 2018. Consequently, there are relatively limited EtO concentration data for air samples. The Air Quality System (AQS) is the USEPA's primary database for housing ambient air quality measurements collected by the USEPA, state, local, and tribal air pollution control agencies. Data for EtO is publicly available through AQS<sup>47</sup> and USEPA's AirData website.<sup>48</sup> Data in AQS are required to be appropriately flagged to indicate the data quality. Null flags are used to invalidate data, and qualifier flags provide users with information that may affect intended data use and results. Multiple agencies that support NATTS and non-NATTS (e.g., the Urban Air Toxics Monitoring Program or UATMP) monitoring programs load EtO data in AQS. USEPA provides NATTS sample analysis through a national contract laboratory and provides QA review of these data, which are available in AQS. Other non-NATTS EtO data in AQS, such as agency provided data using other laboratories, may have their own data quality management programs and do not receive data quality review by USEPA. In addition, EPA assesses NATTS laboratory bias through the Proficiency Testing (PT) program, described in the NATTS Technical Assistance Document.<sup>46</sup> Each laboratory analyzing samples on behalf of NATTS must participate in the PT program.

The EtO canister bias due to growth of EtO over time was identified in late 2020 and is often qualified in AQS with an "LK" (Analyte Identified; Reported Value May Be Biased High) or "LJ" (Identification of Analyte is Acceptable; Reported Value is an Estimate) flag by the analysis laboratory.<sup>47</sup> As mentioned, the positive canister bias is challenging to quantify and varies by canister type, vendor, age, history, and cleaning procedure. Because of this, reported ambient concentrations may vary widely, because the amount of EtO due to canister bias is uncertain. Despite this, there appears to be some seasonality in EtO concentrations measured across NATTS and the Urban UATMP monitoring locations. Quarterly average EtO concentrations appear higher in the spring and summer (April through September) than in the fall and winter (October through March).<sup>47</sup>

The USEPA recommends reporting all measured data to AQS, even if what is measured is below the MDL, assuming the data are valid and qualitative identification and quality assurance (QA) criteria are met.<sup>46</sup> Even if the data below the MDL have higher uncertainty, reporting all measured concentration data is more valuable for data interpretation than adding censored or substituted values. Values not detected are reported to AQS as zeros with the qualifier flag "ND" (No Value Detected, Zero Reported). When calculating

average values over the period of interest, removing zero values may negatively bias the resulting calculated statistics associated with the data, which may not meet the intended data use and, therefore, may not be realistic.

## ■ FUTURE RESEARCH NEEDS

Now that a variety of measurement techniques have been developed and are being utilized for a broad range of applications and concentrations, even while we work to drive sensitivities and detection limits lower, we must turn our focus to the next greatest need: establishing EtO background levels nationally. Because there are still unexplained elevated concentrations in areas with no known source of EtO, determining ambient levels of EtO is necessary to help identify additional potential sources. Research is needed to understand the degree to which the secondary formation of EtO occurs. For these reasons, field testing and monitoring in areas where elevated concentrations are suspected are a key research need. In addition, research is needed to characterize fenceline concentrations, post-emission transport, potential atmospheric processing, and eventual removal from the atmosphere.

There are intriguing possibilities regarding additional EtO sources, with each requiring further investigation. For air environments, the potential for secondary atmospheric EtO formation and EtO in the emissions from incomplete combustion processes is of specific interest. Combustion source emissions are diverse and tracked across a wide variety of commercial, industrial, and residential sectors. Each of these poses a unique set of logistical, methodological, and physical and chemical research challenges, typically requiring its own set of sampling, instrumental measurement, data acquisition, management, analysis, and quality control procedures. To date, despite the vast number of challenges associated with quantifying EtO emissions, USEPA Method TO-15/TO-15A is among the most recognizable and versatile standard measurements for measuring air toxicities across a broad range of concentration levels. It is serendipitous that USEPA TO-15/TO-15A is proving to be sensitive to EtO because the method and its results can be readily applied as part of the existing regulatory framework for many of these sources and the air toxics they emit, serving as a reference point for comparison to newly introduced technologies.

In addition to working toward establishing a better understanding of background EtO and continuing to meet the robust demands of EtO measurement and analysis, the USEPA is conducting further laboratory and field performance evaluations. These include but are not limited to (i) canister, cleaning, and bias effects testing, (ii) humidity and matrix interference checks, and (iii) optimization of the preconcentration, GC separation, and MS ionization steps. In tandem with a low-level standard preparation process, these procedures will be performed to achieve method detection limits near 10–20 pptV. Eventually, a certified EtO reference gas standard will have to be developed, preferably in coordination with the National Institute of Standards and Technology (NIST) and gas manufacturers. An alternative set of source emissions methods involving active and passive sorbent tubes is also being explored by UPSEPA's Office of Research and Development in the event that canister sampling turns out not to be the preferred method. We are also aware of the potential utility of semi-continuous gas chromatography and real-time, direct measurement mass spectrometers and plan to

investigate how these technologies could be integrated into future field research studies.

The USEPA also recognizes the value of being able to respond quickly to characterize EtO emissions when unexpected emissions-based exposures due to transportation or industrial plant storage mishaps occur; for instance, what was observed in 2018 at the Croda EtO production plant in Delaware<sup>49</sup> and more recently in 2023 at the Dow chemical plant in Louisiana.<sup>50</sup> We are currently developing measurement platforms and project plans that can be easily and quickly deployed. These platforms, both mobile and stationary, are novel designs that include robust sensors and high sampling rate optical instrumentation that will be able to characterize EtO emissions and a suite of other pollutants while capturing meteorology data necessary to understand wind direction and estimate dispersion. Sampling from these platforms can be continuous and automated, where sampling can be triggered using wind direction, time, air toxic concentrations, or a simple text from a phone. Some of these portable platforms can also be equipped with bench-scale laboratory equipment such that standardized or USEPA methods like TO-15/TO-15A, with improved guidance as described previously, can be routinely performed in the field. Additionally, while air is the focus presently, EtO may be released to water, and its subsequent mass transfer to air would be of potential interest and will eventually need to be addressed by the scientific community. Knowledge of EtO solubility and mass transfer rates across the air/water interface will be critical to developing life cycle assessments for improving our understanding of the full extent of EtO's potential environmental impacts.

There is little doubt that EtO will be an air and environmental research challenge for the foreseeable future, requiring focus from the entire environmental research community. Harmonization of a variety of analytical, meteorological, fate and transport, measurements, and sampling expertise will be needed to solve our most pressing research issues related to EtO.

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### Notes

The authors declare no competing financial interest.

## Biographies



Dr. Tiffany L. B. Yelverton is a mechanical engineer at the U.S. EPA in the Office of Research and Development's Center for Environmental Measurement and Monitoring. Dr. Yelverton's expertise is in combustion sources, concentrating on measurement and control technologies for mitigating air emissions. During her tenure at the EPA, she has focused her research on emissions from stationary diesel gensets, woodstoves and coal combustion for utilities, with particular interest in using waste or alternative fuels as replacements for traditional fossil fuels. For the past several years she has turned her research focus to gaining a better understanding of ethylene oxide, an air toxic of high priority for the EPA, working with ORD researchers, instrument vendors, and both internal and external partners to develop instrumentation and methodologies for the measurement of emissions.



The research interests of Dr. Hays include combustion chemistry, air pollution, and emissions characterization. He investigates anthropogenic and biogenic source emissions with a focus on the chemical characterization of submicron aerosol particles and gas-phase chemical precursors. Dr. Hays develops and applies analytical technologies and methods for the physical and chemical characterization of volatile and semivolatile organic compounds and aerosols. His analytical-chemical research interests include thermal desorption and extraction, optical spectroscopy, and hyphenated chromatography—mass spectrometry techniques.



Ms. Rice is a Physical Scientist at the EPA in the Air Quality Assessment Division of OAQPS. Ms. Rice has worked in the field of ambient air monitoring and measurements for more than 30 years. She serves as an ambient air monitoring method expert where she provides technical support to a variety of agencies implementing the EPA's national air quality monitoring networks. Ms. Rice is currently working on air toxics, ozone, black carbon, and PM<sub>2.5</sub> chemical speciation air monitoring and measurement issues.

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