Human Exposure to Unconventional Oil and Gas Development: A Literature Survey for Research Planning

HEI-Energy Research Committee

Health Effects Institute–Energy
Boston, MA

TRUSTED SCIENCE, CLEAN ENVIRONMENT, BETTER HEALTH
Publishing history: This document was posted at www.hei-energy.org in September 2019.

Citation for document:

© Health Effects Institute–Energy, Boston, Mass., U.S.A.
## CONTENTS

<table>
<thead>
<tr>
<th>Page</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ABOUT HEI-ENERGY</td>
</tr>
<tr>
<td>3</td>
<td>ACKNOWLEDGMENTS</td>
</tr>
<tr>
<td>X</td>
<td>EXECUTIVE SUMMARY</td>
</tr>
<tr>
<td>x</td>
<td>Approach to the Survey</td>
</tr>
<tr>
<td>xi</td>
<td>Conceptual Framework</td>
</tr>
<tr>
<td>xi</td>
<td>Survey of the Literature</td>
</tr>
<tr>
<td>xi</td>
<td>OVERVIEW OF THE EXPOSURE LITERATURE</td>
</tr>
<tr>
<td>xv</td>
<td>THE COMMITTEE’S FINDINGS</td>
</tr>
<tr>
<td>xiv</td>
<td>Strengths of the Literature in Assessing Human Exposure to UOGD</td>
</tr>
<tr>
<td>xiv</td>
<td>Knowledge Gaps About Human Exposure to UOGD</td>
</tr>
<tr>
<td>xvi</td>
<td>PLANNING FOR EXPOSURE RESEARCH</td>
</tr>
<tr>
<td>xvi</td>
<td>Research Questions</td>
</tr>
<tr>
<td>xvi</td>
<td>Anticipated Attributes of Research</td>
</tr>
<tr>
<td>xvi</td>
<td>Looking Ahead to HEI-Energy’s Research Solicitation</td>
</tr>
<tr>
<td>1</td>
<td>1.0 INTRODUCTION</td>
</tr>
<tr>
<td>1</td>
<td>1.1 BACKGROUND</td>
</tr>
<tr>
<td>1</td>
<td>1.1.1 Increased Rate and Intensity of Oil and Gas Development in the United States</td>
</tr>
<tr>
<td>3</td>
<td>1.1.2 Increased Attention to Potential Exposures and Health Effects Associated with UOGD</td>
</tr>
<tr>
<td>3</td>
<td>1.2 OVERVIEW OF THE REPORT</td>
</tr>
<tr>
<td>5</td>
<td>1.2.1 Scope</td>
</tr>
<tr>
<td>5</td>
<td>1.2.2 Objectives</td>
</tr>
<tr>
<td>5</td>
<td>1.2.3 Organization of the Report</td>
</tr>
<tr>
<td>6</td>
<td>2.0 UNCONVENTIONAL OIL AND GAS DEVELOPMENT</td>
</tr>
<tr>
<td>6</td>
<td>2.1 UOGD DEFINED</td>
</tr>
<tr>
<td>7</td>
<td>2.2 Distinguishing between Conventional and Unconventional Development</td>
</tr>
<tr>
<td>7</td>
<td>2.3 PHASES OF UOGD</td>
</tr>
<tr>
<td>9</td>
<td>2.3.1 Pad Development</td>
</tr>
<tr>
<td>9</td>
<td>2.3.2 Drilling</td>
</tr>
<tr>
<td>11</td>
<td>2.3.3 Well Completion (Hydraulic Fracturing)</td>
</tr>
<tr>
<td>13</td>
<td>2.3.4 Flowback</td>
</tr>
<tr>
<td>15</td>
<td>2.3.5 Production</td>
</tr>
<tr>
<td>16</td>
<td>2.3.6 Post-Production</td>
</tr>
<tr>
<td>17</td>
<td>2.3.7 Waste Management from UOGD</td>
</tr>
<tr>
<td>18</td>
<td>2.4 SUMMARY</td>
</tr>
<tr>
<td>19</td>
<td>3.0 METHODS USED TO SURVEY THE LITERATURE</td>
</tr>
<tr>
<td>19</td>
<td>3.1 Survey Question</td>
</tr>
<tr>
<td>19</td>
<td>3.2 Literature Search</td>
</tr>
<tr>
<td>21</td>
<td>3.3 Survey of the Literature</td>
</tr>
<tr>
<td>21</td>
<td>3.3.1 Potential Human Exposures Framed in a Conceptual Model</td>
</tr>
<tr>
<td>22</td>
<td>3.3.2 Relevance of the Literature to the Range of Possible Exposure Conditions</td>
</tr>
<tr>
<td>24</td>
<td>4.0 SURVEY OF THE LITERATURE</td>
</tr>
<tr>
<td>24</td>
<td>4.1 Summary of Studies</td>
</tr>
<tr>
<td>27</td>
<td>4.2 Air Exposure Pathways</td>
</tr>
<tr>
<td>27</td>
<td>4.2.1 Summary of Studies – Air Exposure Pathway</td>
</tr>
</tbody>
</table>

Page iii of xvii
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2.2</td>
<td>UOGD Sources and Potential Release Mechanisms – Air Exposure Pathway</td>
<td>28</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Potentially Exposed Populations – Air Exposure Pathway</td>
<td>33</td>
</tr>
<tr>
<td>4.2.4</td>
<td>Concluding Remarks – Air Exposure Pathway</td>
<td>36</td>
</tr>
<tr>
<td>4.3</td>
<td>WATER EXPOSURE PATHWAYS</td>
<td>40</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Summary of Studies – Water Exposure Pathway</td>
<td>40</td>
</tr>
<tr>
<td>4.3.2</td>
<td>UOGD Sources and Potential Release Mechanisms – Water Exposure Pathway</td>
<td>41</td>
</tr>
<tr>
<td>4.3.3</td>
<td>Potentially Exposed Populations – Water Exposure Pathway</td>
<td>45</td>
</tr>
<tr>
<td>4.3.4</td>
<td>Concluding Remarks – Water Exposure Pathway</td>
<td>46</td>
</tr>
<tr>
<td>4.4</td>
<td>SOIL AND SEDIMENT EXPOSURE PATHWAYS</td>
<td>49</td>
</tr>
<tr>
<td>4.4.1</td>
<td>Summary of Studies- Soil and Sediment Exposure Pathways</td>
<td>49</td>
</tr>
<tr>
<td>4.4.2</td>
<td>UOGD Sources and Potential Release Mechanisms – Soil and Sediment Exposure Pathways</td>
<td>49</td>
</tr>
<tr>
<td>4.4.3</td>
<td>Potentially Exposed Populations – Soil and Sediment Exposure Pathways</td>
<td>50</td>
</tr>
<tr>
<td>4.4.4</td>
<td>Concluding Remarks- Soil and Sediment Exposure Pathways</td>
<td>50</td>
</tr>
<tr>
<td>4.5</td>
<td>UOGD NOISE, LIGHT, AND ODOR</td>
<td>51</td>
</tr>
<tr>
<td>4.5.1</td>
<td>Summary of Studies- Sensory Exposure Pathway</td>
<td>51</td>
</tr>
<tr>
<td>4.5.2</td>
<td>UOGD Sources and Potential Release Mechanisms – Sensory Exposure Pathway</td>
<td>52</td>
</tr>
<tr>
<td>4.5.3</td>
<td>Potentially Exposed Populations – Sensory Exposure Pathway</td>
<td>53</td>
</tr>
<tr>
<td>4.5.4</td>
<td>Concluding Remarks- Sensory Exposure Pathway</td>
<td>53</td>
</tr>
<tr>
<td>4.6</td>
<td>EXPOSURE BIOMONITORING</td>
<td>54</td>
</tr>
<tr>
<td>4.6.1</td>
<td>Summary of Studies</td>
<td>54</td>
</tr>
<tr>
<td>4.6.2</td>
<td>Distinguishing UOGD Sources in Biomonitoring Studies</td>
<td>56</td>
</tr>
<tr>
<td>4.6.3</td>
<td>Potentially Exposed Populations – Biomonitoring Studies</td>
<td>56</td>
</tr>
<tr>
<td>4.6.4</td>
<td>Concluding Remarks</td>
<td>57</td>
</tr>
<tr>
<td>4.7</td>
<td>SUMMARY OF THE LITERATURE</td>
<td>57</td>
</tr>
<tr>
<td>4.7.1</td>
<td>Conceptual Framework for the Literature Survey</td>
<td>57</td>
</tr>
<tr>
<td>4.7.2</td>
<td>Strengths of the Literature in Assessing Human Exposure to UOGD</td>
<td>58</td>
</tr>
<tr>
<td>4.7.3</td>
<td>Knowledge Gaps About Human Exposure to UOGD</td>
<td>58</td>
</tr>
<tr>
<td>5.0</td>
<td>PLANNING FOR EXPOSURE RESEARCH</td>
<td>60</td>
</tr>
<tr>
<td>5.1</td>
<td>KNOWLEDGE GAPS FRAMED AS RESEARCH QUESTIONS</td>
<td>60</td>
</tr>
<tr>
<td>5.1.1</td>
<td>UOGD Sources</td>
<td>62</td>
</tr>
<tr>
<td>5.1.2</td>
<td>Release Mechanisms and Transport Pathways</td>
<td>65</td>
</tr>
<tr>
<td>5.1.3</td>
<td>Exposed Populations</td>
<td>70</td>
</tr>
<tr>
<td>5.2</td>
<td>ANTICIPATED ATTRIBUTES OF RESEARCH</td>
<td>73</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Scope of Exposure Studies</td>
<td>73</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Study Quality and Scientific Value</td>
<td>73</td>
</tr>
<tr>
<td>5.3</td>
<td>LOOKING AHEAD TO HEI-ENERGY’S RESEARCH SOLICITATION</td>
<td>73</td>
</tr>
<tr>
<td>5.3.1</td>
<td>Expected Utility of Research</td>
<td>73</td>
</tr>
<tr>
<td>5.3.2</td>
<td>The Model for Providing Impartial Science</td>
<td>75</td>
</tr>
<tr>
<td>5.3.3</td>
<td>Assessment of Research Solicitation Applications</td>
<td>75</td>
</tr>
<tr>
<td>6.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>6.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>7.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>7.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>8.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>8.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>9.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>9.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>10.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>10.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>11.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>11.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>12.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>12.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>13.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>13.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>14.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>14.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>15.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>15.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>16.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>16.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>17.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>17.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>18.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>18.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>19.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>19.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>20.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>20.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>21.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>21.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>22.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>22.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>23.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>23.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>24.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>24.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>25.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>25.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>26.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>26.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>27.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>27.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>28.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>28.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>29.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>29.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>30.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>30.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>31.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>31.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>32.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>32.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>33.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>33.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>34.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>34.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>35.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>35.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>36.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>36.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>37.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>37.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>38.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>38.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>39.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>39.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>40.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>40.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>41.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>41.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>42.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>42.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>43.0</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
<tr>
<td>43.1</td>
<td>REFERENCES</td>
<td>77</td>
</tr>
</tbody>
</table>

**Figures**

- **ES-1**: Conceptual model of potential exposure pathways associated with UOGD
- **ES-2**: Number of measurement and modeling studies by year of publication (publication year based on year of electronic publication)
- **ES-3**: Study locations relative to shale basins and plays, by media investigated
<table>
<thead>
<tr>
<th>Page</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>Potential human exposures associated with UOGD. This review focuses on potential environmental exposures that might adversely affect health (designated in blue).</td>
</tr>
<tr>
<td>2-1</td>
<td>Map of shale plays in the United States (U.S. Energy Information Administration, 2016a)</td>
</tr>
<tr>
<td>2-2</td>
<td>Conceptual layout comparing a vertical well with a horizontal well in the Marcellus Shale. Illustration by William Kappel.</td>
</tr>
<tr>
<td>2-3</td>
<td>U.S. tight oil and shale gas production and well counts (U.S. Energy Information Agency, 2019)</td>
</tr>
<tr>
<td>2-4</td>
<td>Satellite image of 1, 2, and 16 well pads in the Pinedale Field (satellite photo from DrillingInfo)</td>
</tr>
<tr>
<td>2-5</td>
<td>Number of horizontal wells drilled per well pad, or pad density, across U.S. shale plays as of January 1, 2005 (a) and January 1, 2019 (b) (created by M. Al-Alwani, merging horizontal well records from FracFrocus and DrillingInfo)</td>
</tr>
<tr>
<td>2-6</td>
<td>Well construction design for a Marcellus gas well (Clark et al. 2012). This figure shows three casing strings covering the drinking water aquifer.</td>
</tr>
<tr>
<td>2-7</td>
<td>UOGD well drilling time compared across shale plays (Weijers et al. 2019)</td>
</tr>
<tr>
<td>2-8</td>
<td>Fracture orientation as a function of horizontal wellbore orientation (Bahrami et al. 2016)</td>
</tr>
<tr>
<td>2-9</td>
<td>Example UOGD wellsite with tank- and truck-based hydraulic fracturing equipment (Suchy and Newell 2012)</td>
</tr>
<tr>
<td>2-10</td>
<td>Production facilities for reduced emissions completions (U.S. EPA 2011b, adapted from BP)</td>
</tr>
<tr>
<td>2-11</td>
<td>Production decline and estimated ultimate recovery for several shale plays (Energy Information Administration 2012)</td>
</tr>
<tr>
<td>2-12</td>
<td>Schematic of hydraulic fractures intersecting abandoned, vertical wells (Brownlow et al. 2017)</td>
</tr>
<tr>
<td>3-1</td>
<td>North American well geometry since 1991, showing the increasing prevalence of horizontal wells over time.</td>
</tr>
<tr>
<td>3-2</td>
<td>Conceptual model of potential exposure pathways associated with UOGD. Adapted from the U.S. EPA’s “Draft Guidelines for Human Exposure Assessment” (US EPA 2016a).</td>
</tr>
<tr>
<td>4-1</td>
<td>Conceptual model of potential exposure pathways assessed in the literature.</td>
</tr>
<tr>
<td>4-2</td>
<td>Number of studies published each year by study media.</td>
</tr>
<tr>
<td>4-3</td>
<td>Number of studies by chemical agent.</td>
</tr>
<tr>
<td>4-4</td>
<td>Total (a) oil and (b) natural gas production over time by U.S. region.</td>
</tr>
<tr>
<td>4-5</td>
<td>Air monitoring or modeling study locations.</td>
</tr>
<tr>
<td>4-6</td>
<td>Sampler placement in air monitoring studies.</td>
</tr>
<tr>
<td>4-7</td>
<td>Air sample averaging times.</td>
</tr>
<tr>
<td>4-8</td>
<td>Number of outdoor air quality studies in four Texas shale basins, by sampling location, time of year, and sample averaging time.</td>
</tr>
<tr>
<td>4-9</td>
<td>Number of water monitoring or modeling studies.</td>
</tr>
<tr>
<td>4-10</td>
<td>Number of studies by type of water sample.</td>
</tr>
</tbody>
</table>
4-11 Potential groundwater contamination mechanisms related to shale gas production (Lefebvre et al. 2016)
4-12 Measured sound levels at drilling and hydraulic fracturing sites with and without sound walls (Radtke et al. 2017)
4-13 Number of biomonitoring studies.
5-1 Overview of HEI-Energy model for providing impartial scientific research, which is selected, implemented, and reviewed independently of the program’s sponsors.

1 **TABLES**

Table ES-1 Knowledge gaps identified from literature and workshops.
Table ES-2 Characteristics of appropriate research identified by HEI Energy Research Committee in alphabetical order.
Table 4-1 Processes leading to ambient emissions.
Table 5-1 Knowledge gaps framed as example research questions.
Table 5-2 Characteristics of appropriate research identified by HEI Energy Research Committee in alphabetical order within each section.
ABOUT HEI-ENERGY

The Health Effects Institute–Energy was formed to provide a multiyear national research program to identify and conduct high-priority research on potential population exposures and health effects from development of oil and natural gas from shale and other unconventional resources (UOGD) across the United States. HEI-Energy plans to support population-level exposure research in multiple regions of the United States. To enable exposure research planning, HEI-Energy conducts periodic reviews of the relevant scientific literature. Once initial research is completed, HEI-Energy will assess the results to identify additional high-priority exposure research needs and, where feasible and appropriate, health research needs for funding in subsequent years.

The scientific review and research provided by HEI-Energy will contribute high-quality and credible science to the public debate about UOGD and provide needed support for decisions about how best to protect public health. To achieve this goal, HEI-Energy has put into place a governance structure that mirrors the one successfully employed for nearly forty years by its parent organization, the Health Effects Institute (HEI), with several critical features:

▪ Receives balanced funding from the U.S. Environmental Protection Agency under a contract that funds HEI-Energy exclusively, and from the oil and natural gas industry. Other public and private organizations periodically provide support;
▪ Independent Board of Directors consisting of leaders in science and policy who are committed to fostering the public–private partnership that is central to the organization;
▪ A research program that is governed independently by individuals having no direct ties to, or interests in, sponsor organizations;
▪ HEI-Energy Research Committee consisting of members who are internationally recognized experts in one or more subject areas relevant to the Committee’s work, have demonstrated their ability to conduct and review scientific research impartially, and have been vetted to avoid conflicts of interest;
▪ Research that undergoes rigorous peer review by HEI-Energy’s Review Committee. This committee will not be involved in the selection and oversight of HEI-Energy studies;
▪ Staff and committees that participate in open and extensive stakeholder engagement before, during, and after research, and communicate all results in the context of other relevant research;
▪ HEI-Energy makes publicly available all literature reviews and original research that it funds and provides summaries written for a general audience; and
▪ Without advocating policy positions, HEI-Energy provides impartial science, targeted to make better-informed decisions.

HEI-Energy is a separately funded affiliate of the Health Effects Institute (www.healtheffects.org).
ACKNOWLEDGMENTS

HEI and the members of the Energy Research Committee wish to extend their gratitude to individuals and
organizations that provided considerable support in this effort:

 Speakers providing very informative and useful presentations at two Research Planning Workshop conducted in
Denver, Colorado in July 2018 and Austin, Texas in September 2018: CAPT Bradley King of the National
Institute of Environmental Health Sciences, Dr. John Adgate of the Colorado School of Public Health, Dr.
Adam Pacsi of Chevron Energy Technology Company, Dr. Michael McCawley of West Virginia University,
Ms. Martha Rudolph of the Colorado Department Public Health and Environment, Dr. Michael Honeycutt of the
Texas Commission on Environmental Quality, Ms. Nichole Saunders of Environmental Defense Fund, Dr.
David Allen of The University of Texas at Austin, Dr. Jeffrey Collett of Colorado State University, Dr. Tiffany
Bredfett of the Texas Commission on Environmental Quality, Dr. Isabelle Cozzarelli of the United States
Geological Survey, Dr. Cloele Danforth of Environmental Defense Fund, Dr. Daniel Soeder of South Dakota
School of Mines and Technology, Dr. Liza McKenzie of the Colorado School of Public Health, Dr. Mike van
Dyke of the Colorado Department of Public Health and Environment, Ms. Megan Garvey of the United States
Environmental Protection Agency, Mr. James Kenney of the United States Environmental Protection Agency,
Dr. Saba Tahmassebi of the Oklahoma Department of Environmental Quality, Mr. Clint Woods of the United
States Environmental Protection Agency, Dr. Kelly Rose of the United States Department of Energy-National
Energy Technology Laboratory, Dr. Tao Wen of the Pennsylvania State University, Dr. Rebecca Hornbrook of
the University Corporation for Atmospheric Research, Mr. Tom Moore of the Western States Air Resources
Council, Mr. John Grant of Ramboll, Dr. Alan Krupnick of Resources for the Future, Dr. Tami McMullen of the
Colorado Department of Public Health and Environment.

 Workshop participants and other individuals and organizations that took time to provide constructive
commentary on the Committee’s research planning effort: Dr. William Allshouse of the Colorado School of
Public Health, Mr. Bruce Baizel of Earthworks, Ms. Allie Bamber of the Colorado Department of Public Health
and Environment, Mr. Rodney Barnwell of XTO Energy Inc., Mr. Michael Bergstrom of Shell Oil Company,
Ms. Uni Blake of the American Petroleum Institute, Dr. Daniel Bon on the Colorado Department of Public
Health & Environment, Dr. Joan Casey of the University of California at Berkeley, Dr. Jane Clougherty of
Drexel University, Dr. Jeffrey Collett of Colorado State University, Dr. Elena Craft of the Environmental
Defense Fund, Dr. Eric Daniels of Chevron, Dr. Joost de Gou of the University of Colorado at Boulder; Dr.
Dennis Devlin of ExxonMobil, Ms. Nathalie Eddy of Earthworks, Dr. James Fabisiak of the University of
Pittsburgh, Ms. Kate Fay of Noble Energy, Mr. Howard Feldman of the American Petroleum Institute, Mr. Kyle
Ferrar of FracTracker Alliance, Mr. Dick Francis of Shell Oil Company, Dr. George Gerton of Perelman School
of Medicine at the University of Pennsylvania, Dr. Jessica Gilman of the National Oceanic and Atmospheric
Administration, Dr. Andrew Glickman of Chevron, Mr. Michael Goo of AJW, Inc., Dr. John Graham of the
Clean Air Task Force, Dr. Richard Haut of the Houston Advanced Research Center, Dr. Detlev Helimg of the
University of Colorado Boulder, Dr. Judy Wenth Hess of Shell Oil Company, Dr. Paul Hodgins of
ConocoPhillips, Dr. Robert Kleinberg of Columbia University and Boston University, Ms. Kristin Koblis of
Noble Energy, Dr. Karlene Lavelle of ExxonMobil Biomedical Sciences, Inc., Mr. Joe Lima of Schlumberger,
Ms. Erin Markovich of Equinor, Dr. Roger McClellan of Inhalation Toxicology and Risk Assessment, Dr. Tami
McMullin of the Colorado Department of Public Health and Environment, Dr. Jana Milford of the University of
Colorado at Boulder, Dr. Ziad Naufal of Chevron, Dr. Mwangi Ndonga of EnCana, Ms. Kelsey Patsch of the
Claude Worthington Benedum Foundation, Dr. Gabriele Pfister of the National Center for Atmospheric
Research, Mr. Gordon Pierce of the Colorado Department of Public Health and Environment, Mr. Wil Porche of
XTO Energy, Inc., Mr. Daniel Raimi of Resources for the Future, Ms. Alejandra Ramirez-Cardenas of the
National Institute for Occupational Safety and Health Western States Division, Mr. Jason Redus of Pioneer
Natural Resources, Dr. Annette Rohr of the Electric Power Research Institute, Dr. Satinder Sarang of Shell Oil
Company, Ms. Kim Schultz of The Endocrine Disruption Exchange, Dr. Kevin Teichman of the United States
Environmental Protection Agency, Ms. Denise Tuck of Halliburton, Dr. Kristina Whitworth of The University
of Texas Health Science Center and Houston, Dr. Nicole Deziel of the Yale School of Public Health, Mr. Steve
Ellison of ConocoPhillips, Dr. Gretchen Goldman of the Union of Concerned Scientists, Dr. Bernard Goldstein
of the University of Pittsburgh Graduate School of Public Health, Mr. Diane Garcia-Gonzales of the UCLA
Institute of the Environment and Sustainability, Ms. Vicki Goodenow of Equinor, Dr. Alea Goodmann of
Chevron, Mr. Joel Holliman of Texas A&M University, Mr. Charles Ingebretson of AJW, Inc., Mr. Matt Lepore of Adamantine Energy, Mr. Rob Lawrence of the United States Environmental Protection Agency, Dr. Elena McDonald-Buller of the University of Texas at Austin, Mr. C. Andrew Miller of the United States Environmental Protection Agency, Dr. Gunnar Schade of Texas A&M University; Ms. Delya Sommerville of BP, Mr. Lance Tolson of Shell Oil Company, Ms. Lindsay Wilcock of BP Lower 48 Exploration and Production.

Individuals who provided important guidance along the way: Mr. Zachary Abbott, Ms. Kate Konshnick, Dr. Alan Krupnick, Dr. Robert Kleinberg, Dr. Isabelle Cozzarelli.

Noble Energy for providing the Energy Research Committee with a tour of oil and gas operations in Weld County, CO.

HEI’s Special Scientific Committee on UOGD for drafting the Strategic Research Agenda, which laid the framework for HEI-Energy.

Foundations who funded the work of HEI’s Special Committee on UOGD, without which HEI-Energy would not be possible: the Claude Worthington Benedum Foundation, the Henry L. Hillman Foundation, the Henry C. and Belle Doyle McEldowney Fund of The Pittsburgh Foundation, and the Richard King Mellon Foundation.
EXECUTIVE SUMMARY

Unconventional oil and natural gas development (UOGD)\(^1\) has expanded rapidly in the United States in recent years. Accompanying this expansion has been a growing body of scientific literature about human exposures to environmental agents arising from UOGD (hereafter “UOGD exposures”). This report surveys the literature relevant to these environmental exposures. The Energy Research Committee (the Committee) of the Health Effects Institute–Energy (HEI-Energy) conducted the survey as part of a larger effort to understand the current state of the science on UOGD exposures and their potential health effects. The Committee will use results from this survey and a companion review of epidemiology literature on potential health effects of UOGD exposures (HEI-Energy Research Committee in press) to inform HEI-Energy’s planning for future research to better understand exposures associated with UOGD.

Approach to the Survey

The Committee consists of multidisciplinary scientists from across the United States with expertise in air quality, epidemiology, exposure assessment, hydrology, medicine, petroleum engineering, risk assessment, and toxicology. Along with HEI-Energy staff, the Committee conducted a survey of peer-reviewed and gray scientific literature that provides information about potential UOGD exposures to determine what is already known, to identify knowledge gaps, and to begin planning for research that addresses the gaps. They also toured UOGD operations and convened two public workshops at the outset of the survey to hear from knowledgeable representatives from federal and state government, the oil and gas industry, environmental and public health nongovernmental organizations, academia, and community organizations about their priorities for research.

Conceptual Framework

Understanding human exposures to UOGD-related chemical agents (e.g., benzene) and non-chemical agents (e.g., noise) represents a complex undertaking. UOGD processes involve a multitude of agents released to air, water, and other environmental media, with levels varying over space and time and by region, extent of operations, operator practices, and other factors. Furthermore, variation in time–activity patterns (e.g., time spent at residential versus work locations and indoor versus outdoor locations) among potentially exposed populations complicates efforts to quantify human exposures to agents originating from UOGD.

The Committee framed its literature survey within a conceptual model of exposure (Figure ES-1) to facilitate understanding of what is known about exposures and where knowledge gaps exist. An ideal

---

\(^1\) UOGD refers to the wave of onshore development and production of oil and natural gas from shale and other unconventional, or low permeability, geologic formations as practiced starting around the beginning of the 21st century through multistage hydraulic fracturing in horizontal wells. UOGD operations include:

- **field development**: exploration, site preparation, vertical and horizontal drilling, well completion (casing and cementing, perforating, acidizing, hydraulic fracturing, 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; and
- **post-production**: well closure and land reclamation.
exposure study would provide information about each element of the conceptual model, including
identification of specific UOGD chemical or non-chemical agents, documentation of the release to the
environment (e.g., emissions rate or noise measurement) and transport to a specific medium, route of
exposure (e.g., inhalation of air in a residential area or ingestion of drinking water), and the magnitude,
frequency, and duration of exposure for a specific population. In so doing, the study would allow one to
determine whether a complete exposure pathway connects a specific UOGD agent with a specific
population and, if so, to have the exposure information necessary to judge its importance for health.

Figure ES-1. Conceptual model of potential exposure pathways associated with UOGD

Survey of the Literature
The survey of the literature was guided by the following question:

What is known about potential UOGD-related human exposures?

The Committee surveyed peer-reviewed and gray literature published between January 1, 2000 and July
10, 2019 that contribute to understanding how people might be exposed to chemical agents or non-
chemical agents released directly from UOGD to the environment. Such releases may be operational (e.g.,
permitted air emissions), accidental (e.g., spills and leaks), or unauthorized (e.g., illegal discharges).

All potentially useful studies were considered whether or not the investigators set out to study human
exposures. This included studies that characterized one or more elements of an exposure pathway, such as
the chemical and non-chemical agents associated with UOGD operations, the ways that these agents are
released to and behave within the environment, the concentrations of agents in air, water, and other
environmental media, and the potentially exposed populations and their time-activity patterns, which
influence whether and how exposures occur. The Committee developed a set of questions to facilitate its
survey of the literature for understanding exposures to UOGD and identifying knowledge gaps (Box ES-
1).

Overview of the Exposure Literature
In response to the rapid increase of UOGD in the United States, scientific inquiries about human exposure
to chemical and non-chemical agents from UOGD operations also increased (Figure ES-2). The literature
search revealed hundreds of citations for studies that have been conducted to understand environmental
impacts associated with UOGD, including many reporting measured or predicted levels of UOGD-related
agents in air, water, and other environmental media. These studies focused on major oil and gas
producing regions in the United States; that is, in shale plays located within sedimentary basins where
UOGD is active (Figure ES-3).

The majority of studies focused on levels of agents in the air (n=114), with most measuring or modeling
concentrations of non-methane volatile organic compounds (VOCs) and particulate matter in or near areas
with UOGD, and with some assessing air quality from secondary pollutant formation (e.g., ozone). Other
studies focused on levels of agents in water (n=82), primarily as a result of accidental releases, with most
measuring or modeling concentrations of VOCs, metals, and other chemicals associated with brine and
produced water.
Many of the water-related studies were conducted in the Marcellus region. Fewer studies characterized noise, odor, and light exposures (n=7) or UOGD-related agents in soil (n=28). Five studies used biomonitoring techniques to measure concentrations of chemicals or related metabolites in people’s blood, urine, or hair.

Most studies focused on a single environmental medium. Methods used in these studies varied from direct sampling and analysis of the media of interest to modeling levels of agents in a given medium over time and space. For example, several regional air studies used modeling techniques to predict secondary pollutant formation under different atmospheric conditions.

Figure ES-2. Number of studies reporting measured or predicted levels of UOGD-related chemical and non-chemical agents by year of publication (Publication year based on year of electronic publication).¹

¹search period: January 1, 2000 to July 10, 2019
The Committee’s Findings

Strengths of the Literature in Assessing Human Exposure to UOGD

Overall, the studies contained useful information for understanding human exposures, including those conducted without this specific goal. The studies helped to characterize UOGD-related human exposures by contributing to our understanding of atmospheric and hydrological conditions that affect fate and transport of agents through the environment, the relationship between operations and types or levels of emissions, and pathways of potential exposures. In addition, some investigators were resourceful in their use of previously published data, such as air quality data collected as part of state monitoring programs.

Some investigators used methods that were useful for isolating UOGD sources. Some measured emissions on well pads and used the data, along with meteorological and topographical data, to analyze air quality changes over space and time. Studies sometimes involved the use of various tracers or markers to estimate the levels of agents in air or water that were attributable to UOGD. Other investigators assessed the chemical concentrations before, during, and after UOGD activities, enabling an evaluation of potential impacts specific to those activities.

Studies of greatest utility for addressing the Committee’s guiding question were those that shed light on spatial variability of agent concentrations (e.g., by sampling at various distances from a well pad) and temporal variability (e.g., by sampling over multiple sampling periods during a variety of UOGD activities, meteorological conditions, seasons, and times of day).

A subset of studies were conducted with the aim of characterizing human exposure to chemicals, noise, and light. To do so, investigators collected samples in areas where people spend much of their time, including air sampling in residential communities and water sampling of drinking-water wells. Some studies involved affected communities through discourse and participation, thereby providing results to the affected communities and benefiting from local knowledge. In addition, some state agencies conducted air sampling in response to community concerns.
Knowledge Gaps About Human Exposure to UOGD

The quantity of data on levels of UOGD-related agents in the environment continues to increase along with efforts to use the data to quantify human exposure. Nevertheless, important knowledge gaps remain in our understanding of who might be exposed, how exposures might arise, how exposures vary over time and across regions, and the likelihood of exposure.

Few studies provided the information necessary for linking environmental concentrations of agents to specific UOGD-related sources (e.g., diesel-powered equipment) or to distinguish between contributions from UOGD and other sources, such as conventional oil and gas development. In addition, the generalizability of study results to UOGD operations, geographic areas, and populations beyond those investigated in the studies is not clear.

Planning for Exposure Research

Given the current state of knowledge on UOGD and potential exposures, the Committee recommends further investigation to improve understanding of human exposures to UOGD to support decision making by community members, public health officials, regulators, oil and gas operators, and others. Informed by its review and input received from workshop participants, the Committee identified priority knowledge gaps and developed a set of characteristics critical to high-quality and policy-relevant research.

Research Questions

The Committee framed knowledge gaps as research questions within the conceptual model of exposure (Figure ES-1; Table ES-1). In general, understanding the agents and mechanisms by which human exposures arise is central to being able to generalize study results to different sets of regional conditions, operational practices, and population characteristics. For each knowledge gap, the Committee provided examples of research activities.

Anticipated Attributes of Research

Based on findings from this review, a parallel review of UOGD-related epidemiology literature (HEI-Energy, in press), and consultations with stakeholders, the Committee will prepare a Research Solicitation requesting proposals to fill knowledge gaps about human exposures to UOGD. The Committee is charged with overseeing selection and implementation of all research and ensuring its quality and utility for understanding human exposure to UOGD.

Although the knowledge gaps in Table ES-1 represent separate elements of the conceptual model of exposure, future research projects funded by HEI-Energy will ideally include multiple, if not all, elements of an exposure pathway. In defining the scope of research, the Committee recognizes the value of a better understanding of air and water-related exposures, achieved with comprehensive, high-quality research that characterizes the range of exposure conditions across regions of the United States. Non-chemical agents of concern include noise and light.

In preparing its Research Solicitation and reviewing proposals submitted in response, the Committee seeks research that possesses the characteristics in Table ES-2. In its Research Solicitation, the Committee will specify that several key components are required for a research program to be selected, including study of agents of potential concern for health, relevant geographic areas, necessary technical and community engagement expertise on the investigator team, a detailed quality assurance project plan, and an a priori study interpretation and communication plan, among other general components of a high-quality study.
Table ES-1. Knowledge Gaps Framed as Example Research Questions.

<table>
<thead>
<tr>
<th>UOGD SOURCES</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. How do the characteristics (i.e., the likelihood, composition, magnitude, frequency, and duration) of potential environmental releases from UOGD vary over space and time as a function of differences in the geological formations, meteorology, and variable practices among operators, across phases of development, or in response to technological innovation, changing regulations and guidance, and community concerns?</td>
<td></td>
</tr>
<tr>
<td>2. a. What is the relative contribution of operational, accidental, and unauthorized releases (^1) to environmental concentrations of UOGD agents in air? How might they contribute disproportionately to total emissions? How can emissions from individual UOGD processes be best quantified? Can measurements of methane releases be used to help inform efforts to estimate non-methane emissions? How can we use longer term observations (e.g., routine ground-based and satellite, including flares) to estimate historical trends in emissions? b. What are the relative contributions of operational, accidental, and unauthorized releases to environmental concentrations of UOGD agents in water?</td>
<td></td>
</tr>
<tr>
<td>RELEASE MECHANISMS AND TRANSPORT PATHWAYS</td>
<td></td>
</tr>
<tr>
<td>3. a. How does variation in regional conditions (e.g., meteorology and topography) affect the levels of UOGD agents in air over various temporal scales (e.g., hourly, diurnally, and seasonally) as a result of chemical transformation and transport? What methods are available to characterize the fate and transport of UOGD releases to the air? b. How does variation in regional conditions (e.g., topography, geochemistry, geophysics, and hydrology) affect the levels of UOGD agents in water over various temporal scales (e.g., seasonally) as a result of chemical transformation and transport? What methods are available to characterize the fate and transport of UOGD releases to water? c. To what extent does UOGD contribute to increased levels of noise, light, and vibration within and across regions and operations?</td>
<td></td>
</tr>
<tr>
<td>4. a. How can levels of UOGD agents in air be distinguished from levels contributed by other natural and anthropogenic sources? What is the relative contribution of air emissions from UOGD to local and regional concentrations? b. How can levels of UOGD agents in water be distinguished from levels contributed by other natural and anthropogenic sources? What is the relative contribution of water releases from UOGD to local and regional concentrations?</td>
<td></td>
</tr>
<tr>
<td>EXPOSED POPULATIONS</td>
<td></td>
</tr>
<tr>
<td>5. What are the characteristics(^2) of populations potentially exposed to UOGD agents at local and regional scales?</td>
<td></td>
</tr>
<tr>
<td>6. Which population behaviors (e.g., time–activity patterns) influence the potential for exposure to UOGD agents? To what extent do exposures to UOGD agents differ among individuals within and among exposed populations?</td>
<td></td>
</tr>
<tr>
<td>7. How can exposure monitoring methods (e.g., study design, instrumentation, and other technologies) accurately characterize total personal and population-wide exposures to UOGD over time and space?</td>
<td></td>
</tr>
</tbody>
</table>

\(^1\)UOGD agents might be released to the environment as:
* Operational releases: In accordance with applicable regulations (e.g., permitted discharges to surface water, equipment emissions to ambient air, and vehicle emissions),
* Accidental releases: As a result of poor practices (e.g., improper waste disposal, accidental releases, and explosions), or
* Unauthorized releases: As a result of unauthorized activities (e.g., illegal disposal of waste materials).

\(^2\)Population characteristics include numerous factors, such as age, sex, race, ethnicity, socioeconomic status, health status, size of the population, activity patterns, and other factors.

Looking Ahead to HEI-Energy’s Research Solicitation
HEI-Energy will fund research that informs policy decisions about how best to protect public health in the oversight of UOGD. The new research program is modeled after HEI’s existing successful model for
providing high quality, impartial scientific information about air quality and health (Figure ES-4). Key components include:

- **Independent governance** of the research program with leadership by a board of directors unaffiliated with sponsors;
- **Balanced funding** from governmental agencies, the oil and gas industry, and occasionally private foundations;
- **High-quality science** with research competitively selected for funding and overseen by the Energy Research Committee, which consists of knowledgeable scientists that have been vetted for bias and conflict of interest;
- **Extensive peer review** of science by an Energy Review Committee, which consists of knowledgeable scientists that have been vetted for bias and conflict of interest, that works independently of the Energy Research Committee to provide peer review and commentary on research;
- **Open and extensive engagement with stakeholders**, including local community members and officials in study locations;
- **Communication** of all results, including both positive and negative findings, in the context of other relevant research; and
- ** Provision of impartial science** for better informed decisions without advocating policy positions.

**Figure ES-4. Overview of HEI-Energy Model for Providing Impartial Scientific Research**

HEI-Energy expects to distribute the Research Solicitation to the broad scientific community, seeking multi-disciplinary teams with the skill and capacity to mobilize exposure studies in one or more major oil and gas-producing regions of the United States. The Research Committee will prioritize proposals that align with the characteristics listed in Table ES-2. The studies may be conducted in two phases, beginning with a feasibility phase, followed by full implementation of the research. Throughout the selection, implementation, and review of research projects, HEI-Energy and the Committee will provide oversight to ensure quality and effective communication with stakeholders about research progress.
<table>
<thead>
<tr>
<th>Criterion</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Overarching Characteristics</strong></td>
<td></td>
</tr>
<tr>
<td>Advances the science</td>
<td>Addresses the most important potential exposures for human health. The exposures under investigation are relevant to large populations or the severity of their effects are likely to be large. The severity of an effect is a function of the frequency, duration, and magnitude of exposure to an agent as well as the hazardous properties of the agent. <strong>Contributes broadly relevant information.</strong> Results will be broadly generalizable across geographic regions, UOGD operating conditions, or populations over time, including periods of low and high UOGD activity.</td>
</tr>
<tr>
<td>Brings value to affected communities</td>
<td>Engages communities and stakeholders. A clear stakeholder engagement plan is conveyed that ensures effective communication throughout the research program and identification of information that is important to communities affected by UOGD.</td>
</tr>
<tr>
<td>Informs decision-making</td>
<td>Communicates results. Investigators will formulate an a priori study interpretation plan that can be effectively communicated to decision-makers. <strong>Focuses on realistic human exposures.</strong> A focus on populations that are or could reasonably be expected to be exposed under current or future conditions, distinguishing among UOGD operational, accidental, and unauthorized sources of potential exposure. <strong>Includes a Study Interpretation Plan.</strong> This plan specifies how findings will be interpreted and communicated, especially for potentially exposed community members and for making decisions about the utility of future exposure or health research.</td>
</tr>
<tr>
<td>Provides high quality information</td>
<td>Gathers highly qualified team. The team possesses the full range of expertise and independence to conduct the exposure research along with expertise about the UOGD operations under study. An ideal team will design a study involving collaboration across multiple sectors (i.e., academic scientists, communities, regulators, public health agencies, industry, and nongovernmental organizations). The team must have access to facilities and equipment needed to support research (e.g., study sites and relevant data sets). With research planned for multiple regions, the team must demonstrate an ability to coordinate research efficiently and consistently among study sites. <strong>Provides high quality technical proposal.</strong> Quality of the proposed study design, approaches, methodology, analytic methods, statistical procedures, and plan for quality assurance in all aspects of the research.</td>
</tr>
<tr>
<td>Produces results cost-effectively</td>
<td>Makes maximum use of existing data. Will collect only the data needed to complement and build on past research and other sources of data, and take other steps to maximize efficiency (e.g., minimizing laboratory analytical costs through careful study design). <strong>Presents reasonable cost proposal.</strong> The proposed costs must be reasonable, and the requested funds appropriately allocated.</td>
</tr>
<tr>
<td><strong>Methodological Considerations</strong></td>
<td></td>
</tr>
<tr>
<td>Covers a complete exposure pathway</td>
<td>Links one or more chemical or non-chemical agents released from a UOGD source to a potentially exposed population. The study is designed to distinguish between agents released from UOGD and non-UOGD sources, and to connect releases of the agent(s) from a specific UOGD source to a potentially exposed population.</td>
</tr>
<tr>
<td>Identifies UOGD sources</td>
<td>Isolates specific UOGD sources of potential exposure. The research allows for the detection of possible causal links between one or more aspects of UOGD operations (e.g., specific equipment, activity, or phase of development) and resulting exposures. In addition, investigators will collect data (e.g., operator time–activity data) to identify the conditions that gave rise to the results, nothing whether exposure is the result of operational, accidental, or unauthorized releases.</td>
</tr>
<tr>
<td>Methods and results support future health research</td>
<td>Collects data (or establishes practical exposure assessment methodologies) for use in a future epidemiology studies or human health risk assessment. Will collect information at resolutions relevant for application in an epidemiology study or risk assessment.</td>
</tr>
</tbody>
</table>
1.0 INTRODUCTION

Onshore development of oil and natural gas from unconventional resources (or “unconventional oil and gas development” [UOGD]1 and defined in Box 1-1) has expanded rapidly in the United States since the early 2000s, along with concern about potential health effects. In 2015, the Health Effects Institute (HEI) released a Strategic Research Agenda to help guide future research about the potential impacts from UOGD (HEI Special Scientific Committee on Unconventional Oil and Gas Development in the Appalachian Basin 2015). HEI-Energy was formed as an affiliate of HEI to address a subset of questions in the Research Agenda related to human exposures and health.

The Research Committee of HEI-Energy (the Committee) will use results from this report and a companion report reviewing epidemiology literature (HEI-Energy Research Committee, in press) to inform HEI-Energy’s planning for research to better understand exposures associated with UOGD.

1.1 BACKGROUND

1.1.1 Increased Rate and Intensity of Oil and Gas Development in the United States

Oil and natural gas development is not new to the United States, with development beginning in the mid-1800s. Historically, oil and natural gas were extracted either without hydraulic fracturing or with lower volumes of hydraulic fracturing fluid than are often used today. Changes in technology have altered industry practices and prompted new questions that need to be answered.

The scale and rate of oil and natural gas development since the early 2000s differ markedly from previous development, stemming from technological changes involving increased use of hydraulic fracturing combined with horizontal drilling to develop low-permeability geologic formations that could not

---

1 UOGD refers to the wave of onshore development and production of oil and natural gas from shale and other unconventional, or low permeability, geologic formations as practiced starting around the beginning of the 21st century through multistage hydraulic fracturing in horizontal wells. UOGD operations include:

- field development: exploration, site preparation, vertical and horizontal drilling, well completion (casing and cementing, perforating, acidizing, hydraulic fracturing, 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; and
- post-production: well closure and land reclamation.
previously be developed profitably (Soeder 2018). Evolving technologies influence where development is economically feasible. As a result, UOGD now sometimes takes place in regions unaccustomed to the current scales of activity. The changes in technology also enable a substantial increase in the rate and intensity of development as described in Section 2. The modified practices affect the potential for both positive and negative consequences on oil and gas workers, people in nearby communities, the structure and function of those communities, and the local, regional, national, and possibly, global environment.

The recent controversy about UOGD in the United States — as well as much of the research in response to it — has been focused largely on potential human exposures, health effects, and climate change. Substantial efforts are underway within industry, government, and the broader scientific community to assess climate change impacts of UOGD (e.g., Allen et al. 2016). The amount of research assessing human exposure and health effects has also increased in recent years. This review and the broader HEI-Energy program are focused on understanding what has been learned about potential exposures and supporting research to address important knowledge gaps that remain.

**Box 1-1. UOGD Definition**

UOGD refers to the wave of onshore development and production of oil and natural gas from shale and other unconventional, or low permeability, geologic formations as practiced starting around the beginning of the 21st century. Industry practices continue to change in response to evolving technologies, regulations, and other factors, with current practice involving horizontal drilling combined with multistage hydraulic fracturing (i.e., fracturing that occurs in sequential stages along a horizontal wellbore). In the future, UOGD could be used more widely with both conventional and unconventional geologic formations. UOGD operations include:

- **Field Development**: Exploration, site preparation, vertical and horizontal drilling, well completion (i.e., casing and cementing, perforating, acidizing, hydraulic fracturing, 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; and
- **Post-Production**: Well closure and land reclamation.

**UOGD in the context of other oil and gas operations.**

Source: Debra Bryant, Avata
1.1.2 Increased Attention to Potential Exposures and Health Effects Associated with UOGD

Today, many people in the United States live near oil and gas development (Czolowski et al. 2017). With this proximity comes the potential for people to be exposed to a variety of chemical and non-chemical agents directly released to the environment from UOGD. Examples include vehicle and equipment emissions, chemicals released during drilling, well completion, and production, and noise and light from drilling and hydraulic fracturing. As the United States shale oil and gas boom accelerated in the early 2000s, scientists began to assess the potential for human health effects from UOGD exposures (e.g., Adgate et al. 2014; Brown et al. 2014; Czolowski et al. 2017).


1.2 OVERVIEW OF THE REPORT

1.2.1 Scope

Acknowledging the full range of potential beneficial and adverse exposures associated with UOGD is important to understanding effects on health1. As a practical step forward, this review focuses on environmental exposures to chemical and non-chemical agents released directly from UOGD that have the potential to adversely affect health so that action can be taken where needed to protect public health (blue highlighted portion of Figure 1-1). Analysis of past studies and their limitations can facilitate designing a study that addresses many of the complexities in quantifying exposure (Box 1-2) to support future exposure and health studies that consider a broad range of exposures (i.e., acute versus chronic exposures and local versus regional-scale exposures).

---

1 In addition to environmental exposures to chemical and non-chemical agents released directly from UOGD, people might be exposed to UOGD-related physical hazards such as traffic accidents (Blair et al. 2018a; Casey et al. 2019; Graham et al. 2015; Maryland Institute for Applied Environmental Health 2014; Muehlenbachs and Krupnick 2013; Witter et al. 2013), fires and explosions (Blair et al. 2017), and earthquakes (Andrews and Holland 2015; Ellsworth 2013; Hornbach et al. 2015; National Research Council 2013). They also might experience social change and community disruption (Becker 2018; Considine 2010; Cooper et al. 2016; Fernando and Cooley 2016; Ferrar et al. 2013a; HEI Special Scientific Committee on Unconventional Oil and Gas Development in the Appalachian Basin 2015; The Academy of Medicine Engineering and Science of Texas 2017) and economic change (e.g. Jacquet et al. 2018; Krupnick and Echarte 2017; Newell and Raimi 2018) that can come with a new or modified industry and its workers. While these types of exposures are important, they fall outside the scope of this literature survey.
Box 1-2. Why is understanding people’s exposures to UOGD-related chemicals and other agents so complex?

Communities near UOGD, regulators, members of industry and others can benefit from an improved understanding of whether and to what extent people are exposed to chemicals and other agents (like noise) from UOGD operations. Information on exposure is needed to determine whether people may experience adverse health effects from UOGD-related agents. Scientists have to collect information that allows them to follow the path from the source of the agents all the way to contact with people who may be exposed. This path is shown here in a simplified flowchart:

 expos

Exposure conditions are not static across time and vary among locations. Levels of UOGD agents in the environment can vary over the course of a day, season, year, and longer periods, depending on the level and type of UOGD activity, the medium of exposure (e.g., air and water), and characteristics of the local environment. Good design of an exposure study accounts for this variability to allow for assessment of short-term peak (acute) exposures and longer term (chronic) exposures. Levels of UOGD agents in the environment can also vary across regions and even across well pads as a function of geology, operator practices, local regulation, and other factors.

Why is it difficult to get this information? At each step in the path, there are challenges. Here are a few examples:

**UOGD Sources**: UOGD involves a collection of complex industrial processes involving numerous chemicals and the processes change through the various stages of oil and gas extraction to longer term changes (Section 2). Processes also differ among locations and operators. These complexities make it difficult to determine the composition and magnitude of releases from place to place and over time.

**Release Mechanisms and Transport Pathways**: After chemicals are released into the environment, they are transported by wind and water and other physical mechanisms. Chemicals can also change due to contact with other chemicals and the sun’s energy. As a result, the composition of mixtures of chemicals is constantly changing from the time they are released to the time they come into contact with people. Scientists struggle with how to best capture air, water, or other environmental samples that reflect these changes and with how to model these changes.

**Media or Types of Exposure**: People are exposed to chemicals in different media (e.g., air and water) to varying degrees because concentrations in these media will vary. For example, some soils may be more likely to hold onto some chemicals than others, so depending on the type of soil in a community, people’s exposures can differ by large amounts. Chemicals measured in media may also represent contributions from a variety of different sources (e.g., traffic and other industries), so researchers need to employ methods to understand the contribution of each source.

**Routes of Exposure**: Part of exposure assessment is understanding how much of a chemical or chemicals people come into contact with. But people vary in terms of how much air they breathe (consider the difference in breathing rates between a runner and someone watching television), how much water they drink, and so on.

**Exposed Populations**: Scientists need to understand how people behave in order to assess exposure and the potential for health risks. Here again things are complicated: some people spend a lot of time outdoors while others spend most of their time inside. Some have lived in a community near UOGD for years while others may have moved nearby recently.

To understand exposure, we may not need information on all of these factors, but with more complete information, scientists can have more confidence in their studies on links between exposure and health outcomes.

---

**Figure 1-1.** Potential human exposures associated with UOGD. This review focuses on potential environmental exposures that might adversely affect health (designated in blue).
1.2.2 Objectives

The primary objectives for this review are to (1) summarize current understanding of potential UOGD exposures in the United States, (2) move the science forward by identifying gaps in knowledge about potential exposures that merit research, and (3) develop research questions to address the knowledge gaps along with a set of anticipated characteristics critical to high-quality and policy-relevant research.

1.2.3 Organization of the Report

This report is organized into four primary sections. Section 2 provides an overview of UOGD operations in the United States, emphasizing aspects that may be important when formulating exposure research. Section 3 summarizes the methods used to survey the literature. Section 4 provides the Committee’s summary of the literature, what it tells us about potential exposures, lessons learned about exposure assessment methods, and gaps in the exposure literature. Section 5 lists a set of research questions defined by the Committee to address gaps in knowledge about potential human exposures to UOGD, along with characteristics that the Committee seeks in a research proposal.
2.0 UNCONVENTIONAL OIL AND GAS DEVELOPMENT

UOGD shares features with conventional oil and gas development, which has been ongoing in the United States since the 1800s, but UOGD differs in ways that can be important for understanding the potential for human exposures associated with it. Therefore, the assessment of human exposure to UOGD requires a fundamental understanding of the underlying operations. This discussion of UOGD is intended to provide a basic overview of UOGD operations, emphasizing operational and regulatory aspects that may be important when formulating exposure research.

2.1 UOGD DEFINED

UOGD refers to the onshore development and production of oil and gas from shale and other unconventional geologic formations. UOGD as practiced started around the beginning of the 21st century. Many of the UOGD operations today extract oil and gas from shale resources (Figure 2-1), which are distributed across the United States in areas with widely varying topographies, climates, levels of industrial and urban development, and population densities.

**Figure 2-1.** Map of Shale Plays in the United States (source: U.S. Energy Information Administration. [https://www.eia.gov/maps/images/shale_gas_lower48.pdf](https://www.eia.gov/maps/images/shale_gas_lower48.pdf))

Currently, UOGD involves horizontal drilling combined with multistage hydraulic fracturing (i.e., fracturing that occurs in sequential stages along a horizontal wellbore). Figure 2-2 provides a graphic illustration of UOGD operations, which include field development, production operations, and post-production.
2.2 Distinguishing Between Conventional and Unconventional Development

Operations employed in UOGD have been used in developing conventional oil and gas reservoirs. Conventional formations are more permeable than unconventional formations (King 2012). In conventional formations, the oil or gas has migrated from source rock to a porous formation and is held there by a sealing rock unit that prevents further migration. Oil or gas from conventional reservoirs flows readily or requires only a small stimulation with hydraulic fracturing for economical extraction by vertical wells. An unconventional formation is one with extremely low permeability (Ahmed and Meehan 2016) in which the oil or gas essentially does not flow without the application of multiple stages of well-stimulation treatments applied along horizontal wells.

Multi-stage fracturing occurs along the lateral section of a horizontal well, which provides massive contact with the formation compared to a vertical well (Figure 2-2). UOGD wells are stimulated, in stages, from the farthest point back to the curve between the horizontal and vertical well sections, as shown. Multiple horizontal wells are drilled from a single, large well pad for operational efficiency (U.S. Energy Information Administration 2012).

Figure 2-2. Conceptual layout comparing a vertical well with a horizontal well in the Marcellus Shale. Note: The illustration is not to scale, and actual fracture distances vary by depth and the type of resource under development. Illustration by William Kappel.

Today, oil and gas are extracted from wells drilled into both conventional formations and unconventional formations, but development focus has shifted to UOGD (Figure 2-3). Most commonly, UOG formations underly conventional oil and gas formations because the hydrocarbon-rich shales are source rocks for conventional oil and gas reservoirs. The co-location of conventional and unconventional oil and gas development presents a challenge in differentiating exposures emanating specifically from UOGD.
Although the individual development activities used in extracting oil and gas from unconventional formations are not new, their combined application in developing shale plays is new as of the early 2000s, particularly as stimulation volumes have continuously increased (Box 2-1).

**Box 2-1. What is new about oil and gas development in the 21st century?**

Hydraulic fracturing, horizontal (or directional) drilling, and extraction of oil and gas from unconventional formations, such as tight (i.e. low permeability) sandstone and shale, are not by themselves new.

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 drilled within the target formation). This combination of technological innovations has made previously uneconomical oil and gas resources valuable enough to develop.

Today’s unconventional oil and gas wells, with their extensive number of fracture stages along lengthy horizontal segments, intersect more of the targeted oil- or gas-bearing rock than earlier vertical wells, which consequently requires the following:

- Larger well pads with extensive amounts of equipment that must be transported to and from the pad;
- More raw materials that must be transported to the well pad for drilling, cementing and hydraulically fracturing the target hydrocarbon-bearing formation to produce the oil or gas;
- More liquid and solid waste from multiple wells drilled on one well pad that must be captured, transported, and treated, for reuse or ultimate disposal;
- A longer period of industrial activity required at a single well pad when multiple wells are developed on it; and
- Increased truck traffic and community change.

### 2.3 PHASES OF UOGD

Operational activities in each phase of UOGD differ in duration and in potential for a release to the environment. This section describes UOGD phases and illustrates some of the temporal, spatial, and operational variations across the United States.
2.3.1 Pad Development

UOGD begins with constructing a well pad, which is a site specifically designed to provide a level area sufficient for the equipment used to drill and then complete a horizontal well, while simultaneously providing space for the logistical support operations. Pads are created using diesel-operated construction equipment (e.g., excavators, backhoes, and bulldozers). Other vehicles may deliver construction materials and personnel to the site. Pad construction (including road building) normally is completed in 2–7 weeks.

Engines, which power trucks and the equipment used for site preparation, emit nitrogen oxides (NOx), particulate matter (PM), volatile organic compounds (VOCs), polyaromatic hydrocarbons (PAHs), and methane (CH4), among other releases to air (Moore et al. 2014). Well pad construction, truck traffic and other on-pad activities can also generate PM by re-suspending dust. Vehicles moving on and off the site may interfere with local traffic. Depending on the location, traffic interruption is often temporary.

UOGD well pads typically occupy multiple acres with size varying depending on the number of wells per pad. For example, UOGD well pad size in the Pinedale Field, Wyoming increases with the number of wells on the pad (Figure 2-4). The number of horizontal wells drilled per well pad has increased since the early 2000s (Figure 2-5a and 2-5b), and pads with 20 wells or more have been constructed in recent years. Note that these figures reflect wells drilled, not the ultimate planned pad density.

Figure 2-4. Satellite image three well pads with 1, 2, and 16 wells, respectively, in the Pinedale Field. (Satellite photo from DrillingInfo.)

Oil and gas infrastructure, such as well pads, new roadways to access pads, gathering flowlines, and compressors, has been constructed on a variety of landscapes, including agricultural land, core forest habitat, and lands with soil that is vulnerable to erosion and sedimentation (Drohan et al. 2012; Pennsylvania Department of Conservation and Natural Resources 2014). Some studies have suggested that runoff related to UOGD may be linked with increased levels of turbidity (Entrekin et al. 2011) and total suspended solids (Olmstead et al. 2013) in receiving waters.

States have various pad design requirements to protect the environment, including spill protection. Pads can be built with multiple types of protections (e.g. protective liners, protection mats, containment units, and earthen berms). Walls may be used around the pad site during drilling and completion to reduce noise and visual disturbances.
Figure 2-5. Number of horizontal wells drilled per well pad, or pad density, across U.S. shale plays as of January 1, 2005 (a) and January 1, 2019 (b). Each icon represents a single well pad, and the color of the icon indicates the number of horizontal wells drilled on each well pad. (Created by M. Al-Alwani, merging horizontal well records from FracFocus and DrillingInfo.)
2.3.2 Drilling

Drilling creates the borehole required to access the shale formation. Drilling occurs in stages: drilling, then running and cementing casing to isolate each successive portion of the well. Multiple strings of casing are used to isolate the well from surrounding strata (Figure 2-6). Once the drilling rig is assembled and ready to drill, the well is “spudded in,” a phrase referring to the commencement of drilling. A short conductor pipe is installed to stabilize the initial hole and secure equipment needed for the deeper parts of the well.

Surface casing is set below the deepest underground source of drinking water, and this casing string is commonly cemented to the surface to protect ground water. The depth of the surface casing varies across shale plays. State regulations often indicate specific impermeable geological layers for setting the bottom of the casing string (referred to as the casing “shoe”). Additional casing is included for deeper sections of the well (Figure 2-6).

An intermediate casing string is frequently used today and may be required by state regulation. The production casing, or liner, is the final casing run in the well and may not be cemented, depending on the hydraulic fracturing system to be used. The current trend is to cement the production casing along the lateral section as shown in Figure 2-6. The multiple strings of casing and cement together are designed to prevent impacts to surrounding groundwater, but the potential for leaks remains, so monitoring is conducted to detect possible upward fluid movement (Box 2-2).

Drilling mud circulates through a continuous loop system from storage tanks (or a lined pit) through mud pumps to the well, then back through equipment that removes sand and natural gases before passing over shale shakers, which separate rock fragments from the drilling fluid. The rock fragments, referred to as “drilling cuttings,” are accumulated for disposal, generally in a confined area near the rig after passing through a centrifuge and dryer to reduce the oil content. The drilling mud is recirculated through the mud pit to the pump and reused in the drilling system. Any drilling mud that has had its physical or chemical properties altered such that it no longer meets the requirements for reuse needs to be stored separately for later treatment and disposal at a licensed facility.

Figure 2-6. Well construction design for a Marcellus gas well. This figure shows three casing strings (surface, intermediate, and production) covering the drinking water aquifer. Source: Clark et al. 2012. Used by permission.
Drilling muds can be water-based, oil-based, or synthetic-based. Both water-based and oil-based muds include chemical additives such as salts, friction reducers, corrosion inhibitors, foamers, and surfactants. In addition, oil-based muds absorb methane, resulting in higher gas emissions at the surface than with use of water-based muds (Thomas et al. 1984). Gas emission estimates from de-gassing drilling mud must be reported under federal regulations (CFR 40, Part 60, Subpart OOOO).

Drilling creates noise and visual disturbances that vary depending on the operation. Near urban settings, operators might erect solid walls surrounding the drilling rig area to reduce these impacts. With increased efficiency, the time required to drill a single well has declined over time (Figure 2-7). Drilling patterns and timing for multiple wells may differ among operators or as a function of market conditions.

Surface emissions during drilling are related to exhaust from generators on the rig as well as support vehicles, resuspended dust from unpaved access roads, drilling mud de-gassing, and any fluid leaks or spills emanating from the mud circulation system. An uncontrolled surface release of drilling mud and well fluids, referred to as a “well blowout,” can occur in approximately one well in a thousand (Patterson et al. 2017).

Figure 2-7. UOGD well drilling time compared across shale plays. Republished from Weijers et al. 2019 with permission of the Society of Petroleum Engineers; permission conveyed through Copyright Clearance Center, Inc.
2.3.3 Well Completion (Hydraulic Fracturing)

After drilling is complete, the drilling rig is removed and well completion equipment is brought to the well pad. The well completion process may begin immediately or up to months after drilling. For example, in March 2019, there were approximately 8500 drilled but not completed wells, a one-year increase of 26% (U. S. Energy Information Administration 2019).

Well completion refers to the processes and materials required to establish flow from the formation to the ground surface. In UOGD, well completion includes hydraulic fracturing, a method of stimulating flow. In hydraulic fracturing, fluid is combined with proppant (normally sand or ceramic) and pumped into the formation containing oil or gas under pressures sufficient to fracture the rock, creating a large surface area that is held open by the proppant, which enhances the flow of oil or gas into the wellbore.

Hydraulic fractures orient and grow perpendicular to the direction of the smallest of three principal subsurface stresses (vertical, horizontal maximum, horizontal minimum) as illustrated in Figure 2-8 (Smith and Montgomery 2015; Soliman and Dusterhoft 2016; Ahmed and Meehan 2016). In most shale basins, the greatest stress is the vertical stress, or “overburden” of the rock strata, and the minimum stress is in a horizontal plane within the shale, as shown by the size and direction of arrows in Figure 2-8. In a horizontal wellbore, drilled in the direction of minimum horizontal stress, it is possible to create many vertical fractures along the lateral, as shown in well B of Figure 2-8. Although the geomechanics of this kind of fracturing has been long understood, the evolution of methods for placing multiple fractures along the lateral section of a horizontal well made it possible to economically produce oil and gas from extremely tight, or low permeability, shale formations.

Fisher and Warpinski (2012) used microseismic data (obtained via a diagnostic method that measures acoustic responses as a fracture propagates through the formation) to investigate whether hydraulic fractures are likely to propagate upward into groundwater. They presented a series of plots demonstrating that it is improbable that fractures can propagate vertically into groundwater. There is significant vertical distance between UOGD completions and groundwater. Well completions in shallower depths will have less vertical height growth due to reduced overburden stress.

In addition to large quantities of fracturing fluid (or “frac fluid”), ample pumping horsepower and pressure are required to create the large fractures needed to produce shale formations economically. Fracturing fluids used in UOGD are most commonly a combination of water and a friction reducer, but gels are sometimes used. Sand is the most common proppant in formations with lower stress and ceramic proppant is used in formations with higher stress values. Higher stresses are typically found in deep formations, such as the Utica shale (Smith and Montgomery 2015; Ahmed and Meehan 2016). The use of finer proppant (similar in particle size to that of flour) has gained popularity in recent years (Kumar et al. 2019).
The fracturing equipment used on a UOGD well pad (Figure 2-9) is a function of the pumping horsepower required for the fracturing treatment and the volumes of fluid and proppant used in each stage of treatment. These, in turn, are a function of the depth of the well and the number of individual stages to be pumped in the well. In the past decade, the number of fracturing stages per well has increased in every shale play (Weijers et al. 2019). A lined water pit (not shown) is often also part of the site.

During fracturing, pumps draw fracturing fluid from tanks (or a lined pit) to the blender tub. Sand is delivered to the blender in several ways. A recent method uses individual closed “boxes” of proppant that are lifted on top of a hopper to reduce sand inhalation during fracturing. The blender mixes the fluid and sand together (referred to as a “slurry”) and the slurry is pumped into the well at a high rate (50–90 barrels/minute). The types of fluid and proppant sizes may differ during different portions of the treatment, or between fracturing stages.

The fracturing process will be repeated as many times as the number of fracturing stages designed for the well. Weijers et al. (2019) reported that average total lateral lengths for wells across multiple shale plays have increased from approximately 4000 ft in 2010, to 7500 ft in 2017. In the same period, stage counts have increased from 9–21 stages per well (depending on shale play) to 30–50 stages per well. Treatment volumes have likewise increased accordingly, all in the same period that well density has increased. The time associated with fracturing a well varies across shale plays, and all plays have experienced reductions in completion time with operational efficiency. (Weijers et al. 2019).

Much attention has been focused on chemicals used in hydraulic fracturing. Although most of the frac fluid used in UOGD is water and proppant, frac fluid also contains biocides, corrosion inhibitors, friction reducers, scale inhibitors, oxygen scavengers, potassium chloride, surfactants and cross-linkers. The U.S. EPA (2016a) provides information regarding chemicals most frequently used in hydraulic fracturing between 2011 and early 2013 and Montgomery (2013) provides an overview of their classification. The types of fluid systems vary across shale plays because formation temperatures and rock properties (such as minerology, clay content, and brittleness), vary among the different formations (Dobson and Houseworth 2013; Li et al. 2019; Ahmed and Meehan 2016; Yuyi et al. 2016).

Releases during hydraulic fracturing can occur from spills or leaks during fluid transport on or offsite, casing failures during injection (Beak et al. 2015), and failures in surface pipe or surface equipment during completion. The U.S. EPA (2016a) extensively discussed spill size and frequency and challenges in characterizing spills and their fate and transport. The specific chemicals released by a spill will vary depending on the fracturing treatment and activity associated with the spill (e.g., leak from a holding tank).

Operators may transport water via trucks, requiring hundreds of truck trips per well. Based on median water volume per well, water use has intensified between 2011 and 2016, ranging from a 20% increase in the Marcellus to a 770% increase in the Permian basin (Kondash et al. 2018), exacerbating the potential for releases that can occur during water transport. Transporting water by truck can increase exposure to

---

Figure 2-9. Example UOGD wellsite with tank- and truck-based hydraulic fracturing equipment (Suchy and Newell 2012).
PM, diesel, and traffic accidents and congestion. More recently industry operators have increasingly employed centralized, lined water pits or lakes, which can provide water directly to multiple well pads.

The American Petroleum Institute (API) has published new API standards for shale development to reduce impacts from hydraulic fracturing (Benge et al. 2018). These standards provide guidance and recommendations for pressure containment and well integrity as well as environmental safeguards for groundwater protection, waste management, emissions reduction, site planning, and worker training. The standards are described in American National Standards Institute (ANSI)/API recommended practice (RP) 100-1 and 100-2. Industry has also developed a stewardship decision-making tool for operators to support UOGD decisions that minimize UOGD impacts and improve sustainability (Wilson 2018).

Box 2-3. Chemical Use in UOGD and FracFocus Database

Hydraulic fracturing fluid can be composed of many chemicals, some of which are not well characterized or are classified as confidential business information. In a 2016 report, EPA identified 1,606 chemicals associated with hydraulic fracturing, including 1,084 chemicals that are used in hydraulic fracturing fluid and 599 chemicals that have been detected in produced water (U. S. EPA 2016a). Additionally, EPA reported that the majority of the 1,606 chemicals lack toxicity reference values for assessing the potential for cancer and non-cancer effects, making risk assessments focused on UOGD releases to water difficult to conduct. In addition to EPA’s review, UOGD operators in twenty-six states provide hydraulic fracturing fluid chemical use data on a voluntary or regulatory basis. These data are made available through FracFocus (www.fracfocus.org), a publicly available database managed by the Groundwater Protection Council (GWPC) and Interstate Oil and Gas Compact Commission (IOGCC).

2.3.4 Flowback

After all fracturing treatments are pumped, pressure is released and the injected fluids, mixed with brines naturally present in the host rock, is allowed to flow back to the surface for a period of time. This period is referred to as “flowback,” and may last from 1–4 weeks. Flowback rates can be several thousand barrels a day per well (Guarnone et al. 2012).

The flowback fluid initially contains dominantly frac fluid, mixed with oil, gas, and sand. Salinity increases occur during long flow back periods, which normally indicates natural formation brine (produced water) is returning with the frac fluid. Much of the frac fluid does not return to the surface after treatment (Kondash and Vengosh 2015). Kondash et al. (2018) reported that across six shale basins, the volume of flowback and produced water generated in the first year has increased by from 55% (Niobara) to 550% (Eagle Ford) between 2011 and 2016 as the volume of injected water increased across this period.

U. S. EPA (2016a) identified 599 unique chemicals in flowback and produced water reported from laboratory studies, including salts, metals, naturally occurring organic compounds, radioactive materials, and hydraulic fracturing chemicals. It was noted that, in general, the composition of these waters is similar to produced water from conventional oil and gas development.

Flowback water may be directed to a lined pit or closed tanks. In the United States, flowback is handled as a reduced-emissions completion in the case of a gas well or wells that produce both oil and gas. A reduced-emissions completion routes flowback through production equipment (Figure 2-10). The gas is routed for use on site, to a sales line, or to a flare if state regulations permit flaring. The liquids from the bottom of the separator are routed to a lined pit or to tanks. Since August 2011, U.S. EPA regulation (CFR 40, Part 60, Subpart OOOO) requires UOGD completions to be handled as reduced-emissions completions unless an exception is granted.
Flowback water is most commonly disposed of in saltwater disposal wells and in many cases is trucked to the disposal location. In the Marcellus Shale most flowback water is treated and reused in future hydraulic fracturing treatments as saltwater disposal well options are limited in Pennsylvania (www.dep.pa.gov/Business/Energy/OilandGasPrograms/OilandGasMgmt/Pages/Underground-Injection-Wells.aspx). U.S. EPA is currently examining options for broadening water reuse and disposal options (U.S. Environmental Protection Agency 2019c).

2.3.5 Production

Production refers to the stage when the well is hooked up to permanent production equipment, which allows for continuous flow of fluids. Production facilities include a wide range of equipment that first separates gas from liquid (water and oil or condensate), then separates produced water for holding and disposal, and moves the fluids through flowlines to sales (e.g., compressors are used to bring gas pressure to transportation or sales line pressures, oil may be pumped through lines or trucked for sales). Oil facilities utilize somewhat different equipment and processes than gas facilities (Arnold and Stewart 2007, 2014).

A well’s production rate is a function of formation pressure as well as formation permeability and flow area. Formation pressure decreases over time and, at some point, there is insufficient energy to bring fluids to the surface. At this point some form of artificial lift is installed, which includes technologies such as rod pumps, gas lift, and electric submersible pumps for producing liquids (Pankaj et al. 2018). The production rate from a UOGD well declines rapidly over time, with the well’s initial rate declining by 40% to 60% in the first year of production (Figure 2-11). Production from the well will last for years, a much longer time than the previous UOGD phases. At this point, the pad will contain only the wellhead(s) and possibly some stored equipment. The rate of production is monitored by lease operators who visit the well site every 24–48 hours. Some companies remotely and continuously monitor producing rates and pressures from wells, along with pressure and fluid levels in facilities. Pressure and level alarms are a common means to alert operators to potential problems so action can be taken to minimize releases.

Most shales produce some amount of water along with hydrocarbons. This produced water contains various chemicals and naturally occurring radioactive materials. Total dissolved solid concentrations in produced water vary widely across the shale plays. The majority of produced water is disposed of in injection wells, piping to the disposal location when possible to minimize storage. Operators are not allowed to discharge flowback or produced water to streams, rivers, or to publicly operated treatment works. Onshore oil and gas extraction activities may discharge produced water in the western part of the United States (west of the 98th meridian) if it is of sufficient quality for agriculture or wildlife uses and is...
put to such use during the period of discharge. The U.S. EPA (2019b) has summarized the challenges and possible directions for produced water disposal and reuse.

Emissions of methane and VOCs to the atmosphere can occur during the production phase, both at the well and production facilities. For example, in a gas well, liquids can accumulate in the well and decrease or interrupt the flow of gas as reservoir pressure is not sufficient to drive production. If this happens, well production is stopped, allowing the pressure to build up again. Once pressure has built to a sufficient level, the well is reopened and the liquids, along with some gas, are unloaded to a vented tank. During this period of ‘liquid unloading,’ emissions of volatile components to air result (Allen 2016). At present, most emissions from liquid unloading are occurring from older, conventional wells (The Academy of Medicine Engineering and Science of Texas 2017). Changes in rules and regulations pertaining to air emissions and the continuing development of new technologies have been aimed at decreasing such emissions.

Production facilities emit methane and other VOCs from tank vents, compressors, and other equipment. These facilities are subject to federal regulation (CFR 40, Part 60, Subpart OOOO). More recent U.S. EPA regulation (CFR 40, Part 60, Subpart OOOOa) established emission standards and compliance schedules for the control of methane, VOC, and SO\textsubscript{2} emissions from affected facilities in the crude oil and gas category that were constructed or modified after September 18, 2015.

2.3.6 Post-Production

When a well is no longer economically viable, an operator may decide to permanently plug the well with cement (plug and abandonment, referred to as P&A). Few UOGD wells have reached this point as yet, but when that occurs, operators are expected to obtain the necessary permit and follow state regulations in the placement of multiple downhole cement plugs. Once a well is closed, operators are typically required by state regulations to reclaim the well pad to original or near-original landscape conditions, including vegetation, contour, and drainage.

Thousands of conventional wells have been plugged and abandoned. Locations for many P&A wells are known, yet states have large numbers of “orphaned” wells (wells which were abandoned without proper closure) for which their location is unknown (U.S. EPA 2018). UOGD wells stimulated near older P&A wells or unidentified orphaned wells may fracture into these older wellbores, creating releases at the surface (Figure 2-12).
2.3.7 Waste Management from UOGD

Waste management refers to containment, handling, storage, and disposal of solid and liquid wastes generated from UOGD activities. Such wastes include drill cuttings, fluid on cuttings, drilling fluid dilutions, tank bottoms, flowback water, produced water.

Non-hazardous wastes typically are disposed at a licensed facility, such as a landfill, or are sent to an intermediate company for processing and recovery of some waste components, with the remainder sent to a landfill. Drill cuttings are primarily disposed of in landfills, although cuttings containing natural radioactive material may be treated first. Some wastes generated by UOGD can be classified as hazardous (e.g., wastes with NORM concentrations that result in classification as hazardous waste) and must be handled by industries that specialize in hazardous waste management. The U.S. EPA has authority over both hazardous and non-hazardous solid waste disposal; however, states have the primary authority to implement and enforce these standards.

Depending on shale play area, flowback and produced water are piped or trucked to saltwater disposal wells or reused (e.g., in future well stimulation treatments). The U.S. EPA has promulgated a series of underground injection control regulations associated with subsurface injection and disposal wells. States with primacy directly regulate these wells through the state’s underground injection control program. If produced water is low in total-dissolved-solids and treated appropriately, discharge to surface water in states west of the 98th meridian may be permitted, although regulation regarding above-ground disposal of liquid waste has changed over time (U.S. EPA 2019).

2.4 SUMMARY

UOGD is a complex process, involving an intricate interplay of technologies, markets, and regulation. As the industry evolves, and the potential for human exposures will vary across regions and over time. A thorough understanding of UOGD operations and how they are changing over time is essential for understanding and studying human exposures associated with UOGD.
3.0 METHODS USED TO SURVEY THE LITERATURE

The Committee, along with HEI-Energy staff, surveyed peer-reviewed and gray scientific literature that provides information about potential UOGD exposures to determine what is already known, to identify knowledge gaps, and to begin planning for research that addresses the gaps. They also toured UOGD operations and convened two public workshops at the outset of the survey in July 2018 in Denver, Colorado (https://hei-energy.org/meeting/Jul-2018-workshop) and in September 2018 in Austin, Texas (https://hei-energy.org/meeting/Sept-2018-workshop). The workshops provided opportunities for participants to engage in a productive exchange with the Committee and other meeting participants about HEI-Energy’s plans for its review of the literature and identification of future research challenges and opportunities. Speakers and other meeting participants represented sponsor organizations, federal and state government, industry, academic research scientists, environmental and public health nongovernmental organizations, community organizations, and HEI-Energy’s Committee and staff.

3.1 SURVEY QUESTION

The Committee’s survey of the literature was guided by a primary question: What is known about potential UOGD-related human exposures?

To answer this question, the Committee sought full text studies that contribute to understanding how people might be exposed in the United States to chemical agents (e.g., benzene) or non-chemical agents (e.g., noise) released directly from UOGD to the environment. All potentially useful studies were considered whether or not the investigators set out to study human exposures. This included studies that characterized one or more elements of an exposure pathway, such as the chemical and non-chemical agents associated with UOGD operations, the ways that these agents are released to and behave within the environment, the concentrations of agents in air, water, and other environmental media, and the potentially exposed populations and their time-activity patterns, which influence whether and how exposures occur.

While UOGD worker exposures fall outside the scope of this survey, literature on this topic was reviewed as worker exposures may inform assessments of community exposures. There is also a sizable literature focused solely on methane emissions (e.g., Allen et al. 2013), and a subset of this literature was reviewed in the context of understanding the potential for exposures to other chemicals (e.g., from fugitive emissions and leaks).

3.2 LITERATURE SEARCH

The Committee searched full text peer-reviewed and gray literature published in English between January 1, 2000 and July 10, 2019. The search period was selected based on an understanding of when UOGD began in the United States (see Section 2, Figure 2-3). Well development data, well geometry data (Figure 3-1), and other information indicate the increasing development of shale and other unconventional resources using horizontal wells combined with multistage hydraulic fracturing. This development began in the early 2000s, peaking around 2014 before declining steeply in 2014, then rising again in 2016.

Peer-reviewed literature was identified using four electronic databases: PubMed (https://www.ncbi.nlm.nih.gov/pubmed/), Web of Science (https://www.webofknowledge.com/), Embase (https://www.embase.com/) and Google Scholar (https://scholar.google.com/). Gray literature was identified using Google Scholar and from literature provided by stakeholders in conjunction with the two HEI-Energy workshops. Endnote management software was used to download and maintain a literature library.
A broad search phrase was employed to capture papers with information potentially useful for assessing exposure from UOGD in the United States:

**Web of Science**

\[
\text{TS}=(\text{oil and gas OR shale OR petroleum OR 'natural gas' OR 'shale gas' OR 'tight gas' OR 'tight resource' OR 'shale oil' OR 'tight oil' OR 'unconventional gas' OR 'unconventional oil' OR 'unconventional resource' OR drilling OR 'well stimulation' OR 'hydraulic fracturing' OR fracking OR flowback OR 'produced water' OR flar*) AND TS=(Appalachian OR Devonian OR Bakken OR Barnett OR Chattanooga OR Cherokee OR 'Denver-Julesburg' OR 'Eagle Ford' OR Fayetteville OR 'Fort Worth' OR 'Greater Green River Basin' OR Haynesville OR Ingelwood OR Marcellus OR Niobrara OR Permian OR Piceance OR San Juan OR Uinta OR Utica OR Wattenberg OR Williston OR 'Wind River Basin' OR Woodford)) AND TS=(brine OR bromide OR BTEX OR 'hydrogen disulfide' OR PAH or hydrocarbon OR isotop* OR methane OR NMHC OR NORM OR radioact* OR silic* OR 'total dissolved solids' OR trace* OR VOC OR noise OR light OR odor OR vibration OR accident OR explosion OR fire OR 'chemical transport' OR concentration OR contamina* OR emission OR leak OR migrat* OR spill OR environment OR quality OR air OR water OR 'drinking water' OR groundwater OR 'surface water' OR wastewater OR soil OR sediment OR food OR 'solid waste' OR inh* OR dermal OR ingest* OR expos* OR biomarker OR biomonitor OR population OR community OR boomtown OR endocrine OR carc* OR tox* OR impact OR hazard OR risk OR health OR safety OR social* OR anxiety OR stress OR depression OR symptom OR epidemiology OR trauma))
\]

**PubMed and Embase**

\[
\text{TS}=(\text{oil and gas OR shale OR petroleum OR “natural gas” OR “shale gas” OR “tight gas” OR “tight resource” OR “shale oil” OR “tight oil” OR “unconventional gas” OR “unconventional oil” OR “unconventional resource” OR drilling OR “well stimulation” OR “hydraulic fracturing” OR fracking OR flowback OR “produced water” OR flar*) AND (Appalachian OR Devonian OR Bakken OR Barnett OR}
\]

---

**Figure 3-1.** North American well geometry since 1991, showing the increasing prevalence of horizontal wells over time.
Chattanooga OR Cherokee OR “Denver-Julesburg” OR “Eagle Ford” OR Fayetteville OR “Fort Worth” OR “Greater Green River Basin” OR Haynesville OR Ingelwood OR Marcellus OR Niobrara OR Permian OR Pieceance OR “San Juan” OR Uinta OR Utica OR Wattenberg OR Williston OR “Wind River Basin” OR Woodford) AND (brine OR bromide OR BTEX OR “hydrogen disulfide” OR PAH OR hydrocarbon OR isotop* OR methane OR NMHC OR NORM OR radioact* OR silic* OR “total dissolved solids” OR trace OR VOC OR noise OR light OR odor OR vibration OR accident OR explosion OR fire OR “chemical transport” OR concentration OR contamina* OR emission OR leak OR migrat* OR spill OR environment OR quality OR air OR water OR “drinking water” OR groundwater OR “surface water” OR wastewater OR soil OR sediment OR food OR “solid waste” OR inhal* OR dermal OR ingest* OR expos* OR biomarker OR biomonitor OR population OR community OR boomtown OR endocrine OR carc* OR tox* OR impact OR hazard OR risk OR health OR safety OR social* OR anxiety OR stress OR symptom OR epidemiology OR trauma).

To find additional peer-reviewed and gray literature not identified with electronic searches, the Committee used the following methods:

- Consulted various databases established for the UOGD literature, such as the Shale Research Clearinghouse (https://www.rff.org/sharc/), the FrackHealth database (https://endocrinedisruption.org/audio-and-video/fracking-related-health-research-database/search-the-database), and the Repository for Oil and Gas Energy Research (https://www.psehealthyenergy.org/our-work/shale-gas-research-library/).
- Consulted with knowledgeable government officials (e.g., National Institute of Environmental Health Sciences, U.S. EPA, U.S. Geological Survey, and National Institute of Occupational Safety and Health), academics, industry experts (e.g., toxicologists, physicians, epidemiologists, and others responsible for health and safety), nongovernmental organization representatives (e.g., environmental health organizations, public health organizations, and community groups) and relevant websites.
- Consulted reference lists of studies, commentaries or letters on studies, relevant reviews, and other non-research articles.

3.3 SURVEY OF THE LITERATURE

The term exposure encompasses the way in which individuals come into contact with an agent over space and time. The Committee performed a broad survey of the literature to identify the ways in which people might be exposed to chemical and non-chemical agents associated with UOGD.

3.3.1 Potential Human Exposures Framed in a Conceptual Model

An ideal exposure study would provide information that allows one to determine whether a complete exposure pathway exists between the source of a specific UOGD agent and a population (Figure 3–2). Exposure pathways are the course an agent takes from the source to the individual or population. People might be exposed to multiple chemical and non-chemical agents and by more than one exposure pathway, the summation of which is referred to as their “total exposure.”

Figure 3–2. Conceptual model of potential exposure pathways associated with UOGD. Adapted from the U.S. EPA’s “Guidelines for Human Exposure Assessment” (U.S. EPA 2016a).
The Committee reviewed how studies contributed to understanding the temporal variability, spatial variability, and likelihood (i.e., probability) of potential exposures to chemical and non-chemical agents and framed its review in the conceptual model of exposure (Figure 3-2). This framing was intended to facilitate understanding of what is known about potential exposure pathways and where knowledge gaps exist. In reviewing each paper, the Committee looked for whether investigators presented data supporting each component of an exposure pathway: UOGD source, release mechanisms and transport pathways, media or type of exposure, routes of exposure, and exposed populations.

The Committee sought clear identification of the **UOGD source** of the release under investigation. Incorporation of source apportionment methods (e.g., collection of detailed operational time–activity information and use of tracers or chemical ratios) might be needed to distinguish between chemical or non-chemical agents originating from UOGD and from other sources. Ideally, investigators would specify whether environmental releases from UOGD sources resulted from operational, accidental conditions, or unauthorized activities (e.g., illegal dumping). To aid in the interpretation of study results and the generalizability to other conditions, the Committee looked for information from each study on whether information on temporal and spatial variations in environmental releases was provided.

The committee examined whether exposure studies identified the **release mechanisms and transport pathways** for specific chemical and non-chemical agents. Following release of a chemical or non-chemical agent from a UOGD source to the environment, its fate in the environment is a function of its own physical and chemical properties and characteristics of the local environment. An understanding of these factors is essential for determining whether a human population might be exposed and by what medium, through what **type (e.g., noise) of exposure**, and by which **route of exposure**.

In the data collection and analytical stages, the committee considered how investigators employed quality assurance and quality control measures, data validation, analytical techniques, and data management. Importantly, the Committee evaluated how investigators contextualized their results within the space and time that the results were collected and provided information that allows for extrapolation to a variety of spatial and temporal conditions and over time.

Potentially **exposed populations**, including vulnerable subpopulations, need to be identified to understand whether an exposure might occur and, if so, to interpret its importance. Information about the population, such as time–activity patterns, and the UOGD source ideally would be sufficient to quantify the magnitude, frequency, and duration of a potential exposure and its likelihood of occurrence. The likelihood of exposure depends on factors related to when and where UOGD operations occur, whether emissions are associated with normal operating conditions, accidents, or unauthorized incidents, atmospheric conditions, and behaviors of both the operator and the exposed individual (i.e., time–activity factors) that influence the extent to which someone might be exposed to the releases. The Committee sought data that indicated the likelihood for an exposure to occur.

### 3.3.2 Relevance of the Literature to the Range of Possible Exposure Conditions

Studies included in this review may contain some or all elements of a complete exposure pathway. The Committee developed a set of questions to facilitate its survey of the literature for understanding exposures to UOGD and identifying knowledge gaps:

1. Did the investigators demonstrate a link between their monitoring or modeling results and UOGD?

2. Did the investigators identify which human populations, if any, could be exposed to the chemical or non-chemical agent(s) investigated in the study?
3. Are the monitoring or modeling results potentially useful for understanding exposure to UOGD-related agents (e.g., likelihood, frequency, duration, or magnitude) for:
   a. The location and population under study?
   b. Other locations and populations?
4. Monitoring studies: Did the investigators select appropriate sampling and analytical methods and use them properly (e.g., proper calibration)?
5. Modeling studies: Was model selection, parameterization, and evaluation appropriate?
6. Both modeling and monitoring studies: Was there evidence of bias (e.g., investigators did not appear to report all results) or other serious concerns with overall study quality that might affect interpretation of study results?
7. Is there information missing from the paper that limits inferences about realized or potential exposures to UOGD-related agents? If so, explain.
8. Are study results subject to important uncertainties with respect to addressing the study objectives? If yes, what are they, and are they quantified or discussed qualitatively?
9. How does the paper inform the potential design of a future exposure study (consider both positive and negative aspects of the study)?

The questions required the Committee to assess the utility of each study for understanding human exposure across various spatial and temporal conditions and to begin to identify knowledge gaps.
4.0 Survey of the Literature

People can be exposed to chemical and non-chemical agents released to the environment from UOGD during routine operations (e.g., permitted emissions to air), accidental conditions (e.g., leaks or spills), or unauthorized events (e.g., illegal dumping of wastes). The potential for exposure varies among phases of UOGD development (e.g., well pad construction, drilling, well completion, and production).

The discussion of the exposure literature is organized in accordance with a conceptual model of exposure, which illustrates the exposure pathways assessed in the literature (Figure 4-1). This organization facilitates identification of links between potential UOGD sources of exposure and populations, and gaps in our understanding of exposures.

Figure 4-1. Conceptual model of potential exposure pathways assessed in the literature. (More detailed conceptual models of potential exposure are available in an HEI Special Report [Appendix C in: HEI Special Scientific Committee on Unconventional Oil and Gas Development in the Appalachian Basin 2015]).

4.1 Summary of Studies

The studies had diverse objectives and designs and, to differing degrees, contributed to an understanding of whether a complete exposure pathway connects a UOGD source with a human population living in communities affected by UOGD. They include studies that reported levels of chemical or non-chemical agents in air, water, and other media based on measurements or modeling (Figures 4-2 and 4-3). The increasing number of studies in recent years (Figure 4-2) parallels the rise of UOGD (Figure 4-4). Most studies measured or modeled VOCs and other chemicals in air, with fewer quantifying VOCs, brines (chemicals associated with produced water), and other chemicals in water. Only a few studies reported chemical concentrations in soil or sediment, levels of sensory agents, or biomonitoring data (Figure 4-2).
Figure 4-2. Number of studies published each year by study media.

Search period: January 1, 2000 to July 10, 2019

Figure 4-3. Number of studies by chemical agent.
Figure 4-4. Total (a) oil and (b) natural gas production over time by U.S. region.

Source of production data: https://www.eia.gov/petroleum/drilling/.
4.2 AIR EXPOSURE PATHWAYS

4.2.1 Summary of Studies – Air Exposure Pathway

Scientists have investigated the potential air quality impacts of UOGD in several major oil- and natural-gas producing regions of the United States (Figure 4-5). Studies included original measurements of air quality (n=72), modeling of air quality (n=16), and both measurement and modeling approaches (n=26). Investigators have measured chemical concentrations in air using a variety of methods, including personal sampling, mobile and stationary sampling at the ground surface, and measurements collected from aircraft and satellites. Other investigators used modeling approaches to assess chemical concentrations in air, whereas some studies included both approaches. Regional ozone or PM concentrations were the subject of several studies, although most studies investigated air quality in areas near UOGD operations. A few of these studies leveraged air quality monitoring data or modeling to assess setback distances and distance decay gradients between UOGD and residences (Banan and Gernand 2018; Garcia-Gonzales et al. 2019a; Haley et al. 2016; McCawley 2013).

Figure 4-5. Air monitoring or modeling study locations.

Studies have measured or modeled atmospheric concentrations of several different chemical compounds associated with UOGD operations, including VOCs (Bari and Kindzierski 2018; Eisele et al. 2016; Helmig et al. 2015; Lim et al. 2019; Maskrey et al. 2016; McMullin et al. 2018; Swarthout et al. 2013), NOx (Goetz et al. 2017; Koss et al. 2017; Majid et al. 2017; Pacsi et al. 2013; Pennsylvania Department of Environmental Protection 2018), black carbon (BC) (Allshouse et al. 2019), PM (Allshouse et al. 2019; Bean et al. 2018; Fann et al. 2018; Frazier 2009; Roohani et al. 2017), and radionuclides (Casey et al. 2015; Mitchell et al. 2016; Walter et al. 2012; Xu et al. 2019b).
Some investigators discussed the conditions under which they collected data. For example, Olaguer et al. (2014) collected data specific to flaring and Hildenbrand et al. (2016c) collected BTEX concentration data specific to mechanical inefficiencies. Other studies (Evans and Helmig 2017; Oltmans et al. 2014) presented data from monitoring of normal operations. McClellan and Snipes (2010) stated that their data represent concentrations "regularly detected and identified" but did not define what they meant by this phrase.

4.2.2 UOGD Sources and Potential Release Mechanisms – Air Exposure Pathway

4.2.2.1 UOGD Releases to Air

Air emissions from UOGD operations are complex and highly variable in terms of both amount and composition. Emissions result from virtually every step of development, production and, post-production phases and may emanate from operations on or off the well pad (HEI Special Scientific Committee on Unconventional Oil and Gas Development in the Appalachian Basin 2015; Vaughn et al. 2018; Zielinska et al. 2014). Several UOGD processes lead to air emissions (Table 4-1). These emissions include components from the oil and gas itself (primarily organic gases), drilling and completion fluids (organic gases, PM), diesel and natural gas combustion (VOCs, NOx, PM), waste management, and subsurface geochemical species (e.g., naturally occurring radioactive material [NORM]) (Glass Geltman and LeClair 2018; HEI Special Scientific Committee on Unconventional Oil and Gas Development in the Appalachian Basin 2015; Moore et al. 2014; The Academy of Medicine Engineering and Science of Texas 2017; Zielinska et al. 2014). The organic gases and NOx can react to form ozone and PM (Nsanzineza et al. 2019). Sulfur dioxide (SO2) and hydrogen sulfide (H2S) emissions also occur due to the sulfur content in diesel fuel and oil and gas. NOx, SO2, and PM are regulated by the U.S. EPA and are cited for having both acute and chronic health impacts (Burnett et al. 2014; Cohen et al. 2017; U.S. EPA 2016b). Additionally, some emitted VOCs (e.g., formaldehyde and benzene) are categorized as hazardous air pollutants by the U.S. EPA, as they are known to cause cancer or other adverse health effects.

Many compounds associated with UOGD have been identified, but some remain proprietary and other chemical species might form from drilling or fracturing fluids under high temperature and pressure conditions in the subsurface environment (Allen 2014; Moore et al. 2014).

Table 4-1. Processes leading to ambient emissions

<table>
<thead>
<tr>
<th>Organic Gases (including BTEX and other air toxics)</th>
<th>Nitrogen Oxides</th>
<th>Particulate Matter</th>
<th>Radionuclides</th>
</tr>
</thead>
<tbody>
<tr>
<td>▪ Engine exhaust (diesel and natural gas)</td>
<td>▪ Flaring</td>
<td>▪ Proppant handling and use (including silica)</td>
<td></td>
</tr>
<tr>
<td>▪ Well completion</td>
<td>▪ Process heating</td>
<td>▪ Site preparation and drilling activities (fugitive dust and diesel exhaust)</td>
<td></td>
</tr>
<tr>
<td>▪ Tanks</td>
<td>▪ Engine exhaust from:</td>
<td>▪ Material transport (engine exhaust, tire, brake and road dust)</td>
<td></td>
</tr>
<tr>
<td>▪ Transfer operations</td>
<td>- Site preparation</td>
<td>▪ Drilling completion</td>
<td></td>
</tr>
<tr>
<td>▪ Flaring</td>
<td>- Material transport</td>
<td>▪ Re-use of wastewater</td>
<td></td>
</tr>
<tr>
<td>▪ Equipment leaks</td>
<td>- Drilling and fracturing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>▪ Pneumatic controllers and valves</td>
<td>- Compression</td>
<td></td>
<td></td>
</tr>
<tr>
<td>▪ Storage and transport of drilling waste</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>▪ Liquid unloadings</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Measured Air Emissions. Direct measurement of emissions from individual UOGD operations and processes have been conducted using a variety of approaches, including tracers, direct measurements, and downwind plume measurement (e.g., Allen 2016; Bell et al. 2017; Nathan et al. 2015). Much effort has been devoted to characterizing methane emissions (e.g., Johnson et al. 2019; Omara et al. 2018; Ren et al. 2019; Sheng et al. 2018), but other chemical emissions have also been measured or modeled, including VOCs (Pétron et al. 2012), black carbon (Schwarz et al. 2015), NOx (Goetz et al. 2015), and dust (Litovitz et al. 2013).

As discussed in Section 2, emissions vary over time as operational conditions change. Some processes resulting in VOC emissions can be of limited duration, such as liquid unloadings, flowback, flaring, product transfer, and tank inspection. Nevertheless, they can be important emission sources. For example, studies have demonstrated emissions from conventional and unconventional development during liquid unloading events, which last for only minutes may be equivalent to emissions from more than one thousand routinely operating wells (Allen et al. 2015b). Other studies, relying on atmospheric observations, suggest that storage-related emissions (e.g. from product transfer and tank inspection) may be a major contributor to VOC emissions (Pétron et al. 2012). Emissions also vary temporally depending on whether operations are continuous or intermittent (Roy et al. 2014). Flaring, for example, occurs intermittently, and is a source of VOCs, NOx, and hazardous air pollutants (Allen et al. 2016; Favole et al. 2016; Franklin et al. 2019; Weyant et al. 2016). The magnitude of emissions may also change over time with the introduction of new technologies and operational practices.

Studies of methane have demonstrated that emissions also can vary by location. Some drilling or processing sites might be well controlled and maintained, whereas other sites have been found to emit much more than others (Lyon et al. 2016; Schwietzke et al. 2017, 2014b, 2014a; Zavala-Araiza et al. 2017, 2015a, 2015b). These instances of large, concentrated emissions are sometimes called “super-emitters”. The potential for super-emitters among UOGD operations is considerable given the variability in operations, site design, construction, and maintenance and the oil and gas composition within and among plays (Allen et al. 2017). For example, it was found that 19% of the pneumatic controllers contribute 95% of the emissions from this type of equipment (Allen et al. 2015a).

Modeled Air Emissions. The temporal and spatial variation in UOGD operations pose a considerable challenge to characterizing emission rates that represent a given area and have led to large discrepancies in estimated emissions at the regional level (e.g., Allen 2014; Bell et al. 2017; Mitchell et al. 2015; Vaughn et al. 2017, 2018; Zavala-Araiza et al. 2015b). Two broad approaches have been used to estimate emissions: bottom-up (or process-oriented) (e.g., Ahmadov et al. 2015; Townsend-Small et al. 2015) or top-down (observation-oriented) (e.g., Allen 2014; Zavala-Araiza et al. 2015b). Both have their strengths and weaknesses. “Bottom-up” emission estimates have historically been developed by multiplying representative emission rates for various source categories by a measure of activity for each category (i.e., a number of sources multiplied by the emission rate for each source) to estimate the annual emissions from an operation or set of operations. The potential presence of super-emitters can be an important contributor to uncertainty in these estimates. The top-down approach combines atmospheric concentrations measured from aircraft and other methods with models to infer emission rates (e.g., Albertson et al. 2016; Brantley et al. 2014, 2015; Englander et al. 2018; Ezani et al. 2018; Johnson et al. 2017; Nathan et al. 2015; Pétron et al. 2014).

Recent basin-scale comparisons of the two approaches reveal that top-down methane emissions estimates typically exceed bottom-up estimates, the magnitude of which depends on the study area (Vaughn et al. 2018; Zavala-Araiza et al. 2015b). Efforts to reconcile methane emission estimates from UOGD operations hint at the complexities involved with estimating emissions and concentrations of other UOGD-related compounds. For example, the work on identifying the influence of super-emitters on...
regional methane emissions suggests that the temporal variability in emissions can explain much of the
difference between bottom-up and top-down estimates (Allen et al. 2017; Vaughn et al. 2017).

Using methane emission estimates to quantify non-methane VOC emissions is complicated by the widely
varying ratios of methane and non-methane compound concentrations within and across basins and during
various UOGD processes (e.g., Allen et al. 2017). Further, methane emission estimates would reflect
processes dominated by methane releases, so relying on methane emissions would miss a wide variety of
other sources of non-methane emissions (e.g., VOCs related to internal combustion engines, NOx, PM,
and dust).

4.2.2.2 Atmospheric Transport

UOGD emissions disperse and can react in the atmosphere, leading to widely varying concentrations from
local to regional scales. Dispersion is highly dependent on meteorological conditions (e.g., reduced air
mixing that can occur at night and during winter), and topography (e.g., valleys trapping pollutants or
hills blocking noise). Some emissions are largely unreactive (e.g., black carbon) whereas others undergo
chemical transformation on the order of hours (e.g., formaldehyde). Like dispersion of emissions,
chemical transformation also depends on meteorological conditions and topography and, under some
conditions, the presence of other compounds. Destruction rates of directly emitted chemicals will vary
from virtually unreactive species (black carbon) to species that have reaction times on the order of hours
(e.g., formaldehyde), and the rates of destruction will depend on time and atmospheric conditions
(including the presence of other compounds).

4.2.2.3 Linking UOGD Sources to Air Concentrations

Investigators employed various methods to link chemical concentrations and emissions with specific
UOGD-related sources.

Sampling location. In an effort to quantify chemical concentrations in air that were attributable to UOGD,
investigators have placed air samplers in a variety of locations proximate to UOGD operations (Figure 4-6).

The ability to link concentrations with UOGD was strongest in studies where investigators linked specific
UOGD operations at high temporal resolution to measured concentrations at locations in proximity to
UOGD (Allshouse et al. 2019; Collett et al. 2016; Eisele et al. 2016; McCawley 2013; Williams et al.
2018). Investigators can also establish a link between UOGD and air quality in studies where samplers
were positioned on UOGD sites (Collett et al. 2016; Collett and Ham 2016; Hildenbrand et al. 2016c;
Williams et al. 2018) and, to a lesser extent, along the fence line of UOGD operations, at varying
distances from well pads, or in rural areas with few other possible sources (e.g., Paulik et al. 2018;
Warneke et al. 2014).

Studies in which investigators positioned air samplers between well pads and residential communities
(Colorado Department of Public Health and Environment 2012, 2017c, 2017b, 2017a; Eastern Research
Group and Sage Environmental Consulting 2011; Macey et al. 2014; McMullin et al. 2017), in close
proximity to and downwind of UOGD activity (Eisele et al. 2016; Frazier 2009; McCawley 2013; Pekney
et al. 2014), and in general areas of UOGD operations (Bien and Helmig 2018; Oltmans et al. 2014;
Schade and Roest 2016) would need to, at a minimum, account for other sources to demonstrate a link
between the measured concentrations and UOGD.

The West Virginia-based Marcellus Shale Energy and Environment Laboratory, a multi-disciplinary
research program for which data are collected to analyze emission trends and profiles unique to different
phases of UOGD, measures emissions at different distances from the well pad and includes collection of detailed operational time–activity data to allow for source attribution (Pekney et al. 2018; Williams et al. 2018).

**Figure 4-6.** Sampler placement in air monitoring studies

![Sampler placement in air monitoring studies](image)

<table>
<thead>
<tr>
<th>Area</th>
<th>Fenceline</th>
<th>Onsite</th>
<th>Residence (Indoors)</th>
<th>Residence (Outdoors)</th>
<th>Residential Area</th>
<th>Various Distances to Wellpad</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NUMBER OF STUDIES</strong></td>
<td><strong>0</strong></td>
<td><strong>10</strong></td>
<td><strong>20</strong></td>
<td><strong>30</strong></td>
<td><strong>40</strong></td>
<td><strong>50</strong></td>
</tr>
</tbody>
</table>

*Area* = non-specific sampling location in proximity to UOGD operations; *fence line* = sampling on or next to the fence surrounding a well pad or UOGD-related facility; *onsite* = on a well pad or the site of other UOGD-related equipment; *residence (indoors)* = sampling inside a residence; *residence (outdoors)* = sampling outside of a residence on homeowner property; *residential area* = sampling in a neighborhood but not on private property; *various distances to well pad* = a deliberate sampling campaign in which samples are taken at various pre-determined distances from the suspected source.

Tracers, signatures, or ratios. To differentiate the contribution of UOGD from other sources of air quality impacts, some investigators used tracers, such as methane, ethane, ethylene, or acetylene (Benedict et al. 2018; Cardoso Saldana et al. 2019; Collett et al. 2016; Collett and Ham 2016; García-Gonzales et al. 2019a; Goetz et al. 2015; Helmig et al. 2015; Koss et al. 2017; Prenni et al. 2016; Swarthout et al. 2015), source signatures (e.g., ethane, propane, hexane, and PM species) (Nathan and Lary 2019), methane or isomer ratios (Halliday et al. 2016; Marrero et al. 2016; Pétron et al. 2012; Rossabi and Helmig 2018; Swarthout et al. 2015; Vinciguerra et al. 2015), or a combination of approaches (Bari and Kindzerski 2018; Evanski-Cole et al. 2017; García-Gonzales et al. 2019a; Gebhart et al. 2018; Halliday et al. 2016; Lindaas et al. 2019). For example, Prenni et al. (2016) used the ratio of pentane isomers (*i*-pentane:*n*-pentane ratio) to indicate UOGD emissions, and estimated air mass age for measurements at one of the sampling locations. The investigators performed additional analyses to assess whether concentrations of VOCs, NOx, and black carbon had collocated sources. Nathan and Lary (2019) used dispersion modeling to predict regional VOC concentrations across the Barnett Shale region and machine learning techniques to identify whether unique source signature groups of hydrocarbons appear in areas downwind of UOG facilities, which can be used in future studies to identify UOGD and for monitoring contribution of UOGD to regional VOC concentrations.
Reference conditions. A limited number of studies compared concentrations measured in areas of high UOGD activity with conditions in the same area before development (Colborn et al. 2013; Majid et al. 2017; Maskrey et al. 2016; Vinciguerra et al. 2015; Williams et al. 2018) or at reference locations (Agency for Toxic Substances and Disease Registry 2016; Eastern Research Group and Sage Environmental Consulting 2011; Garcia-Gonzales et al. 2019a; Penningroth et al. 2013; Rich and Orimoloye 2016; Thompson et al. 2014). Investigators designated reference locations in a number of ways; a drawback associated with their use, as noted by many investigators, is the presence of other sources.

Satellites and aircraft. Some studies, conducted primarily in Colorado and North Dakota, have employed aircraft monitoring (Bahreini et al. 2018; Cheadle et al. 2017; Ethridge et al. 2015; Gvakharia et al. 2017; Halliday et al. 2016; Koss et al. 2017; Majid et al. 2017; McDuffie et al. 2016; Peischl et al. 2018; Prenni et al. 2016). The most effective aircraft monitoring studies coupled aircraft measurements with ground-based sampling of emissions sources (e.g., Ethridge et al. 2015). Although aircraft monitoring avoids the challenges associated with attempting to sample close to or directly on a well pad, it is more difficult to attribute measured concentrations to UOGD. This approach is therefore more effective in areas with few emission sources other than UOGD.

In addition, investigators are starting to take advantage of remote sensing technology placed on satellites to identify sources of UOGD emissions (Franklin et al. 2019) and to characterize air quality impacts of UOGD (Chang et al. 2016; Franco et al. 2016; Majid et al. 2017).

Modeling. Studies of both local and regional air quality have incorporated chemical transport modeling to quantitatively link chemical concentrations in air with specific UOGD sources (e.g., flaring and compressor station emissions) and to distinguish UOGD from other sources. The models typically combined measured emissions and concentrations with meteorological data (Ahmadov et al. 2015; Eastern Research Group and Sage Environmental Consulting 2011; Evanski-Cole et al. 2017; Frazier 2009; Olaguer et al. 2014; Pekney et al. 2018; Pfister et al. 2017; Roohani et al. 2017). Other studies used source apportionment modeling or other statistical techniques to disentangle UOGD activity from other sources (e.g., Ahmadov et al. 2015; Bari and Kindzierski 2018; McDuffie et al. 2016; Nathan and Lary 2019; Rutter et al. 2015; Schade and Roest 2016).

Collett et al. (2016) and Collett and Ham (2016) convened a multi-disciplinary team to quantify emissions from three UOGD phases (hydraulic fracturing, flowback, and production) across two oil and gas regions in Colorado. They used their estimated emission rates to model VOC concentrations in air and compared model predictions with field measurements. In this way, the investigators were able to directly connect UOGD emissions with air quality at two Colorado locations. In general, they observed that emission rates varied across UOGD processes, with the highest VOC emission rates during flowback operations. They also reported no difference in air concentrations among seasons.

Distinguishing UOGD from conventional oil and gas development. Many studies attempted to distinguish UOGD sources from other industrial and urban sources (e.g., Lim et al. 2019), but frequently did not differentiate between UOGD and conventional oil and gas development. Emissions may be similar, with many of the tracers used for UOGD also indicative of conventional resource development (Gilman et al. 2013). Some studies attempted to differentiate chemical concentrations in air between the two types of development by measuring emissions from conventional sources (Marrero et al. 2016), by correlating trends in concentrations with UOGD production rates over time (Swarthout et al. 2015), and sampling near both active unconventional and conventional wells and examining differences in concentrations (Vinciguerra et al. 2015). Other studies attempted to link their results to UOGD by comparing concentrations over a period representing change in UOGD activity or by placing samplers in areas dominated by UOGD rather than conventional development.
4.2.3 Potentially Exposed Populations – Air Exposure Pathway

Some studies provided valuable information for understanding the likelihood, frequency, duration, and magnitude of potential exposures that people might experience.

4.2.3.1 Relevance of Information for Quantifying Exposure

**Likelihood and Magnitude of Exposure.** Modeling studies, especially those informed by monitoring data, can be valuable for predicting the likelihood of exposure under various conditions (e.g., Benedict et al. 2018; Eastern Research Group and Sage Environmental Consulting 2011; Fann et al. 2018; Khalaj and Sattler 2019). Bloomdahl et al. (2014) strengthened the utility of their models for quantifying exposure by pairing air quality data with the location, time–activity patterns, and protective measures in place for potentially exposed populations. In this study, investigators used models to assess the likelihood and magnitude of occupational exposure to VOCs in air.

Many of the air quality modeling studies employed methods that helped to elucidate the factors driving elevated concentrations and thus the likelihood of humans experiencing those concentrations. For example, some ozone-modeling studies combined information about meteorological conditions and UOGD operations (such as those that associated with reactive VOC emissions) to identify the conditions (e.g., meteorology and energy demand) under which elevated ozone concentrations occur (e.g., Bien and Helmig 2018; Evans and Helmig 2017; Lindaas et al. 2019; Nsanzineza et al. 2019; Olaguer et al. 2014; Oltmans et al. 2014, 2019; Pfister et al. 2017). Other models demonstrated the likelihood and magnitude of chemical formation that occurs during specific UOGD phases and activities (Bean et al. 2018). Models of regional concentrations, such as many of those modeling UOGD contribution to regional ozone concentrations, did not have sufficient spatial resolution to assess likelihood or magnitude of exposure (e.g., Majid et al. 2017).

Chemical concentration data can give a sense of exposure magnitude to the extent that investigators place samplers in or use data from areas where humans might be exposed. For example, one study measured personal exposures for oil and gas workers to diesel particulates from UOGD, finding higher than recommended concentrations of elemental carbon from diesel particulates (Esswein et al. 2018). The extent to which these occupational exposures reflect the likelihood or magnitude of exposure of people living near UOGD is not known.

**Temporal Representativeness (Frequency and Duration).** Two Texas studies (Evanoski-Cole et al. 2017; Zavala-Araiza et al. 2014) and a Pennsylvania study (Swarthout et al. 2015) are notable with their collection of data representing substantial temporal (and spatial) variability in VOC or PM$_{2.5}$ concentrations using at least two types of sampling campaigns and combining the resulting data with models that incorporate local meteorological data to assess the contribution of UOGD to chemical concentrations in air. This type of approach can help in understanding the temporal representativeness of study findings.

In other studies, the frequency and duration of sampling programs varied (e.g., Goetz et al. 2015; Koss et al. 2017; Paulik et al. 2016). One important consideration is the time over which individual samples are collected. For example, a sample might be collected over an 8-hour period, and this period would be referred to as the averaging time for the sample. Air sample averaging times varied across studies (Figure 4-7).

The greatest number of studies averaged samples over one hour, an averaging time that can be useful for identifying peak exposures. Grab samples (i.e., single samples taken at one point in time) can also be useful for this purpose. Samples averaged over 24 hours are useful for capturing daily variation but may
mask peak exposures that occur over shorter periods. Given their brief averaging times, such samples have limited utility individually for understanding the frequency, duration, magnitude, and likelihood of exposure.

**Figure 4-7.** Air sample averaging times

![Air sample averaging times diagram](image)

Notes: This figure does not include studies that either did not report an averaging time or measured concentrations in time-series format.

A brief exposure to a high chemical concentration can harm health in a way that is different from a longer exposure to a lower chemical concentration. Being able to evaluate both of these possibilities depends on an appropriate sampling plan as already discussed. In addition, the period over which individual air samples are averaged (i.e., the sample averaging time) should be selected carefully to be representative of a likely exposure, including potential peak exposures and longer exposures that might occur over weeks, months, or longer. A good sampling program would represent the full period of exposure, either with continuous monitoring or multiple sampling campaigns.

The studies of greatest utility for assessing temporal variability of exposure were those that included measurements of concentrations over multiple sampling campaigns representing a variety of UOGD activities, meteorological conditions, seasons, and times of day (e.g., Allshouse et al. 2019; Evansoki-Cole et al. 2017; Pekney et al. 2018). For example, Evansoki-Cole (2017) measured concentrations of PM$_{2.5}$ and its components over two sampling campaigns during winter. The investigators summarized results at daily, 48-hour, and weekly time intervals, information which is useful for understanding acute and sub-chronic exposures during winter. Bunch et al. (2014) used hourly concentration data collected over a ten-year period to provide 1-hour, 24-hour and annual average concentrations. Pekney et al. (2018) outfitted a mobile lab with a range of instrumentation to collect data continuously, thus allowing for longitudinal assessment of concentrations over different phases of UOGD.

**Spatial Representativeness (variation within the study area).** Whether a given sample represents air that is both impacted by UOGD and breathed by potentially exposed populations depends on sampler placement, whether and what type of UOGD operations occurred at the time of sampling, and what non-UOGD sources exist nearby. Some studies collected air samples near residences with the objective of capturing samples representative of human exposure to chemicals in air (Lewis et al. 2016; Macey et al. 2014; Maskrey et al. 2016; McCawley 2013; McKenzie et al. 2012; Paulik et al. 2016, 2018; Pennsylvania...
Department of Environmental Protection 2010; Steinzor et al. 2013). While addressing the end of the
exposure conceptual model, it is unclear what proportion of the reported concentrations are attributable to
UOGD operations and other sources.

Sampling campaigns in some studies quantified spatial variability at the local level using systematic
mobile or stationary monitoring (Eisele et al. 2016; Field et al. 2015; Halliday et al. 2016; Pennsylvania
Department of Environmental Protection 2018; Williams et al. 2018), but it is not clear how well study
results are relevant to human exposures. Data provided in these studies could be useful for characterizing
exposures if combined with information about meteorology, UOGD activity, population proximity and
behavior.

Studies at the regional scale provide valuable information about spatial variability over large areas, but do
not always provide data at spatial resolutions fine enough to quantify variability in human exposure,
particularly involving point sources (e.g., Ahmadi and John 2015; Bahreini et al. 2018; Katzenstein et al.
2003). For example, Fann et al. (2018) used a national-scale, photochemical air quality model to estimate
the health damages associated with UOGD emissions. However, they did not examine exposure levels
near the UOGD emission sources, identify UOGD process-specific impacts on air quality, or assess how
well the model described the effect of UOGD emissions on air quality. There are several notable
exceptions. Cheadle et al. (2017), a study of regional ozone concentrations measured using both mobile
and stationary monitoring, provided information on localized peak concentrations attributable to UOGD,
which may represent human exposure conditions if proximate to residential areas or population centers.
Hildenbrand et al. (2016c) collected mobile air quality measurements at multiple well pads over a 13-
county area and combined the data with records of well pad activities to model concentration intensity
over the region at high spatial and temporal resolution. The investigators attributed peak BTEX
concentrations to flaring stations, condensate tanks, and compressor units on some well pads.

To characterize variability in air quality over a given region, investigators have combined and reviewed
multiple sources of air quality data related to UOGD (Box 4-1).

**Box 4-1. Reviews of existing air quality data.**

Investigators have reviewed existing air quality data (e.g., publicly available data, published peer-reviewed
articles, reports) to summarize what is known about air quality in several UOGD regions of the United States and,
in some cases, to assess the potential for adversely affecting human health.

Long et al. (2019) compiled and summarized air quality data from over 30 datasets representing approximately
200 sampling locations in the Marcellus region of Pennsylvania. The Colorado Department of Public Health and
Environment compiled and summarized air quality data from 47 datasets representing 34 locations in Colorado
(McMullin et al. 2018). Both sets of investigators compared chemical concentrations in air to health-based
benchmarks to assess the health risk for exposed individuals. Garcia-Gonzales et al. (2019c) reviewed air quality
data from 37 peer-reviewed articles investigating hazardous air pollutant (HAP) concentrations near oil and gas
development, and Garcia-Gonzales et al. (2019b) compiled and analyzed the data from these articles to identify
the oil and gas operations that contributed most to HAP concentrations.

The authors noted several limitations in the data that they reviewed and opportunities to remedy them in future
research, such as the use of source apportionment techniques to distinguish between the contributions of UOGD
and other sources to air quality impacts, air monitoring campaigns with shorter averaging times to capture
episodic peak exposures, and coupling air monitoring with biomonitoring and personal monitoring of the
potentially exposed population.

**Generalizability.** Investigators provided minimal information about the generalizability of study results to
other populations, locations, and UOGD operating conditions. Studies that measured air emissions or
concentrations during specific UOGD processes provide useful information that is potentially
generalizable to areas experiencing the same type and scale of UOGD processes (e.g., Roohani et al.
2017). Similarly, studies that linked concentrations measured over time with UOGD production activities
may inform how concentrations vary temporally with changing meteorological conditions or with
2013).

Modeling studies that incorporated methods such as trajectory analysis and chemical age analysis can
apply their methods to other regions (e.g., Evanoski-Cole et al. 2017; Katzenstein et al. 2003; Khalaj and
Sattler 2019; Nathan and Lary 2019; Pekney et al. 2018). Studies that used accurate emission
measurements as model inputs could also apply their results to other areas with similar operational
practices and equipment (e.g., Pétion et al. 2012). A notable example is Khalaj and Sattler (2019), who
used chemical air monitoring and modeling, combined with emissions data and information about equipment
locations and topography to determine whether 1-hour concentrations exceeded National Ambient Air
Quality Standards at various distances from well pads. The modeling approaches used in this study can be
useful for predicting exposures in other locations and populations experiencing similar operations.
Further, many of the modeling studies can simulate secondary pollution formation in other regions with
similar conditions (Edwards et al. 2014; Field et al. 2015; Oltmans et al. 2014; Pfister et al. 2017).
Nevertheless, application of modeling results to other exposure conditions should be done with caution
due to variability in UOGD operational practices and the composition of oil and natural gas resources
across plays.

4.2.3.2 Characteristics of Potentially Exposed Populations

Several air monitoring and modeling studies aimed to quantify potential exposures of people living near
UOGD. Some identified the specific populations they intended to study but did not report whether
sensitive sub-populations might be disproportionately affected by UOGD emissions. Studies that
identified the potentially exposed population were those involving sampler placement inside or on
residential properties (Frazier 2009; Lewis et al. 2016; Maskrey et al. 2016; Paulik et al. 2016, 2018;
Steinzor et al. 2013) or in residential communities (Agency for Toxic Substances and Disease Registry
2010; Colorado Department of Public Health and Environment 2012, 2017c; Crowe et al. 2016; Frazier
2009; Macey et al. 2014; Pennsylvania Department of Environmental Protection 2010, 2018; Swarthout et al.
2015; Thompson et al. 2014; Walther 2011). Some of these studies accounted for wind direction
relative to UOGD operations to connect residential or community concentrations with UOGD. Health
assessments (e.g., Agency for Toxic Substances and Disease Registry 2010) provided information on the
sociodemographic characteristics of the potentially exposed population. Three studies (Haynes et al.
2019; Macey et al. 2014; Steinzor et al. 2013) involved local community members in sampling design and
collection.

4.2.4 Concluding Remarks – Air Exposure Pathway

Despite the size, breadth, and, in many cases, quality of the literature, it collectively falls short of
providing an understanding of the extent of temporal and spatial variability of potential exposures across
major U.S. oil and gas regions.

By way of illustration, consider the 16 air quality studies conducted in major oil and gas-producing
regions of Texas (Figure 4-8). Most studies were conducted in the Barnett Shale where UOGD began,
with only one in each of the Haynesville and Permian shale plays. Investigators primarily collected data
year-round with averaging times of ≤12 hours. These short averaging times can be useful for estimating
acute exposures but have less utility for estimating chronic exposures. Other studies present seasonal
average concentrations, which can be useful for estimating chronic exposure. Focusing on the Barnett
Shale where most studies occurred, investigators collected data at a range of different locations and with different sample averaging times (as shown in the pies in Figure 4-8). Although the Barnett shale studies provided useful information for understanding air quality in the region and the potential for human exposure, they provided a limited amount of information to assess human exposures at any particular location over time (Figure 4-8). This is especially true for Texas shale plays outside of the Barnett region.

Figure 4-8. Number of outdoor air quality studies in four Texas shale basins, by sampling location, time of year, and sample averaging time.

a. Number of Studies in Four Texas Shale Basins, by Season and Sample Averaging Time

<table>
<thead>
<tr>
<th>Shale Play</th>
<th>Number of Studies</th>
<th>Averaging Time ≤12 Hours</th>
<th>Averaging Time &gt;12 Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barnett</td>
<td>14</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Eagle Ford</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Haynesville</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Permian</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

b. Sampling Locations and Collection Methods Relative to UOGD in the Barnett Shale Play

<table>
<thead>
<tr>
<th>Distance to Wellpad</th>
<th>Collection Method</th>
<th>Number of Studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fenceline</td>
<td>Surface Stationary</td>
<td>1</td>
</tr>
<tr>
<td>Community</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Various Distances</td>
<td>Surface Stationary</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Aircraft</td>
<td>1</td>
</tr>
</tbody>
</table>

1This figure includes 16 publications that reported measured outdoor air concentrations of VOCs in Texas shale plays. Studies are counted multiple times if they collected samples in more than one shale play (n=1) or over more than one season (n=2). Four studies reporting outdoor air concentrations of VOCs in Texas are not included because they did not report the shale play where samples were collected and one modeled VOC concentrations but did not report on VOC concentration measurements.

Capturing all elements of the conceptual model of exposure in a single study has not been achieved, even in the most comprehensive undertakings. Although some investigators attempted to measure or model regional and local air quality impacts of UOGD, they had varying success in linking measured concentrations with UOGD and were not always aiming to quantify human exposure. Some studies of note have employed exemplary methods for use in an exposure study (Boxes 4-2 and 4-3).
Box 4-2. Examples of studies that employed useful methods for quantifying a complete air exposure pathway from a UOGD source to a population: Local community exposure to chemical concentrations in air.

Background
Characterizing exposure to UOGD-related atmospheric emissions is complex due to the high spatial and temporal variability in emissions, combined with complex atmospheric transport across scales. Further, not all of the important emissions will occur on-site, as mobile emissions, including those from heavy trucks that transport material off and on the well pad. Few studies have documented short- and long-term variability in concentrations, while documenting a complete exposure pathway and connecting concentrations of agents at the source to concentrations in communities where people might be exposed. Zielinska et al. (2014) endeavors to do so in a pilot study.

Study Summary
Zielinska et al. (2014), studied the Barnett Shale play to quantify air quality changes from UOGD. The two-phase study began with mobile survey sampling to identify emission sources of interest (Phase 1), followed by Phase 2 using saturation monitoring in a community. Phase 1 concentrated on shorter term sampling of gases to determine source profiles. Phase 2 included PM, VOC, and NOx measurements throughout a community and at various distances to a residence. They used the source profiles to conduct source apportionment using a chemical mass balance method. Phase 2 focused on longer term samples that short-term peaks would not be capture. Based on their modeling and acknowledging important sources of uncertainty, they reported that the dominant source of ambient non-methane VOCs was motor vehicles, followed by natural gas and condensate tank emissions.

Notable Features
The two-phase sampling method allowed investigators to identify emission sources and measure air quality in residential communities as a result of the identified sources. The study design provided a nice balance between short-term and longer-term integrated sampling, which are applicable to assessing human exposures. The measurements also capture releases from both stationary and mobile sources. The investigators examined the source contribution to several different chemical concentrations and assessed the rate of degradation of chemical concentrations at various distances from the well pad, thus contributing to an understanding of whether a complete exposure pathway existed between the UOGD sources and residential areas.

Missing Elements
As a pilot, the study was limited to a small community and a short period of time (a month). Therefore, the measurements do not capture variations in chemical concentrations as a function of seasons, phases of development, operator practice, and geographic region. The study results are limited in their generalizability.
Box 4-3. Examples of studies that employed useful methods for quantifying a complete air exposure pathway from a UOGD source to a population: Regional exposure to chemical concentrations in air.

Background
Few studies assessed exposures on a regional scale (hundreds to thousands of kilometers). Ideally, studies would combine air quality monitoring data with emission rate data and use modeling to predict concentrations in areas where people are exposed to air pollution, incorporating methods to identify the source contributions. Zavala-Araiza et al. (2014) exemplifies a study that combines emission and monitoring data to model the contribution of UOGD to concentrations of primary pollutants.

Summary
Zavala-Araiza et al. (2014) measured hourly VOC concentrations over a 20-month period at three sampling sites representing high UOGD density, an urban area, and background conditions in the Barnett Shale region. Investigators also used publicly available emission rate data for UOGD sources of VOCs to predict UOGD contributions to regional VOC concentrations. They reported low temporal variability in VOC emissions during the production phase, that pneumatic devices dominated VOC emissions, and that meteorology, rather than episodic emission events, primarily explained variability in VOC concentrations.

Notable Features
The study design allowed investigators to capture relatively high temporal resolution (hourly) concentrations over a large geographic area, and to capture seasonal and operational variability over the 20 month sampling campaign. Additionally, sampler placement in areas representing different conditions allowed for correction for background concentrations. The availability of an emissions inventory of over 8000 sites provided information on both regional and source type (e.g., separator, vent, and flare) variability across the region. The investigators took full advantage of the emissions dataset by simulating concentrations from specific operational events, and by parameterizing a predictive model with information about topography and meteorology. Such a model, with fine enough resolution and ground-based data, can be useful to predict human exposures under different exposure conditions. Notably, the investigators performed sensitivity analysis on modified emissions factors, which have been cited as under-estimating leaks (Allen et al. 2013).

Missing Elements
Because the investigators did not focus their analysis on human populations, they did not provide information about the potentially exposed populations or the levels at which they could be exposed. Therefore, this study does not cover a full exposure pathway. The study sampling methods will not characterize near-source, peak exposures (e.g., due to a super-emitter) nor exposure to NOx and PM emissions from combustion and mobile sources.
4.3 WATER EXPOSURE PATHWAYS

4.3.1 Summary of Studies – Water Exposure Pathway

Studies with water quality monitoring data (n=282), modeling predictions (n=15), or both (n=10) have been conducted in the major oil- and natural-gas producing regions of the United States (Figure 4-9), with the majority of studies occurring in the Marcellus shale region. Studies included measurements of chemical agents in groundwater (n=39), surface water (n=28), or produced water (n=9) to understand the potential water quality impacts of UOGD (Figure 4-9). Additionally, a subset of studies included assessments of sediment quality (discussed in Section 4.4). The summary of water studies builds on the U.S. EPA’s review of potential water quality impacts of UOGD (U. S. EPA 2016a; Box 4-4).

Figure 4-9. Number of water monitoring or modeling studies.

Notes:
- The size of each pie chart is proportional to the total number of studies in each shale play.
- The largest pie chart on the map represents 46 studies.

Studies involved measurement or modeling of brine indicators, including chloride/bromide ratios (Barth-Naftilan et al. 2018; Hildenbrand et al. 2016b; Llewellyn et al. 2015; Reilly et al. 2015; Woda et al. 2018), beryllium (Burton et al. 2016), barium (Fontenot et al. 2013), strontium (Fontenot et al. 2013; Woda et al. 2018) and chloride (Darrah et al. 2014; Post van der Burg and Tangen 2015; Preston et al. 2014). Investigators also studied microbial indicators of water quality variability in groundwater (Santos et al. 2018) and surface water (Fahrenfeld et al. 2017; Trexler et al. 2014).

Several studies involved collection of samples from municipal water supplies or residential water wells, some by community volunteers (Alawattegama et al. 2015; Boyer et al. 2012; Fontenot et al. 2013; Haynes et al. 2019; Hildenbrand et al. 2015, 2016a; McMahon et al. 2017; Nelson et al. 2015; Steinzor et al. 2013) (Figure 4-10). Other studies leveraged existing data to assess water quality. Maloney et al. (2017) made use of existing data on crude oil, drilling water, hydraulic fracturing solution, and
wastewater spills collected between 2005 and 2014 in Pennsylvania, Colorado, North Dakota, and New Mexico to compare the distance between spills and surface water. They noted that Pennsylvania spills occurred more frequently near watersheds of high relative importance to drinking water than spills in the other states.


Purpose of the Report
The largest review to date on potential UOGD impacts on water in the United States was published by U.S. EPA Office of Research and Development in 2016 (U. S. EPA 2016a). The aim of the report was to assess the likelihood and magnitude of impacts to drinking water resources from the hydraulic fracturing water cycle.

U.S. EPA’s Findings
It identified 1,606 chemicals associated with hydraulic fracturing, including 1,084 chemicals used in hydraulic fracturing fluid and 599 chemicals detected in produced water. The report describes the following activities as “more likely than others to result in more frequent or more severe impacts”:

- Water acquisition that entails water withdrawals in areas with limited water resources;
- Spills of hydraulic fracturing fluids, chemicals, or produced water;
- Injection of hydraulic fracturing fluid directly into groundwater resources or into wells with inadequate integrity that allow for gas or liquid to enter groundwater resources;
- Discharge of inadequately treated wastewater directly to surface water resources; and,
- Use of unlined pits for wastewater storage or disposal.

For each activity, the review identified several practices that may reduce the frequency and severity of UOGD impacts on drinking water quality and quantity. U.S. EPA concluded that several important data gaps in its assessment of impacts on drinking water prevented its estimation of the frequency and severity of impacts on drinking water resources across the country.

Data Gaps Identified in the Report
U.S. EPA noted several data gaps, including (1) limited information on the location of hydraulic fracturing–related activities relative to drinking water resources, (2) insufficient pre-drilling data, (3) difficulty discerning the potential effects of UOGD from other potential sources in the area (e.g., conventional oil and gas operations, other industries, and natural sources) and complexities involved in understanding subsurface migration of contaminants, and (4) lack of information on the identity of unknown chemicals in fracturing fluid and the toxicity reference values of known chemicals in fracturing fluid.

4.3.2 UOGD Sources and Potential Release Mechanisms – Water Exposure Pathway

4.3.2.1 UOGD Releases to Water

UOGD releases to surface water and groundwater can occur as a result of reuse of produced water and permitted discharges, and also under a variety of accidental conditions (U.S. Environmental Protection Agency 2016a). To date, the scientific literature has been focused primarily on possible accidental releases to water.

The potential UOGD contamination of groundwater has been investigated in a number of locations, including Dimock, Pennsylvania (Agency for Toxic Substances and Disease Registry 2016; Hammond 2015; U.S. Environmental Protection Agency 2019a) and Pavillion, Wyoming (American Petroleum Institute 2013; DiGiulio and Jackson 2016; Ling and Heglie 2016; U.S. Environmental Protection Agency...
2011a; Wright et al. 2012). Surface water contamination attributed to UOGD accidental releases and waste management and disposal has also been studied (e.g., Cozzarelli et al. 2017).

Figure 4-10. Number of studies by type of water sample.

Kuwayama et al. (2016) reviewed the literature on water contamination risk associated with storage of produced water in impoundments (often referred to as pits) versus storage tanks. Produced water impoundments are typically lined to reduce the possibility of leaching into the subsurface, but the potential for leaks remains. In addition, impoundments are open to the atmosphere. The potential for volatilization has received limited attention in the literature (Bean et al. 2018). Because UOGD flowback has been exposed to high pressure and temperatures in the drilled bore of the well (downhole), the formation of unknown compounds is possible (Butkovskyi et al. 2017; Luek and Gonsior 2017). Shih et al. (2015) characterized chemical composition of flowback, produced water, and drilling waste samples collected in Pennsylvania from 2009 to 2011, finding high levels of chloride and sodium ions, as well as metals (e.g., barium, strontium).

4.3.2.2 Subsurface Mobility of UOGD-Related Contamination

The possibility that contaminants from UOGD activities might enter groundwater aquifers and be transported to drinking water wells is a consideration in evaluating the risk of potential exposure. Contaminants of concern include (1) chemicals used in hydraulic fracturing fluids that return up the borehole casing once the fracturing work has been completed (flowback and produced fluids), (2) constituents in the water that occur naturally in the shale or other source rock, such as barium and radium, and that flow from the well along with hydrocarbons (produced water), and (3) the hydrocarbons themselves, which are the target of the well development. The mobility of a particular contaminant depends on its chemical and physical characteristics, particularly on how the constituent interacts with the mineral grains of the aquifer or with materials such as casing cement before the fluid reaches an aquifer (Cai et al. 2018).
Three scenarios could lead to groundwater contamination (Figure 4-11). The first scenario is an association with the hydraulic fracturing process itself; that is, the fractures in the source rock may propagate upward from depth leading to a release of hydraulic fracturing fluids and water contained in the source rock upward into overlying aquifers. Direct hydraulic fracture growth into overlying aquifers has been shown implausible (Fisher and Warpinski 2012). Propagation of fractures is more likely if there is an abandoned well or a natural fracture or fault for the hydraulic fracture to intersect that leads to a pathway upward to an aquifer. Even so, the likelihood of an occurrence is considered to be low, especially relative to the other types of cause for a contamination event (Shanafield et al. 2018).

A second cause of an accidental release of a contaminant is through a well casing failure. Contamination of groundwater due to well casing failure is reportedly rare (Wen et al. 2018). Reported incidents have noted that stray gas (methane) has migrated in groundwater to drinking water wells (Darrah et al. 2014; McMahon et al. 2018). Although to date only methane has been linked to impacts of well casing failure, concerns remain about how groundwater contamination with drilling fluids or produced fluids may appear in the future (Lefebvre 2016). To avoid future releases of contaminants into groundwater, precautions in well construction such as intermediate casing strings have come into widespread use.

Spills of chemicals, return flows, and produced waters on and near well pads provide the most likely source of contaminants to shallow groundwater (Lefebvre 2016; Shanafield et al. 2018). Thousands of spills related to UOGD have been documented (Maloney et al. 2017). Contaminants linked with surface operations have been detected in groundwater (Drollette et al. 2015; Llewellyn et al. 2015). Such observed subsurface contamination of water due to UOGD is most likely from surface spills (Shanafield et al. 2018).

### 4.3.2.3 Linking UOGD Sources to Water Concentrations

Quantifying the impact of UOGD on water quality is challenging. The literature reports that multiple sources have the potential to contribute to chemical concentrations, including UOGD, conventional oil and gas development, other anthropogenic sources, and naturally occurring conditions. There is also complexity and uncertainty in understanding subsurface conditions as they relate to potential migration of UOGD-related contaminants. Investigators employed several methods to isolate the influence of UOGD on water quality.

**Sampling location.** Most studies measured chemical concentrations in private drinking water (i.e., groundwater) wells or surface water used as a drinking water source. Investigators typically sampled drinking water wells at residences located near UOGD wells (Alawattegama et al. 2015; Boyer et al.)
Tracers, signatures, or ratios. A number of water studies used tracers, markers, or ratios to isolate contaminants specific to UOGD in surface water and groundwater. For example, studies used geochemical tracers such as hydrocarbon isotopes to determine chemical sources, and used ratios, tracers, and ion geochemistry as measures of groundwater age and origin (e.g., Darrah et al. 2014; Grieve et al. 2018; Jackson et al. 2013; LeDoux et al. 2016; Llewellyn et al. 2017, 2019; Sherwood et al. 2016; Woda et al. 2018). Some studies distinguished natural methane from anthropogenic methane in groundwater to aid in identifying sources (e.g., Christian et al. 2016; Darrah et al. 2014; Grieve et al. 2018; Harkness et al. 2017; Li and Carlson 2014; McMahon et al. 2019). Llewellyn et al. (2015) identified a common constituent of hydraulic fracturing fluid, 2-n-butoxyethanol, in drinking water wells and concluded that UOGD might be the source of contamination (see Box 4-6). Darrah et al. (2014) identified noble gas isotopic signatures in drinking water wells, which the investigators linked to specific events that might lead to contamination, including failure of wellbore annulus cement, faulty production casing, and underground gas well failure.

Reference conditions. Some investigators have attempted to isolate UOGD impacts by documenting conditions before, during, and after drilling. Nelson et al. (2015) evaluated radionuclide concentrations in three private drinking water wells at residences less than 2000 meters from UOGD before and approximately one-year after hydraulic fracturing activities. The investigators reported no significant difference in concentrations between the two sampling periods.

At the National Energy Technology Laboratory’s Hydraulic Fracturing Test Site, Eisenlord et al. (2018) collected air quality and groundwater quality data in the Permian Basin in Texas before operations began, during UOGD fracturing and flowback phases, and during production. They reported a moderate increase in BTEX concentrations in air 1000 feet during flowback and no impact to the local aquifer.

Barth-Naftilan et al. (2018) collected monthly bedrock aquifer samples in a 25 km² area in the Marcellus Shale region over a two-year period during which UOGD well drilling, hydraulic fracturing, and production occurred. They reported large variability in methane concentrations across the study area but minimal variation over time.

Harkness et al. (2017) measured inorganic geochemistry parameters (e.g., Cl⁻, SO₄²⁻, Br⁻), isotopes of selected inorganic constituents (strontium [87Sr/86Sr], boron [d11B], lithium [d7Li], and carbon [d13C-DIC], and selected hydrocarbon molecular and isotopic tracers in drinking water wells to evaluate groundwater quality differences before, during, and after hydraulic fracturing and before and after well installation in West Virginia. The investigators attributed changes in water quality after hydraulic fracturing to migration of naturally occurring methane and reported no changes in water quality after well installation. They also reported surface water contamination, which they attributed to a nearby wastewater spill using isotope ratio markers.

Groundwater studies have also utilized pre-drill datasets collected by oil and gas companies or government agencies (Gross et al. 2013; Li and Carlson 2014; Sherwood et al. 2016; Wen et al. 2018, 2019; Wilson and VanBriesen 2012). Alawattegama et al. (2015) compared pre- and post-drill private
water well samples from 2 of 33 residential wells in their study for which existing pre-drill data from the industry and Pennsylvania Department of Environmental Protection were available. They reported increased metal concentrations during UOGD activities, with a subsequent decrease in concentrations in samples collected after drilling. The investigators also mapped elevation, nearby coal mining, and abandoned well data, noting the potential influence of those factors on chemical concentrations. These data sources have limitations that make it difficult for investigators to contextualize their results and that may lead to potential over- or under-estimation of the effects of UOGD on water quality (Betanzo et al. 2016).

Some studies collected data at reference locations, such as surface water upstream of wastewater treatment facilities (Hladik et al. 2014) or at some distance from UOGD operations (Pelak and Sharma 2014; Walters et al. 2019). Although the use of reference locations and sampling before, during, and after UOGD operations provides useful information about trends over time, these methods may not consider other factors affecting water quality (e.g., earlier oil and gas operations, coal mines, biodegradation of organic material, agriculture, and natural methane). Some investigators acknowledged the lack of baseline or reference data as a limitation of their studies (Hildenbrand et al. 2016a; LeDoux et al. 2016; Steinzor et al. 2013).

Modeling. Investigators employed diverse modeling approaches to provide quantitative linkages between UOGD sources and potential human exposure via the water pathway (Burton et al. 2016; Hill and Ma 2017; Landis et al. 2016; Olmstead et al. 2013; Preston and Chesley-Preston 2015; Shanafield et al. 2018; Shores et al. 2017; Torres et al. 2017; Weaver et al. 2015). Investigators collected their own data to parameterize models (Bean et al. 2018; Drollette et al. 2015; Larson et al. 2018; McMahon et al. 2017; Post van der Burg and Tangen 2015; Preston et al. 2014), or relied on data curated by a state or federal regulatory agency, other investigators, or commercial sources (Burton et al. 2016; DiGiulio and Jackson 2016; Hill and Ma 2017; Olmstead et al. 2013; Preston and Chesley-Preston 2015; Shores et al. 2017; Shores and Laituri 2018; Torres et al. 2017, 2018; Weaver et al. 2015).

The aim of most water modeling was to estimate the impact of increasing UOGD prevalence on groundwater or surface water quality (e.g., Hill and Ma 2017; Olmstead et al. 2013; Shanafield et al. 2018). For example, Burton et al. (2016) created a geospatial model using information about the wellbore, fluid velocity, and reservoir pressure to assess whether changes in groundwater quality were associated with UOGD. They reported that well density and formation pressures, but not proximity of samples to gas wells within 1000 feet, were associated with groundwater quality. Results also indicated the potential for groundwater contamination due to chemical migration from the annular fissures in the wellbore. Several human health risk assessments incorporated modeling approaches to assess risk to human health from exposure to water contaminated by UOGD (Abualfaraj et al. 2018; Durant et al. 2016; Gradient Corporation 2013; Regli et al. 2015; Rish and Pfau 2018; Torres et al. 2018).

Distinguishing UOGD from conventional oil and gas development. Most studies collected water samples in Pennsylvania, Colorado, Texas, and Wyoming — states that have a long history of conventional oil and natural gas development. Some studies have investigated the impact of abandoned conventional wells on water quality (e.g., McIntosh and Ferguson 2019), but it remains difficult to distinguish between the contributions of colocated conventional and unconventional development to changes in water quality.

### 4.3.3 Potentially Exposed Populations – Water Exposure Pathway

#### 4.3.3.1 Relevance of Information for Quantifying Exposure

Temporal and spatial representativeness. The water quality studies related to UOGD are temporally and spatially limited. Use of water quality data from short-term sampling campaigns to quantify longer-term
human exposures can result in under- or over-estimates. Ideally, data to inform human exposure would be collected across seasons and over a period of months or years. Few studies sampled in more than one shale play – two in the Marcellus and Utica shales (Osborn et al. 2011; Penningroth et al. 2013), one in the Eagle Ford, Fayetteville, and Haynesville shales (McMahon et al. 2017), and one in the Barnett and Marcellus shales (Darrah et al. 2014). Studies that reported data from samples in one shale play generally did not discuss whether results were generalizable to other regions.

Some studies reported data for samples of tap water that residents use (e.g., Boyer et al. 2012; Elliott et al. 2018; Steinzor et al. 2013; Yan et al. 2017) and, therefore, identified the exposed population. Surface water monitoring studies provided little or no information on how people used a given surface water body (e.g., drinking, swimming, fishing, or recreational activities), making it challenging to make inferences about the representativeness of surface water quality data to a given population’s exposure.

**Generalizability.** Surface water studies involving collection of samples from upstream and downstream of commercial wastewater treatment facilities may be somewhat generalizable to facilities with similar operating practices. The water modeling studies provided a useful template for extrapolating results from one set of conditions to another; however, they were parameterized with data from one shale play, with the exception of McMahon et al. (2017).

### 4.3.3.2 Characteristics of Potentially Exposed Populations

Some studies characterized potentially exposed populations through well water samples and information about the people using those sources for drinking water. Elliott et al. (2018) sampled household drinking water and collected information about participant demographics, their primary sources of water for drinking and for other uses, and drinking water treatment systems. Steinzor et al. (2013) collected data on health symptoms, occupational history, and past toxic exposures from study participants whose water supplies were tested. Steinzor et al. (2013) also sampled air quality at residences in the study population. Water samples were collected in some studies to address complaints about the smell, taste, color, or odor of drinking water (Boyer et al. 2012; Ling and Heglie 2016; Llewellyn et al. 2015; U.S. Environmental Protection Agency 2011a). For the most part, investigators of these studies did not use methods (aside from distance-based metrics) to directly link concentrations measured in drinking water wells to UOGD operations.

### 4.3.4 Concluding Remarks – Water Exposure Pathway

Although potential UOGD impacts on water quality have been a subject of much concern and numerous complaints have been submitted to state regulatory authorities, few studies to date have demonstrated a complete exposure pathway. Drollette et al. (2015) (Box 4-5) and Llewelyn et al. (2015) (Box 4-6) are among those that come closest to doing so. It is important to note that many of the studies discussed in this review did not set out specifically to assess exposure. Instead, most aimed to measure or model chemical concentrations, noting that these measurements could potentially be used to assess exposure in future studies. Findings from U.S. EPA (2016a) remain relevant; there are limited data to describe the likelihood, magnitude, frequency, or duration of exposure to water potentially contaminated by UOGD, or whether improved regulation and operational practices have decreased the likelihood of releases that affect water quality.
### Box 4.5. Examples of studies that employed useful methods for quantifying a complete water exposure pathway from a UOGD source to a population: Exposure to UOGD wastewater from surface spills

#### Background
Flowback and produced waters from UOGD are a main concern with regard to potential exposures to both introduced chemicals in the hydraulic fracturing process and naturally occurring chemicals in the brines that are produced along with oil and gas. Only a small fraction of these waters are treated and released to the environment (National Academies of Sciences, Engineering, and Medicine 2017) or reused within the oil and gas industry or other applications (U.S. Environmental Protection Agency 2019b). Therefore spills (accidental releases including leaks from pits and tanks) are the most likely release mechanism for wastewater-related contamination of ground or surface water. Although spills occur not infrequently (Maloney et al. 2017), except for rare cases involving major accidental releases (e.g., Cozzarelli et al. 2017), there have been only a few studies that specifically focus on spills. One such report is a paper by Drollette et al. (2015).

#### Study Summary
Drollette et al. (2015) sampled 64 private residential groundwater wells between 2012 and 2014 in northeastern Pennsylvania and in southern New York to look for organic compounds that potentially originated from UOGD. They reported trace levels of VOCs in 6 samples (10%), and low levels of gasoline range (9 of 59 samples) and diesel range (23 of 41 samples) organic compounds. Analyses of inorganic elements, including isotopic ratios, were used as indicators of upward migration of fluids, potential leakage from compromised well casings, or leaks from pits or tanks for storing flowback and produced water. None of these indicators were co-observed with the organics, making subsurface releases or releases from surface storage highly unlikely as explanations for the observed water well contaminants. Bis(2-ethylhexyl) phthalate, a known ingredient of fracturing fluids, was detected in the two well water samples having the highest concentrations of diesel range organic compounds. Based on the evidence presented, the authors concluded that the “data are consistent with a surface-derived source of organic compounds in the study area, possibly from releases of hydraulic fracturing materials near drill sites.”

#### Notable Features
Drollette et al. (2015) is “the first study of its kind to evaluate, on a regional scale, different possible mechanistic sources of organic compounds detected in drinking water wells in the Marcellus region using complementary inorganic chemical analyses.” The authors explored several alternative hypotheses about the potential origin of the chemicals measured in the samples from the drinking water wells.

#### Missing Elements
Drollette et al. (2015) illustrates many of the difficulties of assessing exposures from UOGD waste waters. In this study, the measured contaminants did not identify UOGD as the unique source, so authors used correlations with proximity to UOGD well pads and roadways to develop a “weight-of-evidence” argument for identifying the source. Release via spills of hydraulic fracturing materials near drill sites was inferred because other plausible releases were not easily seen to be consistent with the data. Specifying how material might be transported from UOGD well pads to drinking-water wells is problematic in essentially all hydrogeological settings, but certainly in an area where migration is through fractured rocks. Transport times from spill sites to wells sampled are long according to standard hydrogeological estimates so the only thing that can be said about the measurement of bis(2-ethylhexyl) phthalate in two drinking water wells is that migration “would have to occur via some enhanced transport or solubilization process” (Drollette et al. 2019). Finally, quantifying the routes of exposure and the exposed population would require an even more extensive effort than Drollette et al. (2015) conducted to elaborate on the characteristics of water use by the potentially exposed population as well as to estimate the magnitude, frequency, and timing of exposures.
Box 4-6. Examples of studies that employed useful methods for quantifying a complete water exposure pathway from a UOGD source to a population: Exposure to UOGD wastewater from well-bore releases to an aquifer.

Background
A potential release mechanism for hydraulic fracturing fluids, flowback water, and produced water is through a compromised (or absent) casing, creating a pathway between a UOGD well and a freshwater aquifer. A several percent frequency of barrier failure in UOGD wells (Davies et al. 2014) implies potential problems in a large number of UOGD wells given that tens of thousands have been constructed. Although stray gas has been detected in the vicinity of wells that have had issues with well integrity (Darrah et al. 2014), only a small number of documented cases of non-methane contamination have been reported in the scientific literature. For example, there have been fewer than 10 cases for the Marcellus Shale through 2017 (Brantley et al. 2018). Consequently, exposure assessments for this release scenario are rare.

Study Summary
Llewellyn et al. (2015) reported a case study in which stray natural gas and a foaming agent were reported to have contaminated several domestic groundwater wells in Pennsylvania following the development of five UOGD wells 1–2 km away. The authors used sophisticated analytical techniques (two-dimensional gas chromatography coupled to time-of-flight mass spectrometry) to detect the presence of organic unresolved complex mixtures at very low detection levels (nanograms per liter) in samples from the affected wells. Low levels of unresolved complex mixtures and the surfactant, 2-n-butoxyethanol (known to be used in hydraulic fracturing fluid, were detected in water well samples). Surface casing was installed in the UOGD wells to about 300 meters depth and production casing was used in the Marcellus Shale at depths between 2,100 and 2,300 meters, but at intermediate depths no casing was installed. Hydrogeological patterns indicate that bedding planes, which can facilitate fluid migration, are near the surface at the domestic water wells and dip downward and intersect the UOGD wells between about 180 and 580 meters in depth, that is, in the uncased intermediate section of the UOG wells. The authors indicate that multiple lines of evidence “implicate fluids flowing vertically along gas well boreholes and through intersecting shallow to intermediate flow paths via bedrock fractures” as responsible for the contaminant transport.

Notable Features
The study by Llewellyn et al. (2015) addresses the first parts of the conceptual model of exposure (Figure 4-1). Although samples of the drilling fluids and flowback water for the implicated gas wells were not available, the measurements were consistent with flowback and production waters from other similar unconventional gas wells in Pennsylvania, therefore the source identification is reliable. Release due to pressurization in the borehole is documented. Also, the hydrogeological setting is reasonably well characterized so the identified transport pathway – “stray natural gas and drilling or HF compounds were driven ∼1–3 km along shallow to intermediate depth fractures to the aquifer used as a potable water source” – is supported by evidence.

Missing Elements
The full exposure pathway for a broad population cannot be covered by a single case study. Given that more than 10,000 UOGD wells have been drilled in Pennsylvania over the past ~15 years, there is a need for systematic documentation of contamination events such as that explored by Llewellyn et al. (2015) and of levels of contamination in drinking water supplies that may result. Exploration of large data sets may provide some evidence for contamination potential. For example, Wen et al. (2018) analyzed a large methane data set for one region in Pennsylvania and concluded that slightly elevated concentrations occur near 7 out of the 1,385 shale-gas wells in the region studied. Such analyses might form the basis for more detailed work to investigate whether the elevated methane concentrations are indicators of contamination by wastewater from UOGD and thus are candidates for future research to understand possible water-related exposure pathways.
4.4 SOIL AND SEDIMENT EXPOSURE PATHWAYS

4.4.1 Summary of Studies—Soil and Sediment Exposure Pathways

Few studies have investigated potential UOGD impacts on the quality of soil and sediment that could lead to human exposure. Studies aimed to improve understanding of the mobility and impacts of UOGD-related chemicals in soil (Lyman et al. 2017; Oetjen et al. 2018), measure soil quality impacts from use of produced water to treat roads (Tasker et al. 2018), or quantified sediment quality impacts from discharge of treated produced water to surface water (Skalak et al. 2013; Van Sice et al. 2018). A small body of literature has focused on the potential impacts on food; Bamberger and Oswald (2012, 2014, 2015) interviewed owners of animal farms that are near UOGD about the health of their herds and flocks.

4.4.2 UOGD Sources and Potential Release Mechanisms—Soil and Sediment Exposure Pathways

Soil and sediment contamination from UOGD operations can occur through accidental spills on the well pad or during fluid transport and unauthorized disposal off the well pad (Konkel 2016; Pichtel 2016). Contamination may also occur via casing failure in the wellbore or pipelines, leaks from impoundments, or from produced water reuse for crop irrigation or road de-salting if not properly treated (Al-Ghouti et al. 2019; Shonkoff et al. 2016).

Migration from Soil to Other Media. Contamination in soil can migrate to other media, such as groundwater, surface water, or air, such that exposure occurs via these other media. Two studies examined the mobility of UOGD-related chemicals in soil using lab-based (Oetjen et al. 2018) and field-based methods (Lyman et al. 2017). Oetjen et al. (2018) used bench-scale soil columns to simulate a spill of hydraulic fracturing wastewater from a well in Greeley, Colorado onto agricultural soil under environmental conditions relevant to the region. Investigators reported that copper, lead, magnesium, and iron were mobilized. No surfactants or their transformation products were detected in leachate samples from the experiment, suggesting that they do not travel far from the initial spill location under the experimental conditions.

Lyman et al. 2017 compared fluxes of methane, non-methane VOCs, and carbon dioxide from soil on gas well pads with production, storage, and shut-in equipment with fluxes from soil located in areas without UOGD in the Uinta Basin of Utah. The investigators reported that hydrocarbon fluxes exhibited spatial variability within a single well pad, but the majority of the time the fluxes were higher than the average flux from undisturbed soils. Hydrocarbon fluxes within 2.5 meters of the wellhead were lowest at producing wells and highest at shut-in wells. They concluded that the majority of emission fluxes were likely attributable to raw gas migrating from the subsurface to the atmosphere, with the rest resulting from spilled liquid hydrocarbons.

Reuse of UOGD wastewater. Individual states are considering options for produced water reuse, especially in water-stressed regions of the United States, such as New Mexico and Oklahoma (State of New Mexico and U. S. Environmental Protection Agency 2018; U.S. Environmental Protection Agency 2019c). Produced water reuse can potentially impact soil or sediment quality and could reach other media such as groundwater or nearby surface water bodies. The U.S. EPA (2019c) is currently conducting a study to summarize options for wastewater management from both conventional and unconventional oil and gas development and to gather the perspectives of different stakeholders (e.g., oil and gas industry, environmental nongovernmental organizations, academics, and state regulators) about current practices and potential regulatory changes to expand wastewater management options.
Tasker et al. (2018) analyzed state-level regulation about wastewater reuse and analyzed the chemical composition of samples of wastewater from 14 Pennsylvania townships that was intended to be spread on roads. Oil and gas road spreading data revealed that 35 million and 5 million liters per year of wastewater was spread on Pennsylvania and Ohio roads, respectively, primarily from conventional wells. Using these data, the investigators simulated multiple road spreading and runoff events in lab experiments focused on radium retention in the road material. They reported increases in radium concentrations in soils around roads following simulated spreading and rain events that did not exceed regulatory standards but that were higher than concentrations from wastewater treatment facilities and spills. Skalak et al. (2013) investigated soil impacts from road spreading, reporting that areas that used brines from conventional oil and gas wells for road deicing saw an accumulation of radium-226, as well as extractable strontium, calcium, and sodium in sediment near the roads.

Sediment quality and surface water discharges. Skalak et al. (2013) evaluated the potential for accumulation of alkali-earth elements in the sediment of streams used for surface disposal of produced waters following treatment. The investigators collected surface sediment grab samples upstream and downstream of five publicly owned treatment works (POTWs). The investigators reported no increase in concentrations of total radium (radium-226) and extractable barium, calcium, sodium, or strontium in downstream sediments.

Van Sice et al. (2018) leveraged a 2011 request from the Pennsylvania Department of Environmental Protection that operators recycle rather than treat and discharge UOGD wastewater from centralized waste treatment facilities to determine whether the radium loading to streams decreased. The investigators reported that the voluntary request coincided with a decrease in radium loading to the study stream by approximately 95% between 2011 and 2017.

4.4.3 Potentially Exposed Populations – Soil and Sediment Exposure Pathways

4.4.3.1 Relevance of Information for Quantifying Exposure

Studies of potential UOGD impacts on the quality of soil and sediment did not endeavor to establish a connection between UOGD and a specific population.

4.4.3.2 Characteristics of Potentially Exposed Populations

Studies of potential UOGD impacts on soil and sediment quality did not identify characteristics of populations potentially exposed to chemicals released from UOGD via the soil and sediment pathway.

4.4.4 Concluding Remarks– Soil and Sediment Exposure Pathways

The literature describes how contamination of soil, sediment, and agricultural products might arise. Studies evaluating soil and sediment quality impacts focus on specific incidents or conditions and were not broadly generalizable to other locations and operational conditions. In addition, studies did not include information about potentially exposed populations. Investigators of the studies recommended further research to understand factors that influence chemical mobility in soil (Echchelh et al. 2018; Shariq 2013), particularly as more options of produced water reuse are explored (U.S. EPA 2019c).
4.5 UOGD Noise, Light, and Odor

4.5.1 Summary of Studies—Sensory Exposure Pathway

Several studies have included measurements of exposure to sensory agents\(^1\) from UOGD processes. Five involved noise monitoring (Blair et al. 2018b; Boyle et al. 2017; Lorig 2016; Radtke et al. 2017; Richburg and Slagley 2018), one involved noise and light monitoring (McCawley 2013), and one involved noise, traffic count, and air quality monitoring (Allshouse et al. 2019). All were conducted in either the Denver-Julesburg basin (Allshouse et al. 2019; Blair et al. 2018b; Radtke et al. 2017) or the Marcellus region (Boyle et al. 2017; Lorig 2016; McCawley 2013; Richburg and Slagley 2018). Sampling was conducted at various distances from the well pad (McCawley 2013; Radtke et al. 2017), using area monitoring (Lorig 2016) outdoors on residential property (Blair et al. 2018b) both indoors and outdoors at residences (Boyle et al. 2017), or at a combination of residential and area sampling (Richburg and Slagley 2018). Three studies (Blair et al. 2018b; Boyle et al. 2017; Richburg and Slagley 2018) used samples collected during the day and night, capturing diurnal variation in noise levels.

Radtke et al. (2017) conducted noise monitoring at 23 oil and gas sites in Northern Colorado at various distances from drilling, hydraulic fracturing, and completion sites that varied in their use of noise barriers. Investigators found that noise barriers were effective in dampening noise within 350 feet (Figure 4-12); however, the measured reduction was not sufficient to reduce noise levels below the residential permissible noise standard in Colorado (55 A-weighted decibels (dBA)).

Two studies included measurements of multiple types of exposure. Allshouse et al. (2019) measured 1-minute average A-weighted noise levels (audible to the human ear) and C-weighted noise levels (low frequency sound pressure). These investigators also measured concentrations of PM\(_{2.5}\) and black carbon in air (see Section 4.2) at four Colorado residences located northeast, south, northwest, and east (between 217.9 and 392.6 meters) of the sound wall surrounding a 22-well pad. Traffic counts were also measured near one of the sampling locations. Sampling occurred over a one-year period (2017-2018) at two of the residences during drilling, hydraulic fracturing, flowback, and production phases. Sound levels varied

---

\(1\) Sensory agents include noise, vibration, light, and odor. Odors arise from chemicals in the air, but for the purposes of this report, we discuss this exposure separately.
depending on sampling location and time of day. Continuous A-weighted noise levels exceeded 50 dBA (World Health Organization’s community noise guidelines) during hydraulic fracturing, flowback, and production phases and C-weighted noise levels exceeded 65 C-weighted decibels (dB(C) over all phases. Investigators also found that noise exceedances occurred during higher traffic counts, which occurred during hydraulic fracturing (average 8.9 and 8.5 heavy trucks/hour during the day and night, respectively) and flowback (average 13.5 and 6.6 non-heavy trucks/hour during the day and night, respectively). McCawley et al. (2013) measured both light and noise at six residential and non-residential sites near wells reflecting different operating conditions and obstructions to residential exposure (e.g., residences in a valley and with or without foliage).

Boyle et al. (2017) and Blair et al. (2018b) measured noise levels in West Virginia and Colorado residences, respectively. Boyle et al. (2017) compared 24-hour indoor and outdoor measures of noise in eight homes within 750 meters of the nearest compressor station, and 3 control homes more than 1000 meters from the nearest compressor station. Geometric mean outdoor and indoor noise levels were higher in the exposed homes than the control homes. The differences between indoor noise levels in exposed versus control homes were 13.1 dBA during the day, and 9.4 dBA at night. Blair et al. (2018b) measured noise at four Colorado residences between 320 and 550 meters from a multi-well site permitted for 22 wells. Monitoring was conducted during construction and drilling over three months. The authors noted that, overall, 41.1% of daytime and 23.6% of nighttime dBA 1-min equivalent continuous noise measures exceeded 50 dBA.

Richburg and Slagley (2018) measured noise at a residence and a community near a well pad and in a community near a compressor station. Dosimeters were used to record day–night levels of 53.5–69.4 dBA outside and 37.5–50.1 dBA inside, which the investigators noted exceeds U.S. EPA guidelines. Lorig (2016) is the only noise modeling study to date. Investigators used pre-existing noise measurements taken near compressor stations to model noise across the Pennsylvania state forests in the Marcellus region. Modeling allowed the investigators to understand how noise from compressor stations disperses under different conditions and to identify natural barriers (e.g., basins or valleys) that dampen noise.

4.5.2 UOGD Sources and Potential Release Mechanisms – Sensory Exposure Pathway

Noise is present on the well pad during the development phase, beginning with site preparation. Noise — along with light — continues after site preparation, occurring 24 hours a day, 7 days a week, during the drilling and hydraulic fracturing phases. Flaring is another source of noise, along with on-pad truck traffic, diesel and natural gas engines powering generators, drill rigs, pumps required for hydraulic fracturing, and other machinery. According to a study conducted by the New York State Department of Environmental Conservation (NYSDEC), the highest noise levels are expected during hydraulic fracturing (New York State Department of Environmental Conservation 2015). NYSDEC also determined that artificial lighting from operations can intrude into homes and may be especially intense during flaring operations (New York State Department of Environmental Conservation 2015). Malodorous compounds, such as hydrogen sulfide and some VOCs, can be emitted during the development phase (Colorado Department of Public Health and Environment 2016, 2018c; McCawley 2013; New York State Department of Health 2014; Pennsylvania Department of Environmental Protection 2010).

Light, noise, and odor can continue on the well pad during the production phase. Flaring also produces noise and light. Compressors can produce continuous noise that in some instances has exceeded state maximum allowable noise limits at fence line distances (Maryland Institute for Applied Environmental Health 2014). Similarly, malodorous compounds (e.g., H₂S) have been measured near well pads during the production phase (Eapi et al. 2014; Pennsylvania Department of Environmental Protection 2010).
Like chemical measurements, sensory agents have sources other than UOGD, such as conventional oil and gas operations and local construction projects. Hays et al. (2016) discussed temporal factors (e.g., length of activity phases) that can help distinguish noise derived from conventional oil and gas development and UOGD. However, the studies using measurements of noise did not discuss whether the noise measurements were unique to UOGD activities.

4.5.3 Potentially Exposed Populations – Sensory Exposure Pathway

4.5.3.1 Utility of Information for Quantifying Exposure

The studies conducted to date involved sample sizes consistent with pilot studies. Studies with larger samples across a variety of landscapes would be helpful to assess temporal and spatial variability of these exposures for specific populations, with Allhhouse et al. (2019) providing a useful example with noise, PM$_{2.5}$, and black carbon monitoring during multiple well development phases at varying directions from the pad. Although the noise studies are a relatively small body of literature, they included measurements of concentrations in outdoor air of communities and indoor air of residences, reflecting conditions where people are exposed. Some investigators also designed their studies to compare noise levels among different mitigation techniques, which is helpful to understand how noise exposure varies as a function of these techniques.

4.5.3.2 Characteristics of Potentially Exposed Populations

Two of the studies included samples taken from inside residences, but did not report on characteristics of the residents, particularly their sensitivity to noise (Boyle et al. 2017; Richburg and Slagley 2018). Richburg and Slagley (2018) interviewed residents about their sleep quality and perception of the impact noise was having on their health but did not conduct any quantitative analyses to understand relationships between noise and reported health concerns.

4.5.4 Concluding Remarks- Sensory Exposure Pathway

The current body of literature on sensory exposure potentially attributable to UOGD is spatially and temporally limited. However, in general, the available studies provide evidence that noise levels can exceed maximum permissible levels for residential areas and that sound wall barriers do not effectively block all forms of noise. In addition, some states allow a higher maximum permissible noise level during some activities, such as pipeline or gas facility installation or maintenance, drilling, and hydraulic fracturing. It is not clear how well these few studies reflect the reality of sensory exposures experienced across regions, with or without mitigation measures. The available literature does not address factors related to in-home mitigation techniques, sensitivity of residents to sensory exposure, and the presence of vulnerable populations in residences experiencing sensory exposure attributable to UOGD. In a review of the noise literature, Hays et al. (2016) noted the relative paucity of the research, the diversity of noise types (e.g., intermittent versus continuous, levels of intensity, and high versus low frequency), and the importance of considering subpopulations of individuals with noise sensitivity.
4.6 EXPOSURE BIOMONITORING

4.6.1 Summary of Studies

Five studies reported biomonitoring results for human exposure to VOCs as measured in blood, urine or hair (Figure 4-13; Caron-Beaudoin et al. 2018, 2019; Crowe et al. 2016; Esswein et al. 2014; Texas Department of State Health Services 2010). A summary description of biomonitoring is provided in Box 4-7.

In Caron-Beaudoin et al. (2018), participants collected five urine samples over a 5-day period, but no information was provided on time of day or participant activities prior to the time of sampling. Therefore, it is not known whether the sample concentrations were impacted by activities such as smoking, workplace exposures, driving, pumping gas, etc. The same research group performed a second study in which they measured trace metals in five spot urine (pooled for analysis) and hair samples collected from 29 Indigenous and non-Indigenous pregnant women living in Canada in proximity to UOGD. Investigators collected additional information on lifestyle factors (e.g., smoking habits) and sociodemographic information and compared concentrations between the study population to the general Canadian population.

Figure 4-13. Number of biomonitoring studies.

In response to citizen concerns, the Texas Department of State Health Services (Texas Department of State Health Services 2010) collected urine, blood, and tap water samples from 28 residents of DISH, Texas during a one-time sampling event to determine whether VOC concentrations were in the fifth percentile of U.S. population (using National Health and Nutrition Examination Survey data) values. Investigators also collected field observations of odor, noise, and presence of nearby well pads, storage equipment, and compressor stations.
Box 4-7. Brief Explanation of Biomonitoring

As evidenced by this review, the body of literature examining human exposures to UOGD-related chemicals is extensive and includes models and measurements for estimating intake of chemicals via inhalation and ingestion (with limited studies involving the dermal route of exposure among UOGD workers). To estimate exposure using chemical concentrations in environmental media (e.g., air, water, and soil), these data can be evaluated alone or in combination with intake rates (e.g., volume of air breathed per day, liters of water consumed per day); this is referred to as external exposure. Another approach that is used by scientists to estimate human exposures is biomonitoring, defined as a “…method for assessing human exposure to chemicals by measuring the chemicals or their metabolites in human tissues or specimens, such as blood and urine” (National Research Council 2006). Thus, biomonitoring is an internal measure of exposure.

Biomonitoring is a powerful method for quantifying exposure, but it is worth noting a few important and well-known issues that must be considered when designing and evaluating studies based on biomonitoring (LaKind et al. 2014). First, biomonitoring provides an estimate of internal dose, and therefore it integrates all routes of exposure. Although the incorporation of all routes of exposure is advantageous, a related disadvantage is that this approach does not allow one to distinguish among routes of exposure and so one cannot determine whether, for example, chemical exposure via inhalation or ingestion predominates. Similarly, biomonitoring cannot distinguish among sources of chemical exposure unless the chemical and its metabolites are unique to one source.

Second, many UOGD-related chemicals (e.g., VOCs) have short-physiological half-lives; that is, they remain in the body for short periods of time (perhaps hours to days) before they are metabolized and excreted, generally in urine. Therefore, the chemical concentration measured in a sample of urine may not reflect actual exposures to UOGD-related chemicals. This is illustrated in the hypothetical decline curve below. In this case, the blue curve represents the urinary concentration of a UOGD-related chemical over time; as the body metabolizes and excretes the chemical, the concentration decreases. It is clear, then, that as the time between exposure and urine sampling increases, biomonitoring will capture a smaller fraction of the actual exposure.

Third, chemicals measured in human media such as urine are often metabolites – or break-down products of the compound to which the person was exposed (the parent compound). For example, the body metabolizes benzene (parent compound) to phenol, trans,trans-muconic acid (t,t, ma), and other metabolites. Because different parent compounds can break down to similar metabolites, it can be difficult or impossible to identify the specific parent compound.

Fourth, in a typical population, the metabolism or rate of metabolism of some chemicals may vary widely depending on genetic variation between individuals or the up- or down-regulation of genes induced by medication, certain nutrients, and other factors. Methods for accounting and adjusting for such variation remain limited.

In Crowe et al. (2016), investigators collected 27 blood and urine samples from 11 participants over a 7-day period and measured for VOCs. An advantage of this study is the simultaneous collection of stationary air samples at various locations including downwind from the well pads and personal air monitoring of people living downwind from UOGD operations. Biomonitoring samples were collected approximately 4 hours after air samples were collected to identify potential sources. Although participants
were asked to avoid activities that might expose them to VOCs from sources other than oil and gas development, information on compliance with this request was not provided.

Esswein et al. (2014) collected urine samples from UOGD workers at six completion sites in Colorado and Wyoming during flowback operations. The investigators noted the participants’ job at each site (e.g., flowback lead, flowback tech, production watch lead, production watch technician, and water management operator) in order to investigate how worker exposure varied among different aspects of the completion process. Personal breathing zone sampling was also conducted for workers who participated in the biomonitoring portion of the study. Like other biomonitoring studies in this body of literature, Esswein et al. (2014) did not correct the results of the analysis for smoking or other non-occupational exposures to BTEX.

4.6.2 Distinguishing UOGD Sources in Biomonitoring Studies

The importance of understanding the quantitative linkages between exposure, dose, and biomarker levels has been described (LaKind et al. 2014). However, for many VOCs, including some of those included in the publications reviewed here, these linkages are subject to many uncertainties. For example, there is research indicating inter-individual variability in the rate at which people metabolize benzene to trans,trans-muconic acid (t,t-MA), which is one of the urinary compounds measured as part of two of the studies), which can affect its utility as an exposure metric for benzene (Gobba et al. 1997). Thus, t,t-MA may not be a reliable marker for benzene exposure (Jalai et al. 2017). Similarly, urinary hippuric acid – measured in the Crowe et al. study – may overestimate toluene exposure as other factors such as coffee, tea, fruit, and vegetable intake influence urinary hippuric acid levels (Munaka et al. 2009; Penczynski et al. 2017). Future studies will need to include biomarkers that can accurately describe exposures to parent compounds.

Although VOCs are important components of UOGD-related chemicals, many other important sources of VOCs exist, such as conventional oil and gas activities, traffic exhaust, smoking, fires, personal care products (such as nail polish), occupational exposures, and — in the case of Caron-Beaudoin et al. (2018) — a gas plant. This issue was clearly acknowledged in the report by the Texas Department of State Health Services (Texas Department of State Health Services 2010), which found higher levels of cigarette-related VOCs in the blood and urine of smokers and which also describes various non-oil and gas sources of VOC exposures.

Three of the studies (Caron-Beaudoin et al. 2018, 2019; Crowe et al. 2016) were not designed to distinguish between UOGD and various additional sources of VOCs, including conventional development. Similarly, Esswein et al. (2014) did not attempt to distinguish between other UOGD occupational sources of VOC exposure on the well pad (trucks, compressors, etc.). The study by the Texas Department of State Health Services included questionnaire-derived information on participant activities that may impact internal VOC levels. Further, samples were collected over a short time period (days) and did not capture meteorological, diurnal or seasonal variability in exposure, nor changes in UOGD operations.

4.6.3 Potentially Exposed Populations – Biomonitoring Studies

Utility of Information for Quantifying Exposure – Biomonitoring Studies. Biomonitoring studies will not be able to distinguish between a population that may be exposed from different exposure pathways unless a chemical is specific to one or the other of those media. In order to assess specific exposure pathways of concern, a biomonitoring approach would need to be paired with environmental measures or models. Three studies — Crowe et al. (2016), Esswein et al. (2014), and Texas Department of State Health Services (2010) — did collect air or water samples in parallel with biological samples. The collection of breathing zone samples from personal monitors attached to study participants in Esswein et al. (2014)
allowed the investigators to compare biological sampling results to human-specific exposure via the inhalation pathway.

For the four studies under review, it is important to note that in order to understand exposures fully, information is needed on many factors including work and non-work activities, personal proximity to UOGD activities, as well as diet and other possible influences on VOC exposures. The studies addressed this data gap as a limitation of their analyses. Further, because concentrations of non-persistent chemicals generally vary widely from day to day, the generalizability of a measurement from a single sample (in other words, whether the measurement from a single person represent exposures to a larger population) is unknown.

**Potentially Exposed Populations.** Given the ubiquitous nature of many of the chemicals measured (e.g., benzene, toluene), it is difficult to distinguish between populations exposed to UOGD chemicals and the general population. For many of the chemicals measured by Crowe et al. (2016), general population median urinary levels were higher than those for the population under study. The Texas Department of State Health Services (2010) investigation found that VOCs in blood and urine in the community in and around oil and gas production were similar to a comparison group, and Caron-Beaudoin (2019) found higher concentrations of urinary manganese and some metals measured in hair compared to reference populations. There may be many reasons for this observation, including timing of sample collection in relation to actual exposure and differing levels of non-UOGD sources of exposures. If a chemical specific to UOGD is identified that could be measured in human media such as blood or urine, this might be a useful marker for UOGD-related exposure.

The Texas Department of State Health Services (2010) study included staff who provided blood and urine samples before visiting residences located near compressor stations and gas wells (at the Austin headquarters where there is no exposure to UOGD) and then again after spending 2 to 3 days in DISH, Texas (where UOGD is widespread). This longitudinal approach could potentially be useful for identifying populations exposed to oil and gas-related chemicals; the study, however, found no difference in VOC levels before and after the site visit.

### 4.6.4 Concluding Remarks

Although biomonitoring research is a promising avenue for exploring internal exposure, there are many challenges associated with biomonitoring studies that make them technically and financially difficult to execute, especially in the context of UOGD exposure. The limited body of biomonitoring literature related to UOGD exposure indicates that future biomonitoring studies should focus on finding and testing markers specific to UOGD exposure if they exist.

### 4.7 SUMMARY OF THE LITERATURE

The Committee searched for literature to address its survey question, *What is known about potential UOGD-related human exposures?* As implicated by the survey question, the Committee’s goal was to survey the literature to identify the state of the science of understanding human exposures to UOGD-related chemical and non-chemical agents.

#### 4.7.1 Conceptual Framework for the Literature Survey

Understanding human exposures to UOGD-related chemicals and other agents represents a complex undertaking (see Box 1-2). UOGD processes involve a multitude of agents (e.g., chemicals, light, and noise) released to the environment in a variable manner over time and location. The releases may impact levels of the agents in multiple media (i.e., air, water, or soil), with varying impacts observed at the site of emissions over space within a region, and among regions. Impacts vary due to differences in shale plays,
level of operations, and operator practices among other factors. Furthermore, variation in time–activity-
location patterns (e.g., time spent at residential versus work locations and indoor versus outdoor
locations) among potentially exposed populations complicates quantifying human exposures to agents
originating from UOGD. The Committee conducted their survey of the literature within a conceptual
framework of exposure, identifying exposure pathways leading from UOGD sources to populations
(Figure 3-2).

4.7.2 Strengths of the Literature in Assessing Human Exposure to UOGD

The literature search returned hundreds of studies that have been conducted to understand the
environmental impacts associated with UOGD. The majority of publications focused on levels of agents
in air, with studies conducted across major shale play regions. Many publications also focused on levels
of agents in water (mostly in the Marcellus region), and fewer characterized other environmental media
(e.g., soil) or sensory agents.

Overall, the studies contained useful information for understanding human exposures, including those
conducted without this specific goal. The studies helped to characterize UOGD-related human exposures
by contributing to our understanding of atmospheric and hydrological conditions that affect fate and
transport of UOGD agents through the environment, the relationship between operations and types or
levels of emissions, and pathways of potential exposures. In addition, some investigators were resourceful
in their use of previously published data, such as air quality data collected as part of state monitoring
programs.

Investigators used a wide array of methods to assess potential environmental impacts and human
exposures associated with UOGD. Some investigators used methods that were useful for isolating UOGD
sources. Some measured emissions on well pads and used the data, along with meteorological and
topographical data, to analyze air quality changes over space and time. Studies sometimes involved the
use of various tracers or markers to estimate the levels of agents in air or water that were attributable to
UOGD. Other investigators assessed the chemical concentrations before, during, and after UOGD
activities, enabling an evaluation of potential impacts specific to those activities.

Studies of greatest utility for addressing the Committee’s guiding question were those that shed light on
spatial variability of agent concentrations (e.g., by sampling at various distances from a well pad) and
temporal variability (e.g., by sampling over multiple sampling periods during a variety of UOGD
activities, meteorological conditions, seasons, and times of day).

A subset of studies were conducted with the aim of characterizing human exposure to chemicals, noise,
and light. To do so, investigators collected samples in areas where people spend much of their time,
including air sampling in residential communities and water sampling of drinking-water wells. Some
studies involved affected communities through discourse and participation, thereby providing results to
the affected communities and benefiting from local knowledge. In addition, some state agencies
conducted air sampling in response to community concerns.

4.7.3 Knowledge Gaps About Human Exposure to UOGD

The quantity of data on levels of UOGD-related agents in the environment continues to increase along
with efforts to use the data to quantify human exposure. Nevertheless, important gaps remain in our
understanding of who might be exposed, how exposures might arise, how exposures vary over time and
across regions, and the likelihood of exposure.

Few studies provided the information necessary for linking environmental concentrations of agents to
specific UOGD-related sources (e.g., diesel-powered equipment) or to distinguish between contributions
from UOGD and other sources, such as conventional oil and gas development. In addition, the
generalizability of study results to UOGD operations, geographic areas, and populations beyond those
investigated in the studies is not clear.

Given the current state of knowledge on UOGD and potential exposures, the Committee recommends
further investigation to improve understanding of human exposures to UOGD. The research should be
designed to support decision making by community members, public health officials, regulators, oil and
gas operators, and others about how to protect human health.
5.0 PLANNING FOR EXPOSURE RESEARCH

This section summarizes the Committee’s early planning for research to address knowledge gaps about potential UOGD-related human exposures, and the principles that will guide its preparation of a Research Solicitation and review of proposals submitted in response.

5.1 KNOWLEDGE GAPS FRAMED AS RESEARCH QUESTIONS

The Committee identified gaps in knowledge about UOGD exposures (Table 5-1), framed within a conceptual model of exposure that links a UOGD source to a potentially exposed population. These knowledge gaps derived from the review of literature, supplemented by input from a range of stakeholders from communities, government, industry, nongovernmental organizations, and academia. Stakeholder consultations were important given that UOGD practices and regulation continue to evolve as do concerns in response to these changes, and much of this information is not in the scientific literature.

In defining the research questions, the Committee also looked at a variety of ways to identify research valued by local communities (Brasier et al. 2011; Korfmacher et al. 2014; Krupnick and Siikamäki 2014; Perry 2013; Schafft et al. 2014). The goal was to define research that, when implemented, would provide the knowledge needed to answer the most important questions about potential UOGD exposures.

The Committee recognizes that the research questions are not necessarily of equal importance nor do they fully encompass all worthy research topics. Although the questions individually represent different components of the conceptual model, an ideal future research project would include all elements of an exposure pathway.

Table 5-1. Knowledge Gaps Framed as Example Research Questions.

<table>
<thead>
<tr>
<th>UOGD SOURCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. How do the characteristics (i.e., the likelihood, composition, magnitude, frequency, and duration) of potential environmental releases from UOGD vary over space and time as a function of differences in the geological formations, meteorology, and variable practices among operators, across phases of development, or in response to technological innovation, changing regulations and guidance, and community concerns?</td>
</tr>
<tr>
<td>2. a. What is the relative contribution of operational, accidental, and unauthorized releases to environmental concentrations of UOGD agents in air? How might they contribute disproportionately to total emissions? How can emissions from individual UOGD processes be best quantified? Can measurements of methane releases be used to help inform efforts to estimate non-methane emissions? How can we use longer term observations (e.g., routine ground-based and satellite, including flares) to estimate historical trends in emissions? b. What are the relative contributions of operational, accidental, and unauthorized releases to environmental concentrations of UOGD agents in water?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RELEASE MECHANISMS AND TRANSPORT PATHWAYS</th>
</tr>
</thead>
<tbody>
<tr>
<td>3. a. How does variation in regional conditions (e.g., meteorology and topography) affect the levels of UOGD agents in air over various temporal scales (e.g., hourly, diurnally, and seasonally) as a result of chemical transformation and transport? What methods are available to characterize the fate and transport of UOGD releases to the air? b. How does variation in regional conditions (e.g., topography, geochemistry, geophysics, and hydrology) affect the levels of UOGD agents in water over various temporal scales (e.g., seasonally) as a result of chemical transformation and transport? What methods are available to characterize the fate and transport of UOGD releases to water? c. To what extent does UOGD contribute to increased levels of noise, light, and vibration within and across regions and operations?</td>
</tr>
</tbody>
</table>
Table 5-1. Knowledge Gaps Framed as Example Research Questions.

<table>
<thead>
<tr>
<th>RELEASE MECHANISMS AND TRANSPORT PATHWAYS</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.  a. How can levels of UOGD agents in air be distinguished from levels contributed by other natural and anthropogenic sources? What is the relative contribution of air emissions from UOGD to local and regional concentrations?</td>
</tr>
<tr>
<td>b. How can levels of UOGD agents in water be distinguished from levels contributed by other natural and anthropogenic sources? What is the relative contribution of water releases from UOGD to local and regional concentrations?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EXPOSED POPULATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>5. What are the characteristics(^2) of populations potentially exposed to UOGD agents at local and regional scales?</td>
</tr>
<tr>
<td>6. Which population behaviors (e.g., time–activity patterns) influence the potential for exposure to UOGD agents? To what extent do exposures to UOGD agents differ among individuals within and among exposed populations?</td>
</tr>
<tr>
<td>7. How can exposure monitoring methods (e.g., study design, instrumentation, and other technologies) accurately characterize total personal and population-wide exposures to UOGD over time and space?</td>
</tr>
</tbody>
</table>

1\(^{\text{UOGD agents might be released to the environment as:}}\)
1. **Operational releases**: In accordance with applicable regulations (e.g., permitted discharges to surface water, equipment emissions to ambient air, and vehicle emissions).
2. **Accidental releases**: As a result of poor practices (e.g., improper waste disposal, accidental releases, and explosions), or
3. **Unauthorized releases**: As a result of unauthorized activities (e.g., illegal disposal of waste materials).

\(^{2}\)Population characteristics include numerous factors, such as age, sex, race, ethnicity, socioeconomic status, health status, size of the population, activity patterns, and other factors.

The following series of tables elaborates on each of the research questions in Table 5-1. Each box includes one of the research questions, background information that briefly explains its importance, and example research activities to address the question. The examples are provided to illustrate how the research question might be addressed but are not intended to limit the scope of research.
5.1.1 UOGD Sources

<table>
<thead>
<tr>
<th>Topic:</th>
<th>Source - Characterization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Question:</td>
<td>1. How do the characteristics (i.e., the likelihood, composition, magnitude, frequency, and duration) of potential environmental releases from UOGD vary over space and time as a function of differences in the geological formations, climate, and variable practices among operators, across phases of development, or in response to technological innovation, changing regulations and guidance, and community concerns?</td>
</tr>
</tbody>
</table>

**Background:** Much effort has been directed toward understanding the chemical and non-chemical agents that might be released to the environment from UOGD operations. Examples include the characterization of drilling fluid, hydraulic fracturing fluid, flowback, produced water, and solid waste composition; emissions and air quality impacts; releases to water and water quality impacts, and sensory impacts. Although the identity and toxicity of some chemicals used in and released during UOGD operations are known, this is not always the case, leaving gaps in knowledge about the composition and toxicity of chemical releases to the environment. There is also limited understanding of the spatial and temporal variability in the magnitude and composition of releases across oil and gas-producing regions of the United States. This information is important for understanding the significance of human exposures that might occur.

Numerous spatial and temporal considerations exist in the types of chemicals used and released during UOGD operations (Section 2). The co-location of conventional and UOGD wells must also be considered where appropriate. Variation among state regulations regarding all aspects of UOGD may exist (Zirogiannis et al. 2016) and should be considered in designing exposure studies. Operator and service company approaches during drilling and completion operations and a company’s ability to monitor and respond to releases when they occur might influence the potential releases to the environment. For example, air-related exposures are subject to many variables; one example is how operators manage gas associated with oil production (e.g., by using it in on-site equipment or flaring to the atmosphere). The same is true for water-related exposures. With the exception of those required by regulation, most trends in UOGD operations are adopted over a period of time as new practices gain acceptance by operators, and they are not necessarily documented. The UOGD industry has changed practices over time in response to new understanding of health, safety, and environmental practices; regulatory changes; and technological changes. An understanding of these changes over time and differences among regions is important to understanding how and where exposures might arise.

The increasing use of produced water in hydraulic fracturing is an example. Water reuse differs among the shale plays, in part, because the quality of produced water varies, requiring different levels of freshwater dilution and other treatment before reuse. Such differences impact the composition of potential releases. Also, important operational trends over time and across regions might influence the potential for exposure. For example, across many shale plays, there is a trend toward drilling longer laterals, with increasing numbers of hydraulic fracturing stages and, consequently, use of more fracturing fluid and proppant. This trend may increase the likelihood of releases of fracturing materials, flowback water, or produced water to the environment. Trends in energy production and use during boom and bust cycles also impact emissions and must be considered in predicting the magnitude and likelihood of exposures (Nsanzineza et al. 2019).

**Research Goal and Examples of Research Activities:** The goal of this research would be to characterize the chemicals used and produced during UOGD operations and to improve understanding of factors that influence whether people might be exposed to them. Many details regarding UOGD practices influence whether exposures occur and, if they do, how and where. For example, Jackson and Dusseault (2014) studied gas release mechanisms from wellbores and illustrated that the cemented annulus between the production casing and formation often exhibits sustained annulus pressure (SAP). At present, there is no generally accepted way of quantifying how SAP translates into the probability of gas being released to groundwater. Understanding operational practices used to manage SAP would be helpful in assessing the likelihood of UOGD releases. This type of UOGD operational information is central to understanding human exposures but is typically not published. Investigators would need to consult operators, regulators, and other knowledgeable entities, and perhaps conduct preliminary research to identify UOGD operational variables most affecting exposures before proceeding to full-scale research.
Topic: Source – Releases to Air

Question: 2a. What is the relative contribution of operational, accidental, and unauthorized releases to environmental concentrations of UOGD agents in air? Which of these categories leads to “high emitters” (sometimes called “super emitters”)? What methods have been used to quantify emissions from individual UOGD processes, as well as at site and regional levels? How can measurements of methane releases be used to help inform estimating non-methane emissions associated with UOGD operations? How can we use longer term observations (e.g., routine ground-based and satellite, including flares) observations to estimate historical trends in emissions?

Background: One of the primary potential exposures of concern is inhalation of air pollutants emitted from UOGD-related operations, as well as known and unknown products of chemical reactions involving emitted compounds. The known compounds emitted during UOGD are discussed for each UOGD phase in Section 2.3 and more generally in Section 4.2.2. Temporally, emissions vary due to operational variations (both planned and unplanned), and may be permitted, accidental, or unauthorized. Some short-term processes and specific sites (e.g., super-emitters) are found to dominate emissions. A number of direct and indirect methods have been used to quantify process-specific, site-specific, and regional emissions from UOGD operations. Much of the UOGD health literature reported associations between proximity to wells and adverse health outcomes, so characterizing local-level emissions is important.

Research Goals and Examples of Research Activities: A foundation to understanding inhalation exposures to UOGD operations is to characterize emission rates and composition. Such information can then be used to better estimate compound-specific exposure levels (e.g., through some type of modeling), with a particular emphasis on variability. The goal of this research would be to characterize the composition and rates of release of compounds of concern (e.g., air toxics, PM, NOx, ozone precursors) at the site and regional levels. Such research could entail development or application of new or existing methods to characterize (quantity and composition) emissions at the process or site level; development of distributions of emissions at the process or site level; collection of or use of pre-existing (or concurrent) basin-level observations (likely using ground-based observations and, potentially, drone, aircraft, or satellite observations) of air pollutants for analysis of the accuracy of site-level emissions estimates as well as regional exposures, and analyses of methane and non-methane species emission studies.

Reconciling emissions estimates developed from aggregating process and site-level measurements and regional observations may involve integration of measurements and modeling. Future research should consider better characterizing both known air toxics as well as a more complete understanding of the range of compounds emitted from each process. Specific attention should be focused on linking emissions to specific processes that may be highly variable temporally and on characterizing the variability in emissions between locations. Research opportunities may present themselves through the use of past studies characterizing three-dimensional pollutant concentrations in UOGD-abundant areas, as well as from routine networks.
**Background:** The sources for potential contamination of surface waters and groundwaters due to UOGD activities are discussed by each UOGD phase in Section 2.3 and more generally in Section 4.3.2. The most common operational release of UOGD-related water is as produced water, which can be disposed of in deep injection wells or re-used in fracturing of new wells or other purposes. Some produced water is treated and then released to surface waters (Akob et al. 2016; Ferrar et al. 2013b; Hladik et al. 2014; States et al. 2013; Warner et al. 2013a) and, in some cases, is used for ice control on roads (Allison and Mandler 2018). Currently the U.S. EPA prohibits discharge of produced water from UOGD through publicly owned treatment works (U. S. Environmental Protection Agency 2016a). Another possible operational release results from failure of wellbores, which has been linked to release of methane (“stray gas”) to groundwater aquifers (Soeder 2018). Also, accidental spills of UOGD chemicals and produced water can occur on well pads and during transportation (Clancy et al. 2018). As described in U.S EPA (2016a), there is a lack of understanding of the location of hydraulic fracturing–related activities relative to drinking water resources. There is also limited information about the frequency and likelihood of accidental and unauthorized releases to water.

**Research Goal and Examples of Research Activities:** The goal of research would be to quantify the contribution of UOGD releases to the concentrations of a range of pollutants in surface waters and groundwaters. This would require integration of measurements and modeling. Although many measurements of groundwater quality have been made in shale plays in the United States, the attribution of contamination to UOGD operations has been noted in the scientific literature in only a few cases. Baseline characterization of water quality prior to UOGD operations is essential. Future research should take a strategic or targeted approach to sampling where contamination is suspected and should focus on the use of tracers that can identify UOGD as a source of contamination (McIntosh et al. 2018). Spills of chemicals, whether accidental or by unauthorized dumping, are by their nature difficult to quantify broadly. Research opportunities may present themselves through identification of sites where spills have been recorded with subsequent design of a measurement and modelling program that could contribute to a risk analysis to inform measures protective of human health and the environment (Maloney et al. 2017).
5.1.2 Release Mechanisms and Transport Pathways

<table>
<thead>
<tr>
<th>Topic:</th>
<th>Release Mechanisms and Transport Pathways in Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Question:</td>
<td>3a. How does variation in regional conditions (e.g., meteorology and topography) affect the levels of UOGD agents in air over various temporal scales (e.g., hourly, diurnally, and seasonally) as a result of chemical transformation and transport? What methods are available to characterize the fate and transport of UOGD emissions to the air?</td>
</tr>
</tbody>
</table>

**Background:** After release into the air, UOGD-related emissions are dispersed and can react in the atmosphere, leading to widely varying atmospheric concentrations, and potential exposures, from local to regional scales. A discussion of atmospheric transport as it relates to UOGD emissions is found in Section 4.2.2. Understanding the complexities of atmospheric transport and chemistry of UOGD emissions will be key to quantifying exposures to emissions from the variety of UOGD operations across spatial and temporal scales.

**Research Goals and Examples of Research Activities:** The goal of this research would be to develop and apply methods that can quantify how releases from UOGD sites impact air quality at different scales (near-site to regional) for use in individual and population-based exposure analyses and to characterize how spatially and temporally varying chemical and transport processes affect concentrations.

One potential area of research would be the development and application of methods to conduct the direct measurements of UOGD compounds on and near sites and associated concentrations downwind and at the regional level, as well as the investigation of how those concentrations vary in response to atmospheric conditions and topography. Use of sensitive instruments and of novel approaches, including the use of inexpensive sensors and satellite observations, may be of interest, with satellite-based observations potentially helping to characterize historic exposures during both periods of heavy and light activity. Such observations, which are relatively complete temporally and spatially, can provide a means to extend detailed ground-based observations to periods of different activity levels, though the coarseness of many of the retrievals may limit their ability for use in near-field exposure assessment. The blending of inexpensive sensors, routine measurements, and satellite observations could lead to a multiscale modeling framework to capture both near-field and regional exposures in a consistent fashion. This would likely be combined with atmospheric modeling to identify appropriate methods to relate emissions from unmonitored sites to surrounding concentrations for use in broader scale exposure modeling. A particular interest would be in demonstrating the ability to capture the temporally and spatially varying concentrations of compounds of concern (e.g., air toxics, NO₂, and PM) over a range of atmospheric conditions and topographies.

Another area of research would be in developing and applying methods to assess how accurately emissions from UOGD operations are quantified. At the regional scale, the formation of secondary species via chemical reactions may be an important component of exposure, and the development or application of methods to quantify how UOGD emissions impact secondary air pollutants is of interest. There is also an extensive amount of historical data from both routine monitoring networks and satellites that may be useful for quantifying historical chemical concentrations at various spatial and temporal scales. Ultimately, development and evaluation of accurate approaches to relate compound-specific emissions at UOGD sites to concentrations that vary spatially and temporally is desired. Estimates of uncertainty in their application would be important for their later use in exposure estimation.
Topic: Release Mechanisms and Transport Pathways in Water

Question: 3b. How does variation in regional conditions (e.g., topography, geochemistry, geophysics, and hydrology) affect the levels of UOGD agents in water over various temporal scales (e.g., hourly, diurnally, and seasonally) as a result of chemical transformation and transport? What methods are available to characterize the fate and transport of UOGD releases to water?

Background: There are many complexities that limit our ability to determine how UOGD may affect regional surface water or groundwater quality. A discussion of potential UOGD releases to water is found in Section 4.3.2. Any effect must be discerned against a background of spatial and temporal chemical variations due to natural causes (e.g., storm runoff or seasonal groundwater recharge); to historical extraction of oil, gas, or coal in the region; and to a multitude of other activities (e.g., application of many chemicals in agriculture, spraying roads for dust control or deicing, and discharge of industrial wastes either intentionally or unintentionally). Well-casing failures, which occur during hydraulic fracturing, are typically more readily detected than fluid movement behind pipe. Identifying groundwater contamination from leaking wells is particularly challenging. While spills are more readily detected, they are difficult to generalize. Furthermore, geological features determine when pathways exist that can transport chemicals to shallow aquifers that are used for water supply and also determine how and where elevated concentrations of shale-related chemicals occur due to natural causes (e.g., Kreuzer et al. 2018; Nicot et al. 2017). Drilling in such areas increases the chance of contact with interconnected fractures that can provide pathways for contaminants to migrate into shallow groundwater (Woda et al. 2018).

Research Goal and Examples of Research Activities: The goal of the research would be to determine to what extent chemicals associated with UOGD have migrated to water supplies leading to potential exposures to humans, how these chemicals have migrated (pathways), and what geochemical changes have been induced during transport. These questions need to be answered in a representative region where UOGD operations are taking place, given regional variability. Research could take a retrospective or a prospective approach. Either approach would use data analysis along with modeling to interpret results in the appropriate geological (physical and chemical) context.

Retrospective activities would consider how existing data can illuminate the answers to research questions despite serious limitations on the use of readily available data for this purpose (Betanzo et al. 2016; Bowen et al. 2015). Use of a large data set with interpretation based on the geological context can provide a basis to isolate likely areas where UOGD contaminants may be present in water supplies (Wen et al. 2018). Detailed analysis of existing or newly collected data in areas identified as geologically prone to contaminant migration can provide additional evidence (Woda et al. 2018). If access to data from industry and regulators can be obtained, statistically valid tests of changes in regional water quality are possible (Betanzo et al. 2016; Wen et al. 2019).

A prospective approach would involve a research design to monitor water quality before, during, and after UOGD is initiated in a region. Such activities could cover a relatively broad area (Montcoudiol et al. 2017) or could focus more narrowly on a particular operation (Barth-Naftilan et al. 2018).
<table>
<thead>
<tr>
<th>Topic:</th>
<th>Release Mechanisms and Transport Pathways for Noise, Light, and Vibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Question:</td>
<td>3c. To what extent does UOGD contribute to increased levels of noise, light, and vibration within and across regions and operations?</td>
</tr>
</tbody>
</table>

**Background:** Research on sensory impacts associated with UOGD provide evidence of noise levels that exceed the maximum permissible levels for residential areas. UOGD operations have the potential to contribute to noise, light, and odor disturbances (see Section 4.5). It is not clear how well the few studies investigating sensory impacts, with relatively small sample sizes, reflect the reality of noise exposure experienced across regions and over time, including levels under peak noise and light conditions and under different mitigation scenarios.

**Research Goal and Examples of Research Activities:** In order to more accurately quantify exposure to sensory factors, future studies should consider studying multiple media, recruit large samples of participants with diverse residence structures, consider the impact of noise-reduction techniques, sample across regions with different topographies, and conduct sampling that represents multiple seasons, times of day, and phases of development.
<table>
<thead>
<tr>
<th>Topic:</th>
<th>Release Mechanisms and Transport Pathways for Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Question:</td>
<td>4a. How can levels of UOGD agents in air be distinguished from levels contributed by other natural and anthropogenic sources? What is the relative contribution of air emissions from UOGD to local and regional concentrations?</td>
</tr>
</tbody>
</table>

**Background.** UOGD emissions are released into an already complex mixture of compounds in the atmosphere, and many of the UOGD compounds are also released from other natural and anthropogenic sources. Secondary pollutants impacted by UOGD emissions are also formed from other sources, with which UOGD emissions may also interact. A number of methods have been applied to help tease out the contribution of UOGD operations on atmospheric concentrations, though their application has been limited (see Section 4.2.2.3 for a discussion on the strengths and limitations of these methods). UOGD exposure analyses will depend upon differentiating among the sources affecting air quality.

**Research Goals and Examples of Research Activities:** The goals of research related to these questions would include the development of new methods to quantify the fraction of chemical concentrations in air that come from UOGD operations versus other sources (both natural and anthropogenic), application of one or more methods to atmospheric observations to quantify the contributions of UOGD emissions on concentrations at various temporal scales, and characterizing the uncertainty in various methods.

If successful, such research would provide one or more approaches that could be used to relate atmospheric observations and knowledge of emissions to local to regional-scale concentrations of chemicals in air on a compound-by-compound basis. Preferably, the methods would further provide information on the impact of individual UOGD processes and activities on chemical species concentrations. The methods may use or be applied to longer-term, routine observations to provide historical contributions of UOGD operations on local and regional air quality.
### Topic: Release Mechanisms and Transport Pathways for Water

### Question:
4b. How can levels of UOGD agents in water be distinguished from levels contributed by other natural and anthropogenic sources? What is the relative contribution of water releases from UOGD to local and regional concentrations?

**Background:** Chemical agents that potentially can be released from UOGD activities can also be associated with a host of other activities, including legacy conventional oil and gas development, coal mining, industrial operations, and traffic. The inability to definitively attribute measured contaminants in groundwater and surface water to UOGD specifically has led to controversy about impact assessment. For example, determining whether methane detected in groundwater wells is due to UOGD activities, to legacy oil or coal development, or to natural seepage is a difficult problem (Vidic et al. 2013). The confounded issue of attribution of measured chemicals in natural waters in UOGD areas is one reason why the importance of securing water samples prior to UOGD has been stressed (HEI Special Scientific Committee on Unconventional Oil and Gas Development in the Appalachian Basin 2015).

**Research Goal and Examples of Research Activities:** The goal of the research would be to employ existing techniques, and to develop new techniques as necessary, to identify UOGD sources of contamination as part of an exposure study related to groundwater and surface water exposure pathways. New sensor technologies may be applicable to gain needed temporal resolution of changes in groundwater chemical composition as well as to gather pertinent baseline information (Son et al. 2018). A variety of tracers, particularly stable isotopes, have been indicated as useful to identify gases, brines, and flowback fluids from hydraulic fracturing, for example (Dorman et al. 2018; Warner et al. 2014). In some cases, it may be possible to inject unique tracers as part of the fracturing fluids and then to monitor natural groundwater and surface water for signs of contamination (Hammack et al. 2013). In all cases it is imperative that local geological controls that might allow preferential flow of fluids from deep unconventional source rocks be evaluated as part of any study to identify contamination resulting from UOGD activities (Talma et al. 2018; Woda et al. 2018).
5.1.3 Exposed Populations

**Topic:** Populations

**Question:** 5. What are the characteristics of populations potentially exposed to UOGD agents at local and regional scales?

**Background:** The majority of UOGD epidemiology studies have considered proximity-based metrics for assigning exposures, thus implicitly acknowledging the potential exposure impacts of living near UOGD. Little research is available describing the populations residing close to UOGD operations, nor the potential differences in population characteristics of those living near versus far from the operations (Ish et al. 2019; Konkel 2019). Some of the uncertainty about characteristics of populations relates to lack of knowledge about the full geographic extent of potential exposures. For example, over what area do UOGD emissions to air disperse and under what conditions and distances do they decline? Over what area are noise, light, and vibration perceived? Some investigators have attempted to answer these questions by studying chemical dispersion gradients at various distances to UOGD operations (e.g., Garcia-Gonzales et al. 2019)

Because of likely differences in infrastructure (e.g., rural vs. urban), housing (e.g., costs, quality, and type), and employment opportunities present in locations near and far from UOGD operations, these populations may also differ in susceptibility factors (e.g., age, co-exposures, underlying health conditions, and socioeconomic factors).

Together, the environmental contributions of UOGD releases and population characteristics that affect exposure and susceptibility from UOGD operations contribute to complex exposure pathways that are likely to result in differential UOGD health risk. In order to assess generalizability of epidemiologic results and better predict potential health outcomes, characterization of populations potentially exposed to UOGD agents is needed, including whether and how population characteristics vary at local to regional scales within and between shale play regions.

**Research Goal and Examples of Research Activities:** The goal of the research would be to characterize populations at local and regional scales with respect to UOGD operations. The research should be designed to provide an enhanced understanding of populations residing near UOGD operations and to assess and compare whether populations differ within and between shale play regions over time. The research should also characterize populations living further from UOGD operations (i.e., within regions anticipated to be impacted by UOGD releases) and to assess and compare how populations differ at local and regional scales within these regions. The research would require: (a) defining and justifying the local and regional scales of interest; (b) identifying and justifying population characterization metrics (e.g., targeting population exposure and susceptibility factors such as age, sex, race/ethnicity, income, and health status); and (c) determining data sources and quality (advantages and limitations) for these metrics. The research would likely rely on existing data sources (e.g., census-based sociodemographic data), supplemented with survey or other primary data collection to enhance population characterization. Ultimately, the data should be used to describe populations within and between shale play regions and to identify potential differences in population characteristics that could influence UOGD exposure and health risk at different scales. Community involvement in data collection may bring value to research design and data analysis, but it can also introduce potential bias associated with unblinded, self-report, and non-random sampling.
**Topic:** Populations

**Question:** 6. Which population behaviors (e.g., time–activity–location patterns) influence the potential for exposure to UOGD agents? Do exposures to UOGD agents differ among individuals within and among exposed populations?

**Background:** People living in communities near UOGD or in areas impacted by regional effects of UOGD may be exposed to a variety of UOGD-related chemical and non-chemical agents and possibly by more than one exposure pathway. Addressing an individual’s total exposure is a vitally important component of health risk assessment and exposure research. To fully understand the potential for these stressors to adversely impact health, characterization of these exposures must be undertaken. In addition to data on chemical concentrations in various media, exposure assessment includes information on frequency and duration of exposures to chemicals in different media. Limited information has been incorporated into past studies of exposure–outcome associations.

**Research Goal and Examples of Research Activities:** The goal of research would be to characterize individual and population behaviors that influence frequency and duration of exposure. In addition, researchers would assess the degree to which those behaviors are unique to a given geographic area so that an understanding of the generalizability of the research results can be obtained. Future assessments should consider temporal, spatial, and individual variability. For example, individuals may spend more time outdoors in warm weather months, which would affect temporal variability and activity patterns (which can, for example, influence breathing rates and dermal exposures). Spatial variability considerations may include regional differences in population behaviors that can affect UOGD-related exposures (e.g., differences in outdoor recreational activities by region). Finally, it should be expected that individual day-to-day behaviors will vary. Methods for capturing these differences will be necessary to fully understand exposures.
<table>
<thead>
<tr>
<th>Topic:</th>
<th>Populations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Question:</td>
<td>7. How can exposure monitoring methods (e.g., study design, instrumentation, other technologies, and analytical methods) accurately characterize total personal and population-wide exposures to UOGD over time and space?</td>
</tr>
</tbody>
</table>

**Background:** Whether health effects occur depends on an individual’s total exposure by way of all exposure pathways. The exposure of an individual or a population can be assessed by estimating *external* exposure (e.g., mapping distances to sources, defining job exposure categories, or measuring chemical concentrations in environmental media) or estimating *internal* doses (through biomonitoring).

Assessing external exposure requires information on both media concentrations of chemicals of interest and on factors influencing the concentrations. Much of the exposure literature to date provides information on chemical concentrations in environmental media, but not in combination of factors influencing intake of those chemicals (e.g., breathing rate, soil or water ingestion rate, and dermal exposure area) specific to the potentially exposed populations.

**Research Goal and Examples of Research Activities:** The goal of research would be to determine sufficient time–activity information such that, combined with concentration data, personal exposures to UOGD-related stressors can be estimated. Combinations of technologies can provide paired data on both chemical concentrations and time–activity information to aid in better understanding total exposure. For example, personal air monitors combined with wearables that allow for collection of activity data may provide a better understanding of an individual’s total exposure. Web-based instruments can also be considered assuming that these do not exclude segments of the population(s) of interest. In general, researchers should be open to using a combination of monitoring technologies (including novel ones) while keeping in mind the importance of using methods that have been demonstrated to provide accurate data.

Researchers should consider incorporating both established and innovative approaches. In addition, the research results should shed light on the degree to which the information is generalizable to populations outside of the study population. Research activities should consider different types of populations (e.g., age, gender, race, and susceptible populations) and include validation of proposed approaches and assessments of error in the estimates of exposure. Further, a range of approaches to collecting data may be considered including scientist-based data collection and citizen science approaches.
5.2 **ANTICIPATED ATTRIBUTES OF RESEARCH**

The Research Committee will prepare a Research Solicitation requesting proposals for population-level exposure studies in key representative locations.

5.2.1 **Scope of Exposure Studies**

In defining the scope of research, the Committee recognizes the value of a better understanding of air and water-related exposures, achieved with comprehensive, high-quality research that characterizes the range of exposure conditions across regions of the United States. Non-chemical agents of concern include noise and light. Methane is not believed to be toxic to humans at levels typically associated with UOGD unless, of course, they rise to the level of a safety hazard. Therefore, methane is not expected to be a focus of human exposure research except to the extent that it might function as a tracer of UOGD releases to the environment. In general, research needs to advance the understanding of UOGD agents, the mechanisms by which human exposures to them might arise, and be generalizable to different sets of regional conditions, operational practices, and population characteristics.

5.2.2 **Study Quality and Scientific Value**

The Committee is charged with overseeing selection and implementation of all research and ensuring its quality and utility. In preparing its Research Solicitation and reviewing proposals submitted in response, the Committee seeks research that possesses the characteristics in Table 5-2. The characteristics will be used to make a qualitative rather than quantitative assessment of research topics and proposals.

As reflected in Table 5-2, Committee members will prioritize research that recognizes practical considerations such as efficiency and utility for decision-making and planning.

In its Research Solicitation, the Committee will specify that several key components are required for a research program to be selected, including study of agents of potential concern for health, relevant geographic areas, necessary technical and community engagement expertise on the investigator team, a detailed quality assurance project plan, and an a priori study interpretation and communication plan, among other general components of a high-quality study.

5.3 **LOOKING AHEAD TO HEI-ENERGY’S RESEARCH SOLICITATION**

The Committee will prepare a Research Solicitation for population-level research based on its review of the literature, input provided during the two public workshops, and comments received on the draft version of this report.

5.3.1 **Expected Utility of Research**

With UOGD projected to continue, HEI-Energy’s research program is designed to be the source of high-quality, impartial science needed to support decisions about how best to ensure protection of public health in the oversight and implementation of this development. The overarching goal of the Program is to identify the spatial and temporal range of human exposures arising from UOGD operations across the United States, the conditions under which they occur, and the likelihood of occurrence.
Table 5-2. Characteristics of appropriate research identified by HEI-Energy Research Committee (in alphabetical order within each section)

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Overarching Characteristics</strong></td>
<td></td>
</tr>
</tbody>
</table>
| Advances the science                         | **Addresses the most important potential exposures for human health.** The exposures under investigation are relevant to large populations or the severity of their effects are likely to be large. The severity of an effect is a function of the frequency, duration, and magnitude of exposure to an agent as well as the hazardous properties of the agent.  
  **Contributes broadly relevant information.** Results will be broadly generalizable across geographic regions, UOGD operating conditions, or populations over time, including periods of low and high UOGD activity. |
| Brings value to affected communities          | **Engages communities and stakeholders.** A clear stakeholder engagement plan is conveyed that ensures effective communication throughout the research program and identification of information that is important to communities affected by UOGD.                                                                                       |
| Informs decision-making                      | **Communicates results.** Investigators will formulate an a priori study interpretation plan that can be effectively communicated to decision-makers.  
  **Focuses on realistic human exposures.** A focus on populations that are or could reasonably be expected to be exposed under current or future conditions, distinguishing among UOGD operational, accidental, and unauthorized sources of potential exposure.  
  **Includes a Study Interpretation Plan.** This plan specifies how findings will be interpreted and communicated, especially for potentially exposed community members and for making decisions about the utility of future exposure or health research. |
| Provides high quality information             | **Gathers highly qualified team.** The team possesses the full range of expertise and independence to conduct the exposure research along with expertise about the UOGD operations under study. An ideal team will design a study involving collaboration across multiple sectors (i.e., academic scientists, communities, regulators, public health agencies, industry, and nongovernmental organizations). The team must have access to facilities and equipment needed to support research (e.g., study sites and relevant data sets). With research planned for multiple regions, the team must demonstrate an ability to coordinate research efficiently and consistently among study sites.  
  **Provides high quality technical proposal.** Quality of the proposed study design, approaches, methodology, analytic methods, statistical procedures, and plan for quality assurance in all aspects of the research. |
| Produces results cost-effectively             | **Makes maximum use of existing data.** Will collect only the data needed to complement and build on past research and other sources of data, and take other steps to maximize efficiency (e.g., minimizing laboratory analytical costs through careful study design).  
  **Presents reasonable cost proposal.** The proposed costs must be reasonable, and the requested funds appropriately allocated. |
| **Methodological Considerations**            |                                                                                                                                                                                                                                                                                                                                           |
| Covers a complete exposure pathway            | **Links one or more chemical or non-chemical agents released from a UOGD source to a potentially exposed population.** The study is designed to distinguish between agents released from UOGD and non-UOGD sources, and to connect releases of the agent(s) from a specific UOGD source to a potentially exposed population.                                                                                     |
| Identifies UOGD sources                       | **Isolates specific UOGD sources of potential exposure.** The research allows for the detection of possible causal links between one or more aspects of UOGD operations (e.g., specific equipment, activity, or phase of development) and resulting exposures. In addition, investigators will collect data (e.g., operator time–activity data) to identify the conditions that gave rise to the results, nothing whether exposure is the result of operational, accidental, or unauthorized releases. |
| Methods and results support future health research | **Collects data (or establishes practical exposure assessment methodologies) for use in a future epidemiology studies or human health risk assessment.** Will collect information at resolutions relevant for application in an epidemiology study or risk assessment.                                                                                                           |
5.3.2 The Model for Providing Impartial Science

The new research program is modeled after HEI’s existing successful model for providing high quality, impartial scientific information about air quality (Figure 5-1). Key components include:

- **Independent governance** of the research program with leadership by an independent board of directors not affiliated with sponsors

- **Balanced funding** from the oil and gas industry, governmental agencies, and foundations

- **High-quality science** with research oversight by the Energy Research Committee, which consists of knowledgeable scientists that have been vetted for bias and conflict of interest

- **Extensive peer review** of science by an Energy Review Committee, which works independently of the Energy Research Committee to provide peer review and commentary on research

- **Open and extensive engagement** with stakeholders, including local community members and officials in study locations

- **Communication** of all results, including both positive and negative findings, in the context of other relevant research

- **Provides impartial science** for better informed decisions without advocating policy positions

**Figure 5-1.** Overview of HEI-Energy model for providing impartial scientific research, which is selected, implemented, and reviewed independently of the program’s sponsors.

5.3.3 Assessment of Research Solicitation Applications

The Research Solicitations will be distributed widely among the scientific community. HEI-Energy will be seeking multi-disciplinary teams with the skill and capacity to mobilize exposure studies at locations across the major regions of the country. Applications will be evaluated and scored by External Review Panels specifically identified as having relevant expertise. The Research Committee will then evaluate the proposals with consideration of the External Review Panels’ evaluation and scores and the characteristics listed in Table 5-2 to determine whether the proposed research will (1) improve the understanding of the specific problem under investigation, (2) contribute to HEI-Energy’s overall research program, keeping in mind available resources, and (3) advance the goal of building a coordinated program of related studies designed to answer key questions, and not just completing a collection of independent studies. The Research Committee makes final recommendations regarding funding of studies to the HEI-Energy Board, which makes the final funding decision.

Before research begins, HEI-Energy will negotiate detailed contractual agreements with the research team and, as needed, with owners of facilities, operations, or equipment where some of the research may take place. The agreements will address a number of questions, including data quality assessment, management of confidential business information, data access and dissemination, stakeholder engagement planning, cost management, insurance requirements, and other factors important for successful implementation of research.
Throughout the selection, implementation, and review of research projects, HEI-Energy and the Research Committee provide oversight to ensure its quality and effective communication with stakeholders about research progress. HEI-Energy regards effective communication as equally important to the research.

HEI-Energy expects to release the Research Solicitation in late 2019, with research beginning in multiple oil and gas-producing regions in 2020. HEI-Energy will fund research that informs policy decisions about how best to protect public health in the oversight of UOGD. HEI-Energy expects that results will be used by federal, state, and local regulators, communities, the oil and natural gas industry, environmental organizations, public health experts, and other stakeholders to inform policy development in this important area.
6.0 REFERENCES


Collett JL, Ham J. 2016. Characterizing Emissions from Natural Gas Drilling and Well Completion Operations in Garfield County, CO.


Colorado Department of Public Health and Environment. 2017c. Screening Level Health Risk Evaluation from Inhalation of VOCs in Ambient Air in Response to Health Concerns Related to Triple Creek Oil and Gas Site. Denver, Colorado:Colorado Department of Public Health & Environment.


Czolowski ED, Santoro RL, Srebotnjak T, Shonkoff SBC. 2017. Toward Consistent Methodology to Quantify Populations in Proximity to Oil and Gas Development: A National Spatial Analysis and Review. Env Health Perspect 125:086004; doi:10.1289/ehp1535.


Gradient Corporation. 2019. Public Health Evaluation of Ambient Air Near a Shale Gas Well Site and School Campus: Results from Long-term Air Monitoring at the Yonker Well Site Nearby the Fort Cherry School Campus in Washington County, PA. Cambridge, MA:Gradient Corp.


Pennsylvania Department of Environmental Protection. 2010. Southwestern Pennsylvania Marcellus Shale Short-Term Ambient Air Sampling Report.


Rich AL, Orimoloye HT. 2016. Elevated atmospheric levels of benzene and benzene-related compounds from unconventional shale extraction and processing: human health concern for residential communities. Env Health Insights 10:75–82; doi:10.4137/EHI.S33314.


Texas Department of State Health Services. 2010. DISH, Texas Exposure Investigation: DISH, Denton County, Texas.


Materials Available on the HEI-Energy Website

Appendices A through C contain supplemental material and are available separately at www.hei-energy.org.

Appendix A: Research Priorities and Study Design Elements Recommended by Workshop Participants
Appendix B: Glossary
Appendix C: Biographies of the Energy Research Committee Members
HEI-ENERGY BOARD, RESEARCH COMMITTEE, AND STAFF

HEI-ENERGY BOARD OF DIRECTORS

Jared L. Cohon, Chair, President Emeritus and Professor, Civil and Environmental Engineering and Engineering and Public Policy, Carnegie Mellon University

Enriqueta Bond, President Emerita, Burroughs Wellcome Fund

Michael T. Clegg, Professor of Biological Sciences, University of California, Irvine

HEI-ENERGY RESEARCH COMMITTEE

HEI-Energy convened the Energy Research Committee to conduct scientific reviews and oversee original research funded by HEI-Energy. The Committee is chaired by George M. Hornberger, Distinguished Professor of Civil and Environmental Engineering and of Earth and Environmental Science at Vanderbilt University and director of the Vanderbilt Institute for Energy and the Environment. Committee members are highly regarded experts in a variety of disciplines directly related to unconventional oil and natural gas development and its potential impacts. Special advisors and consultants contribute additional areas of expertise.

George M. Hornberger, Chair, Director, Vanderbilt Institute for Energy & Environment

Judy S. LaKind, President, LaKind Associates, LLC, and Adjunct Associate Professor, Department of Epidemiology and Public Health, University of Maryland School of Medicine

Shari Dunn-Norman, Associate Professor, Missouri University of Science and Technology

Armistead (Ted) G. Russell, Howard T. Tellepsen Chair and Regents Professor of Civil and Environmental Engineering, Georgia Tech

Elaine M. Faustman, Professor and Director of the Institute of Risk Analysis and Risk Communication, School of Public Health, University of Washington

Stefanie Ebelt Sarnat, Associate Professor, Emory University

(Resigned from the committee on November 27, 2018.)

Howard Hu, Professor, School of Public Health, University of Washington and School of Public Health, University of Michigan

OFFICERS AND STAFF

Robert M. O’Keefe, President

Daniel S. Greenbaum, President

Donna J. Vorhees, Vice President and CEO

Rashid Shaikh, Director of Science

Jaqueline C. Rutledge, Treasurer

Annemoon van Erp, Managing Scientist

Emily Alden, Corporate Secretary

Hilary Selby Polk, Managing Editor

Anna Rosofsky, Staff Scientist

Mary K. Brennan, Consulting Editor

Kathryln Liziewski, Research Assistant

Kethural Manokaran, Research Assistant

Lee Ann Adelsheim, Research Assistant

Zachary D. Abbott, Research Assistant

Joanna Keel, Research Assistant

ADDITIONAL ASSISTANCE FROM HEI STAFF

ADDENDUM TO HEI ENERGY RESEARCH COMMITTEE CHARTER