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Measurement of Area and Personal Breathing Zone Concentrations of Diesel Particulate Matter (DPM) during Oil and Gas Extraction Operations, including Hydraulic Fracturing

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Abstract

Diesel engines serve many purposes in modern oil and gas extraction activities. Diesel particulate matter (DPM) emitted from diesel engines is a complex aerosol that may cause adverse health effects depending on exposure dose and duration. This study reports on personal breathing zone (PBZ) and area measurements for DPM (expressed as elemental carbon) during oil and gas extraction operations including drilling, completions (which includes hydraulic fracturing) and servicing work.

Researchers at the National Institute for Occupational Safety and Health (NIOSH) collected 104 full-shift air samples (49 PBZ and 55 area) in Colorado, North Dakota, Texas, and New Mexico during a four year period from 2008-2012 The arithmetic mean (AM) of the full shift TWA PBZ samples was 10 μg/m^3; measurements ranged from 0.1 to 52 μg/m^3. The geometric mean (GM) for the PBZ samples was 7 μg/m^3. The AM of the TWA area measurements was 17 μg/m^3 and ranged from 0.1 to 68 μg/m^3. The GM for the area measurements was 9.5 μg/m^3. Differences between the GMs of the PBZ samples and area samples were not statistically different (P>0.05).

Neither the Occupational Safety and Health Administration (OSHA), NIOSH, nor the American Conference of Governmental Industrial Hygienists (ACGIH) have established occupational exposure limits (OEL) for DPM. However, the State of California, Department of Health Services lists a time-weighted average (TWA) OEL for DPM as elemental carbon (EC) exposure of 20 μg/m^3. Five of 49 (10.2%) PBZ TWA measurements exceeded the 20 μg/m^3 EC criterion. These measurements were collected on Sandmover and Transfer Belt (T-belt) Operators, Blender and Chemical Truck Operators, and Water Transfer Operators during hydraulic fracturing operations.

Recommendations to minimize DPM exposures include elimination (locating diesel-driven pumps away from well sites), substitution, (use of alternative fuels), engineering controls using advanced emissions controls technologies, administrative controls (configuration of well sites), hazard communication and worker training.

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Keywords

Diesel exhaust; diesel particulate matter; elemental carbon; oil and gas extraction; hydraulic fracturing; exposure assessment

INTRODUCTION

Work in contemporary oil and gas extraction [also called exploration and production (E&P) or "upstream work"] involves a wide range of tasks and operations including: site preparation, well drilling, well completions (which includes hydraulic fracturing) and servicing work. Risks for fatalities in E&P work are well described by NIOSH [(1,2,3)] but there is a paucity of peer-reviewed studies describing chemical exposure risks during drilling, completions and well servicing work. NIOSH initiated the Field Effort to Assess Chemical Exposures in Oil and Gas Extraction Workers[4] in 2010 but preliminary hazard assessments began in 2008 with worksite observations, reviews of safety data sheets, area and limited personal breathing zone (PBZ) air sampling, and discussions with work crews, supervisors, and health and safety personnel at upstream work sites. Research results from the NIOSH Field Effort to date include exposure assessments that quantified risks for respirable crystalline silica during hydraulic fracturing, benzene exposures during flowback and tank gauging operations, and evaluations of an engineering control invented by NIOSH (mini baghouse retrofit assembly) to control respirable crystalline silica emissions from sand moving machinery.[5,6,7,8]

Occupational exposure to emissions from diesel engines has been studied in a variety of workplaces including, but not limited to, underground mining, fire stations, dock workers, train crews, transportation drivers and mechanics[9], however workplace DPM exposure measurements for oil and gas extraction workers have not been reported in the peer-reviewed literature. More than 620,000 workers were employed in the U.S. oil and gas extraction industry in 2014.[10] Diesel engines are common on oil and gas extraction sites and workers are often in close proximity, or may be downwind from diesel engine emissions.

Diesel engines operate on oil and gas extraction sites from initial site construction to well servicing operations after production proceeds. Diesel powered earth-moving equipment is required to develop roads into the wellsite, excavate and stabilize well pads, ponds and pits, and to construct earthen/aggregate berms surrounding the pad or pad-mounted equipment (e.g., production tanks). Diesel powered drilling rigs have multiple engines that operate the draw works, top drives, mud pumps, winches and other equipment during drilling, installation of casing, production tubing and myriad connections at the wellhead. Wireline crews at completions sites use diesel engines to raise and lower tools and equipment into and out of the wellbore. Diesel engines power sand moving machines (i.e., Frac Sanders, Sand Kings) and transport belts (i.e., T-belts) to move proppant (typically quartz sand) to diesel powered blender trucks at completions sites. Completions crews conducting hydraulic fracturing require numerous (some sites have 20 or more) diesel-powered pumps to generate the forces required to hydraulically fracture rock formations for enhanced hydrocarbon recovery. Diesel engines are used for on-site water transport systems and fuel delivery for various operating engines on-site. Specialty crews (e.g., rig moving, coiled tubing) also use diesel-driven equipment.

Health Risks for Exposures to Diesel Particulate Matter

Diesel exhaust is a complex aerosol containing numerous gases and respirable particulate (soot) and more than 40 potentially toxic compounds.[11] The particulate fraction of diesel exhaust contains a solid elemental carbon core with thousands of hydrocarbons, oxides of nitrogen, sulfur compounds, and various other carbon compounds adsorbed onto the core.[12,13] The adsorbed compounds comprise 15% to 65% of the total particulate mass and include compounds such as polycyclic aromatic hydrocarbons, many of which are possibly carcinogenic.[10, 11,14,15] Diesel particulate matter is respirable (submicrometer in aerodynamic diameter) and can reach the gas exchange regions of the lungs.[16] Depending on the duration and magnitude of exposure, DPM can cause headaches, dizziness, coughing, eye and upper respiratory irritation and exacerbations of pre-existing asthma.[9]

In 2012, the World Health Organization, International Agency for the Research of Cancer (IARC) determined that DPM exposure is associated with an increased risk for lung cancer in humans and classifies DPM as a Group 1 human carcinogen.[17] NIOSH considers DPM to be a potential occupational carcinogen and that cancer risks for workers exposed to diesel should be reduced by minimizing exposures.[12] Neither OSHA, NIOSH nor ACGIH have an occupational exposure limit for DPM. However, based on a risk assessment conducted by the California Environmental Protection Agency, Office of Environmental Health Hazard Assessment, the California, Department of Health Services, Hazard Evaluation System and Information Service (HESIS) developed a recommended occupational exposure limit for DPM of 20 μg/m^3 as a time-weighted average (TWA) referenced as elemental carbon (EC)[18]. The risk assessment concluded that exposures to DPM at 20 μg/m^3 as a TWA over a working lifetime (typically 40 years) results in excess lung cancer risks greater than 1:1000, often considered to be the threshold for acceptable workplace health risks. Published studies of risks for worker exposure to DPM during oil and gas extraction were not identified in the peer-reviewed literature as of the date of this report.

METHODS

Measurement of PBZ and area concentrations of DPM were conducted through pre-arranged agreements (i.e., Memoranda of Understanding) between the NIOSH Western States Division and several petroleum operators, contractors or servicing companies. The studies were conducted in Colorado, North Dakota, New Mexico and Texas from June 2008 through August 2012. The sites were not selected by NIOSH, but were determined by NIOSH to be representative of typical oil and gas extraction activities. The purpose and intent of the NIOSH Field Effort to Assess Chemical Exposures in Oil and Gas Workers was explained to management and employees prior to sample collection. Most of the area DPM measurements were collected at workstations or locations where employees were observed working or understood to spend a portion of the work shift. Where possible, area samples were located at breathing zone height. Personal breathing zone (PBZ) samples were collected on employees in 25 different job titles who volunteered to participate in the

NIOSH research. Sampling was typically conducted for three consecutive days. Employees were asked to participate each day, but day-after-day participation did not always occur. Following sampling, NIOSH researchers discussed work and site activities with employees and management to confirm the samples collected were representative of normal E&P operations.

Measurement of full-shift PBZ and area DPM concentrations was performed using open-faced, two-piece, shrink wrap banded, 37 millimeter (mm) polystyrene sampling cassettes fitted with quartz-fiber filters (Omega Specialty Division, SKC™ Inc. Eighty Four PA.). Tygon® tubing connected the filter cassettes to SKC™ XR-5000™ high flow personal sampling pumps (SKC™ Inc. Eighty Four PA.) The sampling trains were calibrated to a flow rate of 3 LPM using BIOS® Defender™ 520/530 frictionless piston airflow calibrators (Bios International, Butler Park, NJ). For PBZ samples, the cassettes were located in workers' breathing zone by attaching the filter cassette to the lapel of workers' fire-retardant coveralls. Sampling trains were collected from the workers at the end of their shift, post calibration was performed, and the cassettes stored upright for shipment to the laboratory. Samples were analyzed at an American Industrial Hygiene Association accredited laboratory according to the NIOSH Manual of Analytical Methods (NMAM) method 5040 for elemental carbon using a thermal/optical carbon analyzer.[19] The TWA for each sample was calculated by dividing the laboratory reported value of EC on the sample filter by the volume of air sampled and reporting as μg/m^3 EC. Results were compared to the California Department of Health Services, HESIS, criterion for DPM of 20 μg/m^3 EC as a TWA.

Calculations of descriptive statistics and graphs were made using SAS Enterprise Guide 4.3 (Statistical Analysis System, 2011) and SAS JMP 10 statistical software. If numeric values between the limit of detection (LOD) and the limit of quantification (LOQ) were reported by the analytical laboratory, the same values were included in the statistical analysis of the data set.

RESULTS

Measurement of Personal Breathing Zone and Area DPM Concentrations

Forty-nine PBZ and 55 area samples for DPM were collected at oil and gas extraction sites during drilling, completions and well servicing operations. Seventeen samples (6 PBZ and 11 area) collected during 2008 were originally reported as non-detect as their values were below their calculated EC LOD based on media blanks. The calculated media blank LOD/LOQ values for EC on samples collected in 2008 were 3 and 10 μg/filter punch, respectively. Based on review of the instrumental data, media blanks were found to be many times higher than field blank values. Therefore, it was concluded these high results were likely due to media blank contamination. Consequently, field blank values were used to re-determine LOD/LOQ (1 and 3 μg/filter punch, respectively) for these samples and instrumental values for these samples we used in the calculation of summary statistics. After 2010, improvements in the quality assurance process resulted in lower background elemental carbon concentrations on media blanks for NMAM 5040 and resulted in an average LOD/LOQ of 1 and 3 μg/filter punch, respectively for all sample sets.

The arithmetic mean (AM) for the 49 TWA PBZ measurements was 10μg/m^3 EC; the standard deviation was 9.9 and the range was 0.1 to 52 μg/m^3. Arithmetic means for DPM were 5.4, 7.4 and 11.9 μg/m^3 for servicing, drilling and completions (including hydraulic fracturing) operations, respectively. The geometric mean (GM) for the PBZ samples was 6.8 μg/m^3 and the standard error was 0.9 (Table I).

Five of 49 (10.2%) full-shift PBZ TWA measurements exceeded the 20 μg/m^3 DPM EC criterion. Job titles and TWA values for these measurements included Sandmover Operator (26 μg/m^3), Blender Truck Operator (22 μg/m^3), Transfer Belt (T-belt) Operator (28 μg/m^3), Chemical Truck Operator (41 μg/m^3), and Water Transfer Operator, (52 μg/m^3). All five of these samples were collected during hydraulic fracturing operations, furthermore three of the samples were collected at the same site and date in Colorado (Table II). Two TWA PBZ measurements approached the 20 μg/m^3 occupational health criterion: a Motor Hand working on a drilling rig and an Equipment Operator at a well servicing operation both were 18μg/m^3 as a for DPM as EC. Figure 1 describes percentages and numbers of TWA PBZ sample concentrations that were in ranges of 1-5 μg/m^3 (n=21), 6-10 μg/m^3 (n=11), 11-15 μg/m^3 (n=8), 16-20 μg/m^3 (n=n=4) and 20 μg/m^3 (n=5).

The AM and standard deviation the for the 55 area measurements was 16.9 ± 15.5 μg/m^3 (Table III). The values were in a range of 0.1-68 μg/m^3. Seventeen of 55 (31%) area measurements met or exceeded 20 μg/m^3 for EC. The AM of the 17 samples exceeding the 20 μg/m^3 criterion was 36.4 μg/m^3. Area sample locations exceeding 20 μg/m^3 criterion included: operator stations on sandmover and blender trucks, various locations on a drilling rig (e.g., around mud tanks, pits and pumps, driller work station and rig floor), an operator station for a pump at a produced water containment pit and well servicing locations where diesel engines were in use. Differences in the geometric means of the PBZ and area measurements were compared using SAS PROC TTest and were determined to be *not* statistically significantly different ($P > 0.05$). Job titles, numbers of PBZ measurements and range of TWA values are listed in Table II.

Weather

DPM measurements were made during the summer through late autumn (June-December). Daily temperatures ranged from a low of 27 degrees Fahrenheit (°F) at a hydraulic fracturing site in the mountainous Piceance basin of Colorado in December to 104 °F in August in the desert of the Eagle Ford shale in southwest Texas. Table IV lists a summary of the weather data.

DISCUSSION

Proximity to Sources of DPM and Measurements > 20 μg/m^3 at the Worksites

Diesel engine exhaust was often visible on the well sites depending on work activity, numbers of operating engines, lighting conditions and winds. DPM emissions were often best visualized during pre-dawn hours when DPM aerosols were clearly visible refracted through portable on-site lighting producing a light-scattering effect. An example of strong point sources for DPM emissions is an array of diesel-driven pumps at a hydraulic fracturing site (Figure 2 photograph) where the emission plumes were plainly visible. Workers located downwind from such arrays of diesel engines (or other point sources) are likely to have increased risks for DPM aerosol compared to workers upwind or those working in vans or other vehicles with dedicated heating, ventilation and air-conditioning units. On-site configuration and arrangement of diesel-powered equipment (e.g., pumps, sand movers, T-belts, blender trucks) in relation to worker locations and prevailing wind direction will influence risks for exposures to DPM aerosols.

Wind was always present to some degree on the sites; wind direction and worker location are believed to be contributing factors for the 5 PBZ measurements exceeding the 20 μg/m^3 OEL. This was particularly true for the workers who were known to be downwind from operating diesel engines for the slurry pumps at the hydraulic fracturing sites. Wind direction typically varied with the exception of the DJ/Niobrara site where direction was consistent for the three days on-site. Based on averages for the days the evaluations occurred, average wind speed ranged from 2-15 miles per hour (mph) with higher wind speeds in a range of 16-26 mph.

Three of five TWA PBZ measurements exceeding 20 μg/m^3 EC (52, 41 and 26 μg/m^3) were collected on a Water Transfer, Chemical Truck, and Sandmover Operator at the same site and same day in the Denver Julesburg (DJ)/Niobrara basin of Colorado in July 2011, during hydraulic fracturing operations. None of these workers wore respiratory protection. Another TWA PBZ sample (28 μg/m^3 EC) was collected on a T-belt Operator in the Eagle Ford shale of Texas in September 2010 during hydraulic fracturing operations. That worker wore a full-face respirator with a combination P-100/acid gas cartridge and was observed to be clean shaven. Finally, a sample that exceeded 20 μg/m^3 as a TWA EC (22 μg/m3) was collected on a Blender Truck Operator in the Piceance basin in Colorado in December of 2008 at a hydraulic fracturing operation. Measurements > 20 μg/m^3 were located in close proximity and/or downwind of multiple diesel engines used during hydraulic fracturing. Observations of the workers or the work location with PBZ measurements > 20 μg/m^3 appeared to have nominal natural dilution ventilation due to closely configured on-site equipment, or were observed to be downwind of diesel emission point sources (i.e., engines for fracturing pumps).

Comparisons with Other Studies

A DPM exposure study conducted outside during recovery operations following Hurricane Sandy reported area EC concentrations in a range of ND to 18 μg/m^3 and similar to measurements reported in this study, higher EC concentrations were found in close proximity to diesel powered equipment.[20] A NIOSH Health Hazard Evaluation (HHE) reported measurements similar to ours for DPM exposures in move/load/unload operations at marine container handling terminals. A total of 169 PBZ samples across 15 job titles and 21 area samples were collected. Results of PBZ samples ranged from 1 μg/m^3 to 42 μg/m^3; six (4%) of samples exceeded the 20 μg/m^3 TWA criterion. However, maximum area measurements were below the concentrations measured in this study, ranging from 2.6 μg/m^3 to 10 μg/m^3. The researchers concluded that proximity to diesel engine emissions increased exposures to DPM.[21]

A literature review of occupational exposures to workers in a variety of trades and professions reported EC exposures in a range of 1 to > 100 μg/m^3 including, 1 μg/m^3 for parking attendants, 2-5 μg/m^3 for professional drivers, 5-10 μg/m^3 for construction workers and mechanics, and > 100 μg/m^3 for underground miners.[9]

A recent report described results of a quantitative risk assessment (QRA) for diesel exhaust using imputed data from three well-regarded epidemiological studies of truckers and non-metal miners.[22] The authors' reported derived acceptable risk and maximum tolerable risk concentrations of EC were in a range of 0.01 and 1.0 μg/m^3 far below the criterion referenced here, indeed scarcely achievable with the types of diesel engines commonly used on oil and gas extraction sites (e.g., Tier II and III) and for that matter many occupational environments where stationary diesel engines are used. The authors of the risk assessment acknowledge uncertainties exist in the computed exposure response curve relating to the reported relative risks.

Limiting Worker Exposures to DPM

Controls to minimize DPM exposures involve implementation of the hierarchy of controls: elimination, substitution, engineering controls, administrative controls (including training and hazard communication) and, as a last measure, use of respiratory protection. Elimination can include locating diesel-driven fracturing pump engines in an off-site and ideally downwind location from the well pad. This does not completely eliminate exposure risk because other diesel engines will be on site, but partial removal can eliminate some of the strongest point sources of DPM aerosol which typically are the arrays of diesel-powered pump engines used during hydraulic fracturing. NIOSH researchers have observed off-site location of diesel-driven fracturing pumps at an oil and gas extraction site in Colorado in 2013, but DPM was not measured as part of that study. Substitution of alternative fuels can limit DPM generation. A recent simulated study in the mining industry found that the use of biodiesel 75 and gas/diesel fuel reduced DPM compared to diesel fuel alone and concluded that use of alternative fuels have potential to significantly reduce diesel emissions.[23] Administrative controls include evaluating DPM emission source strengths, prevailing wind patterns and employee worksite locations prior to well site construction and configuring the well site so stationary workers are upwind to the degree possible. Another administrative control is limiting the time employees must spend in locations anticipated or determined to have exposure risks for DPM. One possible and relatively simple consideration for control may involve the use of exhaust stack extensions on stationary sources (e.g., diesel-driven pumps using for hydraulic fracturing) that NIOSH researchers observed at an oil and gas extraction site in 2016. Stack extensions leverage inherent engine exhaust velocity and thermal buoyancy to help eject DPM exhaust emissions higher into the atmosphere for enhanced dilution and dispersion. Discussion of all engineering controls for DPM is beyond the scope of this manuscript but NIOSH has conducted extensive research evaluating DPM exposures and controls in underground mines, including engineering controls such as use of diesel oxidation catalysts, diesel particulate filters, alternative fuels, additive and lubricants.[24] As a last resort, correct use of air-purifying, elastomeric half masks and filtering-face piece respirators having particulate efficiencies of N-95 or greater and half masks configured

P-100 cartridges and acid-gas cartridges can reduce exposures to particulate and gas/vapor phase of DPM emissions.

CONCLUSIONS

Area and full-shift PBZ measurement of DPM was conducted at five sites in four states during hydraulic fracturing, drilling and servicing operations. Measurements of DPM concentrations in oil and gas extraction workers were mostly less than the State of California, HESIS criterion of 20 μg/m^3. Five of 49 (10.2%) of full-shift PBZ TWA measurements exceeded 20 μg/m^3, two of these samples were more than double the criterion. Area measurements of DPM were in a range of 0.1-68 μg/m^3 with an AM TWA of 16.9 μg/m^3. Approximately one third of the TWA area measurements (31%), exceeded the State of California criterion of 20 μg/m^3.

The DPM measurements were found to follow a lognormal distribution; comparisons of GMs for the area and PBZ samples were evaluated and were *not* statistically significantly different, suggesting some degree of uniform dispersion of DPM aerosol at the sites where these measurements were made. This finding suggests that all workers at these sites had some risk for exposures to DPM and that exposure risks were both task and location based. Meaning, workers' whose tasks required being closer to strong point sources (i.e., hydraulic fracturing pump engines) had higher risks for exposure and workers who were stationed downwind from point sources also had higher risk for exposures.

Because the highest DPM exposures were observed at hydraulic fracturing sites, the potential for co-exposures to respirable crystalline silica and DPM needs to be considered and appropriate controls implemented. Both respirable crystalline silica and DPM are respiratory irritants following acute exposures; with chronic exposures, each have been linked to chronic obstructive pulmonary disease and lung cancer. However the human biological effects on workers of combined exposures to DPM and respirable crystalline silica are not known.

RECOMMENDATIONS

Because DPM has been determined to be an occupational carcinogen, worker exposures should be controlled to the lowest feasible concentration, ideally below the State of California, Department of Health Services, HESIS TWA criterion of 20 μg/m^3. Employers with workers on oil and gas extraction sites should consider the hierarchy of controls including: elimination (remote location of diesel driven fracturing pumps), substitution (use of alternative fuels for diesel engines, move to higher EPA standard tier engines), and use of administrative controls to minimize exposures. If respirators are chosen or considered as part of exposure control, a respiratory protection program meeting the criteria of the OSHA respiratory protection standard (29 CFR 1910.134) should be in place.[25]

Performing additional exposure assessments for work crews identified to be at risk for DPM is recommended to better understand the magnitude of risks at the worksites, and controls that can be considered and implemented to minimize exposures.

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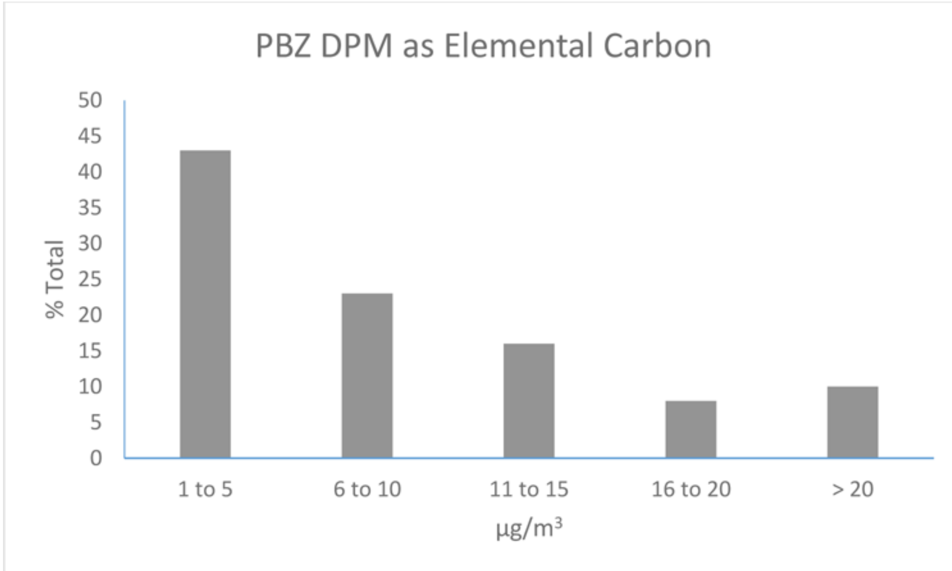

Figure I.

Distribution of Personal Breathing Zone (PBZ) Time Weighted Average (TWA) Values for Diesel Particulate Matter (DPM as Elemental Carbon)

Figure II.
Diesel Exhaust Emission Plumes from Hydraulic Fracturing Pump Engines

Table I

Personal Breathing Zone Measurements of Diesel Particulte Matter (DPM as µg/m^3 Elemental Carbon) by Operation Arithmetic (AM) and Geometric (GM) Means as Time Weighted Averages

Job Title*	Total # of samples	AM ±SD*	GM±SE**	Range	95% CI (lower/upper)
Completions	33	11.9±11.3	8.4±.1.1	1.4-52	6.2/11
Drilling Operations	10	7.4±5.3	5.7±1.4	2.0-18	3.3/10
Servicing Operations	6	5.4±3.8	3.0±2.1	0.1-11	0.5/18
Total	49	10±9.9	6.8±0.9	0.1-52	5.2/9.0

* SD = Standard deviation

** SE =Standard Error

Table II

Job Titles, numbers of Personal Breathing Zone Samples, Value or Range of Diesel Particulate Matter (as μg/m^3 Elemental Carbon) Time Weighted Average (TWA)

Job	n	Percent Total Samples	TWA Range (μg/m^3)
Water Transfer Operator (C)*	2	4.1	15-52
Chemical Truck Operator (C)	4	8.2	3-41
T-Belt Operator (C)	2	4.1	13-28
Sandmover Operator (C)	6	12.2	6-26
Blender Truck Operator (C)	2	4.1	5-22
Maintenance – Roving (C)	2	4.1	11-14
“Frac” Pump Operator Assistant (C)	1	2	9
Safety Lead (C)	1	2	8
Operator (C)	1	2	7
Fuel Safety – Roving (C)	2	4.1	5-8
Wireline Crew Operator (C)	1	2	6
Flowback Technician (C)	1	2	4
Fuel Delivery Technician (C)	1	2	5
Hydro Operator (C)	3	6.1	1-5
Sand Truck Coordinator-Roving (C)	2	4.1	3-5
Supervisor (C)	1	2	5
District Trainer (C)	1	2	2.6
Motor Hand (D)**	2	4.1	2-18
Floor Hand (D)	4	8.2	0.1-12
Gate Man (D)	3	6.1	3-9
Relief Driller (D)	1	2	4
Motor Hand (S)***	1	2	18
Well Servicing Contractor (S)	1	2	13
Floor Hand (S)	3	6.1	1.7-11
Derrick Hand (S)	1	2	2.6
Total	49		0.1-52

* Completions

** Drilling

*** Servicing

Table III

Area Measurement Diesel Particulate Matter (DPM as μg/m^3 Elemental Carbon) by Operation, Arithmetic (AM) and Geometric (GM) Means as Time Weighted Average (TWA)

Operation	Total # of samples	AM ±SD*	GM±SE**	*Range*	95% CI (lower/upper)
Completions	30	18.5±16.6	9.5±.2.7	*0.1-68*	5.3/17
Drilling Operations	21	16.2±15.0	11.0±2.2	*3.0-51*	7.2/17
Servicing Operations	4	8.4±8.4	4.4±3.2	*0.8-18*	0.4/47
Total	55	16.9 ±15.5	9.5±1.7	0.1-68	6.6/13.6

*SD = Standard deviation

**SE =Standard Error

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Table IV

Meteorology, Shale Play and Locations

Name of shale play/State Activity	Season	Range °F (average)	Weather	Wind Direction	Wind speed average, mph	Wind speed max, mph
Eagle Ford, TX Drilling	Summer	79 -104 (90)	Clear	SE	8-15	16-26
Piceance, CO Completions	Late Autumn	17-36 (27)	Rain, Snow	SSE, W, WNW	2-9	20-23
San Juan, NM Drilling	Summer	63-93 (76)	Clear	E, ESE, ENE, N	7-10	11-12
DJ/Niobrara. CO Completions	Summer	61-91 (76)	Clear, cloudy	NNW	4-6	17-21