Shell Chemical Appalachia LLC
300 Frankfort Road
Monaca, PA 15061

March 31, 2023

Mark Gorog P.E., Regional Manager Air Quality Program
Pennsylvania Department of Environmental Protection
Southwest Regional Office
400 Waterfront Drive
Pittsburgh, PA 15222

RE: Shell Chemical Appalachia LLC Response to Pennsylvania Department of Environmental Protection Correspondence Dated March 17, 2023

Dear Mark:

Shell Chemical Appalachia LLC ("Shell") has a petrochemical facility located in Beaver County, Pennsylvania (the "Facility") and is submitting this response to the Pennsylvania Department of Environmental Protection's ("PADEP") March 17, 2023 letter regarding Shell's Emission Exceedance Report and Mitigation Plan.

On December 14, 2022, Shell received a Notice of Violation ("NOV") for Plan Approval PA-04-00740C alleging 12-month rolling emission exceedances that were reported to PADEP by Shell. PADEP also sent a letter to Shell on December 14, 2022, requesting the submission of an Emission Exceedance Report and Mitigation Plan (the "Mitigation Plan") which Shell submitted as required on January 30, 2023. PADEP and Shell subsequently met on March 1, 2023, to discuss the Mitigation Plan and PADEP followed up with a letter on March 17, 2023, requesting additional technical information related to the Mitigation Plan. This letter provides Shell's responses to the additional technical requests.

1. Page 1 – Shell has indicated that the Department neglected to incorporate appropriate "short term or alternative limits" into the plan

approval as follows: "*One important consideration which requires emphasis by Shell, in connection with the NOV, is that the Plan Approval did not include short-term limits which would have been appropriate for the start-up process and that would have accounted for malfunctions that typically occur with the commissioning of a major chemical production facility. The emissions which occurred during the "shakedown period" were not explicitly included in the Facility's potential-to-emit (PTE), which provided the basis for the emission limitations set forth in the Plan Approval. This concern was discussed with PADEP during the permitting process although short term or alternative limits were not incorporated into the permit.*"

a. **Provide a complete list of "short term or alternative limits" that were proposed by Shell and which Shell believes should have been incorporated into the plan approval as federally enforceable limitations.**

SHELL RESPONSE:

Shell did not propose numeric short-term limits for the Facility's emission limitations but engaged in several discussions with PADEP regarding the appropriate treatment of startup, shut down and malfunction emissions during commissioning. Commissioning, as defined, involves the planned coordination and execution of the final stages of construction and the beginning of production; it is a period of time prior to normal production and typically involves troubleshooting and problem-solving activities as a facility proceeds from the construction phase to the operations phase. In retrospect, short term limits would have been well suited during commissioning to address malfunctions and related issues.

2. Page 5 – Regarding ethane cracking unit's (ECU) operational issues resulting from extremely cold ambient temperature operation: given that extreme cold ambient temperature events are not uncommon in southwestern Pennsylvania, detail the possible design changes, work practices, operational procedures, and maintenance changes that

a. **have been taken, or may be taken, to prevent reoccurrence of ECU operational issues during extreme cold ambient temperature events.**

SHELL RESPONSE:

On December 24, 2022, the ECU experienced a shut down due to an unexpected failure of a Boiler Feedwater ("BFW") pump supplying BFW to the ECU. The initiating failure was identified as a frozen suction pressure transmitter coinciding with a wet weather event followed by a sharp drop in temperature. Details of the malfunction event, emission mitigation and preventative actions taken are set forth in Shell's February 6, 2023 Malfunction Report to PADEP.

Short term mitigations involved installing weather protection caps on the suction pressure transmitters that were vulnerable to freezing. Temporary insulation and wind shields/shelters were installed for equipment that may be vulnerable to freezing. Maintenance craft installed additional electrical heat trace ("EHT") and permanent insulation where such needs were identified. Installation of EHT and insulation was completed in February and March 2023, respectively. With these mitigations in place, process equipment has successfully operated through additional cold periods this year including early February 2023.

Additional mitigation measures included installation of approximately fifty (50) instrument transmitters for display of equipment body temperatures in the Utilities, ECU, and PE areas to help prevent freezing of critical equipment in future extreme cold temperature events. Other measures include continuing improvements to the Abnormal Situation Management Guidance for freeze events, development of load shedding plans and updates to the Site Winterization procedure and EHT alarm and repair work process.

3. Page 6 – Regarding the HP Flare System: the EERMP states that the elevated flare has been operated for a total of 134 minutes and that smoking (visible emissions) from the flare tip of the elevated flare has occurred for 46 of those minutes, which is characterized by Shell as approximately 0.03% of the time. Based upon this data, the Department understands that smoking events occurred approximately 34.3% of the total elevated flare operating time. Shell reported the cause of elevated flare visible emissions to be inadequate delivery of steam to the flare tips. Provide an analysis of the root cause of the steam inadequacy issues and measures that are available to reduce the likelihood of a recurrence. The root cause analysis shall discuss the alternatives including possible design changes,

operational changes, and maintenance changes that have been taken, or may be taken, to ensure sufficient steam delivery to the flare tips and eliminate visible emissions during operation of the elevated flare while still maintaining the claimed destruction efficiency for VOC and HAP within the HP flare system.

SHELL RESPONSE:

The steam system at the Facility is a highly integrated and dynamic system that Shell is continuing to optimize as various process conditions are presented. Shell has evaluated the elevated flare visible emission events and has identified and incorporated improvements in timing, tuning and operation of the flare's steam system.

Steam optimization activities have been identified and, in many cases, already implemented to improve response time and overall steam balance at site and during flaring events. The main activities involve resolving design limitations in controller tuning (Steam Turbine Generator ("STG") extraction valve controller tuning and STG ramp rate). In addition to the case-by-case tuning adjustments described above, Shell is evaluating the steam system holistically to identify and make comprehensive system-wide adjustments to bolster efficiency. As part of the broader evaluation, Shell is in the process of modeling the system to further identify hardware and control adjustments that will improve steam availability at the flare and improve overall reliability of the steam system to mitigate scenarios which could result in smoking from the flare. Shell anticipates that this broader evaluation will be completed in the next 120 days and will provide an update to PADEP at that time.

4. Page 7 – Regarding the Operation and Maintenance Procedures: identify methods, techniques, written operator training programs, operational procedures, and work practices that are being employed, or may be employed comprehensively to facility operations to minimize emissions to the atmosphere.

SHELL RESPONSE:

The relevant employees are trained in environmental awareness as provided by the Environmental Department. Console operators have the authority to respond and are trained to take the appropriate corrective actions when responding to incidents (*i.e.,* equipment failure, process swing, etc.) to minimize environmental impact and secure plant equipment. Responses that minimize emissions include actions to stabilize operation of affected equipment, and, when necessary, slowdown of a production unit or shutdown of any affected equipment/unit.

Attachment 1 contains a list of operational procedures from the Flare Minimization Plan.

5. Page 7 – Regarding the Use of Off-Specification Sphere: confirm that this off-spec sphere included in the site inventory and was approved by the Department as part of the plan approval.

SHELL RESPONSE:

The Off-Specification “Ethylene” Sphere, Vessel Number: V-64220, was addressed in the original Plan Approval application dated February 2015 and the vessel and process were permitted as part of Source ID: 201, Ethylene Manufacturing Line.

Specific inventory of the pressure vessel (V-64220) can be found on Table 3-1, Summary of Project Tanks and Vessel, starting on page 3-19 of the application. Regulatory applicability analysis for this pressure vessel starts on page 4-30 and Table 4-4, Tanks not Subject to Control Under NSPS Subpart Kb, where the pressure vessel is listed as well as the result of regulatory applicability.

Use of the Off-Specification Sphere was detailed in Section 1.2.2, Unit-Specific Reductions of the final Flare Minimization Plan that was evaluated and approved in PADEP’s September 22, 2020, Technical Review Memorandum for Plan Approval 04-00740 C and subsequently issued on February 18, 2021.

6. Page 7 – Regarding Designed for Minimum Turndown: define the minimum turndown mode of operation as it applies to the process equipment, including the ECU furnaces, and

- **a. identify methods, techniques, operational procedures, and work practices that are being employed, or may be employed, in order to minimize emissions to the atmosphere.**

SHELL RESPONSE:

Minimum Turndown is not a separate operating mode with respect to the defined furnace operating modes under PA-04-00740C Section E. Group G01 Condition #008. Furnaces which are still operating and cracking ethane at reduced rates are still operating under the "Normal" definition of operation and applicable NOx and CO lb/MMBtu emission limits. Furnaces which are no longer cracking ethane will be operating in another permit-defined mode or under pilots only.

Minimum Turndown as it applies to the process equipment, including ECU, is defined by the minimum operating rates necessary for the ECU to maintain production of on-spec ethylene and stay within designed operating windows for all process equipment in the unit. Emissions to the atmosphere would be minimized through this method of operation due to the reduction of total process stream flow rates within ECU. If any flaring of continuous process streams from ECU is ongoing due to a process upset, then the amount being flared is reduced to the extent possible. Emissions to the atmosphere would also be minimized by the reduction of the number of furnaces in operation and firing fuel gas, and reduction of the fuel firing rate of remaining furnaces that would still be online and cracking ethane. This Minimum Turndown is evidenced at the front end of ECU by the reduction of total ethane feed into the furnaces and reduction of ethane feed rate into individual furnaces.

7. Page 8 – Regarding Continuous Monitoring: for any gas that is flared or emitted to the atmosphere, include representative gas chromatograph (GC) data for the specific inlet gas stream that is being flared, or emitted to the atmosphere if monitored, as part of any malfunction report, emission report, or EERMP report that is submitted to the Department. Supporting documentation of any representative GC data submitted shall include the sample frequency, the constituents analyzed, and a justification as to why the sample is representative for every gas flaring event or emission to the atmosphere.

SHELL RESPONSE:

Shell is required under Section C. Source Level Plan Approval Requirement Condition #018, to provide "an estimate of the quantity of gas flared during each event, as well as an estimate of the quantity of VOC that was emitted," and "the calculations used to determine the quantities." Shell also currently provides

PADEP information on all emissions by pollutant as well as by source and provides its emission protocol showing how the information is derived monthly. Shell is prepared to review the data and other process information used for the calculations with PADEP.

8. Page 8 – Regarding Turnaround Review: and as part of the evaluation of past turnround events, identify design changes, methods, techniques, operator training programs, operational procedures, and work practices that are being employed, or may be employed to minimize emissions to the atmosphere.

SHELL RESPONSE:

Shell continues its commissioning phase and has not had a turnaround event and, therefore, has not conducted a Turnaround Assurance Review ("TAR") Program. The purpose of the TAR is to provide a framework by which Shell can effectively plan, schedule, control, and execute turnaround events while reducing risks. One key element of ensuring operational performance during turnarounds is through continuous improvement by conducting post-turnaround performance review and embedding lessons learned, including environmental lessons learned.

9. Page 9 -Regarding Flare Operational Assurance and Improvements and Totally Enclosed Ground Flare (TEGF) stages 1 through 3 being temporarily taken out of service due to observed damage at the burner tips: Shell reported that the causes of TEGF operational issues and/or visible emissions have been low flow conditions, damage at the burner tips, coking at the burner tips, and refractory defect issues. Provide an analysis of the root cause of the operational issues for, and visible emissions from, each TEGF and measures that are available to reduce the likelihood of a recurrence. The root cause analysis shall discuss alternatives that include design changes, operational changes, and maintenance changes that have been taken, or may be taken, to ensure TEGF reliability and eliminate visible emissions from the flares while still maintaining the claimed destruction efficiency for VOC and HAP within the TEGF flare systems.

SHELL RESPONSE:

Shell's analysis revealed that the TEGF floors, as built, are 2-4 inches lower in places compared to specification, resulting in a floor to tip deviation. Although the floor to tip deviation impacts the fuel air mixing and has resulted in discoloration, tip fouling and failure, as well as refractory issues (which were previously referenced in prior reporting to PADEP), none of these conditions impact the destruction and removal efficiency ("DRE").

The current refractory issues do not impact the DRE; however, when the refractory fails, a hot spot develops, and Shell has mitigated it by using water to cool the wall plate. The hot spots have been evaluated and no structural integrity concerns have been identified. Even accounting for the floor to tip deviation, the flares can be safely and effectively operated.

Shell continues to evaluate other improvements to the TEGFs (including Computational Fluid Dynamic modeling) and plans to incorporate any other improvements at the time the floors are permanently repaired. The floor repairs will occur one flare at a time, so that at least one TEGF flare will be in service. Once the floors are permanently repaired to address the floor to tip deviation, the damaged and fouled tips will also be replaced. Until that time, operational changes have been utilized to minimize visible emissions, which include: Stages 1, 2 and 3 have been temporarily removed from service on each flare (in consultation with the flare manufacturer's confirmation that removing Stages 1-3 does not affect manufacturer's rated DRE), and Stage 4 is being base loaded at a reasonable minimum rate. Shell will continue to operate the TEGF flares with the operational adjustments described herein until the time that the permanent repairs can be undertaken.

10. Page 11 – Regarding the LAER analyses update to determine if additional work practices and controls (technology) are necessary to meet LAER: the focus on LAER by Shell is too narrow and a broader evaluation is required. In light of how the facility is now operating "as built," please evaluate the validity of the initial facility authorization and evaluate any new physical changes or changes in the method of operation which may minimize emissions to the atmosphere. Additionally, reexamine the technical appropriateness, accuracy and reliability of assumptions, emission factors, data, calculations, and any other information relied upon in Shell's plan approval application to ascertain projected emissions from the air contamination sources and air cleaning devices authorized by the Plan Approval; identify any invalid or incorrect assumptions; and identify possible measures which will minimize emissions to the atmosphere.

SHELL RESPONSE:

Shell's third-party contractor, RTP Environmental Associates, performed an updated NOx/VOC LAER analysis for the emissions units at the facility on February 27, 2023. The evaluation was conducted to determine whether the LAER analysis performed in support of the 2015 Plan Approval application was still representative for each emission unit given the possibility that other facilities of this type may have been permitted more recently, constructed, begun actual operation, and achieved more stringent limits since issuance of Shell's 2015 Plan Approval.

RTP summarized their findings as follows, "although there have been several similar projects permitted and that began commercial operation since the Shell Plan Approval was issued, the original limits and work practices still represent NOx and VOC LAER for all the emission units with a few noted differences." RTP explained the noted differences as:

1) NOx LAER – due to their shorter averaging times, ethane cracking furnace limits, which are permitted with the same 0.015 lb/MMBtu limit, noted a one-hour basis and are considered more stringent than Shell's 24-hour rolling average-based limit. Although, this more stringent limit did not apply during shakedown, defined at 180 days or after the stack test is complete;
2) NOx / VOC LAER – combined cycle unit limits noted excluding start-up/shutdown and turbine/control equipment commissioning;
3) VOC LAER – one project was identified having a more stringent DRE (99.99%) required for their LP Thermal Incinerator. RTP noted that additional research would be required to determine if this unit is of similar application and design characteristics as Shell's;
4) VOC LAER – one project was identified having a more stringent DRE (99.99%) required for their Spent Caustic Thermal Incinerator. RTP noted that additional research would be required to determine if this unit is of similar application and design characteristics as Shell's; and
5) VOC LAER – South Coast Air Quality Management District proposed Air Quality Management Plan (air quality control measure ID: FUG-01), is focused on using continuous leak detection measurement methods in lieu of Method 21. Further investigation would be required to determine whether the proposed measures could be used to improve Shell's current LDAR practices.

11. Page 13 – Regarding the Flare Guardian test report: Shell represents that diagnostic testing utilizing Zeeco's Flare Guardian technology was conducted at the facility in January 2023 to demonstrate destruction efficiency of one totally enclosed ground flare (TEGF Unit B) at the facility. Shell is now relying on these results to conclude that actual VOC emissions during commissioning are below permitted 12-month total VOC limits, which is contrary to Shell's previous emission reports. Flare Guardian is presented as an intriguing concept. It is, however, at present a novel, unproven technology. Based upon limited research and review it is the Department's understanding that the Flare Guardian technology calculates flare destruction efficiency based upon the relative concentration of CO2 vs hydrocarbons in the flame. It is premature for Shell to base emission estimates upon limited diagnostic testing utilizing this novel, unproven technology. Accordingly, provide the following:

- **i. a detailed engineering analysis of the operational principles of Flare Guardian technology;**
- **ii. the manufacturer's written tests report(s) for all Flare Guardian testing conducted at the Shell facility;**
- **iii. the methodology used at Shell to verify proper set-up, calibration, operation, maintenance of the equipment in accordance with the manufacturer's specifications and operational procedures;**
- **iv. the rationale and supporting assumptions for the assertion that the January 2023 limited diagnostic testing is representative of the actual continuous destruction efficiency of TEGF Unit B;**
- **v. the rationale and supporting assumptions for the assertion that the January 2023 limited diagnostic testing is representative of the actual continuous destruction efficiency of other untested flare emissions at the facility;**
- **vi. the rationale and supporting assumptions for the assertion that the January 2023 limited diagnostic testing is representative of the actual continuous destruction efficiency and may be applied retroactively to previous flaring events at the facility;**
- **vii. the rationale and supporting assumptions for the assertion that the January 2023 limited diagnostic testing is representative of the actual continuous destruction efficiency and may be applied to prospectively to future flaring events at the facility in the absence of a continuously operating Flare Guardian monitor.**

viii. **an analysis of previously submitted emission estimates, evaluating their credibility for particulate emission (PM) and carbon monoxide emissions during these flaring events and include all supporting assumptions. Regardless of the claimed destruction efficiency for VOC emissions, visible emissions from a flaring event are an indicator of incomplete destruction of carbon (particulate) in the exhaust plume. As such, PM and carbon monoxide emissions may be higher than Shell has asserted for these events.**

SHELL RESPONSE:

Please see Attachment 2 for responsive documents, including Flare Guardian diagnostic testing results dated January, 2023. Further, Flare Guardian is a technology that has been shown to be comparable with other flare emission protocols (*see, e.g.,* Technical Paper for Journal of the Air & Waste Management Association, dated October 2015, included in Attachment 2). Beyond the results provided, and to address PADEP's questions about the nature of the Flare Guardian testing, Shell proposes further testing in coordination with PADEP to demonstrate DRE under a range of flaring conditions. See also response to Question 12 below.

12. The Department identified inconsistencies in the HAP emissions reported in the November and December 2022 emission reports. Calendar year HAP emission totals reported in the December emissions report were significantly less than what was reported for the calendar year in the November report. The change in HAP emissions appear to result from a change in the n-hexane emissions factor used for combustion sources and changes to 1,3 butadiene and methanol from Equipment Components (Source ID 501).

a. **Support and provide rationale for all assumptions for all HAP emission estimates, including the most recent updates to hexane, 1,3 butadiene, and methanol emission factors.**

SHELL RESPONSE:

Relating to HAP Changes for PADEP Air Emissions Inventory, various refinements to the emission calculations were made, as detailed below.

1. DRE for TEGFs. As set forth to PADEP in the Technical Report submitted on January 30, 2023, Shell contracted with its flare vendor to perform DRE testing on TEGF B in January 2023 using flare camera technology (Flare Guardian). The results of the test yielded an average DRE of 99.55% for the TEGF. This was further supported by data captured during an actual flaring event for which results yielded an average DRE of 99.62%. These DRE testing results were used for both TEGFs because they are identically designed and operated control devices. The emissions inventory was updated using the 99.55% DRE for the TEGFs and first submitted the updated emission results in the February 21, 2023 Monthly Report to PADEP. Previously, Shell was using 99% DRE for compounds containing three or fewer carbon atoms and 98% for compounds with greater than three carbon atoms, based upon the Texas Commission on Environmental Quality Air Permits Division, "New Source Review (NSR) Emission Calculations" (APD-ID 6v1, Revised March 2021) supporting a DRE for the TEGFs of 98/99%, depending on the carbon atoms.

2. n-Hexane Emission Factor for Products of Combustion. The February 2020 Plan Approval Application used emission factors contained in USEPA's AP-42 Chapter 1.4, *Natural Gas Combustion,* 7/1998 to conservatively estimate hazardous air pollutants (HAPs), including n-hexane, from the following emission sources:

- Ethane Cracking Furnace (Main Burners and Pilot)
- High Pressure (HP) Flare System
    - Totally Enclosed Ground Flares (TEGFs) and Pilots
    - Elevated Flare and Pilot
- Low Pressure (LP) Flare System
    - Multipoint Ground Flare (MPGF) and Pilots
    - Continuous Vent Thermal Oxidizer (CVTO) and Pilots
    - Spent Caustic Thermal Oxidizer (SCTO) and Pilots

The same USEPA emission factors were used for the emissions inventory, as submitted periodically to PADEP. HAP emissions from the combustion of natural gas may be generated from pollutants contained in the fuel, as well as generated as products of combustion due to incomplete combustion or reactions in the combustion process. AP-42 provides emission factors for the following HAPs:

Pollutant	Emission Factor (lb/mmscf)	EPA AP-42 Emission Factor Quality Rating
n-Hexane	1.8	E – Significantly below average; poorest rating assigned
Formaldehyde	0.075	B – Above average; developed based on sound methodology
Benzene	0.0021	B – Above average; developed based on sound methodology
Dichlorobenzene	0.0012	E – Significantly below average, poorest rating assigned
Toluene	0.0034	C – Average; developed on reasonable number of facilities but lacking background information
Polycyclic Organic Matter (POM), including numerous pollutants such as naphthalene, benzo(a)pyrene, etc.	0.00000068	D/E – Below and significantly below average.
HAP Metals, including arsenic, chromium, lead, mercury, etc.	0.0000059	D – Below average

The emission factors in AP-42 are based on stack testing of utility natural-gas fired boilers and n-hexane emissions are extraordinarily and unrealistically high, comprising 33% of the total VOC factor of 5.5 lb/mmscf. Given that USEPA itself calls its rating for n-hexane "significantly below average; poorest rating assigned" and assigns it an "E" rating, more appropriate alternatives to the use of the AP-42 factor were investigated, identified and subsequently applied.

The California based Bay Area Air Quality Management District ("BAAQMD") guidelines for Toxic Air Contaminants ("TAC") Emission Factors (August 2020) states that for natural gas fired boilers, rather than using the AP-42 Chapter 1.4 emission factors for n-hexane, which "*seemed inordinately high (33% of the total VOC factor)*." BAAQMD chose to use the maximum n-hexane emission factor from the Ventura County Air Pollution Control District ("VCAPCD"), AB 2588 Combustion Emission Factors, May 17, 2001. A comparison of the AP-42

Chapter 1.4 n-hexane emission factor to the VCAPCD factors for external combustion sources and flares is shown below:

Pollutant	Emission Factor <10 MMBtu VCAPD (lb/mmscf)	Emission Factor 10-100 MMBtu VCAPD (lb/mmscf)	Emission Factor >100 MMBtu VCAPD (lb/mmscf)	Emission Factor Flares VCAPD (lb/mmscf)	Emission Factor AP-42 Section 1.4 (lb/mmscf)
n-Hexane	0.0063	0.0046	0.0013	0.029	1.8

In line with BAAQMD's determination that the n-hexane factor is inordinately high and thus unrealistic, a more realistic data should be used for n-hexane to better represent the HAP emissions. Shell continues to utilize AP-42 Chapter 1.4 for the other HAPs in accordance with the February 2020 Plan Approval Application. A sounder path forward for estimating n-hexane emissions is as follows:

- Ethane Cracking Furnaces (Main Burners): Shell intends to use the VCAPCD emission factor for n-hexane until site-specific stack test results are available. Note that the recycling and mixing of hydrogen with methane and natural gas in the furnace fuel is also expected to result in overall lower HAP emissions relative to natural gas combustion factors. Furnaces can fire purely natural gas, but the primary fuel is recycled hydrogen and methane and not identical to natural gas alone. Hydrogen has a higher adiabatic flame temperature than methane which would contribute to greater organic compound destruction.

Initial performance testing of all furnaces has been completed, and Shell intends to use the following:

- CVTO: the VCAPCD emission factor for n-hexane until site-specific stack test results are available.
- SCTO: the VCAPCD emission factor for n-hexane until more realistic factors/approaches become available.

- HP Flare System (TEGFs and Elevated Flare) and LP Flare System (MPGF): the VCAPCD emission factor for n-hexane until more realistic factors/approaches become available.
    - Stack testing of these flares for HAPs would not be feasible for the TEGFs (due to their large diameters) and would be extremely difficult for the Elevated Flare; however, the stack test results of the CVTO and Furnaces can be used to justify that the AP-42 emission factor is inordinately high and use of the VCAPCD emission factors is reasonable.
    - Note that use of the AP-42 Chapter 1.4 emission factors is not common practice for flares. Potential removal of the use of AP-42 Section 1.4 HAP emission factors for the flares is warranted, however, the more realistic VCAPCD emission factors for n-hexane for the flares is a reasonable approach to estimate emissions.
- Pilots for Furnaces and Flares: use the VCAPCD emission factor.

Shell implemented the change in the n-hexane factor in January 2023 and first reported the results of the change to PADEP in the January 21, 2023, Monthly Report.

3. HP Flare System – HAPs in Flared Waste Gas. HAPs that may be contained in the flared waste gas from the ECU have been added to the inventory. Previously, only HAPS that were generated as products of combustion were included in the inventory. The HAP emissions are based on vent gas mass to the flare, continuous inline analyzer results for C4 olefin (to potentially include 1,3 butadiene) and C6+ (to potentially include benzene, toluene, ethylbenzene and n-hexane), then speciating the C4 olefins and C6+ mass using C3+ composition from lab analysis. The DRE of 99.55% for the TEGFs and 99/98% for the elevated flare is then applied to determine emissions. The addition of these HAPs in flared waste gas were added to the emissions inventory in February 2023 and show an increase of HAP emissions from what was submitted in the February 21, 2023, Monthly Report to PADEP.

4. Equipment Components. Shell uses LeakDAS to manage the LDAR program. LeakDAS houses the various equipment components and monitoring data and calculates emissions based on the monitoring data. The program relies on the emissions approaches identified in USEPA's "Protocol for Equipment Leak Emission Estimates" November 1995. For unmonitored

components, the program utilizes the *Average Emission Factor Approach,* which yields unrealistically high mass emissions. Once the component is monitored, the program then switches to the *EPA Correlation Approach,* which is based on actual monitoring results and yields significantly lower, more realistic mass emissions. LeakDAS then retroactively corrects the emissions that were originally based on the *Average Emission Factor Approach* using the *EPA Correlation Approach.* This approach is considered valid because the first leak rate measured for a component will be the highest leak rate since the in-service date (i.e. the leak rate would not be higher in the past and leak would not be fixing itself). Therefore, due to the startup of the facility, many of the original calculations of actual emissions were inflated because the component was not yet monitored and relied on the higher emissions factor approach.

5. Wastewater Treatment Plant ("WWTP"). Shell worked with the WWTP Operations Group to review and refine the assumptions that are used in USEPA's Water9 Program. Furthermore, additional wastewater composition results became available and were utilized along with the process knowledge of the operators on application of the composition data. These refinements will show a decrease in VOC and HAP emissions as normal cases and upset cases were more clearly defined based on process conditions.

If you have any questions regarding this matter, please contact me at (724) 709-2467 or kimberly.kaal@shell.com.

Sincerely,

Kimberly J. Kaal

Kimberly Kaal
Environmental Manager

cc: James Miller
Melissa Jativa
Sherri Guerrieri

ATTACHMENT 1: OPERATIONAL PROCEDURES

Procedure Name	Procedure Number	Unit	Operating Conditions	Flares Utilized	Description
---	UGF-590-0001.1	UGF	---	HP	---
---	UGF-590-0001.2	UGF	---	HP	---
---	UGF-590-0001.3	UGF	---	HP	---
---	UGF-590-0001.4	UGF	---	HP	---
---	UGF-590-0001.5	UGF	---	HP	---
---	UGF-590-0001.6	UGF	---	HP	---
---	UGF-590-0001.7	UGF	---	HP	---
---	UGF-590	UGF	---	LP	---
Cracked Gas Compressor Startup with Cracked Gas	ECU-131-0001-SU	ECU/131	---	HP	---
Cracked Gas Compressor Shutdown (Long)	---	ECU/131	---	HP	---
Cracked Gas Compressor K-13101 Turbine KT-13102 Normal Shutdown Short/Compressor Actions	ECU-131-0001-SD	ECU/131	---	HP	---
Cracked Gas Compressor Restart after a trip	---	ECU/131	---	HP	---
Propane Refrigerant Compressor Inventory C3C with Propane	ECU-146-0005-SU	ECU/146	---	HP	---
Propane Refrigerant Compressor Startup	ECU-146-0006-SU	ECU/146	---	HP	---
Propane Refrigerant Compressor Shutdown (Long)	---	ECU/146	---	HP	---
Propane Compressor Restart after a Trip	ECU-146-0007-SU	ECU/146	---	HP	---
Propane Refrigerant Compressor - Secure Compressor after a Trip	ECU-146-0002-SD	ECU/146	---	HP	---
Ethylene Refrigerant Compressor Startup with Ethane	ECU-144-0001-ISU	ECU/144	---	HP	---
Ethylene Refrigerant Compressor Inventory with Ethylene	---	ECU/144	---	HP	---
Ethylene Refrigerant Compressor Startup with Ethylene	---	ECU/144	---	HP	---
Ethylene Refrigerant Compressor Shutdown (Long)	---	ECU/144	---	HP	---
Ethylene Compressor Restart after a Trip	---	ECU/144	---	HP	---
PSA Normal Startup	ECU-148-0001-SU	ECU/148	---	HP	---
Hydrogen Compressor K-14802A/B Startup	---	ECU/148	---	HP	---
Methanol Normal Startup	ECU-187-0001-SU	ECU/187	---	HP	---
Ethylene Atmospheric Storage Tank T-64210 Startup	ECU-642-0001-SU	ECU/642	---	LP	---
BOG Compressor Normal Startup	---	ECU/642	---	LP	---
Propane Compressor K-64241 Startup	ECU-642-0003-SU	ECU/642	---	LP	---
Methanol V-64230 System Startup	ECU-642-0002-SU	ECU/642	---	LP	---

Procedure Name	Procedure Number	Unit	Operating Conditions	Flares Utilized	Description
Ethylene Off Spec Vessel V-64220 Startup	ECU-642-0001-ISU	ECU/642	---	LP	---
Ethylene Storage Tank Pump P-64211A/B Return from Maintenance	---	ECU/642	---	LP	---
Ethylene Storage tank Pump P-64211A/B Prepare for Maintenance	---	ECU/642	---	LP	---
C2 Splitter C-14301 Startup	ECU-143-0001-SU	ECU/143	---	HP	---
C2 Splitter C-14301 Shutdown	---	ECU/143	---	HP	---
C2 Splitter C-14301 Restart after Loss of Feed	---	ECU/143	---	HP	---
Demethanizer Feed Train and Demethanizer Startup with Cracked Gas	ECU-140-0001-SU	ECU/140	---	HP	---
Demethanizer C-14101 and Feed System Restart after Loss of Feed	ECU-140-0002-SU	ECU/140	---	HP	---
C2 Hydrogenation Reactor R-13901 Off Spec for Acetylene	ECU-139-0001-NOP	ECU/139	---	HP	---
Deethanizer and AC Reactor Startup with Cracked Gas	ECU-138-0001-SU	ECU/138	---	HP	---
C3 Absorber/Deethanizer (C-13801/C-13802) Shutdown	---	ECU/138	---	HP	---
Cold Side Total Loss of Feed	ECU-GEN-0001-SD	ECU/GEN	---	HP	---
C3 Absorber/Deethanizer C-13801/C-13802 Restart after Loss of Feed	ECU-138-0005-SU	ECU/138	---	HP	---
Deethanizer Reboilers E-13811A/B Prepare for Maintenance	ECU-138-0003-NOP	ECU/138	---	HP	---
Deethanizer Reboilers E-13811A/B Return from Maintenance	ECU-138-0007-NOP	ECU/138	---	HP	---
Heavy Hydrocarbon Absorber and Dryers C-13601/D-13641A/B/C Startup	ECU-136-0001-SU	ECU/136	---	HP	---
Heavy Hydrocarbon Absorber and Dryers (C-13601/D-13641A/B/C) Shutdown	---	ECU/136	---	HP	---
Cracked Gas Dryers (D-13641A/B/C) Shutdown for Maintenance	ECU-136-0002-SD	ECU/136	---	HP	---
Cracked Gas Dryers (D-13641A/B/C) Return from Maintenance	---	ECU/136	---	HP	---
Water/HC Heater (E-13614) Bypass/Shutdown for Maintenance	ECU-136-0003-SD	ECU/136	---	HP	---
Water/HC Heater (E-13614) Return from Maintenance/Place on Line	---	ECU/136	---	HP	---
Ethane Feed Preheating Warm Branch Startup	ECU-125-0002-ISU	ECU/125	---	HP	---
Ethane Dryers D-12541A/B Shutdown for Maintenance	ECU-125-0002-SD	ECU/125	---	HP	---
Ethane Dryers D-12541A/B Return from Maintenance	---	ECU/125	---	HP	---
Quench System Startup	ECU-128-0001-SU	ECU/128	---	HP	---
Caustic Scrubber Startup	ECU-134-0001-SU	ECU/134	---	HP	---
Caustic Scrubber Shutdown (Long)	---	ECU/134	---	HP	---

Procedure Name	Procedure Number	Unit	Operating Conditions	Flares Utilized	Description
Spent Caustic Stripper C-13501 Startup	ECU-135-0001-SU	ECU/135	---	HP	---
Spent Caustic Stripper (C-13501) Shutdown (Long)	---	ECU/135	---	HP	---
Gasoline Redistillation System Startup	---	ECU/158	---	HP	---
Gasoline Redistillation System Shutdown (Long)	---	ECU/158	---	HP	---
Gasoline Redistillation Tower Reboiler E-15811A/B Preparation for Maintenance	ECU-158-0005-NOP	ECU/158	---	HP	---
Gasoline Redistillation Tower Reboiler E-15811A/B Return from Maintenance	ECU-158-0004-NOP	ECU/158	---	HP	---
Wash Oil System Startup	ECU-188-0001-SU	ECU/188	---	HP	---
Wash Oil System Shutdown (Long)	---	ECU/188	---	HP	---
Methanol Vaporizer E-19012 Startup	---	ECU/190	---	HP	---
Fuel Gas System Initial Startup	ECU-184-0002-ISU	ECU/184	---	HP	---
Regeneration System Startup Tail Gas	ECU-189-0001-ISU	ECU/189	---	HP	---
Loss of Cooling water	ECU-192-0001-ESD	ECU/192	---	HP/LP	---
Loss of Ethane Feed	---	ECU/125	---	HP	---
Trip of all Furnaces	---	ECU/101-107	---	HP	---
Loss of Boiler Feed Water	---	ECU/183	---	HP	---
Loss of Power	ECU-100-0001-ESD	ECU/100	---	HP	---
Loss of Instrument Air	---	ECU/185	---	HP	---
Quench System Shutdown (Long)	---	ECU/128	---	HP	---
Ethane Cleanup	ECU-GEN-0005-ISU	ECU/125	---	HP	---
Ethane Feed Preheating Cold Branch Startup	ECU-125-0001-ISU	ECU/125	---	HP	---
C2 Hydrogenation Methanol System Startup/Inventory	ECU-139-0001-SU	ECU/139	---	HP	---
Caustic Slop Drum V-19732 and System Startup	ECU-197-0001-ISU	ECU/197	---	HP	---
Propane Refrigerant Compressor Shutdown Short/Process Actions	ECU-146-0003-SD	ECU/146	---	HP	---
Loss of Nitrogen	ECU-186-0001-ESD	ECU/186	---	HP/LP	---
Natural Gas Initial Startup	ECU-184-0001-ISU	ECU/184	---	HP	---
Ethane Feed Preheating Shutdown	---	ECU/125	---	HP	---
Ethane Feed Preheating Restart after Loss of Feed	---	ECU/125	---	HP	---
Ethane Superheater II E-12512 Bypassing/Shutdown	ECU-125-0003-SD	ECU/125	---	HP	---
Ethane Superheater II E-12512 Startup	ECU-125-0003-SU	ECU/125	---	HP	---
Shut down of process steam generator E-13011x	ECU-130-0002-SD	ECU/130	---	HP	---
Cracked Gas Compressor Secure after a Trip	---	ECU/131	---	HP	---

Procedure Name	Procedure Number	Unit	Operating Conditions	Flares Utilized	Description
Deethanizer Bottoms Pumps (P-13872A/B) Startup/Swap	ECU-138-0003-SU	ECU/138	---	HP	---
Deethanizer Reflux Pumps (P-13871A/B) Startup/Swap)	ECU-138-0004-SU	ECU/138	---	HP	---
Demethanizer C-14101 and Feed System Shutdown	---	ECU/140	---	HP	---
LP Tail gas Expander/Booster KT-14103/K-14105 Startup	ECU-141-0001-SU	ECU/141	---	HP	---
HP Tail gas Expander/Booster KT-14102/K-14104 Startup	ECU-141-0002-SU	ECU/141	---	HP	---
LP Tail gas Expander/Booster KT-14103/K-14105 Shutdown	ECU-141-0001-SD	ECU/141	---	HP	---
HP Tail gas Expander/Booster KT-14102/K-14104 Shutdown	ECU-141-0002-SD	ECU/141	---	HP	---
Ethylene Refrigerant Compressor Shutdown Short/Process Actions	ECU-144-0002-SD	ECU/144	---	HP	---
Ethylene Refrigerant Compressor - Secure after a Trip	---	ECU/144	---	HP	---
PSA Normal Shutdown	---	ECU/148	---	HP	---
Hydrogen Compressor (K-14802 A/B) Shutdown Procedure	---	ECU/148	---	HP	---
Fuel Gas System Shutdown	---	ECU/184	---	HP	---
Methanol Normal Shutdown	ECU-187-0001-SD	ECU/187	---	HP	---
DMDS System Startup	ECU-188-0003-SU	ECU/188	---	HP	---
Ammonia Water System Startup	ECU-188-0005-SU	ECU/188	---	HP	---
Regeneration System Line Up for Ethane - Ethane Cleanup	ECU-189-0003-ISU	ECU/189	---	HP	---
Regeneration System Line Up for Tail Gas - Normal Lineup	ECU-189-0001-NOP	ECU/189	---	HP	---
Methanol Vaporizer E-19012 Shutdown	---	ECU/190	---	HP	---
BOG Compressor Normal Shutdown	---	ECU/642	---	LP	---
Propane Compressor K-64241 Shutdown	---	ECU/642	---	LP	---
Propane Compressor - Secure after a Trip	---	ECU/642	---	LP	---
Ethylene storage tank Pump (P-64211A/B) Startup procedure	---	ECU/642	---	LP	---
---	UGF-584-0001	UGF	---	HP/LP	---
---	UGF-590UZ410	UGF	---	LP	---
---	UGF-590-590UZ	UGF	---	LP	---
---	UGF-590-0001	UGF	---	LP	---
---	UGF-590-0002	UGF	---	LP	---

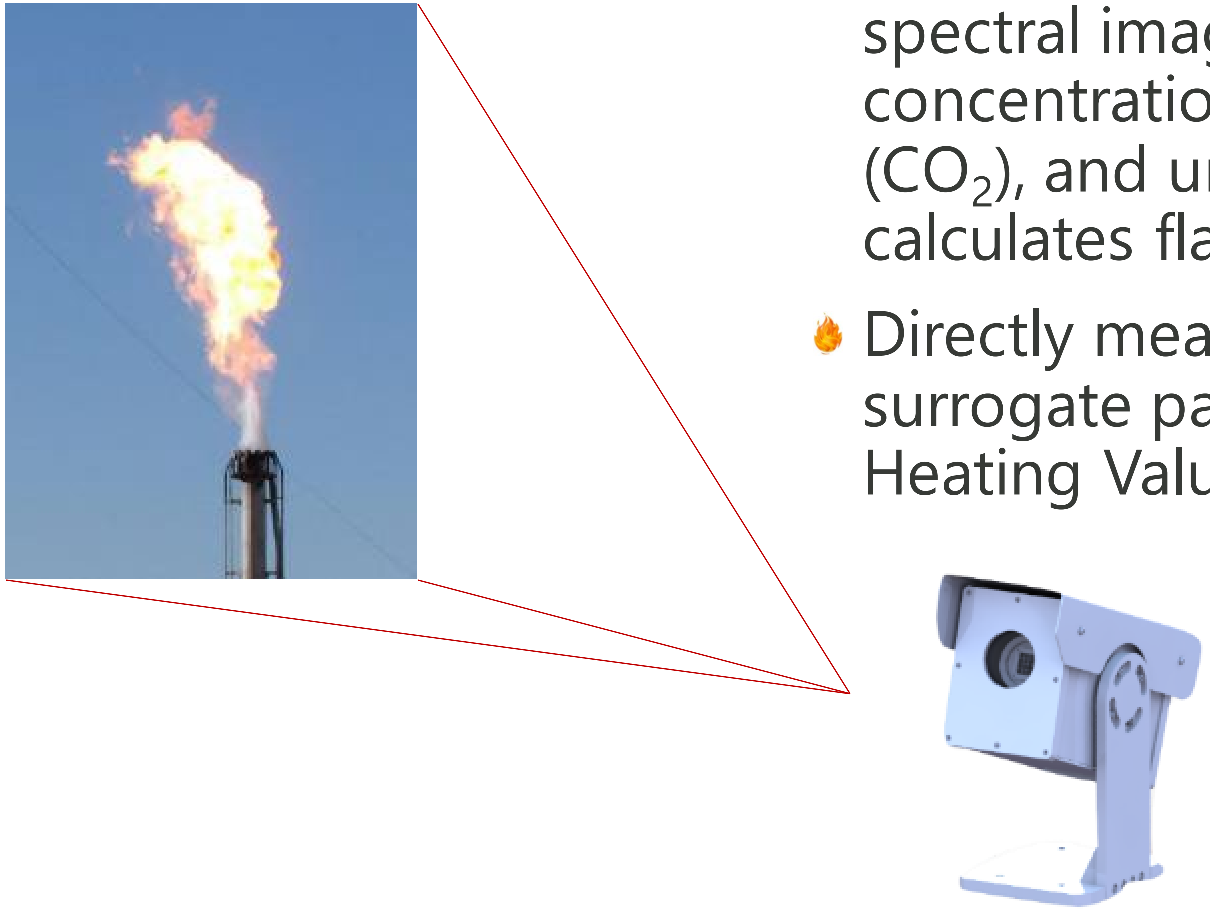
ATTACHMENT 2

PROVIDENCE PHOTONICS

FlareGuardian Measurement of Enclosed Ground Flare

Shell Monaca
January 2023

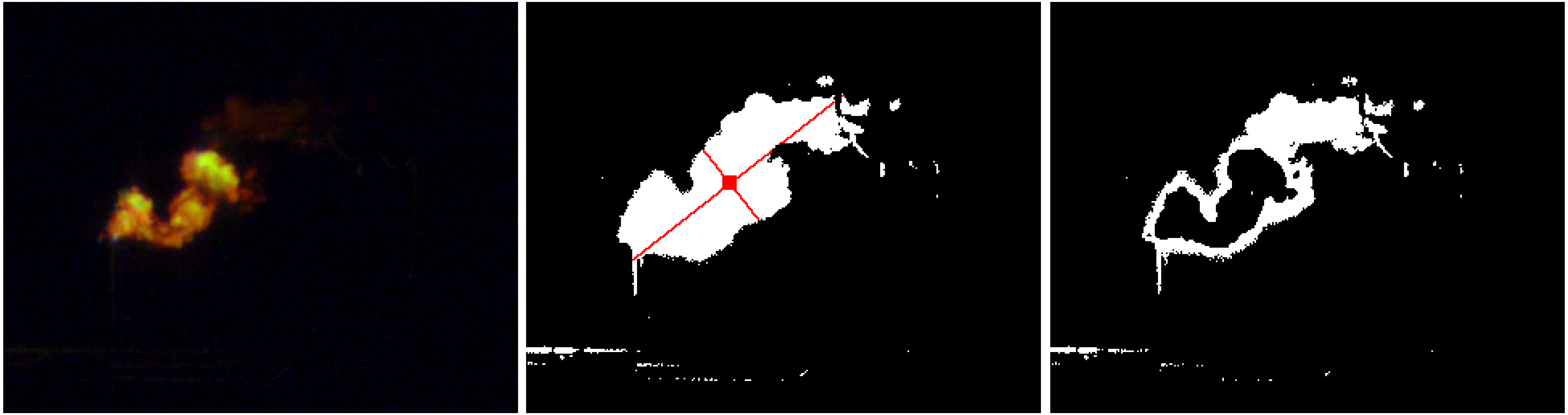
FlareGuardian utilizes the VISR Method



- Video Imaging Spectral Radiometer (VISR) is a multi-spectral imager. It directly measures relative concentrations of combustion product, carbon dioxide (CO_2), and unburned hydrocarbon (HC) in the flame, and calculates flare combustion efficiency (CE) in real time
- Directly measuring CE eliminates the uncertainty of using surrogate parameters such as Combustion Zone Net Heating Value (NHVcz) and flare tip velocity

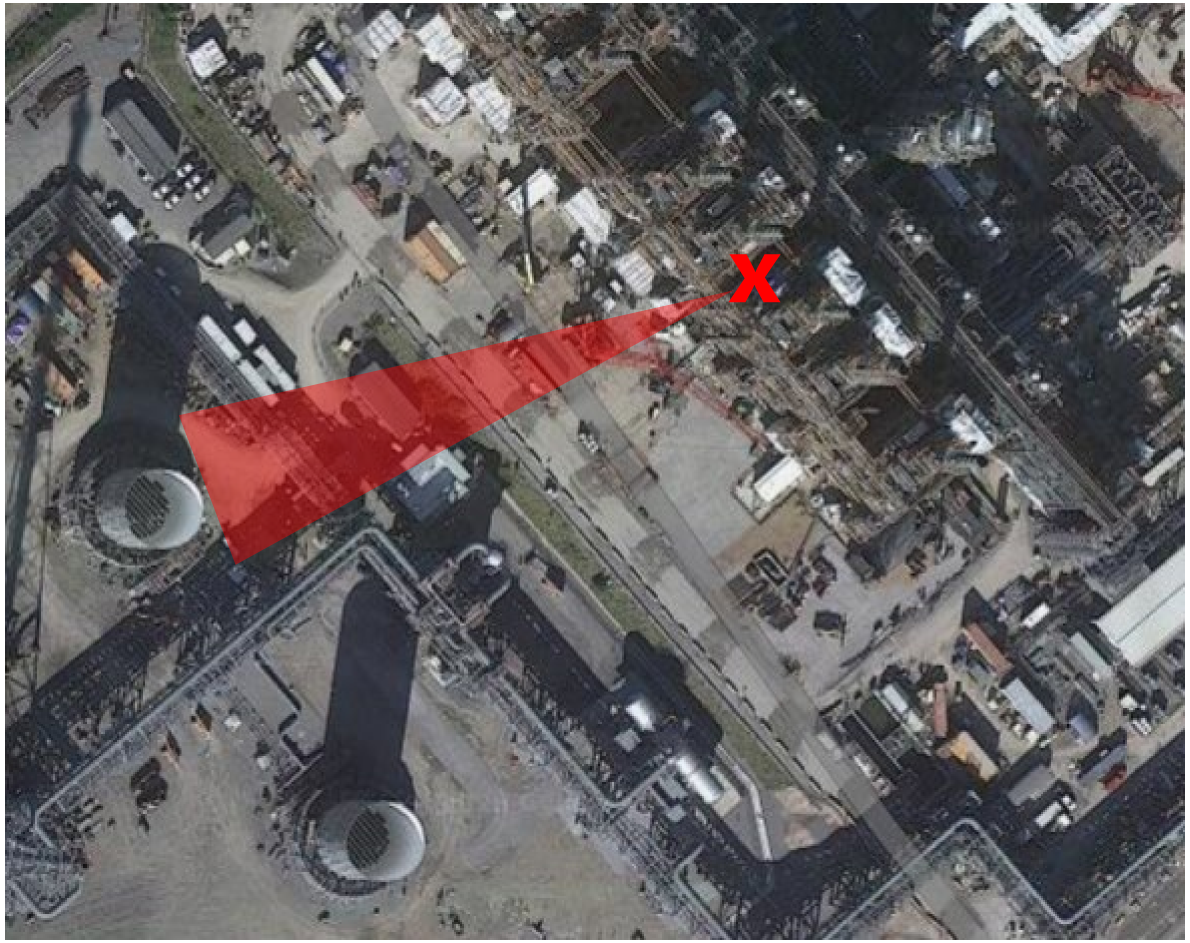
FlareGuardian utilizes the VISR Method

- ***Flare CE*** is determined by measuring relative concentrations of CO_2 and HC on the combustion envelope where combustion has ceased
  - Spatially averaged across all pixels on the combustion envelope
  - Temporally averaged across all frames captured in 1 second (typically about 30)
  - Data reduction is automatic with no latency



Measurement performed at Monaca on 1/13/2023

- FlareGuardian was installed near furnace 5
- Distance of 130 meters from flare
- Height about the same as top of flare enclosure
- Post combustion gases must be above 400°C for valid measurement



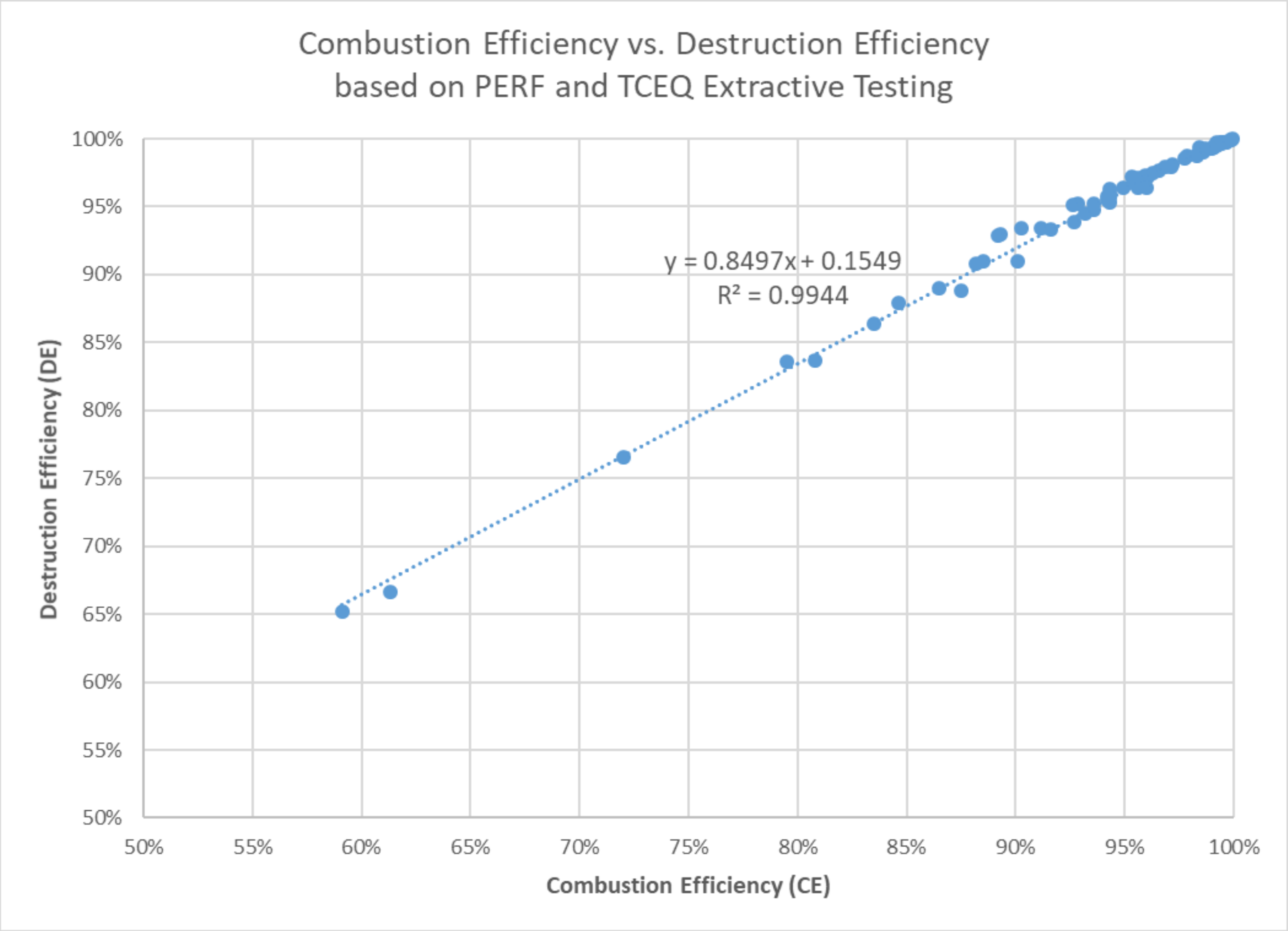
Summary Results

- Two flare tests and one flaring event were measured
- First flare test has sporadic data
- Second flare test and flaring event have continuous 1-second data

Date	Start Time (Local)	End Time (Local)	Process Condition	CE Avg (%)	DRE Avg (%)	SI Avg	FF Avg (m2)	FH Avg (MMBTU/HR)
1/13/2023	1:45 PM	1:53 PM	Flare test - Methane/Hydrogen	97.39	98.24	0.7	187	0.31
1/19/2023	11:25 AM	12:23 PM	Flare test - Ethane/Methane	98.93	99.55	0.7	195	0.49
1/20/2023	8:03 AM	9:02 AM	Flaring event	99.01	99.62	1.2	150	0.21

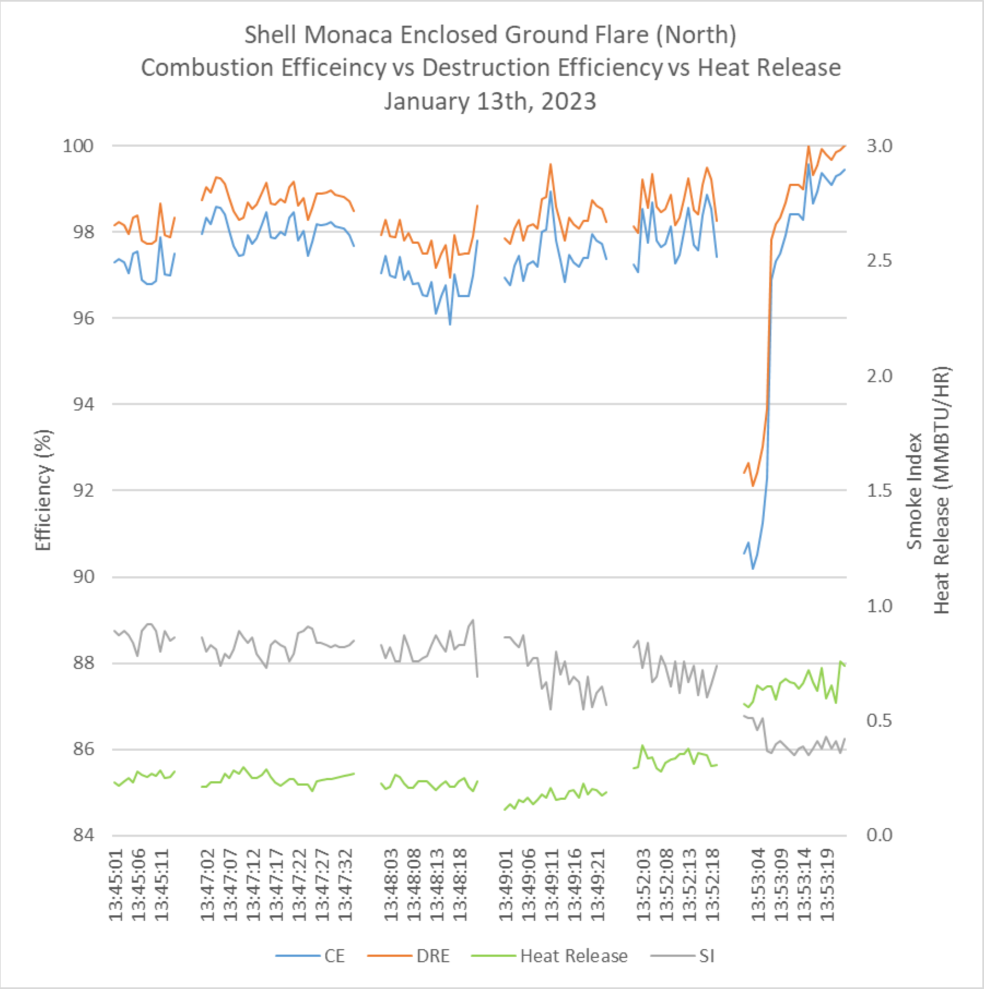
Combustion Efficiency vs Destruction Efficiency

- FlareGuardian measures combustion efficiency (CE)
- Extractive testing during 2010 TCEQ test and 2018 PERF test provides correlation between CE and destruction efficiency (DE)
- Used this correlations, we can convert CE to DRE



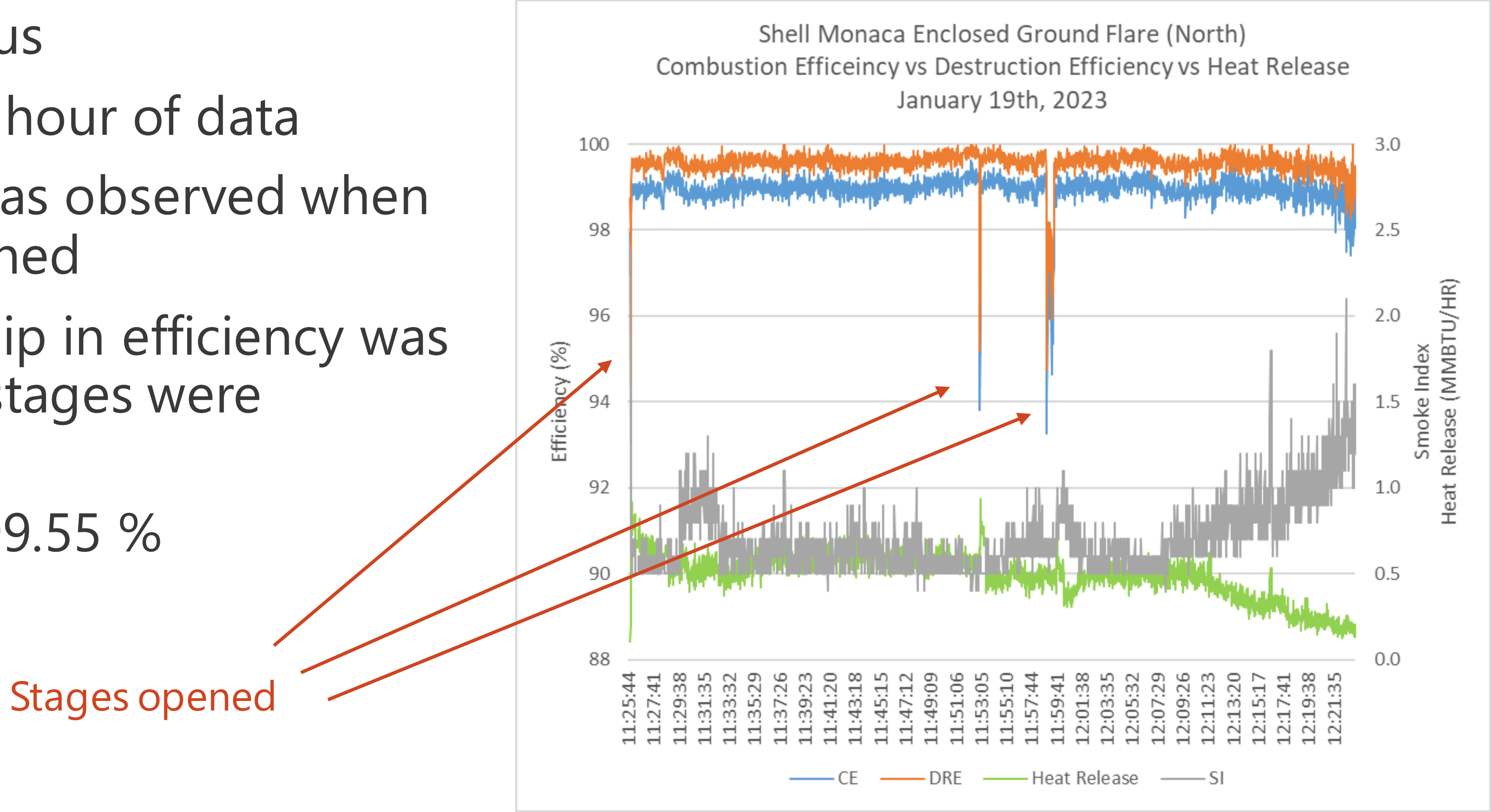
Methane/Hydrogen Flare Test – Jan. 13th, 2023

- Data is not continuous
- Short radiometric recordings are post processed to provide semi-continuous result
- Collected 2 minutes of the 15 minute flare test
- Brownish haze was observed throughout the test
- Average DRE was 98.24%



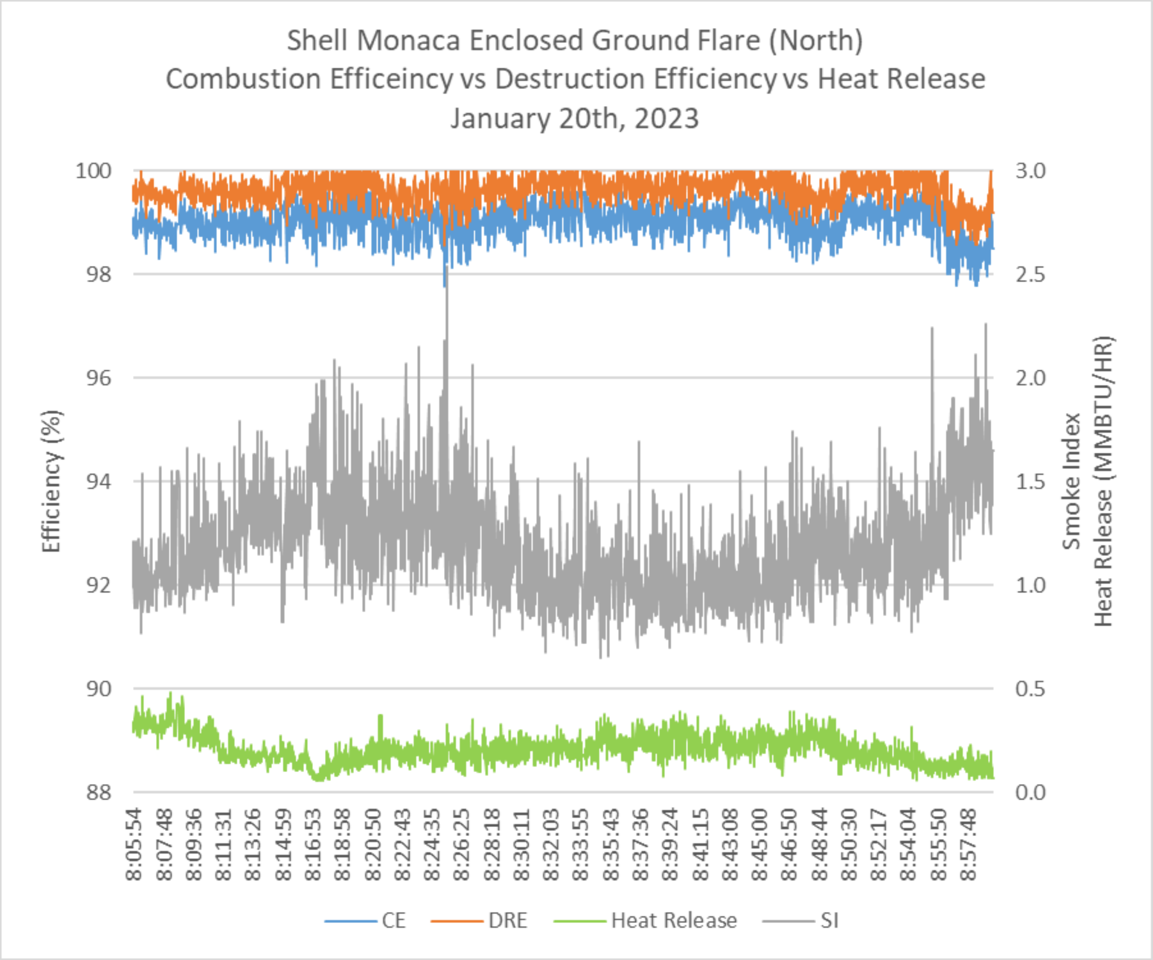
Ethane/Methane Flare Test – Jan. 19th, 2023

- Data is continuous
- Approximately 1 hour of data
- Brownish haze was observed when stages were opened
- Corresponding dip in efficiency was observed when stages were opened
- Average DRE is 99.55 %



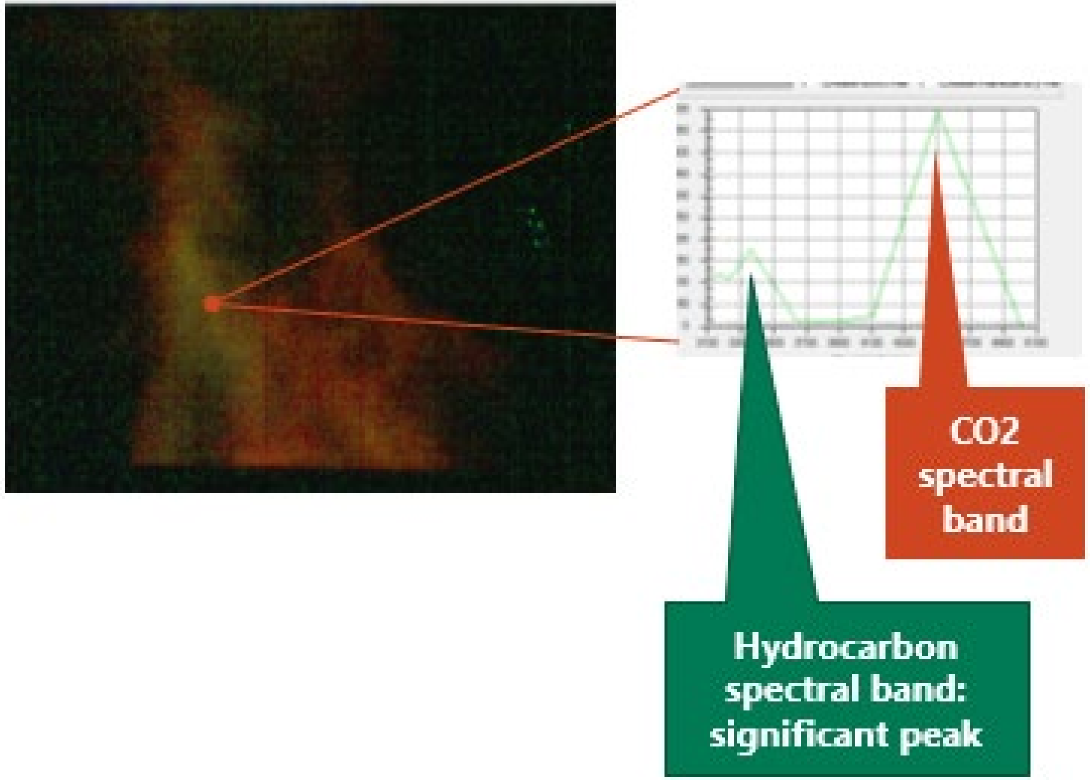
Flaring Event – Jan. 20th, 2023

- Flaring event occurred on morning of January 20th, 2023
- Approximately 1 hour of data
- Data is continuous 1-second
- Average DRE 99.62 %

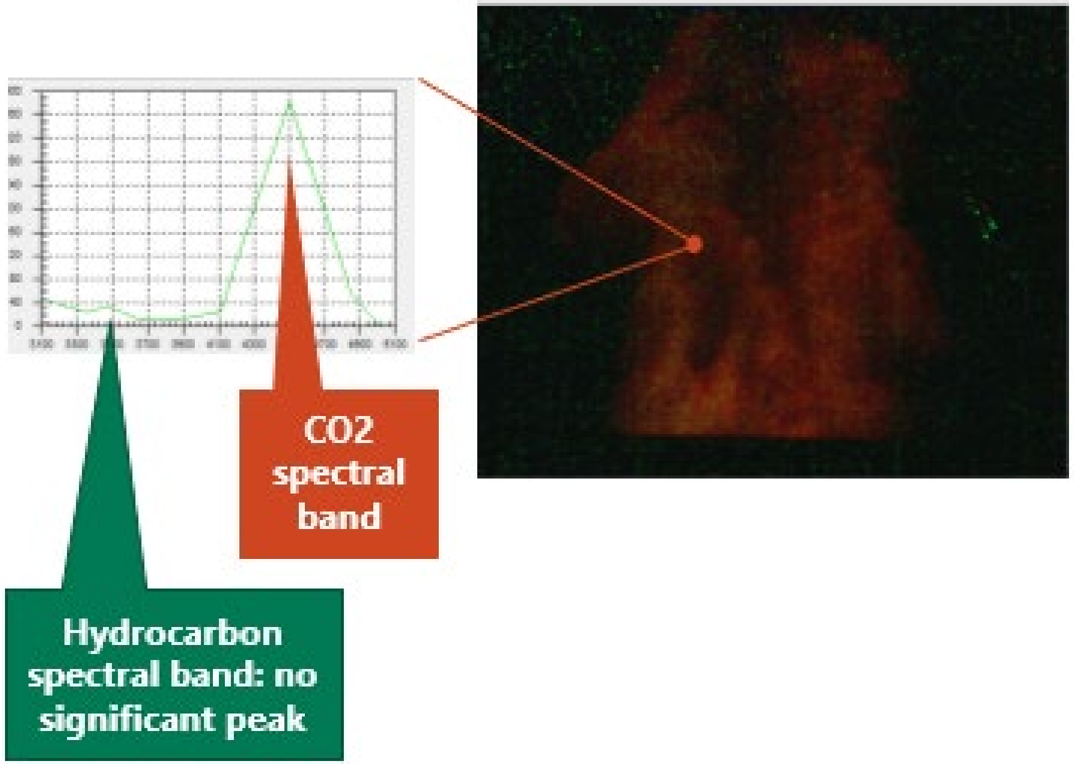


Compare Monaca enclosed flare 1/13/2023 Test vs. 1/19/2023 Test

- Monaca enclosed flare, 1/13/2023 1:53 PM



- Monaca enclosed flare, 1/19/2023 11:48 AM



Thank You!

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REDEFINING [COMBUSTION]

Date: March 16, 2023
RE: FlareGuardian Combustion Measurement

To the team at Shell,

The VISR flare monitor was recently deployed to ascertain the Combustion performance of the enclosed ground flares at Shell Monaca. This technology is a unique remote optical monitoring device investigating the infrared spectral radiance of combustion products and remnant unburnt hydrocarbons in the combustion plume to determine the combustion performance of flares. The VISR device directly measures combustion efficiency in the plume of the flame.

The accuracy and efficacy of this technique has been demonstrated through a large body of testing consisting of hundreds of unique test points over the last decade. In various testing conditions, the VISR method has been validated against the EPA-founded extractive method, which was used in both the 1983 CMA and 2010 TCEQ flare studies. Validation testing has been conducted internally by Zeeco and its technology partners, by third-party industry consortiums, as well as the US EPA. The body of testing has demonstrated statistical agreement (using a 95% confidence interval) between the VISR and extractive sampling method. The extractive sampling method is measuring Destruction or Removal Efficiency (DRE), which is the EPA evaluation basis. The large body of prior testing has established very clear and defined relationships between Combustion Efficiency and DRE, full allowing the VISR technology to be a valid surrogate for determination of the DRE of combustion equipment of many types.

In the recent testing at the Monaca, Pennsylvania facility, the combustion products measured out of the flare were of sufficient temperature and radiance to render useful and accurate the VISR combustion calculations and methodology. The vantage point, distance to the flare, flare gas composition, and environmental conditions were all within previously established VISR method parameters. The combination of the performance history of this device, the parameters which were tested at Monaca, and the resulting spectrometry measurements gives Zeeco confidence the resulting combustion calculations are true and accurate.

Best regards,

Scot K. Smith, PE
Director, Flare Systems Products
Zeeco Inc.

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Validation of a new method for measuring and continuously monitoring the efficiency of industrial flares

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TECHNICAL PAPER

Validation of a new method for measuring and continuously monitoring the efficiency of industrial flares

Yousheng Zeng[a], Jon Morris[a], and Mark Dombrowski[b]

[a]Providence Photonics, LLC, Baton Rouge, Louisiana, USA; [b]Surface Optics Corporation, San Diego, California, USA

ABSTRACT
A new method has been developed for a direct and remote measurement of industrial flare combustion efficiency (CE). The method is based on a unique hyper-spectral or multi-spectral Infrared (IR) imager which provides a high frame rate, high spectral selectivity and high spatial resolution. The method can be deployed for short-term flare studies or for permanent installation providing real-time continuous flare CE monitoring.

In addition to the measurement of CE, the method also provides a measurement for level of smoke in the flare flame regardless of day or night. The measurements of both CE and smoke level provide the flare operator with a real-time tool to achieve "incipient smoke point" and optimize flare performance.

The feasibility of this method was first demonstrated in a bench scale test. The method was recently tested on full scale flares along with extractive sampling methods to validate the method. The full scale test included three types of flares – steam assisted, air assisted, and pressure assisted. Thirty-nine test runs were performed covering a CE range of approximately 60-100%. The results from the new method showed a strong agreement with the extractive methods (r^2=0.9856 and average difference in CE measurement=0.5%).

Implications: Because industrial flares are operated in the open atmosphere, direct measurement of flare combustion efficiency (CE) has been a long-standing technological challenge. Currently flare operators do not have feedback in terms of flare CE and smoke level, and it is extremely difficult for them to optimize flare performance and reduce emissions. The new method reported in this paper could provide flare operators with real-time data for CE and smoke level so that flare operations can be optimized. In light of EPA's focus on flare emissions and its new rules to reduce emissions from flares, this policy-relevant development in flare CE monitoring is brought to the attention of both the regulating and regulated communities.

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Introduction

Industrial flares are widely used primarily as safety devices in chemical process industries (e.g., petroleum refineries, chemical plants, etc.) and oil and gas fields. Waste process gases, particularly gases released due to process upset or emergency, are vented to flares to be safely combusted over the flare tips, avoiding industrial accidents and reducing air pollution. Although comprehensive emission inventories of flares and their associated emissions are not readily available, some anecdotal information is available to provide a sense of scale for the emission of volatile organic compounds (VOC) and greenhouse gases (GHG) from flares due to imperfect combustion. In the Fact Sheet for the Proposed Petroleum Refinery Sector Risk and Technology Review and New Source Performance Standards, the U.S. Environmental Protection Agency (EPA) states that the proposed new standards for flares will reduce VOC emissions from flares in this sector by 33,000 tons per year (EPA, 2014). In the same Fact Sheet, the total VOC emission reductions for all affected sources in this proposed rule are projected to be 52,000 tons per year. The flare portion accounts for 63% of the total reductions. There are more flares in chemical and petrochemical sectors. In 2007, the Texas Commission on Environmental Quality (TCEQ) conducted a special emission inventory of Highly Reactive Volatile Organic Compounds (HRVOC) in Harris County for the period from February 1, 2006 to January 31, 2007. HRVOC is a subset of VOC that represents the most potent ozone precursors. Results of this special emission inventory showed that the HRVOC emissions from flares were 1,469.5 tons out of a total HRVOC emission inventory of 2,433.4 tons in

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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/uawm.

Harris County, Texas; that is, flare emissions accounted for 60.8% of total HRVOC emissions (ENVIRON, 2008).

Emissions from flares also represent a significant contribution to GHG emissions. According to a report by GE Energy, approximately 150 billion cubic meters of natural gas are flared in the world each year, roughly the same as the annual household consumption for the entire United States. The flaring of 150 billion cubic meters of natural gas produces 400 million tons per year of carbon dioxide (CO_2), equivalent to annual emissions from 77 million cars (34% of the U.S. fleet) (Farina, 2011). The GHG impact for 1 lb of methane emissions is equivalent to 21 lb of CO_2 emissions. Since the amount of methane emission is a function of flare combustion efficiency (CE), estimation of CE for these flares has a large impact on these GHG emission estimates.

Current practice is to assume that flares control 98% of the hydrocarbons (largely VOC) fed to flares, provided that some surrogate parameters (e.g., heat content of the vent gases and exit velocity of gases at the flare tip) are within established ranges. Field studies and modeling analyses conducted in Texas (e.g., Texas Air Quality Study of 2000, and Texas Air Quality Study II in 2006) have demonstrated that these assumptions regarding flare CE may be inaccurate, and total flare emissions in this airshed could be significantly underestimated. The uncertainty introduced into emission inventories due to flare CE assumptions could be significant enough to alter the outcome of large-scale air quality management decision making. Despite its importance, determining flare CE (and therefore emission rates) remains a technological challenge. Unlike other emission sources, the combustion for an industrial flare occurs in open air, leaving no practical method for capturing postcombustion gases. As a result, it is not possible to routinely apply traditional methods (such as extractive sampling) for analysis of the postcombustion gases or determination of control efficiency. Flare operations typically involve a drastic "turn-down ratio," that is, changes in the volume of gases sent to flares in a very short period of time when an upset or emergency release occurs. The sharp changes in throughput can significantly disrupt the proper steam or air to fuel ratio and therefore alter flare efficiency. Due to these factors, determination of flare CE and destruction and removal efficiency (DRE) is extremely difficult. In 2009, TCEQ contracted with the University of Texas Austin (UT) to conduct a comprehensive study on flare CE and DRE (Allen and Torres, 2011). Results from this study (hereafter referred to the TECQ 2010 flare study) are very valuable in characterizing flare CE and DRE under the test conditions, and they have had a lasting impact on flare operations and flare management programs. One of the findings demonstrated that even if a flare is operated in accordance with the federal regulation 40 CFR §60.18, it still may not achieve assumed 98% CE. A reduction in CE from 98% to 90% represents a fivefold increase in flare emissions.

While the TCEQ 2010 flare study was a major undertaking, it demonstrated that realistic operating conditions can result in a large variability in flare CE. In many cases flare operators do have the means to optimize flare operating conditions (e.g., changing the steam to vent gas ratio, adding supplemental fuel, etc.). However, their ability to optimize the flare to achieve a high flare CE is severely limited by the lack of a real-time measurement of flare CE. Currently there is no technology that can provide real-time autonomous and direct measurement of flare CE.

A new flare CE measurement and monitoring method has been proposed by Zeng et al. (2012). This method utilizes a multispectral infrared (IR) imager to simultaneously measure the relative concentrations of combustion products, carbon dioxide (CO_2), and unburned hydrocarbon (HC) at a pixel level. The relative concentrations of CO_2 and HC levels measured at each pixel are used to calculate the CE for that pixel, which represents a path-averaged CE for a column of combustion gases represented by the pixel. A CE value representing the flare at any given moment is calculated by averaging CE values of the pixels that represent the outer layer of the combustion zone of the flare. The imager has a high frame rate (11–30 frames per second) that results in a data acquisition cycle of 91–33 msec. The short data acquisition cycle means that the path length through the plume depth can be considered constant for each measurement (frame). This addresses the significant limitation of other imaging based technologies with long data acquisition cycles (e.g., 1 sec). As the data acquisition cycle increases, the uncertainty due to the changing conditions (plume depth) increases and the accuracy of the method will suffer. The proposed method provides the first practical, autonomous, real-time measurement of flare CE.

An experiment was conducted using full-scale flares to validate this new method. The experiment setup and results are presented in this paper.

Experiment setup

Flare CE is determined by the following equation (Allen and Torres, 2011):

$$CE(\%) = \frac{[C]_{CO2}}{\sum_i n_i[C]_{HCi} + [C]_{CO} + [C]_{CO2}} \times 100 \quad (1)$$

where CE(%) is the combustion efficiency, as a percentage; $[C]_{CO2}$ the volume concentration of CO_2 in the plume once combustion has ceased; $[C]_{CO}$ the volume concentration of carbon monoxide (CO) in the plume once combustion has ceased; $[C]_{HCi}$ the volume concentration of the ith HC compound remaining in the plume once combustion has ceased; n_i the number of carbon atoms in the ith HC compound; and i the ith hydrocarbon compound in the flare vent gas. When there is only one compound, $i = 1$.

When there is no unburned HC ($[C]_{HCi} = 0$) and no product of incomplete combustion such as CO in the plume ($[C]_{CO} = 0$), the combustion is complete and CE = 100%. Strictly speaking, there may be other products of incomplete combustion (such as soot), which are generally at trace levels and ignored. Under most common conditions, the concentration of CO as a product of incomplete combustion is orders of magnitude lower than either CO_2 or HC. For this experiment, CO is also neglected in the CE calculation. Therefore, eq (1) becomes eq (2):

$$CE(\%) = \frac{[C]_{CO2}}{\sum_i n_i[C]_{HCi} + [C]_{CO2}} \times 100 \quad (2)$$

Because eq (2) directly compares unburned HC and its ultimate combustion product (CO_2), the CE calculated by eq (2) can also be used as approximation of destruction and removal efficiency (DRE) for HC, that is, how much HC is destroyed regardless of how much is in the CO stage.

The experiment was conducted in November 2014 at the flare test facility of Zeeco, Inc., located near Tulsa, OK. Three full-scale fares were tested: a 16-inch steam assisted flare (Zeeco model QFS), a 10-inch air-assisted flare (Zeeco Model AFDS), and a multipoint sonic flare (also referred to as a pressure assisted flare and used as a ground flare; Zeeco model MPGF). Figure 1 is a picture of these three flares used in the experiment.

The experiment setup is illustrated in Figure 2. For this experiment, a hyperspectral infrared (IR) imager (model SOC750 by Surface Optics Corp.) was used to image flares at a distance of 300 ft from the base of the flare stacks. The optics of SOC750 includes a 50 mm lens with a field of view (FOV) of 8.8 degrees. The SOC750 is a "staring" hyperspectral imager with 42 spectral bands in the wavelength of 2–5 μm. The spectral resolution is approximately 73 nm. As a staring imager, it has high frame rate. It is radiometrically calibrated. Its sensor is a 256 × 240 cooled midwave infrared (MWIR) focal plane array. For this experiment, the SOC750 was operated to acquire and process spectral imagery at a rate of approximately 11 data cubes (256 × 240 pixels × 42 bands) per second. For each test run, SOC750 acquired data for 30 sec, generating 325 cubes for each test run.

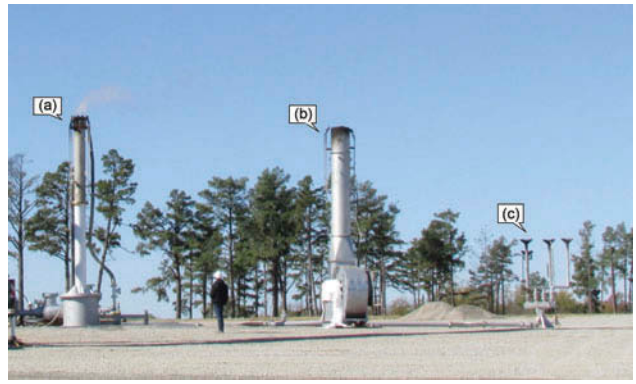

Figure 1. Three flares used in the experiment: (a) QFS steam-assisted flare; (b) AFDS air-assisted flare; and (c) MPGF multi-point sonic flare.

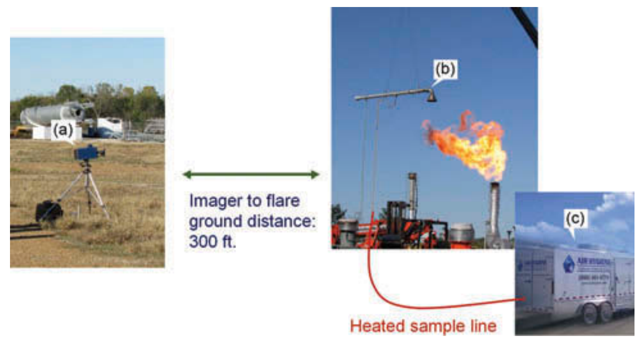

Figure 2. Experiment setup. (a) SOC750 hyper-spectral imager; (b) extractive sampling apparatus; and (c) gas monitoring trailer.

In order to validate this new method, an extractive sampling system was used (see Figure 2). An inductor with a sampling hood was suspended over the flare using a crane. A portion of the gases captured by the inductor was extracted and transported via a heated sampling line to the monitoring trailer. Inside the trailer, a contracted stack tester continuously analyzed samples for combustion products carbon dioxide (CO_2) and carbon monoxide (CO), unburned hydrocarbon (HC), and oxygen (O_2). The analyzers used for CO_2, CO, HC, and O_2 measurements were Servomex model 1440, ThermoFisher Scientific model 48C, VIG model 210, and Servomex model 1440, respectively. The test methods and procedures used were consistent with standard EPA methods for stack testing.

Thirty-nine test runs were completed (test numbers 0–39; test number 33 was aborted because the imager was not ready). The test conditions are summarized in

Table 1. Flare test conditions.

Test No.	Flare Type	Fuel	Fuel Flow Rate (lb/hr)	Air Rate (SCFM)	Stoichio-metric Air	Steam Rate (lb/hr)	Steam /HC (lb/lb)	CZNHV (Btu/SCF)	Notes
0	AFDS	Propane (100%)	7,994	0					Heavy smoke
1	AFDS	Propane (100%)	7,994	9,107	33.29%			259	
2	AFDS	Propane (100%)	7,994	9,107	33.29%			259	
3	AFDS	Propane (100%)	7,994	9,107	33.29%			259	
4	AFDS	Propane (100%)	6,670	9,107	39.89%			221	
5	AFDS	Propane (100%)	6,670	9,107	39.89%			221	
6	AFDS	Propane (100%)	5,278	9,107	50.42%			178	
7	AFDS	Propane (100%)	5,278	9,107	50.42%			178	
8	AFDS	Propane (100%)	3,063	9,107	86.87%			107	
9	AFDS	Propane (100%)	3,063	9,107	86.87%			107	
10	AFDS	Propane (100%)	237	9,107	1122.75%			9	Very small flame footprint
11	AFDS	Propane (100%)	237	9,107	1122.75%			9	Very small flame footprint
12	AFDS	None							Pilot only
13	AFDS	None							Pilot only
14	QFS	Propane (100%)	5,105			0	0	2,316	Heavy smoke
15	QFS	Propane (100%)	5,105			0	0	2,316	Heavy smoke
16	QFS	Propylene (100%)	4,891			0	0	2,183	Heavy smoke
17	QFS	Propylene (100%)	4,910			2,350	0.48	1,031	
18	QFS	Propylene (100%)	4,910			2,350	0.48	1,031	
19	QFS	Propylene (100%)	539			2,350	4.36	195	Very small flame footprint
20	QFS	Propylene (100%)	539			2,350	4.36	195	Very small flame footprint
21	MPGF	Propane (100%)	5,079						
22	MPGF	Propane (100%)	5,079						
23	MPGF	Propylene (100%)	4,952						
24	MPGF	Propylene (100%)	4,952						
25	MPGF	Propane/N_2 (50/50)	2,448						
26	MPGF	Propane/N_2 (50/50)	2,448						
27	MPGF	Natural Gas (100%)	3,300						
28	MPGF	Natural Gas (100%)	3,300						
29	QFS	Propane (100%)	4,640			2,350	0.52	1,035	
30	QFS	Propane (100%)	4,640			2,350	0.52	1,035	
31	QFS	Propane (100%)	1,879			2,350	1.25	571	
32	QFS	Propane (100%)	1,879			2,350	1.25	571	
33	QFS	Propane (100%)							Imager not ready; test aborted.
34	QFS	Propane (100%)	1,537			2,350	1.53	489	
35	QFS	Propane (100%)	1,537			2,350	1.53	489	Very small flame footprint
36	QFS	Propane (100%)	1,537			2,350	1.53	489	
37	QFS	Propane (100%)	1,537			2,350	1.53	489	
38	QFS	Propane (100%)	3,328			2,350	0.71	850	
39	QFS	Propane (100%)	3,328			2,350	0.71	850	

Table 1. The flares were operated by Zeeco personnel and the information in Table 1 was provided by Zeeco, except for the notes added by the authors based on observation. As discussed earlier, three types of flares were tested: air-assisted (AFDS), steam-assisted (QFS), and pressure-assisted (MPGF). Four types of fuels were used in the test: propane, propane/nitrogen blend (50:50), propylene, and natural gas. For the air-assisted flare, air-flow rates are provided in Table 1 with the unit of standard cubic feet per minute (SCFM). Based on the fuel flow, the amount of air supplied was also expressed as a percentage of stoichiometric air needed for the combustion. In addition to the supplied air, combustion can occur utilizing air from the atmosphere. For the steam-assisted flare, both steam rates and steam to HC ratio (on a mass basis) are provided in Table 1. Table 1 also provides combustion zone net heating values (CZNHV) for air-assisted and steam-assisted flares, an important parameter used by EPA for these types of flares.

Among the 39 test runs, 28 were designed to validate this method using the data from the extractive sampling system. The remaining 11 of the 39 test runs were designed to test the capability of this method under some extreme conditions. Among these 11 runs, four of them (test numbers 0, 14, 15, and 16) had heavy smoke. Five of them (test numbers 10, 11, 19, 20, and 35) were operated at extremely low vent gas rates (very small flame footprints). Two of them (test numbers 12 and 13) had no vent gas and were designed to test the imager's capability to image the pilot at the 300-ft distance.

Results and discussion

As described in the previous section, in total, 325 data cubes were acquired by the SOC750 hyperspectral imager for each of the 39 test runs. For each test run, an average data cube was derived by averaging the 325 cubes temporally. The reason for this averaging was to reduce the number of data sets to be processed manually in this study to a more manageable numbers. This averaging was appropriate because the flare was operated under a steady-state condition during each 30-sec test run and the images were inspected to ensure there was no significant change in the pattern of the flare flame. When this method is deployed in a monitoring instrument and data analysis is automated, this temporal averaging step will be eliminated to preserve the short analytical cycle in rapidly changing flare conditions. The final flare CE values can be averaged over a period of time desired by flare operators.

For each pixel of the average data cube, relative concentrations of CO_2 and HC, which were represented by the IR intensities in their respective spectral bands, were used in eq (2) to calculate CE for that pixel. There were 256 × 240 pixels. For the pixels that represent the flare flame ("flame pixels"), the IR intensity was high and the CE calculation was carried out. The rest of the 256 × 240 image is background scene where the IR intensity registered by the imager was virtually zero. For these nonflame, background-scene pixels ("background pixels"), no CE values were calculated.

Within the flame pixels, there was a subset of pixels that represented an outer combustion envelope where combustion ceased. Inside the combustion envelope the combustion is still progressing, unburned hydrocarbon concentrations tended to be high (particularly at the center of the flame near the flare tip), and CE values at the pixel level tended to be low. The pixels inside the combustion envelope do not represent the CE of the flare; rather, the pixels on the outer combustion envelope represent the true CE. Therefore, only the pixels representing the outer combustion envelope were averaged to derive a single CE value, which was used to represent the flare CE during the 30-sec test run. The same approach could be used for different temporal intervals, for example, 10, 20, or 60 sec, and the resulting CE values would provide corresponding time-averaged CE for the flare being monitored.

Once the CE value was calculated using the new method, it was compared to the CE value determined by the extractive method. The extractive method generated concentrations of CO_2 and HC at a 1-sec time interval. From these second-by-second CO_2 and HC data, CE was calculated using eq (2) in the same way as the new method. The time stamps of both the new method and the extractive method were synchronized, and the 30-sec test period of the new method was matched with the corresponding time window in the continuous data stream generated by the extractive method. Figure 3 is an example showing how the two data sets are matched for test numbers 36–39. The CE values generated by the extractive method during each 30-sec data cube were averaged and compared with the CE result from the new method.

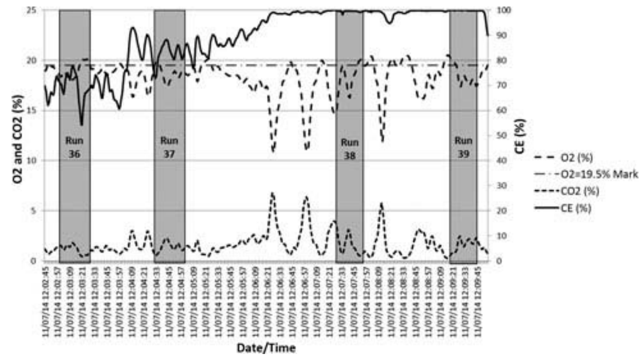

Figure 3. Example O_2, CO_2, and CE data from extractive method overlaid with imager test time for test numbers 36, 37, 38, and 39.

Results from 28 CE validation tests

The results of the 28 CE validation tests are summarized in Table 2. The first seven columns of data in Table 2 show the flare operating data (provided by Zeeco) that were presented in Table 1 and are repeated in Table 2 for convenience. The "CE-extractive method" and "CE-new method" are the results from the two methods, and the column labeled "CE difference" is the difference between the two methods. The column labeled "Smoke Index" is discussed in a later section. The last column is the 30-sec average of oxygen in the extracted sample. If the value in this column is close to 21%, it suggests that the extracted sample was significantly diluted by ambient air, possibly due to positioning of the extraction hood in relation to the changing flare plume or a small flare plume. It is ideal to capture as much of the flare combustion gases as possible with minimum ambient air dilution. For this experiment, extractive sampling data points with an oxygen level less than 19.5% are considered to be a higher quality data, that is, better plume extraction and less ambient air dilution. Among the 28 tests in Table 2, 18 are in this category.

Overall, the CE values measured by the new method agree well with the CE values measured by the extractive method. The average difference between the two methods is 0.50% when all 28 tests are included. The average difference is smaller (0.10%) when only the 18 higher quality extractive data points are considered. In addition to the extractive sampling data quality, the CE level appears to play a role in the accuracy of the method. The difference between the two methods is larger when the CE is low (e.g., test numbers 32, 34, and 36, with their CE being 67.48%, 59.99%, and 70.57%, respectively). Under these low CE conditions, the new method tends to overestimate the CE when compared to the extractive results. The

Table 2. Flare CE validation test results.

Test No.	Flare Type	Fuel	Fuel Flow Rate (lb/hr)	Stoichio-metric Air	Steam /HC (lb/lb)	CZNHV (Btu/SCF)	CE-Extractive Method	CE-New Method	CE Difference	Smoke Index	Avg. O_2 in Extracted Sample
1	AFDS	Propane (100%)	7,994	33.29%		259	99.94%	97.40%	-2.54%	2.85	21.13%
2	AFDS	Propane (100%)	7,994	33.29%		259	99.99%	98.80%	-1.19%	2.46	19.45%
3	AFDS	Propane (100%)	7,994	33.29%		259	99.98%	98.70%	-1.28%	4.58	19.37%
4	AFDS	Propane (100%)	6,670	39.89%		221	99.99%	98.80%	-1.19%	2.87	17.63%
5	AFDS	Propane (100%)	6,670	39.89%		221	99.97%	98.60%	-1.37%	2.70	18.84%
6	AFDS	Propane (100%)	5,278	50.42%		178	99.97%	99.20%	-0.77%	2.66	19.83%
7	AFDS	Propane (100%)	5,278	50.42%		178	99.95%	99.20%	-0.75%	2.50	20.03%
8	AFDS	Propane (100%)	3,063	86.87%		107	99.33%	99.00%	-0.33%	0.72	20.53%
9	AFDS	Propane (100%)	3,063	86.87%		107	99.77%	98.70%	-1.07%	1.44	18.94%
17	QFS	Propylene (100%)	4,910		0.48	1,031	99.86%	99.00%	-0.86%	3.99	19.93%
18	QFS	Propylene (100%)	4,910		0.48	1,031	99.90%	99.10%	-0.80%	2.24	19.98%
21	MPGF	Propane (100%)	5,079				100.00%	99.90%	-0.10%	0.24	18.77%
22	MPGF	Propane (100%)	5,079				100.00%	99.70%	-0.30%	0.27	18.07%
23	MPGF	Propylene (100%)	4,952				100.00%	99.90%	-0.10%	1.41	17.92%
24	MPGF	Propylene (100%)	4,952				100.00%	99.90%	-0.10%	1.36	17.38%
25	MPGF	Propane/N_2 (50/50)	2,448				99.97%	99.30%	-0.67%	0.23	19.48%
26	MPGF	Propane/N_2 (50/50)	2,448				99.99%	99.80%	-0.19%	0.35	18.19%
27	MPGF	Natural Gas (100%)	3,300				100.00%	99.80%	-0.20%	0.26	17.03%
28	MPGF	Natural Gas (100%)	3,300				100.00%	99.90%	-0.10%	0.32	15.76%
29	QFS	Propane (100%)	4,640		0.52	1,035	99.99%	98.70%	-1.29%	0.56	19.91%
30	QFS	Propane (100%)	4,640		0.52	1,035	99.97%	99.10%	-0.87%	0.70	17.60%
31	QFS	Propane (100%)	1,879		1.25	571	97.75%	97.50%	-0.25%	0.46	19.90%
32	QFS	Propane (100%)	1,879		1.25	571	67.48%	77.20%	9.72%	0.83	20.24%
34	QFS	Propane (100%)	1,537		1.53	489	59.99%	73.60%	13.61%	0.17	19.94%
36	QFS	Propane (100%)	1,537		1.53	489	70.57%	76.60%	6.03%	0.15	18.75%
37	QFS	Propane (100%)	1,537		1.53	489	83.15%	85.10%	1.95%	0.21	18.38%
38	QFS	Propane (100%)	3,328		0.71	850	99.67%	99.10%	-0.57%	0.40	17.38%
39	QFS	Propane (100%)	3,328		0.71	850	99.82%	99.40%	-0.42%	0.46	18.86%
Average CE difference between the two methods - all 28 tests:									0.50%		
Number of tests with oxygen < 19.5% (indication for good extraction):											18
Average CE difference between the two methods - 18 tests with oxygen < 19.5%:									-0.10%		

two methods correlate well with an r^2 of 0.9856. However, the projected regression line does not pass through the origin (see Figure 4), which is consistent with the positive bias of the new method in the low CE region. It should be noted that the flares are not designed to operate with such a low CE. However, low CE conditions may occur, for example, over-steaming (Allen and Torres, 2011). Currently there is no practical means to alert flare operators the presence of low CE operating conditions. The new method should be capable of providing real-time CE to flare operators so that low CE (i.e., high emission) conditions can be detected and rectified.

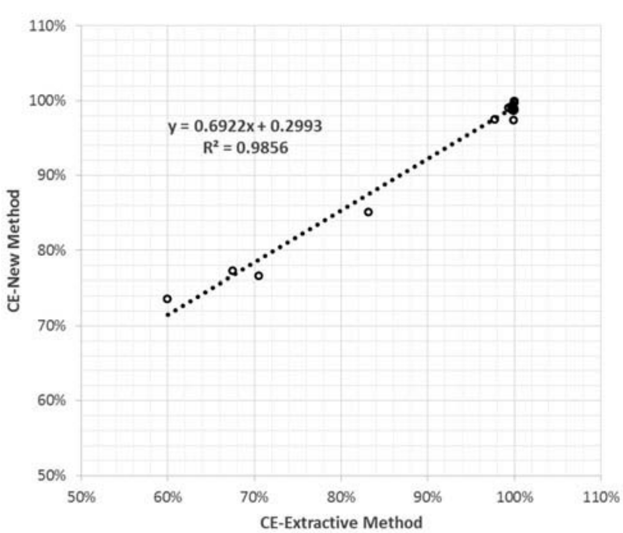

Figure 4. Flare CE measured by extractive method and by new method in 28 validation test runs.

As the CE level in these tests increased, the hydrocarbon level decreased significantly and became particularly small in comparison to the level of CO_2. For the tests that had high CE values, the hydrocarbon level was very low for both methods. In many of these tests, the hydrocarbon concentration in the extracted samples was in 0.05–1 ppm range, which was fairly close to the hydrocarbon analyzer baseline and significantly lower than the span of gas concentration of the analyzer. Similarly, the hydrocarbon peak in the imager spectral data was barely recognizable. This challenge generally exists in any instrument attempting to measure both extremely high and low concentrations at the same time. This factor could be a contributor to the difference between the two methods at high CE levels.

Duplicate test runs were conducted to provide a measure of repeatability for the new method used. Out of the 28 validation tests listed in Table 2, 26

Table 3. Repeatability - duplicated tests.

Flare Type	Paired Test Nos.	CE-Extractive Method 1st Test	CE-Extractive Method 2nd Test	CE-Extractive Method Absolute Difference	CE-New Method 1st Test	CE-New Method 2nd Test	CE-New Method Absolute Difference
AFDS	2 & 3	99.99%	99.98%	0.01%	98.80%	98.70%	0.10%
	4 & 5	99.99%	99.97%	0.02%	98.80%	98.60%	0.20%
	6 & 7	99.97%	99.95%	0.02%	99.20%	99.20%	0.00%
	8 & 9	99.33%	99.77%	0.44%	99.00%	98.70%	0.30%
QFS	17 & 18	99.86%	99.90%	0.04%	99.00%	99.10%	0.10%
	29 & 30	99.99%	99.97%	0.02%	98.70%	99.10%	0.40%
	31 & 32	97.75%	67.48%	30.27%	97.50%	77.20%	20.30%
	36 & 37	70.57%	83.15%	12.58%	76.60%	85.10%	8.50%
	38 & 39	99.67%	99.82%	0.15%	99.10%	99.40%	0.30%
MPGF	21 & 22	100.00%	100.00%	0.00%	99.90%	99.70%	0.20%
	23 & 24	100.00%	100.00%	0.00%	99.90%	99.90%	0.00%
	25 & 26	99.97%	99.99%	0.02%	99.30%	99.80%	0.50%
	27 & 28	100.00%	100.00%	0.00%	99.80%	99.90%	0.10%
Average, excluding (31 & 32) and (36 & 37)				0.07%			0.20%

tests were paired with a duplicate result with flare conditions held as steady as possible. Only test numbers 1 and 34 did not have a paired test. The absolute difference between the 13 paired tests was calculated separately for the extractive method and the new method. The results are summarized in Table 3. Tests 31–37 were designed to create low CE conditions by oversteaming. As a result, it was difficult to hold the flare condition constant between two duplicated tests for the desired amount of time. For two of the 13 paired tests (test numbers 31 and 32 and test numbers 36 and 37), the CE values were not repeatable. It should be noted that the difference between the extractive method and the new method in the contemporaneous time frame among these four tests actually agreed reasonably well. Excluding these two pairs that were not actually paired, the average difference in the measured CE is 0.07% and 0.20% for the extractive method and the new method, respectively. These differences suggested strong repeatability for the new method.

Results for heavy smoke conditions

Flares should not be operated with visible smoke. There are regulatory limits on opacity for flare operations. Flare technology has progressed over the decades with flare manufacturers designing flares that can achieve smokeless operations by means of assisting the flare with steam, air, or pressure. One of the major findings of the 2010 TCEQ flare study is that flare CE can be severely reduced when oversteaming occurs, and the best CE is achieved when the flare is operated at an "incipient smoke point"—the condition where the steam is reduced to a point just before smoke is observed (Allen and Torres, 2011). In practice, it is difficult to operate a flare at an incipient point without some measure of the level of smoke in the flare plume. Relying on the operator's visual observation of smoke is generally impractical and will be technically infeasible at night.

In addition to continuous and autonomous CE measurements, the newly proposed method can detect and measure the presence of aerosols. In the case of flare combustion, the aerosol represents soot or smoke in the flare plume. A unitless metric called the "smoke index" has been developed to measure the level of smoke, as illustrated in Figure 5. An optically transparent flare plume results in a smoke index (SI) of zero, and the SI progressively increases as the smoke level in the flare plume increases. It is anticipated that flare operators can observe the flare smoke condition in conjunction with the SI provided by this new monitoring method to establish an operational SI range. When the flare is operated within this range, no visible smoke is expected. For this particular study, no visible smoke was observed when the smoke index was below 6. However, there was not a sufficient number of tests designed to cover the transition from smoke to non-smoke conditions. Therefore, the upper limit for the operational SI range may be less than 6. Nevertheless, SI = 6 is used as a preliminary dividing line between smoke and smokeless conditions. In future tests, the flare opacity determined using EPA Method 9 can be recorded simultaneously with the SI generated by this method. If the two metrics exhibit a close correlation, the SI can be used quantitatively as a flare operational control parameter or even as a surrogate to opacity monitoring for flares.

Because the new CE measurement method is an optically based method, it was expected that a significant level of smoke or soot in the flare might interfere with the CE measurement. The experiment included

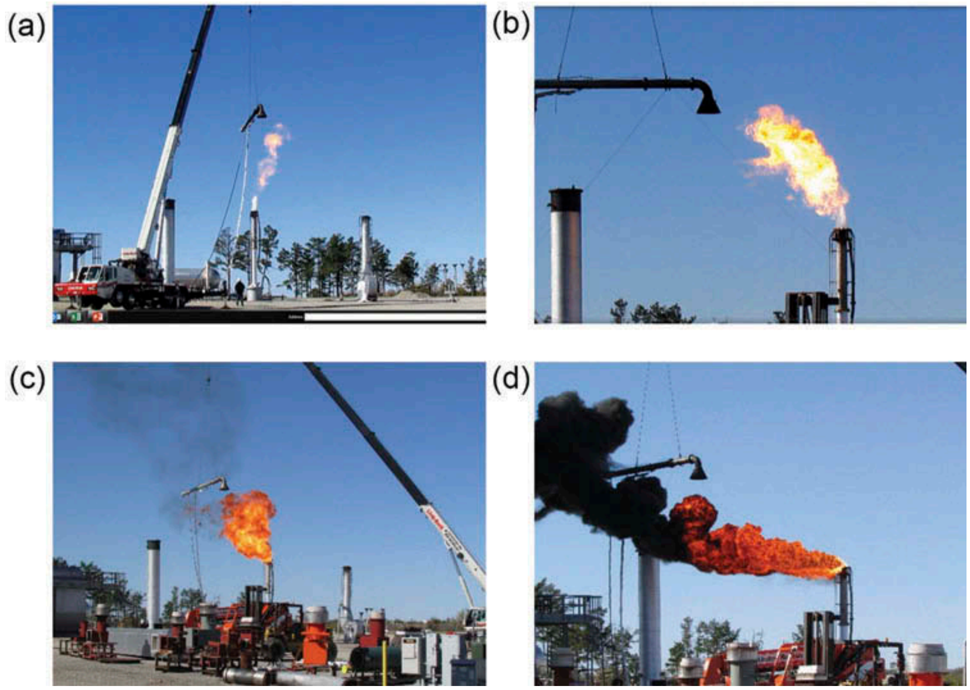

Figure 5. Examples of smoke level and smoke index: (a) test 29, smoke index = 0.56; (b) test 18, smoke index = 2.24; (c) test 14, smoke index = 7.41; and (d) test 16, smoke index = 8.89.

test conditions to study this assumption. Four tests were conducted under heavy smoke conditions and the test results are summarized in Table 4. During these four tests, air assist (test number 0) or steam assist (test numbers 14–16) was turned off, resulting in heavy smoke. In some cases, the extractive hood had to be positioned further away to avoid black smoke, as indicated by relatively high oxygen levels in the extracted samples in Table 4. The extracted samples were filtered by a sample conditioning system in the test trailer to remove soot, and the results indicated good CE values. As expected, the new method did not agree with the extractive method as well as it did under smokeless conditions in Table 2, especially for test number 15. For test number 16, the smoke was overwhelming (also see Figure 5d), and the data was inadequate for CE calculation. From a practical viewpoint, bringing the flare into a smokeless condition would be a higher priority for the flare operators than getting more accurate CE readings under such a heavy smoke condition. The data from the extractive method showed that the CE was high during this heavy smoke condition.

The significance of the SI is that it can provide a meaningful metric for flare operators to gauge the level of smoke in a flare plume from the control room day and night. The combination of the two parameters, CE and SI, in real time can provide flare operators the information needed to optimize flare operations.

Flare flame size and imager optics

Four of the 39 test runs (test numbers 10, 11, 19, and 20) were conducted when the flare was operated at very low fuel rates (see Table 1), This resulted in very small flame sizes in the IR images captured by the SOC750 at 300 ft ground distance. The results of these tests are summarized in Table 5, in the upper

Table 4. Flare CE tests with smoke conditions.

Test No.	Flare Type	Fuel	Fuel Flow Rate (lb/hr)	Stoichio-metric Air	Steam /HC (lb/lb)	CZNHV (Btu/SCF)	CE-Extractive Method	CE-New Method	CE Difference	Smoke Index	Avg. O_2 in Extracted Sample
0	AFDS	Propane (100%)	7,994	0.00%			99.70%	97.00%	-2.70%	6.14	20.27%
14	QFS	Propane (100%)	5,105		0	2,316	97.38%	95.90%	-1.48%	7.41	19.46%
15	QFS	Propane (100%)	5,105		0	2,316	99.83%	86.60%	-13.23%	7.44	20.66%
16	QFS	Propylene (100%)	4,891		0	2,183	99.86%	(a)	(a)	8.89	19.83%

Note: (a) smoke level was too high and CE calculation could not be performed.

Table 5. Flare CE tests at very low fuel rates and small flame sizes.

Test No.	Flare Type	Fuel	Fuel Flow Rate (lb/hr)	Stoichio-metric Air	Steam /HC (lb/lb)	CZNHV (Btu/SCF)	CE-Extractive Method	CE-New Method	CE Difference	No. of Usable Pixels	Avg. O_2 in Extracted Sample
10	AFDS	Propane (100%)	237	1122.75%		9	94.94%	97.60%	2.66%	1	20.75%
11	AFDS	Propane (100%)	237	1122.75%		9	93.89%	97.10%	3.21%	4	20.64%
19	QFS	Propylene (100%)	539		4.36	195	46.62%	75.80%	29.18%	3	20.62%
20	QFS	Propylene (100%)	539		4.36	195	89.30%	71.10%	-18.20%	2	20.87%
34	QFS	Propane (100%)	1,537		1.53	489	59.99%	73.60%	13.61%	251	19.94%
35	QFS	Propane (100%)	1,537		1.53	489	20.38%	78.40%	58.02%	1	20.55%
36	QFS	Propane (100%)	1,537		1.53	489	70.57%	76.60%	6.03%	627	18.75%
37	QFS	Propane (100%)	1,537		1.53	489	83.15%	85.10%	1.95%	203	18.38%

portion. To provide a perspective of the flame image sizes, both an IR image from one spectral band of SOC750 (i.e., image corresponding to one spectral slice of the 30-sec average data cube) and a snapshot visible image of test 19 (fuel rate: 237 lb/hr) are provided in Figure 6, along with similar IR and visible images of test 18 (fuel rate: 4,910 lb/hr, nearly 10 times higher than test 19). The images of tests 10, 11, 19, and 20 are so small at this distance and with this lens that there are only 1–4 pixels on the outer combustion envelope (see Table 5, column labeled "Number of usable pixels"). Consequently, the CE results derived from such a small number of pixels are not very consistent with the CE results from the extractive sampling, and they are considered unreliable. Under these conditions, even the extractive

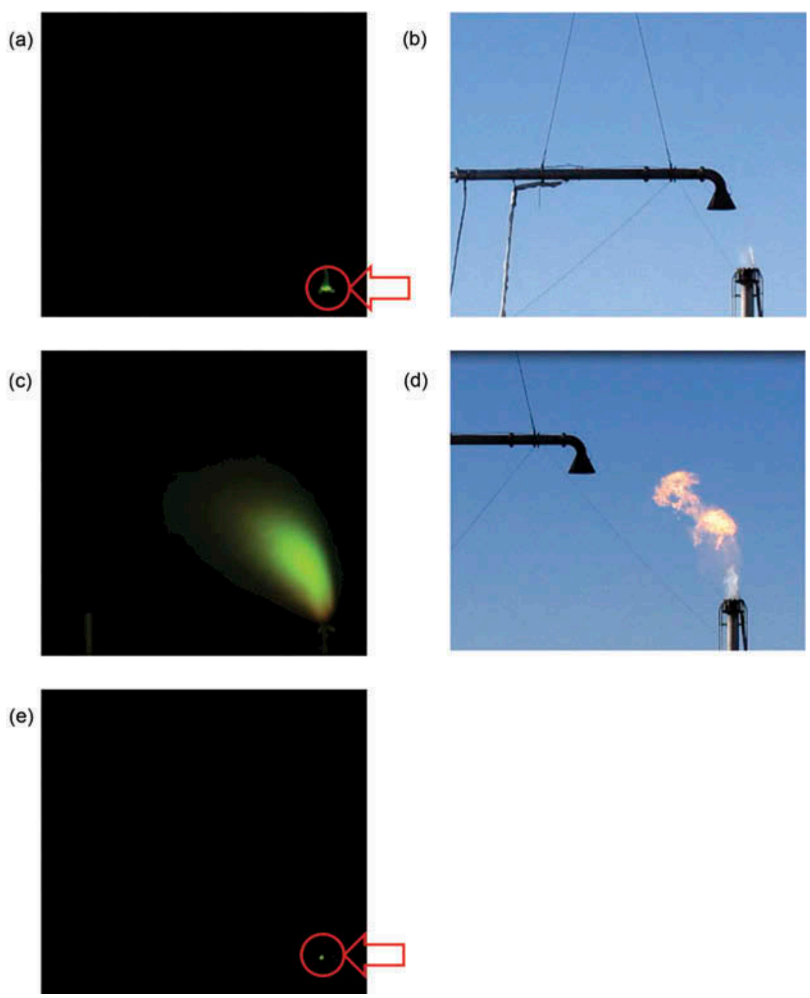

Figure 6. Images of small flare sizes and pilot: (a) IR image of Test 19; (b) visible image of test 19; (c) IR image of test 18; (d) visible image of test 18; and (e) IR image of test 13—no vent gas, lit pilot only.

sampling system may not produce reliable results because the flame is small and the hood may not capture a representative sample of combustion gases. This speculation is supported by the fact that oxygen levels in the four extracted samples were very close to the ambient air oxygen level. It should be noted that the new method made measurements based on what was in the combustion zone, whereas the extractive method was based on what was extracted. The two might not have been the same under unstable, poor combustion conditions.

Tests 34–37 were operated at high steam, low fuel conditions. The CE measured by the extractive method were low, 20.38–83.15% (see the lower portion of Table 5). Particular attention was given to test 35, which was problematic for both methods. This test had very low CE and the flame size was so small that only 1 pixel was usable for CE calculation in the new method. It also had a near ambient air oxygen level, indicating that the extractive sampling method had poor plume extraction due to the small flame size. The discussions in the preceding paragraph are applicable to test 35. For these reasons, test 35 was excluded from validation test shown in Table 2 and Figure 4. The remaining three tests in this group (test numbers 34, 36, and 37) had a higher CE measured by the extractive method, better extraction indicated by oxygen levels, and most importantly more than 200 usable pixels in the SOC750 images to make CE calculations. The results of these three tests are included in Table 2 and Figure 4, along with other validation tests.

The issue of small flame size as it relates to the number of usable pixels in the new method (as indicated in Table 5 and discussed earlier) should be viewed in the context of the distance from the imager to the flare and the optics of the imager. If a lens with a longer focal length and narrower field of view (FOV) is used, the flare image will be magnified and the number of usable pixels will increase, resulting in a suitable number of pixels for this new method. Similarly, positioning the imager closer to the flare may also yield a suitable number of usable pixels for small flame sizes. An elegant solution will be an imager equipped with two optical paths, a wider FOV when the flare is operated at high rates and a narrower FOV when the flare is operated at low rates.

Tests 12 and 13 were designed to test if the pilot of the flare could be imaged by SOC750 at this distance when there was no flame other than the small flame of the lit pilot (see Table 1). No CE measurement was made by extractive method. However, the SOC750 was used to capture the same 30 sec of IR images as in other tests. The CE calculation was not performed because the pilot flame was too small to be represented by a sufficient number of usable pixels for the method. The image of the pilot was detected by the SOC750 (see Figure 6e), which allowed for the detection of the lit pilot based on the concentration of the pilot flame combustion product (CO_2). The same result was observed during test 12. Collectively, test numbers 12 and 13 suggest that the new method can be used to confirm the presence of a lit pilot, which is a critical piece of information for flare operators.

Conclusion

Operation of an industrial flare is a very dynamic process and the combustion efficiency (CE) of the flare is of utmost importance. Currently there is no method to directly measure flare CE in real time and to provide feedback for control and optimization of such a dynamic process. The experiment conducted on three of the most common types of flares (steam-assisted, air-assisted, and pressure-assisted flares) has demonstrated the technical feasibility of using a hyper-spectral or multispectral staring infrared imager to directly and remotely measure flare CE. Thirty-nine tests were conducted using this new method and a conventional extractive method simultaneously to evaluate the capability and validity of the new method. While the extractive method is not practical for routine operations due to the cumbersome and manual extraction process, it does serve the purpose of providing validation for the new method. The 28 validation tests have shown strong agreement between the two methods with an average difference of 0.50% in CE measurement, and strong correlation with an r^2 of 0.9856. In 11 pairs of duplicated tests conducted under steady flare operating conditions, the average absolute difference between duplicated tests is 0.20% while the same measurement is 0.07% for the extractive method, indicating good repeatability for both methods.

The new method utilizes an imager to collect data. The entire flare is imaged and the data from the outer combustion envelope are used to determine the combustion efficiency. Unlike path-based optical measurement techniques, the imaging capability of this new method eliminates the need for aiming the optical path at certain regions of the flare plume where the combustion has completed and it can tolerate variability of the flare influenced by atmospheric conditions.

The new method also provides a metric called the smoke index, which serves as an indicator for level of smoke in the flare plume. The smoke index is a unitless metric derived from the IR characteristics of soot in the flare plume, and it should monotonically vary with the level of smoke. In a future study, it will be worthwhile to explore the relationship between the smoke index and the opacity of the flare.

Recent studies have concluded that performance is the best when the flare is operated near the incipient smoke point. To achieve this optimal operating condition, flare operators need to strike a balance between CE and the level of smoke, and both these parameters are currently not available to operators. The new method will provide both metrics continuously and in real time.

The new method can be applied to various sizes of flares. Although the method needs a reasonable number of pixels representing the flare plume, this requirement can be met by combination of imager's optics (i.e., field of view or magnification power) and the distance between the flare and the imager.

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