

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

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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

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- 36 Colorado School of Public Health.
- 37 The authors declare they have no competing financial interests.

38 **Abbreviations¹**

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

¹ 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 C₅ to C₁₈ aliphatic and C₆ to C₁₈ 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 < C₅ 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/m³ 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.

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447

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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 ^aTime weighted average based on 20-month contribution from well completion samples
583 and 340- month contribution from natural gas development samples.