



CALCULATING $NHV_{cz-limit}$ AND NHV_{cz} FOR STEAM-ASSISTED FLARES

All abbreviations, constants, and variables are defined in the Key on Page 6 of this Appendix.

Steps in the Calculations

Step 1: Determine the Lower Flammability Limit (“LFL”) of Each Individual Vent Gas Compound

Take the LFL values of each individual Vent Gas compound from Table 1 in this Appendix.

Step 2: Calculate the LFL of the vent gas mixture

The average lower flammability limit of the vent gas is calculated by Le Chatelier’s equation shown below as Equation 1. This calculation uses the weighted average of the LFLs of the individual compounds weighted by their volume fraction of the vent gas. All inerts, including nitrogen, are assumed to have an infinite lower flammability limit (e.g. $LFL_{N_2} = \infty$).

$$LFL_{vg} = \frac{1}{\sum_{i=1}^n \left(\frac{x_i}{LFL_i} \right)} \quad \text{Equation 1}$$

Step 3: Determine the Net Heating Value of the Vent Gas (NHV_{vg})

If a Gas Chromatograph is used: The net heating value of the vent gas is calculated and reported from the GC at the conclusion of each analytical cycle (~10-15 minutes). Equation 2 is used by the GC to calculate the vent gas net heating value from each individual compound net heating value. Individual compound volume fractions, except for water, are measured directly by the GC. A company is not required to measure water in Vent Gas. If a company chooses to measure water, then: (i) if the water measurement is taken upstream of a knock-out drum, then water does not have to be included in the calculation of NHV_{vg} ; (ii) if no knock-out drum exists or if the water measurement is taken after the knock-out drum, then the company must include water in the calculation of NHV_{vg} and adjust the concentration of the compounds measured by the GC to a wet basis. Individual compound net heating values, including water, are listed in Table 1 of this Appendix.

$$NHV_{vg} = \sum_{i=1}^n (x_i \cdot NHV_i) \quad \text{Equation 2}$$

If a Net Heating Value Analyzer/Calculator is used: Use the measured value.

NOTE: Table 1 includes two alternative values for the Net Heating Value of hydrogen: the actual NHV of hydrogen (274 BTU/scf) and an “adjusted” NHV of hydrogen (1212 BTU/scf).

Companies have the option of using either in calculating NHV_{vg} ; however, whichever option is selected also must be used in calculating NHV_{cz} .

Step 4: Calculate the NHV_{vg} at its LFL (NHV_{vg-LFL})

Using LFL_{vg} from Equation 1 and NHV_{vg} from Equation 2, the NHV_{vg-LFL} is calculated by Equation 3.

$$NHV_{vg-LFL} = NHV_{vg} \cdot LFL_{vg} \quad \text{Equation 3}$$

Step 5: Multiply NHV_{vg-LFL} by the Combustion Efficiency Multipliers to calculate the $NHV_{cz-limit}$

The Net Heating Value of the Gases in the Combustion Zone (NHV_{cz}) of a Flare that is needed to ensure an acceptable Combustion Efficiency is determined by multiplying NHV_{vg-LFL} by Combustion Efficiency Multipliers appropriate to the flare category and the volume percent of hydrogen in the Vent Gas as defined in Table 2.

The Net Heating Value of Combustion Zone Gas Limit is calculated as follows:

$$NHV_{cz-limit} = (A + B \cdot x_{propylene}) \cdot NHV_{vg-LFL} \quad \text{Equation 4}$$

Step 6: Calculate the Net Heating Value of the Combustion Zone Gas (NHV_{cz})

The NHV in the combustion zone (NHV_{cz}) combines the $NHVs$ of the Vent Gas, pilot gas, and steam and is calculated by Equation 5a (based on mass flow measurement) or 5b (based on volumetric flow measurement). These two equations are equivalent for combustion zone conditions, as shown in Addendum A to this Appendix. The NHV of steam is assumed to be zero. Vent Gas flow rate ($\dot{m}_{vg}$ or Q_{vg}) and steam flow rate ($\dot{m}_s$ or Q_s) are measured by on-line flow meters. The pilot gas flow rate ($\dot{m}_{pg}$ or Q_{pg}) is constant for each flare and set by an orifice.

$$NHV_{cz} = \frac{\left(\frac{\dot{m}_{vg} \cdot NHV_{vg}}{MW_{vg}}\right) + \left(\frac{\dot{m}_{pg} \cdot NHV_{pg}}{MW_{pg}}\right)}{\left(\frac{\dot{m}_{vg}}{MW_{vg}}\right) + \left(\frac{\dot{m}_{pg}}{MW_{pg}}\right) + \left(\frac{\dot{m}_s}{MW_{H_2O}}\right) + \left(\frac{\dot{m}_{air}}{MW_{air}}\right)} \quad \text{Equation 5a}$$

OR

$$NHV_{cz} = \frac{(Q_{vg} \cdot NHV_{vg}) + (Q_{pg} \cdot NHV_{pg})}{Q_{vg} + Q_{pg} + Q_s + Q_{air}} \quad \text{Equation 5b}$$

The values for $\dot{m}_s$, $\dot{m}_{air}$, Q_s and Q_{air} are determined as follows based on the type of flare:

Steam-Assisted Flare without a Minimum Steam Reduction System (“MSRS”)

$\dot{m}_s$ or Q_s = measured value

$\dot{m}_{air}$ or Q_{air} = 0

Steam-Assisted Flare with MSRS

$\dot{m}_s$ or Q_s = measured value

$\dot{m}_{air}$ or Q_{air} = result from Equation 13 in Step 6a

OR

$\dot{m}_{air}$ or Q_{air} = 0 with vendor certification that the MSRS equipment installed on the flare is not capable (even at minimum vent gas flow) of inspiring more than twice the stoichiometric volume of air into the vent gas.

The molecular weight of the vent gas (MW_{vg}) is calculated by the GC using Equation 6. An on-line ultrasonic flow meter may also be used to calculate MW_{vg} . Individual compound molecular weights are listed in Table 1 of this Appendix.

$$MW_{vg} = \sum_{i=1}^n (x_i \cdot MW_i) \quad \text{Equation 6}$$

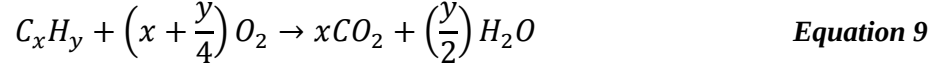
The NHV of the pilot gas (NHV_{pg}) and MW of the pilot gas (MW_{pg}) are calculated using Equations 7 and 8, respectively. These calculations are similar to the vent gas calculations, except the individual compound volume fractions are that of the pilot gas and not the vent gas. Individual compound volume fractions are measured by laboratory analysis of a pilot gas sample, or may be taken from the natural gas supplier’s laboratory certificate of analysis.

$$NHV_{pg} = \sum_{i=1}^n (pg_i \cdot NHV_i) \quad \text{Equation 7}$$

$$MW_{pg} = \sum_{i=1}^n (pg_i \cdot MW_i) \quad \text{Equation 8}$$

Step 6a: Calculation of air mass flow rate for flares equipped with MSRS.

The complete combustion of an organic compound comprised of a combination of carbon and hydrogen atoms is shown in Equation 9:



Note: x and y values for each compound are found in Table 1 of this Appendix.

Therefore, the stoichiometric oxygen molar flow rate (moles/hr) for any given combustible compound flow is defined by Equation 10a (mass basis) or Equation 10b (volumetric basis):

$$n_{O_2-stoich} = x_j \left(\frac{\dot{m}_{vg}}{MW_{vg}} \right) \left(x + \frac{y}{4} \right) \quad \text{Equation 10a}$$

OR

$$\dot{n}_{O_2-stoich} = x_j \left(\frac{Q_{vg}}{385.5} \right) \left(x + \frac{y}{4} \right) \quad \text{Equation 10b}$$

The stoichiometric oxygen mass flow rate for the vent gas (lb/hr) or stoichiometric oxygen volumetric flow rate for the vent gas (scfh) is given by Equation 11a (mass basis) or 11b (volumetric basis).

$$\dot{m}_{O_2-stoich-vg} = MW_{O_2} * \sum_{j=1}^n n_{O_2-stoich_j} \quad \text{Equation 11a}$$

OR

$$Q_{O_2-stoich-vg} = 385.5 * \sum_{j=1}^n n_{O_2-stoich_j} \quad \text{Equation 11b}$$

The stoichiometric air mass flow rate (lb/hr) or stoichiometric air volumetric flow rate (scfh) for the vent gas is given by Equation 12a (mass basis) or Equation 12b (volumetric basis).

$$\dot{m}_{air-stoich-vg} = \frac{MW_{air}}{0.21 \cdot MW_{O_2}} * \dot{m}_{O_2-stoich-vg} \quad \text{Equation 12a}$$

OR

$$Q_{air-stoich-vg} = \frac{Q_{O_2-stoich-vg}}{0.21} \quad \text{Equation 12b}$$

The air mass flow (lb/hour) or air volumetric flow (scfh) used in Equation 5a or 5b is given by subtracting two times the stoichiometric air from the total air provided by the MSRS. This is shown in Equation 13a and 13.b.

$$\dot{m}_{air} = \dot{m}_{air-MSRS} - (2 * \dot{m}_{air-stoich-vg}) \quad \text{Equation 13a}$$

OR

$$Q_{air} = Q_{air-MSRS} - (2 * Q_{air-stoich-vg}) \quad \text{Equation 13b}$$

The equation for $\dot{m}_{air-MSRS}$ or $Q_{air-MSRS}$ is specific to the MSRS installed and must be provided by the MSRS vendor. The factor of 2 used in Equation 13 is based on the best information available as of the Date of Lodging. If new information becomes available thereafter, the parties may modify that factor; any such modification does not constitute a material modification to the Consent Decree.

If $\dot{m}_{air} < 0$ then $\dot{m}_{air} = 0$

OR

If $Q_{air} < 0$ then $Q_{air} = 0$

Step 7: Ensure that during flare operation, $NHV_{cz} \geq NHV_{cz-limit}$

The flare must be operated to ensure that NHV_{cz} is equal to or above $NHV_{cz-limit}$ to ensure acceptable combustion efficiency. Equation 14 shows this relationship.

$$NHV_{cz} \geq NHV_{cz-limit} \quad \text{Equation 14}$$

Key to the Abbreviations:

0.21 = mole fraction of oxygen in air (0.21 lb-mol O_2 /lb-mol air)
385.5 = conversion from pound moles to standard cubic feet (385.5 scf/lb-mol)
 A = overall combustion efficiency multiplier for NHV_{vg-LFL} (unitless)
 B = propylene combustion efficiency multiplier for NHV_{vg-LFL} (unitless)
 C_{vg} = concentration of VOC in the vent gas (vol %)
 i = individual numbered compound from column i in Table 1 (unitless)
 j = individual numbered compound from column j in Table 1 (unitless)
 k = individual gaseous component of the combustion zone (unitless)
 LFL_i = lower flammability limit of individual compound (vol %)
 LFL_{vg} = lower flammability limit of vent gas (vol %)
 $\dot{m}_{air}$ = mass flow rate of air (lb/hr)
 $\dot{m}_{air-MSRS}$ = total mass flow rate of air introduced by an MSRS (lb/hr)
 $\dot{m}_{air-stoich-vg}$ = stoichiometric air mass flow for the vent gas (lb/hr)
 $\dot{m}_k$ = mass flow rate of individual combustion zone gas component (lb/hr)
 $\dot{m}_{O_2-stoich-vg}$ = stoichiometric oxygen mass flow for the vent gas (lb/hr)
 $\dot{m}_{pg}$ = mass flow rate of pilot gas (lb/hr)
 $\dot{m}_s$ = mass flow rate of total steam (lb/hr)
 $\dot{m}_{vg}$ = mass flow rate of vent gas (lb/hr)
 $\dot{n}_{O_2-stoich}$ = stoichiometric oxygen molar flow for an individual compound (mol/hr)
 MW_{H_2O} = molecular weight of water (18.02 lb/lb-mol)
 MW_i = molecular weight of individual compound (lb/lb-mol)
 MW_k = molecular weight of individual combustion zone gas component (lb/lb-mol)
 MW_{O_2} = molecular weight of oxygen (32.0 lb/lb-mol)
 MW_{air} = molecular weight of air (28.9 lb/lb-mol)
 MW_{pg} = molecular weight of pilot gas (lb/lb-mol)
 MW_{vg} = molecular weight of vent gas (lb/lb-mol)
 n = list of individual compounds from Table 1 (unitless)
 NHV_{cz} = net heating value of the combustion zone (BTU/scf)
 NHV_i = net heating value of individual compound (BTU/scf)
 NHV_{vg-LFL} = net heating value vent gas at lower flammability limit (BTU/scf)
 $NHV_{cz-limit}$ = limit net heating value of the combustion zone (BTU/scf)
 NHV_{pg} = net heating value of pilot gas (BTU/scf)
 NHV_{vg} = net heating value of vent gas (BTU/scf)
 P_{cz} = pressure of combustion zone gas (psia)
 P_{std} = ambient pressure at standard conditions (14.696 psi)
 pg_i = individual compound volume fraction in pilot gas (vol fraction)
 $Q_{air-MSRS}$ = total volumetric flow rate of air introduced by an MSRS (scfh)
 $Q_{air-stoich-vg}$ = stoichiometric air volumetric flow for the vent gas (scfh)
 Q_k = individual vent gas component volumetric flow rate (scfh)
 $Q_{k,acf}$ = individual vent gas component volumetric flow rate (ft^3/hr)
 $Q_{O_2-stoich-vg}$ = stoichiometric oxygen volumetric flow for the vent gas (scfh)
 Q_{vg} = vent gas volumetric flow rate (scfh)
 Q_{pg} = pilot gas volumetric flow rate (scfh)
 Q_s = steam volumetric flow rate (scfh)
 Q_{air} = air volumetric flow rate (scfh)
 R = gas constant ($10.73 ft^3 \cdot psi/lb-mol \cdot R$)
 T_{cz} = absolute temperature of combustion zone gas ($^{\circ}R$)
 T_{std} = absolute temperature at standard conditions ($528^{\circ}R$)
 x = moles of carbon per mole of C_xH_y (mol/mol)
 x_i = individual compound volume fraction in the vent gas (vol fraction)
 x_j = individual combustible compound volume fraction in the vent gas (vol fraction)
 $x_{propylene}$ = volume fraction of propylene in the vent gas (vol fraction)
 y = moles of hydrogen per mole of C_xH_y (mol/mol)

Table 1
Individual Compound Properties

i⁽¹⁾	j	Compound	NHV_i (Btu/scf)	MW_i (lb/lbmol)	LFL_i (vol fraction)	C_x	H_y
1	1	Hydrogen	274 or 1212 ⁽²⁾	2.02	0.040	0	2
2	-	Oxygen	0	32.00	∞	n/a	n/a
3	-	Nitrogen	0	28.01	∞	n/a	n/a
4	-	CO ₂	0	44.01	∞	n/a	n/a
5	-	CO	316	28.01	0.125	n/a	n/a
6	2	Methane	896	16.04	0.050	1	4
7	3	Ethane	1595	30.07	0.030	2	6
8	4	Ethylene	1477	28.05	0.027	2	4
9	5	Acetylene	1404	26.04	0.025	2	2
10	6	Propane	2281	44.10	0.021	3	8
11	7	Propylene	2150	42.08	0.024	3	6
12	8	iso-Butane	2957	58.12	0.018	4	10
13	9	n-Butane	2968	58.12	0.018	4	10
14	10	iso-Butene	2928	56.11	0.018	4	8
15	11	trans-Butene	2826	56.11	0.017	4	8
16	12	cis-Butene	2830	56.11	0.016	4	8
17	13	1,3-Butadiene	2690	54.09	0.020	4	6
18	14	Pentane+ (C ₅ +)	3655	72.15	0.014	5	12
19	-	Water ⁽³⁾	0	18.02	∞	n/a	n/a

¹ i=all compounds, j=organic compounds and hydrogen

² If using an H₂-adjusted NHV_{vg} and NHV_{cz}, then use 1212 BTU/scf for hydrogen.

³ A GC does not measure water. If water is measured by means of another instrument, the properties of water listed in this row shall be used.

Note: Benzene is not required to be speciated by the Gas Chromatograph for this refinery settlement (see Appendix 1.9) because benzene is present in the Vent Gas only in *de minimis* quantities. Because benzene speciation is not required, it is not listed in Table 1 of this Appendix. The Vent Gas composition involved in other future settlements should be evaluated on a case-by-case basis to determine if benzene speciation should be required.

Table 2
Combustion Efficiency Multipliers for Steam-Assisted Flares:
Variables Based on Minimum Steam Requirements
and VOC Concentration in the Vent Gas

Minimum Steam	VOC Vent Gas Concentration	A Multiplier	B Multiplier*	
			Condition X	Condition Y
≤ 1000 lb/hr	≤ 20.0%	6.45	4.0	0.0
≤ 1000 lb/hr	> 20.0%	6.85	4.0	0.0
> 1000 lb/hr	≤ 20.0%	7.1	4.0	0.0
> 1000 lb/hr	> 20.0%	7.4	4.0	0.0

*The B Multiplier used depends on the relationship of hydrogen and propylene in the vent gas as follows:
Condition X: $3 \leq \text{H}_2\% \leq 8$ and $\text{Propylene}\% \geq \text{H}_2\%$ (all percentages are volume or mole percentages)
Condition Y: Any condition not meeting the requirements for Condition X.

Note: The specifications for Condition X are based on the best information available as of the Date of Lodging. If new information becomes available thereafter, the parties may modify these conditions; any such modification does not constitute a material modification to the Consent Decree.

The “VOC Vent Gas Concentration” shall be calculated on an annual average basis as follows:

$$C_{vg} = \sum_{j=4}^n x_j * 100 \quad \text{Equation 15}$$

Note: The summation does not include methane or ethane.

Addendum A

Verification of Equation 5a and Equation 5b Equivalency

In this Appendix, all gaseous flows (i.e, vent gas, steam, pilot gas, and air) may be measured on either a mass basis (lb/hr) or a volumetric basis (scfh). Depending on which measurement methodology is used, different versions of some equations must be used. These versions are designated with an “a” or “b” (e.g. Equation 5a or 5b). In all cases, these equations are equivalent. This Addendum demonstrates the equivalence of the two methods for calculating NHV_{cz} .

Equation 5b uses volumetric flow rates for the calculation of NHV_{cz} :

$$NHV_{cz} = \frac{(Q_{vg} * NHV_{vg}) + (Q_{pg} * NHV_{pg})}{Q_{vg} + Q_{pg} + Q_s + Q_{air}} \quad \text{Equation 5b}$$

The ideal gas law provides a method for determining volumetric flow rate of a specific gas, k , in the combustion zone at standard conditions:

$$Q_k = Q_{k,acf} * \frac{P_{cz}}{P_{std}} * \frac{T_{std}}{T_{cz}} \quad \text{Equation A1}$$

$$Q_{k,acf} = \frac{\dot{m}_k RT_{cz}}{MW_k P_{cz}} \quad \text{Equation A2}$$

$$Q_k = \frac{\dot{m}_k RT_{cz}}{MW_k P_{cz}} * \frac{P_{cz}}{P_{std}} * \frac{T_{std}}{T_{cz}} = \frac{\dot{m}_k RT_{std}}{MW_k P_{std}} \quad \text{Equation A3}$$

$$Q_k = \frac{\dot{m}_k * 10.73 * 528}{MW_k * 14.696} = 385.5 \frac{\dot{m}_k}{MW_k} \quad \text{Equation A4}$$

Substitution of this expression into Equation 5b gives NHV_{cz} in terms of mass flow:

$$NHV_{cz} = \frac{\left(385.5 \frac{\dot{m}_{vg}}{MW_{vg}} * NHV_{vg}\right) + \left(385.5 \frac{\dot{m}_{pg}}{MW_{pg}} * NHV_{pg}\right)}{385.5 \frac{\dot{m}_{vg}}{MW_{vg}} + 385.5 \frac{\dot{m}_{pg}}{MW_{pg}} + 385.5 \frac{\dot{m}_s}{MW_{H_2O}} + 385.5 \frac{\dot{m}_{air}}{MW_{air}}} \quad \text{Equation A5}$$

Because the combustion zone is well-mixed, each gaseous component of the combustion zone is at the same temperature and pressure. Thus, the last expression reduces to Equation 5a:

$$NHV_{cz} = \frac{\left(\frac{\dot{m}_{vg} \cdot NHV_{vg}}{MW_{vg}}\right) + \left(\frac{\dot{m}_{pg} \cdot NHV_{pg}}{MW_{pg}}\right)}{\left(\frac{\dot{m}_{vg}}{MW_{vg}}\right) + \left(\frac{\dot{m}_{pg}}{MW_{pg}}\right) + \left(\frac{\dot{m}_s}{MW_{H_2O}}\right) + \left(\frac{\dot{m}_{air}}{MW_{air}}\right)} \quad \text{Equation 5a}$$

This demonstrates the equivalence of Equations 5a and 5b.