Final Report

Validation of Reduced Spacing from Residences for Enclosed Combustors

18-ARPC-02

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Mining & Energy, Process Development

SRC Publication No. 14523-4C19

October 2019

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DISCLAIMER

Abstract: SRC has provided independent third-party field testing on the BGR 36 LP Combustor, including dispersion modeling, safety review, and validation services. Nuisance testing determined no measurable light was emitted from the combustor, and the noise generated was less than that of the existing equipment on site. Methane destruction efficiency was calculated at >99.99% for the 100% load runs and between 45% and 54% on average for the 10% load runs. The results of the dispersion modelling indicate compliance with published standards. From the safety review completed by SRC, the BGR-36LP appears to meet the requirements of Saskatchewan, Alberta, and British Columbia. The methane destruction efficiency during the 10% load tests was lower than the 99% or greater required in several jurisdictions. This result is discussed, and suggestions made for further work, should the project stakeholders wish to assess the technology further.

EXECUTIVE SUMMARY

The Saskatchewan Research Council (SRC) was contracted to provide independent third-party emissions and performance testing of the Black Gold Rush Industries Ltd. (BGR) 36 LP Combustor. The material presented in this report could be used by operators requesting exemption to “distance to residence” regulatory requirements (SK Direction S10, AB Directive 056 and 060, and BC Drilling and Production Regulations, Section 47c, and 48) and/or associated guidance (such as the BC Flaring and Venting Reduction Guideline). The results of this testing may also be used to inform regulations related to combustor operation, pending regulator priorities. If so, exploration and production companies will have added flexibility when designing and operating facilities near occupied residences.

SRC has provided independent third-party field testing on the BGR 36 LP Combustor, dispersion modeling, a safety and regulatory review, and validation services on this project. The field testing took place at a Western Canadian oil producer site. Gas production at this site was around 95% methane, typical of heavy oil sites and natural gas production. An industry partner provided the site, and BGR provided a stack extension containing the appropriate sample ports. SRC personnel travelled to the site with one of SRC’s Centre for the Demonstration of Emissions Reductions (CeDER) trailers during the week of May 27-31, 2019. Personnel from BGR were on-site to observe the data collection.

Nuisance testing determined no measurable light was emitted from the combustor, and the noise generated was less than that of the existing equipment on site. Methane destruction efficiency was calculated at >99.99% for the 100% load condition and between 45% and 54% on average for the 10% load condition. The methane destruction efficiency during the 10% load tests was lower than the 99% or greater required by Alberta’s regulation D60 and BC’s Flaring and Venting Guideline. The degree to which this is significant will be assessed by the individual provincial regulators, based on their priorities. It is uncommon to operate at such a high turn-down ratio, as most combustors will be sized for the flow anticipated at a site. Still, inconsistent flow is typical of production operations.

Incomplete combustion at 10% load still reduced the amount of methane and non-methane hydrocarbons emitted to the atmosphere when compared to venting. Some nitrogen oxides (NOx) were generated, though not as much as from combustion at the higher (100%) load. As one would expect, incomplete combustion resulted in greater formation of BTEX and carbon monoxide than complete combustion. It generated BTEX at 0.011 g/h and significantly more carbon monoxide than during complete combustion at 100% of the maximum inlet flowrate (0.5% vs 0.03%).

Despite the incomplete combustion during the 10% load tests, the results of the dispersion modelling indicate compliance with the standards listed in Appendix G. Dispersion modelling found VOC, CO, NO_X, and particulate measurements were well below the ambient air quality objectives and/or standards listed in Table G-6 of Appendix G for all test runs.

From the safety review completed by SRC, the BGR-36LP appears to meet the requirements of Saskatchewan, Alberta, and British Columbia. Best practices for operation and integrity management systems for critical components are recommended based on Alberta Boiler Safety Association's document AB-512 "Owner-User Pressure Equipment Integrity Management Requirements".

Alberta's D60, and BC's Flaring and Venting Guideline require combustion efficiency of 99% or greater. BGR combustors at or near capacity were able to achieve >99.99% destruction efficiency of methane during this testing. However, at 10% load destruction efficiency was measured to be 45% and 54%. These results suggest that enclosed combustors can meet or exceed regulations when properly sized to the application.

Additional test work is recommended, pending regulator and AUPRF approval, to explore the boundary operating conditions for enclosed combustors with high-methane content natural gas such as that observed at the test site, and identify at what turndown ratio they no longer meet emission regulations. In this case, SRC would propose to monitor methane, carbon monoxide, oxygen, fuel conversion efficiency, and temperature to conduct partial load testing to establish lower operating limits governed by destruction efficiency limits. This methodology is recommended to minimize costs and timelines in future projects. It is also recommended that the combustor outlet be tested at a site with H_2S and higher inlet concentrations of volatile organic compounds to confirm the reduction efficiency. It is not appropriate to assume destruction efficiencies are equivalent for all compounds. Additional options for future testing are discussed further in the Section 6.2.

ACKNOWLEDGEMENTS

The authors would like to extend gratitude for the financial assistance provided by Petroleum Technology Alliance Canada (PTAC) (through the Alberta Upstream Petroleum Research Fund (AUPRF)), the British Columbia Oil and Gas Research Innovation Society (BC OGRIS), and the Saskatchewan Ministry of Energy and Resources, – Energy Regulation Division. We also gratefully acknowledge the facilitation work by PTAC, and the technical oversight provided by the members of the steering committee: the Saskatchewan Ministry of Energy and Resources, the Alberta Energy Regulator, the British Columbia Oil and Gas Commission (BC OGC), Canadian Association of Petroleum Producers (CAPP), and NAL Resources Ltd.

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1. INTRODUCTION

1.1 Project Description

Oil and gas producers operating in Western Canada, with support from government regulators, want independent third-party emissions and performance testing on the Black Gold Rush (BGR) 36 LP Combustor. SRC was contracted to provide this testing using funding from the Saskatchewan Ministry of Energy and Resources, the Alberta Upstream Petroleum Research Fund Program (the "AUPRF Fund"), and the BC Oil and Gas Research Innovation Society (BC OGRIS). These combustors are designed to destroy volatile hydrocarbons using an enclosed high-efficiency burner system with no visible flame. Conversion of methane is purported to be nearly complete. The material presented in this report could be used by operators for requesting exemption to "distance to residence" regulatory requirements (SK Direction S10, AB Directive 056 and 060, and BC Drilling and Production Regulations, Section 47c, and 48) and/or associated guideline (such as the BC Flaring and Venting Reduction Guideline). Regulators could also take the results of this testing into consideration when setting new requirements for industry.

SRC has provided independent third-party field testing on the BGR 36 LP Combustor, dispersion modeling, a safety review, and validation services on this project. The field testing took place at a Western Canadian oil producer site in Alberta. An industry partner provided the site and access to their combustor, and BGR installed an extended stack containing the appropriate sample ports. SRC personnel travelled to the site with one of SRC's Centre for the Demonstration of Emissions Reductions (CeDER) trailers, which housed the equipment required to measure the key performance parameters.

1.2 About the Combustor

The 36 LP vapour combustor made by Black Gold Rush Industries (BGR) is an enclosed vapour combustor. Enclosed combustors have the burner located at the bottom of the stack, concealed by an enclosure. Air is pulled into the stack by natural convection from the hot flue gas, mixing and cooling as it moves to the stack exit. The maximum design throughput is 2,800 m3/day or 4,317 MJ/hr. According to BGR, "The patented high efficiency burner inside the combustor chamber provides low pressure continuous burning capabilities, high combustion efficiency, low emissions, reduced odors, no visible flame and increased flame stability with excellent turndown ratios for low pressure applications." (BGR, 2019) This project was designed to investigate the performance of the combustor.

1.3 About SRC

The Saskatchewan Research Council (SRC) is Saskatchewan's leading provider of applied research, development and demonstration (RD&D) and technology commercialization. Saskatchewan Research Council's Mining and Energy Division provides Smart Science Solutions™ to clients in the areas of applied R&D, scale-up, demonstration and commercialization across all sectors. The Mining and Energy Division is well-positioned to participate in all forms of energy production, conversion, and conservation leading towards the goal of significant economic and positive environmental impacts for Saskatchewan.

CeDER is a Saskatchewan-based test and validation platform managed and led by SRC that provides real-world testing, demonstration and validation of emissions measurement, reduction, capture and conversion technologies. Designed to accelerate industry adoption of practical and economic technologies, CeDER offers independent, industry-recognized, third-party validation.

SRC's CeDER mobile facilities are modular, meaning that the instrumentation and equipment required for each project can be mobilized as needed. This mobile capability has been designed to be flexible and to provide a wide range of testing for diverse technology scenarios. Wireless data acquisition systems allow us to use industry standard instrumentation on-site.

CeDER's trailers can be deployed to test technologies in the field at full- or pre-commercial scales and can be moved easily between locations. While SRC's home base is in Saskatchewan, it operates in field locations across Canada.

1.4 Safety

Prior to conducting any field activities, SRC conducted a Job Safety Analysis in order to ensure that all the hazards associated with the various project activities were assessed and appropriate controls implemented. SRC also ensured that all project field staff were in compliance with the additional safety requirements and training required by the site operator, including:

- H_2S Alive training
- WHMIS training
- Corporate Orientation
- Site Specific Orientation
- Permit Receiver Training

The Alberta Energy Regulator provided a waiver for an exemption to of the flare and incinerator spacing requirements in section 7.8 of Directive 060: Upstream Petroleum Industry Flaring, Incinerating, and Venting (March 2016) to allow for the use of the uninsulated stack extension The waiver that would normally be required for a large venting exemption during testing was not necessary as SRC and the site operator were able to install a calibrated orifice meter into the system to divert excess gas to a second combustor.

2. VALIDATION PLAN AND METHODOLOGY

2.1 Field Test Plan

The Validation Plan was provided to and approved by the Project Team, BGR, and the industrial partner in April 2019, prior to field testing. The plan is summarized at a high level in this section.

BGR was to modify an existing 36 LP enclosed combustor by extending the stack as pictured in **Figure 2**, such that the stack testing ports would be close to the normal combustor outlet, where destruction efficiency is expected to be at a maximum. The stack extension included two 6 in. ports required for sampling the stack output; this design results in the testing occurring at approximately 10 in. from the normal combustor outlet. The sampling location was chosen using exhaust temperature data provided by BGR.

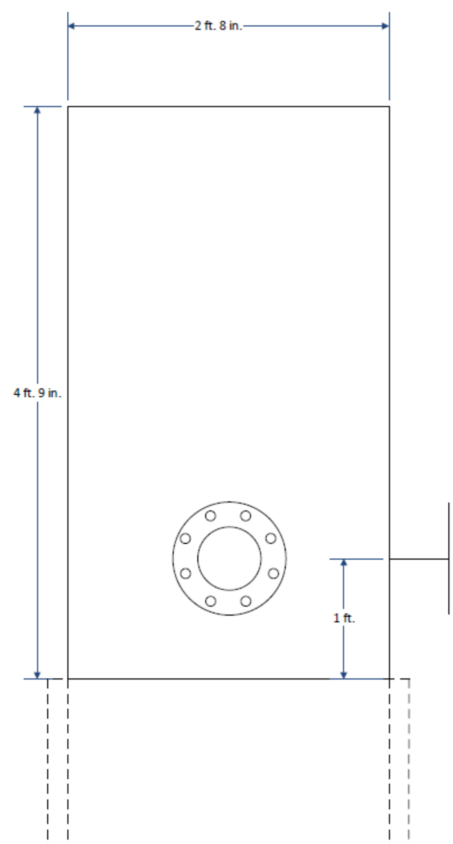

Figure 1 – Stack extension design sketch

BGR and the site operator were to install the stack extension on the combustor and prepare the site for testing. After installation, SRC was to conduct the final safety training and procedural overviews required before arriving on site. The CeDER trailer was to be prepared for mobilization; including trailer organization, calibrations, and equipment checks. SRC would also work with the site operator to submit the test plan to the Alberta provincial regulator to apply for any required exemptions to Directive 060: Upstream Petroleum Industry Flaring, Incinerating, and Venting (March 2016) for the duration of the test period.

SRC was to transport a CeDER trailer to the field test site for the week of May 27 to 31, 2019. SRC personnel planned to be on site for approximately five days to perform process monitoring, stack testing, and nuisance testing. During testing, the combustor throughput was varied by altering the flowrate of associated gas into the combustor. Excess gas was directed to the second on-site combustor. Testing was planned for both 100% of full load and 10% of full load. After each input flowrate change, a period of time was elapsed to allow the combustor to reach steady state operation. Once operating at steady state, samples of the outlet gases were to be taken, and process variables were to be recorded. This was to continue until three samples at each of the two flowrates had been recorded, for a total of six runs.

Collecting "nuisance" data from the combustor without the extension required luminance testing at night. Although the validation plan originally called for it to be collected at night, sound data was collected during the afternoon on the final day of testing, to minimize working hours on site. One flowrate near the high end of the LP36 combustor's throughput range provided a "worst-case" test scenario.

2.2 Test Site

An AUPRF member partner provided a combustor site for all required testing. The site characteristics and location were approved by the Project Team. The specific site location and identity of the site owner are confidential. The site had the following specifications:

- The site flow is 3.5-4 x 10^3 m^3/day
- There are two combustors on this site. One combustor was retrofitted for emissions testing while light and noise sampling were completed on the other (unmodified) combustor.
- There was no 110v power on this site. SRC provided a generator for all power needs during field testing
- Scaffolding was erected for stack sampling port access.

The composition of the associated gas from the test site was measured previously by the site operator. It is provided in **Table 1**. This composition is typical of heavy oil operations, while also being applicable to natural gas production sites because of its high methane content and low concentration of contaminants.

Table 1 – Gas Composition at Proposed Site

Composition (wt. %)	
Helium	0.0257
Oxygen	0.0247
Nitrogen	2.6924
Carbon dioxide	0.6703
Methane	95.9639
Ethane	0.6102
Propane	0.0096
i-butane	0.0004
n-butane	0.0009
i-pentane	0.0002
n-pentane	0.0002
Hexane	0.0000
Heptane	0.0015
Hydrogen sulfide	Not detected
Heating Value (H_2O free)	36.60 MJ/m^3
Density	0.7040 kg/m^3

2.3 Data Collection Methodology

1) Process Measurements

Process variables were measured using internally developed procedures. The volumetric flow rate of the associated gas into the combustor was controlled using an orifice plate and GoR flow transmitter rented from Guest Control Systems. A ½ in orifice plate was used for the 10% (of maximum) load tests, and a 1 in. orifice plate was used for the 100% (of maximum) load tests.

The temperature of the inlet gas was measured using a thermocouple placed on the pipe surface. Gas pressure of the inlet gas was measured using wireless differential pressure cells. The composition of the inlet gas was determined through analysis of samples by gas chromatograph (GC). All process variables were monitored continuously throughout the test period.

Flowrate, composition, temperature, and pressure of the outlet were measured during stack testing; see bullet 2 for methodology.

2) *Stack Tests (outlet gas composition)*

- Methane was measured using a Fourier Transform Infrared (FTIR) analyzer and US EPA Method 320. Test duration was approximately ½ hour.
- Non-methane hydrocarbons (NMHC) was measured using US EPA Method 18 – THC (Total Hydrocarbons) as Methane and VOC (Volatile Organic Compounds) Test duration was approximately 1 hour.
- Total reduced sulfur (TRS) was measured using US EPA method 18 and analyzed by ASTM method D5504. ASTM method D5504, reduced sulfur analysis, measures 18 individual sulfur compounds by gas chromatography and calculates total sulfur mathematically. Test duration was approximately 1 hour.
- Nitrogen oxides (NOx) were measured using US EPA Method 7E – Instrumental NO_x (Nitrogen Oxides) Test duration was approximately ½ hour.
- Benzene, toluene, ethylbenzene, and xylene (BTEX) were measured using a Fourier Transform Infrared (FTIR) analyzer and US EPA Method 320. Sample bags were analyzed by gas chromatograph as back-up. Test duration was approximately ½ hour.
- Carbon dioxide was measured using US EPA Method 3a – Carbon Dioxide and Oxygen Concentration in Emissions. Test duration was approximately ½ hour.
- Carbon monoxide was measured using US EPA Method 10 – Instrumental CO (Carbon Monoxide). Test duration was approximately ½ hour.
- Stack Gas Temperature, Velocity, Volumetric Flow and Moisture were measured using US EPA Methods 2 and 4. Test duration was 10 minutes per traverse point.

3) *Nuisance Measurements*

- A noise survey was conducted using an internally developed method based on CSA-Z107.58-15. Sound level readings were taken for a period of 10 minutes at distances of 1m and 3m. The sound level meter was used to take short-term readings on slow response on the A-filter scale.

- Light monitoring was conducted using an internally developed method and a commercial luminance meter. Luminance readings were taken in an unobstructed direction hourly over a period of four hours. A picture was also taken with a digital camera at the time of testing.

2.4 Instruments and Calibration

1) *Volumetric flowmeter*

A GoR flow transmitter, model 4202 with an orifice plate of 1 in. was used for the 100% load tests. A ½ in. orifice plate was installed for the 10% load tests. The flowmeter was calibrated by Guest Control Services before installation. The calibration data for this meter was reviewed by SRC and is in included in **Appendix A**.

2) *Thermocouples*

Thermocouple accuracy was verified in fluids of known temperature before transportation to the field site.

3) *Gas Chromatograph (GC)*

A Shimadzu (model 8AIT) gas chromatograph was used to analyze gases (nitrogen, oxygen, carbon monoxide, carbon dioxide, and hydrogen) and hydrocarbons (methane, ethane, propane, butanes, pentanes, hexanes, and heptanes) in the field. The software package is “PeakSimple”. The Shimadzu GC was calibrated, and the method confirmed prior to field deployment, and recalibrated daily on testing days using a certified calibration gas.

4) *Differential Pressure Cells*

A Siemens differential pressure transmitter (Model SITRANS P DS III) was used to measure the pressure at the combustor inlet. The transmitter is 4–20 mA output HART capable and can be ranged to measure 0-1 bar differential pressures. Wireless communication devices were fitted to the transmitter.

5) *Stack Sampling Analyzers*

Temperatures were monitored using pre-calibrated thermocouples and stack gas velocity was measured using s-type Pitot tubes which were pre-calibrated at the University of Saskatchewan.

Gas measurements on the BGR-36LP stack were performed using a Gasmet TMDX 4000 Fourier Transform Infrared (FTIR) spectrometer, which is designed for measuring a wide range of organic and inorganic pollutants from flue streams. The measurements followed the EPA Method 320 (Reference 5).

Samples for total non-methane hydrocarbons, reduced sulfur compounds and total volatile organic compounds (including BTEX) from both the inlet and exhaust of the BGR-36LP combustor were collected in either a silico-coated 6L steel cannister or 10L Tedlar bag and analyzed by gas chromatograph equipped with a mass spectrometer or flame ionization detector.

Samples for carbon monoxide, carbon dioxide, nitrogen oxides (NOX) and moisture on the combustor exhaust were measured using a Fourier Transform Infrared Spectrometer (FTIR).

Methane results from the combustor exhaust were measured using FTIR and concentrations were validated using the cannister gas chromatography method. Whereas, methane results from the combustor fuel inlet were measured and reported using the cannister gas chromatography method only.

Quality assurance and control procedures were followed for measuring stack gas parameters and collecting velocity and gaseous samples. They include the following:

- Regular calibration of the pitot tubes, thermocouples and temperature readout.
    - All stack testing equipment is put through a rigorous preventative maintenance schedule once per year.
    - All equipment is checked and tested prior to use in the field by conducting gas audits, leak checks, visual inspections and function testing.
    - Dry gas meters are annually calibrated against a standard test meter that is also annually calibrated via wet test meter in the United States.
    - Pitot tubes are checked prior to each use and are calibrated annually against a standard pitot using the Department of Engineering Wind Tunnel at the University of Saskatchewan.
    - Temperature display and thermocouples are annually calibrated against NIST traceable thermometers as per manufacturer's specifications.

    - Nozzles are accurately measured and scrutinized in criteria adherence prior to each use.
    - Pumps are serviced, (oil & vane change) annually

- Regular maintenance of all stack sampling equipment as well as calibration gases for all gas analysers.
    - All equipment is treated with care and respect.
    - Anytime a piece of equipment fails to pass the criteria of a field inspection or fails to work properly at all, it is tagged-out and not used.
    - Defective equipment is repaired and re-calibrated prior to being returned to duty.

- Standard operating procedures (SOPs) for gaseous sampling.
- On-site leak checks of all equipment.
- Strict adherence to US-EPA Stack Sampling Protocol (References 1 through 5).
- QA/QC on the stack sampling reports.
- Certification of the stack sampling operators as evidenced by a training certificate

6) Luminance meter

A Konica Minolta LS-110 luminance meter was acquired for use in this project. The meter was factory calibrated before use.

7) Sound Level Meter

A Reed R8080 sound level meter with data logger was used to record the noise measurements. The sound level meter was calibrated before and after use, as per the operating manual.

3. Results and Discussion

3.1 Field Test Description

SRC completed field testing of the BGR 36LP Combustor at a western Canadian heavy oil site during the period of May 27-31, 2019. Data was collected during May 28th and 29th for the purpose of validating the combustor's performance, as specified in the validation plan. Personnel from Black Gold Rush were on site to observe the data collection.

The site had a two combustor set up, with one combustor modified for access using a stack extension with two 6 in ports, and one combustor left unmodified for nuisance testing. The second combustor was used to minimize excess gas venting during testing at reduced flow rates. **Figure 3** shows CeDER at the test site, with the two combustors and access (stack extension and scaffolding).

Figure 2 – CeDER mobile facility at field site

The field test included:

- Premobilization preparation – trailer organizing, calibrations, and equipment checks
- Mobilization of the trailer with required equipment
- Setup at the site for process monitoring of technology inputs and outputs to collect data for performance validation.
- Performing the on-site data collection (sample collection and analysis) according to the validation plan.
- Demobilization back to SRC

The maximum flowrate at the site is approximately 4.0×10^3 m^3/day, while maximum design throughput for the BGR LP36 combustor is 2.8×10^3 m^3/day. Each parameter was measured three times at loads of 10% and 100% maximum, for a total of 6 test runs. The parameters included the following using the methods approved by the Project Team:

- Inlet gas flowrate
- Exhaust gas flowrate
- Inlet gas composition (Methane, non-methane hydrocarbons (NMHC), H2S, Total Reduced Sulphur (TRS), NOx, BTEX, carbon monoxide, carbon dioxide)
- Outlet gas composition (Methane, non-methane hydrocarbons (NMHC), Total Reduced Sulphur (TRS), NOx, BTEX, carbon monoxide, carbon dioxide)
- Inlet gas temperature
- Outlet gas temperature
- Inlet gas pressure
- Atmospheric pressure

3.2 Nuisance Testing Results

According to BC's Drilling and Production Regulation, Section 40, "A permit holder must ensure that operations at a well or facility for which the permit holder is responsible do not cause excessive noise or excessive emanation of light." Collecting luminance data from the unmodified combustor required testing at night. One flowrate near the high end of the LP36 combustor's throughput range provided a "worst-case" test scenario. The measured luminance was below detectable limits, with the visual record taken at night showing no light detectable by the naked eye. The recorded luminance data is provided in **Table 2** and a photograph in **Figure 4**.

Table 2 – Luminance Data

Time	Luminance (cd/m²)
12:48:00 AM	pictures taken
12:50:00 AM	0.0
12:50:00 AM	0.0
12:51:00 AM	0.0
12:52:00 AM	0.0
12:52:00 AM	0.0
12:53:00 AM	0.0
12:54:00 AM	0.0
12:55:00 AM	0.0
12:55:00 AM	0.0
Average	0.0

Figure 3 – Combustor at night

The noise survey was conducted during the afternoon of May 29th, using a Reed R8080 sound level meter. The noise caused by other site operations, particularly the engine, was too high to accurately determine the noise produced by the combustor alone. The sound level data has been tabulated in **Table 3** and plotted as a sound level map in **Figure 5**. **Figure 6** shows the location of the engine shack relative to the combustors. As can be seen, the noise level drops as one moves west, because the bulk of the combustor blocks the pump shack. Noise levels also drop as one moves south, which is further from the pump shack. The noise from the combustor is not greater than the noise produced during normal operations without a combustor. British Columbia's Noise Control Best Practices Guideline allows for the calculation of a permissible sound level of 40 dB plus an additional 10 dB for daytime conditions. It is not possible to determine if the combustor meets the permissible sound level of 50 dB from this data.

Table 3 – Sound Level Data

Location	Sound Level (dB)
1 m North	86.0
1 m East	87.9
1 m South	86.1
1 m West	77.7
1 m West repeat	79.2
3 m North	86.2
3 m East	90.2
3 m South	84.0
3 m West	77.5
3 m West repeat	79.4

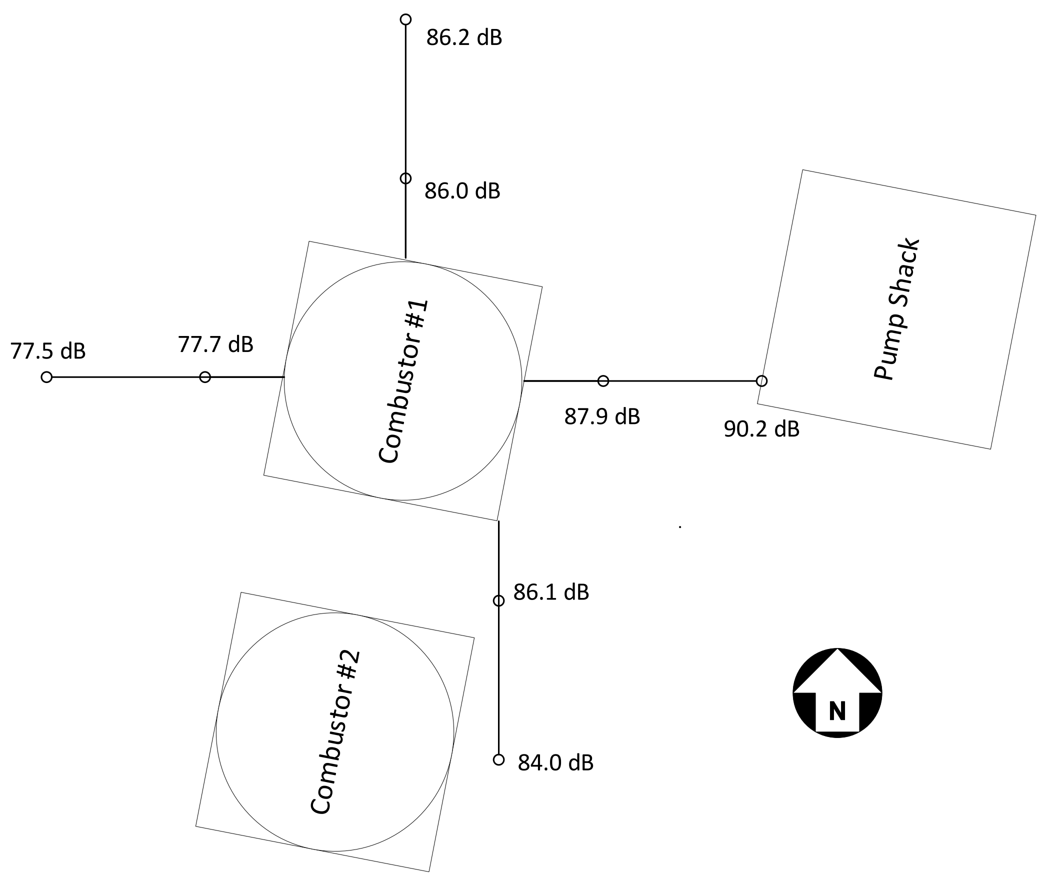

Figure 4 – Sound Level Map

Figure 5 – Pump shack in relation to combustors (viewed from the East)

3.3 Inlet Gas Testing Results

Gas chromatography (GC) was performed on site in the CeDER trailer to provide immediate feedback on the composition of the inlet gas. The columns used during this testing were calibrated to identify hydrogen, helium, oxygen, nitrogen, carbon dioxide, carbon monoxide, methane (C1), ethane (C2), propane (C3), butane (C4), pentane (C5), hexane (C6), and hydrogen sulfide. Other trace components, such as total reduced sulfur, were measured using a different method, as described in **Section 2.3**. Inlet gas samples were analyzed by GC during the test runs, as well as at the beginning and end of the test period. Each sample was analyzed twice, and the results were averaged and normalized. The full test data is provided in **Appendix B**, with the averaged results presented here in **Table 4**.

Table 4 – Average Inlet Gas Composition during Testing

Component	Weight percent (%)
Helium	0.0118
Hydrogen	0.0000
Oxygen	0.0344
Nitrogen	2.6621
Methane	95.8941
CO	0.0000
CO2	0.7212
Ethene	0.0000
Ethane	0.6501
H2S	0.0001
Propane	0.0155
Propene	0.0000
i-Butane	0.0039
n-Butane	0.0052
i-Pentane	0.0017
n-Pentane	0.0000
n-Hexane	0.0000
Total	100.0000

Methane content varied from 94.93% to 96.31%, with an overall average of 95.89% during the test period. Hydrogen sulfide (H_2S) was below 10 ppm (0.001%) in all the samples, as expected. The measured gas composition was comparable to that from an earlier analysis provided by the site operator, which had a methane content of 94.67% (see **Table 1**).

Inlet flow rate was measured using a ½ in. orifice plate with an inline flow transmitter, as described in **Section 2**. Some variability was observed in the flow rate under the 10% of maximum flow conditions. During Run 2 the feed gas valve was accidentaly closed, causing the flame to go out. The combustor was restarted within five minutes, and the test continued. The flameout period and the low-pressure outlier at 16:18 (in red font) were removed from the average flowrate calculated for Run 2. See **Table 5**.

According to BGR, the combustor's burner management system will try and relight three times automatically in the case of a flame-out, and will alarm if unsuccessful. On the day of testing an the valve was opened and the combustor re-lit from the operating panel. According to the site operator there is no audible alarm on site (since it is not a manned site), instead the operator is notified remotely through the SCADA system. In this case, the operators were made aware of the testing beforehand and did not respond separately to the alarm.

Table 5 – Run 2 Inlet Conditions

Time	Flowrate (m3/day)	Pressure (kPa)	Temperature (°C)
15:00	399	1.14	30.6
15:10	335.9	1.004	30.6
15:20	348.8	1.18	30.7
15:30	367.7	1.14	30.4
15:32	Burner flame out		
15:47	Restart combustor		
15:48	300.8	0.789	32.4
15:58	349.1	1.047	32.5
16:08	346.9	1.11	32.5
16:18	267.9	0.45	31.5
Average	339.5	0.98	31.4
Remove outliers	346.8	1.06	31.4

The inlet data for the remaining test runs is provided in **Appendix C**; only the averages are reproduced in **Table 6**. As can be seen the flowrate at the 10% load condition was closer to 12% of the combustor maximum. Inlet pressure varied, with higher pressures correlated to higher flowrates, as expected. Inlet gas temperature was between 27-33°C, which was the ambient temperature during the test period.

Table 6 – Average Inlet Conditions for 10% and 100% Loads

Run	Date	Inlet Flowrate (%)	Inlet Flowrate (m3/day)	Pressure (kPa)	Temperature (°C)
1-3	May 28	10	339.16	3.33	31.12
4-6	May 29	100	2596.05	14.77	28.88

Three samples were collected on both the inlet and exhaust of the combustor under both 10% and 100% load for total and speciated reduced sulphur compounds (RSC) as well as total and speciated volatile organic compounds (TVOC); including methane, non-methane hydrocarbons (NMHC) and BTEX. The results for the inlet samples are presented in **Table 7** and **Table 8**. Unfortunately, upon analysis it was discovered that the samples from runs 1 and 5 suffered inadvertent dilution, and the sample container from run 6 failed. Results from these samples have been excluded when calculating the totals presented in the following tables.

Table 7 – Average Inlet Composition for 10% Load

BGR-36LP Inlet at 10% Load*	
Non-Methane Hydrocarbon Concentration (as Toluene)	43840 mg/drm^3 (11650 ppm v/v dry)
BTEX Concentration (as Toluene)	0.0664 mg/drm3 (0.0176 ppm v/v dry)
Methane Concentration	600500 mg/drm3 (916500 ppm v/v dry)
RSC Concentration (as Hydrogen sulphide)	0.90 mg/drm^3 (0.64 ppm v/v dry)

*Two-test average (suspected inadvertent dilution of Run 1).

Table 8 – Average Inlet Composition for 100% Load

BGR-36LP Inlet at 100% Load**	
Non-Methane Hydrocarbon Concentration (as Toluene)	43650 mg/drm^3 (11600 ppm v/v dry)
BTEX Concentration (as Toluene)	0.0664 mg/drm3 (0.0176 ppm v/v dry)
Methane Concentration	596900 mg/drm^3 (911000 ppm v/v dry)
RSC Concentration (as Hydrogen sulphide)	0.50 mg/drm^3 (0.36 ppm v/v dry)

**Only Run 4 results are displayed (suspected inadvertent dilution of Run 5, Run 6 was lost in transit to laboratory).

The methane concentration agrees closely with that measured on-site by GC. Sulfur and BTEX concentrations are low (<10 ppm), as expected.

3.4 Stack Test Results / Outlet Gas Test Results

The feed stream and exhaust flue of a model BGR-36LP combustor manufactured by Black Gold Rush Industries Ltd (BGR) was sampled on May 28th and 29th, 2019 at a heavy oil production site in Alberta. Three samples were collected on both the inlet and exhaust of the combustor under both 10% and 100% load for total and speciated reduced sulphur compounds (RSC) as well as total and speciated volatile organic compounds (TVOC); including methane, non-methane hydrocarbons (NMHC) and BTEX. Additionally, the combustor exhaust was sampled for carbon monoxide, carbon dioxide, methane, NOX and moisture by Fourier Transform Infrared Spectroscopy (FTIR). The complete stack data set is provided in **Appendix D**. The results are discussed below.

Tables 9 and **10** display the results of the FTIR tests performed on the BGR-36LP Combustor stack at 10% and 100% load. Included in the FTIR test results are the concentration and emission data for moisture content, carbon monoxide, carbon dioxide, nitrogen oxides, sulphur dioxide, methane and oxygen. Reference and background spectra are saved and stored at SRC. Results were processed using Calcmet software version 12 supplied by Gasmet Technologies Dy of Helsinki, Finland. Spikes were prepared using an environics 4040 mixer/diluter in accordance with EPA method 205.

Under full fuel load, the BGR-36LP combustor exhibits inorganic gaseous composition similar to typical boiler exhaust. However, during the 10% load tests, incomplete combustion becomes apparent with unburnt methane concentrations averaging 4541 ppm v/v dry (compared to 2.46 ppm v/v dry during 100% rate). Under full load, the total NO_X concentrations increased by a factor of twenty and CO_2 concentrations by a factor of seven. CO_2 and NO_x are products of combustion, so this is not unexpected.

Total non-methane hydrocarbons (NMHC) in the exhaust stream showed an average concentration of 52.1 ppm v/v during the 10% load tests. Whereas, the total NMHC concentration was below detection limits (<0.080 ppm v/v dry) under full load. Reduced sulphur compounds (RSC) also exhibit lower concentrations in the exhaust when compared to the inlet gas stream.

Although showing an overall reduction in stack gas velocity by a factor of three between the two conditions, the dry volumetric flow rate was only reduced by 16.4%.

Table 9 – FTIR Test Results – BGR-36LP Combustor Exhaust (10% Load) - May 28, 2019

Run #	Start Time	End Time	H_2O (%)	CO_2 (%)	CO (ppm)	NO (ppm)	NO_2 (ppm)	SO_2 (ppm)	CH_4 (ppm)	O_2 (%)	NO_x** (ppm)
1	12:34	13:38	1.22	0.56	18.08	0.00	1.70	0.00	2723.06	19.30	1.70
2	14:59	16:19	1.13	0.53	24.30	0.02	2.41	0.00	4973.99	18.75	2.43
3	17:08	18:09	1.29	0.59	42.02	0.33	1.92	0.00	5924.95	18.38	2.25
		Average:	**1.22**	**0.56**	**28.13**	**0.11**	**2.01**	**0.00**	**4540.67**	**18.81**	**2.12**
Run #	**Start Time**	**End Time**	**H_2O (mg/drm^3)***	**CO_2 (mg/drm^3)**	**CO (mg/drm^3)**	**NO (mg/drm^3)**	**NO_2 (mg/drm^3)**	**SO_2 (mg/drm^3)**	**CH_4 (mg/drm^3)**	**O_2 (mg/drm^3)**	**NO_x** (mg/drm^3)**
1	12:34	13:38	9007	10080	20.70	0.00	3.20	0.00	1784	252461	3.20
2	14:59	16:19	8337	9478	27.82	0.02	4.53	0.00	3259	245199	4.56
3	17:08	18:09	9521	10526	48.11	0.40	3.61	0.00	3882	240377	4.23
		Average:	**8955**	**10028**	**32.21**	**0.14**	**3.78**	**0.00**	**2975**	**246012**	**4.00**
Run #	**Volumetric Flow (drm^3/s)***		**H_2O (kg/h)**	**CO_2 (kg/h)**	**CO (kg/h)**	**NO (kg/h)**	**NO_2 (kg/h)**	**SO_2 (kg/h)**	**CH_4 (kg/h)**	**O_2 (kg/h)**	**NO_x** (kg/h)**
1	0.593		19.2	21.5	0.044	0.00	0.0068	0.00	3.81	539	0.0068
2	0.694		20.8	23.7	0.070	0.00005	0.011	0.00	8.14	613	0.011
3	0.740		25.3	28.0	0.13	0.0011	0.010	0.00	10.3	640	0.011
		Average:	**21.8**	**24.4**	**0.081**	**0.00037**	**0.0093**	**0.00**	**7.43**	**597**	**0.010**

*drm^3 = dry reference cubic metres; reference conditions 101.3 kPa, 25 °C.
**NOx by mass expressed as NO_2.

Table 10 – FTIR Test Results – BGR-36LP Combustor Exhaust (100% Load) - May 29, 2019

Run #	Start Time	End Time	H_2O (%)	CO_2 (%)	CO (ppm)	NO (ppm)	NO_2 (ppm)	SO_2 (ppm)	CH_4 (ppm)	O_2 (%)	NO_x** (ppm)
4	9:28	10:28	5.70	3.62	5.41	40.07	3.23	0.00	3.09	14.11	43.30
5	11:13	12:22	7.75	3.90	10.02	40.34	8.33	0.00	1.87	13.63	48.67
6	13:08	14:09	8.07	3.90	8.98	42.41	7.60	0.00	2.43	13.60	50.01
	Average:		**7.17**	**3.81**	**8.13**	**40.94**	**6.38**	**0.00**	**2.46**	**13.78**	**47.33**
Run #	**Start Time**	**End Time**	**H_2O (mg/drm^3)***	**CO_2 (mg/drm^3)**	**CO (mg/drm^3)**	**NO (mg/drm^3)**	**NO_2 (mg/drm^3)**	**SO_2 (mg/drm^3)**	**CH_4 (mg/drm^3)**	**O_2 (mg/drm^3)**	**NO_x** (mg/drm^3)**
4	9:28	10:28	41927	65187	6.19	49.14	6.07	0.00	2.02	184570	81.43
5	11:13	12:22	56986	70086	11.47	49.47	15.66	0.00	1.23	178287	91.53
6	13:08	14:09	59392	70184	10.28	52.01	14.29	0.00	1.59	177925	94.05
	Average:		**52768**	**68486**	**9.31**	**50.21**	**12.01**	**0.00**	**1.61**	**180261**	**89.00**
Run #	**Volumetric Flow (drm^3/s)***		**H_2O (kg/h)**	**CO_2 (kg/h)**	**CO (kg/h)**	**NO (kg/h)**	**NO_2 (kg/h)**	**SO_2 (kg/h)**	**CH_4 (kg/h)**	**O_2 (kg/h)**	**NO_x** (kg/h)**
4	0.771		116	181	0.017	0.14	0.017	0.00	0.0056	512	0.23
5	0.780		160	197	0.032	0.14	0.044	0.00	0.0034	501	0.26
6	0.858		184	217	0.032	0.16	0.044	0.00	0.0049	550	0.29
	Average:		**153**	**198**	**0.027**	**0.15**	**0.035**	**0.00**	**0.0047**	**521**	**0.26**

*drm^3 = dry reference cubic metres; reference conditions 101.3 kPa, 25 °C.

**NOx by mass expressed as NO_2.

The dates, times, average concentrations (in milligrams per dry reference cubic meter, mg/drm3); and emission rates (in kilograms per hour, kg/h), are given below for each analyte at both load conditions for the combustor exhaust testing.

Table 11 – Average Outlet Composition for 10% Load

BGR-36LP Exhaust at 10% Load	
Carbon Dioxide Concentration	10028 mg/drm^3 (0.56% v/v dry)
Carbon Dioxide Emission	24.4 kg/h
Carbon Monoxide Concentration	32.2 mg/drm^3 (28.1 ppm v/v dry)
Carbon Monoxide Emission	0.081 kg/h
Nitric Oxide and Nitrogen Dioxide Concentration (as NO2)	4.00 mg/drm^3 (2.12 ppm v/v ref)
Nitric Oxide and Nitrogen Dioxide Emission (as NO2)	0.010 kg/h
Non-Methane Hydrocarbon Concentration (as Toluene)	196 mg/drm^3 (52.1 ppm v/v dry)
Non-Methane Hydrocarbon Emission (as Toluene)	0.49 kg/h
BTEX Concentration (as Toluene)	0.0049 mg/drm^3 (0.0013 ppm v/v dry)
BTEX Emission (as Toluene)	0.011 g/h
Methane Concentration	2975 mg/drm^3 (4541 ppm v/v dry)
Methane Emission	7.43 kg/h
RSC Concentration (as Hydrogen sulphide)	0.0067 mg/drm^3 (0.0048 ppm v/v dry)
RSC Emission (as Hydrogen sulphide)	0.016 g/h

Table 12 – Average Outlet Composition for 100% Load

BGR-36LP Exhaust at 100% Load	
Carbon Dioxide Concentration	68490 mg/drm^3 (3.81% v/v dry)
Carbon Dioxide Emission	198 kg/h
Carbon Monoxide Concentration	9.31 mg/drm3 (8.13 ppm v/v dry)
Carbon Monoxide Emission	0.027 kg/h
Nitric Oxide and Nitrogen Dioxide Concentration (as NO2)	89.0 mg/drm^3 (47.3 ppm v/v ref)
Nitric Oxide and Nitrogen Dioxide Emission (as NO2)	0.26 kg/h
Non-Methane Hydrocarbon Concentration (as Toluene)	0.30 mg/drm^3 (0.080 ppm v/v dry)
Non-Methane Hydrocarbon Emission (as Toluene)	0.00087 kg/h
BTEX Concentration (as Toluene)	0.0024 mg/drm^3 (0.0006 ppm v/v dry)
BTEX Emission (as Toluene)	0.0067 g/h
Methane Concentration	1.61 mg/drm^3 (2.46 ppm v/v dry)
Methane Emission	0.0047 kg/h
RSC Concentration (as Hydrogen sulphide)	0.0049 mg/drm^3 (0.0035 ppm v/v dry)
RSC Emission (as Hydrogen sulphide)	0.014 g/h

As discussed earlier, some of the samples collected at the BGR-36LP Combustor inlet were compromised and exhibited signs of inadvertent dilution. These samples were excluded from the results.

The average methane concentration within the combustor inlet during the 10% fuel load testing was 916500 ppm v/v dry while the combustor exhaust showed a methane concentration of 4541 ppm v/v dry under the same conditions.

The average methane concentration within the combustor inlet during the 100% fuel load testing was 911000 ppm v/v dry while the combustor exhaust showed a methane concentration of 2.46 ppm v/v dry under the same conditions.

Outlet flowrate, temperature, and pressure were also recorded during testing as per the validation plan. The averages at 10% and 100% load are given in **Table 13**:

Table 13 – Average Outlet Conditions for 10% and 100% Loads

Run	Inlet Flowrate (%)	Pressure (kPa)	Temperature (°C)	Velocity (m/s)	Flowrate (drm3/s)
1-3	10	0.003	147.04	2.24	0.97
4-6	100	0.011	717.78	6.76	1.16

The results presented here are representative of the conditions experienced at the time of sampling.

3.4 Mass and Energy Balance

Combining the data collected above with the simplified process flow diagram (PFD), **Figure 7,** allows mass and energy balances to be calculated for each of the load conditions tested. The PFD has been simplified for illustrative purposes, and to define the stream numbers used in the mass balance; it is not a representation of the actual field piping. A full piping and instrumentation diagram (P&ID) for the combustor is provided in **Appendix E**.

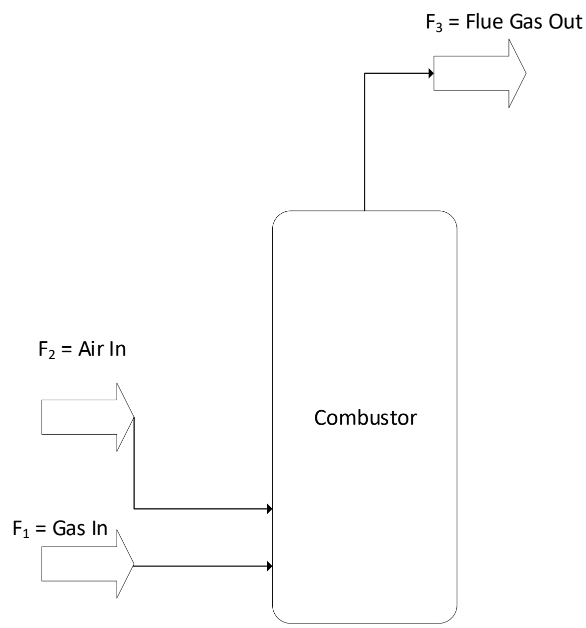

Figure 6 – Simplified Process Flow Diagram of a Combustor

If the mass balance is performed based on the inlet flowrate measure by the flowmeter, there is a discrepancy such that the mass of methane combusted plus that leaving the system is higher than the mass added to it for the 10% load runs. The inlet flow meter and outlet velocity measurement were both calibrated (see **Appendix A** and **Appendix D)**, but at low flows and concentrations, imbalances in mass balance calculations are difficult to avoid. Any small measurement discrepeancy or change in flow during the test period is multiplied many-fold by the low outlet concentration and high outlet volumes. To resolve this inconsistency, the inlet flowrate has been re-calculated based on the carbon dioxide balance, such that enough combustible material must be added to the system to produce the amount of carbon dioxide measured leaving the stack. Additional methane was measured in the stack outlet in the 10% flow tests and has been included as well. The full mass balance calculations are provided in **Appendix F**. The resulting mass balances for 10% and 100% average load conditions are included in **Tables 14** and **15**.

Table 14 – Mass Balance for Average 10% Load

Components	Methane (CH_4)	Nitrogen (N_2)	Non-Methane Hydro-carbons (NMHC)	Carbon Dioxide (CO_2)	Oxygen (O_2)	Water (H_2O)	Overall
In (kg/h)	14.78	2258.68	0.21	2.13	692.09	0	3006.19
Out (kg/h)	-6.73	-2258.68	-0.48	-24.39	-598.29	-21.78	-2859.50
Generated	0.00	0	0.00	22.07	0.00	18.052	
Consumed	-8.04	0		0	-32.09		
Balance	0.00	0.00	-0.27	-0.19	61.71	-3.73	146.69
% Difference			128%	1%	9%	17%	5%
Destruction Efficiency	54.43						

Table 15 – Mass Balance for Average 100% Load

Components	Methane (CH_4)	Nitrogen (N_2)	Non-Methane Hydro-carbons (NMHC)	Carbon Dioxide (CO_2)	Oxygen (O_2)	Water (H_2O)	Overall
In (kg/h)	69.91	2772.90	0.9049	3.62	849.05	0	3743.36
Out (kg/h)	-0.0014	-2772.90	-0.0009	-198.04	-521.25	-152.59	-3685.42
Generated	0.00	0	0.00	194.46	0.00	158.525	
Consumed	-69.91	0	-0.9040	0	-285.25		
Balance	0.00	0.00	0.00	0.04	42.54	5.94	57.93
% Difference			0%	0%	5%	4%	2%
Destruction Efficiency	99.9979						

The methane remaining in the outlet gas stream during the 10% load tests is higher than the reported destruction efficiency, but the degree to which this is significant will be assessed by the individual provincial regulators based on their priorities. It is uncommon to operate at such a high turn-down ratio, as most combustors will be sized for the amount of flow anticipated at a site and not much larger, in an attempt to control capital costs. Still, inconsistent gas flow is typical of oil production operations.

Non methane hydrocarbons (NMHC) were included in the mass balance calculations as they made up a measurable portion of the inlet and outlet streams. At the 10% load condition, the NMHC's did not balance; i.e. more NMHC was measured in the outlet than ethane, propane, and butane in the inlet. This is attributed to differences in the measurement technique between the GC, which measured inlet ethane, propane, and butane, and the FTIR, which was used to measure outlet NMHC as a group. A more accurate destruction efficiency for NMHC is calculated in Section 3.5. Water also had a large difference at the 10% load, as the amount of humidity in the inlet air was neglected in the calculation. The overall balance was within 5% in each case, an acceptable difference for a mass balance. Individual species of pollutant were measured during the stack testing and are reported in **Appendix D**.

An energy balance was conducted in ChemCAD version 7.1.5, a chemical process simulator. Calculated exit temperatures are higher than recorded in **Table 13**, which can be attributed to radiative heat loss from the combustor. The results are presented in **Tables 16-17**.

Table 16 – Energy Balance for 10% Rate

No.		1	2	3
Stream		Natural Gas	Air	Flue Gas
Temperature	C	31.12	31.12	273.0338
Pressure	kPa	104.63	104.63	101.325
Enthalpy	MJ/h	-72.13	1.4545	-70.676

Table 17 – Energy Balance for 100% Rate

No.		1	2	3
Stream		Natural Gas	Air	Flue Gas
Temperature	C	28.88	28.88	941.7974
Pressure	kPa	116.091	116.091	101.3
Enthalpy	MJ/h	-376.72	-6.5792	-383.27

3.5 Comparison of 10% and 100% of maximum load

As discussed in the previous section, significant amounts methane remained uncombusted in the 10% load test. Using the compositions measured by the FTIR combined with the flowrates from the mass balance, we can compare the destruction efficiency and byproduct generation from partial combustion at 10% load to nearly complete combustion at 100% load. The results are given in **Tables 18-22**.

Table 18 – Destruction Efficiency of Methane (CH_4)

Load	CH_4 in (mg/drm3)	CH_4 in (kg/h)	CH_4 out (kg/h)	DE CH_4 (%)
10%	600500	13.60	7.43	45.37
100%	596900	63.82	0.0047	99.99

Table 19 – Destruction Efficiency of Non-methane Hydrocarbons (NMHC)

Load	NMHC in (mg/drm3)	NMHC in (kg/h)	NMHC out (kg/h)	DE NMHC (%)
10%	43840	0.99	0.49	50.65
100%	43650	4.67	0.00087	99.98

Table 20 – Destruction Efficiency of BTEX

Load	BTEX in (mg/drm3)	BTEX in (g/h)	BTEX out (g/h)	Destruction Efficiency BTEX (%)
10%	0.0664	0.0015	0.011	-631.41
100%	0.0664	0.0071	0.0067	5.62

Table 21 – Destruction Efficiency of Sulfur

Load	Sulfur In (mg/drm3)	Sulfur In (g/h)	Sulfur out (g/h)	Destruction Efficiency Sulfur (%)
10%	0.90	0.0204	0.016	21.51
100%	0.50	0.0535	0.014	73.81

Table 22 – Carbon Monoxide and Nitrogen Oxide Generation

Load	NOx out (kg/h)	NOx Generated (%)	CO out (kg/h)	CO Generated (%)
10%	0.010	0.0621	0.081	0.5030
100%	0.26	0.3122	0.027	0.0324

Partial combustion at 10% load reduced the amount of methane and non-methane hydrocarbons emitted to the atmosphere. Some nitrogen oxides (NOx) were generated, though not as much as from combustion at the higher load. It also generated BTEX at 0.011 g/h and significantly more carbon monoxide than during complete combustion at 100% of the maximum inlet flowrate (0.5% vs 0.03%). As one would expect, incomplete combustion resulted in greater formation of BTEX and carbon monoxide.

4. Dispersion Modelling

Data analysis and dispersion modelling were completed off-site following the testing. Dispersion modeling using Aermod was originally proposed but, at the recommendation of the BC representative, Aerscreen was selected by the Project Team instead for preliminary dispersion modeling. Aerscreen provides a more conservative estimate than Aermod. This section summarizes the Aerscreen dispersion model for the BGR 36LP combustor. It is representative of the gas composition and concentrations tested. The full Aerscreen dispersion modelling results are included in **Appendix G**.

The dispersion modelling was conducted using aerscreen version 16216. Aerscreen is a U.S. EPA model based on Aermod; the Aerscreen model used the Aermod EPA executable 18081. The current model was conducted using Breeze Aerscreen version 1.9 as a software interface. The facility was modelled with two scenarios; maximum (100%) load and reduced (10%) load. It is not known if a linear response can be drawn between the two scenarios; no conclusions should be inferred at other production rates.

Reference standards for Saskatchewan are required for air contaminants that may cause harm; requiring utilization of standards from other jurisdictions in some cases. For example, to evaluate the potential VOC risk, it is necessary to find standards from alternate jurisdictions; the recommendation is Alberta, Ontario, and Texas.

Alberta utilizes a set list of compounds with standards. For the purpose of this report compounds without a standard in Alberta, but with standards in Saskatchewan, will use Saskatchewan as reference.Ambient standards were utilized from Canadian Council of Ministers and Environment (CCME), Alberta (AB), Saskatchewan (SK), British Columbia (B.C.), Ontario, and Texas. In Saskatchewan an *air contaminant* is defined as a solid, liquid or gas or combination of any of them that may cause or is causing an adverse effect. To that end ambient standards from Alberta and other jurisdictions are deemed to apply within Saskatchewan.

The tested emissions required comparisons to numerous standards; the VOC standards for Texas are the most inclusive and are presented in Table G-6 of Appendix G. Alongside the values in the table are the average measured inlet and outlet concentrations. In all cases VOC emissions were already below ambient standards at the release point. In cases where the released compound is not detectable, no modelling is required. BTEX, CO, NOx, sulfur, and particulate emissions were also measured and modelled in Appendix G. The results of this report indicate compliance with standards at both flowrates tested.

Other air concerns such as National Pollutant Release Inventory (NPRI) and Greenhouse Gas (GHG) reporting considerations were not included in the scope of this report. Other environmental considerations were out of scope for this project and may require further review.

As a reference for the model, cultivated land was chosen to represent generic terrain. Figure 9 illustrates the aerscreen predictions of concentration vs. distance for a generic 1 g/s release. In the first 50 m it is normal for ambient concentrations to increase, this is the distance it takes to reach the ground from the stack exhaust. From approximately 50 m outwards there is a rapid decrease in concentration until the concentrations start levelling off. Although the model predicts continuation of concentration past 10 km, it is largely a relic. In contrast to the 100% load the reduced load profile (Figure 10) shows a lower dilution rate and higher concentrations further out. The reduction in initial vertical mixing is expected at lower exhaust rates and temperatures.

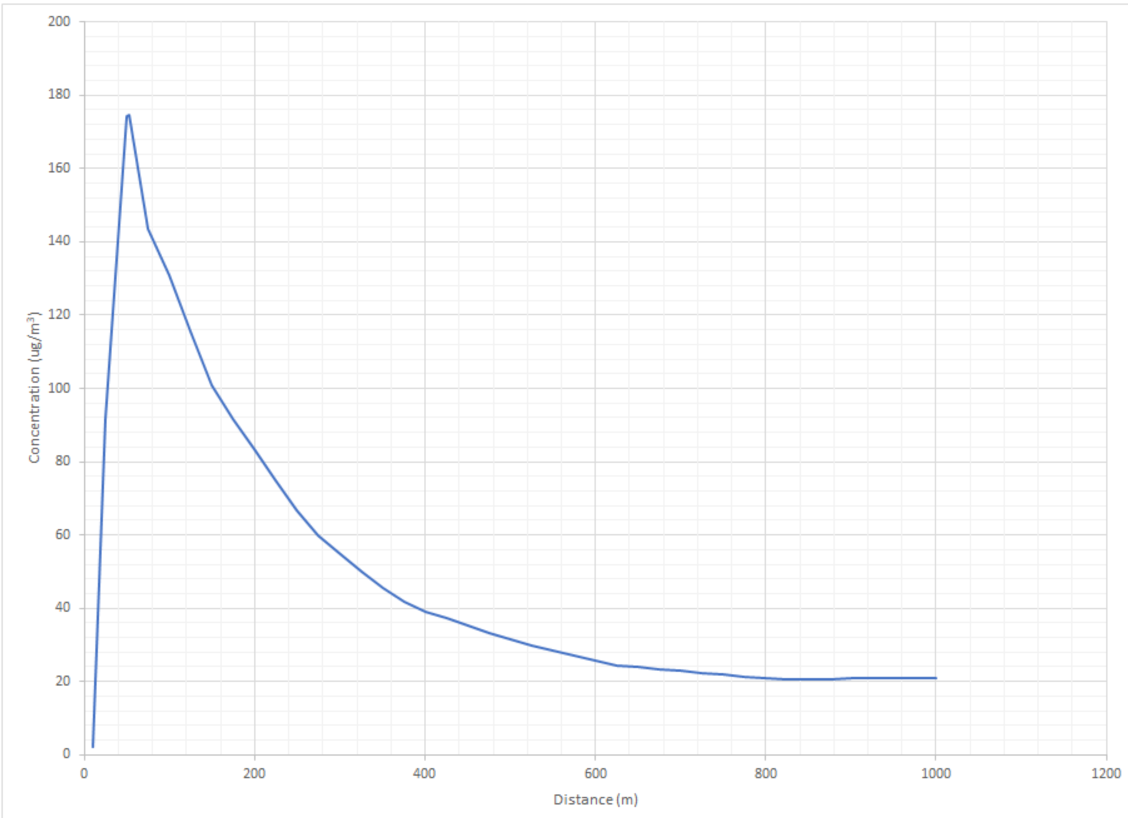

Figure 7 – Concentration vs. Distance for 100% load

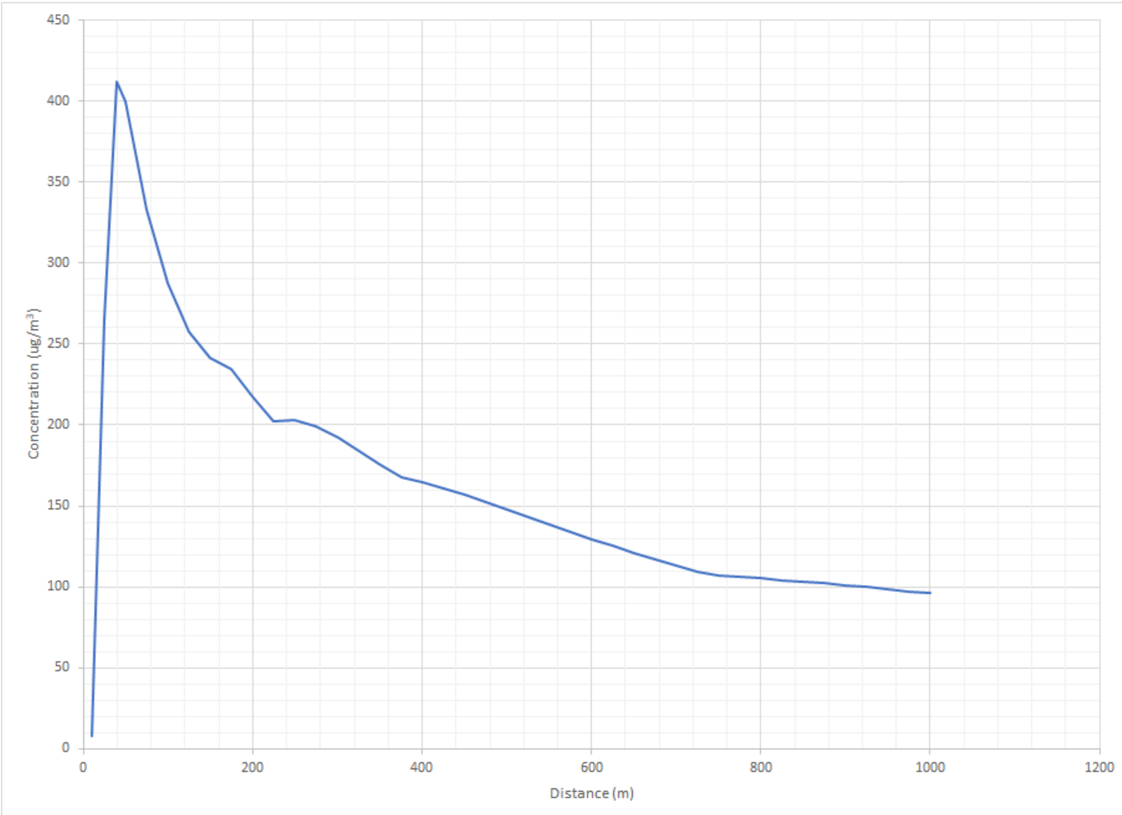

Figure 8 – Concentration vs. Distance for 10%load

Table 25 and **Table 26** may be used to estimate the percentage reduction of the plume. At full load the residual (%) of the initial release concentration is presented from 10 m to 1000 m. Included is the peak value at 35 m for reference. The table can be used to estimate ambient ground levels; or used to calculate the maximum concentration release if a desired level is known.

Table 23 – Percentage Remaining of Initial Release

Distance	% Remaining	Distance	% Remaining	Distance	% Remaining	Distance	% Remaining
10	0.0001987%	275	0.0059754%	525	0.0029941%	775	0.0021293%
25	0.0091487%	300	0.0054564%	550	0.0028382%	800	0.0020757%
50	0.0174180%	325	0.0049820%	575	0.0026923%	825	0.0020456%
52	0.0174780%	350	0.0045553%	600	0.0025560%	850	0.0020615%
75	0.0143570%	375	0.0041742%	625	0.0024361%	875	0.0020735%
100	0.0131040%	400	0.0039126%	650	0.0023902%	900	0.0020820%
125	0.0115420%	425	0.0037150%	675	0.0023410%	925	0.0020875%
150	0.0100830%	450	0.0035220%	700	0.0022896%	950	0.0020901%
175	0.0091590%	475	0.0033365%	725	0.0022367%	975	0.0020902%
200	0.0083584%	500	0.0031603%	750	0.0021831%	1000	0.0020881%
225	0.0074886%						
250	0.0066639%						

Table 24 – Percentage Remaining of Initial Release from Reduced Operation

Distance	% Remaining	Distance	% Remaining	Distance	% Remaining	Distance	% Remaining
10	0.0008045%	275	0.0199070%	525	0.0143130%	775	0.0105970%
25	0.0265270%	300	0.0192380%	550	0.0138490%	800	0.0105150%
50	0.0412200%	325	0.0184240%	575	0.0133910%	825	0.0104230%
52	0.0400020%	350	0.0175480%	600	0.0129450%	850	0.0103220%
75	0.0333290%	375	0.0167620%	625	0.0125120%	875	0.0102140%
100	0.0287730%	400	0.0164730%	650	0.0120950%	900	0.0101000%
125	0.0257590%	425	0.0161060%	675	0.0116930%	925	0.0099805%
150	0.0241120%	450	0.0156900%	700	0.0113070%	950	0.0098579%
175	0.0234270%	475	0.0152430%	725	0.0109380%	975	0.0097325%
200	0.0217480%	500	0.0147810%	750	0.0106660%	1000	0.0096050%
225	0.0202630%						
250	0.0203040%						

The tests indicate lower concentration reductions at 10% load, though it is not clear if the response is linear over the load ranges.

No VOC was released at a concentration greater than the Annual Texas limit, which is much lower than the daily or hourly limits (See Table G-6 in Appendix G). Although dilution will occur, it is not necessary to achieve ambient limits.

Some compounds appear to be formed during the combustion of the gases. It is not known if the formation fully occurs inside the stack or if these continue to form upon gas cooling; stack test results only indicate formation at the point of sample location and do not account for further formation. The aerscreen model indicates that there is a considerable buffer between expected results, based on the concentrations in the stack test reports and the various ambient limits. As noted previously the measured concentrations were below ambient limits prior to release and dilution.

Ambient temperature effects are the most pronounced at the extremes (-43°C to 47°C) and the model results will change outside this range. It is not expected to encounter ambient temperatures outside this range for the proposed region. At temperatures between the extremes the model results are lower.

Complicated terrain scenarios may change the model results and may require further modelling. Examples of complicated terrain include valleys surrounded by mountains, in some cases inversions form and trap emissions. For much of the prairies this is not a concern; however, it may apply to the foothills of Alberta or BC and some prudence is advised; the disclaimer applies to all aerscreen models and is not limited to the current model.

Detailed VOC compounds were measured at the outlet and inlet. The inlet concentrations were below Texas AMCV suggesting it is not necessary to measure the outlet concentrations of all compounds unless it is expected compounds are forming during combustion. A select group of compounds are formed including the BTEX group; these compounds should be measured as close to the outlet as possible. A reduced total VOC list could be used in future measurements.

CO and NO_X measurements were well below the ambient air quality objectives and/or standards. NO_X was modelled as a total conversion to NO_2 which is a conservative (high) bias; a refined approach is not necessary. Particulate, based upon emission factors for natural gas combustion, is below the ambient standards.

At low concentrations of air contaminants, similar to the test conditions in this report, it is expected the combustor will achieve desired results. At higher concentrations the combustor has not been tested to confirm burn characteristics will be similar. It is recommended the burner effluent be tested for H2S at a site with higher inlet concentrations to confirm the reduction efficiency. It is not appropriate to assume destruction efficiencies are equivalent for all compounds.

5. SAFETY REVIEW

5.1 Scope of Safety Review

As part of the overall enclosed combustor validation project, the Project Team had requested a safety review of the BGR 36LP. This safety review provides:

- A brief description of the BGR Combustors
- Safety Regulations in Saskatchewan, Alberta and British Columbia
- Best Design Practices, and
- Operational management for safety and performance.

The piping system being considered is limited to the combustor unit including the burner, pilots, ignitors, and gas train as documented by Black Gold Rush's drawing number BGR-18019PID-01. Piping systems and components upstream of this have regulatory requirements and design standards but are out of scope for this review. This review is intended to evaluate the combustor and the integral gas trains and burner management system.

5.2 Brief Description of the BGR Combustors

Two model BGR-36LP combustors made by Black Gold Rush Industries are installed at a well located in Alberta, and are therefore permitted and regulated in Alberta. This assessment reviews the regulatory requirements in Saskatchewan, Alberta, and BC since the project has stakeholders from all three provinces.

The enclosed combustor made by Black Gold Rush Industries is an enclosed vapour combustor. The maximum design throughput of the BGR LP36 combustor is 2,800 m3/day or 4,317 MJ/hr. In imperial units this is 99,000 scf/day or 4,091,700 Btu/hr. The pilot system is an ACL 1500 with a Btu rating of 4,000 Btu/h. The ACL 1500 pilot assembly uses a single integrated ignitor rod and flame sensor using flame ionization. The pilot air/fuel mixer operates with a supply pressure of 5 to 10 psig. The burner management system is the ACL CSC-400 which provides burner ignition control and flame fail sensing. The controller is CSA approved for Class 1 Div. 2, and CSA B149.3-15. The controller includes solenoid drivers, and three type-K thermocouple inputs, although only one is used for the given application.

The combustor is inherently a safer, and more environmentally friendly option compared to flares due to the use of a self-aspirating burner. Self-aspirating burners are commonly used in heating appliances and they have the benefit of producing short, hot, robust flames with high fuel conversion efficiency. The primary safety benefits are:

- There is no external flame,
- The stack or vertical tube is not at risk of generating fuel and air mixtures in the tube at start-up. This eliminates the need to purge the stack with gas/fuel to eliminate the air, which in turn reduces methane emissions.

One potential drawback is that there is no visual feedback on the combustion process as the flame is not visible. Variations in feed gas composition or supply pressure may result in low quality combustion with poor conversion efficiency, instabilities, and flame outs with no visible feedback to the operator. As a result, manufacturers should provide minimum flow rates in addition to the maximum capacity to ensure that owner/operators understand the constraints for minimizing methane emissions. An inspection port is available for the BGR 36LP, though operators must be in close proximity to make us of it.

5.3 Safety Regulations

This section provides a review of the safety regulations in Saskatchewan, Alberta, and British Columbia (BC) along with the following overview of standard versus regulatory codes. As previously mentioned, the scope is limited to the combustor, the integral main gas train, and pilot gas train so there is no review of the regulations applying to the upstream piping systems. The primary regulations are Alberta's Directive 060, Saskatchewan's Directive S-20, and BC's Flaring and Venting Reduction Guideline and Oil and Gas Activities Act.

Standards such as CSA standards are not automatically mandatory. They become mandatory only when a regulatory authority calls for compliance to the standard. In this case, the standard becomes a regulatory code. It should be noted that standards like ASME B31.3, and Z662 generally do not apply to the gas trains, pilots, burner, and burner controls that are integral to the combustor; but they may apply to piping systems upstream of the combustor. In Alberta, the Gas Safety Information Bulletin G-03-11-ABSA provides some clarity on the break point between what is covered under the Gas Code Regulation (Alberta Regulation 111/2010), and the Pressure Equipment Safety Regulation (Alberta Regulation 49/2006).

In Saskatchewan, a portion of B149.3 is enforced while Alberta enforces B149.1 and B149.3 on the combustor pilot. The following reviews the regulatory requirements and the associated authority having jurisdiction; first for Saskatchewan, then Alberta, and then for. British Columbia.

Saskatchewan Authorities

Saskatchewan Ministry of Energy and Resources (MER), Field Services Branch

MER is responsible for the enforcement of Directive S-20, Saskatchewan Upstream Flaring and Incineration Requirements. Directive S-20 contains the standards by which wells or facilities are licensed or approved under The Oil and Gas Conservation Act and/or The Oil and Gas Conservation Regulations.

Directive S-20 indicates that if the gas contains less than 10 mol/kmol (1%) of H2S, then no minimum residence time is required. The gas being used in this application is less than this amount. This is the case for the application being considered. Similarly, no maximum exit temperature is required.

The directive calls out a maximum radiant heat intensity at ground level of 4.73 kW per square meter. The value was neither calculated nor measured in this project.

Sections 3.7 and 3.8 call out the requirements for liquid separation and say it must be “adequate to protect”. Given the low pressure, high methane content gas source, very little is required to be adequate and a strainer would meet the requirements.

Section 3.9 calls out the requirement for backflash control with respect to the stack. This is generally not applicable to a combustor such as the BGR 36. The BGR 36 is more similar to a gas appliance with a flue stack. Note that flares have combustible gas and air traveling up the stack with combustion at the exit, while the BGR36 uses a gas mixer and burner located near the base of the stack, with flue gases (products of combustion) passing through the remainder of the stack. The burner also includes a burner management system to eliminate the possibility of the air and fuel mixtures from accumulating in the stack or flue. It should also be noted that the main gas train also contains an inline flame arrestor, but this is not believed to be done to meet the requirements of Directive 060.

It should be noted that Directive S-20 does not require the use of a flame arrestor on the intake of flares or combustors, but from a safety perspective, this likely should be part of the system.

In summary, the installed system appears to be compliant with Saskatchewan’s Directive S-20.

SaskPower Gas Inspections

Pressure piping systems are regulated in Saskatchewan with SaskPower Gas Inspections permitting all new gas installations. Codes under this jurisdiction that are relevant to combustors include B149.1-15 – Natural Gas and Propane Installation Code and B149.3-15 – Code for the Field Approval of Fuel-related Components on Appliances and Equipment. Saskatchewan also has the Saskatchewan Codes of Practice Gas Installation Supplement CSA-B149.3-15 which dictates that Annex E of B149.3 is adopted in Saskatchewan as mandatory requirements for flare pilot systems. Note that SaskPower's Gas and Electrical Inspections Division is moving to TSASK in the fall of 2020. TSASK is responsible for regulating boilers, pressure vessels, and other areas including the design and construction of pressure piping systems according to ASME B31.1, B31.3, and B31.5. B31.3 Process Piping would have applicability to the process piping upstream of the appliance or equipment (out of scope for this assessment).

SaskPower has been consulted on the applicability of CSA B149 in Saskatchewan. SaskPower has indicated "Although not required to meet CSA B149.3, the waste gas stream shall meet the relevant requirements of CSA B149.1." SaskPower has also confirmed that Annex E of CSA B149.3 governing pilots is applicable to combustors regardless of whether the pilot uses LPG or waste gas, so there is one exception to the statement that CSA 149.3 is not applicable. The 2020 version of CSA B149.3 has moved the requirements of Annex E into the body of the code as section 18. Since part of CSA B149.3 is applicable in Saskatchewan, we will compare the combustor design against the applicable part of B149.3 covering the pilot gas valve train.

CSA-B149.3-15 Annex E Guidelines for flare pilot systems

- Typical applications use LPG to fuel the pilot, but in this case, the associated gas or casing gas is used to fuel the pilot given the high quality (high methane content) of the gas.
- Use of 1 pilot should be considered an acceptable variance since the combustor uses a burner utilizing premixed air and gas so it does not perform as a utility flare
- The pilot capacity is approximately 4,000 Btu/hr (less than 20,000 Btu/hr) so only one safety shut-off valve is required
- Flame detection and an ignitor are employed with the pilot as per requirements of Annex E of B149.3-15.
- A y-strainer is employed as per the requirements of Annex E of B149.3-15.
- A manual shut-off valve is used for isolation
- A relief valve is used
- The fuel to the pilot is pressure regulated and the regulator has a positive shut-off

- The pilot system has critical measurements including fuel pressure and loss of flame.
- There is capability to isolate process gas from the flare
- The BGR combustor used a burner management system that provides automatic re-ignition of the pilot,
- The trial-for-ignition period of a pilot shall not exceed 10 seconds and it is likely that the BGR burner management system does this.

In summary, the BGR-36LP appears to meet the requirements of Annex E from B149.3 as required in Saskatchewan.

Alberta Authorities

Alberta Energy Regulator (AER)

AER is responsible for enforcing Directive 060: Upstream Petroleum Industry Flaring, Incinerating, and Venting which will be updated January 1st, 2020. This is the primary regulation governing the combustors. The following is an assessment of the combustor design compared to Directive 060 to reflect the most recently developed requirements. This new directive combined with Directive 017: Measurement Requirements for Oil and Gas Operations are intended to reduce methane emissions by 45% from 2014 levels by 2025. This is done through fugitive emissions management and vent gas management.

Directive 060 Section 7 covers Performance Requirements including operational management which is beyond the scope of this safety review which is limited to the design of the system only. Section 7 states that ANSI/API Standard 521: Pressure-Relieving and Depressurizing Systems, as well as applicable fire safety codes, electrical codes, CSA standards, and mechanical engineering standards are all necessary references for the design of combustors. Section 7.1.2 calls out a minimum residence time of 0.5 seconds at maximum flow. It also states that incinerators must operate with a minimum exit temperature of 600 °C if the gas being combusted contains more than 1% H2S (which is not the case for the application being considered).

AER also requires that the that conversion efficiency of an incinerator be 99 percent or more. Conversion efficiencies less than 99% would be considered to operate as a flare. Note that the BGR36 is a combustor designed to destruct volatile organic compounds (VOC's) and BTEX's (benzene, toluene, ethylbenzene, and xylene). Test data has shown that the unit destroyed more than 99% of the VOCs at full load testing. BTEX destruction cannot be reported given the very low levels in the supply gas, and even lower levels in the flue gas. The result is the measurement of values near the detection limit and large potential error relative to the reading making it impossible to accurately calculate a destruction efficiency. Note that destruction efficiency becomes irrelevant when the levels start low in the gas being combusted.

Section 7.1.3 of Directive 060 dictates that surface temperatures must be below a level that would ignite a flammable substance, or that the hot surfaces are shielded to prevent contact with the hot surface. Since no field inspection of surface temperature was done, we cannot confirm that the BGR-36 meets this requirement.

Section 7.1.3 also indicates that exhaust gases must be below the auto-ignition temperature of a flammable substance present in the surrounding area. Peak exhaust temperatures at full load were in the range of 700°C. A detailed analysis would be needed, but this appears to be an acceptable exhaust temperature due to the height of the stack, even though it is above the theoretical autoignition temperature of stoichiometric air/methane mixtures.

In addition, Section 7.1.3 of the Directive provides the requirement that flame arrestors be used on intakes. This requirement would be dependent on the hazardous area classification. If the region around the intake is classified as Class 1, Div. 1 or 2, then the combustion chamber of the combustor should be such that it cannot ignite the mixtures near the intake. A good mitigation measure would be to use a flame arrestor on the intake, preferably one that is certified or at least designed to a standard.

No smoke production was observed at the time of testing, so the combustor appears to be compliant with the requirements of section 7.2. It should be noted that even though the gas composition does not have a propensity for smoking, the design of the combustor using a self-aspirating mixer and burner will result in significantly reduced propensity for smoking when compared to a utility flare.

Section 7.4 requires that the total radiant heat intensity at ground level not exceed 4.73 kilowatts per square meter. Heat intensity was not measured during this project.

Section 7.6 requires that there is “Proper gas-liquid separation facilities adequate to protect the pipeline system or gas combustion system must be used”. Since the installation is a low-pressure application using high-methane content gas, it does not use a knock-out drum. A strainer is used in the main gas train located near the combustor which would be considered adequate for the application. Directive 060 appears to call out the need for liquid separation equipment regardless of the pressure, so this may have to be called out as a variance in the application.

Section 7.7 calls out the need for backflash control which is addressing backflash down the stack of a flare. This is relevant to flares, but not combustors since the vertical section of the combustor above the burner is a flue and does not transport fuel like a flare stack does.

Section 7.8 dictates that enclosed combustors must be at least 10 m from wells, storage tanks, processing equipment, and other sources of ignitable vapours. From a plot plan it is clear that the two BGR 36 LP combustors are located at least 10 m from the storage tanks, and 10 meters from the well head. One combustor appears to be located closer than 10 meters to a propane tank which is considered a fuel tank and not under AER jurisdiction. The AER issued a waiver for the purpose of this study, as the 10m spacing requirement does not take effect until Jan 1, 2020.

Directive 60 calls out requirements for Sour and Acid gas combustion, but this is not applicable for the application being considered.

Section 8 addresses Vent Gas Limits, and Fugitive Emissions Management which are both beyond the scope of this safety review.

In summary, the installed system appears to be meet the safety performance requirements of Alberta's Directive 060 with the only uncertainty being surface temperatures.

Public Safety Division of Alberta Municipal Affairs

The Public Safety Division is responsible for regulating gas codes under Alberta's Safety Codes Act and the Gas Code Regulation (AR 111/2010) which enforces six CSA standards including CSA-B149.1 (covering downstream of a meter) and B149.3 covering field approval of fuel burning appliances and equipment. Note that CSA B149 has only become part of Alberta's safety regulations on January 1st of 2016 and compliance to the Legacy Equipment Management System has been an acceptable alternative. Note that B149.3 is the most relevant standard that could be enforced with respect to the combustor gas systems, but it appears that combustors and flares are exempt from B149.3 since the fuel used is considered a waste product rather than a fuel. This is an interpretation that is subject to change since the waste associated gas used is often natural gas grade fuel. From the perspective of a manufacturer, it would be advisable to consider the design codes as being B149.1, B149.2, and B149.3 as a best practice, even if compliance is not regulated. Uncertified equipment and appliances require field approval by either a certification body or an accredited inspection body.

Alberta Boiler Safety Association (ABSA)

ABSA is mentioned here since they are the regulatory authority for a great deal of the piping system supplying gas to the combustor. However, ABSA does not regulate the gas trains, burner, and burner management systems that are integral to the combustor which is the limit of the scope for this assessment.

ABSA is the regulatory authority in Alberta responsible to ensure that pressure equipment is designed, constructed, installed, operated, maintained and decommissioned in a manner that protects public safety. ABSA's Pressure Piping Construction Requirements AB-518 calls out the need for pressure piping compliance with ASME B31.1, B31.3, 31.5, and 31.9. ASME B31.3 has relevance to piping systems delivering gas to combustors, up to the point that the piping becomes part of the equipment. Registration of the piping system designed to ASME B31.3 would be registered with ABSA.

Note that Alberta Regulation 49/2006 Pressure Equipment Safety Regulation enforces CSA Standard B51-14 and CSA Standard Z662, Oil and gas pipeline systems, ASME Boiler and Pressure Vessel Code, and B31.1, B31.3, B31.5, and B31.9 and several other standards but this does not appear to be applicable to the integral gas trains of the combustor.

Note that even if B149.3 is not applicable to the combustor, it would be considered a best design practice.

British Columbia Authorities

BC Oil and Gas Commission

The BC Oil and Gas Commission is responsible for regulating oil and gas activities in BC including the Flaring and Venting Reduction Guideline and the Oil and Gas Activities Act.

Chapter 6 of the Reduction Guideline covers Performance Requirements. In terms of safety requirements, there is a requirement for adequate auto-ignition systems, flame-out detection with operation shut down and alarm, and backflash control.

Chapter 9 covers Incineration Evaluation and provides requirements for:

- 0.5 second residence time from top of the burner to end of the stack,
- Minimum exit temperature of 600°C, and
- A conversion efficiency of 99% or greater.

Generally, the guideline contains fewer specific safety control requirements than exists in Saskatchewan or Alberta. Instead, the requirement for safety is addressed through the requirement to have a professional engineer who is licensed or registered under the Engineers and Geoscientists Act and is responsible for the design or review of flare and incinerator systems.

The BC Oil and Gas Commission also requires that stamped engineering drawings exist for fuel gas trains designed to the CSA B149.3 code. No inspection, or certification that the gas train meets code is required as all the onus is placed on the owner and the professional engineer to ensure that the code has been followed.

Technical Safety BC

Technical Safety BC is the regulatory authority for much of the piping system supplying gas to the combustor. However, Technical BC does not regulate the gas trains, burner, and burner management systems that are integral to the combustor which is the limit of the scope for this assessment.

Technical Safety BC adopts ASME B31.1, B31.3, 31.5, 31.9, and 31.11. ASME B31.3 has relevance to piping systems delivering gas to combustors, up to the point that the piping becomes part of the equipment. Registration of the piping system designed to ASME B31.3 would be registered with Technical Safety BC.

5.4 Best Design Practice

In addition to regulatory requirements there are a host of engineering and design standards, along with industrial best practices that promote diligence and rigour as it relates to the safety of combustors. The most relevant standard related to the integral gas trains of the combustor is CSA B149.3. The following is a partial assessment of the combustor's gas systems in comparison to B149.3.

Pilot Train

Annex E of B149.3, or Section 18 of the 2020 code, provides requirements for safety flares and process flares. The requirements are essentially the same, but a process flare is allowed to use an approved manual ignition procedure. The combustor will be considered a safety flare; so the pilot generally needs to meet the requirements for safety flares as follows:

- The number of safety flare pilots required per outlet diameter or the flare. Note that since this is not a utility flare, but is a combustor with and aspirating mixer, the size of the outlet is not relevant to the number of pilots required.
- Pilot shall be equipped with flame detection which the BG36 has.
- Pilot shall have a reliable ignition which the BG36 has.
- The pilot train shall have a means to ensure the gas is clean and free from liquid. The BG36 has a strainer which is acceptable.
- The pilot system shall have critical measurements to allow for rapid diagnostics including fuel pressure, loss of flame, and level of liquids. The BG36 has a pressure indicator, loss of flame sensor, and a strainer for checking liquid levels to meet the requirements of this clause.

Main Gas Train Requirements as per CSA B149.3

The main gas train consists of a manual shut-off valve, and a positive shut-off pressure regulator (both are owner supplied), along with a pneumatically actuated proof-of-closure shut-off valve, a 2 inch (5 cm) strainer, and a BGR two-inch (5 cm) inline, flame arrestor. It also includes an owner supplied pressure relief valve set at 6 psig.

The above, meets most of the requirements of B149.3 with the exception of including a test firing valve as per section 5.5. Note that CSA B149.3 requires (as one alternative) a single burner appliance rated in excess of 200,000 Btuh and up to 5,000,000 Btuh be equipped with one safety shut-off valve equipped with a proof of closure switch that is connected into the start-up circuit of the combustion safety control. The BGR-36 meets this requirement.

Compliance with the requirements of section 5.6 for the main burner could not be assessed in this project, but it is safe to assume that the construction of the burner is in accordance with reasonable concepts, substantiality, and durability.

The capacity of the relief valve is equal to the maximum flow rate which would meet the requirements of section 5.7 subject to proper physical sizing to meet the specified flow rate.

The requirements set out in the following sections of 149.3 were not evaluated:

- Section 7 Applications
- Section 8 Ignition Systems

- Section 9 Safety Controls
- Section 10 Electrical Requirements

In summary, it appears that the gas trains have been designed with consideration of B149.3 since the majority of the requirements have been met. The only variance was the absence of a test firing valve located downstream of all safety shut-off valves and as close as practicable to the burner.

The following standards should also be considered at the engineering and design stage with the first reference being the most critical:

- ANSI/API Standard 537 Flare Details for General Refinery and Petrochemical Service (ISO 25457:2008)
- API -RP-521: Guide for Pressure-Relieving and Depressurizing Systems
- CSA Z662 Oil and Gas Pipeline Systems Code
- API -RP-505: Recommended Practice for Classification of Locations for Electrical Installations at Petroleum Facilities
- ANSI/API Specification 6A Specification for Wellhead and Christmas Tree Equipment
- AER Flare User Guide

Additional standards and guidelines that may be referenced at the engineering and design stages includes:

- ISO 23251 Pressure-relieving and depressurizing systems
- NFPA 497 Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapor and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas
- ISO 16852:2016 Flame Arrestors – Performance requirements, test methods and limits for use.
- IEC 61508 Functional Safety of electrical/electronic /programmable electronic safety-related systems; and UNI DEI EN ISO 80079-36 Explosive Atmospheres – Part 36: Non-electrical Equipment for Explosive Atmospheres – Basic Method and Requirements. Package providing methods on how to apply, design, deploy, and maintain automatic protection systems.

- IEC 61511-1 Functional Safety – Safety Instrumented systems for the process industry sector – Part 1 Framework, definitions, system, hardware and application programming requirements
- ATEX Directive requiring compliance with standard EM13463-1 for non-electrical equipment for potentially explosive atmospheres
- The Institute of Petroleum Model Code of Practice (Area Classification Code for Petroleum Installations, 2002), and
- The Institution of Gas Engineers Safety Recommendations SR25, (2001).
- ANSI Z21.21 Automatic Valves for Gas Appliances
- CSA 3.9-M94 Automatic Safety Shut-Off Valves

5.5 Operational management for safety and performance

Best practices extend beyond the engineering and construction stages. Ongoing operational management is critical to both safety, and emissions reductions. Although not directly applicable, ABSA's document AB-512 "Owner-User Pressure Equipment Integrity Management Requirements" provides a good basis for establishing integrity management systems for critical components.

Procedures should include:

- Visual inspection routine
- Thermal scan inspections evaluating external temperatures
- Bump testing and calibration of LELs
- Routine testing of automatic shut-down/isolation valves
- Gas train leak detection schedule
- Pressure relief valve integrity management
- Inspection and replacement schedule
- Management of change to control repairs or alteration

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

SRC has provided independent third-party field testing on the BGR 36 LP Combustor, dispersion modeling, a safety review, and validation services on this project. SRC completed field testing of the BGR 36LP Combustor at a western Canadian heavy oil site during the period of May 27-31, 2019. Nuisance testing determined no measurable light was emitted from the combustor, and the noise generated was less than that of the existing equipment on site.

Methane destruction efficiency was calculated at >99.99% for the 100% load condition and between 45% and 54% on average for the 10% load condition. Non-methane hydrocarbon (NMHC) destruction efficiency was calculated at 99.98% for the 100% load condition and 50.65% for the 10% load condition. The destruction efficiency during the 10% load tests were lower than the 95-99% presently required in most jurisdictions. The degree to which this is significant will be assessed by the provincial regulators based on their individual priorities. It is uncommon to operate at such a high turn-down ratio, as most combustors will be sized for the amount of flow anticipated at a site. However, inconsistent gas flow is typical of production operations.

Incomplete combustion at 10% load reduced the amount of methane and non-methane hydrocarbons emitted to the atmosphere. It generated some nitrogen oxides (NOx), though not as much as combustion at higher rates. It also generated small amounts of BTEX and significantly more carbon monoxide than during complete combustion at 100% rate.

Despite the incomplete combustion during the 10% load tests, the results of the dispersion modelling indicate compliance with standards, due to a combination of low starting concentrations and high dilution rates. The dispersion modelling found VOC, CO, NO_X, and particulate measurements were well below the standards for all test runs. At low concentrations of air contaminants, it is expected the combustor will achieve desired results.

From the safety review completed by SRC, the BGR-36LP appears to meet the safety performance requirements of all three jurisdictions, SK, AB, and BC. Best practices for operation and integrity management systems for critical components were recommended based on ABSA's document AB-512 "Owner-User Pressure Equipment Integrity Management Requirements".

6.2 Recommendations

Regulations in Alberta and BC require that combustors destroy >99% of the carbon and sulfur in the inlet gas. BGR combustors at or near capacity were able to achieve >99.99% destruction efficiency of methane during this testing. However, at 10% load they were not able to meet regulations. These results suggest that enclosed combustors can meet or exceed regulations when properly sized to the application. A range of additional test work is recommended, pending regulator and AUPRF priorities.

Some options for future testing include:

- Measure methane concentration at a variety of flowrates to find the 99% threshold

SRC recommends testing at a variety of flowrates to explore the boundary operating conditions for enclosed combustors with high-methane content natural gas such as that observed at the test site and identify at what turndown ratio they no longer meet emission regulations. In this case, SRC would monitor methane fuel conversion efficiency and temperature while conducting partial load testing to establish lower operating limits governed by destruction efficiency limits. This methodology is recommended to minimize cost and timeline. This could be as an extension to the present work or for future projects. It is also be possible to recreate the complete stack testing, as in this project, at series of flowrates between 10-100%.

- Perform stack testing with different gas compositions at a limited number of flowrates

Should the stakeholders wish to test combustor operation with alterantive inlet gas compistions, SRC recommends that the combustor be tested at a site with higher inlet concentrations of volatile organic compounds, and H_2S, to confirm destruction efficiencies. Destruction efficiencies cannot be assumed to be equivalent for all compounds. This testing could be completed at a live field site or at a fixed location with controlled inlet gases.

- Perform noise testing in a laboratory setting to mimic a quiet field site

Sound levels have been stated to be of interest to regulators. If a quiet field site without competing equipment noise cannot be found, the noise level testing could be repeated in a controlled laboratory environnment.

- Perform stack testing for a series of combustors of varying manufacture

Due to differences in burner design and operation, enclosed combustors from varying manufacturers may have differing test results. SRC recommends that the testing be repeated on several combustors from different manufacturers if the regulators are looking to develop or revise regulations for all enclosed combustors.

7. Comments from Black Gold Rush (BGR)

BGR was provided the opportunity to review the data and mass balance calculation and provide a comment. They were also provided the validation plan prior to testing and invited to provide feedback should they have any concerns regarding the testing conditions and combustor performance.

According to BGR, "Doing a test at 10% of the max rate may not reflect how a combustor should be operated. If the combustor is consistently seeing 10% of the max rate, the burner should be changed out to reflect that extremely low flow. I would expect a combustor to have a maximum of a 5 to 1, or 6 to 1 turndown, consistent with a flare."

"At the end of the day the 10% flow rate is not a representative test for the BGR 36 LP combustor as we would be recommending a BGR 18 or a BGR 24 combustor for this scenario. When we run such a low flow through a burner which is designed for a larger volume we do not get the mixing of air and fuel as we require in order to get the 99.9% destruction efficiency and this has been well represented in the findings."

7.1 Comparison to previous (non-SRC) testing

BGR provided data from previous combustor testing, which has been included here for comparison to the current test results. These tests were neither performed, nor validated by SRC, and are included for discussion only.

In the U.S., testing required for enclosed combustors is driven by New Source Performance Standards (NSPS) Subparts OOOO and OOOOa. These testing requirements are also referenced by National Emissions Standards for Hazardous Air Pollutants (NESHAP) Subparts HH and HHH. In these requirements, the U.S. EPA requires manufacturers who wish to certify 95% destruction efficiency of volatile organic compounds (VOCs) and benzene to test combustors using propylene as the inlet waste material at the following rates:

- 90-100% of the maximum rate, holding a steady maximum rate
- 70-100% of the maximum rate, cycling the rate up and down from 70% to 100% of the maximum rate
- 30 – 70% of the maximum rate, cycling the rate up and down from 30% to 70% of the maximum rate
- 0 – 30% of the maximum rate, cycling the rate up and down from the lowest stable rate to 30% of the maximum rate

In 2014 Metco Environmental conducted a source emission survey of the BGR 18 inch (45.7 cm) combustor. The destruction efficiencies calculated during that testing are included below:

Table 25 – Condition I (90-100%) Test Results (Metco, 2014)

Emission Parameter	Average	Allowable Parameter
Carbon Monoxide Emissions - ppmvd	4.29	<= 10
Total Hydrocarbon Emissions as Propane - ppmvw	0.34	<= 10
Total Hydrocarbon Destruction Efficiency - %	>99.99	>= 95

Table 26 – Condition IV (0-30%) Test Results (Metco, 2014)

Emission Parameter	Average	Allowable Parameter
Carbon Monoxide Emissions - ppmvd	2.60	<= 10
Total Hydrocarbon Emissions as Propane - ppmvw	0.23	<= 10
Total Hydrocarbon Destruction Efficiency - %	99.98	>= 95

Condition I corresponds with 90-100% of max throughput, and Condition IV was 0-30% of max flow. However, these results were obtained using propylene, which has different combustion characteristics than methane.

A source emission survey conducted by AGAT laboratories in 2015 measured destruction efficiencies of 99%, but there is no indication in the report of the combustor model that was tested, or of the composition and flowrate of the inlet gas.

In a 2018 source emission survey conducted by AGAT laboratories the BGR combustor had a destruction efficiency of >99%. According to the report, these tests were conducted on a combustor with a 36 inch (91.4 cm) inner diameter – the BGR 36LP combustor has a 30 inch (76.2 cm) inner diameter, although possibly the reporting of a 36 inch inner diamter was in error. The inlet gas was composed of propane for 3 of the 4 tests, and natural gas for the fourth. The inlet flowrate for the natural gas test was 99,975 ft^3/d (2830m^3/d), which is comparable to the 100% flow condition tested in this report. Results were comparable; >99.97% in the 2018 report vs >99.99% in this report. However, tests at lower flow rates cannot be compared due to the change in fuel type.

In summary, previous testing of natural gas at 100% load achieved similar results to those measured during this test. No previous test data is available for natural gas at lower throughput (i.e. 10% load).

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