FINAL TECHNICAL REPORT

March 2, 2015

Inventory of Atmospheric Emissions from Heavy Oil Production Facilities in the Three Creeks Area.

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EXECUTIVE SUMMARY

Clearstone Engineering Ltd. has compiled an emission inventory for heavy oil operations in the Three Creeks area. Three Creeks is approximately 20 to 60 km northeast of Peace River, Alberta and is approximately five ranges by two townships in size and includes cold heavy oil production (CHOPS) and in-situ thermal operations. Active producers in the area include Baytex Energy Ltd., Murphy Oil Company Ltd., Penn West Petroleum Ltd. and Shell Canada Ltd.

The overall project objective is to produce an inventory of 2004 to 2012 and projected VOC, RSC and CAC emissions for the Three Creeks study area. The following emission source categories are considered in the inventory development. Quantification methodologies for each category are consistent with those published in the National Inventory of Greenhouse Gas (GHG), Criteria Air Contaminant (CAC) and Other Priority Substance Emissions by the Upstream Oil and Gas Industry: Volume 3 (Environment Canada, 2014).

- Flaring
- Fugitive Emissions
- Glycol Dehydrator Regenerator Emissions
- Production Tank Cleaning Emissions
- Production Tank Losses
- Residential Heaters
- Stationary Fired Equipment
- Truck Loading Losses
- Vehicle Combustion Emissions
- Waste Oil Reclaiming and Disposal

Inventory results rely on best available data provided by producers and the companion report "Field Measurements of Heavy Oil Truck Loading and Tank Cleaning Activities in Three Creeks" summarizing field measurements completed by Clearstone during the summer and fall of 2014. Field observations and measurements enhance the inventory as follows:

- Instead of using EPA truck loading emission quantification methodology (U.S. EPA, 2008), the average dry-gas venting to loaded product factors (GOR) and air-in gas compositions measured for oil and water trucks are used.
- Three Creeks compositions for casing gas, tank vapour, oil truck vapour and water truck vapour from Alberta Innovates Technologies Futures (AITF) laboratory results are applied.
- Tank cleaning emission estimates are based on a schedule of 12 de-sanding and 1 clean-out events per year.

- Sulphur control efficiency[1] of 81 percent is applied to production and truck tank venting for operators that have implemented scrubber control technologies.
- The equipment inventory is aligned with equipment observed during field visits.

Final inventory results are of sufficient quality and detail to answer emission release characteristic questions presented by the Three Creeks Industry Air Quality Working Group. Emissions and production in the Three Creeks area from 2004 to 2012 are presented in Table ES-1. Production increased 4.5 times between 2004 and 2012 while emission increases depend on the substance group of interest and whether controls are implemented. For example, Figure ES-1 shows VOC emissions increase as production rates increase from 2004 until 2008 when mitigating actions begin to be implemented. Between 2009 and 2012 VOC emissions decrease by approximately 50 percent even though production continues to increase.

Table ES-1: Target emissions and production between 2004 and 2012 in Three Creeks.

Year	Target Substance Group Emissions (tonnes per year)						Total Production (m^3 OE/yr)
	Volatile Organic Compounds	Total Reduced Sulphur[1]	Sulphur Dioxide	Oxides of Nitrogen	Carbon Monoxide	Total Particulate Matter[2]	
2004	38.4	0.44	2,158.4	338.4	230.7	4.9	579,671
2005	56.1	0.49	3,451.5	372.0	243.9	5.6	672,268
2006	125.9	0.66	2,483.7	371.5	260.1	7.2	737,982
2007	363.2	1.33	3,288.6	526.2	434.9	7.7	1,284,671
2008	846.7	4.16	3,499.0	632.1	561.9	10.5	1,548,286
2009	771.8	3.08	2,175.1	738.4	857.0	48.1	1,652,313
2010	728.3	3.00	1,457.3	1,298.1	1,665.3	62.5	1,821,484
2011	737.9	2.30	137.6	1,032.7	1,227.9	44.7	1,839,222
2012	430.7	1.76	135.5	1,375.0	1,698.1	55.9	2,635,999

1 TRS emissions from 2004 to 2010 do not account for sour fuel combustion at the 05-21 thermal plant and are therefore understated.

2 From combustion sources only (does not include road dust).

[1] Well maintained scrubbers should provide 100 percent control of target substances, however, some were observed to operate with expired catalyst causing the average control efficiency to be less than 100 percent.

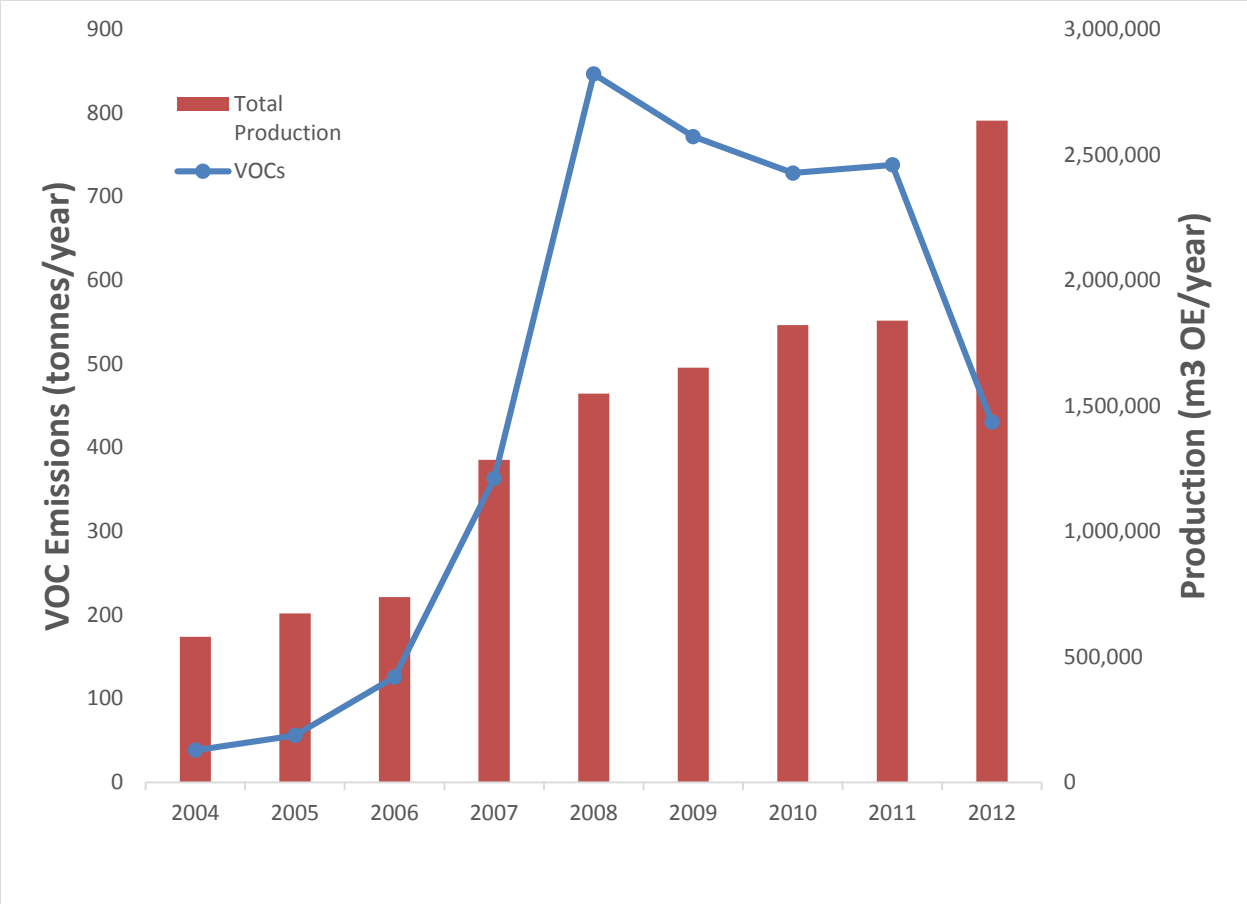

Figure ES-1: VOC emissions and production in Three Creeks from 2004 to 2012.

As illustrated in Figure ES-2, 2012 VOC emissions are primarily from truck loading (33%) and natural gas fuel combustion (22%) followed by fugitives (13%), storage losses (12%), flaring (9%) and tank cleaning (6%) emissions. Vehicle combustion, dehydrators, pneumatics and casing venting only represent 4 percent of VOC emissions.

Figure ES-3 shows 2012 RSC emissions are primarily from natural gas fuel combustion (56%), flaring (15%) and truck loading (12%) followed by fugitives (9%), tank losses (5%), and tank cleaning (2%). Dehydrators, pneumatics and casing venting only represent 1 percent of RSC emissions.

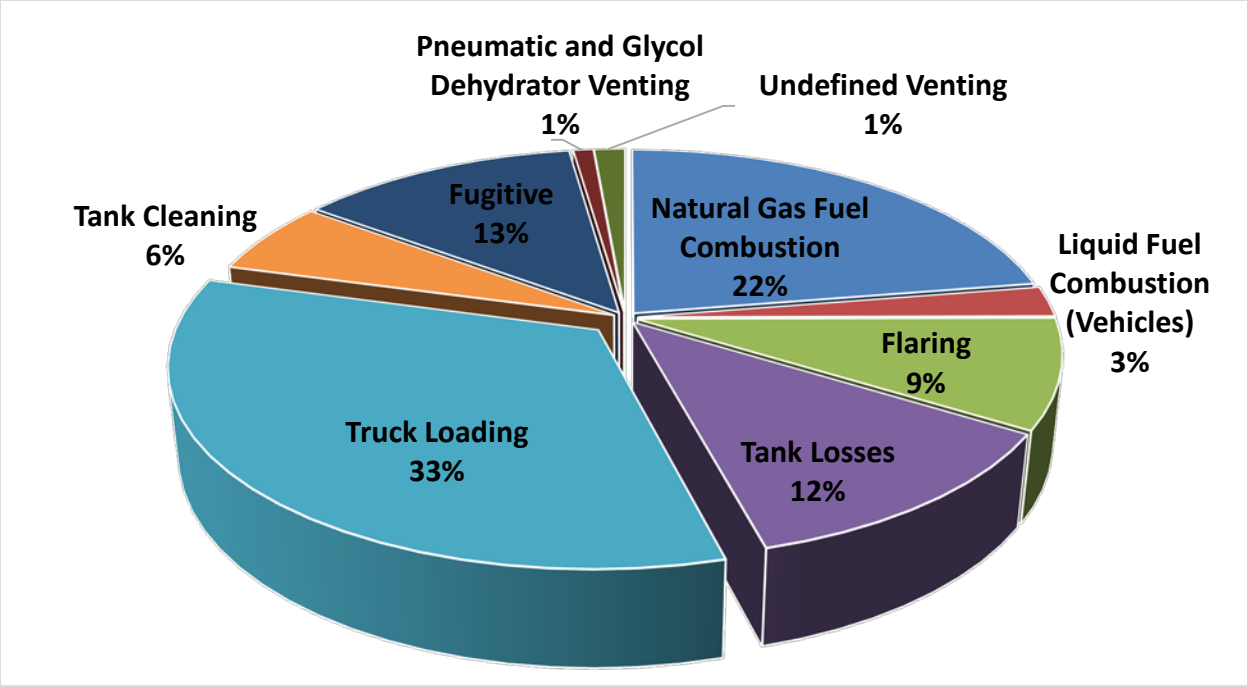

Figure ES-2: Distribution of 2012 VOC emissions by source category in Three Creeks.

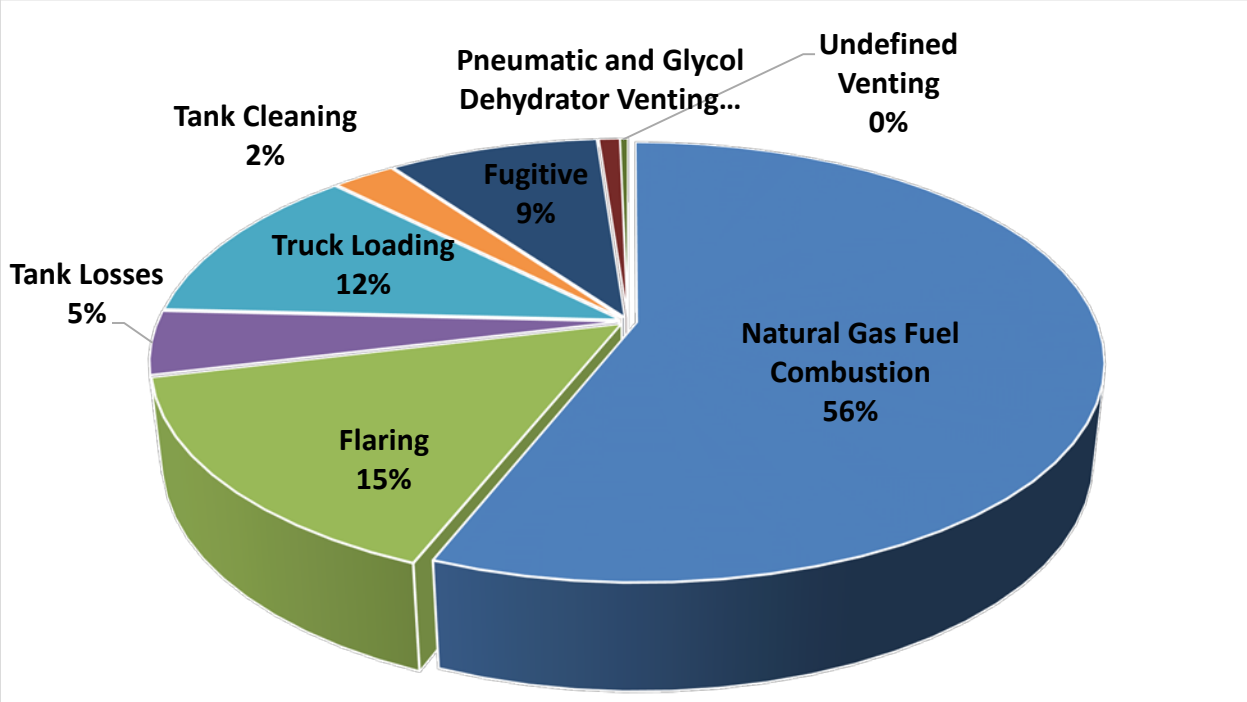

Figure ES-3: Distribution of 2012 RSC emissions by source category in Three Creeks.

Emission mitigating actions described by producers and observed during 2014 field visits indicate CHOPS well-pads now emit 85 to 90 percent less VOC emissions than well-pads that operated in the mid-2000s (with minimal emission controls). Further efforts to reduce VOC emissions from truck loading and other sources may achieve another 4 percent reduction per pad[2].

Detailed gas analysis results for selected substances are presented in Table ES-2 for CHOPS production tank and oil/water truck tank vapours. Substances are priority ranked according to their risk of exceeding Alberta Ambient Air Quality Objectives (AAAQO), odour detection thresholds and Occupational Exposure Limits (OEL) for streams most likely vented to atmosphere. The magnitude of exceedances and approximate number of dilutions required before source concentrations would fall below AAAQO, odour and OEL thresholds is also presented in Table ES-2. This provides a coarse indication of the distance required before a receptor would not observe concentrations of concern. Field measurements completed by Clearstone suggest 3 meters of separation downwind results in a dilution of 50 times while 25 meters of separation dilutes the source concentration 1,000 to 60,000 times depending on the substance and atmospheric conditions[3]. In general odours were not observed on sites where the source of continuous emissions was fuel combustion, flaring and fugitives. Whereas, persistent odours were observed at sites where tank tops were freely venting or during truck loading.

Further review of total annual emissions for substances presented in Table ES-2 indicates BTEX compounds (i.e., aromatic hydrocarbons with 6 to 9 carbon molecules) and H_2S have the largest emissions in 2012, with truck loading being the dominant source (now that tank top emissions are no longer freely vented to atmosphere).

The following should be considered to better understand and mitigate air emissions in the Three Creeks area.

1. Investigate scrubbers designed to remove hydrocarbons (C_6^+) in addition to RSC substances from oil and water truck load venting.

2. Maintain scrubbers according to manufacturer specifications.

3. Investigate incineration of excess casing gas and tank vapours via auxiliary burners (installed in tank heater exhaust stacks) for CHOPS well-pads with low gas production rates (e.g., less than 14 m^3/hour/well). This approach will produce less emissions than flaring or natural gas fired compression for low gas-flow sites.

[2] As presented in Table 19.
[3] Rigorous dispersion modelling is required to predict ground level concentrations at receptor locations.

4. Production tank vapours should not be vented to atmosphere (e.g., those listed in Table 8) due to the risk of causing off-site AAAQO exceedances and odour complaints. This includes tank blowdowns occurring before tank clean-outs. Production tanks should be depressurized to the flare header.

5. Investigate methanol, instead of aromatic naphtha based, demulsifiers that may reduce concentrations of BTEX in truck tank vapours (because C_6 to C_9 compounds become volatile when heated to 80 ^oC).

6. Investigate controls (including manual observation) to prevent free water in heated production tanks from contacting burners. This may prevent tank pressure relief events and flare flame quenching due to excessive steam formation.

7. Investigate controls to prevent flare flame quenching that may occur during periods of excessive winds or unexpected steam, nitrogen or carbon dioxide in the waste gas. Flare flames should always be lit.

8. A Directed Inspection and Maintenance (DI&M) program should be implemented by each operator to control fugitive emissions.

9. The projected emission inventory (previously identified as year 2020) could be completed to incorporate gas flows reported in Petrinex after gas conservation was fully implemented in the fall of 2014. Calculating the emissions inventory with 2013, 2014 and 2015 Petrinex volumes will provide a consistent time-series and good indication of future emission levels[4].

[4] Updating Table 12 in Section 3-2 will be sufficient for this purpose.

Table ES-2: List of substances observed in Three Creeks CHOPS production tank and oil/water truck vapours ranked according to Alberta AAAQO, odour threshold and OEL comparisons.

CAS Number	Substance Name	Average analysis Results (mol fraction)[1]			Source concentration divided by 1-hour AAAQO			Source concentration divided by 8-hour OEL			Source concentration divided by odour detection threshold		
		Oil Truck Vent	Water Truck Vent	Production Tank	Oil Truck Vent	Water Truck Vent	Production Tank	Oil Truck Vent	Water Truck Vent	Production Tank	Oil Truck Vent	Water Truck Vent	Production Tank
7783-06-4	**Hydrogen Sulphide**	5.9E-05	3.2E-05	1.7E-04	5,942	3,194	17,433	6	3	17	6,321	3,397	18,545
108-88-3	**Toluene**	1.8E-04	2.6E-04	2.8E-04	356	519	568	4	5	6	111	162	177
CEL0014	**m,p-Xylene**	1.1E-04	1.8E-04	1.1E-04	215	337	208	1	2	1	21	33	20
95-47-6	**o-Xylene**	4.5E-05	7.1E-05	4.5E-05	85	133	85	0	1	0	8	13	8
75-15-0	**Carbon Disulphide**	1.8E-06	BDL	8.7E-07	176	NA	87	2	NA	1	110	NA	54
100-41-4	**Ethylbenzene**	6.1E-05	8.8E-05	7.4E-05	132	191	162	1	1	1	659	956	809
98-82-8	**Isopropylbenzene**	1.0E-05	1.7E-05	1.3E-05	100	170	130	0	0	0	312	533	406
75-08-1	**Ethyl Mercaptan**	8.1E-06	BDL	2.8E-06	NA	NA	NA	16	NA	6	20,300	NA	7,110
74-93-1	**Methyl Mercaptan**	3.3E-06	3.0E-08	1.2E-06	NA	NA	NA	7	0	2	6,130	55	2,200
110-54-3	**n-Hexane**	5.6E-04	2.8E-04	6.4E-04	93	47	108	11	6	13	9	5	11
110-82-7	**Cyclohexane**	1.2E-03	6.9E-04	1.9E-03	NA	NA	NA	12	7	19	2	1	2
78-78-4	**Isopentane**	2.8E-03	7.2E-04	5.9E-03	NA	NA	NA	5	1	10	24	6	49
108-87-2	**Methylcyclohexane**	1.7E-03	1.2E-03	2.6E-03	NA	NA	NA	4	3	6	NA	NA	NA
95-63-6	**1,2,4-Trimethylbenzene**	1.6E-05	6.2E-05	1.8E-05	NA	NA	NA	1	2	1	7	26	7
108-67-8	**1,3,5-Trimethylbenzene**	1.1E-05	2.8E-05	1.2E-05	NA	NA	NA	0	1	0	5	13	5
106-97-8	**Butane**	1.9E-03	2.0E-04	3.9E-03	NA	NA	NA	2	0	4	2	0	3
109-79-5	**Butyl Mercaptan**	BDL	BDL	1.2E-06	NA	NA	NA	NA	NA	2	NA	NA	1,203
74-99-7	**Propyne**	2.8E-03	4.2E-04	4.6E-03	NA	NA	NA	3	0	5	NA	NA	NA
107-83-5	**2-Methylpentane**	1.4E-03	4.9E-04	2.5E-03	NA	NA	NA	3	1	5	NA	NA	NA
96-14-0	**3-Methylpentane**	1.1E-03	4.0E-04	2.0E-03	NA	NA	NA	2	1	4	NA	NA	NA
109-66-0	**n-Pentane**	1.3E-03	4.0E-04	1.6E-03	NA	NA	NA	2	1	3	NA	NA	NA
589-34-4	**3-Methylhexane**	5.7E-04	3.2E-04	9.2E-04	NA	NA	NA	1	1	2	NA	NA	NA

[1] Concentrations are presented on a dry, air-in basis and are the numerical average of valid samples collected.

BDL Below laboratory detection limit

NA Not applicable

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AAAQO	Alberta Ambient Air Quality Objectives
AER	Alberta Energy Regulator
AIHA	American Industrial Hygiene Association
AITF	Alberta Innovates Technologies Futures laboratory
AMML	Above maximum measurable limit
ASTM	American Society for Testing and Materials
Baytex Reno	All Baytex Reno field operations
BDL	Below detectible limit
BMP	Best Management Practise
BS&W	Basic sediment and water
BTEX	benzene, toluene, ethylbenzene, and xylene
CAC	Criteria Air Contaminants
CAPP	Canadian Association of Petroleum Producers
CAS	Chemical Abstracts Service
CCME	Canadian Council of Ministers of the Environment
C1C4	C_1 to C_4 hydrocarbon identification and quantification
CE	Combustion efficiency
CEL	Clearstone Engineering Ltd.
CH_4	Methane
CHOPS	Cold Heavy Oil Production with Sand
CO	Carbon monoxide
CO_2	Carbon dioxide
CSS	Cyclic Steam Simulation
DI&M	Directed Inspection and Maintenance Program
EPA	Environmental Protection Agency
EPEA	(Alberta) Environmental Protection and Enhancement Act
ESRD	(Alberta) Environment and Sustainable Resource Development
FWKO	Free Water Knock Out
g	gram
GC	Gas chromatograph
GC/MS	Gas chromatograph/mass spectrometer
GJ	Gigajoule
GOR	Gas to oil ratio
HC	Hydrocarbon
HHV	Higher Heating Value
HP	High pressure
kg	kilogram
L	Litre

LDL	Lower detection limit
LHS	Left hand side
LP	Low pressure
MDL	Minimum Detection Limit
mg	milligram
NA	Not applicable
NO_x	Oxides of nitrogen
NPRI	National Pollutant Release Inventory
NTIS	National Technical Information Service
OE	Oil Equivalent
OEL	Occupational Exposure Limits
O_2	Oxygen
P&ID	Piping and Instrumentation Diagram
PAH	Poly aromatic hydrocarbon
PFD	Process Flow Diagram
PM	Particulate matter
ppb	part per billion
ppm	part per million
PUF	Polyurethane filter
PVRV	Pressure vacuum relief valve
RHS	Right hand side
RSC	Reduced sulphur compounds
RSD	Relative standard deviation
s	Second
SAGD	Steam Assisted Gravity Drainage
SWB	Single well battery
TCPL	TransCanada PipeLines Ltd.
THC	Total hydrocarbon
TOC	Total organic carbon
TPM	Total particulate matter
TRS	Total reduced sulphur
UEL	Upper Explosive Limit
UOG	Upstream Oil and Gas
USEPA	United States Environmental Protection Agency
VOC	Volatile organic compound
VRU	Vapour Recovery Unit
µg	micrograms

1 INTRODUCTION

Three Creeks area oil production facilities are located 20 to 60 km northeast of Peace River Alberta. The study area boundary is presented in Figure 1 and includes townships 84 to 85 and ranges 16 to 20 as well as ranges 18 and 19 in township 83. Three Creeks is host to thermal and cold heavy oil production types as well as custom treating, waste disposal (injection wells), waste processing and power generation facilities. Active producers during 2012 were Baytex Energy Ltd., Husky Energy, Murphy Oil Company Ltd., Penn West Petroleum Ltd., Chinook Energy Inc. (Iteration Energy), and Shell Canada Ltd. Tervita Corporation operates oil custom treating and waste processing facilities while Genalta Power Inc. operates the Cadotte power generation facility. Oil and natural gas production volumes for 2012 by operating company are presented in Table 1

Table 1: 2012 Oil and natural gas production volumes[1] for each company operating in the Three Creek study area.

Company Name	Oil Production	Gas Production	Oil Equivalent	
	(m^3)	(10^3m^3)	(m^3 OE)	(%)
BAYTEX	1,014,472	34,609	1,124,163	42.6%
HUSKY	104,737	13,008	125,224	4.8%
ITERATION		151	147	0.0%
MURPHY	61,742	3,883	70,143	2.7%
PENN WEST	67,499	7,006	79,364	3.0%
SHELL	1,034,277	128,848	1,236,959	46.9%
Grand Total	2,282,727	187,506	2,636,000	100.0%

[1] Production volumes are measured or estimated by operators in compliance with the AER Directive 017

In 2012, approximately 81 percent of Three Creeks oil was produced by the Cold Heavy Oil Production with Sand (CHOPS) method with wells and production facilities located at production pads. The production pads include one or more multi-leg horizontal production wells operating at depths of about 600 meters to recover oil from the Bluesky formation. A single pad may include one or more production wells. CHOPS facilities include:

- 21 single well oil batteries
- 97 multi well oil batteries
- 6 water injection facilities (disposal)
- 405 oil wells

Approximately 19 percent of Three Creeks oil is produced by the in-situ steam assisted gravity drainage (SAGD) and cyclic steam stimulation (CSS) thermal methods. Steam is produced in large boilers at the main plant and injected into the reservoir via injection wells located at field

production pads. Emulsion is produced from wells and delivered into group and test separators located at a main battery. Thermal oil facilities include:

- 2 in-situ oil sands batteries
- 2 steam injection facilities
- 92 thermal oil wells

Solution gas from these facilities is collected by a network of 7 gas gathering systems. There is also a small amount of dedicated gas production from 2 gas batteries. The study also includes custom treating, waste processing and power generation facilities.

The overall project objective is to produce an inventory of 2004 to 2012, and projected VOC, RSC and CAC emissions for the Three Creeks study area. Final inventory results are of sufficient quality and detail to answer Three Creeks Industry Air Quality Working Group questions presented in Section 3.3 and 3.4. Inventory results rely on best available data provided by producers and Three Creeks field measurement results (Clearstone, 2014a). Specific inventory enhancements achieved by field measurements include:

1. Instead of using EPA truck loading emission quantification methodology (U.S. EPA, 2008), the average dry-gas venting to loaded product factors (GOR) and air-in gas compositions measured for oil and water trucks are used.
2. Three Creeks compositions for casing gas, tank vapour, oil truck vapour and water truck vapour from Alberta Innovates Technologies Futures (AITF) laboratory results are applied.
3. Tank cleaning emission estimates are based on a schedule of 12 de-sanding and 1 clean-out events per year.
4. Sulphur control efficiency of 81 percent is applied to production and truck tank venting for operators that have implemented scrubber control technologies.
5. The equipment inventory is aligned with equipment observed during field visits.

This report also relies on combustion factors determined from 2013 field measurements at Baytex facilities in the nearby Reno field (Clearstone, 2013).

A detailed description of field operations, emission sources and assumptions used to bridge data gaps is presented in Section 2. Inventory results and discussion (i.e., responses to questions listed in Section 3.3 and 3.4) are presented in Section 3 while conclusions and references cited are presented in Sections 4 and 5. Emission quantification methodologies are delineated in Appendix I.

1.1 BACKGROUND

Over the last several years, there have been numerous complaints about nuisance odours and emissions in the area. An Air Monitoring Subcommittee was formed in November 2011 to support the Three Creeks Working Group, a multi-stakeholder group consisting of residents, industry, Northern Sunrise County, Alberta Environment and Sustainable Resource Development (ESRD) and the Alberta Energy Regulator (AER). Moreover, an Industry Air Quality Working Group was formed in 2013 to support the Air Monitoring Subcommittee. The objectives of the Air Monitoring Subcommittee are to gain a better understanding of local meteorology, air emissions, and air quality, as well as to gather data that will strengthen future decision making with regards to air quality management in the Three Creeks area.

The inventory must identify what emissions are being released to the air within the Three Creeks area, and address key questions presented in Sections 3.3 and 3.4.

1.2 CALCULATION DATABASE

All emission calculations are performed using the ClearCALC SQL database designed and maintained by Clearstone in accordance with the quantification methodology presented in Section 7. Modifications to this tool are documented and implemented according to Clearstone Software Development Best Practices (a copy of this technical standard can be provided upon request). Emission results are populated into standardized spreadsheets by the ClearCALC report generator.

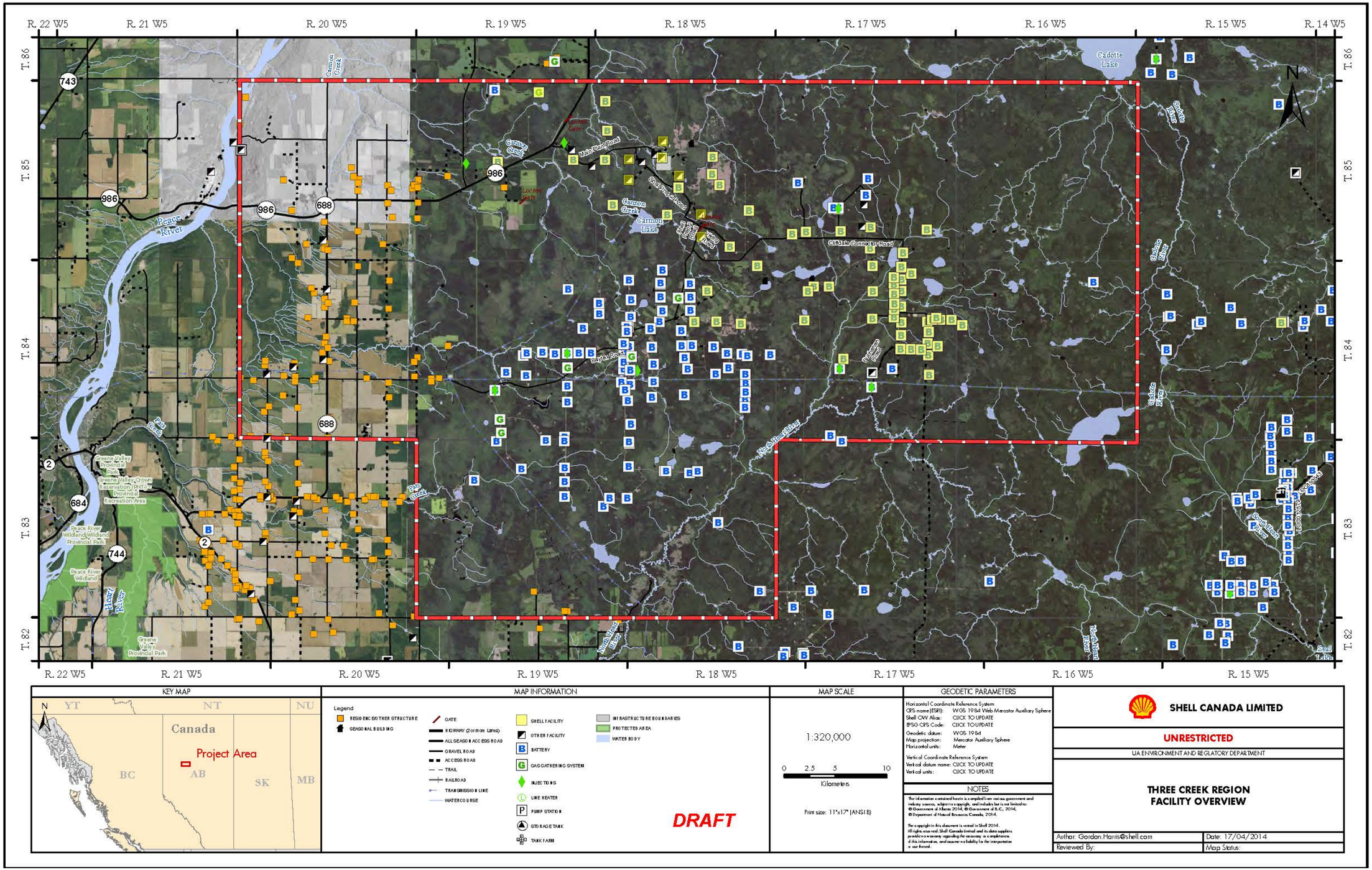

Figure 1. Three Creeks study area showing residential as well as oil and gas facility locations.

2 FIELD OPERATIONS AND EMISSION SOURCES

Three Creeks CHOPS and SAGD production facilities, operations and potential emissions sources are described in the following sections.

2.1 DESCRIPTION OF COLD HEAVY OIL PRODUCTION

A CHOPS well pad may consist of one or more individual wells. Surface facilities for a well include the well head, a hydraulically operated motor that drives a down-hole fluid production pump, and produced fluid piping to convey the fluid to a series of production tanks. In addition to the produced fluid, casing gas is produced separately from the reservoir and conveyed to the casing gas management system. At locations where casing gas is produced in excess of well pad requirements the excess gas is flared or a casing gas compressor is included to facilitate shipment of the excess gas to a gas gathering system. The hydraulic motor and compressor are normally driven by one or more natural gas and/or propane-fired engines. To prevent freezing of casing gas in the fuel or gathering systems; pipelines are heat traced, injected with methanol or gas may be dried using desiccant.

The produced fluids, including oil, water, sand and solution gas; are flow-lined to production tanks often operating in series. Aided by heat, demulsifier chemical and gravity; water and oil separate into discrete layers with sand eventually settling to the bottom. The production tanks are typically maintained at 70 to 80 °C with casing gas-fired, in-tank, tube heaters. However, tank temperatures can range from lows of 0 - 49 ^{o}C to highs of 90 – 95 ^{o}C. Solution gas disengages from the oil in the production tank and is conserved with a vapour recovery unit (VRU), sent to a flare or vented to the atmosphere. Solution gas will disengage (flash) in the first production tank receiving emulsion. However, in some cases a crossover pipe connects production tanks, and subject to the effective settings and/or conditions on the PVRVs actual emissions may be released through either or both tanks. To prevent air emissions, some operators in the Three Creeks area will shut-in producing wells when the VRU or gathering system is off-line.

Produced oil is removed from the production tanks and loaded into trucks for disposition to central treatment (e.g., wells featuring 1 tank and limited chemical treatment) or sales terminal facilities (e.g., wells featuring chemical treatment and 3 to 5 tanks in series) depending on the water in oil fraction. Water is also removed from production tanks, loaded into trucks and injected into producing formation (as steam or liquid) or disposed. Sediment is periodically removed from the tank with vacuum trucks (e.g., tank cleaning or de-sanding operations) and disposed. When produced oil, water or sediment is removed from the production tanks; air (if the tank communicates freely with the atmosphere) or blanket casing gas (if the tank is tied into a flare or VRU) is drawn into the tank vapour space.

Loading oil or water into truck tanks displaces evaporated vapours which are exhausted to the atmosphere via the truck vent line. Removal of sediment from the tank is usually completed with a truck equipped with a suction compressor. In this case the volume of gas discharged to the atmosphere is based on the capacity of the vacuum system and the duration is based on the condition of the sediment in the bottom of the tank. Some operators scrub the displaced vapours with a SulfaTreat solid media scavenger to remove RSCs before venting to atmosphere.

2.2 DESCRIPTION OF IN-SITU STEAM ASSISTED GRAVITY DRAINAGE

Steam is produced in large boilers at the main plant and injected into the reservoir via injection wells located at production pads. Emulsion is produced at the well pads and delivered into group and test separators located at a main battery. There are typically no oil storage tanks at well pads and therefore no tank or truck loading losses. Casing gas from the well pads is delivered to the main plant and mixed with solution, tank blanket and TransCanada PipeLines (TCPL) gas and used as steam generator fuel. The produced emulsion enters the battery and flows through free-water-knock-out (FWKO), treater and crude stabilization vessels where the produced water and remaining gas is separated and diluent is added to the bitumen. Bitumen blended with diluent is then sent to the sales tanks and ultimately delivered to downstream upgraders and refineries by pipeline. Produced water from the FWKO, treater and separators is further processed to remove oil and prepare it for injection well disposal.

2.3 TARGET SUBSTANCES AND KEY GROUPINGS

The major target substance groups summarized and presented in Section 3 include:

- Criteria Air Contaminants (CAC) that include oxides of nitrogen (NOx), sulphur oxides (SOx), carbon monoxide (CO) and total particulate matter (TPM).
- Volatile organic compounds (VOC) are any substance containing carbon; excluding carbon monoxide and carbon dioxide; that will react with nitrogen oxides in the presence of solar radiation to produce photochemical oxidants (e.g., ozone). All hydrocarbons except methane and ethane are classified as VOCs.
- Reduced sulphur compounds (RSC) are a complex family of substances characterized by the presence of sulphur in a reduced state (e.g., hydrogen sulphide and mercaptans). Total reduced sulphur (TRS) results are presented as H_2S equivalent and include all sulphur bearing substances except SO_2.

2.3.1 PURCHASED CHEMICALS

The list of chemicals purchased for use in heavy oil operations are presented in Table 2. Chemical compositions and possible atmospheric release points were reviewed. Most of the purchased chemicals do not contain substances of interest with respect to air emissions because they:

- are introduced into closed system processes that do not communicate with the atmosphere;
- have zero or very low vapour pressures and will not volatilize;
- are present in very low quantities (i.e., less than 100 liters per year); or
- are non-hazardous.

Table 2: Chemical purchased in 2012 for use in the Three Creeks area.

Intended Purpose	Chemical Name
Asphaltene Dispersant	AX-231
Biocide	X-Cide 102W
Corrosion inhibitor	CX-480
Corrosion Inhibitor	EC1253A
Corrosion Inhibitor	HTF Iron Inhibitor DRS
Corrosion Inhibitor	Nalco 39M
Corrosion Inhibitor	NExGuar 22300
DEFOAMER	BDFO91
Defoamer	DFX-105
Demulsifier	Breaxit EC2529A
Demulsifier	DMO8665

Table 2: Chemical purchased in 2012 for use in the Three Creeks area.	
Intended Purpose	**Chemical Name**
Demulsifier	DX-749
Demulsifier	RE9314DMO
Demulsifier	X-1491
Demulsifier	X-743
Demulsifier	X-8013
FOAMER	BFMO3946
FOAMER	BFMW3915
Fracturing Fluid	Gyptron T-387
Fuel Additive	Petrosol 5139
Glycol	Antifreeze Universal 50/50 4L
Glycol	Norkool SLH 50% Premix
Glycol	TEG Inhib 0.5% CFT-1755CW
Glycol	Triethylene Glycol
H_2S Scavenger	Gas Treat 137
H_2S Scavenger	HR-2725
H_2S Scavenger	Petrosweet HSW2001
H_2S Scavenger	Sulfa-Check EC5493A
H_2S Scavenger	HX-202A
OF PARAFFIN CONTROL	BPAO2346
OF PARAFFIN CONTROL	BPAW4
OILFD CORR INHIB	BCGO4050C
OILFD CORR INHIB	BCGO9178C
OILFD CORR INHIB	BCRO9946DC
OILFD CORR INHIB	BCRW132
OILFD H2S SCAV	BHSW705
Oxygen Scavenger	EC6360A
Oxygen Scavenger	OXW5200
Processing Aid	Ammonia Solution 26D-Bulk
Processing Aid	CHEMBREAK
Processing Aid	CX-422
Processing Aid	HYDROCHLORIC ACID
Sand Dispersant	SX-204
Scale Inhibitor	SCW5350
Solvent	Solvent
Surfactant	Polyclean 7.11 PolyClean#7
Surfactant	SX-205
WATER CLARIFIER	BRBW528
WATER CLARIFIER	BRBW918
WATER CLARIFIER	BRBW921

Table 2: Chemical purchased in 2012 for use in the Three Creeks area.	
Intended Purpose	**Chemical Name**
Water Clarifier	WX-807
WATER IN OIL DEMUL	BDMO484X
WATER IN OIL DEMUL	BDMW8760
WATER IN OIL DEMUL	BRE30467DMO
WATER IN OIL DEMUL	BRE9175DMO
WATER IN OIL DEMUL	BRE9848DMO
Water Treatment	Aluminex OS8
Water Treatment	Caustic Soda Solution 50%
Water Treatment	Chlorine NSF Ton
Water Treatment	Gold Plus Calcium Chloride
Water Treatment	Nalclear 7768
Water Treatment	Nalco DT-9472

Commercial products that contain substances of interest include demulsifiers, defoamers and corrosion inhibitors added upstream of heavy oil storage tanks. When present in heated tanks, substances can evaporate into the tank vapour space and be released to atmosphere. Mole fractions for substances observed to be present in Three Creeks tank vapour samples are identified in Table 3 (Clearstone, 2014a). The analytical method TO-15 applied by the AITF laboratory is applicable to all VOCs listed in Table 3 but will not return results for semi-volatile naphthalene or formic acid (US EPA, 1999a). This constraint was discussed with the Air Monitoring Subcommittee and it was decided that the presence of semi-volatile PAHs should be monitored at receptor and not source locations. The presence of formic acid (at ppm levels) is confirmed using a Dreager Dosimeter Tube.

Table 3: List of substances that may be present in tank vapours that originate from demulsifiers, defoamers and corrosion inhibitors.				
Substance Name	**CAS Number**	**Molecular Weight**	**Saturation Vapour Pressure (kPa)**	**Observed Tank Vapour Mole Fraction**
Methanol	67-56-1	32.04	255.5	BDL
Toluene	108-88-3	92.14	54.1	3.062E-04
Formic Acid	64-18-6	46.03	72.5	>1.0E-05
Isopropanol	67-63-0	60.10	136.9	3.538E-10
Xylenes	1330-20-7	106.17	23.3	1.684E-04
Ethyl Benzene	100-41-4	106.17	24.2	8.326E-05
Benzene, (1-methylethyl)-	98-82-8	120.19	14.3	1.185E-05
1,2,4-Trimethyl Benzene (and isomers)	95-63-6	120.20	7.9	2.027E-05

Kerosene	8008-20-6	198.39	4.9	BDL
2-Ethylhexyl Alcohol	104-76-7	130.23	2.6	BDL
Naphthalene	91-20-3	128.17	1.6	--
Amine derivatives	68910-93-0	--	0	BDL
Ethoxylated Nonylphenol	68412-54-4	--	0	BDL
1,2-Ethanediamine, polymer with methyloxirane and oxirane	26316-40-5	--	0	BDL
Epoxy Resin	68214-46-0	--	0	BDL
Oxyalkylated alkylphenolic resin	63428-92-2	--	0	BDL

BDL – Below Laboratory Detection Limit

2.4 GAS COMPOSITIONS

Sampling and analytical methodologies patterned after published methodologies for VOCs and RSCs (EPA, 1999 and EPA, 1991) were applied in the determination of Three Creeks gas compositions (Clearstone, 2014a). Approximately 155 substances were identified in the truck tank, production tank and well casing gas streams. When available, site-specific analysis is utilized in the emissions inventory. Otherwise, numerically averaged compositions presented in Section 7 are applied as follows:

- Well casing gas is assigned to fuel combustion, well casing vents and most fugitive sources.
- Tank vapour is assigned to production tank and tank cleaning sources.
- Oil and water truck tank vapours are assigned accordingly.
- Numerically averaged well casing and production tank vapour is assigned to flaring sources.

2.5 PETRINEX PRODUCTION AND DISPOSITION FLOWS

Process fluid flows for all facilities and wells in the study area are obtained from Petrinex by running the Volumetric Facility Activity Report (Penn West, 2013). This report includes production and disposition volumes for all gas, oil, water and waste flows measured (or estimated) by operators in compliance with the Alberta Energy Regulator (AER) Directive 017. Annual oil and natural gas production volumes reported by the major producers, between 2004 and 2012, are presented in Table 4. Produced gas volumes balance with disposition (i.e., sales, fuel, flare, vent and injection) volumes and are the primary driver for emission calculations.

In general, emphasis is placed on accurately measuring and reporting oil flow volumes because of their economic value and stringent uncertainty tolerances are specified in Directive 017 (e.g., +- 1% for production less than 100 m^3/day). Directive 017 uncertainty tolerances are larger

for gas flows (e.g., +- 20% for all flaring and venting) and have historically received less emphasis. The quality of gas measurement and reporting has improved over time due to metering enhancements and more frequent measurements.

For CHOPS, the total gas to oil ratio (GOR) will be smallest at the beginning of a well's production life. The reservoir GOR should remain constant, however, as the well matures and down-hole pressure decreases, gas is allowed to disengage from reservoir oil and migrate to the well casing (Craft and Hawkins, 1991). Thus, casing gas production rates increase over time while solution gas released in production tanks should remain relatively constant. This partially explains the wide variation in well GORs provided for this study (casing GORs ranged from 0 to almost 2400, while solution GORs ranged from 1 to 10).

Table 4: Oil and natural gas production from major operators in the Three Creeks area between 2004 and 2012.																
Year	**SHELL**			**BAYTEX**			**HUSKY**			**MURPHY**			**PENN WEST**			**Total Three Creek GOR**
	Oil[1] (m^3)	**Gas[2] (10^3m^3)**	**GOR[3]**	**Oil[1] (m^3)**	**Gas[2] (10^3m^3)**	**GOR[3]**	**Oil[1] (m^3)**	**Gas[2] (10^3m^3)**	**GOR[3]**	**Oil[1] (m^3)**	**Gas[2] (10^3m^3)**	**GOR[3]**	**Oil[1] (m^3)**	**Gas[2] (10^3m^3)**	**GOR[3]**	
2004	468,678	46,145	98													98
2005	519,060	46,978	91	31,812	975	31	209	2	8							87
2006	594,325	42,000	71	23,888	119	5	5,724	70	12	465	3	6	5,316	4	1	67
2007	1,007,601	46,861	47	63,600	520	8	41,118	118	3	2,927	15	5	25,401	503	20	42
2008	1,069,933	76,642	72	215,205	3,818	18	32,427	71	2	6,742	562	83	32,557	2,520	77	61
2009	882,166	86,047	98	296,997	6,541	22	226,383	2,227	10	9,855	887	90	25,046	3,832	153	69
2010	827,559	100,039	121	526,446	17,462	33	185,037	4,108	22	13,584	406	30	24,611	5,243	213	81
2011	591,687	99,765	169	790,680	26,311	33	120,971	10,330	85	44,035	605	14	32,396	5,696	176	91
2012	1,034,277	128,848	125	1,014,472	34,609	34	104,737	13,008	124	61,742	3,883	63	67,499	7,006	104	82
Total	6,995,286	673,325	96	2,963,101	90,354	30	716,607	29,934	42	139,350	6,361	46	212,825	24,803	117	75

1. Cold flow and thermal oil production reported in Petrinex. Oil volumes do not include basic sediment and water (BS&W) and should meet a measurement accuracy of +-1%.
2. Casing and solution gas production from cold flow and thermal oil facilities. According to Directive 017, produced gas, flared gas, or vented gas volume exceeding 2 10^3m^3/day must be measured, while fuel gas flows exceeding 0.5 10^3m^3/day must be measured. If gas measurement is required, the single point measurement uncertainty is +-3%. Flows less than this can be estimated with an uncertainty up to +-20%.
3. GOR is calculated based on total gas (1000 m^3) divided by total net oil (m^3) production reported by each company in Petrinex.

2.6 EMISSIONS SOURCES

A brief description of each emission category, and data sources are presented below.

2.6.1 STATIONARY FIRED EQUIPMENT

Combustion emissions from natural gas, propane and diesel fuel consumption in stationary internal (e.g., reciprocating engines) and external (e.g., heaters and boilers) combustion devices occur at oil and gas facilities in the Three Creeks area.

Stationary combustion emissions are quantified according to methodology presented in Section 6.5. Natural gas fuel volumes are obtained from Petrinex, while liquid propane and diesel volumes are provided by operators (2012 liquid fuel volumes prorated back to other years based on production rates). Natural gas fuel consumption is distributed between reciprocating engines (approximately 41 percent) and heaters/boilers (approximately 59 percent) based on field observations (Clearstone, 2014a). The detailed composition for well casing gas in Table 25 is used to determine heating values (HHV) for natural gas fuel streams, while combustion factors are based on those observed at Baytex facilities operating in the Reno area (Tables 8, 9 and 10 in Clearstone, 2013). Vehicle combustion emissions are discussed separately below.

2.6.2 FLARING

Flaring is a common method for disposing of waste gas volumes at Three Creeks facilities. Waste gas streams include solution and casing gas that exceeds local fuel demands as well as gas from emergency relief events. Stacks are designed to provide safe atmospheric dispersion of the effluent. Flares are normally used where the waste gas contains odorous or toxic components (e.g., hydrogen sulphide).

Flaring emissions are quantified according to methodology presented in Section 6.1 and flaring volumes reported in Petrinex. The detailed composition in Table 27 is applied to flare streams. The location of flaring events reported in Petrinex was observed to be generally consistent with flare stacks identified on process flow diagrams (PFDs).

2.6.3 FUGITIVE EMISSIONS

Fugitive emissions are unintended releases of gas to the atmosphere from equipment components that leak as a result of wear, damage, manufacturing flaws, poor design or improper installation. Sources of fugitive emissions include but are not limited to valves, connectors, open-ended lines, pressure relief valves, pumps, flanges, etc.

Fugitive emissions are quantified using the factor-based approach described in Section 6.2. Major equipment counts are based on field observations (Clearstone, 2014a), obtained from PFDs or based on typical heavy oil facility configurations when PFDs are not available.

Component counts and service for each major equipment unit are based on average counts presented in Table 31 and 32 in Volume 3 of Environment Canada, 2014. Emission factors for each component are from CAPP, 2014 and account for emission reductions resulting from the CAPP Fugitive Emission Management Best Management Practice (BMP) (CAPP, 2007) and implementation of directed inspection and maintenance programs. Emissions are speciated using the detailed composition in Section 7.

2.6.4 PRODUCTION TANK LOSSES

Production tanks can emit as a result of both normal evaporation and from product flashing. Evaporative losses occur when volatile hydrocarbon products, which are stored in tanks, are vented to the atmosphere. As the product evaporates, the vapour space in the tank becomes saturated. These vapours are expelled during tank filling (working losses) and due to diurnal temperature and pressure changes (breathing losses). Produced hydrocarbon liquids frequently contain a certain amount of gas in solution which flashes or boils off when the product enters the tank. The amount is determined using the Vasquez and Beggs correlation with the temperature and pressure of the first vessel upstream of the production tanks (i.e., usually the wellhead) unless solution GORs are provided. Most production tanks are tied into a flare header or gas gathering system. Tanks that vented directly to the atmosphere during 2012 are limited to those listed in Table 8.

Production tank losses are quantified according to methodology presented in Section 6.7, throughput volumes from Petrinex, tank configurations observed on PFDs and process conditions provided by operators. Where tanks are connected in series, flashing (majority of emissions) and breathing losses are calculated at the first tank. Only breathing and working losses are calculated for subsequent tanks because the majority of solution gas is flashed off in the first tank. A summary of the atmospheric and upstream conditions and liquid properties used in this inventory is presented in Table 5. The detailed tank vapour composition in Table 26 is used to speciate all storage losses. For sites that report oil production but no available tank or pipeline data, two 1000-barrel ‘theoretical’ tanks are assumed. This assumption is required to calculate flashing losses and only applies to 22 of approximately 800 tanks included in the study.

Table 5: Typical atmospheric and upstream conditions and liquid properties applied to production tank loss calculations.

Condition	Typical Value	Unit
Average Ambient Temperature	2.3	^{o}C
Average Ambient Pressure	92.3	kPa
Average Ambient Temperature change	12.47	^{o}C
Average Production Tank Temperature	80	^{o}C
Upstream Temperature	10 to 30	^{o}C
Upstream Pressure	131 to 441	kPaa

Reid Vapour Pressure (RVP) of Oil	40.5	kPa
Oil specific gravity with respect to water	0.915	dimensionless

2.6.5 TRUCK LOADING LOSSES

Most CHOPS well pads in the Three Creeks area transport oil and water from well pad production tanks to central terminal or disposal facilities via trucks. Some oil is transported outside the study area to a transloading facility in Falher, Alberta operated by Altex Energy. Emissions occur during truck tank loading where oil or water displaces truck tank vapours to the atmosphere. Some operators are directing truck tank vapours through SulfaTreat^{TM} scrubbers, designed to remove sulphur compounds from the gas stream, before venting to atmosphere. An 81 percent sulphur compound control efficiency[5] is applied where sulphur scrubbers are utilized (with zero control efficiency for non-sulphur compounds). The amount of emissions depends on the vapour pressure of the liquid product, loading volume, method of loading and presence of emission controls.

Loading losses are quantified based on gas to loaded liquid ratios determined in Clearstone, 2014a and presented in Section 6.8 as well as throughput volumes from Petrinex. The detailed truck tank vapour compositions in Table 28 and Table 29 are used to speciate loading losses. Oil produced at SAGD well pads is transported by pipeline so no truck loading emissions occur at these sites.

2.6.6 PRODUCTION TANK CLEANING EMISSIONS

The following two methods are used to clean production tanks depending on the mobility of sand and sludge accumulated in the tank. The annual volume of gas vented from tank cleaning activities is 177 m^3 per tank. This estimate is based on Clearstone, 2014a measurement results and frequency of 12 de-sanding plus one clean-out events per tank per year. Emissions are calculated according to Section 6.6 methodology and speciated with the tank vapour composition in Table 26.

2.6.6.1 TANK DE-SANDING

Tank-bottom sand/sludge removal by vacuum truck is a common practice in Three Creeks and can occur as frequently as once per week depending on production rates and sediment loads. No water injection (e.g., with a stinger) or tank top venting occur during this activity. Instead, vapours associated with vacuum truck removal of sand/sludge from the tank bottom are released at the vacuum truck vent. Production tanks remain connected to gas blanket and flare/VRU piping during this operation.

[5] Well maintained scrubbers should provide 100 percent control of target substances, however, some were observed to operate with expired catalyst causing the average control efficiency to be less than 100 percent.

2.6.6.2 TANK CLEAN-OUT

When tank bottom solids accumulation impairs production and can no longer be removed by the de-sanding activity described in Section 2.6.6.1, a complete tank clean-out is scheduled. The tank is isolated from production, opened to atmosphere and cleaned with water jets (i.e., stingers). Tank clean-outs occur much less frequently (e.g., every one to five years per tank depending on production rates and solids content) and include the following work procedures:

1. isolate tank from production,
2. drain below man-way door with vacuum truck,
3. isolate from drains, VRU and cross-overs,
4. relieve pressure to atmosphere,
5. remove man-way cover,
6. clean tank bottom with water cannon (stinger),
7. remove sludge/slurry with vacuum truck,
8. inspect, install man-way cover and return to service.

Emissions released from the vacuum truck vent, during steps 2 and 7, are characterized by large flow rates and small total hydrocarbon (THC) concentrations. Emissions also occur during the step 4 tank blowdown.

2.6.7 GLYCOL DEHYDRATOR REGENERATOR EMISSIONS

There are only two glycol dehydrators identified in the study area and both are operated by Shell. Regenerator still column and flash tank off-gas streams from the 03-25-084-17W5 dehydrator are disposed by thermal oxidation with a destruction efficiency of 90 percent. Emission estimates determined by Shell using GRI-GLYCalc Version 4.0, are presented in Table 6 and included in the inventory. Combustion source emissions from the regenerator are addressed in Section 2.6.1.

Off-gas streams from the 05-21-085-18W5 dehydrator are tied into gas pipelines for use as fuel or sale. Therefore, zero emissions are released directly from this glycol dehydrator.

Table 6: Glycol dehydrator regenerator emissions to atmosphere in the Three Creeks area (tonnes per year) assuming 8760 hours per year of operation.

Component	03-25-084-17W5	05-21-085-18W5
Hydrogen sulphide	0.00789	0.0
Methane	10.18197	0.0
Ethane	0.04091	0.0
Propane	0.05706	0.0
n-Butane	0.11394	0.0
i-Butane	0.09580	0.0

Table 6: Glycol dehydrator regenerator emissions to atmosphere in the Three Creeks area (tonnes per year) assuming 8760 hours per year of operation.		
Component	**03-25-084-17W5**	**05-21-085-18W5**
i-Pentane	0.06033	0.0
n-Pentane	0.16366	0.0
Hexane	0.02767	0.0
Heptane	0.15658	0.0
Octane	0.40751	0.0
Cyclopentane	0.05606	0.0
Cyclohexane	0.15150	0.0
Methylcyclopentane	0.05652	0.0
Benzene	0.11158	0.0
Methylcyclohexane	0.20194	0.0
Toluene	0.21010	0.0
Ethylbenzene	0.04563	0.0
m-Xylene	0.31697	0.0
2,2,4-Trimethylpentane	0.23560	0.0

2.6.8 RESIDENTIAL HEATERS

There are approximately 402 residential locations within the study area that are each assigned a very small propane 'residential heater.' The primary intent for assigning propane heaters is to ensure residential locations are included in emission inventory output files for consideration in possible dispersion modelling work. Total emissions from residential heaters is negligible (e.g., total VOC emissions equal ~1 kg per year) relative to oil and natural gas activities.

2.6.9 VEHICLE COMBUSTION EMISSIONS

Vehicle traffic surveys completed by the Three Creeks Transportation Group indicate roughly 250 to 500 vehicles travelled on Township 842 road every day during 2013 (Three Creeks Transportation Group, 2013). Approximately 60 percent of the traffic is light duty vehicles (i.e., less than 7 meters in length) and 40 percent heavy duty. The majority of heavy duty vehicles are for the transport of oil and water from well-site production tanks to central batteries or the Tervita waste processing facility.

Vehicle combustion emissions are calculated using the estimated annual distance travelled by light and heavy duty vehicles presented in Table 7. The reader is cautioned that traffic data for the Three Creeks area is limited and emission results are uncertain. The 'order-of-magnitude' emission estimates presented in Section 3 assume the following:

- The number of heavy duty trucks travelling in the study area is a function of oil and water production volumes from cold-flow heavy oil sites.
- The average oil truck tank capacity is 8,400 gallons (24 m^3 average fill) and each heavy duty truck hauls 2.5 loads per day.
- Heavy duty truck haul distances are estimated to be 8 kilometers (one-way) for oil deliveries and 16 kilometers (one-way) for water deliveries. Each truck travels approximately 15 kilometers within the study area before and after daily hauling activities for 365 days per year.
- Light duty trucks travel approximately 50 kilometers per day within the study area for 252 days per year.
- The average diesel fuel consumption by light duty trucks is approximately 10.2 km/L (US DOE, 2014) while heavy duty trucks is 2.55 km/L (Truckers Report, 2014).

Table 7: Estimated truck traffic from oil and gas operations in the Three Creeks area from 2004 to 2012.

Year	Number of Trucks per Day		Distance Travelled per Year (km)	
	Heavy Duty	Light Duty	Heavy Duty	Light Duty
2004	1	10	32,000	126,000
2005	2	10	56,000	126,000
2006	9	14	264,000	174,000
2007	43	65	1,328,000	819,000
2008	61	91	1,879,000	1,149,000
2009	73	109	2,207,000	1,375,000
2010	84	126	2,583,000	1,582,000
2011	95	143	2,955,000	1,797,000
2012	137	206	4,270,000	2,590,000

2.6.10 WASTE OIL RECLAIMING AND DISPOSAL

The types of waste that may be produced by oil and gas producers include oily water, tank bottoms, treater bottoms, scrapings from pigging operations, sludge from vessels, sludge from surface impoundments, drilling fluids, oil spill debris, and oily sand and sedimentary material. The emissions that result from the disposal of these wastes may be ascribed to four source categories: transportation contractors, waste reclaimers, land farms, and landfilling. The majority of oil field waste in the Three Creeks area is delivered to the custom treating, waste processing and disposal facility located at 12-24-085-19W5 or the class II & III landfill located at SW-02-084-20W5.

Emissions from transportation of waste materials are estimated based on traffic assessments described in Section 2.6.9.

Potential emissions from waste reclaiming activities at the 12-24-085-19W5 facility were evaluated with the support of Tervita Corporation. Treater combustion emissions are accounted as described in Section 2.6.1. Storage and processing tanks are blanketed with natural gas and tied into a VRU. Treater off-gas as well as truck tank vents[6] are also tied into the VRU. Recovered vapours are disposed by flaring with emissions calculated as described in Section 2.6.2. Waste receipt hoppers and centrifuges are tied into an odour management system and scrubbed before being released to atmosphere. Three air monitoring inspections were completed at the 12-24-085-19W5 facility during 2013 and 2014 by the AER. Infrared camera and sensory inspections detected zero emission sources and off-lease odours (Tervita, 2014). Notwithstanding, fugitive emissions from this site are estimated as described in Section 2.6.3.

Known land spreading in the Three Creeks area includes waste from the Tervita 12-24-085-19W5 custom treater and the Peace River pulp mill operated by Daishowa-Marubeni International Ltd. Given that off-lease odours were not detected by AER at the Tervita 12-24-085-19W5, materials spread from this site are not considered problematic. Land spreading of pulp mill waste is a low-frequency event that would not be responsible for the 847 documented odour complaints between February 2010 and September 2013. Therefore, emissions from land spreading are not quantified in this inventory.

Potential emissions from the East Peace Landfill (SW-02-084-20W5) were evaluated. However, landfill gas emissions are primarily methane with trace H_2S whereas canister sampling of ambient air indicates butane, pentane and hexane related compounds are the largest contributors (Stantec, 2014). Moreover, no air monitoring is required by the facility EPEA Approval 20252-02-00 so emissions from this site are not quantified.

2.7 EMISSION MITIGATION

Given local air quality concerns, noteworthy effort is applied to mitigate air emissions in the Three Creeks area. Beginning in 2009, facilities that vented more than 900 m^3 per day were identified and flares installed to comply with AER Directive 060. In 2010, gas gathering systems were installed by Shell and Baytex to conserve well casing gas not already utilized as fuel in tank heaters and well pumps. In 2011, flares and some VRUs were installed to mitigate solution gas venting off tank tops. In 2012, Genalta Power began operations at 10-28-084-18W5M to use Husky casing and solution gas as fuel to generate electricity. Most PFDs provided for this study indicate that in 2012 well casing gas and solution gas off tank tops is collected and burned as fuel on-site; directed into gas gathering systems for sale; or flared. In 2013, Genalta Power began

6 Truck loading at the 12-24-085-19W5 facility only occurs in the rare event that the oil sales pipeline is off-line.

operating the Galloway power plant using Shell casing and solution gas as fuel to generate electricity.

Without extensive field monitoring it is difficult to confirm the extent and effectiveness of emission mitigating measures. Therefore, the following assumptions are applied and intended to produce a conservative estimate of emissions.

- For 2012, a 95 percent control efficiency[7] is applied to all production tanks connected to a flare or VRU (i.e., 5 percent of tank-top gas is vented even though operator records indicate control efficiency may be as high as 99 percent). Casing gas is understood to be used as fuel or flared (and reported as such in Petrinex). Sites where PFDs indicate direct venting to the atmosphere are listed in Table 8 and accounted as such in the emission inventory database.
- Some sites use scavengers to remove sulphur from gas before it is vented. An 81 percent sulphur compound control efficiency is applied to these vents starting in 2011.
- For 2011 and earlier, no emission control is applied to solution gas venting from production tanks. Casing gas is understood to be used as fuel or flared (and reported as such in Petrinex).

Table 8: Production tanks in the Three Creeks area where solution gas is vented to the atmosphere in 2012.

Operator	Location	Comment
BAYTEX	04-15-084-17W5	7 venting production tanks
	04-16-084-17W5	2 venting production tanks
	05-16-084-17W5	1 venting production tank
HUSKY	12-33-084-18W5	4 production and shipping tanks with SulfaTreat scrubbers before venting to atmosphere
	13-21-084-18W5	2 production and shipping tanks with SulfaTreat scrubbers before venting to atmosphere
PENN WEST	15-01-083-18W5	2 production tanks with SulfaTreat scrubbers before venting to atmosphere
	03-30-083-18W5	2 venting production tanks
	04-29-083-18W5	5 venting production tanks
	04-32-083-18W5	6 production tanks with SulfaTreat scrubbers before venting to atmosphere
	10-24-084-19W5	3 production tanks with SulfaTreat scrubbers before venting to atmosphere
	13-32-083-18W5	6 production tanks with SulfaTreat scrubbers before venting to atmosphere
	14-27-083-18W5	2 venting production tanks

[7] 95 percent control efficiency is the minimum required by CCME, 1995 and conservatively applied to determine worst case production tank emissions.

Table 8: Production tanks in the Three Creeks area where solution gas is vented to the atmosphere in 2012.		
Operator	**Location**	**Comment**
	15-01-083-18W5	2 production tanks with SulfaTreat scrubbers before venting to atmosphere

3 RESULTS AND DISCUSSION

Summaries of 2012 target substance-group results are presented in the Sections 3.1 and 3.2 while working group questions are answered in Sections 3.3 and 3.4. Complete emission results for each facility, source category and substance emitted in 2012 are presented in the enclosed spreadsheet (see "Complete Results" tab in 2012 Three Creeks Summary_v4.xlsx). These detailed results are suitable for evaluating specific substances not presented in the target substance-groups

A comparison of emissions versus production yields the following VOC and RSC emission intensities. Companies with the largest production (i.e., Shell and Baytex) have lower emission intensities than the smaller producers.

The 2012 VOC intensity for each producer was:

BAYTEX = 164 g VOC per m^3 OE
HUSKY = 258 g VOC per m^3 OE
MURPHY = 254 g VOC per m^3 OE
PENN WEST = 466 g VOC per m^3 OE
SHELL = 111 g VOC per m^3 OE

The 2012 RSC intensity for each producer was:

BAYTEX = 0.60 g RSC per m^3 OE
HUSKY = 1.09 g RSC per m^3 OE
MURPHY = 0.97 g RSC per m^3 OE
PENN WEST = 1.31 g RSC per m^3 OE
SHELL = 0.57 g RSC per m^3 OE

3.1 TARGET SUBSTANCE GROUP EMISSIONS BY SOURCE CATEGORY

Emissions are presented by source category in Figure 2, Figure 3, Table 9, and Table 10 (categories are described in Section 2.6). In 2012, VOC emissions are primarily from truck loading (33%) and natural gas fuel combustion (22%) followed by fugitives (13%), storage losses (12%), flaring (9%) and tank cleaning (6%) emissions. Vehicle combustion, dehydrators, pneumatics and casing venting only represent 4 percent of VOC emissions. In 2011, VOC emissions from storage losses are a much larger contributor (56%) and responsible for most of the difference between 2011 and 2012 emissions.

Moreover, C_5^+ concentrations observed in oil truck vent streams are roughly the same as production tank vapour and Reno solution gas streams A comparison of Three Creeks versus Reno gas compositions are presented in Table 11.

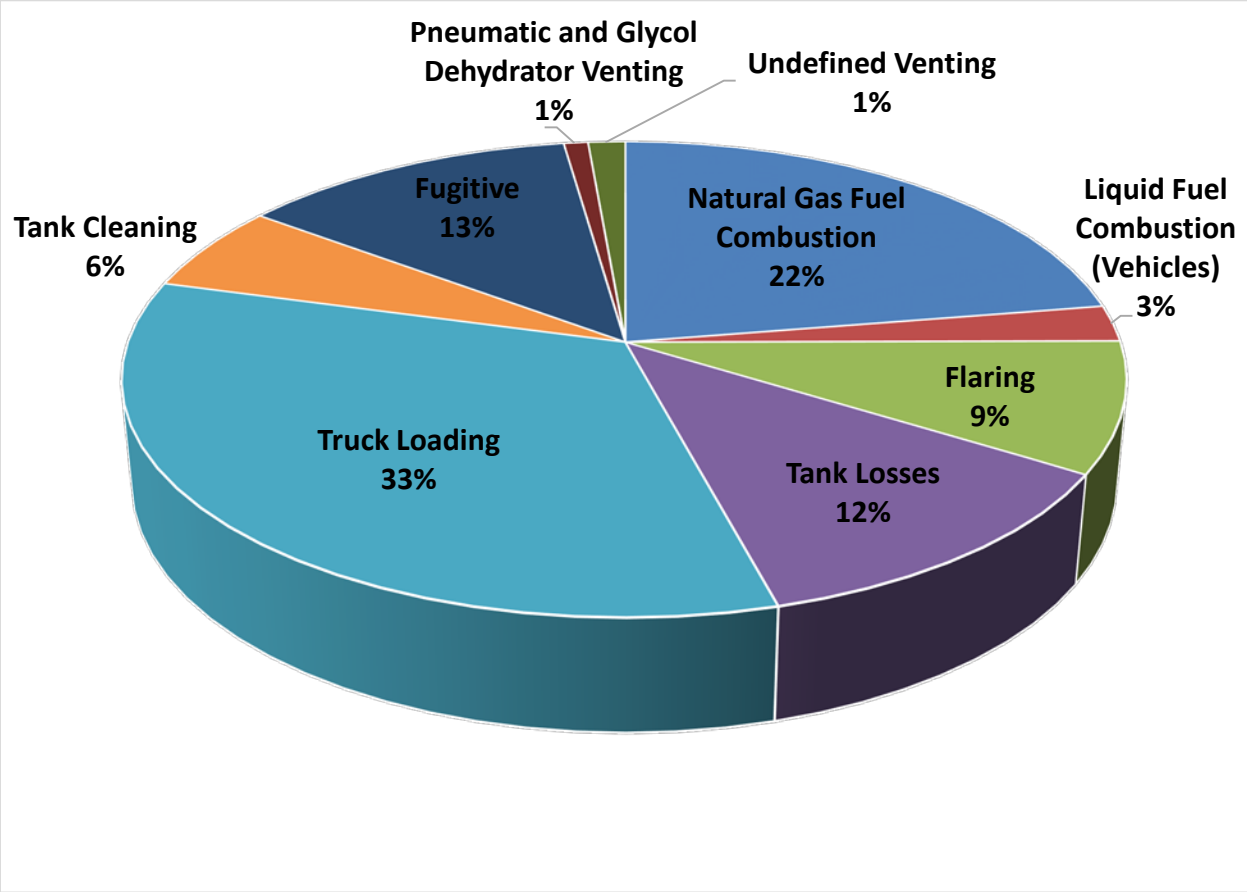

Figure 2: Distribution of 2012 VOC emissions by source category.

In 2012, RSC emissions are primarily from natural gas fuel combustion (56%), flaring (15%) and truck loading (12%) followed by fugitives (9%), tank losses (5%), and tank cleaning (2%). Dehydrators, pneumatics and casing venting only represent 1 percent of RSC emissions.

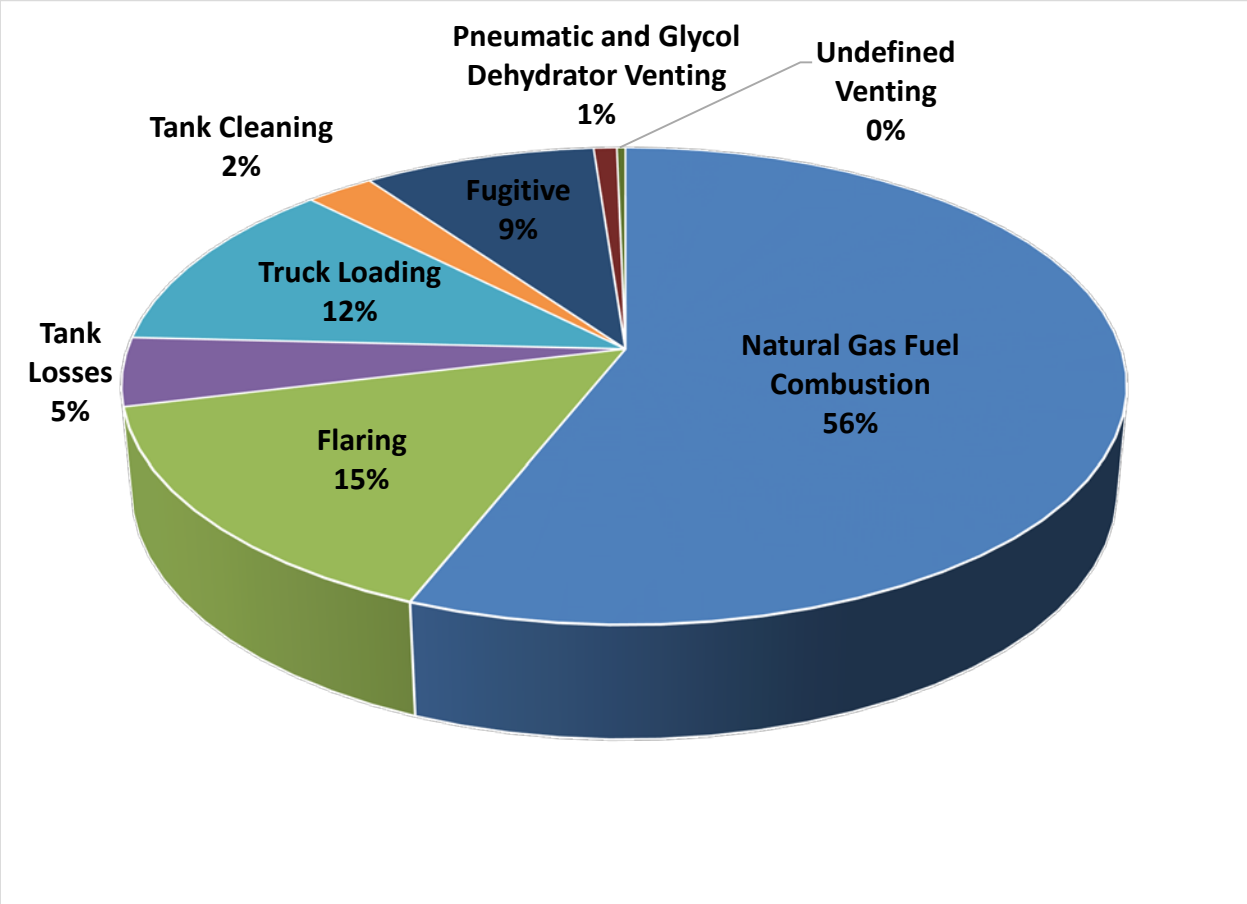

Figure 3: Distribution of 2012 RSC emissions by source category.

Emissions of SO_2, NOx, CO and TPM are entirely from combustion activities.

Table 9: 2012 Emissions by target substance group and source category in the Three Creeks area.										
Target Substance Group	**Emissions (tonnes per year)**									
	Natural Gas Fuel Combustion	**Liquid Fuel Combustion (Vehicles)**	**Flaring**	**Tank Losses**	**Truck Loading**	**Tank Cleaning**	**Fugitive**	**Pneumatic and Glycol Dehydrator Venting**	**Undefined Venting (from Petrinex)[1]**	**Total**
Volatile Organic Compounds	96.7	10.6	38.2	51.7	144.0	25.5	54.1	3.9	6.0	430.7
Total Reduced Sulphur	0.986		0.266	0.082	0.208	0.045	0.152	0.015	0.006	1.760
Sulphur Dioxide	61.5	65.4	8.6							135.5
Oxides of Nitrogen	1,200.2	154.2	20.6							1,375.0
Carbon Monoxide	1,553.5	32.3	112.2							1,698.1
Total Particulate Matter[2]	5.3	10.4	40.2							55.9

[1] Venting reported in Petrinex is primarily from casing gas and two water tanks at the Shell PRC facility that vent TCPL blanket gas.

[2] From combustion sources only (does not include road dust).

Table 10: 2011 Emissions by target substance group and source category in the Three Creeks area.										
Target Substance Group	**Emissions (tonnes per year)**									
	Natural Gas Fuel Combustion	**Liquid Fuel Combustion (Vehicles)**	**Flaring**	**Tank Losses**	**Truck Loading**	**Tank Cleaning**	**Fugitive**	**Pneumatic and Glycol Dehydrator Venting**	**Undefined Venting (from Petrinex)[1]**	**Total**
Volatile Organic Compounds	70.8	7.3	29.8	416.1	109.0	19.5	49.5	4.9	31.0	737.9
Total Reduced Sulphur	0.774		0.226	0.735	0.171	0.034	0.146	0.015	0.203	2.304
Sulphur Dioxide	55.8	74.5	7.3							137.6
Oxides of Nitrogen	909.9	105.6	17.2							1,032.7
Carbon Monoxide	1,112.2	22.2	93.5							1,227.9
Total Particulate Matter[2]	4.1	7.1	33.5							44.7

[1] Venting reported in Petrinex is primarily from casing gas and two water tanks at the Shell PRC facility that vent TCPL blanket gas.

[2] From combustion sources only (does not include road dust).

Table 11: Comparison of Three Creeks versus Reno gas stream mol fractions (grouped by substance carbon number).															
Gas Stream	**Carbon Number**														
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**12**	**13**	**15**	**24**
Reno Solution Gas	0.1076	0.8513	0.0032	0.0024	0.0024	0.0063	0.0163	0.0098	0.0006	0.0002	3.E-05				
Reno Casing and Solution Mix	0.0207	0.9724	0.0024	0.0006	0.0004	0.0007	0.0015	0.0011	0.0002	0.0001	3.E-06				
Three Creeks Casing Gas	0.0461	0.9402	0.0043	0.0048	0.0023	0.0010	0.0008	0.0004	0.0001	0.0001	2.E-09	2.E-06			
Three Creeks Production Tank Vapour	0.0620	0.8768	0.0066	0.0087	0.0189	0.0087	0.0106	0.0069	0.0006	0.0001	1.E-06	1.E-06	4.E-09	6.E-10	8.E-09
Three Creeks Water Truck Vapour	0.9397	0.0515	0.0002	0.0005	0.0017	0.0012	0.0024	0.0020	0.0004	0.0003	1.E-05				
Three Creeks Oil Truck Vapour	0.9089	0.0578	0.0009	0.0046	0.0093	0.0057	0.0076	0.0045	0.0005	0.0002	2.E-05				

3.2 TARGET SUBSTANCE GROUP EMISSIONS OVER TIME

Emissions and production in the Three Creeks area from 2004 to 2012 are presented in Table 12. Production has increased 4.5 times since 2004 while emission increases depend on the substance group of interest and whether controls are implemented. For example, VOC emissions increase as production rates increase from 2004 until 2008 when the mitigating actions described in Section 2.7 begin to be implemented. Even though production increased from 2009 to 2012, VOC emissions decreased. No controls are identified for NOx, CO and TPM emissions which have steadily increased with increasing production, and more importantly, increased fuel consumption and flaring. Although NOx and CO emissions increased, Mobile Air Monitoring Laboratory (MAML) measurements completed by ERSD indicate ground level concentrations are much lower than Alberta ambient air quality objectives (AAAQO) and therefore not the primary concern (Stantec, 2014).

SO_2 emissions from 2004 to 2010 are primarily from sour fuel consumption and flaring at the 05-21-085-18W5 thermal plant (Stantec, 2014) and are obtained from Environment Canada's online NPRI database. SO_2 reductions observed between 2009 and 2011 are due to the utilization of sweet fuel gas and consistent with ambient air monitoring results (see Figure 6-2 in Stantec, 2014). SO_2 ground level concentrations after 2010 are lower than 30-day AAAQO of 11 ppb and therefore not the primary concern.

Table 12: Target emissions and production between 2004 and 2012 in Three Creeks.

Year	Target Substance Group Emissions (tonnes per year)						Total Production (m^3 OE/yr)
	Volatile Organic Compounds	Total Reduced Sulphur[1]	Sulphur Dioxide	Oxides of Nitrogen	Carbon Monoxide	Total Particulate Matter[2]	
2004	38.4	0.44	2,158.4	338.4	230.7	4.9	579,671
2005	56.1	0.49	3,451.5	372.0	243.9	5.6	672,268
2006	125.9	0.66	2,483.7	371.5	260.1	7.2	737,982
2007	363.2	1.33	3,288.6	526.2	434.9	7.7	1,284,671
2008	846.7	4.16	3,499.0	632.1	561.9	10.5	1,548,286
2009	771.8	3.08	2,175.1	738.4	857.0	48.1	1,652,313
2010	728.3	3.00	1,457.3	1,298.1	1,665.3	62.5	1,821,484
2011	737.9	2.30	137.6	1,032.7	1,227.9	44.7	1,839,222
2012	430.7	1.76	135.5	1,375.0	1,698.1	55.9	2,635,999

[1] TRS emissions from 2004 to 2010 do not account for sour fuel combustion at the 05-21 thermal plant and are therefore understated.

[2] From combustion sources only (does not include road dust).

3.3 SOURCE CHARACTERIZATION

The Industry Air Quality Working Group presented the following questions (italicized) with respect to emission sources. Responses are based on information provided to Clearstone and the resulting emissions inventory.

a. *What type of emission sources exist (i.e., production tanks including de-sanding operations, incinerators, flares, tanker trucks, other industrial sources)?*

Emission source types are described in Section 2.6 with results summarized in Section 3.1.

b. *How many sources are there and where are they located (i.e., geo referenced locations)?*

In 2012, the following CHOPS and thermal oil facilities operated in the study area. The description and count of oil and gas emission sources are presented in Table 13 while point source locations are enclosed (see "Complete Results" tab in "2012 Three Creeks Summary_v4.xlsx").

- 21 single well oil batteries
- 97 multi well oil batteries
- 6 water injection facilities (disposal)
- 404 oil wells
- 1 gas well
- 2 in-situ oil sands batteries
- 2 steam injection facilities
- 92 thermal oil wells

Table 13: 2012 oil and gas emission source counts for the Three Creeks study area

Emission Source Description	Count
Diesel engines[1]	3
Flares	94
Glycol dehydrators	2
Heaters and boilers	1000
Hydraulic pumping units	400
Hydrocarbon production tanks	900
Gas metering	130
Pig traps	60
Power generators	40
Propane heaters[1]	1400
Compressors (electric driven)	9
Compressors (natural gas driven)	45
Separators	23

Table 13: 2012 oil and gas emission source counts for the Three Creeks study area	
Emission Source Description	**Count**
Tank cleaning points	900
Truck loading points	900
Well casing vents	30

[1] Equipment counts for diesel and propane combustion devices are understated because emission calculations are determined using purchased liquid fuel volumes instead of equipment details. Moreover, propane is a backup fuel for most natural gas fired equipment at oil facilities.

c. What contaminants of concern are generated?

Substances of concern are ranked by comparing observed concentrations relative to their Alberta occupational exposure limits (OEL) in Table 14; Alberta ambient air quality objectives (AAAQO) in Table 15; and odour detection threshold in Table 17. The complete list of 214 substances quantified in the 2012 inventory are presented in Appendix III and organized by annual release quantity.

Alberta OELs

Oil and water truck tank vapours are of concern because they are released in close proximity to truck operators. 18 substances exceed the 8-hour average Alberta OELs and are presented in Table 14 (MJSTL, 2009). The magnitude of the exceedance and approximate number of dilutions required before the substance concentration would fall below the OEL is also presented in Table 14. This provides a coarse indication of the distance required before a receptor would observe concentrations below the OEL. Field measurements suggest 3 meters of separation downwind results in a dilution of 50 times while 25 meters of separation dilutes the source concentration 1,000 to 60,000 times depending on the substance and atmospheric conditions (Clearstone, 2014c). Thus, substances in Table 14 are a concern to truck operators who typically work within 1 to 10 meters of truck vents but will likely[8] be below OELs if operators avoid immediate downwind contact with the plume.

Substances with values less than 1 are not included in Table 14. When an 8-hour exposure limit is set, the basic premise is that nearly all workers can be exposed day-after-day (8 hours per day/40 days per week) to these concentrations without suffering adverse health effects. However, adjustments to OELs should be considered for unusual work schedules (i.e., shift work) and concurrent chemical exposures (MEI, 2011) if no additional controls are applied to this source.

8 Rigorous dispersion modelling is required to predict ground level concentrations at receptor locations.

Table 14: List of substances observed in Three Creeks oil and water truck tank vapours that exceed Alberta OELs and magnitude of the exceedance.					
CAS Number	**Substance Name**	**Average Analysis Results (mol fraction)[1]**		**Source concentration divided by 8-hour OEL**	
		Oil Truck Vent	**Water Truck Vent**	**Oil Truck Vent**	**Water Truck Vent**
75-08-1	Ethyl Mercaptan	8.12E-06	BDL	16	
110-82-7	Cyclohexane	1.19E-03	6.87E-04	12	7
110-54-3	n-Hexane	5.56E-04	2.81E-04	11	6
74-93-1	Methyl Mercaptan	3.31E-06	2.95E-08	7	0
7783-06-4	Hydrogen Sulphide	5.94E-05	3.19E-05	6	3
78-78-4	Isopentane	2.85E-03	7.16E-04	5	1
108-87-2	Methylcyclohexane	1.70E-03	1.17E-03	4	3
108-88-3	Toluene	1.78E-04	2.59E-04	4	5
74-99-7	Propyne	2.83E-03	4.24E-04	3	0
107-83-5	2-Methylpentane	1.40E-03	4.90E-04	3	1
96-14-0	3-Methylpentane	1.08E-03	4.04E-04	2	1
109-66-0	n-Pentane	1.28E-03	4.01E-04	2	1
106-97-8	Butane	1.94E-03	1.97E-04	2	0
75-15-0	Carbon Disulphide	1.76E-06	BDL	2	
589-34-4	3-Methylhexane	5.74E-04	3.23E-04	1	1
74-98-6	Propane	1.42E-03	8.54E-05	1	0
CEL0014	m,p-Xylene	1.14E-04	1.79E-04	1	2
95-63-6	1,2,4-Trimethylbenzene	1.63E-05	6.18E-05	1	2

[1] Concentrations are presented on a dry, air-in basis and are the numerical average of valid samples collected.

AAAQO

Eleven substances identified by the AAAQO (ESRD, 2013) are detected in the sampled vapours and presented in Table 15. The concentrations of these substances, where detected, generally exceed the 1-hour ground-level objectives at their source. The magnitude of the source exceedance and approximate number of dilutions required before the substance concentration would fall below the AAAQO is also presented in Table 15. Although AAAQO are only relevant to off-site receptor locations (not source concentrations), Table 15 results are presented to identify substances at risk of exceeding AAAQO. Moreover, the coarse plume dilution characteristics discussed above indicate that 25 meters of downwind separation would drop all substances concentrations below the AAAQOs[9].

Further review of total annual emissions for substances with AAAQOs indicates BTEX compounds (i.e., aromatic hydrocarbons with 6 to 9 carbon molecules) and H_2S have the largest emissions in 2012, with truck loading being the dominant source. These results are presented in Table 16 and suggest further review of truck loading emission controls should be considered.

9 Rigorous dispersion modelling is required to predict ground level concentrations at receptor locations.

Odour Detection Thresholds

There are 17 substances presented in Table 17 that exceed their OEL or AAAQO and have an odour detection threshold (AIHA, 1997). Of these, the top 3 substances of odour concern are sulphur compounds present in the truck vents, production tanks and casing gas in the low parts per million range. These have very low odour thresholds (e.g., in the low part per billion level), and can contribute to offsite odours, even when present in relatively low amounts. Ethylbenzene, isopropylbenzene and toluene are observed in source concentrations several hundred times greater than their odour detection thresholds that could be detected offsite.

The remaining substances omitted from Table 17 are either below their odour detection threshold or no threshold is published in AIHA, 1997.

Table 15: List of substances observed in Three Creeks well casing gas as well as production and truck tank vapours that exceed AAAQO 1-hour ground level concentration limits and magnitude of the exceedance.													
CAS Number	**Substance Name**	**Average Analysis Results (mol fraction)[1]**						**Source concentration divided by 1-hour AAAQO**					
		Oil Truck Vent	**Water Truck Vent**	**Production Tank**	**Well Casing**	**De-Sanding (vacuum truck vent)**	**Ambient Air**	**Oil Truck Vent**	**Water Truck Vent**	**Production Tank**	**Well Casing**	**De-Sanding (vacuum truck vent)**	**Ambient Air**
7783-06-4	**Hydrogen Sulphide**	5.94E-05	3.19E-05	1.74E-04	7.51E-05	BDL	BDL	5,942	3,194	17,433	7,507		
108-88-3	**Toluene**	1.78E-04	2.59E-04	2.84E-04	4.03E-05	4.75E-06	2.36E-09	356	519	568	81	10	0
CEL0014	**m,p-Xylene**	1.14E-04	1.79E-04	1.10E-04	1.87E-05	5.59E-06	6.92E-09	215	337	208	35	11	0
95-47-6	**o-Xylene**	4.51E-05	7.06E-05	4.50E-05	7.43E-06	2.11E-06	2.64E-09	85	133	85	14	4	0
75-15-0	**Carbon Disulphide**	1.76E-06	BDL	8.68E-07	BDL	BDL	BDL	176		87			
100-41-4	**Ethylbenzene**	6.06E-05	8.80E-05	7.44E-05	1.15E-05	2.16E-06	2.37E-09	132	191	162	25	5	0
98-82-8	**Isopropylbenzene**	9.98E-06	1.70E-05	1.30E-05	1.76E-06	3.73E-07	2.33E-09	100	170	130	18	4	0
110-54-3	**n-Hexane**	5.56E-04	2.81E-04	6.43E-04	1.40E-04	1.39E-05	1.01E-08	93	47	108	24	2	0
71-43-2	**Benzene**	BDL	BDL	BDL	8.64E-06	BDL	BDL				960		
67-56-1	**Methanol**	BDL	BDL	BDL	5.33E-10	7.41E-09	BDL				0	0	
67-63-0	**Isopropyl alcohol**	BDL	BDL	BDL	3.27E-10	BDL	BDL				0		

[1] Concentrations are presented on a dry, air-in basis and are the numerical average of valid samples collected.

Table 16: 2012 Emissions of substances with AAAQOs by source category in the Three Creeks area.									
Priority Substance	**Emissions (tonnes per year)**								
	Fuel Combustion	**Flaring**	**Production Tank Losses**	**Truck Loading**	**Tank Cleaning**	**Fugitive**	**Pneumatic and Glycol Dehydrator Venting**	**Undefined Venting**	**Total**
n-Hexane	3.30E+00	5.60E-01	8.04E-01	3.88E+00	3.93E-01	7.52E-01	3.77E-02	3.99E-02	9.77E+00
Toluene	7.86E-02	2.88E-01	3.90E-01	1.42E+00	1.89E-01	3.90E-01	2.17E-01	5.59E-03	2.98E+00
Xylenes	4.07E-01	1.81E-01	2.47E-01	1.56E+00	1.19E-01	2.61E-01	5.83E-03	4.53E-03	2.79E+00
Hydrogen Sulphide	8.86E-01	2.52E-01	7.44E-02	8.80E-02	4.08E-02	1.25E-01	1.32E-02	4.15E-03	1.48E+00
Ethylbenzene	2.90E-01	8.81E-02	1.22E-01	5.89E-01	5.96E-02	1.26E-01	4.82E-02	2.02E-03	1.32E+00
Isopropylbenzene	5.16E-01	1.37E-02	1.97E-02	1.22E-01	9.38E-03	2.05E-02	4.40E-04	3.42E-04	7.02E-01
Benzene	1.17E-01	1.06E-02				1.54E-02	1.13E-01	6.21E-03	2.62E-01
Carbon disulphide	3.91E-03		8.06E-04	1.46E-04	4.41E-04	7.30E-04			6.03E-03
2-Propanol		3.05E-07		1.15E-06		4.40E-07	4.07E-08	3.16E-08	1.97E-06
Methanol		2.68E-07				3.87E-07	3.58E-08	2.78E-08	7.19E-07

Table 17: List of substances with odour detection thresholds observed in Three Creeks that also exceed their OEL or AAAQO.											
CAS Number	**Substance Name**	**Average Analysis Results (mol fraction)[1]**					**Source concentration divided by odour detection threshold**				
		Oil Truck Vent	**Water Truck Vent**	**Production Tank**	**Well Casing**	**De-Sanding (vacuum truck vent)**	**Oil Truck Vent**	**Water Truck Vent**	**Production Tank**	**Well Casing**	**De-Sanding (vacuum truck vent)**
75-08-1	Ethyl Mercaptan	8.12E-06	BDL	2.84E-06	2.84E-06	BDL	20,300		7,110	7,093	
7783-06-4	Hydrogen Sulphide	5.94E-05	3.19E-05	1.74E-04	7.51E-05	BDL	6,321	3,397	18,545	7,986	
74-93-1	Methyl Mercaptan	3.31E-06	2.95E-08	1.19E-06	1.31E-06	BDL	6,130	55	2,200	2,434	
100-41-4	Ethylbenzene	6.06E-05	8.80E-05	7.44E-05	1.15E-05	2.16E-06	659	956	809	125	23
98-82-8	Isopropylbenzene	9.98E-06	1.70E-05	1.30E-05	1.76E-06	3.73E-07	312	533	406	55	12
108-88-3	Toluene	1.78E-04	2.59E-04	2.84E-04	4.03E-05	4.75E-06	111	162	177	25	3
75-15-0	Carbon Disulphide	1.76E-06	BDL	8.68E-07	BDL	BDL	110		54		
CEL0014	m,p-Xylene	1.14E-04	1.79E-04	1.10E-04	1.87E-05	5.59E-06	21	33	20	3	1
78-78-4	Isopentane	2.85E-03	7.16E-04	5.88E-03	1.56E-03	4.47E-05	24	6	49	13	0
110-54-3	n-Hexane	5.56E-04	2.81E-04	6.43E-04	1.40E-04	1.39E-05	9	5	11	2	0
95-47-6	o-Xylene	4.51E-05	7.06E-05	4.50E-05	7.43E-06	2.11E-06	8	13	8	1	0
95-63-6	1,2,4-Trimethylbenzene	1.63E-05	6.18E-05	1.76E-05	1.24E-05	1.57E-06	7	26	7	5	1
108-67-8	1,3,5-Trimethylbenzene	1.09E-05	2.79E-05	1.18E-05	5.57E-06	6.56E-07	5	13	5	3	0
106-97-8	Butane	1.94E-03	1.97E-04	3.90E-03	2.04E-03	3.88E-05	2	0	3	2	0
110-82-7	Cyclohexane	1.19E-03	6.87E-04	1.88E-03	2.01E-04	2.23E-05	2	1	2	0	0
109-79-5	Butyl Mercaptan	BDL	BDL	1.20E-06	BDL	BDL			1,203		
142-82-5	n-Heptane	1.07E-04	5.33E-05	1.71E-04	1.60E-05	1.37E-06	0	0	1	0	0

[1] Concentrations are presented on a dry, air-in basis and are the numerical average of valid samples collected.

d. What is the chronological pattern of growth in the area (i.e., number of tanks)?

The increase in production from 2004 to 2012 is presented in Section 3.2. The corresponding number of production tanks presented in Table 18 is a useful analog for quantifying the proliferation of surface equipment associated with this growth.

Table 18: Count of production tanks operating in Three Creeks between 2004 and 2012.

Year	Tank Count
2004	18
2005	45
2006	174
2007	366
2008	412
2009	536
2010	745
2011	701
2012	903

e. What is the estimated magnitude (rate) of emissions from each source and based on production rates, how are these emissions changing over time?

Annual emissions for each target substance group from 2004 to 2012 are discussed in Section 3.2. Moreover, a detailed emission inventory from all point sources in the study area was prepared to support this report.

3.4 TYPICAL SITES

The industry Air Quality Working Group intended the inventory to answer the following questions (italicized) with respect to typical facility configurations and their impact on emissions. Responses focus on the VOC substance group because this analog best reflects the substances with AAAQOs listed in Table 15.

a. What are the estimated emissions from the various typical well pad configurations (i.e., from sites with a Vapour Recovery Unit (VRU), without a VRU, with flaring, with venting, with scrubbers)? What is the actual control efficiency of these technologies?

VOC emissions from five different single well battery (SWB) design scenarios are presented in Table 19. The design scenarios reflect complementary and increasingly effective emission control strategies from case 5 (zero control) to case 1 (best control). Control efficiency values in

Table 19 are calculated relative to case 5 (zero) while production volumes are based on typical volumes observed in Three Creeks.

- Case 5 is illustrated in Figure 4 where all well casing gas, production tank vapours and truck tank vapours are vented directly to the atmosphere. Moreover, tank heaters and the hydraulic pump engine are fueled by purchased propane. The dominant VOC emission source is well casing venting (87 percent) followed by production tank losses (8 percent).

- Case 4 is similar to case 5 but approximately half of the casing gas volume is utilized as fuel by the heaters and engine. Propane fuel combustion is eliminated and venting is reduced which results in a 40 percent decrease in VOC emissions.

- Case 3 is illustrated in Figure 5 and features a flare to dispose excess casing gas not combusted by the heaters and engine. Installing the flare results in an 85 percent decrease in VOC emissions. The dominant emission source is now production tank losses (55 percent) because production tanks are still venting to atmosphere.

- Case 2 is illustrated in Figure 6 where casing gas and production tank venting is eliminated by installing a VRU[10] compressor to conserve and sell excess gas. This results in a 90 percent emission reduction relative to case 5. However, installing a VRU increases fuel combustion and fugitive emissions which are now the dominant source of emissions (50 and 25 percent, respectively). Truck loading is the next largest contributor at 18 percent.

- Case 1 features an incinerator instead of a VRU compressor to combust excess gas on site. Incorporating the incinerator into the tank heater exhaust stack is an innovative method to achieve better combustion efficiencies[11] and less visibility than flaring. It further reduces VOC emissions by 0.2 tonnes per pad (2.4 percent) relative to case 2.

- Case 0 is illustrated in Figure 7 and features an activated carbon adsorption system to control truck loading VOC emissions[12]. The carbon scrubber reduces VOC emissions by 0.14 tonnes per pad (1.7 percent) relative to case 1. Moreover, the case 0 control scenario results in a 94 percent emission reduction relative to case 5. The dominant emission source for case 0 is fuel combustion (63 percent) followed by fugitive emissions (23 percent).

10 Storage tank control efficiency is conservatively set to 95 percent when tank vapours are directed to a VRU. This is the minimum control efficiency required by CCME, 1995 and may result in overstated tank losses.

11 Combustion efficiency of 99.93 percent was observed for heaters in the Reno area (Clearstone, 2013) while Spartan Controls indicates VOC destruction efficiency greater than 99 percent for their SlipStream GTS Technology.

12 A VOC control efficiency of 95 percent is conservatively applied while greater control efficiencies are possible (e.g., APC Technologies indicates 99%+ control). SulfaTreat scrubbers observed in the Three Creeks area do not control VOC emissions (sulphur compounds only).

Table 19: Comparison of VOC emission control scenarios for a typical single well battery operating in Three Creeks.										
Case #	Design Description[1]	VOC Control Efficiency[2]	VOC Emissions (tonnes per year)							
			Fuel Combustion	Flaring	Production Tank Losses	Truck Loading	Tank Cleaning	Fugitive	Well Casing Vent	Total
0	SWB conserving casing gas and tank vapours as fuel with remaining incinerated. Truck vapours controlled with VOC scrubber.	94%	0.307	0.000	0.034	0.007	0.028	0.110	0.000	0.488
1	SWB conserving casing gas and tank vapours as fuel with remaining incinerated. Truck vapours vented.	92%	0.307	0.000	0.034	0.146	0.028	0.110	0.000	0.627
2	SWB conserving casing gas and tank vapours as fuel with remaining to sales VRU.	90%	0.415	0.000	0.034	0.146	0.028	0.206	0.000	0.830
3	SWB conserving casing gas as fuel with remaining flared. Tank vapours are vented.	85%	0.208	0.075	0.689	0.146	0.028	0.110	0.000	1.257
4	SWB conserving casing gas as fuel with remaining casing gas and tank vapours vented.	40%	0.208	0.000	0.689	0.146	0.028	0.110	3.727	4.909
5	SWB with propane fuel and casing gas/tank vapours vented.	0%	0.011	0.000	0.689	0.146	0.028	0.156	7.135	8.166

[1] All design cases assume the same oil and gas production volumes.

[2] VOC control efficiency is calculated relative to case 5 (i.e., no control) and equals $(1 - Case_i/Case_4)*100\%$

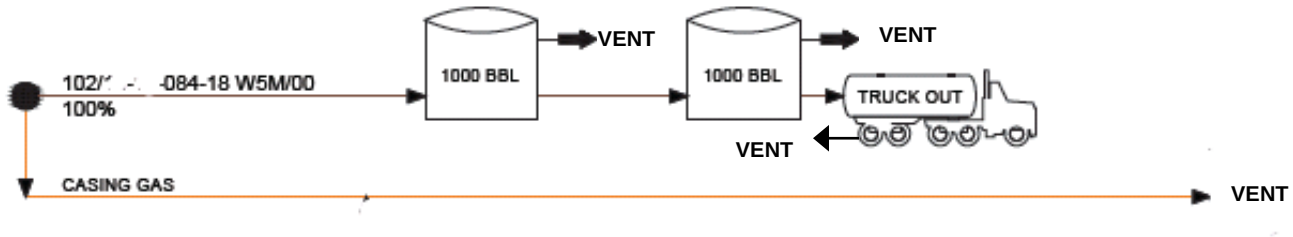

Figure 4: PFD for a SWB with well casing gas and tank vapours vented to atmosphere.

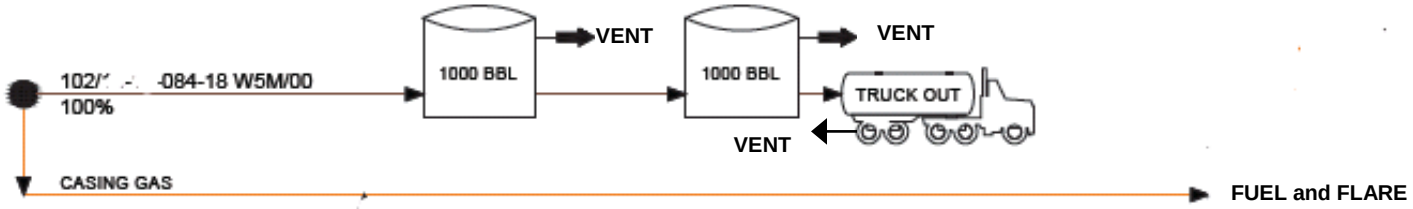

Figure 5: PFD for a SWB with well casing gas used as fuel or flared and tank vapours vented.

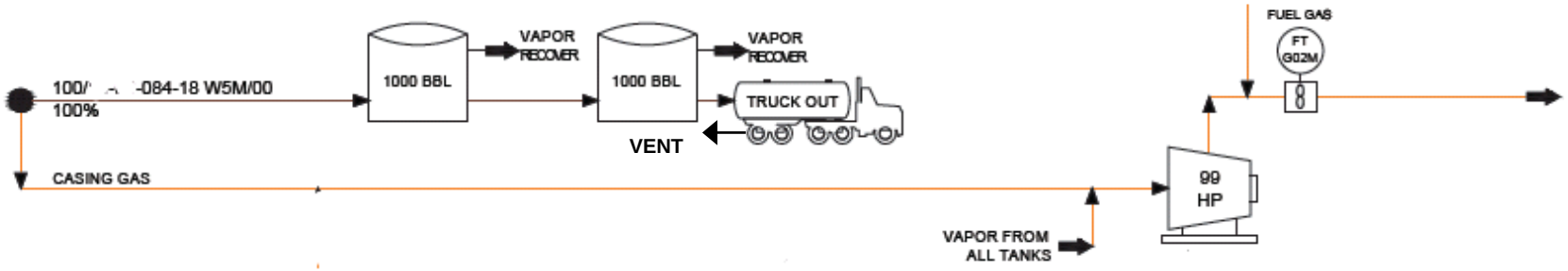

Figure 6: PFD for a SWB with well casing gas and tank vapours used as fuel or conserved with a VRU and sold.

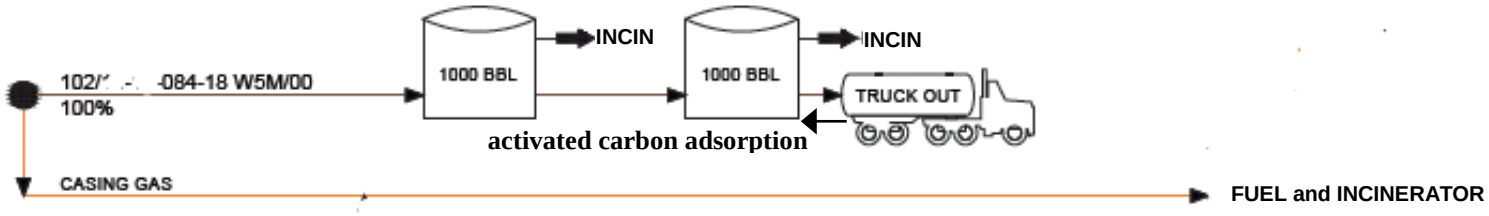

Figure 7: PFD for a SWB with well casing gas and tank vapours used as fuel or incinerated while truck loading losses are released through an activated carbon adsorption unit.

b. *How is oil managed from wellhead to tanker truck?*

A description of CHOPS and thermal oil production flows is provided in Sections 2.1 and 2.2.

c. *What do typical Process and Instrumentation Drawings (P&IDs) look like?*

Process flow diagrams are much more suitable for identifying and communicating air emission sources. Typical PFDs are presented in Figure 4 through Figure 7. P&IDs are referenced when detailed site information is required (e.g., PSV set-points, equipment dimensions and models, etc.).

d. *What are the important characteristics of each source that impact emissions (i.e., tank size, emissions controls)?*

The most important consideration for controlling VOC emissions is to capture and dispose or conserve produced gas streams. Moreover, the following controls should be considered for reducing or eliminating emissions from the source categories presented in Section 2.6.

Stationary Fired Equipment

Casing gas and tank vapour streams are suitable fuel sources and should be preferentially utilized on-site whenever possible. In general, heaters and boilers have better combustion efficiency and lower VOC[13] and RSC emissions than engines or flares. Therefore, minimizing propane fuel use so that produced gas combustion by tank heaters is maximized can be an effective control strategy. For example, cross-over piping that connects casing gas production from multiple wells to the fuel gas supply header on the same pad will reduce propane demand if wells are shut-in or GORs decrease.

Other strategies to ensure efficient use of fuel in engines and heaters through improved inspection, maintenance and operating practices are detailed in relevant modules of the CAPP BMP for Fuel Gas Reduction.

Flaring

For sites with low GORs and very uneconomical gas conservation opportunities, the SlipStream GTS technology may be a more effective emission control strategy than flaring or compression. This technology combusts excess gas in an auxiliary burner (installed in the tank heater exhaust stack); requires a minimum gas supply pressure of 1.75 kPag; and can dispose gas flows from 0 to 14 m^3 per hour. For sites with larger gas flows in the range of 12 to 120 m^3 per hour, a micro-condenser was considered to remove condensable hydrocarbons. However, the C_3^+ fraction in Three Creeks is not large enough to make this option practicable. The residue gas from the micro-condenser would be cleaner burning than the untreated waste gas, resulting in lower VOC

13 Combustion testing in the Reno area resulted in a VOC emission factor of approximately 10 ng/J for tank heaters and 80 ng/J for engines (Clearstone, 2013).

emissions from combustion. This approach is currently under consideration for stranded gas in Mexico, China and Nigeria for sites where C_3^+ content is greater than 15 percent (Pemex, 2014 and Clearstone, 2014d).

Other strategies to reduce flaring are presented in the CAPP BMP for Facility Flare Reduction.

Fugitive Emissions

Given that a small percent of leaking components typically account for most fugitive emissions, the key objective for mitigating emissions is the identification and repair of high risk components. Components subject to vibration, high use, or temperature cycles are the most leak-prone. Moreover, high risk components are often a function of unique characteristics and operations of a facility and identified by completing a comprehensive leak survey of all equipment in gas service. The most common and largest leaking components are high risk and should be subject to more frequent inspection.

This is consistent with establishing a Directed Inspection and Maintenance (DI&M) program described in the CAPP BMP for Fugitive Emissions Management.

Production Tanks

Further to the source characteristics described in Section 2.6.4; tank temperatures of 70 to 80 ^oC will promote evaporation of heavier hydrocarbons. This is observed in the sampled tank vapours (Table 26) where C_4^+ compounds represent 4.6 percent of the vapour (C_2 and C_3 compounds only represent 1.5 percent). Aromatic solvents listed in Table 3 will evaporate in the tank ullage if they are present in demulsifiers and other chemical aids added to heated production tanks. Interestingly, very little methanol is observed in tank vapours even though it has a very high vapour pressure and is the dominant component of some demulsifiers. Methanol may end up in water streams instead of evaporating because of its high solubility in water. If this is the case, selecting methanol instead of aromatic naphtha (i.e., dominated by BTEX) based demulsifiers may reduce concentrations of BTEX in tank vapours.

Otherwise, capturing and directing tank vapour to sales pipelines or for disposal is an important emission control strategy.

Truck Loading

Truck tank vapour saturation is minimized by avoiding free fall and splashing of volatile products. Trucks in Three Creeks were observed to do this by bottom loading oil and water. The product flow rate at the start of a loading operation should be much less than the normal high-flow rate to prevent ‘jetting’ at the point of entry. High flow rates should proceed when the point of entry is submerged.

End of pipe scrubbers can be an effective method for controlling selected compounds. Field measurements indicate existing SulfaTreat scrubbers, that are well maintained, provide 100 percent Sulphur control efficiency. Moreover, scrubbers that are not maintained, and operate with expired catalyst beds, provide little control of target substances (Clearstone, 2014a). Activated carbon adsorption systems can be installed in series with sulphur scrubbers to provide similar control of VOC emissions (Shepherd, 2001). Alternatively, caustic impregnated carbon (CalgonCarbon, 2012); catalytic carbon (Evoqua, 2014) and enhanced chemical solutions (Almont, 2014) can provide control of both sulphur and VOC emissions. Issues to be aware of when selecting a scrubber include: active media replacement frequency and cost; disposal or recycling of hazardous materials (depending on BTEX accumulation); as well as the possibility of exothermic reactions and bed fires (Bafrali and Graham, 2005).

Another option is to enrich truck tank vapours with casing gas, so that the mixture is well above the upper explosive limit (UEL is 15 percent for methane), and direct the vapours to the flare stack.

A vapour balance system connecting the shipping and receiving tanks can eliminate tank venting. However, it is not recommended for Three Creeks CHOPS facilities because truck vapours are predominately air. Routing air to the ullage of the tank from which product is being pumped introduces an unacceptable explosion hazard.

Production Tank Cleaning

During vacuum truck suction of tank bottom sludge, emissions are characterized by high velocities and very low VOC and RSC concentrations. Notwithstanding the low concentrations, high velocity releases may impact long-range receptors and the utilization of scrubbers described above is appropriate. Gas samples taken before and after the vacuum truck scrubber, in Table 20, indicate some VOC control may be occurring and that all sulphur compounds were below the laboratory detection limit (Clearstone, 2014a). However, scrubber technology details are not known so it is unclear whether the VOC reduction is by design or a product of analysis uncertainty.

Table 20: Vacuum truck vent gas compositions[1] upstream and downstream of a scrubber during tank de-sanding in Three Creeks.

Source Description	C_1 to C_4 Compounds	C_5 to C_{12}^+ Compounds	Sulphur Compounds
Downstream of Scrubber	0.00046	0.00027	BDL
Upstream of Scrubber	0.00064	0.00042	BDL
Control efficiency	28%	34%	NA

[1] Concentrations are presented as mol fractions on a dry, air-in basis.

When tanks are isolated from service for a full clean-out, tanks are blown-down to atmospheric pressure before the man-way is opened. Instead of venting tank vapours directly to atmosphere

(which is understood to be the current practice), pressure should be relieved to the flare header and vapours disposed by combustion.

e. What are the key operating parameters that impact emissions (i.e., production rate, gas-to-oil ratio, tank temperature)?

Without the controls described above; increasing production rates, the number of facilities or tank temperatures will increase emissions. Operating parameter not already discussed, include:

- **Water contact with tank burners**: If the water layer in production tanks gets too close or comes into contact with tank burner tubes, steam is produced. Steam volumes will quickly exceed normal hydrocarbon evaporation rates in the tank ullage and may cause tank pressure relief events or flare flame quenching. Therefore, controls should be implemented to ensure free water does not come into contact with tank burners.

- **Unlit flares**: Instances of quenched flare flames will result in venting of casing gas and tank vapours at a high elevation and velocity which may impact long-range receptors. Quenching may be caused by excessive winds or unexpected steam, nitrogen or carbon dioxide in the waste gas.

- **BTEX content of demulsifier and other chemical additives**: The BTEX content of chemicals added to heated production tanks should be minimized because C_6 to C_9 compounds become volatile when heated to 80 ^oC. Minimizing tank vapour concentrations of aromatic compounds with low odour detection thresholds will reduce the risk of OEL, AAAQO and odour exceedances.

- **Spills**: Emulsion or oil spills outside of vessels equipped with emission controls will result in the evaporation of VOC and RSC substances.

- **Slug-flow oil production**: Oil is not always produced from the well at a constant rate. Slug production will result in periods where storage losses and flaring emissions are larger than others.

f. How are well production differences accounted for in an emissions inventory?

Emission inventory is driven by actual production rates reported to Petrinex. Reliability of results are a function of gas and oil metering; data management and reporting.

g. What are the before and after control emissions rates, and how much do they differ?

Before and after controls for a typical single well battery are presented in Table 19. Field measurements to determine sulphur scrubber control efficiency are presented in Section 4.4 of Clearstone, 2014a.

h. How do theoretical emission estimations compare to existing measured data?

A comprehensive fugitive emission survey was completed by Clearstone of facilities operated by Murphy Oil in Three Creeks during the fall of 2014 (Clearstone, 2014b). All leaks were quantified for the 15 sites surveyed and an average emission rate of 1.1 tonnes THC per site was observed. These measurement results are approximately 30 percent greater than the average 2012 inventory leak rate of 0.8 tonnes THC per site determined by the ClearCALC database application. Given that leak factors can produce very uncertain fugitive emission results (i.e., orders of magnitude different) when applied to a small number of sources, the good agreement of theoretical and measurement results provides confidence in the inventory assessment of fugitive emissions.

Moreover, odours were not observed at the 15 sites surveyed in Three Creeks unless in very close proximity to a leaking component (Clearstone, 2014b). The primary source of continuous VOC and RSC emissions at these sites was fuel combustion in pump engines and tank heaters; flaring and fugitives (tank tops were tied into flare headers). Whereas, persistent odours were observed at sites surveyed southeast of Three Creeks where tank tops were freely venting. This suggests tank venting is a more problematic odour source than fugitive or combustion emissions.

Inventory results can also be compared to truck loading measurements available in Clearstone, 2014a. Multiplying the average ratio of THC emissions to product loaded (0.057 m^3 gas/m^3 liquid for oil trucks and 0.012 m^3 gas/m^3 liquid for water trucks) by the total volume of oil (1,860,450 m^3) and water (1,133,491 m^3) transported by truck during 2012; yields truck loading emissions of 117 tonnes THC. This is about 20 percent less than the inventory result of 144 tonnes for 2012 but still confirms ClearCALC produces reasonable results. The difference in results is primarily due to uncertainty in truck vapour composition across all facilities in the study area.

Otherwise, Three Creeks field measurements are not available to confirm inventory results. However, the best available estimation methodology is applied to quantify other emission sources.

i. What are the typical source data (i.e., emissions temperature, release height, stack tip exit diameter, emissions velocity, flow impedance details, emission area for fugitive sources, and other data as required)?

Typical point source characteristics for CHOPS facilities in Three Creeks are presented in Table 21. These values are based on field observations during the summer of 2014 and published in Appendix C of Clearstone, 2014a.

Table 21: Typical point source characteristics for Three Creeks CHOPS facilities.

Process Equipment Description	Stack Height (m)	Stack Diameter (m)	Stack Exit Temperature (°C)	Maximum Stack Exit Velocity (m/s)[1]	Flow Impedance Description
Tank Heater	10.3	0.251	110	2.3	approximately 1/3 of stacks are capped
Pump Engine	3.0	0.051	250	18.4	equal number of horizontal and vertical stacks
Compressor Engine	4.1	0.062	230	21.6	equal number of horizontal and vertical stacks
Generator Engine	3.5	0.051	220	16.9	horizontal stacks
Flare	11.0	0.076	640	5.9[2]	

[1] Exit velocity determined from Reno combustion testing (Clearstone, 2013) and presented at standard reference conditions 15 °C and 101.325 kPa

[2] Average flare exit velocity estimated from available Petrinex monthly volumes.

4 CONCLUSIONS

A detailed bottom-up inventory of air emissions from oil and natural gas activities in the Three Creeks area between 2004 and 2012 has been completed. Inventory results are of sufficient quality and detail to answer the questions presented by Three Creeks Industry Air Quality Working Group.

Inventory results indicate VOC emissions decreased from a peak level of 847 tonnes in 2008 to 431 tonnes in 2012 despite production increases. Emission mitigating actions described by producers and observed during 2014 field visits, indicate CHOPS well-pads now emit 85 to 90 percent less VOC emissions than well-pads that operated in the mid-2000s (with minimal emission controls). Further efforts to reduce VOC emissions from truck loading and other sources may achieve another 4 percent reduction per pad.

In 2012, the primary source of VOC emissions in the entire Three Creeks area are from truck loading losses (33%) and natural gas fuel combustion (22%) followed by fugitives (13%), storage losses (12%), flaring (9%) and tank cleaning (6%). Further review of a typical single well battery, featuring complete capture of produced gas, indicates the largest source of VOC emissions is from natural gas fuel combustion followed by fugitives and truck loading losses. RSC emissions are primarily from natural gas fuel combustion (56%), flaring (15%) and truck loading (12%) followed by fugitives (9%) and storage losses (5%). Tank Cleaning, dehydrators, pneumatics and casing venting only represent 3 percent of RSC emissions.

Detailed gas analysis results from AITF laboratory are included in the inventory with selected substances presented in Table 22 for CHOPS production tank and oil/water truck tank vapours. Substances are priority ranked according to their risk of exceeding AAAQOs, odour thresholds and OELs for streams most likely vented directly to atmosphere. Odours were generally not observed on sites where the source of continuous emissions was fuel combustion, flaring and fugitives. Whereas, persistent odours were observed at sites where tank tops were freely venting or during truck loading.

Controls can be applied to free venting sources (e.g., truck loading, blow-downs, production tank not tied into flare/VRU, etc) that will reduce emissions below current levels.

Table 22: List of substances observed in Three Creeks CHOPS production tank and oil/water truck vapours ranked according to the magnitude they exceed Alberta AAAQO, odour thresholds and OELs.													
CAS Number	**Substance Name**	**Average analysis Results (mol fraction)[1]**			**Concentration divided by 1-hour AAAQO**			**Concentration divided by 8-hour OEL**			**Concentration divided by odour detection threshold**		
		Oil Truck Vent	**Water Truck Vent**	**Production Tank**	**Oil Truck Vent**	**Water Truck Vent**	**Production Tank**	**Oil Truck Vent**	**Water Truck Vent**	**Production Tank**	**Oil Truck Vent**	**Water Truck Vent**	**Production Tank**
7783-06-4	**Hydrogen Sulphide**	5.9E-05	3.2E-05	1.7E-04	5,942	3,194	17,433	6	3	17	6,321	3,397	18,545
108-88-3	**Toluene**	1.8E-04	2.6E-04	2.8E-04	356	519	568	4	5	6	111	162	177
CEL0014	**m,p-Xylene**	1.1E-04	1.8E-04	1.1E-04	215	337	208	1	2	1	21	33	20
95-47-6	**o-Xylene**	4.5E-05	7.1E-05	4.5E-05	85	133	85	0	1	0	8	13	8
75-15-0	**Carbon Disulphide**	1.8E-06	BDL	8.7E-07	176	NA	87	2	NA	1	110	NA	54
100-41-4	**Ethylbenzene**	6.1E-05	8.8E-05	7.4E-05	132	191	162	1	1	1	659	956	809
98-82-8	**Isopropylbenzene**	1.0E-05	1.7E-05	1.3E-05	100	170	130	0	0	0	312	533	406
75-08-1	**Ethyl Mercaptan**	8.1E-06	BDL	2.8E-06	NA	NA	NA	16	NA	6	20,300	NA	7,110
74-93-1	**Methyl Mercaptan**	3.3E-06	3.0E-08	1.2E-06	NA	NA	NA	7	0	2	6,130	55	2,200
110-54-3	**n-Hexane**	5.6E-04	2.8E-04	6.4E-04	93	47	108	11	6	13	9	5	11
110-82-7	**Cyclohexane**	1.2E-03	6.9E-04	1.9E-03	NA	NA	NA	12	7	19	2	1	2
78-78-4	**Isopentane**	2.8E-03	7.2E-04	5.9E-03	NA	NA	NA	5	1	10	24	6	49
108-87-2	**Methylcyclohexane**	1.7E-03	1.2E-03	2.6E-03	NA	NA	NA	4	3	6	NA	NA	NA
95-63-6	**1,2,4-Trimethylbenzene**	1.6E-05	6.2E-05	1.8E-05	NA	NA	NA	1	2	1	7	26	7
108-67-8	**1,3,5-Trimethylbenzene**	1.1E-05	2.8E-05	1.2E-05	NA	NA	NA	0	1	0	5	13	5
106-97-8	**Butane**	1.9E-03	2.0E-04	3.9E-03	NA	NA	NA	2	0	4	2	0	3
109-79-5	**Butyl Mercaptan**	BDL	BDL	1.2E-06	NA	NA	NA	NA	NA	2	NA	NA	1,203
74-99-7	**Propyne**	2.8E-03	4.2E-04	4.6E-03	NA	NA	NA	3	0	5	NA	NA	NA
107-83-5	**2-Methylpentane**	1.4E-03	4.9E-04	2.5E-03	NA	NA	NA	3	1	5	NA	NA	NA
96-14-0	**3-Methylpentane**	1.1E-03	4.0E-04	2.0E-03	NA	NA	NA	2	1	4	NA	NA	NA
109-66-0	**n-Pentane**	1.3E-03	4.0E-04	1.6E-03	NA	NA	NA	2	1	3	NA	NA	NA
589-34-4	**3-Methylhexane**	5.7E-04	3.2E-04	9.2E-04	NA	NA	NA	1	1	2	NA	NA	NA

[1] Concentrations are presented on a dry, air-in basis and are the numerical average of valid samples collected.

BDL Below laboratory detection limit

NA Not applicable

The following should be considered to better understand and mitigate air emissions in the Three Creeks area.

1. Investigate scrubbers designed to remove hydrocarbons (C_6^+) in addition to RSC substances from oil and water truck load venting.

2. Maintain scrubbers according to manufacturer specifications.

3. Investigate incineration of excess casing gas and tank vapours via auxiliary burners (installed in tank heater exhaust stacks) for CHOPS well-pads with low gas production rates (e.g., less than 14 m^3/hour/well). This approach will produce less emissions than flaring or natural gas fired compression for low gas-flow sites.

4. Production tank vapours should not be vented to atmosphere (e.g., those listed in Table 8) due to the risk of causing off-site AAAQO exceedances and odour complaints. This includes tank blowdowns occurring before tank clean-outs. Production tanks should be depressurized to the flare header.

5. Investigate methanol, instead of aromatic naphtha based, demulsifiers that may reduce concentrations of BTEX in truck tank vapours (because C_6 to C_9 compounds become volatile when heated to 80 ^oC).

6. Investigate controls (including manual observation) to prevent free water in heated production tanks from contacting burners. This may prevent tank pressure relief events and flare flame quenching due to excessive steam formation.

7. Investigate controls to prevent flare flame quenching that may occur during periods of excessive winds or unexpected steam, nitrogen or carbon dioxide in the waste gas. Flare flames should always be lit.

8. A DI&M program should be implemented by each operator to control fugitive emissions.

9. The projected emission inventory (previously identified as year 2020) could be completed to incorporate gas flows reported in Petrinex after gas conservation was fully implemented in the fall of 2014. Calculating the emissions inventory with 2013, 2014 and 2015 Petrinex volumes will provide a consistent time-series and good indication of future emission levels[14].

[14] Updating Table 12 in Section 3-2 will be sufficient for this purpose.

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6 APPENDIX I: INVENTORY METHODOLOGY

The quantification methodologies and emission factors presented below are consistent with those utilized by the ClearCALC software, which is a proprietary program developed by Clearstone to calculate emissions.

All gas volumes are presented at standard reference conditions of 101.325 kPa and 15°C unless stated otherwise.

6.1 FLARING

Combustion emissions for each flare source are calculated monthly using Equation (1) which is equivalent to WCI.023 Equation 20-7 for CO_2 emissions. Emission factors are determined by mass balance and account for all substances in the waste gas (as described in Section 7.12). The N_2O emission factor equals 0.0952 ng/J as specified in WCI.363(k). Total annual emissions are determined by including months January through December of the reporting year in the summation described in Equation (1).

$$E_i^{COMB} = \sum_{m=1}^{12}\left(\frac{Q_{Flare\_m} \times EF_i \times HHV_{Flare}}{10^6}\right) \quad (1)$$

Where:

E_i^{COMB}	=	Combustion emissions of compound *i* (t/year)
EF_i	=	Combustion emission factor for compound *i* (ng/J)
HHV_{Flare}	=	Higher heating value of the flared gas (MJ/m^3)
Q_{Flare_m}	=	Monthly flared gas volume ($10^3 m^3$/month)
i	=	Chemical compound released to the atmosphere

6.2 FUGITIVE EMISSIONS

This section applies to fugitive equipment leaks and includes the calculation methodologies for pneumatic controller venting. Population emissions factors and component counts are used as described in Equation (2) to estimate total fugitive emissions.

$$E_i^{FUG} = \sum_k \sum_j \left(\frac{EF_{k,j}}{THC_k} * N_{k,j} * X_{k,i} * (1 - CF)\right) * 8.760 \quad (2)$$

Where:

E_i^{FUG} = Emissions of compound *i* (t/y)
$EF_{k,j}$ = Average emission factor for service *k* and component type *j* published in CAPP, 2014 (kg/h)
$N_{k,j}$ = Number of components in service *k* and component type *j* (number)
$X_{k,i}$ = Mass fraction of service *k* and compound *i* (mass fraction)
THC_k = Total hydrocarbon content of service *k*
8.760 = Conversion factor from kg/h to t/y
CF = Control factor (dimensionless)
k = Components can be in Gas/Vapour, Fuel Gas or Liquid service as specified in Tables 3.1, 3.2, and 4.1 in Volume 5 of CAPP (2004).
j = Component types are presented in Tables 3.1 and 3.2 in Volume 5 of CAPP (2004).
i = Chemical compound released to the atmosphere

The uncertainty associated with fugitive emissions estimates is high; consequently, the fugitive numbers should be used with caution. Further discussion on the uncertainty associated with this methodology is available in Volumes 3 and 5 of CAPP (2004).

6.3 FORMATION CO_2

Formation CO_2 emissions are not applicable to the Three Creek inventory; consequently, no calculation methodology is provided.

6.4 INDUSTRIAL PROCESS

Industrial process emissions are from industrial processes involving chemical or physical reactions other than combustion, and where the primary purpose of the industrial process is not energy production (e.g., hydrogen production via steam-methane reforming). These activities are. not applicable to the Three Creek area; consequently, no calculation methodology is provided.

6.5 STATIONARY COMBUSTION EMISSIONS

Emissions for each combustion source are calculated monthly using Equation (3). CO_2, H_2S and SO_2 emission factors are based on the carbon or sulfur content of the fuel as described in Section 7.12. Emission factors for all other substances are obtained from field investigations completed in the nearby Reno Field (Clearstone, 2013).

$$E_i^{COMB} = \sum_{m=1}^{12} \left(\frac{Q_{Fuel\_m} \times EF_i \times HHV_{Fuel}}{10^6} \right) \quad (3)$$

Where:

E_i^{COMB} = Combustion emissions of compound *i* (t/year)
EF_i = Combustion emission factor for compound *i* (ng/J)
HHV_{Fuel} = Higher heating value of the fuel gas specified (MJ/m^3)
Q_{Fuel_m} = Monthly volume of fuel consumed by source ($10^3 m^3$/month)
i = Chemical compound released to the atmosphere

Given that the production accounting data source typically manages a single fuel volume per facility, the volume of fuel consumed by individual combustion units is determined based on the theoretical fuel allocation method presented in Equations (4) and (5). When multiple fuel streams with different gas compositions exist at a facility, fuel streams are assigned to corresponding combustion devices based on metering schematics, discussions with facility operators and/or site inspections. In this manner, the appropriate fuel gas carbon content and heating values are assigned to individual combustion devices with accurate unit volumes consistently assigned.

$$Q_{Fuel\_m,j} = \frac{Q_{theoretical\_m,j}}{\sum Q_{theoretical\_m,j}} \times Q_{actual\_m} \quad (4)$$

Where:

$Q_{Fuel\_m,j}$ = Monthly fuel consumed by source *j* ($10^3 m^3$/mo)
Q_{actual_m} = Total monthly fuel reported for the entire facility ($10^3 m^3$/mo)
$Q_{theoretical\_m,j}$ = Monthly theoretical fuel for each source *j* ($10^3 m^3$/mo)

$$Q_{\text{theoretical\_m,j}} = \frac{P_{rated\ j}}{EFF_j} \times \frac{LD_j}{HHV_j} \times OH_{m,j} \times n_j \times 0.0036 \quad (5)$$

Where:

$P_{rated\ j}$ = Rated power for source *j* (kW)
LD_j = Load for source *j* (fraction)
$OH_{m,j}$ = Monthly operating hours for source *j*

EFF_j = Equipment efficiency for source *j* which is equal to 0.8 for Heaters; 0.35 for recip. engines; 0.33 for turbines (Environment Canada, 2014) and 0.028 for thermal electric generators.

HHV_j = Higher heating value of the fuel used by source *j* (MJ/m^3)

n_j = quantity of units per source ID (dimensionless)

6.6 VENTING EMISSIONS

When venting volumes are available from Petrinex, emission estimates are calculated monthly using Equation (6).

$$E_i^{VENT} = \sum_{m=1}^{12} Q_{VENT\_m} \, x \, MW_i \, x \frac{Y_i}{MVC} \qquad (6)$$

Where:

E_i^{VENT} = Vent emissions of compound *i (t/y)*

Q_{VENT_m} = Volume of gas vented per month ($10^3 m^3$/month),

MW_i = Molecular weight of compound *i* (kg/kmol)

Y_i = Mole fraction of compound *i* (dimensionless),

MVC = Volume occupied by 1 kmol of gas at 15ºC, 101.325 kPa (23.6449 m^3/kmole)

i = Chemical compound released to the atmosphere

6.7 STORAGE TANK LOSSES

Total storage losses for each chemical compound are determined using Equation (7) which incorporates the use of a control device to reduce tank emissions.

$$ER_i = \frac{(L_F + L_B + L_W) \times (1 - CF) \times x_i}{1000} \qquad (7)$$

Where:

ER_i = Emission rate of compound *i* (t/y)

L_F = Flashing losses (kg/y)

L_B = Breathing Losses (kg/y)

L_W = Working losses (kg/y)

CF = Control factor (default value set to zero). The following control options and corresponding efficiencies are applied if identified for a specific tank.

- Vapour Recovery Unit = 95% reduction of all emissions.
- Floating Roof/Incinerator = 99.995% reduction of all emissions (typically, vapours are directed to an incinerator for floating roof tanks).
- Tied into Flare = 100% reduction of all emissions. Selection of this control option indicates that all storage losses are included in the flaring volume reported by production accounting (and therefore already included in the assertion).

x_i = Mass fraction of compound *i*. Tank vapours are based on solution gas analysis in the nearby Reno field (Clearstone, 2013).

Evaporative (i.e., breathing and working) losses are estimated using the 'Evaporative Loss from Fixed-Roof Tanks' algorithm (API, 1991 and Environment Canada, 2014) as follows.

6.7.1 WORKING LOSSES

$$L_W = 4.17 \text{x} 10^{-4} M_V P_V Q_o K_N K_C \quad (8)$$

Where:

L_W = Working loss (kg/y)
M_V = Tank vapour molecular weight (kg/kmol)
P_V = True vapour pressure at bulk liquid temp (kPa) determined by Equation (9)

$$P_V = 6.8929 \exp\left[\left(\frac{1555}{T} - 2.227\right)\left(\log_{10}(RVP) - 0.8384\right) - \frac{4033.89}{T} + 12.82\right] \quad (9)$$

RVP = Reid Vapour Pressure of liquid (kPa)
T = Average liquid temperature (353 K)
Q_0 = Tank throughput (m^3/yr)
N = Number of turnovers per year = Q/V
K_N = Turnover factor
K_C = Product factor 0.84 for crude oil; 1.0 for organic liquids

$$\text{If } N > 36, \text{K}_\text{N} = \frac{180 + N}{6N}$$

$$\text{If } N \leq 36, K_N = 1$$

6.7.2 BREATHING LOSSES

$$L_B = 0.1093 \times M_V \left(\frac{P_V}{P_A - P_V} \right)^{0.68} D^{1.73} H^{0.51} \Delta T^{0.5} F_P C K_C \quad (10)$$

Where:

L_B = Breathing loss (kg/y)
M_V = Tank vapour molecular weight (kg/kmol)
P_V = True vapour pressure at bulk liquid temp (kPa) determined by Equation (9)
P_a = Atmospheric Pressure (default 92.3 kPa)
D = Tank Diameter (m)
H = Average Vapour Space Height (m)
ΔT = Average Ambient Temperature Change (default is 12.47)
F_p = Paint factor (default to 1 for white)
C = Small Tank Adjustment Factor (default to 1 because L_B may underestimate emissions)
K_c = Product Factor
= 0.65 for crude oil and = 1.0 for other organic liquids

6.7.3 FLASHING LOSSES

Storage tank flashing losses are calculated using Equation (11).

$$L_F = GOR \times Q_o \times Y_i \times \rho_i \times 0.001 \quad (11)$$

Where:

L_F = Flashing emissions of compound i (t/y)
Q_o = Oil production rate (m^3/y).
ρ_i Density of compound i at standard conditions of 101.325 kPa and 15 ^oC
Y_i = Mole fraction of compound *i* in tank vapour.
0.001 = Conversion factor (tonnes/kg).
GOR = Gas Oil Ratio (Sm^3 gas/m^3 oil) of solution gas provided by companies. When a GOR is not available, the Vasquez and Beggs correlation from Section 8.2.1 in Volume 3 of Environment Canada, 2014 is used to predict the GOR. The Vasquez and Beggs correlation in Equation (12) is accurate to within 10 percent more than 85 percent of the time when input data in the range of values listed in Table 3-2 of CAPP, 2002 are used. The temperature and pressure of the last vessel upstream of the storage tank is applied to estimate how much gas is absorbed in the oil.

$$GOR = C_1 \gamma_g P_u^{C_2} \exp\left(\frac{C_3}{\gamma_\circ T_u} - \frac{C_4}{T_u}\right) \quad (12)$$

γ_o = oil specific gravity with respect to water (dimensionless)

$$= \frac{141.5}{131.5 + {}^{o}API}$$

γ_g = solution gas specific gravity with respect to air (dimensionless)

T_u = upstream temperature (K)

P_u = upstream pressure (kPaa)

	$\gamma_o < 0.876$	**$\gamma_o > 0.876$**
C_1	3.204×10^{-4}	7.803×10^{-4}
C_2	1.1870	1.0937
C_3	1881.24	2022.19
C_4	1748.29	1879.28

6.8 TRUCK TANK LOADING

The loading losses for low-vapour-pressure (LVP) carriers are calculated using the equation presented below and factors derived from Clearstone, 2014a. This approach replaces that published by U.S. EPA (2008). Losses that occur during the transit of LVP products are not evaluated (this potential source is small and there are no known factors or procedures available for estimating losses from transport of crude oil or natural gas liquids by tanker vehicles).

$$\boldsymbol{ER_i = \frac{GLLR \cdot Q \cdot Y_i \cdot \delta_i}{1000} \cdot (1.0 - CF)} \quad (13)$$

where,

ER_i = emission rate of substance i due to evaporation losses from loading of product (t/y),

GLLR = average gas to liquid loaded ratio measured in Three Creeks (Clearstone, 2014a).

= 0.700 m^3 dry, air-in gas per m^3 **oil** loaded, or

= 0.559 m^3 dry, air-in gas per m^3 **water** loaded

Q = annual volume of the oil or water product loaded (m^3), and

Y_i = mol fraction of substance i in the truck tank vapour (Table 27and Table 28)

δ_i = density of substance i present in the emitted vapours from the loaded LVP product (kg/m^3),

CF = average control factor for the LVP product loaded (dimensionless).

6.9 WASTE AND WASTEWATER DISPOSAL

Emissions from waste and wastewater treatment and disposal activities that are directed to a flare are quantified according to Section 7.1. Fugitive emissions from lagoons or landfills are not quantified at this time.

6.10 BIOMASS COMBUSTION

Emissions from biomass combustion are not applicable to oil and gas operations; consequently, no calculation methodology is provided.

6.11 VEHICLE EMISSIONS

In general, vehicle emissions have higher uncertainty because the input data is not subject to regulatory controls. Emissions from vehicle travel are computed based on the number of kilometres travelled multiplied by the appropriate emission factors from IPCC (1999) and IPCC (2006), Volume 2, Chapter 3.

6.12 DEVELOPMENT OF COMBUSTION EMISSION FACTORS

6.12.1 FUEL GAS COMBUSTION FACTORS

Combustion emission factors determined with Equation (13) are based on *good practice* guidelines presented in Chapter 2 of IPCC (2006). The methodology employed assumes the complete oxidation of carbon contained in fuels and 98 percent oxidation of carbon contained in flared gas. Equation (13) is derived from the stoichiometric combustion of gaseous fuels and accounts for particulates, ash, or soot in the flue gas with combustion efficiency (CE).

$$EF_{CO_2} = \left(\sum_{i=1}^{n} y_i C_i \times CE + [CO_2] \right) \times \frac{MW_{CO_2}}{MVC \times HHV} \times 10^6 \qquad (13)$$

Where:

EF_{CO2} = CO_2 emission factor (combusted and non-combusted) (ng CO_2/J of fuel)
C_i = Carbon number of hydrocarbon compound *i* (dimensionless)
y_i = Mole fraction of hydrocarbon compound *i* (mole fraction)
$[CO_2]$ = Mole fraction of carbon dioxide in the reactants. Carbon dioxide is inert and therefore not discounted by combustion efficiency.
MW_{CO2} = Molecular weight of CO_2 (44.01 kg/kmole)

MVC = Volume occupied by 1 kmole of gas at 15°C, 101.325 kPa (i.e. 23.6445 m^3/kmole)

CE = Combustion efficiency (0.98 for flares and 1.0 for heaters, boilers, engines and turbines)

HHV = Higher heating value of gas.

n = The number of hydrocarbon compounds present in the combusted gas.

Emission factors for all other substances are presented in Section 9.5 and are from field investigations completed in the nearby Reno field (Clearstone, 2013). N_2O emission factors for stationary combustion are obtained from Table 3.3 in Volume 5 of CAPP (2004).

6.12.2 FLARING FACTORS

The methodology employed assumes 2 percent of the gas disposed by flaring is not oxidized and is released directly to the atmosphere. The flaring emission factors are determined using Equation (14).

$$EF_{Flare} = \frac{y_i * MW_i}{MVC} \times \frac{(1 - FE)}{HHV} \times 10^6 \qquad (14)$$

Where:

EF_{Flare} = Emission factor for substance *i*, (ng /J of flared gas)

y_i = Mole fraction of substance *i* (includes all hydrocarbons and H_2S)

MW_i = Molecular weight of substance *i* (kg/kmole)

MVC = Volume occupied by 1 kmole of gas at 15°C, 101.325 kPa (23.6449 m^3/kmole)

FE = Flaring Destruction Efficiency equal to 0.98 (API, 2009)

HHV = Higher heating value of flared gas.

6.13 TOTAL PRODUCTION

Total production in barrels of oil equivalent (BOE) is calculated using Equation (15). OE conversion factors are provided in Table 2-6 (CAPP, 2003), which are determined by dividing the HHV of the subject product by the HHV of light/medium crude oil (i.e., 38.5 GJ/m^3).

$$TAP = \sum_{m=1}^{12} \sum_{i=1}^{n} (Q_{m,i} \; x \, OE_i) \times 6.2898 \qquad (15)$$

Where:

TAP = Total Annual Production (BOE)
$Q_{m,i}$ = Monthly volume of product *i* obtained from production accounting
OE_i = Oil equivalent conversion factor for product *i*.
= $HHVi / HHV_{Light\ Oil}$
6.2898 = Conversion factor (m^3OE to BOE)

Table 23: Oil Equivalent Conversion Factors on an energy equivalent basis.	
Product	**m^3OE Conversion Factor**
Crude oil in m^3	1.0
Heavy Crude oil in m^3	1.075
Natural gas in 1000 m^3	0.971
Liquid ethane in m^3	0.48
Liquid propane in m^3	0.66
Liquid butane in m^3	0.75
Liquid condensate C5+ in m^3	0.85
NGL in m^3 (gas plant NGL sales)	0.72
Solid sulphur in tonnes	0.24

6.14 CALCULATION OF EMISSIONS

All emission calculations are performed using the ClearCALC SQL database designed and maintained by Clearstone in accordance with the quantification methodology presented above. Modifications to these tools are documented and implemented according to Clearstone Software Development Best Practices (a copy of this technical standard can be provided upon request). Results are obtained from ClearCALC via automated reports.

7 APPENDIX II: AVERAGE GAS COMPOSITIONS FOR THREE CREEKS

Gas compositions utilized in ClearCALC for well casing gas (i.e., fuel), production tank vapour and flare gas (mixed casing and tank vapour) sources are presented in Table 24, Table 25 and Table 26, respectively. These analysis represent a numerical average of the subject samples collected in Three Creeks (Clearstone, 2014a) and are presented as mol fractions on a normalized, dry, air-free basis. Oil and water truck tank venting are presented in Table 27 and Table 28. These results are presented on a normalized, dry, air-in basis consistent with calculation methodologies presented in Section 6.8.

Substances with analysis results below the laboratory detection limit are not included. Concentrations presented for Formic Acid are qualitative. This compound is not included in AITF analysis scans and an on-site dosimeter tube[15] reading was required to determine concentrations.

Table 24: Average casing gas analyses (dry and air-free) determined from AITF laboratory results for sites visited in Three Creeks during the summer and fall of 2014

Substance Name	CAS Number	Formula	MW	Mol Fraction
Methane	74-82-8	CH4	16.042	8.575E-01
Carbon Dioxide	124-38-9	CO2	44.010	8.269E-02
Nitrogen	7727-37-9	N2	28.014	4.600E-02
Propane	74-98-6	C3H8	44.096	4.484E-03
Ethane	74-84-0	C2H6	30.069	4.245E-03
i-Butane	75-28-5	C4H10	58.122	1.506E-03
i-Pentane	78-78-4	C5H12	72.149	7.515E-04
n-Butane	106-97-8	C4H10	58.122	5.049E-04
Propyne	74-99-7	C3H4	40.064	3.232E-04
Ethylacetylene	107-00-6	C4H6	54.090	2.810E-04
2-Methylpentane	107-83-5	C6H14	86.175	2.204E-04
n-Pentane	109-66-0	C5H12	72.149	1.810E-04
3-Methylpentane	96-14-0	C6H14	86.175	1.675E-04
Methylcyclohexane	108-87-2	C7H14	98.186	1.595E-04
Cyclohexane	110-82-7	C6H12	84.159	1.329E-04
Methylcyclopentane	96-37-7	C6H12	84.159	1.153E-04
2,3-Dimethylbutane	79-29-8	C6H14	86.175	8.246E-05
Hydrogen Sulphide	7783-06-4	H2S	34.076	7.227E-05
Cyclopentane	287-92-3	C5H10	70.133	7.173E-05
3-Methylhexane	589-34-4	C7H16	100.202	5.690E-05
Hexane	110-54-3	C6H14	86.177	5.383E-05
2,3-Dimethylpentane	565-59-3	C7H16	100.202	4.879E-05
Toluene	108-88-3	C7H8	92.138	3.611E-05
cis-2-Butene	590-18-1	C4H8	56.106	3.550E-05
2,4-Dimethylpentane	108-08-7	C7H16	100.202	3.491E-05

15 Only Dreager tubes with a concentration range of 0 to 15 ppmv were commercially available. These provide a qualitative indication that Formic Acid is present when concentrations greater than 15 ppmv are observed.

Table 24: Average casing gas analyses (dry and air-free) determined from AITF laboratory results for sites visited in Three Creeks during the summer and fall of 2014				
Substance Name	**CAS Number**	**Formula**	**MW**	**Mol Fraction**
Neohexane	75-83-2	C6H14	86.175	3.227E-05
2-Methylhexane	591-76-4	C7H16	100.202	2.976E-05
m,p-Xylene	CEL0014	C8H10	106.168	1.820E-05
Propylene	115-07-1	C3H6	42.080	1.466E-05
Heptane	142-82-5	C7H16	100.202	1.364E-05
3-Methylheptane	589-81-1	C8H18	114.229	1.254E-05
m-Ethyltoluene	620-14-4	C9H12	120.192	1.229E-05
Formic Acid	64-18-6	CH2O2	46.025	1.208E-05
124 Trimethylbenzene	95-63-6	C9H12	120.194	1.201E-05
Ethylbenzene	100-41-4	C8H10	106.165	1.132E-05
2-Methylheptane	592-27-8	C8H18	114.229	9.115E-06
Benzene	71-43-2	C6H6	78.112	8.420E-06
o-Xylene	95-47-6	C8H10	106.165	7.231E-06
Pentyl mercaptan	110-66-7	C5H12S	104.215	6.246E-06
o-Ethyltoluene	611-14-3	C9H12	120.192	6.046E-06
p-Ethyltoluene	622-96-8	C9H12	120.192	5.698E-06
1,3,5-Trimethylbenzene	108-67-8	C9H12	120.192	5.354E-06
n-Propylbenzene	103-65-1	C9H12	120.192	4.989E-06
Dimethyl disulphide	624-92-0	C2H6S2	94.201	3.478E-06
2-Ethylthiophene	872-55-9	C6H8S	112.193	3.320E-06
3-methyl Thiophene	616-44-4	C5H6S	98.167	3.157E-06
Ethyl mercaptan	75-08-1	C2H6S	62.135	2.784E-06
2,5-Dimethylthiophene	638-02-8	C6H8S	112.193	2.604E-06
1,2,3-Trimethylbenzene	526-73-8	C9H12	120.192	2.563E-06
Isopropyl mercaptan	75-33-2	C3H8S	76.162	2.480E-06
Thiophene	110-02-1	C4H4S	84.141	2.453E-06
2-methyl Thiophene	554-14-3	C5H6S	98.167	2.399E-06
Pentane, 2,3,4-trimethyl-	565-75-3	C8H18	114.229	2.372E-06
Dodecane	112-40-3	C12H26	170.335	2.295E-06
Isopropylbenzene	98-82-8	C9H12	120.192	1.694E-06
Methyl mercaptan	74-93-1	CH4S	48.108	1.264E-06
Dimethyl sulphide	75-18-3	C2H6S	62.135	8.102E-07
tert-Butyl mercaptan	75-66-1	C4H10S	90.188	4.965E-07
Neopentane	463-82-1	C5H12	72.149	3.277E-08
1-Pentanol, 4-methyl-	626-89-1	C6H14O	102.104	2.108E-08
tert-butylcyclopropane	4741-87-1	C7H14	98.110	1.391E-08
1-Pentene, 2-methyl-	763-29-1	C6H12	84.094	1.222E-08
1-Dodecanol	112-53-8	C12H26O	186.198	1.136E-08
Cyclohexane, 1,3-dimethyl-	591-21-9	C8H16	112.213	1.084E-08
1-Butanol, 2-ethyl-	97-95-0	C6H14O	102.104	9.490E-09
1-Heptene	592-76-7	C7H14	98.110	9.050E-09

Table 24: Average casing gas analyses (dry and air-free) determined from AITF laboratory results for sites visited in Three Creeks during the summer and fall of 2014				
Substance Name	**CAS Number**	**Formula**	**MW**	**Mol Fraction**
Cyclopentane, 1,2,3-trimethyl-, (1.alpha	2613-69-6	C8H16	112.213	8.378E-09
Cyclopentane, 1,1-dimethyl-	1638-26-2	C7H14	98.186	7.680E-09
Cyclopentane, 1,2-dimethyl-	2452-99-5	C7H14	98.186	7.436E-09
1-Heptanol	111-70-6	C7H16O	116.120	7.351E-09
Cyclohexane, 1,1,3-trimethyl-	3073-66-3	C9H18	126.239	6.876E-09
Cyclopentane, 1,3-dimethyl-	2453-00-1	C7H14	98.186	6.803E-09
3-Ethylcyclopentanone	10264-55-8	C7H12O	112.089	6.043E-09
1-Buten-1-one	20334-52-5	C4H6O	70.042	5.615E-09
Cyclopentane, 1,1,2-trimethyl-	4259-00-1	C8H16	112.125	5.463E-09
2-Pentene, 2,4,4-trimethyl-	107-40-4	C8H16	112.125	5.155E-09
Cyclohexane, 1,1-dimethyl-	590-66-9	C8H16	112.213	5.051E-09
Cyclopentane, ethyl-	1640-89-7	C7H14	98.186	4.776E-09
cis-2-iodo-1,3,3-trimethylcyclopentane	VOC-K-312	C8H15I	238.022	4.654E-09
Cyclobutanone, 2,3,3-trimethyl-	28290-01-9	C7H12O	112.000	4.605E-09
7-methyl-tetracyclo[4.1.0.0(2,4).0(3,5)]heptane	77481-22-2	C8H10	106.078	4.527E-09
Cyclohexane, ethyl-	1678-91-7	C8H16	112.213	2.445E-09
Butane, 1-bromo-2-methyl-	10422-35-2	C5H11Br	150.004	2.427E-09
(1R*,2R*)-1,2-Dimethyl-1-propioloylcyclopentane	81825-31-2	C10H14O	150.104	2.086E-09
2-Butanone, 3,3-dimethyl-	75-97-8	C6H12O	100.089	1.493E-09
Cyclobutanone, 2,2-dimethyl-	1192-14-9	C6H10O	98.073	1.387E-09
Pentane, 1,5-dibromo-	111-24-0	C5H10Br2	227.915	1.305E-09
2,2-Dichloro-4-methyl-3-pentanone	66250-08-6	C6H10Cl2O	168.011	1.245E-09
Ethane, 1,1-difluoro-	75-37-6	C2H4F2	66.028	9.360E-10
2-Heptenal, (Z)-	57266-86-1	C7H12O	112.089	7.821E-10
Cyclopropane, (1-methylethyl)-	3638-35-5	C6H12	84.094	7.815E-10
Cyclopropane, [(2-propenyloxy)methyl]-	18022-46-3	C7H12O	112.089	6.574E-10
Methanol	67-56-1	CH4O	32.042	5.173E-10
1-Methyl-bicyclo[3.2.0]heptan-6-one	5212-68-0	C8H12O	124.089	3.770E-10
2-Propanol	67-63-0	C3H8O	60.095	3.135E-10

Table 25: Average tank vapour analyses (dry and air-free) determined from AITF laboratory results for sites visited in Three Creeks during the summer and fall of 2014				
Substance Name	**CAS Number**	**Formula**	**MW**	**Mol Fraction**
Methane	74-82-8	CH4	16.042	7.540E-01
Carbon Dioxide	124-38-9	CO2	44.010	1.228E-01
Nitrogen	7727-37-9	N2	28.014	6.185E-02
i-Butane	75-28-5	C4H10	58.122	8.772E-03
Ethane	74-84-0	C2H6	30.069	6.593E-03
i-Pentane	78-78-4	C5H12	72.149	6.397E-03
Ethylacetylene	107-00-6	C4H6	54.090	5.671E-03
Propyne	74-99-7	C3H4	40.064	4.813E-03
n-Butane	106-97-8	C4H10	58.122	4.159E-03
Propane	74-98-6	C3H8	44.096	3.870E-03
Methylcyclohexane	108-87-2	C7H14	98.186	2.769E-03
2-Methylpentane	107-83-5	C6H14	86.175	2.731E-03
3-Methylpentane	96-14-0	C6H14	86.175	2.164E-03
Cyclohexane	110-82-7	C6H12	84.159	2.048E-03
Methylcyclopentane	96-37-7	C6H12	84.159	1.674E-03
n-Pentane	109-66-0	C5H12	72.149	1.632E-03
2,4-Dimethylpentane	108-08-7	C7H16	100.202	1.321E-03
3-Methylhexane	589-34-4	C7H16	100.202	1.023E-03
2,3-Dimethylbutane	79-29-8	C6H14	86.175	1.015E-03
2,3-Dimethylpentane	565-59-3	C7H16	100.202	7.630E-04
Hexane	110-54-3	C6H14	86.177	6.750E-04
Cyclopentane	287-92-3	C5H10	70.133	6.660E-04
2-Methylhexane	591-76-4	C7H16	100.202	5.441E-04
Neohexane	75-83-2	C6H14	86.175	3.408E-04
Toluene	108-88-3	C7H8	92.138	3.062E-04
cis-2-Butene	590-18-1	C4H8	56.106	2.952E-04
Heptane	142-82-5	C7H16	100.202	1.971E-04
Hydrogen Sulphide	7783-06-4	H2S	34.076	1.814E-04
2-Methylheptane	592-27-8	C8H18	114.229	1.591E-04
3-Methylheptane	589-81-1	C8H18	114.229	1.489E-04
m,p-Xylene	CEL0014	C8H10	106.168	1.176E-04
Ethylbenzene	100-41-4	C8H10	106.165	8.326E-05
Pentane, 2,3,4-trimethyl-	565-75-3	C8H18	114.229	5.544E-05
o-Xylene	95-47-6	C8H10	106.165	5.079E-05
124 Trimethylbenzene	95-63-6	C9H12	120.194	2.027E-05
Formic Acid	64-18-6	CH2O2	46.025	1.852E-05
m-Ethyltoluene	620-14-4	C9H12	120.192	1.735E-05
o-Ethyltoluene	611-14-3	C9H12	120.192	1.580E-05
n-Propylbenzene	103-65-1	C9H12	120.192	1.388E-05
Isopropylbenzene	98-82-8	C9H12	120.192	1.185E-05
p-Ethyltoluene	622-96-8	C9H12	120.192	1.096E-05

Table 25: Average tank vapour analyses (dry and air-free) determined from AITF laboratory results for sites visited in Three Creeks during the summer and fall of 2014				
Substance Name	**CAS Number**	**Formula**	**MW**	**Mol Fraction**
1,3,5-Trimethylbenzene	108-67-8	C9H12	120.192	1.093E-05
1,2,3-Trimethylbenzene	526-73-8	C9H12	120.192	6.364E-06
trans-2-Butene	624-64-6	C4H8	56.106	3.336E-06
Thiophene	110-02-1	C4H4S	84.141	3.138E-06
Ethyl mercaptan	75-08-1	C2H6S	62.135	2.956E-06
Isopropyl mercaptan	75-33-2	C3H8S	76.162	2.273E-06
3-methyl Thiophene	616-44-4	C5H6S	98.167	1.605E-06
2,5-Dimethylthiophene	638-02-8	C6H8S	112.193	1.544E-06
2-methyl Thiophene	554-14-3	C5H6S	98.167	1.391E-06
Dodecane	112-40-3	C12H26	170.335	1.363E-06
Methyl mercaptan	74-93-1	CH4S	48.108	1.264E-06
Pentyl mercaptan	110-66-7	C5H12S	104.215	1.226E-06
Butyl mercaptan	109-79-5	C4H10S	90.188	1.159E-06
m-Diethylbenzene	141-93-5	C10H14	134.218	1.145E-06
Dimethyl sulphide	75-18-3	C2H6S	62.135	1.133E-06
Carbon disulphide	75-15-0	CS2	76.143	8.795E-07
tert-Butyl mercaptan	75-66-1	C4H10S	90.188	6.989E-07
Propyl mercaptan	107-03-9	C3H8S	76.162	1.986E-07
Cyclopentane, 1,1,2-trimethyl-	4259-00-1	C8H16	112.125	7.139E-08
Cyclohexane, 1,3-dimethyl-	591-21-9	C8H16	112.213	3.525E-08
Cyclopentane, 1,2,4-trimethyl-	2815-58-9	C8H16	112.213	3.064E-08
Cyclopentane, 1,2-dimethyl-	2452-99-5	C7H14	98.186	2.868E-08
Neopentane	463-82-1	C5H12	72.149	2.663E-08
Cyclopentane, 1,2,3-trimethyl-	2815-57-8	C8H16	112.213	2.656E-08
Cyclohexane, 1,1,3-trimethyl-	3073-66-3	C9H18	126.239	2.575E-08
Cyclohexane, 1,2-dimethyl-, trans-	6876-23-9	C8H16	112.213	2.564E-08
Cyclopentane, 1,2,3-trimethyl-, (1.alpha	2613-69-6	C8H16	112.213	2.500E-08
Cyclopentane, 1-ethyl-3-methyl-	3726-47-4	C8H16	112.125	2.295E-08
Pentane, 2,2-dimethyl-	590-35-2	C7H16	100.202	2.201E-08
Cyclopentane, 1,3-dimethyl-	2453-00-1	C7H14	98.186	2.119E-08
Cyclopentane, 1-ethyl-2-methyl-	3726-46-3	C8H16	112.213	2.068E-08
Cyclohexane, ethyl-	1678-91-7	C8H16	112.213	1.976E-08
Cycloheptane, methyl-	4126-78-7	C8H16	112.125	1.947E-08
1-Pentene, 3,4-dimethyl-	7385-78-6	C7H14	98.110	1.935E-08
Heptane, 3,4-dimethyl-	922-28-1	C9H20	128.157	1.758E-08
Cyclohexane, propyl-	1678-92-8	C9H18	126.141	1.698E-08
tert-butylcyclopropane	4741-87-1	C7H14	98.110	1.584E-08
Cyclopentane, ethyl-	1640-89-7	C7H14	98.186	1.493E-08
1-Pentanol, 4-methyl-	626-89-1	C6H14O	102.104	1.471E-08
1-methyl-2-ethylcyclopentane isomer 2	VOC-K-041	C8H16	112.125	1.413E-08
1-Pentene, 2-methyl-	763-29-1	C6H12	84.094	1.319E-08

Table 25: Average tank vapour analyses (dry and air-free) determined from AITF laboratory results for sites visited in Three Creeks during the summer and fall of 2014				
Substance Name	**CAS Number**	**Formula**	**MW**	**Mol Fraction**
Cyclopentane, 1,1-dimethyl-	1638-26-2	C7H14	98.186	1.020E-08
1-Heptanol	111-70-6	C7H16O	116.120	9.762E-09
7-methyl-tetracyclo[4.1.0.0(2,4).0(3,5)]heptane	77481-22-2	C8H10	106.078	9.385E-09
Cyclohexane, 1,1-dimethyl-	590-66-9	C8H16	112.213	8.390E-09
1,1-Dioctyloxyoctane	VOC-K-313	C24H50O2	370.381	7.893E-09
Bicyclo[2.1.1]hexan-1-ol	VOC-K-182	C6H10O	98.073	7.754E-09
1-Buten-1-one	20334-52-5	C4H6O	70.042	7.371E-09
1-Decanol	112-30-1	C10H22O	158.167	6.709E-09
1,2-Dichlorooctane	VOC-K-318	C8H16Cl2	182.063	6.488E-09
cis-2-iodo-1,3,3-trimethylcyclopentane	VOC-K-312	C8H15I	238.022	4.961E-09
Cyclobutanone, 2,3,3-trimethyl-	28290-01-9	C7H12O	112.000	4.232E-09
2-Pentene, 2,4,4-trimethyl-	107-40-4	C8H16	112.125	3.726E-09
acetonyl decyl ether	40657-11-2	C13H26O2	214.193	3.708E-09
Cyclobutanone, 2,2-dimethyl-	1192-14-9	C6H10O	98.073	3.625E-09
3-Hexanone	589-38-8	C6H12O	100.089	3.251E-09
Butane, 1-bromo-2-methyl-	10422-35-2	C5H11Br	150.004	3.060E-09
2-Butanone, 3,3-dimethyl-	75-97-8	C6H12O	100.089	1.420E-09
N-OCTAN-3-ENE	VOC-K-317	C8H16	112.125	1.266E-09
Ethane, 1,1-difluoro-	75-37-6	C2H4F2	66.028	1.214E-09
decamethylcyclopentan	84979-99-7	C15H30	210.235	5.655E-10

Table 26: Average flare gas analyses (dry and air-free) determined from AITF laboratory results for sites visited in Three Creeks during the summer and fall of 2014				
Substance Name	**CAS Number**	**Formula**	**MW**	**Mol Fraction**
Methane	74-82-8	CH4	16.042	8.057E-01
Carbon Dioxide	124-38-9	CO2	44.010	1.027E-01
Nitrogen	7727-37-9	N2	28.014	5.392E-02
Ethane	74-84-0	C2H6	30.069	5.419E-03
i-Butane	75-28-5	C4H10	58.122	5.139E-03
Propane	74-98-6	C3H8	44.096	4.177E-03
i-Pentane	78-78-4	C5H12	72.149	3.574E-03
Ethylacetylene	107-00-6	C4H6	54.090	2.976E-03
Propyne	74-99-7	C3H4	40.064	2.568E-03
n-Butane	106-97-8	C4H10	58.122	2.332E-03
2-Methylpentane	107-83-5	C6H14	86.175	1.476E-03
Methylcyclohexane	108-87-2	C7H14	98.186	1.464E-03
3-Methylpentane	96-14-0	C6H14	86.175	1.166E-03
Cyclohexane	110-82-7	C6H12	84.159	1.090E-03
n-Pentane	109-66-0	C5H12	72.149	9.066E-04
Methylcyclopentane	96-37-7	C6H12	84.159	8.944E-04
2,4-Dimethylpentane	108-08-7	C7H16	100.202	6.777E-04
2,3-Dimethylbutane	79-29-8	C6H14	86.175	5.485E-04
3-Methylhexane	589-34-4	C7H16	100.202	5.398E-04
2,3-Dimethylpentane	565-59-3	C7H16	100.202	4.059E-04
Cyclopentane	287-92-3	C5H10	70.133	3.689E-04
Hexane	110-54-3	C6H14	86.177	3.644E-04
2-Methylhexane	591-76-4	C7H16	100.202	2.869E-04
Neohexane	75-83-2	C6H14	86.175	1.865E-04
Toluene	108-88-3	C7H8	92.138	1.711E-04
cis-2-Butene	590-18-1	C4H8	56.106	1.654E-04
Hydrogen Sulphide	7783-06-4	H2S	34.076	1.268E-04
Heptane	142-82-5	C7H16	100.202	1.054E-04
2-Methylheptane	592-27-8	C8H18	114.229	8.411E-05
3-Methylheptane	589-81-1	C8H18	114.229	8.071E-05
m,p-Xylene	CEL0014	C8H10	106.168	6.790E-05
Ethylbenzene	100-41-4	C8H10	106.165	4.729E-05
o-Xylene	95-47-6	C8H10	106.165	2.901E-05
Pentane, 2,3,4-trimethyl-	565-75-3	C8H18	114.229	2.890E-05
124 Trimethylbenzene	95-63-6	C9H12	120.194	1.614E-05
Formic Acid	64-18-6	CH2O2	46.025	1.530E-05
m-Ethyltoluene	620-14-4	C9H12	120.192	1.482E-05
Propylene	115-07-1	C3H6	42.080	1.466E-05
o-Ethyltoluene	611-14-3	C9H12	120.192	1.092E-05
n-Propylbenzene	103-65-1	C9H12	120.192	9.435E-06
Benzene	71-43-2	C6H6	78.112	8.420E-06

Table 26: Average flare gas analyses (dry and air-free) determined from AITF laboratory results for sites visited in Three Creeks during the summer and fall of 2014				
Substance Name	**CAS Number**	**Formula**	**MW**	**Mol Fraction**
p-Ethyltoluene	622-96-8	C9H12	120.192	8.330E-06
1,3,5-Trimethylbenzene	108-67-8	C9H12	120.192	8.142E-06
Isopropylbenzene	98-82-8	C9H12	120.192	6.771E-06
1,2,3-Trimethylbenzene	526-73-8	C9H12	120.192	4.463E-06
Pentyl mercaptan	110-66-7	C5H12S	104.215	3.736E-06
Dimethyl disulphide	624-92-0	C2H6S2	94.201	3.478E-06
trans-2-Butene	624-64-6	C4H8	56.106	3.336E-06
2-Ethylthiophene	872-55-9	C6H8S	112.193	3.320E-06
Ethyl mercaptan	75-08-1	C2H6S	62.135	2.870E-06
Thiophene	110-02-1	C4H4S	84.141	2.795E-06
3-methyl Thiophene	616-44-4	C5H6S	98.167	2.381E-06
Isopropyl mercaptan	75-33-2	C3H8S	76.162	2.376E-06
2,5-Dimethylthiophene	638-02-8	C6H8S	112.193	2.074E-06
2-methyl Thiophene	554-14-3	C5H6S	98.167	1.895E-06
Dodecane	112-40-3	C12H26	170.335	1.829E-06
Methyl mercaptan	74-93-1	CH4S	48.108	1.264E-06
Butyl mercaptan	109-79-5	C4H10S	90.188	1.159E-06
m-Diethylbenzene	141-93-5	C10H14	134.218	1.145E-06
Dimethyl sulphide	75-18-3	C2H6S	62.135	9.718E-07
Carbon disulphide	75-15-0	CS2	76.143	8.795E-07
tert-Butyl mercaptan	75-66-1	C4H10S	90.188	5.976E-07
Propyl mercaptan	107-03-9	C3H8S	76.162	1.986E-07
Cyclopentane, 1,1,2-trimethyl-	4259-00-1	C8H16	112.125	3.843E-08
Cyclopentane, 1,2,4-trimethyl-	2815-58-9	C8H16	112.213	3.064E-08
Neopentane	463-82-1	C5H12	72.149	2.970E-08
Cyclopentane, 1,2,3-trimethyl-	2815-57-8	C8H16	112.213	2.656E-08
Cyclohexane, 1,2-dimethyl-, trans-	6876-23-9	C8H16	112.213	2.564E-08
Cyclohexane, 1,3-dimethyl-	591-21-9	C8H16	112.213	2.304E-08
Cyclopentane, 1-ethyl-3-methyl-	3726-47-4	C8H16	112.125	2.295E-08
Pentane, 2,2-dimethyl-	590-35-2	C7H16	100.202	2.201E-08
Cyclopentane, 1-ethyl-2-methyl-	3726-46-3	C8H16	112.213	2.068E-08
Cycloheptane, methyl-	4126-78-7	C8H16	112.125	1.947E-08
1-Pentene, 3,4-dimethyl-	7385-78-6	C7H14	98.110	1.935E-08
Cyclopentane, 1,2-dimethyl-	2452-99-5	C7H14	98.186	1.806E-08
1-Pentanol, 4-methyl-	626-89-1	C6H14O	102.104	1.790E-08
Heptane, 3,4-dimethyl-	922-28-1	C9H20	128.157	1.758E-08
Cyclohexane, propyl-	1678-92-8	C9H18	126.141	1.698E-08
Cyclopentane, 1,2,3-trimethyl-, (1.alpha	2613-69-6	C8H16	112.213	1.669E-08
Cyclohexane, 1,1,3-trimethyl-	3073-66-3	C9H18	126.239	1.631E-08
tert-butylcyclopropane	4741-87-1	C7H14	98.110	1.488E-08
1-methyl-2-ethylcyclopentane isomer 2	VOC-K-041	C8H16	112.125	1.413E-08

Table 26: Average flare gas analyses (dry and air-free) determined from AITF laboratory results for sites visited in Three Creeks during the summer and fall of 2014				
Substance Name	**CAS Number**	**Formula**	**MW**	**Mol Fraction**
Cyclopentane, 1,3-dimethyl-	2453-00-1	C7H14	98.186	1.400E-08
1-Pentene, 2-methyl-	763-29-1	C6H12	84.094	1.270E-08
1-Dodecanol	112-53-8	C12H26O	186.198	1.136E-08
Cyclohexane, ethyl-	1678-91-7	C8H16	112.213	1.110E-08
Cyclopentane, ethyl-	1640-89-7	C7H14	98.186	9.855E-09
1-Butanol, 2-ethyl-	97-95-0	C6H14O	102.104	9.489E-09
1-Heptene	592-76-7	C7H14	98.110	9.049E-09
Cyclopentane, 1,1-dimethyl-	1638-26-2	C7H14	98.186	8.940E-09
1-Heptanol	111-70-6	C7H16O	116.120	8.557E-09
1,1-Dioctyloxyoctane	VOC-K-313	C24H50O2	370.381	7.893E-09
Bicyclo[2.1.1]hexan-1-ol	VOC-K-182	C6H10O	98.073	7.754E-09
7-methyl-tetracyclo[4.1.0.0(2,4).0(3,5)]heptane	77481-22-2	C8H10	106.078	6.956E-09
Cyclohexane, 1,1-dimethyl-	590-66-9	C8H16	112.213	6.720E-09
1-Decanol	112-30-1	C10H22O	158.167	6.709E-09
1-Buten-1-one	20334-52-5	C4H6O	70.042	6.493E-09
1,2-Dichlorooctane	VOC-K-318	C8H16Cl2	182.063	6.488E-09
3-Ethylcyclopentanone	10264-55-8	C7H12O	112.089	6.043E-09
cis-2-iodo-1,3,3-trimethylcyclopentane	VOC-K-312	C8H15I	238.022	4.808E-09
2-Pentene, 2,4,4-trimethyl-	107-40-4	C8H16	112.125	4.441E-09
Cyclobutanone, 2,3,3-trimethyl-	28290-01-9	C7H12O	112.000	4.418E-09
acetonyl decyl ether	40657-11-2	C13H26O2	214.193	3.708E-09
3-Hexanone	589-38-8	C6H12O	100.089	3.251E-09
Butane, 1-bromo-2-methyl-	10422-35-2	C5H11Br	150.004	2.743E-09
Cyclobutanone, 2,2-dimethyl-	1192-14-9	C6H10O	98.073	2.506E-09
(1R*,2R*)-1,2-Dimethyl-1-propioloylcyclopentane	81825-31-2	C10H14O	150.104	2.086E-09
2-Butanone, 3,3-dimethyl-	75-97-8	C6H12O	100.089	1.456E-09
Pentane, 1,5-dibromo-	111-24-0	C5H10Br2	227.915	1.305E-09
N-OCTAN-3-ENE	VOC-K-317	C8H16	112.125	1.266E-09
2,2-Dichloro-4-methyl-3-pentanone	66250-08-6	C6H10Cl2O	168.011	1.245E-09
Ethane, 1,1-difluoro-	75-37-6	C2H4F2	66.028	1.075E-09
2-Heptenal, (Z)-	57266-86-1	C7H12O	112.089	7.821E-10
Cyclopropane, (1-methylethyl)-	3638-35-5	C6H12	84.094	7.815E-10
Cyclopropane, [(2-propenyloxy)methyl]-	18022-46-3	C7H12O	112.089	6.574E-10
decamethylcyclopentan	84979-99-7	C15H30	210.235	5.655E-10
Methanol	67-56-1	CH4O	32.042	5.173E-10
1-Methyl-bicyclo[3.2.0]heptan-6-one	5212-68-0	C8H12O	124.089	3.770E-10
2-Propanol	67-63-0	C3H8O	60.095	3.135E-10

Table 27: Average oil truck vapour analyses (dry and air-in) determined from AITF laboratory results for sites visited in Three Creeks during the summer and fall of 2014				
Substance Name	**CAS Number**	**Formula**	**MW**	**Mol Fraction**
Nitrogen	7727-37-9	N2	28.014	7.599E-01
Oxygen	7782-44-7	O2	31.999	1.489E-01
Carbon Dioxide	124-38-9	CO2	44.010	3.675E-02
Methane	74-82-8	CH4	16.042	2.106E-02
Ethylacetylene	107-00-6	C4H6	54.090	3.906E-03
i-Pentane	78-78-4	C5H12	72.149	3.657E-03
i-Butane	75-28-5	C4H10	58.122	3.308E-03
Propyne	74-99-7	C3H4	40.064	2.990E-03
Methylcyclohexane	108-87-2	C7H14	98.186	2.223E-03
n-Butane	106-97-8	C4H10	58.122	1.994E-03
2-Methylpentane	107-83-5	C6H14	86.175	1.843E-03
Propane	74-98-6	C3H8	44.096	1.575E-03
Cyclohexane	110-82-7	C6H12	84.159	1.571E-03
n-Pentane	109-66-0	C5H12	72.149	1.496E-03
3-Methylpentane	96-14-0	C6H14	86.175	1.427E-03
Methylcyclopentane	96-37-7	C6H12	84.159	1.241E-03
Ethane	74-84-0	C2H6	30.069	8.958E-04
3-Methylhexane	589-34-4	C7H16	100.202	7.686E-04
Hexane	110-54-3	C6H14	86.177	6.932E-04
2,3-Dimethylbutane	79-29-8	C6H14	86.175	5.951E-04
Cyclopentane	287-92-3	C5H10	70.133	5.631E-04
2,3-Dimethylpentane	565-59-3	C7H16	100.202	4.997E-04
2-Methylhexane	591-76-4	C7H16	100.202	4.140E-04
2,4-Dimethylpentane	108-08-7	C7H16	100.202	3.067E-04
Neohexane	75-83-2	C6H14	86.175	1.851E-04
Toluene	108-88-3	C7H8	92.138	1.659E-04
Heptane	142-82-5	C7H16	100.202	1.335E-04
m,p-Xylene	CEL0014	C8H10	106.168	1.144E-04
3-Methylheptane	589-81-1	C8H18	114.229	1.116E-04
2-Methylheptane	592-27-8	C8H18	114.229	1.086E-04
cis-2-Butene	590-18-1	C4H8	56.106	8.731E-05
Ethylbenzene	100-41-4	C8H10	106.165	6.218E-05
Nonane	111-84-2	C9H20	128.255	5.321E-05
Hydrogen Sulphide	7783-06-4	H2S	34.076	5.313E-05
Pentane, 2,3,4-trimethyl-	565-75-3	C8H18	114.229	4.482E-05
o-Xylene	95-47-6	C8H10	106.165	4.296E-05
Decane	124-18-5	C10H22	142.282	2.290E-05
m-Ethyltoluene	620-14-4	C9H12	120.192	1.960E-05
2-Ethylthiophene	872-55-9	C6H8S	112.193	1.710E-05
Thiophene	110-02-1	C4H4S	84.141	1.630E-05
124 Trimethylbenzene	95-63-6	C9H12	120.194	1.567E-05

Table 27: Average oil truck vapour analyses (dry and air-in) determined from AITF laboratory results for sites visited in Three Creeks during the summer and fall of 2014				
Substance Name	**CAS Number**	**Formula**	**MW**	**Mol Fraction**
o-Ethyltoluene	611-14-3	C9H12	120.192	1.518E-05
n-Propylbenzene	103-65-1	C9H12	120.192	1.410E-05
3-methyl Thiophene	616-44-4	C5H6S	98.167	1.351E-05
2,5-Dimethylthiophene	638-02-8	C6H8S	112.193	1.330E-05
Isopropylbenzene	98-82-8	C9H12	120.192	1.114E-05
1,3,5-Trimethylbenzene	108-67-8	C9H12	120.192	1.110E-05
Ethyl mercaptan	75-08-1	C2H6S	62.135	1.099E-05
2-methyl Thiophene	554-14-3	C5H6S	98.167	1.033E-05
Dimethyl sulphide	75-18-3	C2H6S	62.135	9.851E-06
p-Ethyltoluene	622-96-8	C9H12	120.192	9.516E-06
tert-Butyl mercaptan	75-66-1	C4H10S	90.188	8.876E-06
Isopropyl mercaptan	75-33-2	C3H8S	76.162	8.086E-06
Pentyl mercaptan	110-66-7	C5H12S	104.215	7.114E-06
1,2,3-Trimethylbenzene	526-73-8	C9H12	120.192	6.500E-06
Methyl mercaptan	74-93-1	CH4S	48.108	3.885E-06
Formic Acid	64-18-6	CH2O2	46.025	9.366E-07
Cyclopentane, 1,2-dimethyl-	2452-99-5	C7H14	98.186	4.234E-08
Cyclohexane, 1,3-dimethyl-	591-21-9	C8H16	112.213	2.905E-08
Pentane, 3-ethyl-	617-78-7	C7H16	100.125	2.847E-08
1-Pentene, 3,4-dimethyl-	7385-78-6	C7H14	98.110	2.534E-08
Cyclohexane, 1,1,3-trimethyl-	3073-66-3	C9H18	126.239	2.367E-08
Cyclopentane, 1,2,4-trimethyl-	2815-58-9	C8H16	112.213	2.296E-08
Cyclopentane, 1,2,3-trimethyl-	2815-57-8	C8H16	112.213	2.197E-08
Cyclohexane, ethyl-	1678-91-7	C8H16	112.213	2.079E-08
Cyclopentane, 1-ethyl-3-methyl-	3726-47-4	C8H16	112.125	1.872E-08
1-Pentene, 2-methyl-	763-29-1	C6H12	84.094	1.762E-08
Cycloheptane, methyl-	4126-78-7	C8H16	112.125	1.700E-08
Cyclopentane, 1,2,3-trimethyl-, (1.alpha	2613-69-6	C8H16	112.213	1.665E-08
(1R*,2R*)-1,2-Dimethyl-1-propioloylcyclopentane	81825-31-2	C10H14O	150.104	1.658E-08
Pentane, 2,2-dimethyl-	590-35-2	C7H16	100.202	1.649E-08
Cyclohexane, 1,2-dimethyl-, trans-	6876-23-9	C8H16	112.213	1.628E-08
1-Octene	111-66-0	C8H16	112.125	1.567E-08
Hexane, 2,3-dimethyl-	584-94-1	C8H18	114.141	1.508E-08
1-methyl-2-ethylcyclopentane isomer 2	VOC-K-041	C8H16	112.125	1.383E-08
Cyclopentane, 1,3-dimethyl-	2453-00-1	C7H14	98.186	1.232E-08
Butane, 2,2,3-trimethyl-	464-06-2	C7H16	100.125	1.129E-08
Cyclopentane, ethyl-	1640-89-7	C7H14	98.186	9.489E-09
Cyclopentane, 1,1,2-trimethyl-	4259-00-1	C8H16	112.125	9.150E-09
cis-2-iodo-1,3,3-trimethylcyclopentane	VOC-K-312	C8H15I	238.022	7.024E-09
1-Buten-1-one	20334-52-5	C4H6O	70.042	6.957E-09

Table 27: Average oil truck vapour analyses (dry and air-in) determined from AITF laboratory results for sites visited in Three Creeks during the summer and fall of 2014				
Substance Name	**CAS Number**	**Formula**	**MW**	**Mol Fraction**
Cyclohexane, 1,1-dimethyl-	590-66-9	C8H16	112.213	6.130E-09
7-methyl-tetracyclo[4.1.0.0(2,4).0(3,5)]heptane	77481-22-2	C8H10	106.078	5.720E-09
1-Heptanol	111-70-6	C7H16O	116.120	5.516E-09
Heptane, 3,4-dimethyl-	922-28-1	C9H20	128.157	5.252E-09
Butane, 1-bromo-2-methyl-	10422-35-2	C5H11Br	150.004	2.978E-09
Cyclobutanone, 2,3,3-trimethyl-	28290-01-9	C7H12O	112.000	2.553E-09
2-Pentene, 2,4,4-trimethyl-	107-40-4	C8H16	112.125	2.520E-09
4-Methyl-2-methyleneoxepane	64507-65-9	C8H14O	126.104	2.306E-09
N-OCTAN-3-ENE	VOC-K-317	C8H16	112.125	1.764E-09
2-Propanol	67-63-0	C3H8O	60.095	3.538E-10

Table 28: Average water truck vapour analyses (dry and air-in) determined from AITF laboratory results for sites visited in Three Creeks during the summer and fall of 2014				
Substance Name	**CAS Number**	**Formula**	**MW**	**Mol Fraction**
Nitrogen	7727-37-9	N2	28.014	7.351E-01
Oxygen	7782-44-7	O2	31.999	2.045E-01
Carbon Dioxide	124-38-9	CO2	44.010	4.215E-02
Methane	74-82-8	CH4	16.042	9.366E-03
Ethylacetylene	107-00-6	C4H6	54.090	1.349E-03
Methylcyclohexane	108-87-2	C7H14	98.186	1.097E-03
i-Pentane	78-78-4	C5H12	72.149	6.813E-04
Cyclohexane	110-82-7	C6H12	84.159	6.468E-04
2-Methylpentane	107-83-5	C6H14	86.175	4.615E-04
Propyne	74-99-7	C3H4	40.064	4.438E-04
Methylcyclopentane	96-37-7	C6H12	84.159	4.213E-04
n-Pentane	109-66-0	C5H12	72.149	3.825E-04
3-Methylpentane	96-14-0	C6H14	86.175	3.815E-04
3-Methylhexane	589-34-4	C7H16	100.202	3.041E-04
Hexane	110-54-3	C6H14	86.177	2.662E-04
Toluene	108-88-3	C7H8	92.138	2.429E-04
n-Butane	106-97-8	C4H10	58.122	2.072E-04
Ethane	74-84-0	C2H6	30.069	2.013E-04
i-Butane	75-28-5	C4H10	58.122	1.847E-04
2,3-Dimethylpentane	565-59-3	C7H16	100.202	1.803E-04
m,p-Xylene	CEL0014	C8H10	106.168	1.652E-04
Cyclopentane	287-92-3	C5H10	70.133	1.508E-04
2,3-Dimethylbutane	79-29-8	C6H14	86.175	1.433E-04
2-Methylhexane	591-76-4	C7H16	100.202	1.331E-04
Propane	74-98-6	C3H8	44.096	9.099E-05
Ethylbenzene	100-41-4	C8H10	106.165	8.251E-05
o-Xylene	95-47-6	C8H10	106.165	6.505E-05
124 Trimethylbenzene	95-63-6	C9H12	120.194	5.889E-05
2-Methylheptane	592-27-8	C8H18	114.229	5.631E-05
Heptane	142-82-5	C7H16	100.202	5.154E-05
3-Methylheptane	589-81-1	C8H18	114.229	5.142E-05
m-Ethyltoluene	620-14-4	C9H12	120.192	4.442E-05
Neohexane	75-83-2	C6H14	86.175	3.894E-05
o-Ethyltoluene	611-14-3	C9H12	120.192	3.308E-05
Hydrogen Sulphide	7783-06-4	H2S	34.076	3.147E-05
1,3,5-Trimethylbenzene	108-67-8	C9H12	120.192	2.625E-05
1,2,3-Trimethylbenzene	526-73-8	C9H12	120.192	2.608E-05
n-Propylbenzene	103-65-1	C9H12	120.192	2.543E-05
Pentane, 2,3,4-trimethyl-	565-75-3	C8H18	114.229	1.982E-05
Formic Acid	64-18-6	CH2O2	46.025	1.940E-05
p-Ethyltoluene	622-96-8	C9H12	120.192	1.647E-05

Table 28: Average water truck vapour analyses (dry and air-in) determined from AITF laboratory results for sites visited in Three Creeks during the summer and fall of 2014				
Substance Name	**CAS Number**	**Formula**	**MW**	**Mol Fraction**
Isopropylbenzene	98-82-8	C9H12	120.192	1.559E-05
Nonane	111-84-2	C9H20	128.255	1.036E-05
m-Diethylbenzene	141-93-5	C10H14	134.218	8.408E-06
Decane	124-18-5	C10H22	142.282	6.073E-06
3-methyl Thiophene	616-44-4	C5H6S	98.167	3.684E-06
2,5-Dimethylthiophene	638-02-8	C6H8S	112.193	2.995E-06
2-Ethylthiophene	872-55-9	C6H8S	112.193	2.587E-06
2-methyl Thiophene	554-14-3	C5H6S	98.167	1.984E-06
Undecanes	1120-21-4	C11H24	156.308	1.869E-06
Thiophene	110-02-1	C4H4S	84.141	1.481E-06
cis-2-Butene	590-18-1	C4H8	56.106	7.210E-07
Dimethyl sulphide	75-18-3	C2H6S	62.135	5.330E-07
Cyclohexane, 1,3-dimethyl-	591-21-9	C8H16	112.213	9.303E-08
Cyclohexane, 1,1,3-trimethyl-	3073-66-3	C9H18	126.239	8.427E-08
Cyclopentane, 1,3-dimethyl-	2453-00-1	C7H14	98.186	7.423E-08
Cyclopentane, 1,1,2-trimethyl-	4259-00-1	C8H16	112.125	5.933E-08
Cyclopentane, 1,2-dimethyl-	2452-99-5	C7H14	98.186	5.606E-08
Cyclohexane, ethyl-	1678-91-7	C8H16	112.213	5.409E-08
Cyclopentane, 1-ethyl-2-methyl-	3726-46-3	C8H16	112.213	3.999E-08
Cyclohexane, 1,2-dimethyl-, trans-	6876-23-9	C8H16	112.213	3.984E-08
Cyclohexane, propyl-	1678-92-8	C9H18	126.141	3.706E-08
Cyclooctane, 1,4-dimethyl-, trans-	13151-98-9	C10H20	140.157	3.588E-08
Hexane, 3-ethyl-	619-99-8	C8H18	114.141	3.571E-08
Cyclopentane, 1,2,4-trimethyl-	2815-58-9	C8H16	112.213	3.453E-08
Cyclopentane, 1-ethyl-3-methyl-	3726-47-4	C8H16	112.125	3.405E-08
1-Pentene, 3,4-dimethyl-	7385-78-6	C7H14	98.110	3.228E-08
1,1,2,3-TETRAMETHYLCYCLOHEXANE	71186-28-2	C10H20	140.157	3.058E-08
Methyl mercaptan	74-93-1	CH4S	48.108	2.911E-08
Cyclopentane, 1,2,3-trimethyl-	2815-57-8	C8H16	112.213	2.691E-08
Cycloheptane, methyl-	4126-78-7	C8H16	112.125	2.266E-08
Isopropyl mercaptan	75-33-2	C3H8S	76.162	1.717E-08

8 APPENDIX III: LIST OF SUBSTANCES RELEASED DURING 2012

Table 29: Total 2012 emissions by substance released in the Three Creeks area.

Substance Name	CAS Number	Emissions (tonnes/year)
Carbon Dioxide	124-38-9	4.4E+05
Carbon Monoxide	630-08-0	1.7E+03
Oxides of Nitrogen	CEL0002	1.4E+03
Methane	74-82-8	1.3E+03
Sulphur Dioxide	7446-09-5	1.4E+02
Undecanes	1120-21-4	6.6E+01
Total Particulate Matter	CEL0003	5.6E+01
Potassium	7440-09-7	4.2E+01
i-Pentane	78-78-4	3.7E+01
i-Butane	75-28-5	3.5E+01
Ethane	74-84-0	3.3E+01
Methylcyclohexane	108-87-2	2.7E+01
Ethylacetylene	107-00-6	2.6E+01
Propane	74-98-6	2.4E+01
n-Butane	106-97-8	2.2E+01
2-Methylpentane	107-83-5	2.0E+01
n-Pentane	109-66-0	1.7E+01
Cyclohexane	110-82-7	1.6E+01
3-Methylpentane	96-14-0	1.6E+01
Propyne	74-99-7	1.5E+01
Methylcyclopentane	96-37-7	1.3E+01
Hexane	110-54-3	9.8E+00
Nitrous Oxide	10024-97-2	9.7E+00
3-Methylhexane	589-34-4	9.5E+00
Chlorine	7782-50-5	7.3E+00
2,3-Dimethylbutane	79-29-8	7.0E+00
2,4-Dimethylpentane	108-08-7	7.0E+00
2,3-Dimethylpentane	565-59-3	6.6E+00
Ammonia	7664-41-7	5.8E+00
2-Methylhexane	591-76-4	5.0E+00
Cyclopentane	287-92-3	4.7E+00
Calcium	7440-70-2	4.0E+00
124 Trimethylbenzene	95-63-6	3.7E+00
Ethylene	74-85-1	3.5E+00

Table 29: Total 2012 emissions by substance released in the Three Creeks area.		
Substance Name	**CAS Number**	**Emissions (tonnes/year)**
Toluene	108-88-3	3.0E+00
m-Ethyltoluene	620-14-4	2.6E+00
Sodium	7440-23-5	2.5E+00
Neohexane	75-83-2	2.3E+00
1,2,3-Trimethylbenzene	526-73-8	2.1E+00
3-Methylheptane	589-81-1	2.1E+00
o-Ethyltoluene	611-14-3	2.0E+00
Heptane	142-82-5	1.9E+00
2-Methylheptane	592-27-8	1.8E+00
m,p-Xylene	CEL0014	1.7E+00
1,3,5-Trimethylbenzene	108-67-8	1.7E+00
Hydrogen Sulphide	7783-06-4	1.5E+00
p-Diethylbenzene	105-05-5	1.5E+00
n-Propylbenzene	103-65-1	1.4E+00
Ethylbenzene	100-41-4	1.3E+00
p-Ethyltoluene	622-96-8	1.2E+00
o-Xylene	95-47-6	1.1E+00
cis-2-Butene	590-18-1	1.0E+00
Propylene	115-07-1	9.9E-01
m-Xylene	108-38-3	9.5E-01
Aluminum	7429-90-5	9.4E-01
m-Diethylbenzene	141-93-5	9.4E-01
Magnesium	7439-95-4	7.9E-01
Decane	124-18-5	7.8E-01
Nonane	111-84-2	7.3E-01
Isopropylbenzene	98-82-8	7.0E-01
Boron	7440-42-8	7.0E-01
Pentane, 2,3,4-trimethyl-	565-75-3	6.5E-01
Acetylene	74-86-2	6.0E-01
Sulphur	7704-34-9	5.7E-01
Octane	111-65-9	4.1E-01
Dimethyl trisulphide	3658-80-8	3.1E-01
Benzene	71-43-2	2.6E-01
2,2,4-Trimethylpentane	540-84-1	2.4E-01
Silicon	7440-21-3	2.1E-01
Iron	7439-89-6	1.9E-01

Table 29: Total 2012 emissions by substance released in the Three Creeks area.		
Substance Name	**CAS Number**	**Emissions (tonnes/year)**
Formaldehyde	50-00-0	1.8E-01
1-Butene	106-98-9	1.6E-01
Zinc	7440-66-6	9.6E-02
2-Ethylthiophene	872-55-9	9.4E-02
Formic Acid	64-18-6	8.1E-02
2,5-Dimethylthiophene	638-02-8	8.0E-02
3-methyl Thiophene	616-44-4	7.4E-02
Thiophene	110-02-1	7.2E-02
Strontium	7440-24-6	5.8E-02
Pentyl mercaptan	110-66-7	5.6E-02
2-methyl Thiophene	554-14-3	5.5E-02
Dimethyl disulphide	624-92-0	5.0E-02
Ethyl mercaptan	75-08-1	3.9E-02
Isopropyl mercaptan	75-33-2	3.7E-02
tert-Butyl mercaptan	75-66-1	3.4E-02
Dimethyl sulphide	75-18-3	2.8E-02
Xylenes	1330-20-7	2.6E-02
Acetaldehyde	75-07-0	2.5E-02
Dodecane	112-40-3	2.3E-02
trans-2-Butene	624-64-6	2.2E-02
Phosphorous	7723-14-0	2.1E-02
1-Hexene	592-41-6	2.0E-02
1-Pentene	109-67-1	1.5E-02
Barium	7440-39-3	1.5E-02
Methyl mercaptan	74-93-1	1.2E-02
Vanadium	7440-62-2	7.6E-03
Nickel	7440-02-0	7.0E-03
Carbon disulphide	75-15-0	6.0E-03
Butyl mercaptan	109-79-5	4.8E-03
Chromium	7440-47-3	4.6E-03
Naphthalene	91-20-3	3.9E-03
Carbonyl sulphide	463-58-1	3.8E-03
Cadmium	7440-43-9	3.7E-03
Molybdenum	7439-98-7	3.7E-03
Tin	7440-31-5	3.1E-03
Acrolein	107-02-8	3.0E-03

Table 29: Total 2012 emissions by substance released in the Three Creeks area.		
Substance Name	**CAS Number**	**Emissions (tonnes/year)**
Copper	7440-50-8	2.8E-03
Dichlorobenzene	25321-22-6	2.2E-03
Titanium	7440-32-6	1.9E-03
Lead	7439-92-1	1.5E-03
Silver	7440-22-4	1.3E-03
2-Pentene, (Z)-	627-20-3	1.3E-03
1,3-Butadiene	106-99-0	1.3E-03
Manganese	7439-96-5	1.3E-03
Phenanthrene	85-01-8	9.8E-04
Fluorene	86-73-7	9.5E-04
Mercury	7439-97-6	8.7E-04
Propyl mercaptan	107-03-9	6.9E-04
Cyclohexane, 1,3-dimethyl-	591-21-9	6.7E-04
Arsenic	7440-38-2	6.6E-04
Cyclohexane, 1,1,3-trimethyl-	3073-66-3	6.2E-04
Cyclopentane, 1,1,2-trimethyl-	4259-00-1	5.8E-04
Antimony	7440-36-0	5.3E-04
Cyclopentane, 1,2-dimethyl-	2452-99-5	5.1E-04
Lithium	7439-93-2	4.9E-04
Cyclopentane, 1,2,4-trimethyl-	2815-58-9	4.1E-04
Cyclohexane, ethyl-	1678-91-7	3.9E-04
Cyclopentane, 1,3-dimethyl-	2453-00-1	3.8E-04
Cyclohexane, 1,2-dimethyl-, trans-	6876-23-9	3.6E-04
Cyclopentane, 1,2,3-trimethyl-	2815-57-8	3.6E-04
Cyclopentane, 1-ethyl-3-methyl-	3726-47-4	3.4E-04
1-Pentene, 3,4-dimethyl-	7385-78-6	3.1E-04
Cobalt	7440-48-4	2.8E-04
Cycloheptane, methyl-	4126-78-7	2.8E-04
Fluoranthene	206-44-0	2.5E-04
Cyclopentane, 1,2,3-trimethyl-, (1.alpha	2613-69-6	2.4E-04
Cyclopentane, 1-ethyl-2-methyl-	3726-46-3	2.4E-04
Cyclohexane, propyl-	1678-92-8	2.3E-04
Pentane, 2,2-dimethyl-	590-35-2	1.9E-04
cis-2-iodo-1,3,3-trimethylcyclopentane	VOC-K-312	1.7E-04
Pyrene	129-00-0	1.6E-04
Acenaphthylene	208-96-8	1.6E-04

Table 29: Total 2012 emissions by substance released in the Three Creeks area.		
Substance Name	**CAS Number**	**Emissions (tonnes/year)**
1-Pentene, 2-methyl-	763-29-1	1.6E-04
Neopentane	463-82-1	1.6E-04
1-methyl-2-ethylcyclopentane isomer 2	VOC-K-041	1.6E-04
Pentane, 3-ethyl-	617-78-7	1.5E-04
(1R*,2R*)-1,2-Dimethyl-1-propioloylcyclopentane	81825-31-2	1.4E-04
Heptane, 3,4-dimethyl-	922-28-1	1.4E-04
1,1-Dioctyloxyoctane	VOC-K-313	1.4E-04
Cyclooctane, 1,4-dimethyl-, trans-	13151-98-9	1.4E-04
1-Pentanol, 4-methyl-	626-89-1	1.4E-04
Cyclopentane, ethyl-	1640-89-7	1.2E-04
1,1,2,3-TETRAMETHYLCYCLOHEXANE	71186-28-2	1.2E-04
Hexane, 3-ethyl-	619-99-8	1.1E-04
tert-butylcyclopropane	4741-87-1	1.1E-04
1-Heptanol	111-70-6	1.1E-04
Thorium	7440-29-1	1.1E-04
Cyclohexane, 1,1-dimethyl-	590-66-9	9.5E-05
1-Octene	111-66-0	9.2E-05
1-Dodecanol	112-53-8	9.2E-05
Hexane, 2,3-dimethyl-	584-94-1	9.1E-05
7-methyl-tetracyclo[4.1.0.0(2,4).0(3,5)]heptane	77481-22-2	8.8E-05
Cyclopentane, 1,1-dimethyl-	1638-26-2	6.6E-05
Anthracene	120-12-7	6.5E-05
Butane, 2,2,3-trimethyl-	464-06-2	6.2E-05
1-Buten-1-one	20334-52-5	6.1E-05
Benz(a)anthracene	56-55-3	5.8E-05
1,2-Dichlorooctane	VOC-K-318	5.6E-05
Butane, 1-bromo-2-methyl-	10422-35-2	5.5E-05
Cyclobutanone, 2,3,3-trimethyl-	28290-01-9	5.2E-05
2-Pentene, 2,4,4-trimethyl-	107-40-4	5.2E-05
1-Decanol	112-30-1	5.1E-05
Bismuth	7440-69-9	5.0E-05
Acenaphthene	83-32-9	4.9E-05
2-Methyl Naphthalene	91-57-6	4.4E-05
1-Butanol, 2-ethyl-	97-95-0	4.2E-05
Beryllium	7440-41-7	4.0E-05
Selenium	7782-49-2	4.0E-05

Table 29: Total 2012 emissions by substance released in the Three Creeks area.		
Substance Name	**CAS Number**	**Emissions (tonnes/year)**
1-Heptene	592-76-7	3.9E-05
acetonyl decyl ether	40657-11-2	3.8E-05
Bicyclo[2.1.1]hexan-1-ol	VOC-K-182	3.6E-05
3-Ethylcyclopentanone	10264-55-8	2.9E-05
Dimethylbenz(a)anthracene	57-97-6	2.9E-05
Dibenzo(a,h)anthracene	53-70-3	2.1E-05
Cyclobutanone, 2,2-dimethyl-	1192-14-9	1.9E-05
Uranium	7440-61-1	1.8E-05
Indeno(1,2,3-c,d)pyrene	193-39-5	1.8E-05
N-OCTAN-3-ENE	VOC-K-317	1.7E-05
3-Hexanone	589-38-8	1.6E-05
4-Methyl-2-methyleneoxepane	64507-65-9	1.5E-05
Chrysene	218-01-9	1.5E-05
Pentane, 1,5-dibromo-	111-24-0	1.3E-05
2-Butanone, 3,3-dimethyl-	75-97-8	1.1E-05
Benzo(k)fluoranthene	207-08-9	1.0E-05
Benzo(a)pyrene	50-32-8	9.7E-06
2,2-Dichloro-4-methyl-3-pentanone	66250-08-6	9.1E-06
Benzo(b)fluoranthene	205-99-2	8.7E-06
Thallium	7440-28-0	6.2E-06
decamethylcyclopentan	84979-99-7	5.7E-06
Ethane, 1,1-difluoro-	75-37-6	5.4E-06
2-Heptenal, (Z)-	57266-86-1	3.8E-06
20-Methylcholanthrene	56-49-5	3.3E-06
Cyclopropane, [(2-propenyloxy)methyl]-	18022-46-3	3.2E-06
Cyclopropane, (1-methylethyl)-	3638-35-5	2.9E-06
Benzo(g,h,i)perylene	191-24-2	2.2E-06
1-Methyl-bicyclo[3.2.0]heptan-6-one	5212-68-0	2.0E-06
2-Propanol	67-63-0	2.0E-06
Cyclohexane, 1,3,5-trimethyl-	1795-26-2	9.1E-07
Methanol	67-56-1	7.2E-07