

1 **Human Health Risk Assessment of Air Emissions from Development of Unconventional**  
2 **Natural Gas Resources**

3 **Lisa M. McKenzie<sup>a</sup>, Roxana Z. Witter<sup>a</sup>, Lee S. Newman<sup>a</sup>, John L. Adgate<sup>a</sup>**

4 <sup>a</sup>Colorado School of Public Health, University of Colorado – Anschutz Medical Campus,  
5 Aurora, Colorado, USA

6 Address correspondence to L. McKenzie, Colorado School of Public Health, 13001 East 17<sup>th</sup>  
7 Place, Mail Stop B119, Aurora, CO 80045 USA. Telephone: (303) 724-5557. Fax: (303) 724-  
8 4617. [lisa.mckenzie@ucdenver.edu](mailto:lisa.mckenzie@ucdenver.edu).

9

10 **Abstract**

11 **Background:** Technological advances (e.g. directional drilling, hydraulic fracturing), have led  
12 to increases in unconventional natural gas development (NGD), raising questions about health  
13 impacts.

14 **Objectives:** We estimated health risks for exposures to air emissions from a NGD project in  
15 Garfield County, Colorado with the objective of supporting risk prevention recommendations in  
16 a health impact assessment (HIA).

17 **Methods:** We used EPA guidance to estimate chronic and subchronic non-cancer hazard indices  
18 and cancer risks from exposure to hydrocarbons for two populations: (1) residents living  $> \frac{1}{2}$   
19 mile from wells and (2) residents living  $\leq \frac{1}{2}$  mile from wells.

20 **Results:** Residents living  $\leq \frac{1}{2}$  mile from wells are at greater risk for health effects from NGD  
21 than are residents living  $> \frac{1}{2}$  mile from wells. Subchronic exposures to air pollutants during well  
22 completion activities present the greatest potential for health effects. The subchronic non-cancer  
23 hazard index (HI) of 5 for residents  $\leq \frac{1}{2}$  mile from wells was driven primarily by exposure to  
24 trimethylbenzenes, xylenes, and aliphatic hydrocarbons. Chronic HIs were 1 and 0.4. for  
25 residents  $\leq \frac{1}{2}$  mile from wells and  $> \frac{1}{2}$  mile from wells, respectively. Cumulative cancer risks  
26 were 10 in a million and 6 in a million for residents living  $\leq \frac{1}{2}$  mile and  $> \frac{1}{2}$  mile from wells,  
27 respectively, with benzene as the major contributor to the risk.

28 **Conclusions:** Risk assessment can be used in HIAs to direct health risk prevention strategies.  
29 Risk management approaches should focus on reducing exposures to emissions during well  
30 completions. These preliminary results indicate that health effects resulting from air emissions  
31 during unconventional NGD warrant further study. Prospective studies should focus on health  
32 effects associated with air pollution.

33

34 **Key Words:** natural gas development; risk assessment; air pollution; hydrocarbon emissions

- 35 This study was supported by the Garfield County Board of County Commissioners and the
- 36 Colorado School of Public Health.
- 37 The authors declare they have no competing financial interests.

## 38 **Abbreviations<sup>1</sup>**

### 39 **1.0 Introduction**

40           The United States (US) holds large reserves of unconventional natural gas resources in  
41 coalbeds, shale, and tight sands. Technological advances, such as directional drilling and  
42 hydraulic fracturing, have led to a rapid increase in the development of these resources. For  
43 example, shale gas production had an average annual growth rate of 48 percent over the 2006 to  
44 2010 period and is projected to grow almost fourfold from 2009 to 2035 (US EIA 2011). The  
45 number of unconventional natural gas wells in the US rose from 18,485 in 2004 to 25,145 in  
46 2007 and is expected to continue increasing through at least 2020 (Vidas and Hugman 2008).  
47 With this expansion, it is becoming increasingly common for unconventional natural gas  
48 development (NGD) to occur near where people live, work, and play. People living near these  
49 development sites are raising public health concerns, as rapid NGD exposes more people to  
50 various potential stressors (COGCC 2009a).

51           The process of unconventional NGD is typically divided into two phases: well  
52 development and production (EPA 2010a, US DOE 2009). Well development involves pad  
53 preparation, well drilling, and well completion. The well completion process has three primary  
54 stages: 1) completion transitions (concrete well plugs are installed in wells to separate fracturing  
55 stages and then drilled out to release gas for production); 2) hydraulic fracturing (“fracking”: the  
56 high pressure injection of water, chemicals, and propants into the drilled well to release the

---

<sup>1</sup> BTEX, benzene, toluene, ethylbenzene, and xylenes; COGCC, Colorado Oil and Gas Conservation Commission; HAP, hazardous air pollutant; HI, hazard index; HIA, health impact assessment; HQ, hazard quotient; NATA, National Air Toxics Assessment; NGD, natural gas development

57 natural gas); and 3) flowback, the return of fracking and geologic fluids, liquid hydrocarbons  
58 (“condensate”) and natural gas to the surface (EPA 2010a, US DOE 2009). Once development  
59 is complete, the “salable” gas is collected, processed, and distributed. While methane is the  
60 primary constituent of natural gas, it contains many other chemicals, including alkanes, benzene,  
61 and other aromatic hydrocarbons (TERC 2009).

62 As shown by ambient air studies in Colorado, Texas, and Wyoming, the NGD process  
63 results in direct and fugitive air emissions of a complex mixture of pollutants from the natural  
64 gas resource itself as well as diesel engines, tanks containing produced water, and on site  
65 materials used in production, such as drilling muds and fracking fluids (CDPHE 2009; Frazier  
66 2009; Walther 2011; Zielinska et al. 2011). The specific contribution of each of these potential  
67 NGD sources has yet to be ascertained and pollutants such as petroleum hydrocarbons are likely  
68 to be emitted from several of these NGD sources. This complex mixture of chemicals and  
69 resultant secondary air pollutants, such as ozone, can be transported to nearby residences and  
70 population centers (Walther 2011, GCPH 2010).

71 Multiple studies on inhalation exposure to petroleum hydrocarbons in occupational  
72 settings as well as residences near refineries, oil spills and petrol stations indicate an increased  
73 risk of eye irritation and headaches, asthma symptoms, acute childhood leukemia, acute  
74 myelogenous leukemia, and multiple myeloma (Glass et al. 2003; Kirkeleit et al. 2008; Brosselin  
75 et al. 2009; Kim et al. 2009; White et al. 2009). Many of the petroleum hydrocarbons observed  
76 in these studies are present in and around NGD sites (TERC 2009). Some, such as benzene,  
77 ethylbenzene, toluene, and xylene (BTEX) have robust exposure and toxicity knowledge bases,  
78 while toxicity information for others, such as heptane, octane, and diethylbenzene, is more  
79 limited. Assessments in Colorado have concluded that ambient benzene levels demonstrate an

80 increased potential risk of developing cancer as well as chronic and acute non-cancer health  
81 effects in areas of Garfield County Colorado where NGD is the only major industry other than  
82 agriculture (CDPHE 2007; Coons and Walker 2008; CDPHE 2010). Health effects associated  
83 with benzene include acute and chronic nonlymphocytic leukemia, acute myeloid leukemia,  
84 chronic lymphocytic leukemia, anemia, and other blood disorders and immunological effects.  
85 (ATSDR 2007, IRIS 2010). In addition, maternal exposure to ambient levels of benzene recently  
86 has been associated with an increase in birth prevalence of neural tube defects (Lupo 2010).  
87 Health effects of xylene exposure include eye, nose, and throat irritation, difficulty in breathing,  
88 impaired lung function, and nervous system impairment ( ATSDR 2007b). In addition,  
89 inhalation of xylenes, benzene, and alkanes can adversely affect the nervous system (Carpenter  
90 et al. 1978; Nilsen et al. 1988; Galvin et al. 1999; ATSDR 2007a; ATSDR 2007b).

91 Previous assessments are limited in that they were not able to distinguish between risks  
92 from ambient air pollution and specific NGD stages, such as well completions or risks between  
93 residents living near wells and residents living further from wells. We were able to isolate risks  
94 to residents living near wells during the flowback stage of well completions by using air quality  
95 data collected at the perimeter of the wells while flowback was occurring.

96 Battlement Mesa (population ~ 5,000) located in rural Garfield County, Colorado is one  
97 community experiencing the rapid expansion of NGD in an unconventional tight sand resource.  
98 A NGD operator has proposed developing 200 gas wells on 9 well pads located as close as 500  
99 feet from residences. Colorado Oil and Gas Commission (COGCC) rules allow natural gas wells  
100 to be placed as close as 150 feet from residences (COGCC 2009b). Because of community  
101 concerns, as described elsewhere, we conducted a health impact assessment (HIA) to assess how

102 the project may impact public health (Witter et al. 2011), working with a range of stakeholders to  
103 identify the potential public health risks and benefits.

104 In this article, we illustrate how a risk assessment was used to support elements of the  
105 HIA process and inform risk prevention recommendations by estimating chronic and subchronic  
106 non-cancer hazard indices (HIs) and lifetime excess cancer risks due to NGD air emissions.

## 107 **2.0 Methods**

108 We used standard United States Environmental Protection Agency (EPA) methodology to  
109 estimate non-cancer HIs and excess lifetime cancer risks for exposures to hydrocarbons (US  
110 EPA 1989, US EPA 2004) using residential exposure scenarios developed for the NGD project.  
111 We used air toxics data collected in Garfield County from January 2008 to November 2010 as  
112 part of a special study of short term exposures as well as on-going ambient air monitoring  
113 program data to estimate subchronic and chronic exposures and health risks (Frazier 2009,  
114 GCPH 2009, GCPH 2010, GCPH 2011, Antero 2010).

### 115 ***2.1 Sample collection and analysis:***

116 All samples were collected and analyzed according to published EPA methods. Analyses  
117 were conducted by EPA certified laboratories. The Garfield County Department of Public  
118 Health (GCPH) and Olsson Associates, Inc. (Olsson) collected ambient air samples into  
119 evacuated SUMMA® passivated stainless-steel canisters over 24-hour intervals. The GCPH  
120 collected the samples from a fixed monitoring station and along the perimeters of four well pads  
121 and shipped samples to Eastern Research Group for analysis of 78 hydrocarbons using EPA's  
122 compendium method TO-12, Method for the Determination of Non-Methane Organic  
123 Compounds in Ambient Air Using Cryogenic Preconcentration and Direct Flame Ionization  
124 Detection (US EPA 1999). Olsson collected samples along the perimeter of one well pad and



125 shipped samples to Atmospheric Analysis and Consulting, Inc. for analysis of 56 hydrocarbons  
126 (a subset of the 78 hydrocarbons determined by Eastern Research Group) using method TO-12.  
127 Per method TO-12, a fixed volume of sample was cryogenically concentrated and then desorbed  
128 onto a gas chromatography column equipped with a flame ionization detector. Chemicals were  
129 identified by retention time and reported in a concentration of parts per billion carbon (ppbC).  
130 The ppbC values were converted to micrograms per cubic meter ( $\mu\text{g}/\text{m}^3$ ) at 01.325 kilo Pascals  
131 and 298.15 Kelvin.

132 Two different sets of samples were collected from rural ( population < 50,000) areas in  
133 western Garfield County over varying time periods. The main economy, aside from the NGD  
134 industry, of western Garfield County is agricultural. There is no other major industry.

#### 135 *2.1.1 NGD Area Samples*

136 The GCPH collected ambient air samples every six days between January 2008 and  
137 November 2010 (163 samples) from a fixed monitoring station located in the midst of rural home  
138 sites and ranches and NGD, during both the well development and production. The site is  
139 located on top of a small hill and 4 miles upwind of other potential emission sources, such as a  
140 major highway (Interstate-70) and the town of Silt, CO (GCPH 2009, GCPH 2010, GCPH 2011).

#### 141 *2.1.2 Well Completion Samples*

142 The GCPH collected 16 ambient air samples at each cardinal direction along 4well pad  
143 perimeters (130 to 500 feet from the well pad center) in rural Garfield County during well  
144 completion activities. The samples were collected on the perimeter of 4 well pads being  
145 developed by 4 different natural gas operators in summer 2008 (Frazier 2009). The GCPH  
146 worked closely with the NGD operators to ensure these air samples were collected during the  
147 period while at least one well was on uncontrolled (emissions not controlled) flowback into

148 collection tanks vented directly to the air. The number of wells on each pad and other activities  
149 occurring on the pad were not documented. Samples were collected over 24 to 27-hour intervals,  
150 and samples included emissions from both uncontrolled flowback and diesel engines (i.e., from  
151 trucks and generators supporting completion activities). In addition, the GCPH collected a  
152 background sample 0.33 to 1 mile from each well pad (Frazier 2009). The highest  
153 hydrocarbon levels corresponded to samples collected directly downwind of the tanks (Frazier  
154 2009, Antero 2010). The lowest hydrocarbon levels corresponded either to background samples  
155 or samples collected upwind of the flowback tanks (Frazier 2009, Antero 2010).

156 Antero Resources Inc., a natural gas operator, contracted Olsson to collect eight 24-hour  
157 integrated ambient air samples at each cardinal direction at 350 and 500 feet from the well pad  
158 center during well completion activities conducted on one of their well pads in summer 2010  
159 (Antero 2010). Of the 12 wells on this pad, 8 were producing salable natural gas; 1 had been  
160 drilled but not completed; 2 were being hydraulically fractured during daytime hours, with  
161 ensuing uncontrolled flowback during nighttime hours; and 1 was on uncontrolled flowback  
162 during nighttime hours.

163 All five well pads are located in areas with active gas production, approximately one mile  
164 from Interstate-70.

## 165 ***2.2 Data assessment***

166 We evaluated outliers and compared distributions of chemical concentrations from NGD  
167 area and well completion samples using Q-Q plots and the Mann-Whitney U test, respectively, in  
168 EPA's ProUCL version 4.00.05 software (US EPA 2010b). The Mann-Whitney U test was used  
169 because the measurement data were not normally distributed. Distributions were considered as  
170 significantly different at an alpha of 0.05. Per EPA guidance, we assigned the exposure

171 concentration as either the 95 percent upper confidence limit (UCL) of the mean concentration  
172 for compounds found in 10 or more samples or the maximum detected concentration for  
173 compounds found in more than 1 but fewer than 10 samples. This latter category included three  
174 compounds: 1,3-butadiene, 2,2,4-trimethylpentane, and styrene in the well completion samples.  
175 EPA's ProUCL software was used to select appropriate methods based on sample distributions  
176 and detection frequency for computing 95 percent UCLs of the mean concentration (US EPA  
177 2010b).

### 178 ***2.3 Exposure assessment***

179 Risks were estimated for two populations: (1) residents  $> \frac{1}{2}$  mile from wells; and (2)  
180 residents  $\leq \frac{1}{2}$  mile from wells. We defined residents  $\leq \frac{1}{2}$  mile from wells as living near wells,  
181 based on residents reporting odor complaints attributed to gas wells in the summer of 2010  
182 (COGCC 2011).

183 Exposure scenarios were developed for chronic non-cancer HIs and cancer risks. For  
184 both populations, we assumed a 30-year project duration based on an estimated 5-year well  
185 development period for all well pads, followed by 20 to 30 years of production. We assumed a  
186 resident lives, works, and otherwise remains within the town 24 hours/day, 350 days/year and  
187 that lifetime of a resident is 70 years, based on standard EPA reasonable maximum exposure  
188 (RME) defaults (US EPA 1989).

#### 189 ***2.3.1 Residents $> \frac{1}{2}$ mile from well pads***

190 As illustrated in Figure 1, data from the NGD area samples were used to estimate chronic  
191 and subchronic risks for residents  $> \frac{1}{2}$  mile from well development and production throughout  
192 the project. The exposure concentrations for this population were the 95 percent UCL on the  
193 mean concentration and median concentration from the 163 NGD samples.

194 **2.3.2 Residents  $\leq$  1/2 mile from well pads**

195 To evaluate subchronic non-cancer HIs from well completion emissions, we estimated  
196 that a resident lives  $\leq$  1/2 mile from two well pads resulting a 20- month exposure duration based  
197 on 2 weeks per well for completion and 20 wells per pad, assuming some overlap between  
198 activities. The subchronic exposure concentrations for this population were the 95 percent UCL  
199 on the mean concentration and the median concentration from the 24 well completion samples.  
200 To evaluate chronic risks to residents  $\leq$  1/2 mile from wells throughout the NGD project, we  
201 calculated a time-weighted exposure concentration ( $C_{S+c}$ ) to account for exposure to emissions  
202 from well completions for 20-months followed by 340 months of exposure to emissions from the  
203 NGD area using the following formula:

204 
$$C_{S+c} = (C_c \times ED_c/ED) + (C_S \times ED_S /ED)$$

205  
206 where:

207  
208  $C_c$  = Chronic exposure point concentration ( $\mu\text{g}/\text{m}^3$ ) based on the 95 percent UCL of the  
209 mean concentration or median concentration from the 163 NGD area samples

210  $ED_c$  = Chronic exposure duration

211  $C_S$  = Subchronic exposure point concentration ( $\mu\text{g}/\text{m}^3$ ) based on the 95 percent UCL of  
212 the mean concentration or median concentration from the 24 well completion samples

213  $ED_S$  = Subchronic exposure duration

214  $ED$  = Total exposure duration

215 **2.4 Toxicity assessment and risk characterization**

216 For non-carcinogens, we expressed inhalation toxicity measurements as a reference  
217 concentration (RfC in units of  $\mu\text{g}/\text{m}^3$  air). We used chronic RfCs to evaluate long-term exposures  
218 of 30 years and subchronic RfCs to evaluate subchronic exposures of 20-months. If a subchronic

219 RfC was not available, we used the chronic RfC. We obtained RfCs from (in order of preference)  
220 EPA's Integrated Risk Information System (IRIS) (U. S. EPA 2011), California Environmental  
221 Protection Agency (CalEPA) (CalEPA 2003), EPA's Provisional Peer-Reviewed Toxicity  
222 Values (ORNL 2009), and Health Effects Assessment Summary Tables (U.S. EPA 1997). We  
223 used surrogate RfCs according to EPA guidance for C<sub>5</sub> to C<sub>18</sub> aliphatic and C<sub>6</sub> to C<sub>18</sub> aromatic  
224 hydrocarbons which did not have a chemical-specific toxicity value (U.S. EPA 2009a). We  
225 derived semi-quantitative hazards, in terms of the hazard quotient (HQ), defined as the ratio  
226 between an estimated exposure concentration and RfC. We summed HQs for individual  
227 compounds to estimate the total cumulative HI. We then separated HQs specific to neurological,  
228 respiratory, hematological, and developmental effects and calculated a cumulative HI for each of  
229 these specific effects.

230 For carcinogens, we expressed inhalation toxicity measurements as inhalation unit risk  
231 (IUR) in units of risk per  $\mu\text{g}/\text{m}^3$ . We used IURs from EPA's IRIS (US EPA 2011) when  
232 available or the CalEPA (CalEPA 2003). The lifetime cancer risk for each compound was  
233 derived by multiplying estimated exposure concentration by the IUR. We summed cancer risks  
234 for individual compounds to estimate the cumulative cancer risk. Risks are expressed as excess  
235 cancers per 1 million population based on exposure over 30 years.

236 Toxicity values (i.e., RfCs or IURs) or a surrogate toxicity value were available for 45  
237 out of 78 hydrocarbons measured. We performed a quantitative risk assessment for these  
238 hydrocarbons. The remaining 33 hydrocarbons were considered qualitatively in the risk  
239 assessment.

## 240 **3.0 Results**

### 241 ***3.1 Data assessment***

242 Evaluation of potential outliers revealed no sampling, analytical, or other anomalies were  
243 associated with the outliers. In addition, removal of potential outliers from the NGD area  
244 samples did not change the final HIs and cancer risks. Potential outliers in the well completion  
245 samples were associated with samples collected downwind from flowback tanks and are  
246 representative of emissions during flowback. Therefore, no data was removed from either data  
247 set.

248 Descriptive statistics for concentrations of the hydrocarbons used in the quantitative risk  
249 assessment are presented in Table 1. A list of the hydrocarbons detected in the samples that were  
250 considered qualitatively in the risk assessment because toxicity values were not available is  
251 presented in Table 2. Descriptive statistics for all hydrocarbons are available in Supplemental  
252 Table 1. Two thirds more hydrocarbons were detected at a frequency of 100 percent in the well  
253 completion samples (38 hydrocarbons) than in the NGD area samples (23 hydrocarbons).  
254 Generally, the highest alkane and aromatic hydrocarbon median concentrations were observed in  
255 the well completion samples, while the highest median concentrations of several alkenes were  
256 observed in the NGD area samples. Median concentrations of benzene, ethylbenzene, toluene,  
257 and m-xylene/p-xylene were 2.7, 4.5, 4.3, and 9 times higher in the well completion samples  
258 than in the NGD area samples, respectively. Wilcoxon-Mann-Whitney test results indicate that  
259 concentrations of hydrocarbons from well completion samples were significantly higher than  
260 concentrations from NGD area samples ( $p < 0.05$ ) with the exception of 1,2,3-trimethylbenzene,  
261 n-pentane, 1,3-butadiene, isopropylbenzene, n-propylbenzene, propylene, and styrene  
262 (Supplemental Table 2).

### 263 ***3.2 Non-cancer hazard indices***

264 Table 3 presents chronic and subchronic RfCs used in calculating non-cancer HIs, as well  
265 critical effects and other effects. Chronic non-cancer HQ and HI estimates based on ambient air  
266 concentrations are presented in Table 4. The total chronic HIs based on the 95% UCL of the  
267 mean concentration were 0.4 for residents  $> \frac{1}{2}$  mile from wells and 1 for residents  $\leq \frac{1}{2}$  mile from  
268 wells. Most of the chronic non-cancer hazard is attributed to neurological effects with  
269 neurological HIs of 0.3 for residents  $> \frac{1}{2}$  mile from wells and 0.9 for residents  $\leq \frac{1}{2}$  mile from  
270 wells.

271 Total subchronic non-cancer HQs and HI estimates are presented in Table 5. The total  
272 subchronic HIs based on the 95% UCL of the mean concentration were 0.2 for residents  $> \frac{1}{2}$   
273 mile from wells and 5 for residents  $\leq \frac{1}{2}$  mile from wells. The subchronic non-cancer hazard for  
274 residents  $> \frac{1}{2}$  mile from wells is attributed mostly to respiratory effects (HI = 0.2), while the  
275 subchronic hazard for residents  $\leq \frac{1}{2}$  mile from wells is attributed to neurological (HI = 4),  
276 respiratory (HI = 2), hematologic (HI = 3), and developmental (HI = 1) effects.

277 For residents  $> \frac{1}{2}$  mile from wells, aliphatic hydrocarbons (51 percent),  
278 trimethylbenzenes (22 percent), and benzene (14 percent) are primary contributors to the chronic  
279 non-cancer HI. For residents  $\leq \frac{1}{2}$  mile from wells, trimethylbenzenes (45 percent), aliphatic  
280 hydrocarbons (32 percent), and xylenes (17 percent) are primary contributors to the chronic non-  
281 cancer HI, and trimethylbenzenes (46 percent), aliphatic hydrocarbons (21 percent) and xylenes  
282 (15 percent) also are primary contributors to the subchronic HI.

### 283 **3.3 Cancer Risks**

284 Cancer risk estimates calculated based on measured ambient air concentrations are  
285 presented in Table 6. The cumulative cancer risks based on the 95% UCL of the mean  
286 concentration were 6 in a million for residents  $> \frac{1}{2}$  from wells and 10 in a million for residents  $\leq$

287 ½ mile from wells. Benzene (84 percent) and 1,3-butadiene (9 percent) were the primary  
288 contributors to cumulative cancer risk for residents > ½ mile from wells. Benzene (67 percent)  
289 and ethylbenzene (27 percent) were the primary contributors to cumulative cancer risk for  
290 residents ≤ ½ mile from wells.

## 291 **4.0 Discussion**

292 Our results show that the non-cancer HI from air emissions due to natural gas  
293 development is greater for residents living closer to wells. Our greatest HI corresponds to the  
294 relatively short-term (i.e., subchronic), but high emission, well completion period. This HI is  
295 driven principally by exposure to trimethylbenzenes, aliphatic hydrocarbons, and xylenes, all of  
296 which have neurological and/or respiratory effects. We also calculated higher cancer risks for  
297 residents living nearer to wells as compared to residents residing further from wells. Benzene is  
298 the major contributor to lifetime excess cancer risk for both scenarios. It also is notable that these  
299 increased risk metrics are seen in an air shed that has elevated ambient levels of several  
300 measured air toxics, such as benzene (CDPHE 2009, GCPH 2010).

### 301 ***4.1 Representation of Exposures from NGD***

302 It is likely that NGD is the major source of the hydrocarbons observed in the NGD area  
303 samples used in this risk assessment. The NGD area monitoring site is located in the midst of  
304 multi-acre rural home sites and ranches. Natural gas is the only industry in the area other than  
305 agriculture. Furthermore, the site is at least 4 miles upwind from any other major emission  
306 source, including Interstate 70 and the town of Silt, Colorado. Interestingly, levels of benzene,  
307 m,p-xylene, and 1,3,5-trimethylbenzene measured at this rural monitoring site in 2009 were  
308 higher than levels measured at 27 out of 37 EPA air toxics monitoring sites where SNMOCs  
309 were measured, including urban sites such as Elizabeth, NJ, Dearborn, MI, and Tulsa, OK



310 (GCPH 2010, US EPA 2009b). In addition, the 2007 Garfield County emission inventory  
311 attributes the bulk of benzene, xylene, toluene, and ethylbenzene emissions in the county to  
312 NGD, with NGD point and non-point sources contributing five times more benzene than any  
313 other emission source, including on-road vehicles, wildfires, and wood burning. The emission  
314 inventory also indicates that NGD sources (e.g. condensate tanks, drill rigs, venting during  
315 completions, fugitive emissions from wells and pipes, and compressor engines) contributed ten  
316 times more VOC emissions than any source, other than biogenic sources (e.g plants, animals,  
317 marshes, and the earth) (CDPHE 2009) .

318 Emissions from flowback operations, which may include emissions from various sources  
319 on the pads such as wells and diesel engines, are likely the major source of the hydrocarbons  
320 observed in the well completion samples. These samples were collected very near (130 to 500  
321 feet from the center) well pads during uncontrolled flowback into tanks venting directly to the  
322 air. As for the NGD area samples, no sources other than those associated with NGD were in the  
323 vicinity of the sampling locations.

324 Subchronic health effects, such as headaches and throat and eye irritation reported by  
325 residents during well completion activities occurring in Garfield County, are consistent with  
326 known health effects of many of the hydrocarbons evaluated in this analysis (COGCC 2011;  
327 Witter et al. 2011). Inhalation of trimethylbenzenes and xylenes can irritate the respiratory  
328 system and mucous membranes with effects ranging from eye, nose, and throat irritation to  
329 difficulty in breathing and impaired lung function (ATSDR 2007a; ATSDR 2007b; US EPA  
330 1994). Inhalation of trimethylbenzenes, xylenes, benzene, and alkanes can adversely affect the  
331 nervous system with effects ranging from dizziness, headaches, fatigue at lower exposures to  
332 numbness in the limbs, incoordination, tremors, temporary limb paralysis, and unconsciousness

333 at higher exposures (Carpenter et al. 1978; Nilsen et al. 1988; US EPA 1994; Galvin et al. 1999;  
334 ATSDR 2007a; ATSDR 2007b).

#### 335 ***4.2 Risk Assessment as a Tool for Health Impact Assessment***

336 HIA is a policy tool used internationally that is being increasingly used in the United  
337 States to assess multiple complex hazards and exposures in communities. Comparison of risks  
338 between residents based on proximity to wells illustrates how the risk assessment process can be  
339 used to support the HIA process. An important component of the HIA process is to identify  
340 where and when public health is most likely to be impacted and to recommend mitigations to  
341 reduce or eliminate the potential impact (Collins and Koplan 2009). This risk assessment  
342 indicates that public health most likely would be impacted by well completion activities,  
343 particularly for residents living nearest the wells. Based on this information, suggested risk  
344 prevention strategies in the HIA are directed at minimizing exposures for those living closet to  
345 the well pads, especially during well completion activities when emissions are the highest. The  
346 HIA includes recommendations to (1) control and monitor emissions during completion  
347 transitions and flowback; (2) capture and reduce emissions through use of low or no emission  
348 flowback tanks; and (3) establish and maintain communications regarding well pad activities  
349 with the community (Witter et al 2011).

#### 350 ***4.3 Comparisons to Other Risk Estimates***

351 This risk assessment is one of the first studies in the peer-reviewed literature to provide a  
352 scientific perspective to the potential health risks associated with development of unconventional  
353 natural gas resources. Our results for chronic non-cancer HIs and cancer risks for residents  
354 > than ½ mile from wells are similar to those reported for NGD areas in the relatively few  
355 previous risk assessments in the non-peer reviewed literature that have addressed this issue

356 (CDPHE 2010, Coons and Walker 2008, CDPHE 2007, Walther 2011). Our risk assessment  
357 differs from these previous risk assessments in that it is the first to separately examine residential  
358 populations nearer versus further from wells and to report health impact of emissions resulting  
359 from well completions. It also adds information on exposure to air emissions from development  
360 of these resources. These data show that it is important to include air pollution in the national  
361 dialogue on unconventional NGD that, to date, has largely focused on water exposures to  
362 hydraulic fracturing chemicals.

363

#### 364 ***4.4 Limitations***

365 As with all risk assessments, scientific limitations may lead to an over- or  
366 underestimation of the actual risks. Factors that may lead to overestimation of risk include use  
367 of: 1) 95 percent UCL on the mean exposure concentrations; 2) maximum detected values for  
368 1,3-butadiene, 2,2,4-trimethylpentane, and styrene because of a low number of detectable  
369 measurements; 3) default RME exposure assumptions, such as an exposure time of 24 hours per  
370 day and exposure frequency of 350 days per year; and 4) upper bound cancer risk and non-cancer  
371 toxicity values for some of our major risk drivers. The benzene IUR, for example, is based on  
372 the high end of a range of maximum likelihood values and includes uncertainty factors to  
373 account for limitations in the epidemiological studies for the dose-response and exposure data  
374 (US EPA 2011a). Similarly, the xylene chronic RfC is adjusted by a factor of 300 to account for  
375 uncertainties in extrapolating from animal studies, variability of sensitivity in humans, and  
376 extrapolating from subchronic studies (US EPA 2011a). Our use of chronic RfCs values when  
377 subchronic RfCs were not available may also have overestimated 1,3-butadiene, n-

378 propylbenzene, and propylene subchronic HQs. None of these three chemicals, however, were  
379 primary contributors to the subchronic HI, so their overall effect on the HI is relatively small.

380         Several factors may have lead to an underestimation of risk in our study results. We were  
381 not able to completely characterize exposures because several criteria or hazardous air pollutants  
382 directly associated with the NGD process via emissions from wells or equipment used to develop  
383 wells, including formaldehyde, acetaldehyde, crotonaldehyde, naphthalene, particulate matter,  
384 and polycyclic aromatic hydrocarbons, were not measured. No toxicity values appropriate for  
385 quantitative risk assessment were available for assessing the risk to several alkenes and low  
386 molecular weight alkanes (particularly < C<sub>5</sub> aliphatic hydrocarbons). While at low concentrations  
387 the toxicity of alkanes and alkenes is generally considered to be minimal (Sandmeyer, 1981), the  
388 maximum concentrations of several low molecular weight alkanes measured in the well  
389 completion samples exceeded the 200 - 1000µg/m<sup>3</sup> range of the RfCs for the three alkanes with  
390 toxicity values: n-hexane, n-pentane, and n-nonane (US EPA 2011a, ORNL 2009). We did not  
391 consider health effects from acute (i.e., less than one hour) exposures to peak hydrocarbon  
392 emissions because there were not appropriate measurements. Previous risk assessments have  
393 estimated an acute HQ of 6 from benzene in grab samples collected when residents noticed odors  
394 they attributed to NGD (CDPHE 2007). We did not include ozone or other potentially relevant  
395 exposure pathways such as ingestion of water and inhalation of dust in this risk assessment  
396 because of a lack of available data. Elevated concentrations of ozone precursors (specifically,  
397 VOCs and nitrogen oxides) have been observed in Garfield County's NGD area and the 8-hr  
398 average ozone concentration has periodically approached the 75 ppb National Ambient Air  
399 Quality Standard (NAAQS) (CDPHE 2009, GCPH 2010).

400 This risk assessment also was limited by the spatial and temporal scope of available  
401 monitoring data. For the estimated chronic exposure, we used 3 years of monitoring data to  
402 estimate exposures over a 30 year exposure period and a relatively small database of 24 samples  
403 collected at varying distances up to 500 feet from a well head (which also were used to estimate  
404 shorter-term non-cancer hazard index). Our estimated 20-month subchronic exposure was  
405 limited to samples collected in the summer, which may have not have captured temporal  
406 variation in well completion emissions. Our ½ mile cut point for defining the two different  
407 exposed populations in our exposure scenarios was based on complaint reports from residents  
408 living within ½ mile of existing NGD, which were the only data available. The actual distance at  
409 which residents may experience greater exposures from air emissions may be less than or greater  
410 than a ½ mile, depending on dispersion and local topography and meteorology. This lack of  
411 spatially and temporally appropriate data increases the uncertainty associated with the results.

412 Lastly, this risk assessment was limited in that appropriate data were not available for  
413 apportionment to specific sources within NGD (e.g diesel emissions, the natural gas resource  
414 itself, emissions from tanks, etc.). This increases the uncertainty in the potential effectiveness of  
415 risk mitigation options.

416 These limitations and uncertainties in our risk assessment highlight the preliminary  
417 nature of our results. However, there is more certainty in the comparison of the risks between  
418 the populations and in the comparison of subchronic to chronic exposures because the limitations  
419 and uncertainties similarly affected the risk estimates.

#### 420 ***4.5 Next Steps***

421 Further studies are warranted, in order to reduce the uncertainties in the health effects of  
422 exposures to NGD air emissions, to better direct efforts to prevent exposures, and thus address

423 the limitations of this risk assessment. Next steps should include the modeling of short- and  
424 longer-term exposures as well as collection of area, residential, and personal exposure data,  
425 particularly for peak short-term emissions. Furthermore, studies should examine the toxicity of  
426 hydrocarbons, such as alkanes, including health effects of mixtures of HAPs and other air  
427 pollutants associated with NGD. Emissions from specific emission sources should be  
428 characterized and include development of dispersion profiles of HAPs. This emissions data,  
429 when coupled with information on local meteorological conditions and topography, can help  
430 provide guidance on minimum distances needed to protect occupant health in nearby homes,  
431 schools, and businesses. Studies that incorporate all relevant pathways and exposure scenarios,  
432 including occupational exposures, are needed to better understand the impacts of NGD of  
433 unconventional resources, such as tight sands and shale, on public health. Prospective medical  
434 monitoring and surveillance for potential air pollution-related health effects is needed for  
435 populations living in areas near the development of unconventional natural gas resources.

## 436 **5.0 Conclusions**

437 Risk assessment can be used as a tool in HIAs to identify where and when public health  
438 is most likely to be impacted and to inform risk prevention strategies directed towards efficient  
439 reduction of negative health impacts. These preliminary results indicate that health effects  
440 resulting from air emissions during development of unconventional natural gas resources are  
441 most likely to occur in residents living nearest to the well pads and warrant further study. Risk  
442 prevention efforts should be directed towards reducing air emission exposures for persons living  
443 and working near wells during well completions.

## 444 **6.0 Acknowledgements**

445 We extend special thanks to J. Rada, P. Reaser, C. Archuleta, K. Stinson, and K. Scott. We are  
446 very grateful to the Garfield County Department of Public Health.

447

448 **7.0 References**

- 449 Antero. 2010. Air Quality Sampling Summary Report Well Completion and Flowback  
450 Development Scenario Watson Ranch Pad Garfield County Colorado December 22,  
451 2010. Antero Resources: Denver, CO.
- 452 ATSDR. 2007a. Toxicological Profile for Benzene. Atlanta, GA: Agency for Toxic Substances  
453 and Disease Registry, US Department of Health and Human Services.
- 454 ATSDR. 2007b. Toxicological Profile for Xylenes. Atlanta, GA: Agency for Toxic Substances  
455 and Disease Registry, US Department of Health and Human Services.
- 456 Brosselin, P., Rudant, J., Orsi, L., Leverger, G., Baruchel, A., Bertrand, Y., et al. 2009. Acute  
457 Childhood Leukaemia and Residence Next to Petrol Stations and Automotive Repair  
458 Garages: the ESCALE study (SFCE). *Occupational & Environmental Medicine* 66 (9):  
459 598-606.
- 460 CalEPA. 2003. Toxicity Criteria Database. California Environmental Protection Agency, Office  
461 of Environmental Health Hazard Assessment. Available:  
462 <http://oehha.ca.gov/risk/chemicalDB/index.asp> [Accessed May 2011].
- 463 Carpenter, C. P., Geary, D.L., Myers, R.C., Nachreiner, D.J., Sullivan, L.J., King, J.M.  
464 1978. Petroleum Hydrocarbons Toxicity Studies XVII. Animal Responses to n-Nonane  
465 Vapor. *Toxicol. Appl. Pharmacol* 44: 53-61.
- 466 CDPHE. 2009. Garfield County Emissions Inventory. Denver, CO: Air Pollution Control  
467 Division, Colorado Department of Public Health and Environment. Available:  
468 [http://www.garfieldcountyaq.net/default\\_new.aspx](http://www.garfieldcountyaq.net/default_new.aspx) .
- 469 CDPHE. 2007. Garfield County Air Toxics Inhalation: Screening Level Human Health Risk  
470 Assessment: Inhalation of Volatile organic Compounds Measured in Rural, Urban, and



471 Oil & Gas Areas in Ambient Air Study (June 2005 – May 2007). Denver, CO:  
472 Environmental Epidemiology Division, Colorado Department of Public Health and  
473 Environment. Available: [http://www.garfieldcountyaq.net/default\\_new.aspx](http://www.garfieldcountyaq.net/default_new.aspx) .

474 CDPHE. 2010. Garfield County Air Toxics Inhalation: Screening Level Human Health Risk  
475 Assessment: Inhalation of Volatile Organic Compounds Measured In 2008 Air Quality  
476 Monitoring Study. Denver, CO: Environmental Epidemiology Division, Colorado  
477 Department of Public Health and Environment. Available:  
478 [http://www.garfieldcountyaq.net/default\\_new.aspx](http://www.garfieldcountyaq.net/default_new.aspx) .

479 COGCC. 2009a. Statement of Basis, Specific Statutory Authority, and Purpose: New Rules and  
480 Amendments to Current Rules of the Colorado Oil and Gas Conservation Commission, 2  
481 CCR 404-1. Colorado Oil and Gas Conservation Commission. Available:  
482 <http://cogcc.state.co.us/> .

483 COGCC. 2009b. Rules and Regulations, 2 CCR 404-1. Colorado Oil and Gas Conservation  
484 Commission. Available: <http://cogcc.state.co.us/> .

485 COGCC. 2011. Inspection/Incident Database, Denver, CO: Colorado Oil and Gas Information  
486 System, Colorado Oil and Gas Conservation Commission. Available:  
487 <http://cogcc.state.co.us/> .

488 Collins J, Koplan JP. 2009. Health Impact Assessment: A Step Toward Health In All Policies.  
489 JAMA. 302(3):315-317.

490 Coons, T. , Walker R. 2008. Community Health Risk Analysis of Oil and Gas Industry in  
491 Garfield County. Grand Junction, CO: Saccommano Research Institute. Available:  
492 [http://www.garfieldcountyaq.net/default\\_new.aspx](http://www.garfieldcountyaq.net/default_new.aspx) .

493 Frazier, A. 2009. Analysis of Data Obtained for the Garfield County Air Toxics Study Summer  
494 2008. Rifle Denver, CO: Air Pollution Control Division, Colorado Department of Public  
495 Health and Environment. Available: [http://www.garfieldcountyaq.net/default\\_new.aspx](http://www.garfieldcountyaq.net/default_new.aspx) .

496 Galvin, J. B. and Marashi, F. 1999. n-Pentane. Journal of Toxicology and Environmental Health  
497 Part 1 58: 35-56.

498 GCPH. 2009. Garfield County 2008 Air Quality Monitoring Summary Report. Rifle CO:  
499 Garfield County Public Health Department. Available:  
500 [http://www.garfieldcountyaq.net/default\\_new.aspx](http://www.garfieldcountyaq.net/default_new.aspx).

501 GCPH. 2010a. Garfield County 2009 Air Quality Monitoring Summary Report. Rifle CO:  
502 Garfield County Public Health Department. Available:  
503 [http://www.garfieldcountyaq.net/default\\_new.aspx](http://www.garfieldcountyaq.net/default_new.aspx).

504 GCPH. 2011. Garfield County Quarterly Monitoring Report. Fourth Quarter October 1 through  
505 December 31, 2010. Rifle CO: Garfield County Public Health Department. Available:  
506 [http://www.garfieldcountyaq.net/default\\_new.aspx](http://www.garfieldcountyaq.net/default_new.aspx).

507 Glass, D.C., Gray, C.N., Jolley, D.J., Gibbons, C., Sim, M.R., Fritschi, L., et al. 2003. Leukemia  
508 Risk Associated with Low-Level Benzene Exposure. *Epidemiology* 14(5): 569-577.

509 Kim, B.M., Park, E.K. LeeAn, S.Y., Ha, M., Kim, E.J., Kwon, H., et al. 2009. BTEX Exposure  
510 and Its Health Effects in Pregnant Women Following the Hebei Spirit Oil Spill. *Journal*  
511 *of Preventive Medicine & Public Health / Yebang Uihakhoe Chi* 42(2): 96-103.

512 Kirkeleit, J., Riise, T., Bråtveit, M., Moen, B. 2008. Increased Risk of Acute Myelogenous  
513 Leukemia and Multiple Myeloma in a Historical Cohort of Upstream Petroleum Workers  
514 Exposed to Crude Oil. *Cancer Causes and Control* 19(1): 13-23.

515 Nilsen, O.G., Haugen, O.A., Zahisen, K., Halgunset, J., Helseth, A., Aarset, A., Eide, I. 1988.  
516 Toxicity of n-C9 to n-C13 Alkanes in the Rat on Short Term Inhalation. *Pharmacol.*  
517 *Toxicol* 62: 259-266.

518 ORNL 2009. The Risk Assessment Information System. Oak Ridge National Laboratory, TN:  
519 US Department of Energy. Available: <http://rais.ornl.gov/> [Accessed May 2011].

520 Sandmeyer, E.E. 1981. Aliphatic Hydrocarbons, P. 3175-3220. In: Patty's Industrial Hygiene  
521 and Toxicology, Third Edition, Volume IIB, John Wiley, New York.

522 US DOE. 2009. "Modern Shale Gas Development in the United States: A Primer," Office of  
523 Fossil Energy and National Energy Technology Laboratory, United States  
524 Department of Energy. [http://www.netl.doe.gov/technologies/oil-](http://www.netl.doe.gov/technologies/oil-gas/publications/EPreports/Shale Gas Primer 2009.pdf)  
525 [gas/publications/EPreports/Shale Gas Primer 2009.pdf](http://www.netl.doe.gov/technologies/oil-gas/publications/EPreports/Shale Gas Primer 2009.pdf) (accessed January 2012).

526 US EIA. 2011. Annual Energy Outlook 2011 with Projections to 2035. Washington DC: Energy  
527 Information Administration, United States Department of Energy.

528 US EPA. 1989. Risk Assessment Guidance for Superfund (Part A). Washington, DC: Office of  
529 Emergency and Remedial Response, US Environmental Protection Agency.

530 US EPA. 1994. Chemicals in the Environment: 1,2,4-trimethylbenzene (C.A.S. No. 95-63-6).  
531 Washington, DC: Office of Pollution Prevention and Toxics, US Environmental  
532 Protection Agency.

533 US EPA. 1997. Health Effects Assessment Summary Tables. Washington, DC: US  
534 Environmental Protection Agency.

535 US EPA. 1999. Method for the Determination of Non-Methane Organic Compounds (NMOC) in  
536 Ambient Air Using Cryogenic Preconcentrations and Direct Flame Ionization Detection

537 (PDFID). Cincinnati OH: Office of Research and Development, US Environmental  
538 Protection Agency.

539 US EPA 2004. The OAQPS Air Toxic Risk Assessment Library. US Environmental Protection  
540 Agency. Available: [http://www.epa.gov/ttn/fera/risk\\_atra\\_main.html](http://www.epa.gov/ttn/fera/risk_atra_main.html).

541 US EPA. 2009a. Provisional Peer Reviewed Toxicity Values for Complex Mixtures of Aliphatic  
542 and Aromatic Hydrocarbons. Cincinnati Ohio: Superfund Health Risk Technical Support  
543 Center National Center for Environmental Assessment: Office of Research and  
544 Development., US Environmental Protection Agency.

545 US EPA. 2009b. Technology Transfer Network Air Quality System. Washington DC: Office of  
546 Air and Radiation, US Environmental Protection Agency. Available:  
547 <http://www.epa.gov/ttn/airs/airsaqs/>.

548 US EPA. 2010a. Greenhouse Gas Emissions Reporting from the Petroleum and Natural Gas  
549 Industry Background Technical Support Document. Washington DC: Climate Change  
550 Division, US Environmental Protection Agency.

551 US EPA. 2010b. ProUCL Version 4.00.05 Technical Guide Statistical Software for  
552 Environmental Applications for Data Sets With and Without Nondetect  
553 Observations(Draft). Washington DC: Office of Research and Development, US  
554 Environmental Protection Agency.

555 US EPA. 2011a. Integrated Risk Information System (IRIS). Washington DC:, US  
556 Environmental Protection Agency. Available: <http://www.epa.gov/IRIS/> [Accessed May  
557 2011].

558 TERC 2009. VOC Emissions from Oil and Condensate Storage Tanks. Texas Environmental  
559 Research Consortium. The Woodlands, TX: 1-34 Available online at:  
560 <http://files.harc.edu/Projects/AirQuality/Projects/H051C/H051CFinalReport.pdf>.

561 Vidas, H., Hugman, B. ICF International. Availability, Economics, and Production Potential of  
562 North American Unconventional Natural Gas Supplies. Prepared for The INGAA  
563 Foundation, Inc. by: ICF International, 2008.

564 Walther, E. 2011. Screening Health Risk Assessment Sublette County, Wyoming. Pinedale WY:  
565 Sierra Research, Inc. Available:  
566 <http://www.sublettewyo.com/DocumentView.aspx?DID=438> .

567 White, N., teWaterNaude, J. van der Walt, A., Ravenscroft, G., Roberts, W., Ehrlich, R. 2009.  
568 Meteorologically Estimated Exposure but not Distance Predicts Asthma Symptoms in  
569 School Children in the Environs of a Petrochemical Refinery: a Cross-Sectional Study.  
570 Environmental Health 8(1): 45.

571 Witter, R., McKenzie, L., Towle, M., Stinson, K., Scott, K., Newman, L., Adgate, J. 2011 Draft  
572 Health Impact Assessment for Battlement Mesa, Garfield County, Colorado. Colorado  
573 School of Public Health. Available: [http://www.garfield-](http://www.garfield-county.com/index.aspx?page=1408)  
574 [county.com/index.aspx?page=1408](http://www.garfield-county.com/index.aspx?page=1408).

575 Zielinska, B., Fujita, E., Campbell, D. 2011. Monitoring of Emissions from Barnett Shale  
576 Natural Gas Production Facilities for Population Exposure Assessment. Houston TX:  
577 Desert Research Institute. Available:  
578 [http://www.sph.uth.tmc.edu/mleland/attachments/Barnett%20Shale%20Study%20Final%](http://www.sph.uth.tmc.edu/mleland/attachments/Barnett%20Shale%20Study%20Final%20Report.pdf)  
579 [20Report.pdf](http://www.sph.uth.tmc.edu/mleland/attachments/Barnett%20Shale%20Study%20Final%20Report.pdf) .

580 **Figure 1:** Relationship between completion samples and natural gas development area  
581 samples and residents living  $\leq \frac{1}{2}$  mile and  $> \frac{1}{2}$  mile from wells.

582 <sup>a</sup>Time weighted average based on 20-month contribution from well completion samples  
583 and 340- month contribution from natural gas development samples.