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Vancouver, Canada

May 31 – June 3, 2017/ *Mai 31 – Juin 3, 2017*

POTENTIAL AIR QUALITY IMPACTS DUE TO HYDRAULIC FRACTURING IN WESTERN NEWFOUNDLAND

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ABSTRACT

Due to presence of potential Hydraulic Fracturing (HF) reserves in Western Newfoundland, there has been an increased interest in exploring these. However, due to the environmental concerns associated with HF a study was undertaken to identify environmental implications of HF in Western Newfoundland. This paper presents environmental and human health impacts associated with HF activities on air quality. Several studies have recognized that HF activities may lead to an increase in the type of air pollutants generally found at conventional operations, including those other pollutants specific to fracturing, such as silica sand, fracturing chemicals, and flowback wastewater. This study identified key air pollutants and their health impacts due to HF activities. An air quality modelling is conducted to study the dispersion of pollutants emissions as a result of HF activities. The emissions of pollutants were estimated based on EPA emission factors and other criteria, and using these emissions modelling of selected criterial pollutants were conducted in two domains in Western Newfoundland. Modelling exercise revealed that peak concentrations of NO_2 were relatively high while other pollutants were predicted low. Relative high concentrations of NO_2 is a cause of concern due to its health impact as well as its role in formation of tropospheric Ozone.

Keywords: - Hydraulic Fracturing; Newfoundland; Air quality; Air Dispersion Modeling

1.0 INTRODUCTION

Depending on the characteristics of the rock, hydrocarbon reservoirs are classified as either conventional or unconventional. In conventional reservoirs, layers of sandstone and fluid typically allow oil or natural gas to flow readily into wellbores. On the other hand, in unconventional reservoirs, due to the low permeability of the rock formation, the hydrocarbon cannot easily flow out unless a path is created artificially, for example, by hydraulic fracturing (HF), which is linked with the horizontal drilling of wells (GNLDNR, 2014 a).

Historically, oil and gas (O&G) have been largely extracted from the ground by drilling a vertical well into a hydrocarbon reservoir, called conventional reservoirs, and allowing the oil or gas to flow into the well by natural pressures. As conventional resources become limited, the exploitation of unconventional resources such as shales, tight sands, and coalbed methane is gaining recognition. Tapping shale reserves is not economically feasible for producing O&G without sophisticated technologies. To resolve this issue, research and innovation by O&G industries have produced advanced techniques for extracting the O&G trapped in shale formations. A key technology for accessing unconventional hydrocarbon resources is hydraulic fracturing, or fracking. HF involves pumping a mixture of water, sand, and chemicals into shale at a high pressure to create fissures or fractures in a tight rock formation. These fractures lead to an increase in the flow of natural gas and other hydrocarbons from the formation to the well. Fracking has gained popularity due to its capability to increase the exploration and production of shale O&G (PTAC, 2012). However, this expansion of fracking has also increased concerns from federal, provincial, and local agencies, including the public, about its associated potential environmental impacts on land, water, and air. Scientific research and investigations continue to look for an environmentally friendly use of HF. The HF operation consumes significant energy, which also brings new environmental management challenges for the O&G industry.

Due to the presence of potential HF reserves in Western Newfoundland, there has been an increased interest in exploring these reserves. However, due to the environmental concerns associated with HF a study was undertaken to identify the environmental implications of HF in Western Newfoundland. The main goal of this paper is to present the environmental impacts on air quality associated with the HF activities. The objectives of this paper include: identifying the main air pollutants and their health risks, evaluating the meteorology of the Western Newfoundland, estimating the air pollutants emissions, performing air dispersion modelling, and assessing the impacts.

2.0 AIR POLLUTANTS AND SOURCES

Conventional O&G operations have been known to create harmful air emissions. These pollutants include diesel particle emissions, hydrocarbons, VOCs (e.g., benzene), particulate matter (PM), and greenhouse gases (GHGs). The emissions of air pollutants from fracturing operations is similar to that from conventional O&G operations, but it is of a higher magnitude around fracturing sites because of the greater effort required (Green, 2014). The United States Environmental Protection Agency (USEPA) is also concerned about air pollutants that result from HF; according to USEPA (2014), there have been well-documented air quality impacts in areas with active natural gas developments, with increases in the emissions of methane (CH_4), VOCs, and hazardous air pollutants (HAPs). The main regional air emission issue is the generation of Ozone (O_3), which in some circumstances could adversely affect air quality (CCA, 2014).

Studies recognize that fracturing activity may lead to an increase in the type of air pollutants generally found at conventional O&G operations, including those other pollutants specific to fracturing, such as silica sand, fracturing chemicals, and flowback wastewater (Srebotnjak and Rotkin-Ellman, 2014). In general, the air emissions involved in fracturing operations can be categorized as:

- On-site criteria pollutants and their precursors such as carbon monoxide (CO), lead, nitrogen oxides (NO_x), O_3, PM, sulfur dioxide (SO_2) and VOCs.
- Air toxics and other HAPs, including fugitive emissions from mixing chemicals, spills, and flowback fluids (which can also include VOCs); and
- GHG emissions such as carbon dioxide (CO_2) and CH_4.

The sources of these emissions include combustion engines, powering on-site and transportation equipment, drilling process wastewater and condensate tanks, underground/downhole sources such as flowback fluids, and fugitive emissions from sand, dust, mixing chemicals, spills, or other uncontrolled gas releases (Tyner et al., 2014). Table 1 summarizes the potential activities/equipment and possible air pollutant emissions from a typical fracturing operation.

2.1 Criteria Pollutants

HF activities releases thousands of tons of air pollutants in the atmosphere, for example in 2012 fracturing activities in US emitted 13,000, 170,000, 250,000, 23,000 and 600 tons of PM, NO_x, CO, VOCs and SO_2 respectively (Ridlington and Rumpler, 2013). This potentially will pose significant impact on the local air quality in Western Newfoundland. The following sections elaborates on various criteria pollutants and their impact on health.

2.1.1 Particulate Matter (PM)

Particulate emissions originate from the combustion engines of heavy trucks and machinery used during well-site preparation, drilling, and production. PM is a complex mixture of very small particles and liquid droplets found in the air, including dust, dirt, soot, and smoke. The size of the particulate is directly linked to its potential for causing health problems. PM that is 10 micrometres (µm) in diameter or smaller (PM_{10}) poses a health concern because it can pass through the throat and nose and accumulate in the respiratory system. PM less than 2.5 µm in diameter ($PM_{2.5}$) is believed to pose the greatest health risk because it can get deep into a person's lungs and even into the bloodstream (USEPA, 2010). Total particulate matter (TPM) is the term applied to any particle suspended in the atmosphere, but typically it is limited to PM less than 44 µm in diameter. PM larger than 10 micrometres in diameter is typically associated with a nuisance rather than a health issue (DECNL, 2013). According to USEPA (2010), each well requires on average of between 2 and 5 million gallons of water per HF event. Water is generally transported by diesel trucks, each of which has an approximate capacity of 3,000 gallons (USEPA, 2011). It has been estimated that approximately 2,300 trips by heavy-duty trucks are required for each horizontal well during the early stages of shale gas development (USEPA, 2011). With thousands of such wells concentrated in high-development regions, the levels of truck traffic and diesel-associated air pollution will increase in these areas. In addition to diesel PM, other pollutants prevalent in diesel emissions, such as NO_x and VOCs, react in the presence of sunlight and produced ground-level O_3.

Table 1: Typical HF activities, sources, and air emissions from HF

Activity and Associated Equipment	Emissions & Sources	Potential air pollutants
Well site preparation and road construction	Trucks and heavy machinery	Diesel PM, NO_x, CO_2, CO, BTEX, PAH, and dust
Well drilling, hydraulic fracturing, and well completion	Drilling	Diesel PM, NO_x, CO_2, CO, BTEX, PAH, CH_4, volatile drilling mud fluids, and volatile hydrocarbons from drill cuttings
	Hydraulic fracturing	Silica dust, volatile fracturing chemicals, BTEX, other volatile hydrocarbons, PM, NO_x, CO_2, and CO
	Flowback and produced water	Volatile fracturing fluids, BTEX, other volatile hydrocarbons, and hydrogen sulfide (H_2S)
Production	Produced water	BTEX, other volatile hydrocarbons, and H_2S
	Gas flaring/venting	CH_4, NO_x, CO_2, CO, PM, H_2S, BTEX, and other volatile hydrocarbons
	Work-over and maintenance	Diesel PM, NO_x, CO_2, CO, CH_4, BTEX, PAH, and other volatile hydrocarbons
Processing and storage	Gas venting	CH_4, H_2S, BTEX, and other volatile hydrocarbons
	Separators and condensate tanks	CH_4, BTEX, and other volatile hydrocarbons
	Compressors	diesel PM, NO_x, CO_2, CO, BTEX, PAH, and other volatile hydrocarbons
Transmission	Pipelines	CH_4, BTEX, and other volatile hydrocarbons
	Compressor stations	Diesel PM, NO_x, CO_2, CO, BTEX, PAH, and other volatile hydrocarbons
	Gas venting	CH_4, H_2S, BTEX, and other volatile hydrocarbons
Well abandonment and site rehabilitation	Trucks and heavy machinery	Diesel PM, NO_x, CO_2, CO, BTEX, and PAH
	Abandoned orphaned wells	CH_4

Compiled from Srebotnjak and Rotkin-Ellman, 2014; Tyner et al., 2014

2.1.2 Nitrogen Oxides (NO_x)

Nitric oxide (NO) and nitrogen dioxide (NO_2) are collectively referred to as NO_x. These are generally produced due to combustion activities. In Canada, the main sources of NO_x are from transportation (50%), petroleum industry (22%), electric power generation (10%), natural source (8%) and other industrial and non-industrial sources (10%).

2.1.3 Carbon monoxide (CO)

CO is a colourless and odourless gas which reduces the delivery of oxygen (O_2) to the body's organs. Generally, incomplete oxidation of fuel results in the formation of CO. However, if sufficient O_2 is not present to complete the combustion of the hydrocarbon fuel, the oxidation to CO_2 and water (H_2O) is not completed, and hence CO is emitted.

According to Natural Resources Canada (NRC) (2012), shale gas has a low CO_2 content, similar to typical conventional gas production. Therefore, as more shale gas development occurs, the GHG emission per unit of shale gas produced and consumed should be similar to that from conventional natural gas production and use.

2.1.4 Volatile organic compounds (VOCs)

Fracturing fluids can contain VOCs such as benzene, which can be released into the atmosphere when the fluid evaporates (Colborn et al., 2011). The wellheads themselves vent VOCs such as benzene and toluene that can combine with combustion by-products to create smog (Conrad et al., 2010). However, according to Bunch et al. (2014), shale gas production activities did not result in community-wide exposure to concentrations of VOCs at levels that would pose a health concern.

2.1.5 Ozone (O_3)

O_3 is a secondary pollutant that is formed in polluted areas by atmospheric reactions involving two main types of precursor pollutants: VOCs and NO_x. CO from the incomplete combustion of fuels is also an important precursor for O3 formation. The formation of O_3 and other oxidation products (e.g., peroxyacyl nitrates and hydrogen peroxide), including oxidation products of the precursor chemicals, is an extremely complex reaction that depends on the intensity and wavelength of sunlight, atmospheric mixing and interactions with cloud and other aerosol particulates, the concentration of VOCs and NO_x in the air, and the rates of all chemical reactions. The majority of ground-level O_3 is formed when the O_3 precursors NO_x, CO, and VOCs react in the atmosphere in the presence of sunlight (Conrad et al., 2010). VOC sources can come from ponds, condensers, and other gas-processing equipment and compressor-transmission operation (Conrad et al., 2010).

2.2 Greenhouse Gas (GHG) Emissions

HF operations require a significant amount of energy and, as HF locations are generally remote, that energy has to be generated on-site (Green, 2014). In most cases, conventional power generators fueled by diesel fuel, natural gas, or other fossil fuels are used. The combustion of such fuel leads to the emission of GHGs (Green, 2014). In addition, improperly drilled wells may leak CH_4 and other GHGs to the atmosphere during and after the production period of the well. The literature claims that HF would increase natural gas emissions to the atmosphere due to leakage during the HF process and at the beginning of gas recovery (Green, 2014). CH_4 is considered to be one of the most potent GHGs. It is estimated that 100 million tons of CO_2 equivalent is released since 2005 due to HF activities in US, thus contributing to global warming (Ridlington and Rumpler, 2013).

More recently, reduced emissions completions (RECs), or “green completions,” which capture and separate natural gas during well completion and workover activities, have become a key technology to limit the amounts of CH_4, VOCs, and HAPs that can be vented during the flowback period without the disadvantage of flaring. RECs use portable equipment that allows operators to capture natural gas from the flowback water. After the mixture passes through a sand trap, a three-phase separator removes natural gas liquids and water from the gas, which is then sent to sales pipelines for distribution. REC operations have been found to be very cost-effective even with low natural gas prices (Green, 2014).

According to Natural Resources Canada (NRC) (2012), “most prospective shale gas developments have low CO content, similar to typical conventional gas production. Therefore, as more shale gas development occurs, the greenhouse gas emissions per unit of shale gas produced and consumed should be similar to that from conventional natural gas production and use.”

Numerous other cost-effective technologies have been developed to reduce natural gas leakage, such as plunger lift systems, dry seal systems, and no-bleed pneumatic controllers. Through the use of these technologies and practices, nearly 90 percent of the natural gas leakages could be addressed (PTAC, 2012). To further reduce the emissions impacts at well sites in densely populated areas, electric motors could be used instead of internal combustion engines (Clark et al., 2013).

3.0 POTENTIAL HEALTH RISKS

The specific health effects due to air contaminants and their extent are dependent on a variety of factors such as the type and length of exposure to a contaminant as well as the health status and lifestyle of the exposed individual. Along with the concern of increased GHG emissions, the impact of air emissions from HF has become a debated issue in the environmental movement. Due to a low emission rate, some emissions have been acknowledged to be relatively harmless to human health. Naturally occurring radioactive materials (NORM), one identified source of emissions, are brought to the surface during shale gas production but remain in such places as rock pieces with the produced water (USDOE, 2009). As the radiation from these NORMs is weak, it cannot penetrate dense materials or cause extreme risks from exposure. However, radiation hazards must be evaluated so that it does not exceed regulatory standards concentrations.

Other chemicals have been detected in drilling locations that are highly detrimental, particularly to air quality. For example, with benzene, a carcinogen that typically causes leukemia, health concerns arise when its level reaches 1.4 parts per billion (ppb). In 2009, air samples from a Targa Resources compressor station outside Decatur, Texas, revealed that the level of benzene reached 1,100 ppb; a sample from a nearby Devon Energy well revealed 15,000 ppb (Hawes, 2009). Of the 300 air samples taken from 30 facilities in north central Texas, 50 exceeded the Texas Commission of Environmental Quality's standard for long-term health risk (WISE, 2010).

Air emissions can also be attributed to the equipment used to extract natural gas by HF. Millions of gallons of water are commonly transported by tanker trucks; for instance, over 1,000 truck trips were required for one fracture (WISE, 2010). Each truck trip could stir up dust and release PM, NO_x, and CO_2 into the air. Diesel engines needed to run the drilling equipment use large amounts of fuel that also produce a significant amount of emissions.

A health impact assessment conducted by Witter et al. (2008) for O&G development concluded that air quality is most likely affected during well-pad construction and well completion and through truck traffic. Fugitive emissions from production equipment are another possible long-term source of air contamination that needs to be controlled. Table 2 lists the potential health and environmental effects from criteria air pollutants and BTEX respectively, released from HF operations.

A human health risk assessment of air emissions carried out in a region of Colorado with a shale gas development near a rural population detected several different air emissions in close proximity to the development. The study found that the highest air pollution concentrations occurred during well development and completion (McKenzie et al., 2012). Overall, two-thirds more hydrocarbons were detected during well completion than during the production phase. The range of concentrations detected for several VOCs and BTEX during completion was large. For instance, the minimum detected concentration of m-xylene/p-xylene was 2.0 $\mu g/m^3$ of air, whereas the maximum was 880 $\mu g/m^3$ of air (McKenzie et al., 2012). Health Canada's tolerable concentrations over a lifetime for xylene isomers (m-xylene/p-xylene) are 180 $\mu g/m^3$ and 348 $\mu g/m^3$ respectively (Ruth, 1986; Health Canada, 1996).

4.0 METEOROLOGY OF WESTERN NEWFOUNDLAND

4.1 General Climate

The western Newfoundland area is located between the latitudes 46º36' and 51º38'. Due to the influence of ocean, the area experiences slightly warmer winter and cooler summer than the inland areas. The average temperature in summer remains in the 20-25°C range, while winter temperatures are below zero. Geographically, the whole area is located in westerlies winds (30-60º of latitude), the dominating wind direction prevail from west. However, with the influence of ocean currents the wind direction of the area varies.

4.2 Winds

The winds were analyzed based on five-year meteorological data (2010-2014) obtained from National Centers for Environmental Information (NCEI) for various weather stations in western Newfoundland. Three stations i.e., Stephenville, Deer Lake and St. Anthony were selected to analyze the wind patter. Due to the influence of ocean currents, wind direction varies in different seasons of western Newfoundland. The dominant winds tend to prevail from W sectors for six stations with the exception of Wreck House, which the dominate winds tend to prevail from N and S.

Five-year wind rose plots indicated that the wind speed of areas on the coast is generally will be higher than it of inland areas. The dominate wind speed of Deer Lake is 3.00-5.70 m/s in summer and 5.70-8.80 m/s in winter, while it is 5.70-8.80 m/s in summer at St. Anthony and Stephenville, and over 8.80 m/s in winter at these two stations. Wind speed in summer could be 1-2 classes lower than it in winter. The dominate wind direction of all three stations are prevail from W in winter and SW in summer. In recent years, the trend of wind direction of St. Anthony is tending to SW in winter and SE in summer and varies in spring and fall. At Deer Lake station, the dominate wind direction prevail to WSW and NE all year round. In spring, NE is the dominate wind direction, while WSW in summer and winter. The trend of the wind direction of Deer Lake is moving to SW and SSW in summer. At Stephenville station, the dominate wind direction prevail from W and E. WSW is the dominate wind direction in summer, while E in spring. W and WNW are the dominate wind direction in winter. Recent years trend indicates that in summer the dominate wind direction prevail to WSW, while W in winter and ENE in spring.

Table 2: Air contaminants associated with HF and their effects

Substance	Potential Health Effects	Environmental and Climate Effects
Particulate Matter (PM)	Non-fatal heart attacks Irregular heartbeat Aggravated asthma Reduced lung function Increased respiratory symptoms (e.g., coughing, difficulty breathing) Premature death in people with heart or lung disease	Impairs visibility, adversely affects ecosystem processes, and damages and/or soils structures and property. Variable climate impacts depending on particle type. Most particles are reflective and lead to net cooling, while some (especially black carbon) absorb energy and lead to warming. Other impacts include changing the timing and location of traditional rainfall patterns
Oxides of Sulfur (SO_x) from process unit (EESI, 2011)	Aggravate asthma, leading to wheezing, chest tightness and shortness of breath, increased medication use, hospital admissions, and ER visits; very high levels can cause respiratory symptoms in people without lung disease.	Contributes to the acidification of soil and surface water and mercury methylation in wetland areas. Causes injury to vegetation and local species losses in aquatic and terrestrial systems. Contributes to particle formation with associated environmental effects. Sulfate particles contribute to the cooling of the atmosphere.
Nitrogen Oxides (NO_x)	Irritated respiratory system aggravated asthma, bronchitis, or existing heart disease Combines with VOCs to form O_3	Contributes to the acidification and nutrient enrichment (eutrophication, nitrogen saturation) of soil and surface water. Leads to biodiversity losses. Impacts levels of O_3, particles, and CH_4 with associated environmental and climate effects.
Carbon Monoxide (CO)	Exacerbation of cardiovascular disease behavioural impairment Reduced birth weight increased daily mortality rate	Contributes to the formation of CO_2 and O_3, GHGs gases that warm the atmosphere.
Volatile Organic Compounds (VOCs)	Carcinogen (some VOCs) Leukemia and other blood disorders (benzene) Birth defects (some VOCs) Eye, nose, and throat irritation (some VOCs) Adverse nervous systems effects	Contributes to O_3 formation with associated environmental and climate effects. Contributes to the formation of CO_2 and O_3, GHGs that warm the atmosphere.
Ground Level Ozone (O_3) (Smog)	Reduced lung function Aggravated asthma or bronchitis Permanent lung damage	Damages vegetation by visibly injuring leaves, reducing photosynthesis, impairing reproduction and growth, and decreasing crop yields. O_3 damage to plants may alter ecosystem structure, reduce biodiversity, and decrease plant uptake of CO_2. O_3 is also a GHG that contributes to the warming of the atmosphere.
Methane (CH_4)	Asphyxiation in confined spaces. May cause rapid breathing, rapid	

Substance	Potential Health Effects	Environmental and Climate Effects
	heart rate, clumsiness, emotional upset, and fatigue. At greater exposure, may cause vomiting, collapse, convulsions, coma, and death.	

Source: Fierro et al., 2001; USEPA, 2013a, 2013b, 2013d; McKenzie et al., 2012

5.0 DISPERSION MODELLING

5.1 Dispersion Models

Several air dispersion models have been developed so far, however three main models are widely used, namely AERMOD (AERMOD, 2004), CALPUFF (Scire et al., 2000 a) and CMAQ (CMAS, 2015). AERMOD is a steady-state plume dispersion model designed to predict near field concentration of pollutants, while CALPUFF is a lagrangian Gaussian puff dispersion model for both near and far field applications. CMAQ is a 3D grid-based photochemical air quality model and it specialized in simulating O_3 and photochemical oxidants. These models have been developed by US EPA and used as regulatory model for several purposes. CALPUFF is selected for modelling a hypothetical scenario in Western Newfoundland, as it is recommended model for all regulatory applications in NL (NL Guideline for Plume Dispersion Modelling, 2012).

5.2 Modelling Scenario

In order to study the extent of impact of air emissions, two hypothetical release scenarios are developed and modelled. Table 3 shows the drill rig emissions per well for criteria pollutants, HAPs, and GHG.

The estimates are based on the following assumptions:

- It requires approximately 600 hours of operation (approximately 25 days at 24 hour/day).
- Drill rig horse power is 1, 500 hp
- Diesel fuel sulfur content 0.0005 % (EPA standard)
- AP-42 emission factors are used.

The emissions from a single well activity is very low, however HF drilling are performed in large numbers for sustainable production. In US, over 13,000 wells are drilled per year.

Two modelling scenarios were undertaken in this report, one assuming 500 wells will be drilled per year in the Western Newfoundland (hereafter referred to as South-West NL run), and the second scenario assumed 80 wells per year in a small domain near Port au Port bay (hereafter referred to as Port au Port run). Table 4 illustrates the calculation of number of wells that needs to be drilled simultaneously. It is assumed that the drilling operations are executed only during summer months due to adverse weather conditions in other months.

5.3 Study Area and Modelling Domain

HF activities potentially could occur in entire Western Newfoundland; hence study must cover the geography of Western Newfoundland. Further, small areas of interest may be selected and fine resolution modelling could be done to study the local impacts of the air pollutants. This study selected two domains: Domain 1, and Domain 2. The pollutants modelled were PM_{10}, $PM_{2.5}$, NO_x CO and SO_2. However, similar study must be done for other domains and pollutants. The meteorological Domain 1 was 130 km x 130 km with a resolution of 4 km as shown in Figure 1a. This domain was scaled down to 17.5 km x 17.5 km near Port au port with a resolution of 500 m to study the local impacts in the area as shown in Figure 1b.

5.4 Meteorological Modelling

The CALPUFF simulation model requires meteorological data to represent the transport and dispersion of pollutants in the domain. The meteorological characteristics over the domain vary both spatially and temporally. The CALMET diagnostic model was used to provide CALPUFF model the spatial and temporal meteorological parameters. The WRF prognostic meteorological model was used to generate input for CALMET as described briefly in the following sections.

Table 3: Drill Rig Emissions Per Well of Criteria Pollutants and VOC (Adopted from Drill Rig Emissions, 2012)

Species	Drilling Rig Emission Factor	Per Well (lb/hr)	Per well (g/s)
Criteria Pollutants & VOC			
NO_x [a]	0.0152	9.12	1.1490
CO [a]	5.73E-03	3.44	0.4330
PM_{10} [a]	4.00E-04	0.24	0.0302
$PM_{2.5}$ [b]	4.00E-04	0.24	0.0302
SO_2 [b]	4.05E-06	2.43E-03	0.0003
VOC [a]	2.20E-03	1.32	0.396
HAPs			
Benzene [d]	5.82E-06	3.49E-03	1.05E-03
Toluene [d]	2.11E-06	1.26E-03	3.79E-04
Xylenes [d]	1.45E-06	8.69E-04	2.61E-04
Formaldehyde [d]	5.92E-07	3.55E-04	1.07E-04
Acetaldehyde [d]	1.89E-07	1.13E-04	3.40E-05
Acrolein [d]	5.91E-08	3.55E-05	1.06E-05
Naphthalene [e]	9.75E-07	5.85E-04	1.76E-04
Total PAH [e, f]	1.59E-06	9.54E-04	2.86E-04
Greenhouse Gases			
CO_2 [b]	1.16	696	207
CH_4 [b, c]	7.05E-04	0.423	0.127

[a] Emission factors for Tier II non-road diesel engine emission standards from dieselnet.com (NOX, CO, VOC and PM) - Tier II emission standards are not set for VOC (listed as Hydrocarbons), so the Tier I Standard is used - Tier II or Tier I emission standards are not set for PM2.5, so thePM10 emission factor is used

[b] AP-42 Volume I, Large Stationary Diesel Engines Tables 3.4-1 and 3.4-2 Diesel Fuel, 10/96. VOC emission factor represents total Hydrocarbon Emissions

[c] CH4 Emission Factor listed in notes of AP-42 Table 3.4-1 as 9% of Total Organic Compounds

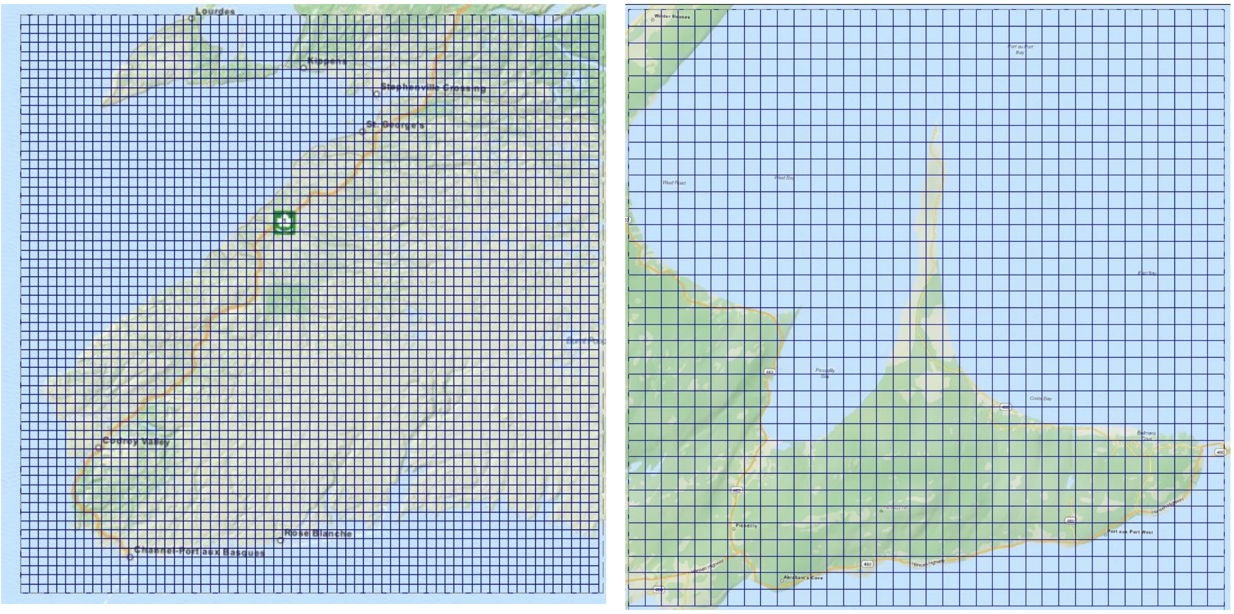
[d] AP-42 Volume I, Large Stationary Diesel Engines Table 3.4-3

[e] AP-42 Volume I, Large Stationary Diesel Engines Table 3.4-4

[f] PAH (Polycyclic Aromatic Hydrocarbons) includes naphthalene and are a HAP because they are polycyclic organic matter (POM)

Table 4: Calculation of number of wells to be drilled simultaneously

Item	500 Wells/Year	80 Wells/Year
Number of wells to be drilled per year	500	80 wells
Number of days required per well	25	25 days
Total drilling days	500 x 25 = 12,500	80 x 25 = 2, 000
Available days for drilling (May, June, July, August, September)	150 days	150 days
Simultaneous drilling	12,500/150 ~ 83 wells	2,00/150 ~ 13 wells



(a) Southwest (b) Port au port

Figure 1: Meteorological grids for dispersion modelling

5.4.1 CALMET Ready WRF Data

WRF version 3.4.1 (next-generation mesoscale model) is a prognostic meteorology model developed in partnership by the National Center for Atmospheric Research, the National Oceanic and Atmospheric Administration, the Air Force Weather Agency, the Naval Research Laboratory, the University of Oklahoma, and the Federal Aviation Administration. The model is a hydrostatic, terrain-following, eta-coordinate model designed to simulate or predict mesoscale and regional-scale atmospheric circulation. WRF was primarily developed using FORTRAN coding, is used as a community model in over 150 countries and is updated on an annual basis. For the current simulation, CALMET ready files were obtained from Lakes Environmental based on the WRF model for 2014 with horizontal resolution of 4 km.

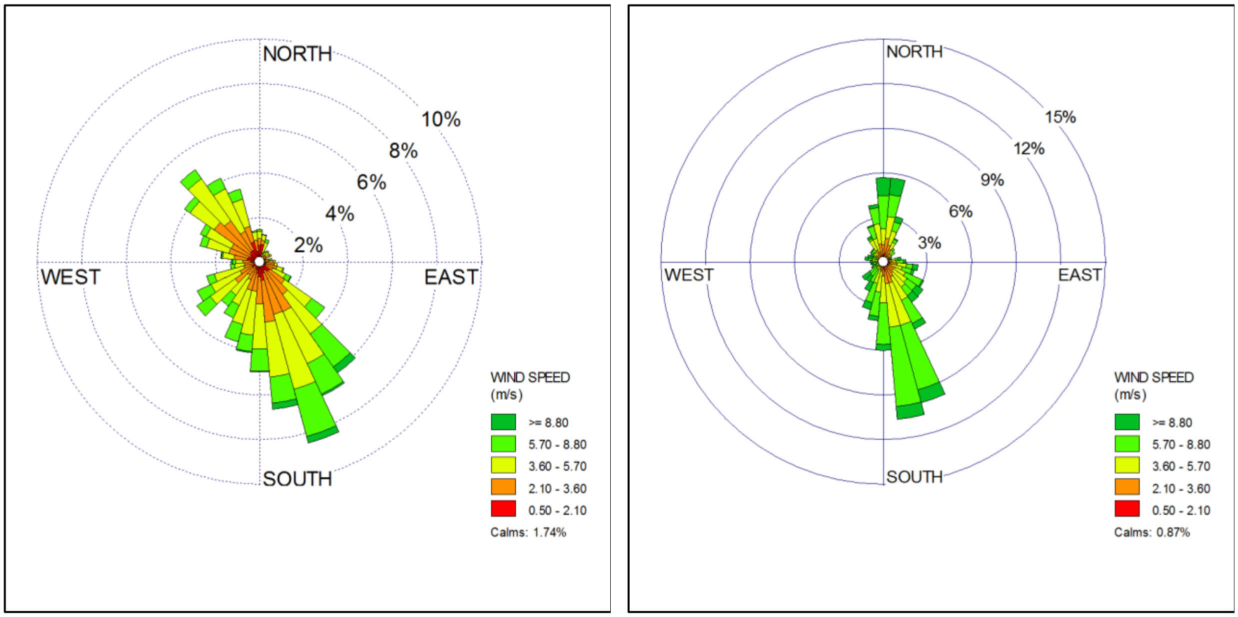
5.4.2 CALMET

CALMET is a diagnostic meteorological model that produces 3-D wind fields based on parameterized treatments of terrain effects such as slope flows, terrain blocking effects, and kinematic effects. Using available sources of meteorological and geophysical information it produces a spatially varying wind field that is consistent with the local terrain and land use features, as well as atmospheric stability conditions and mixing height values necessary for the dispersion modeling.

The domain size configured in CALMET for South-West run was 128 km x 128 km, slightly less than WRF domain. The horizontal domain was downscaled to 2 km to study the dispersion of pollutants in detail. It consisted of 64 x 64 grid cells with a Universal Transverse Mercator (UTM) map projection of 21N and datum of WGS-84. Similarly, for Port au port run, the domain was 17.5 km x 17.5 km with a resolution of 500m and 36 x 36 grid cells.

In order to properly simulate pollutant transport and dispersion, it is important to define the vertical profile of meteorological parameters such as wind speed, temperature, turbulence intensity and wind direction with the atmospheric boundary layer. Eleven vertical levels are centred at 10, 30, 60, 120, 240, 480, 820, 1250, 1850, 2600, and 3500 meters above the ground. The cell face heights corresponding to these grid points are 0, 20, 40, 80, 160, 320, 640, 1000, 1500, 2200, 3000 and 4000 meters.

The resolution of terrain and land use data used in the modelling were 23 meters and 25 meters respectively. The source of terrain data was from Canada Digital Elevation Data (CDED, 1999) and the source of land use was Earth Observation for Sustainable development (EOSD, 2003. CALMET derived wind rose diagram during summer 2014 at the center of domain at an elevation of 10 m is shown in Figure 2 for South-West and Port au Port domain. As observed, winds in South-West were either blowing from south-east or north-west, however were predominant from south-east. The wind speed was most of the time in the range of 5-8 m/s with about 1% calm conditions. This shows that the pollutants are expected to disperse in all direction with a higher tendency to move towards north-west.



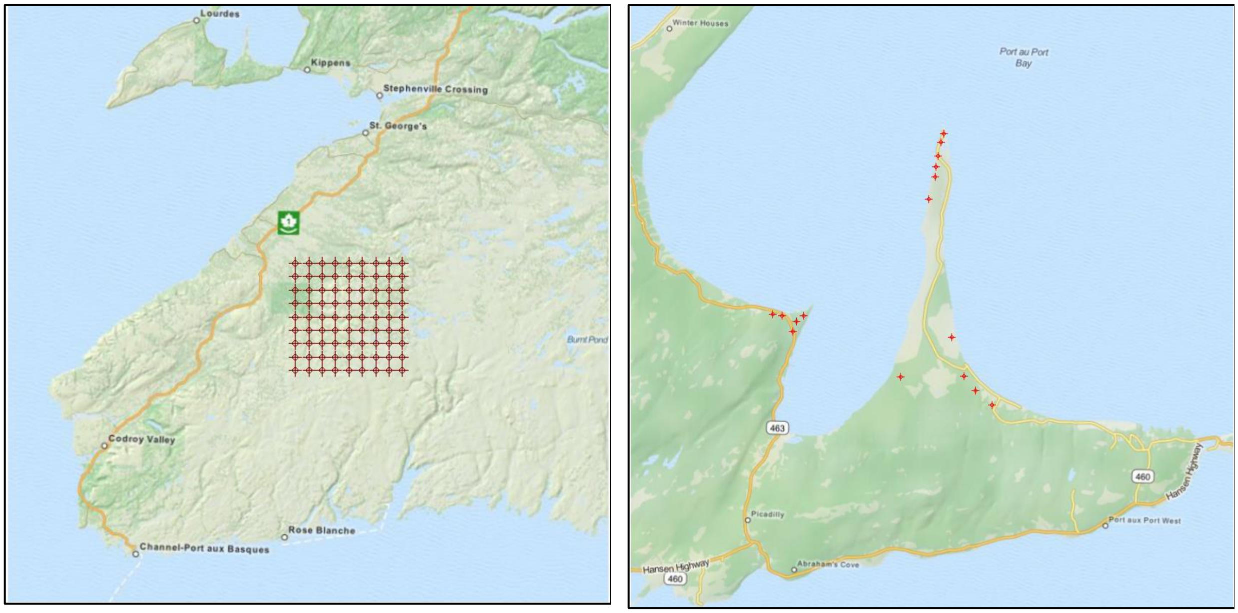
(a) Southwest (b) Port au port

Figure 2: CALMET derived wind rose at 10 m elevation at the center of the domains in summer 2014 (winds directions are blowing from)

5.4.3 CALPUFF Modelling

In this modelling study, the CALPUFF simulations were conducted using these model options: Gaussian near-field distribution, Transitional plume rise, Stack tip downwash, Turbulence based dispersion coefficients, Transition of σy to time-dependent (Heffter) growth rate, Partial plume path adjustment for terrain, Modeling of dry deposition, Consideration of chemical transformations and, No consideration of wet deposition.

CALPUFF View™, the Lakes Environmental graphical user interface was used to process the input and output. CALPUFF Version 7 was applied on five months (May-Sep) CALMET data. Continuous release of five criteria pollutants from 81 wells for five months was assumed. For the South-West run, the wells were assumed to be in the middle of the domain as shown in Figure 3a, while wells are scattered over the coastline for Port au Port run as shown in Figure 3b. The CALPUFF computational grid was same as CALMET, species modelled for both runs were NO_x, CO, PM_{10}, $PM_{2.5}$, and SO_2. The input emissions are provided to CALPUFF by variable point emission sources files, these are prepared by specialized processors in the format PTMAERB. The format is defined in the CALPUFF user guide (Scire et al., 2000 a).



(a) Southwest (b) Port au port

Figure 3: HF drilling locations

5.5 Dispersion Results

The results of South-West and Port au Port runs are summarized in Table 5. The peak concentrations in the domain are compared with NL ambient air quality standards. The peak concentrations of all the pollutants are within the standards, however NO_2 shows significant high values. The peak concentrations of NO_2 were 168.71 µg/m^3 and 115.15 µg/m^3 for the South-West and Port au Port runs respectively. Due to highly varying winds the pollutants dispersed in all directions. The location of peak for the Port au Port run was towards south near the peninsula, while the peak for South-West run were in the vicinity of the assumed drilling location in the center of the domain. The spatial variation of the pollutants is presented as contour plots. Figures 4 and Figure 5 show contours plots for modelled pollutants for NO_2 in the two domains.

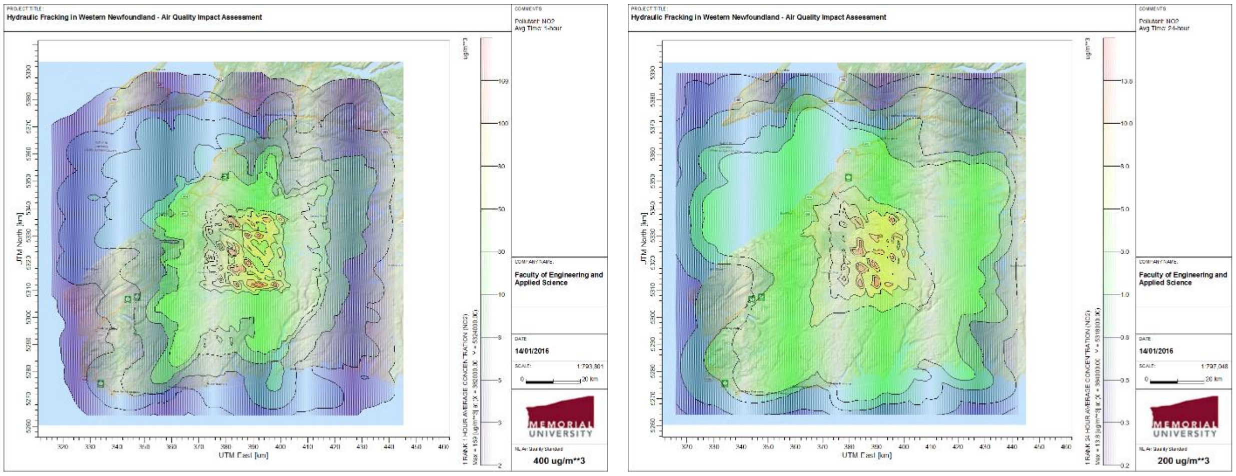
Table 5: Modelled peak concentrations of criteria pollutants

	NL Air Quality Standard (µg/m^3)	Peak Concentration (µg/m^3)	
		South-West Run[1]	Port au Port Run[2]
NO_2			
1-hour	400	168.71	115.15
24-hour	200	13.76	12.81
Annual	100	2.59*	1.92*
PM_{10}			
24-Hour	50	0.37	0.36
Annual		0.07*	0.05*
$PM_{2.5}$			
24-hour	25	0.37	0.36
Annual	-	0.07*	0.05*
CO			
1-hour	35,000	64.51	42.04
8-hour	15,000	14.56	8.63
SO_2			
1-hour	900	0.04	0.02
24-hour	300	0.004	0.003
Annual	60	0.0006*	0.0005*

[1] Based on drilling 500 wells/year (81 simultaneous) spread over western NL domain (300 km x 300 km)

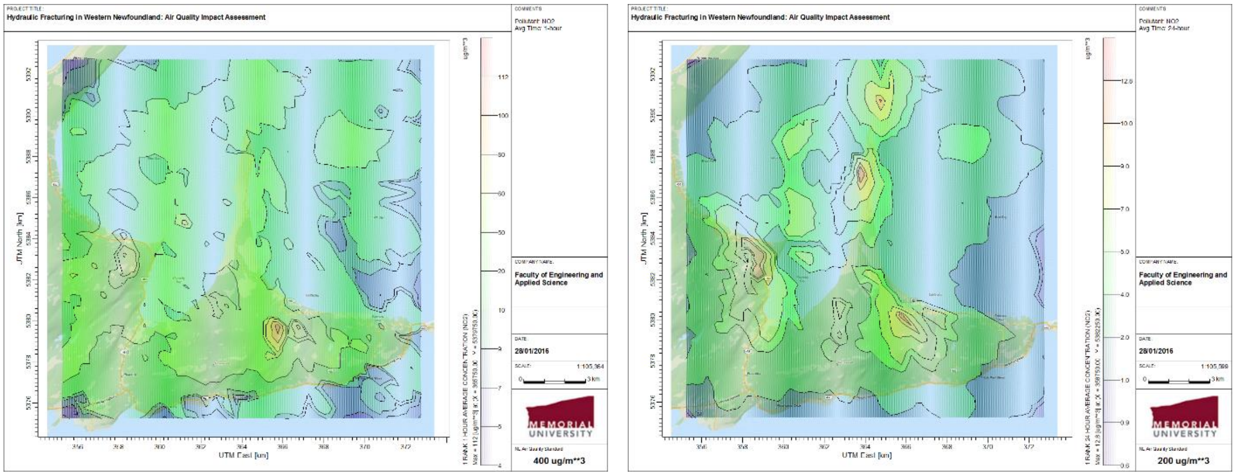
[2] Based on drilling 80 wells/year (15 simultaneous) spread in Port au Port bay domain (17.5 km 17.5 km)

* Values are run length average (5 months)



(a) 1-hour average (b) 24-hour average

Figure 4: Southwest run – Peak 1-hour and 24-hour average NO$_2$ concentrations



(a) 1-hour average (b) 24-hour average

Figure 5: Port au port run – Peak 1-hour and 24-hour average NO$_2$ concentrations

6.0 CONCLUSIONS

Although state-of-the-art technologies are employed in current HF operations, these technologies are not without any environmental footprint, including that on air quality. The main sources of air-quality pollutants during HF operations are emissions from trucks and heavy machinery, flowback and produced water, gas flaring venting activities, compressor stations, and separators and condensate tanks. The primary pollutants are particulate matter (PM), nitrogen compounds, volatile organic compounds (VOCs), and benzene, toluene, ethylbenenze, and xylene (BTEX), which are harmful to humans as well as to flora and fauna. Thousands of tons of these pollutants are known to be released due to HF activities. Methane (CH$_4$) which is one of the potent greenhouse gases (GHGs) may be leaked due to improperly drilled wells. Dispersion of pollutants depends largely on the meteorology of the area. Average summer temperatures in the area were in the range of 20-25 ^{0}C while winters are below zero. The wind blows predominantly from west as geographically this area is located in westerlies, however due to the influence of ocean currents the wind direction varies highly in certain areas. The emissions of criteria pollutant per well were estimated based on EPA emission factors. Using these emissions, a preliminary air dispersion study of selected criterial pollutants was conducted in two domains. The first domain was a large area covering south-west NL, and the second one a small and high resolution area covering Port au Port peninsula. The modelling exercise revealed that the peak concentrations of NO_2 were relatively high while other pollutants were predicted very low. All modelled pollutants were below NL ambient air quality standards however, relative high concentrations of NO_2 is a cause of concern due to its health impact as well as its role in the formation of O_3. Therefore, a detailed photochemical modelling is highly recommended to study the regional O_3 formation in addition to detailed dispersion study for other criteria pollutants including BTEX which is an occupational health hazard. Appropriate air quality mitigation measures include avoiding venting, taking measures to reduce greenhouse gases, and conducting periodic site-specific air-quality monitoring.

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