OFFICE OF AIR QUALITY PLANNING AND STANDARDS
RESEARCH TRIANGLE PARK, NC 27711

August 1, 2024

Yousheng Zeng, Ph.D., PE
Chief Executive Officer
Providence Photonics, LLC
1201 Main Street
Baton Rouge, Louisiana 70802

Dear Mr. Zeng:

This letter is a modification to my original letter dated July 12, 2024, in which I responded to your March 22, 2024 request for approval of a broadly applicable alternative test method to be used to monitor the net heating value of the flare combustion zone at facilities subject to 40 CFR part 60, Subpart OOOOb – Standards of Performance for Crude Oil and Natural Gas Facilities for which Construction, Modification or Reconstruction Commenced after December 6, 2022, (Subpart OOOOb). The U.S. Environmental Protection Agency's (EPA) Office of Air Quality Planning and Standards is the delegated authority for approval/disapproval determinations on any major alternatives to test methods and other compliance determination procedures required under 40 CFR parts 59, 60, 61, 63, and 65.

Proposed Alternative Test Method

According to the information provided, you seek the use of a Simplified Video Imaging Spectral Radiometry (Simplified VISR) method as detailed in Other Test Method 56 - Determination of Flare Combustion Zone Net Heating Value via Combustion Index Using Video Imaging Spectral Radiometer (OTM-56) (attached). You propose to use OTM-56 to measure the Combustion Zone Net Heating Value (NHVcz) of industrial steam-assisted flares and Net Heating Value Dilution Parameter (NHVdil) of air-assisted flares at a standoff distance as an alternative to the methods prescribed in §60.5417b(d)(8), which specifies the use of a calorimeter, gas chromatograph (GC), mass spectrometer (MS), or grab samples at an 8-hour sampling interval. Your proposed alternative uses a multispectral Infrared (IR) imaging spectral radiometer that measures IR radiances of the ultimate combustion product, carbon dioxide (CO_2), and other species in the combustion zone in their respective IR spectrum to derive a signal called "Combustion Index" (CI), which is calibrated to NHVcz (or NHVdil for flares with perimeter assist air). The method continuously monitors flare NHVcz/NHVdil at a one second interval, documenting the actual flare performance in real time.

<u>Justification</u>

As justification for your proposed alternative method, you note the following potential benefits:

- ***Can help optimize flare performance and minimize emissions.*** When used as a feedback mechanism, the use of OTM-56 can provide the flare operator with real-time feedback or become a part of a closed loop control system to optimize the flare performance and minimize emissions of air pollutants.
- ***Meets the precision and accuracy requirements***. The validity of this alternative method for flare NHVcz/NHVdil monitoring has been demonstrated through comprehensive tests against the reference method.
- ***More stringent***. This alternative method is more stringent than the requirements in the applicable regulation. This alternative method provides monitoring data at a 1-second interval, significantly more frequently than the minimum of one data point per 15-minutes required by §60.5417b(d)(8) if a calorimeter, GC, or MS is used per §60.5417b(d)(8)(ii)(A), (B), or (C) respectively. The more frequent measurement is significantly more beneficial to the environment as some flaring events are short in duration and flare conditions can change rapidly during a flaring event. The 1-second measurement will ensure that nothing is missed. The comparison between this alternative method and the grab sample at an 8-hour interval allowed under §60.5417b(d)(8)(ii)(D) is much more drastic. The latter method has the potential to miss significant flaring events entirely.
- ***More representative***. This alternative method is more representative of actual flare combustion conditions than the method specified in §60.5417b(d)(8) because the method specified in §60.5417b(d)(8) measures the gas properties in the inlet gas and does not take into consideration environmental conditions (e.g., wind) which could impact the efficiency of the combustion.
- ***Can enable flare optimization and reduce emissions***. When a monitored flare is air assisted or steam assisted and the level of assist can be controlled, this alternative method provides a mechanism for flare optimization that the method in the regulation doesn't provide. In addition to monitoring NHVcz/NHVdil as a surrogate to flare efficiency, the alternative method also monitors the level of smoke in the flare through a metric called Smoke Index (SI). The use of the two flare performance parameters, NHVcz/NHVdil and SI, provides the only practical, instrument-based mechanism to achieve the optimal flare operating condition known as "Incipient Smoke Point" (ISP). ISP provides the lowest possible emissions without smoke (i.e., visible emissions). The combination of NHVcz/NHVdil and SI measured without any latency also enables closed loop control of flare operations, further reducing emissions.
- ***Cost effective***. The method specified in §60.5417b(d)(8)(ii)(A) through (C) requires installation of inline instrumentation (calorimeter, GC, or MS). For an air assisted or steam assisted flare, flowmeters, temperature sensors, and pressure sensors must also be installed on both the vent gas line and the air or steam line in order to calculate NHVcz or NHVdil. A minimum of 7 process instruments are required to implement the specified method. The costs associated with instrument purchase, installation, and O&M expenses required by the specified method well exceed the cost of purchasing, installing, and operating a single device required by the alternative method. If an operator chooses the fourth option of the specified method, *i.e.*, grab samples every 8 hours per

§60.5417b(d)(8)(ii)(D), the costs associated with sample collection, lab analysis, data reduction are expected to be even higher. Because the device in the alternative method is a remote sensing device, process shutdowns to install instrumentation are not required, further reducing the costs of the alternative method. In addition, the device in the alternative method can simultaneously monitor the presence of the pilot flame as required by §60.5417b(d)(8)(i) and visible emissions as required by §60.5417b(d)(8)(v). Additional cost savings will be realized when the device in the alternative method is also used to satisfy the monitoring requirements of pilot flame and visible emissions.

- ***More reliable***. The alternative method uses a single remote sensing, non-contacting device positioned at a distance from flare. Typical issues with inline instruments, such as corrosion, clogging, etc., do not exist. This will increase the monitoring system reliability and will enhance the compliance.
- ***Will ease the anticipated industry-wide shortage in monitoring instruments and lab capacities***. In other industry sectors, the number of new facilities that become affected by the promulgation of a new source performance standard are typically in the single or double digits. This upstream and midstream oil and gas sector is unique. The new facilities that are affected are in the thousands. Based on EPA's RIA for the Subpart OOOOb rule, the number of flares that will be subject to the rule is 4,700 initially in 2024 and 55,000 in 2028 when Subpart OOOOc (40 CFR part 60) takes effect with an average newly affected flares of 5,100 per year between 2024 and 2027 and 2,700 per year between 2027 and 2038. Though some of the flares can be exempted by process design, most of these newly regulated flares must be continuously monitored or undergo a 14-day test to possibly exempt them from continuous NHV monitoring. Both procedures will require monitoring instruments (e.g., calorimeter, GC, MS) or lab analysis of the grab samples (at least 28 samples per flare), and they must be done within 60 days of the effective date of the rule or within 60 days after the new facility reaches its design capacity. An industry-wide shortage in these process instruments and lab capacity is anticipated, at least initially, until the supply catches up with the demand. This alternative method will provide another avenue for affected facilities to meet the compliance deadline when other avenues are overwhelmed.

In summary, you assert that this alternative method is more than adequate for determining compliance and will be more stringent than the underlying regulation. Additionally, you state that the alternative method will enhance the underlying regulation and make the determination of compliance simpler and more streamlined for both the regulatory authority and the affected facility.

Determination

Based on a thorough review of the information you provided, we conclude that use of a Simplified VISR method as detailed in OTM-56 yields results that are typically no less stringent and often more conservative when compared to those of the existing requirements and is thus adequate to determine compliance. Therefore, with this letter, I approve the use of the Simplified VISR method as detailed in OTM-56 to meet the following requirements:

- §60.5417b(d)(8)(ii) for continuous monitoring,
- §60.5417b(d)(8)(iii) for 14-day demonstration, or

- §60.5417b(d)(8)(vi) for continuous monitoring of air-assisted or steam-assisted flares.

When this alternative method is used, the operating limit will be based on the Combustion Zone Net Heating Value (NHVcz) of 270 Btu/scf for steam-assisted and unassisted flares and Net Heating Value Dilution Parameter (NHVdil) of 22 Btu/ft^2 for air-assisted flares, instead of inlet gas NHV and corresponding operating limits as specified in §60.5417b(d)(8)(ii) and (iii).

This approval is made with the specific limitations listed below:

- Affected facilities using OTM-56 must notify the responsible agency before use of this alternative method and notification must include a copy of this letter.

- Facilities must include a copy of this letter and method with each quarterly report presenting results using OTM-56.

Because the alternative method described herein may be of use to other entities subject to §60.5417b(d)(8), and we believe it is reasonable to apply it broadly to other subject facilities, we will post this letter as ALT-156 on the EPA website at *https://www.epa.gov/emc/broadly-applicable-approved-alternative-test-methods* for use by interested parties.

If you have any questions regarding this approval or need further assistance, please contact Kim Garnett at (919) 541- 1158 or *garnett.kim@epa.gov*.

Sincerely,

STEFFAN JOHNSON
Digitally signed by STEFFAN JOHNSON
Date: 2024.08.01 16:18:46 -04'00'

Steffan M. Johnson, Group Leader
Measurement Technology Group

Attachment

cc: Kim Garnett, OAQPS/AQAD (garnett.kim@epa.gov)
Gregory Fried, OECA/OC (fried.gregory@epa.gov)
Regional Testing Contacts

Other Test Method 56 – Determination of Flare Combustion Zone Net Heating Value via Combustion Index Using Video Imaging Spectral Radiometer (VISR)

1.0 Scope and Application

Video Imaging Spectral Radiometry (VISR) is a method which utilizes a multi-spectral (or hyperspectral) imager which can produce radiometrically calibrated data cubes with both spectral and spatial dimensions. This VISR method has been validated for direct and remote measurement of Combustion Zone Net Heating Value (NHV_{cz}) of industrial steam-assisted flares and Net Heating Value Dilution Parameter (NHV_{dil}) of air-assisted flares. Both NHV_{cz} and NHV_{dil} are defined in the Chapter 40 of Code of Federal Regulations (40 CFR) Part 63, Section 670 (§63.670(m)). The validation was performed using the method specified in §63.670(m) as the reference method. This method uses a VISR imager to remotely and directly measure Infrared (IR) radiance emitted from the flare in different spectral bands. These radiance values are used to derive a parameter which is strongly correlated to NHV_{cz} or NHV_{dil}. For the purposes of this document, the correlated parameter is called Combustion Index (CI). The CI exhibits a predicable relationship with NHV_{cz} and NHV_{dil}, and can be calibrated to measure NHV_{cz} or NHV_{dil} (hereafter may be described as NHV for both unless explicitly stated).

1.1 *Scope*. The end result of the VISR method is NHV, which is not a conventional "analyte" of an analytic method. The method relies on the IR radiance emitted from combustion product Carbon Dioxide (CO_2, CAS # 124-38-9) and the IR radiance emitted by other substances in the combustion zone, including hydrocarbons and aerosols/soot. The hydrocarbons may include but are not limited to the following gases:

- Methane (74-82-8)
- Ethane (74-84-0)
- Ethylene (74-85-1)
- Propane (74-98-6)
- Propylene (115-07-1)
- Butane (general)
- Pentane (general)

1.2 *Applicability*. This method can be used by an operator for short-term testing of flare NHV. It can also be permanently installed for continuous and autonomous monitoring of flare NHV. This method can be applied to an open flare that is steam assisted, air assisted, pressure assisted, or unassisted.

1.3 *Method Range and Sensitivity*

1.3.1 Method range: For flares subject to the NHVcz requirement, a calibration has been established for the NHV_{cz} range of 150-550 Btu/scf. For flares subject to the NHV_{dil} requirement, a calibration has been established for the NHV_{dil} range of 10-150 Btu/ft^2.

1.3.2 This method is a remote-sensing based measurement method. The VISR imager needs to be positioned correctly to meet the following siting criteria:

- The VISR imager must have a clear line of sight to the flare tip.
- The flare flame must be captured within the field of view (FOV) of the VISR imager.
- The flare flame image must occupy enough pixels to provide a representative CI. A data quality indicator must be used to demonstrate that this condition has been met (for example, the flare flame must occupy at least 50 pixels). Depending on the FOV for the VISR imager and the size of the flame, this could translate to a maximum distance ranging anywhere from 100 to 2,000 feet from the flare.
- Other than the target flare, there should be no high temperature objects (including reflection of high temperature objects) in the FOV.
- The minimum distance should exceed the flare height to avoid the flare stack itself blocking the flame when the VISR imager is in the upwind position. This ensures that the viewing angle is less than 45 degrees.

2.0 Summary of Method

The approach described in this method is Video Imaging Spectral Radiometer (VISR). The VISR acronym has four parts, each describing a characteristic of the device:

- **V**ideo: the sensor is capable of generating video images
- **I**maging: produces an image which has 2 spatial dimensions
- **S**pectral: multiple spectral bands
- **R**adiometer: radiometrically calibrated to accurately measure radiance in each spectral band.

A VISR imager is a multi-spectral (or hyperspectral) Mid-Wave Infrared (MWIR) imager with a cooled or uncooled detector sensitive to Infrared (IR) radiance emitted by unburned hydrocarbons, aerosols/soot, and the ultimate combustion product – carbon dioxide (CO_2). A VISR imager has sufficient spectral bands to accurately and separately measure IR radiance from these substances in the combustion zone and derive a parameter (CI, or Combustion Index) which is strongly correlated to NHV. The VISR imager should cover the spectral range of 3-5 micrometer (μm) in wavelength, and at a minimum one spectral band should cover a CO_2 band. Through a calibration process using the NHV measured by the method specified in 40 CFR 63.670 as the reference method, the CI-NHV correlation can be established for each type of VISR imager (called Method Calibration for the purposes of this document). Once the Method Calibration is established for a particular type of VISR imager, it can be used to measure flare NHV.

Each instance of a VISR imager is radiometrically calibrated by the manufacturer with a blackbody (called Radiometric Calibration for the purposes of this document) to ensure that the results measured at the pixel level accurately reflect the radiance in each respective spectral band.

The VISR imager is positioned at a distance from the flare and continuously captures radiometric data. Each analytical cycle generates a data cube – two spatial dimensions and one spectral dimension. Multiple data cubes are generated within a second (typically 6 data cubes per second or higher depending on specific sensor configuration). Each data cube is analyzed by an on-board computer to derive the CI and other flare performance metrics. These parameters are then averaged to 1-second values. The 1-second CI value is then used to calculate the flare NHV using the established calibration. The result is one NHV value reported for the flare every second. A continuous data stream of NHV values at a one-second interval provides real-time flare NHV monitoring data with no latency.

3.0 Definitions

Combustion Index (CI) means a parameter derived from a VISR imager that is highly correlated to NHV and can be used as a measurement signal with a predictable relationship to NHV_{cz} or NHV_{dil}.

Method Calibration refers to the process of calibrating CI (measurement signal) to NHV for a particular type of VISR imager using the method specified in 40 CFR 63.670(m) as the reference method.

Radiometric Calibration refers to the process of radiometrically calibrating a specific instance of a VISR imager with a blackbody to ensure that the results measured at the pixel level accurately reflect the radiance in each respective spectral band.

Net Heating Value (NHV) is a term which is used interchangeably to refer to either NHVcz or NHVdil, as defined in 40 CFR 63.670(m).

Combustion Zone Net Heating Value (NHV_{cz}) means the same parameter as defined in 40 CFR 63.670(m).

Net Heating Value Dilution Parameter (NHV_{dil}) means the same parameter as defined in 40 CFR 63.670(m).

Video Imaging Spectral Radiometer (VISR) means a multi-spectral (or hyperspectral) Infrared (IR) imager that meets the following criteria:

- Capable of capturing IR images in multi-spectral bands at a video frame rate.
- Radiometrically calibrated, meaning that the reading of each pixel value in each spectral band is calibrated to the IR radiance of a blackbody calibration standard in a temperature range of 600-1,000 ^{O}C (or wider).

4.0 Interferences

4.1 <u>Chemical/spectral interference</u>. For composition of flare gases found in oil and gas sector, no spectral interference caused by chemical species has been observed for either the CI or the NHV measurement.

4.2 <u>Interference due to reflective structures</u>. If a structure is behind the target flare within the field of view of the VISR imager and oriented in such a way that the IR rays radiated from the target flare (or any other combustion sources) can be reflected back (i.e., are highly reflective materials such as polished steel or aluminum) to the VISR imager, such a structure has the potential to interfere with the CI measurement. For an elevated flare, this scenario is unlikely because (a) the flare is typically far away from any structure for safety reasons, and (b) the flare tip is higher than the VISR imager and any surrounding structures so that the reflection, if it exists, is directed away from the VISR imager. This potential interference would be a concern for a ground flare. In the case of a ground flare, care should be taken when positioning the VISR imager to avoid reflective objects behind the flare tips and within the VISR imager field of view. If this scenario cannot be avoided, persistent reflections can be removed by software masking of specific regions in the field of view.

4.3 <u>*Blockage of flare stack to flare flame*</u>. Under certain site conditions, the flare stack could block a significant portion of the flame. For example, if the flare vent gas exit velocity is low and the wind speed is high, the flame may be blown by the wind causing a horizontal orientation to the flare tip. Under such a condition, if the VISR imager is positioned upwind from the flare stack (especially when the VISR imager is relatively close to the flare stack and the viewing angle greater than 45 degrees upward from the ground), the flare stack itself may block a significant portion of the flame. When this happens, the CI measurement will be distorted.

4.4 <u>*Interference due to dense fog*</u>. Validation testing shows that dense fog tends to cause reflections or scattering of the IR rays from the flare flame, causing distortion of the spectral profile and the CI-NHV calibration. The impact due to light to moderate fog is negligible.

4.5 <u>*Interference due to heavy rain*</u>. Rain will attenuate the IR signal from the flare to the imager. Due to the large size of rain drops (relative to the wavelength of 3-5 μm), the attenuation is spectrally non-discriminatory and should not cause interference. As a result, the impact of rain to this method is negligible unless the rain is so heavy that it blocks nearly all of the IR radiance transmitting from the flare to the imager.

4.6 <u>*The sun in the field of view*</u>. If the sun is in the field of view, the IR radiance from the sun may cause distortion of spectral profile and the CI-NHV calibration. For short term testing, the VISR imager should be oriented to avoid the sun in the field of view. For continuous monitoring, it is preferred that the VISR imager is installed with a North/South orientation to avoid prolonged periods with the sun in the field of view.

5.0 Safety

This method does not involve the use of chemicals. During installation, users should follow established safety procedures for lifting or handling equipment with consideration to the size and weight of the VISR imager. If the VISR imager uses a standard 110V 50/60 Hz or 220V 50/60 Hz single phase power supply, users should follow established safety procedures for electrical hazards. For installed systems, electrical classifications (such as ATEX or Class/Div) for the equipment should be considered when selecting the location. Unless the VISR imager is certified for electrically classified areas, it should be placed outside of electrically classified areas.

6.0 Equipment and Supplies

The typical equipment required for this method is illustrated in the schematic shown in Figure 1. There are no consumables used in this method. A single 110V 50/60 Hz or 220V 50/60 Hz power supply is typically required. Data generated by the VISR method can be recorded locally or fed to a plant Distributed Control System (DCS), Programmable Logic Controller (PLC), or data historian.

Figure 1. Schematic showing typical equipment for the VISR method

7.0 Reagents and Standards

No reagents or standards are used in this method.

8.0 Sample Collection, Preservation, Storage, and Transport

This is a remote sensing multi-spectral Infrared imaging method. No physical sample is collected, preserved, stored, or transported.

9.0 Quality Control

Quality control for the VISR method should be achieved through continuous monitoring of multiple instrument health status indicators and data quality control flags, collectively referred to as Data Quality Indicators (DQI's). These DQI's should be automatically generated by the VISR method.

At the instrument level, the key health indicator is the sensor temperature of the VISR imager. The sensor operating temperature range is dictated by the type of sensor and the manufacturer of the sensor. For example, if a cooled sensor is used (e.g., an Indium Antimonide (InSb) sensor), the sensor is fully encapsulated in an Integrated Dewar Cooler Assembly (IDCA) and the sensor temperature is tightly controlled. If the cooler fails or malfunctions, the sensor temperature will fall outside of this range and the sensor will typically not generate video images. This condition should be detected automatically through the use of a DQI. If an uncooled sensor is used for this method, the sensor temperature will be affected by the environmental temperature. In this case, the sensor is considered to be working within an acceptable range as long as the sensor temperature is between the lower bound and upper bound established through the radiometric calibration discussed in Section 10. If the sensor temperature moves outside of this established range, the condition should be detected automatically through the use of a DQI.

In addition to monitoring the system health of the VISR imager, multiple DQI's are used at the method level to indicate the quality and validity of each CI value, which in turn is used to derive the compliance parameter NHV_{cz} or NHV_{dil}. These DQI's are described below.

- <u>*Number of flame pixels*</u>. This DQI measures the number of valid flame pixels used per frame. For each type of VISR imager, a minimum threshold for the number of flame pixels must be established during the Method Calibration to ensure quality data. This threshold should then be monitored continuously to ensure that the CI measurement (and NHV measurement) is of sufficient quality. For example, during initial setup, if the VISR imager is positioned too far from the flare (relative to the size of the flare flame) or simply not aimed properly (ref. Section 11 regarding siting and aiming), the number of flame pixels will be below the established threshold and the quality of the CI measurement will be low. During continuous measurements, a flame pixel count below the established threshold could be caused by the flare operations (e.g. flaring rate drops too low or flare is extinguished) or by VISR imager issues (e.g., imager was moved and is no longer aimed correctly). This DQI is averaged over the 1-second data period. If the average number of valid pixels drops below the required threshold (as established during the Method Calibration) then the CI value (and resulting NHV) is considered to be of low quality or invalid. Note 1: the system may still generate a CI value unless the valid number of flame pixels is zero. This condition could occur when virtually no flame is detected. Note 2: if the VISR imager is also used to monitor the presence of the pilot flame, a flame pixel count below the established threshold can still be used to indicate the presence of a pilot flame.

- *Number of edge pixels*. The VISR imager used for the NHV measurement should be positioned in such way that the entire flame is captured in the VISR imager's field of view (FOV). If the VISR imager is too close to the flare so that a portion of the flame is not captured in the FOV, the measurement of CI and NHV will not be accurate. When this happens, there will be significant number of flame pixels on the edge of the VISR imager's FOV. These pixels are called edge pixels. If the number of edge pixels is greater than 10, it is considered significant in the CI measurement and the corresponding CI value (and NHV) is considered to be of low quality or invalid.
- *Data cube rate*. A data cube is one complete spectral data set for the VISR imager field of view. The data cube rate should be above the minimum threshold established during Method Calibration. A low data cube rate can be an indication of either a very unstable flame or sensor malfunction. When the data cube rate drops below the established threshold, then the CI value is considered low quality or invalid.

A list of DQI's and their bounds of tolerance for a specific model of uncooled VISR imager are provided in the table below as an example.

DQI	**Valid range or bounds of Tolerance**
Sensor temperature	Vary by the type of sensor used. • For cooled/temperature-controlled sensor, the sensor temperature must be within the operating range specified by the sensor manufacturer. For example, the operating temperature for InSb sensor is 77 K. • For uncooled sensor, the sensor temperature must be between the lower bound and upper bound used during radiometric calibration (see Section 10), e.g., 10 – 50 ^{O}C.
Number of flame pixels	• > 50 for CI measurement. • >4 for pilot flame presence monitoring
Number of edge pixels	< 10 edge pixels or < 5% of flame pixels, whichever is larger
Data cube rate	≥ 2 data cubes per second

10.0 Calibration and Standardization

There are two aspects of the calibration for this method, Radiometric Calibration and Method Calibration.

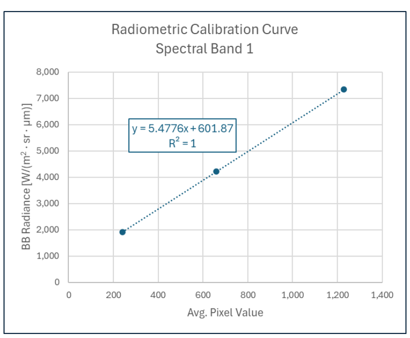
10.1 *Radiometric Calibration*

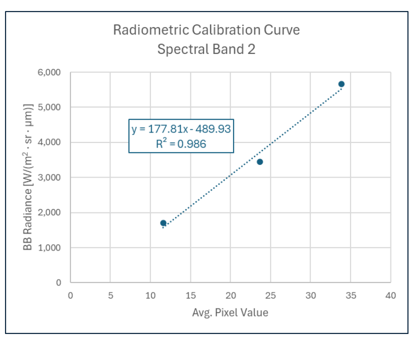
The Radiometric Calibration must be performed for each instance of a VISR imager. The calibration procedure should include, at a minimum, the procedures specified in this section. It should be noted that as industry standard for imaging sensors, uniformity correction should have been performed by the sensor manufacturer and therefore not included in this section.

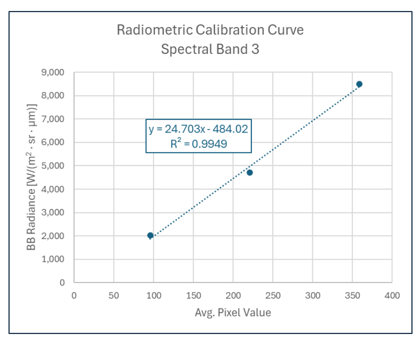
10.1.1 An optical grade blackbody calibration device (NIST traceable to +/- 0.2°C) is used for calibration. The blackbody is placed in front of the VISR imager to be calibrated. The VISR imager, in its designed operating mode, will generate readings, in each spectral band, in pixels that represent the active area of the blackbody. The calibration must be performed at three or more IR radiance levels covering a minimum blackbody temperature range from 600 ^{O}C to 1,000 ^{O}C.

10.1.2 The Radiometric Calibration must be performed on each spectral band, and for each blackbody temperature. Each pair of spectral band and blackbody temperature form a calibration point. For example, if a VISR imager has three spectral bands, there will be a minimum of nine calibration points: 3 spectral bands x 3 blackbody temperatures.

10.1.3 For each calibration point, an expected IR radiance, R, is calculated using the Planck's equation with the given blackbody temperature and the wavelength that equals to the center wavelength of the given spectral bands. The pixel value generated by the sensor of the VISR imager and IR radiance R are used to construct a calibration curve. For example, if the VISR imager has three spectral bands, there will be three calibration curves as shown below.







A Radiometric Calibration equation is derived from the calibration curve of each spectral band. Once calibration equations are established, the pixel readings of the VISR imager can be used to measure IR radiance in each spectral band.

10.1.4 The Radiometric Calibrations must be evaluated by the following procedures.

- Set the blackbody at 600 ^{O}C. For each spectral band, there is a corresponding IR radiance, **R**, determined by the Planck's equation with the given blackbody temperature and the wavelength that equals to the center wavelength of the given spectral band.
- Position the VISR imager to image the blackbody. Collect pixel values for the pixels that represent the active area of the blackbody. Calculate the measured IR radiance, **R**', using the established calibration equation. The **R**' value can be the spatial average of all pixels representing the active area of the blackbody.
    - Repeat this measurement **m** times, where **m** must be greater than 10. Each time there will be a measured $\mathbf{R}_{i,j}$ for band i and measurement j. If the VISR imager uses an uncooled sensor, the 10 or more repetitions must be conducted with the sensor temperature at the lower bound of the operating range, the upper bound of the operating range and at least 8 additional sensor temperature approximately equally spaced between the lower bound and upper bound.
- Calculate calibration precision. The precision is measured as Relative Standard Deviation (RSD) for each spectral band i across all repeated measurements, i.e.,

$$R'_{i,avg} = \frac{\sum_{j=1}^{m} R'_{i,j}}{m}$$

$$SD_i = \sqrt{\frac{\sum_{j=1}^{m}(R'_{i,j} - R'_{i,avg})}{m-1}}$$

$$RSD_i = \frac{SD_i}{R'_{i,avg}} \times 100$$

Where

$R'_{i,j}$ =	calculated radiance for the j-th measurement in spectral band i
m =	number of repeated measurements
$R'_{i,avg}$ =	average value of m calculated radiance in spectral band i
SD_i =	standard deviation of repeated measurements in spectral band i
RSD_i =	relative standard deviation in spectral band i

- Calculate calibration accuracy. The calibration accuracy is measured as relative bias of calculated radiance against the expected blackbody radiance, i.e.,

$$B_i = \frac{R'_{i,avg} - R_i}{R_i} \times 100$$

Where

R_i =	expected IR radiance calculated using Plank's equation, given blackbody temperature, and the center wavelength of the given spectral band
B_i =	calibration bias

- Repeat the above procedures with blackbody temperature set at 1,000 ^{O}C or higher.
- Calibration precision and accuracy must meet the following criteria:

For Blackbody Temperature	Precision, RSD	Accuracy, Bias
600 ^{O}C	<10%	<10%
1,000 ^{O}C or higher	<5%	<5%

10.1.5 A Radiometric Calibration check should be performed in an interval not to exceed 3 years. A calibration check can be performed against an optical grade blackbody at a single temperature. If the radiance in each spectral band is within the initial calibration range, no further action is needed. If the radiance is outside of the initial calibration range, the VISR imager must be recalibrated following the procedures in the above subsection 10.1.1 through 10.1.4.

10.2 *Method Calibration*

The Method Calibration must be performed for each type of VISR imager. The primary parameter measured by the VISR method is CI. The CI is then calibrated against NHV measured by the method specified in 40 CFR 63.670 (m),for NHV_{cz} and 40 CFR 63.670 (n) for NHV_{dil}. An example CI-NHV_{cz} calibration for steam assisted flares is illustrated in Figure 2. An example CI-NHV_{dil} calibration for air assisted flares is illustrated in Figure 3. The operator can choose to use a CI-NHV calibration provided by the manufacturer or perform a site-specific calibration if an alternative NHV measurement using the method specified in 40 CFR 63.670 is available.

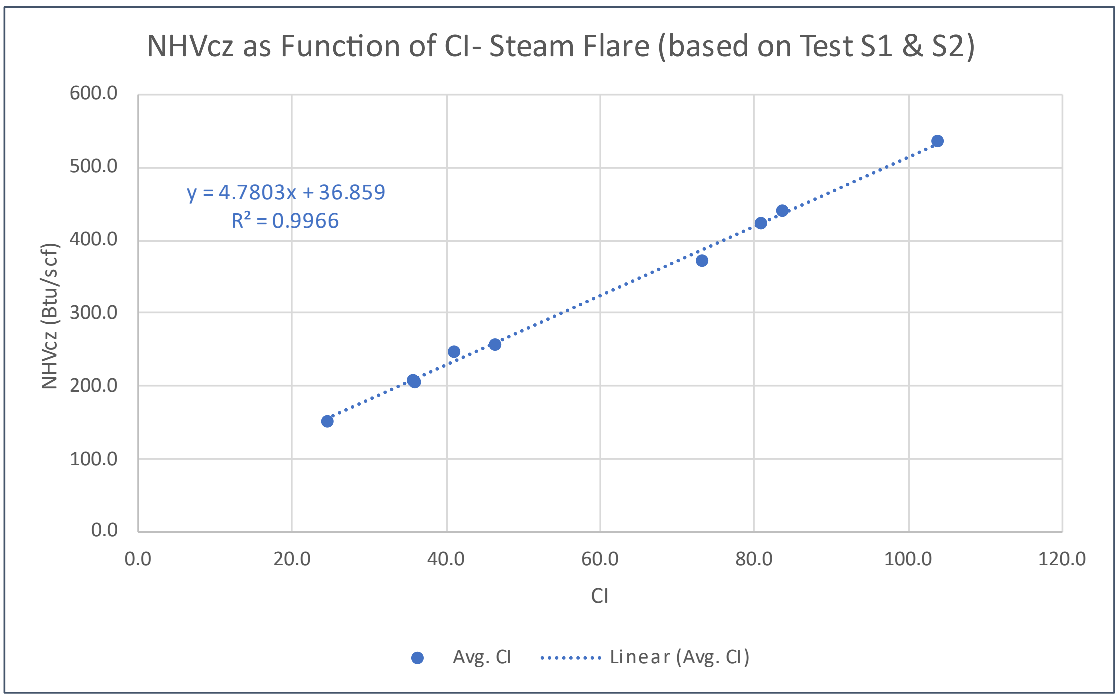


Figure 2. Example CI-NHV_{cz} calibration for steam assisted flares.

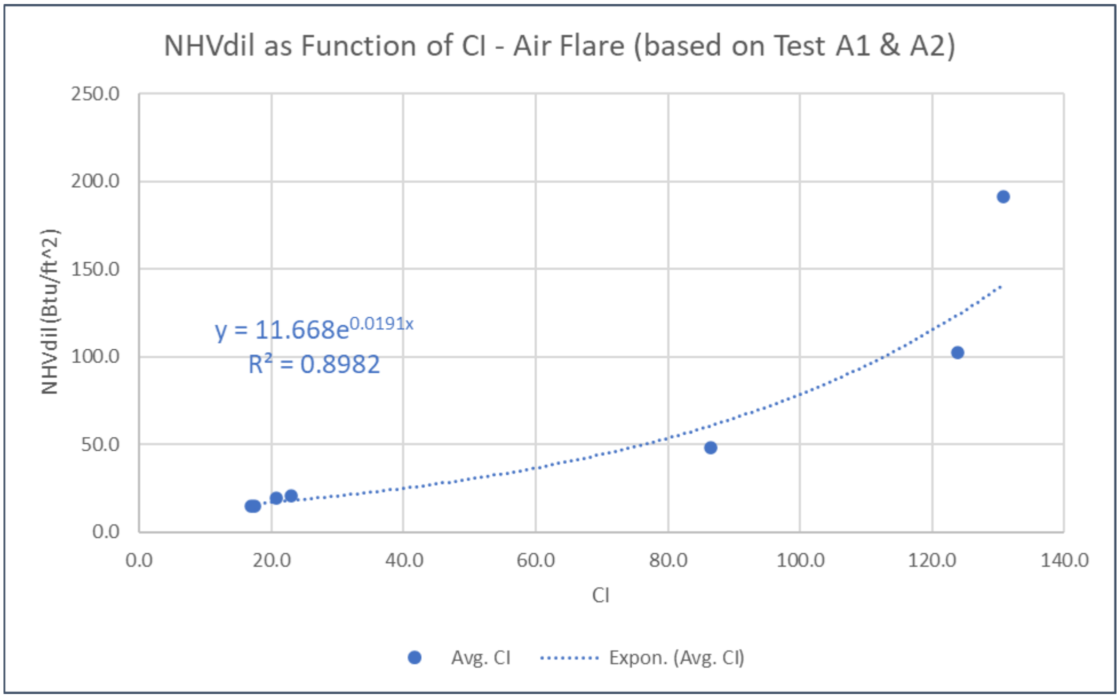


Figure 3. Example CI-NHV_{dil} calibration for air assisted flares.

11.0 Procedure

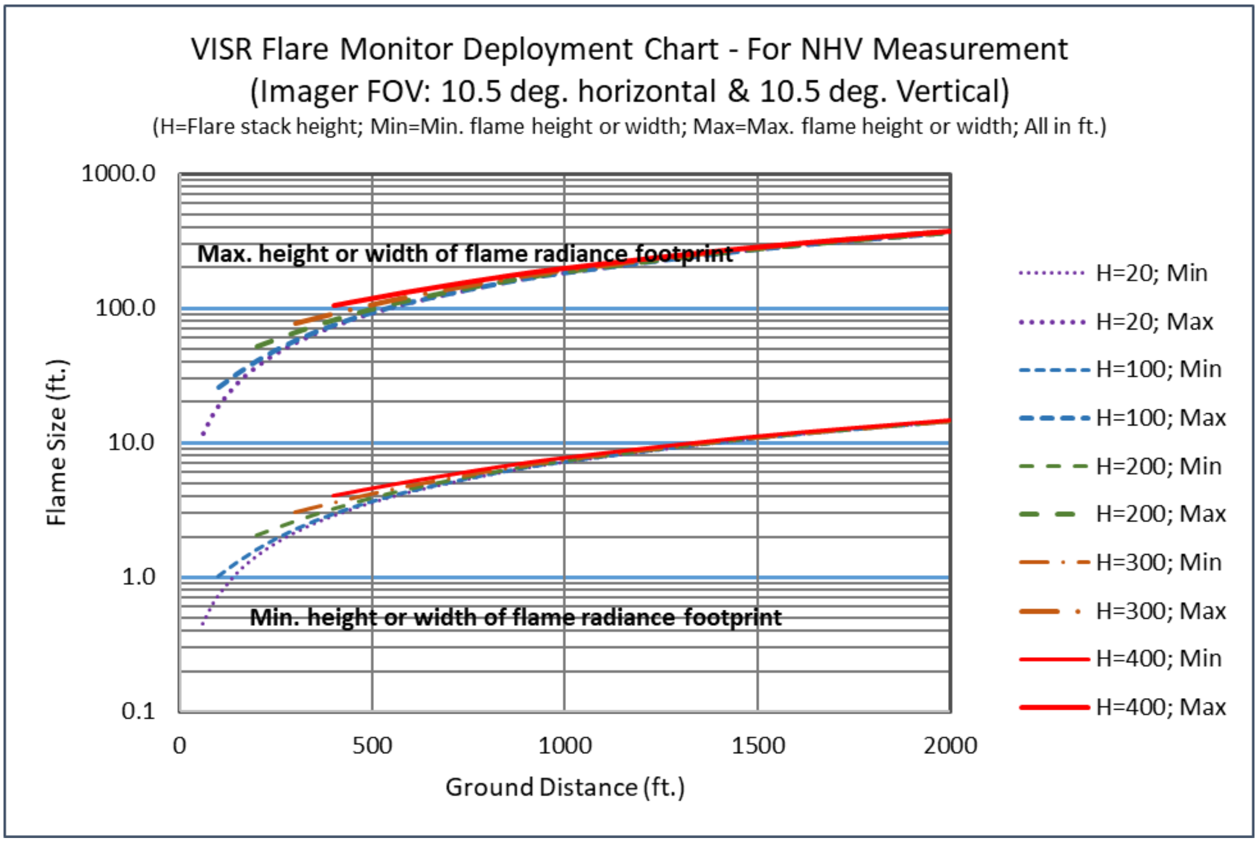
11.1 Siting the VISR imager

A clear line of sight from the VISR imager location to the flare tip is required. The acceptable distance from the VISR imager to the flare tip is a function of the following factors:

- VISR imager's optics (Field of View, or FOV, of the lens)
- VISR imager's pixel resolution
- Size of the expected flame (e.g. the cross-sectional area of its thermal footprint, not necessarily the cross-sectional area of its visible footprint).

When determining a suitable position for the VISR imager, the maximum allowable distance is the farthest distance which generates the minimum required flame pixels (as established during Method Calibration) for the smallest expected flame size (typically when the flare is in an idle or purge condition). The minimum allowable distance from the base of the flare to the VISR imager is the greater of: 1) height of the flare, 2) distance which captures the entire thermal footprint of the flare at it largest expected flame size.

In practical terms, these distance-based criteria can produce a wide range of acceptable distances for the VISR imager. For example, a VISR imager with pixel resolution of 128 x 128 can capture a flaring rate turndown ratio as high as 10,000:1 at a fixed optimum location. A VISR imager with a higher pixel resolution can cover even a higher flare turndown ratio. On the other hand, at a less optimal distance, the VISR imager will cover a lower flare turndown ratio. Because the maximum turndown ratio the imager can cover (e.g., 10,000:1) is higher than most flares, there is significant flexibility for siting the VISR imager, and rigorous engineering calculations to determine the location are generally not necessary. Simple trial and error (or prior experience) will generally suffice. For operators with no prior experience, manufacturer's recommendations should be followed. Figure 4 is provided as an example of a manufacturer's deployment chart for a specific VISR imager. In this example, if the VISR imager is positioned at a ground distance of 500 ft., it should be able to image a flare size as small as about 5 ft. and as large as 100 ft. in one dimension, which translates to volume high-to-low ratio of approximately 8,000:1 or flaring turndown ratio of 8,000:1.



Note 1: The expected flame height or width is based on the thermal image footprint of the flame, and can be significantly larger than the flame footprint visible to naked eyes.

Figure 4. Example of manufacturer's deployment chart for a specific VISR imager.

In addition to the distance, care should be taken to avoid locations which introduce reflective objects behind the flare flame. As a general guideline, the viewing angle between the VISR imager line of sight and the ground should be less than 45 degrees, preferably less than 30 degrees. A viewing angle which exceeds 45° increases the risk of the flare stack itself blocking the flame when the VISR imager is in an upwind position and the vent gas exit velocity is low.

11.2 *<u>Aiming and Focusing the VISR Imager</u>*

After installation of the VISR imager, aiming should be performed. This process will require a flame present to assess both the field of view and the focus. The VISR imager must be equipped with, or be capable of connecting to, a user interface that can display a video of the flame generated by the VISR imager. This function of video display is only necessary for the purpose of aiming and focusing and is not required for subsequent measurement of CI (or NHV). The VISR imager must be equipped with an adjustable mounting bracket to accommodate different viewing angles. The VISR imager must be aimed so that the base of the flame is located in the bottom 20% of the field of view and centered horizontally. Once the VISR imager is positioned, the position must be fixed and secured to avoid any drift in the aim.

The VISR imager must achieve focus per manufacturer's procedures. Alternatively, the VISR imager focus can be set to infinity provided the distance from the VISR imager to the flare tip is greater than the hyperfocal distance specified by the manufacturer.

11.3 *<u>Start Monitoring</u>*

The VISR method can be used for short term measurements (mobile) or permanently installed for continuous measurement. For short-term (mobile) measurements, data and associated DQIs will typically be recorded to the host computer (or laptop). For fixed installations, the monitoring data and associated DQIs will be transmitted to a host computer, a Programable Logic Controller (PLC), a plant Distributed Computing System (DCS), a data historian system, etc. In either mode, there should be a piece of software or firmware that performs automatic data reduction and validation so that the measurement results (flare CI and other flare performance metrics) are validated, stored, or transmitted.

12.0 Data Analysis and Calculations

The CI generated by the VISR method is expected to correlate to NHVcz in linear fashion (see Figure 2). Once the Method Calibration is established for a specific type of VISR imager (ref. Section 10.2), NHVcz can be calculated using the calibration equation, which has the following generic form:

$$NHVcz = a \times CI + b$$

Where a and b are constants established through Method Calibration described in Section 10.2.

For flares with perimeter air assist, the relevant compliance parameter is NHV_{dil}. The CI generated by the VISR method is expected to correlate to NHV_{dil} in a non-linear fashion (see Figure 3). In the case shown in Figure 3, the NHV_{dil} can be calculated using an exponential equation, i.e.,

$$NHVdil = a \times e^{b \times CI}$$

Where a and b are constants established through Method Calibration described in Section 10.2.

Users of the VISR method could opt to conduct their own CI-NHV calibration using procedures described in Section 10.2 to develop their own site-specific calibration equation, provided they have the instrumentation needed to provide the reference method specified in 40 CFR 63.670(m).

Calculation of CI, NHV (either NHVcz or NHVdil), and DQIs for the VISR method are automated.

13.0 Method Performance

For steam assisted flares, the accuracy of the VISR method (measured as an average difference between the VISR method NHV_{cz} and the reference method NHV_{cz}) is in the range of -4.4% to 1.5%. For air assisted flares, the accuracy of the VISR method (measured as an average different between the VISR method NHVdil and the reference method NHV_{dil}) is in the range of -8.2% to -4.1%. when the NHV_{dil} is in the range of 10-150 Btu/ft^2. This NHVdil range is well suited for compliance monitoring with respect to the regulatory threshold of 22 Btu/ft^2. The precision of the method (measured as Relative Standard Deviation, RSD, for repeated tests under the same flare conditions) is within 7.3% and 12.2% for NHV_{cz} and NHV_{dil}, respectively, and below the 20% threshold required.

The measurement parameters, measurement ranges, precision, and accuracy of this method are summarized in the table below.

	NHV_{cz} Measurement (Btu/scf)	NHV_{dil} Measurement (Btu/ft^2)
Range	150-550	10-150
Precision, as RSD	10%	15%
Accuracy	+/- 5%	+/- 10%

14.0 Pollution Prevention

This section does not apply because no chemical reagents or supplies are used in this method.

15.0 Waste Management

This section does not apply because no waste is generated by this this method.

16.0 References

See accompanying documents listed below:

- Presentation entitled “VISR Method Testing at John Zink in Nov. 2022 – Preliminary Results for Discussions”.

- Category III QA Project Plan, "VISR Precision Test with Additional Matrix Elements: John Zink Facility", prepared for U.S. EPA by Eastern Research Group, Inc., September 2022.

17.0 Tables, Diagrams, Flowcharts and Validation Data

When used, tables, diagrams, flowcharts, and validation data are presented in appropriate individual sections above.